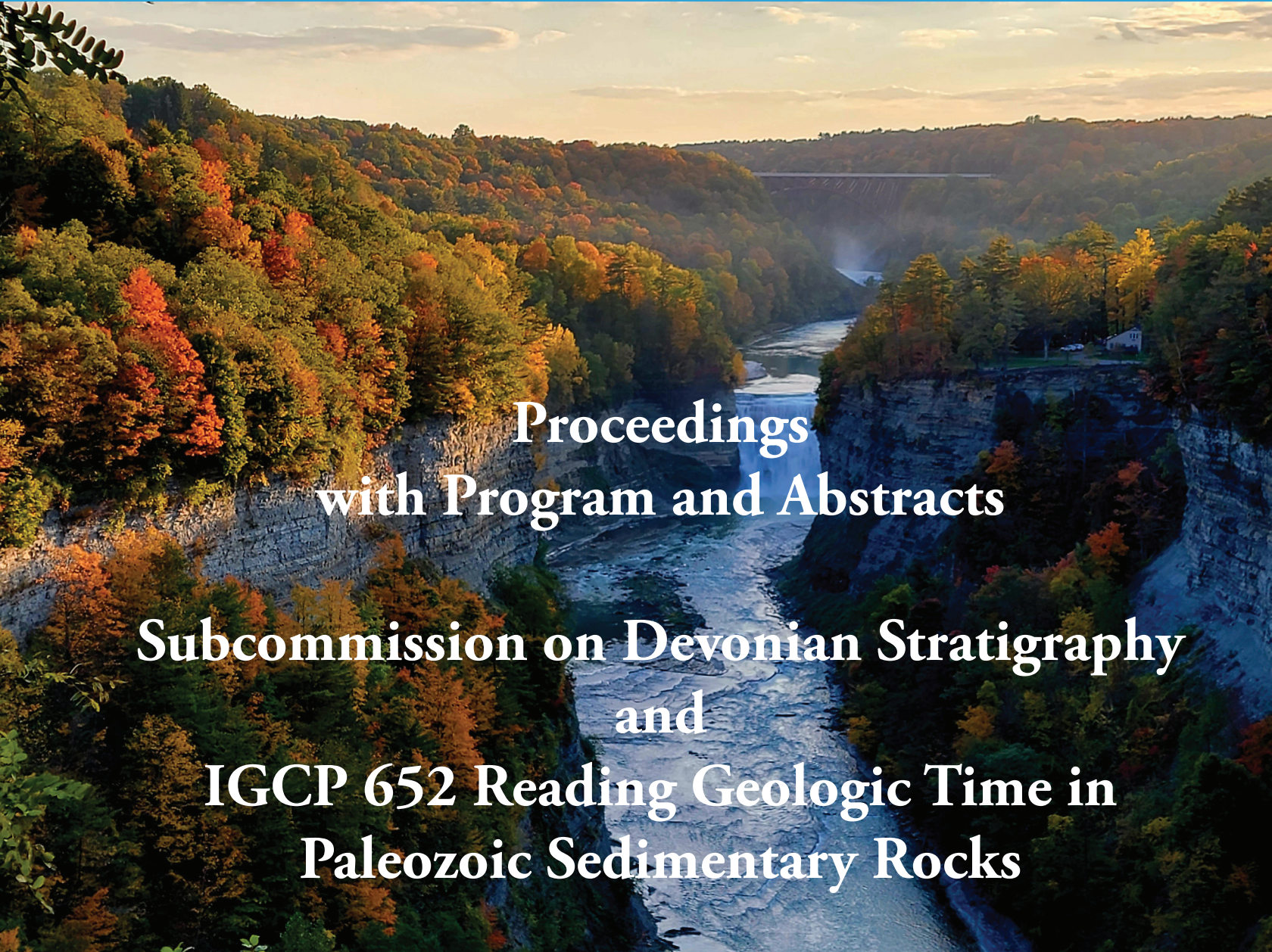


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Number 411, January 2025



Proceedings
with Program and Abstracts

Subcommission on Devonian Stratigraphy
and
IGCP 652 Reading Geologic Time in
Paleozoic Sedimentary Rocks

Edited by D. Jeffrey Over

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On the cover: View from Inspiration Point, looking southwest at middle and upper falls of the Genesee River in Letchworth State Park. Upper Devonian strata of the West Falls Group; upper falls is formed on the Nunda Sandstone over the West Hill and Gardeau formations. Photograph by Robert Jacobi.

Bulletins of **American Paleontology**

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Subcommission on Devonian Stratigraphy and IGCP 652 Reading Geologic Time in Paleozoic Sedimentary Rocks

Geneseo, New York, 27 July–06 August 2023

Edited by
D. Jeffrey Over



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CONTENTS

Volume Editors, Consultants, and Contributors	4
Meeting Organizers	4
Subcommission on Devonian Stratigraphy	5
IGCP 652—Reading Geological Time in Sedimentary Rocks	5
Geneseo, New York	5
 General Meeting Schedule	 6
Field Trip Itineraries	6
Program	7
 Contributed Papers	
Regional mudstone darkening effect: overlooked regional maturity measure in outcrop and cores	13
G. C. Baird, C. E. Brett, and D. R. Blood	
 Stratigraphy, sedimentology, and diagenesis of centimeter-scale black shale beds and associated strata in the uppermost deposits of the Upper Devonian (Famennian) Hanover Shale, western New York, U.S.A.	 23
D. Randy Blood, Scott D. McCallum, and Ashley S. B. Douds	
 Northwest thinning of Famennian beds in western New York State: How it enables wider recognition of the west-dipping Laona siltstone and poses questions for Lake Erie and adjacent Canada.	 43
Raymond C. Vaughan	
 Abstracts	 65
 Index	 134
 Group Photo	 137

Supplementary information available online at <https://www.priweb.org/devonian-ny/>.

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SUBCOMMISSION ON DEVONIAN STRATIGRAPHY

The International Union of Geosciences (IUGS), amongst other tasks, features the International Commission on Stratigraphy (ICS), which is composed of subcommissions on individual systems and the Precambrian that build the formal, officially, and internationally defined time units (chronostratigraphic units) of Earth History. The Subcommission on Devonian Stratigraphy has been one of the most active subcommissions of the ICS since it formed in 1973, which is mostly based on a highly successful integration of all leading specialists of Devonian stratigraphy, regardless of their specialization or their origin. SDS currently comprises three officers (chairman, vice-chairman, secretary/second vice chairman), 18 Titular Members, and ~80 Corresponding Members, covering all continents and all stratigraphic methods.

Official website of the Subcommission on Devonian Stratigraphy: <http://devonian.stratigraphy.org/>.

IGCP 652—READING GEOLOGICAL TIME IN SEDIMENTARY ROCKS

The IGCP is a cooperative enterprise of United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Union of Geological Sciences (IUGS) and has been stimulating comparative studies in the Earth Sciences since 1972. After three decades of successful work, the “International Geological Correlation Programme” continued, as “International Geoscience Programme.” To this day, IGCP has made research results available to a huge number of scientists around the world with ~400 projects.

The thesis of IGCP 652 is that major events punctuated the Paleozoic, such as ecological crises and diversifications, shifts in ocean chemistry, and climatic changes. One of the key obstacles in understanding these events is the difficulty of providing precise estimates of the duration represented by a sequence of Paleozoic sedimentary rocks. This lack of temporal precision severely hampers the evaluation of forcing mechanisms and rates of climatic, ecological, or biogeochemical changes. It is therefore essential to first improve the Paleozoic timescale to then unravel the history of the Paleozoic Earth system. Cyclostratigraphy is a powerful chronometer, based on the detection of the Milankovitch cycles in the sedimentary record. Those cycles result from periodic variations in the Earth-Sun system, affecting the distribution of solar energy over the planet influencing Earth’s climate on time scales between 104 and 106 years. Through the integration of this astronomical time scale with biostratigraphy and radioisotopic dating, this project intends to document the environmental evolution during the Paleozoic with a focus on the Ordovician to Devonian (485–359 million years). It gathers participants (> 200) from all over the world (36 countries) and promotes the participation of young scientists and scientists from developing countries.

Website of IGCP Project 652: http://www.geolsed.ulg.ac.be/IGCP_652/index.html.

Business Meeting SDS and IGCP 652: 30 July 2023.

GENESEO, NEW YORK

New York State has been the focus of Devonian studies for over 200 years. 2023 marks the 200th anniversary of several publications by Amos Eaton (and Eaton and Beck) that described the geology of Albany County as well as the lands between the Susquehanna and Hudson rivers. It is fitting that the SDS recognize and celebrate this with a return to New York and the type Devonian of North America.

Geneseo—sandy bank—was founded in 1832 in the historic lands of the Seneca Nation in the rural western Finger Lakes of New York State. It is the seat of Livingston County and home of the State University of New York College at Geneseo. The National Historic Landmark village, with a population of 9,000, is in the heart of rich farm land sitting above the broad Genesee River Valley adjacent to Letchworth State Park that features a deep gorge cut into Upper Devonian strata. Toronto, Canada (3 hours), Buffalo, New York (1.2 hours), and Rochester, New York (40 minutes) are nearby metropolitan areas. In July, the average high temperature is 80°F (27°C) and the low temperature is 60°F (16°C). It rains one in four days through the month.

GENERAL MEETING SCHEDULE

- 26 July Arrive Cleveland, Ohio for pre-meeting field trip; departure from Geneseo and Rochester at 1:00 pm
- 27 July Field trip departs, Upper Devonian strata; spend night in Erie, Pennsylvania
- 28 July Field trip, Upper Devonian strata; spend night in Fredonia, New York
- 29 July Field trip, Upper Devonian strata; spend night in Geneseo, New York
Non-field trip conference participants arrive in Geneseo; welcome gathering at Livingston Lanes, 4260 Lakeville Road
- 30 July Conference begins, stay in Geneseo
- 31 July Intra-conference field trip; Upper Devonian strata or Niagara Falls, stay in Geneseo, New York
- 01 August Conference, stay in Geneseo
- 02 August Field trip to Lower and Middle Devonian strata and PRI-MOTE in Ithaca; banquet; spend night in Ithaca, New York
- 03 August Field trip, Middle Devonian strata; spend night in Tully, New York
- 04 August Field trip, Middle Devonian strata; spend night in Schoharie, New York
- 05 August Field trip, Lower and Middle Devonian strata; spend night in Saugerties, New York
- 06 August Field trip, Lower and Middle Devonian strata; spend night in Saugerties, New York; end of field trip
- 07 August Return to Geneseo/Rochester; transport to travel hubs

FIELD TRIP ITINERARIES

Pre-meeting Field Trip: 26–29 July

Features will be the Devonian-Carboniferous boundary, clastic strata in northeastern Ohio and northwestern Pennsylvania, Upper Devonian offshore clastic-dominated strata in western New York that contain the Middlesex event, Rhinestreet event, Kellwasser bed equivalents, and the Frasnian-Famennian boundary.

- 26 July Depart Geneseo or Rochester 1:00. Arrive La Quinta on 150th Street and I-71, 4222 W 150th St, Cleveland, OH 44135, (216) 251-8500 where rooms for participants have been reserved.
- 27 July Depart from La Quinta Inn at 8:00. Stops in greater Cleveland, Ohio area. Dinner at Black Jax Sports Bar. Lodging at Quality Inn Erie, PA.
- 28 July Depart Quality Inn Erie at 8:00. Stops in Union City, PA, Titusville, PA, and Panama, NY. Dinner at Buddy Brewster's Ale House, Lodging at Quality Inn Fredonia.
- 29 July Depart Quality Inn Fredonia at 8:00. Stops in Silver Creek, NY, Pike Creek, NY, Sturgeon Point, NY, and Eden, NY. Dinner in Eden, NY. Lodging as arranged by participants in Geneseo.

Intrameeting Field Trip

Field trip to Frasnian-Famennian boundary strata in northern Pennsylvania or Niagara Falls and Silurian strata; includes transportation and lunch.

Post-Meeting Field Trip: 02–06 August

Features will be the disconformable Devonian-Silurian contact in western New York, Middle Devonian reef, Middle Devonian black shales, platform clastic and carbonates through the Finger Lakes region, and then Lower and Middle Devonian carbonate- to siliciclastic-dominated to thick terrestrial strata in eastern New York State. The trip will start in Geneseo, New York, and finish in Catskill, New York, ~3 hr north of New York City. Transportation will be provided back to Geneseo or Rochester. Participants can also opt to be dropped off in Albany, Hudson, or Poughkeepsie, where the bus or train services New York City.

- 02 August Depart Quality Inn Geneseo at 8:00. Stops in LeRoy, NY, Geneseo, NY, Trumansburg, NY, Banquet at PRI-Museum of the Earth. Lodging at Quality Inn Ithaca.
- 03 August Depart Quality Inn Ithaca at 8:00. Dinner at Heuga's Alpine Restaurant.
- 04 August Depart Quality Inn Tully at 8:00. Dinner at Bull's Head Inn.
- 05 August Depart Quality Inn Schoharie at 8:00. Dinner at Zicatellas.
- 06 August Depart Comfort Inn Saugerties at 8:00. Dinner at Hunter Mountain Brewery (must arrive by 6:30).
- 07 August Depart Comfort Inn Saugerties at 8:00.

PROGRAM

30 July 2023 (Sunday)—Newton Hall 204 on the Campus of SUNY Geneseo

8:30 WELCOME AND INTRODUCTION
President Denise Battles and D. Jeffrey Over

Devonian Stratigraphy and Structure—Linda Ivany and Nicholas Hogancamp, presiding

8:45 THE DEVONIAN IN NEW YORK AND NORTH AMERICA/LAURENTIA
Ver Straeten, C. A.

9:15 BASAL EMSIAN GSSP – POSSIBILITIES IN THE PRAGUE SYNFORM
Slavík, L., Weinerová, H., Weiner, T., and Hladil, J.

9:35 MARINE STRATA OF THE MIDDLE AND UPPER HAMILTON GROUP (MIDDLE DEVONIAN, LOWER GIVETIAN), EASTERN OUTCROP BELT IN NEW YORK STATE
Bartholomew, A. J., and Ver Straeten, C. A.

9:55 DEVONIAN CONODONT STRATIGRAPHY AND FACIES DEVELOPMENT OF THE AZROU REGION (EASTERN PART OF WESTERN MOROCCAN MESETA)
Aboussalam, Z. S., Becker, R. T., Hartenfels, S., and El Hassani, E.

10:15–10:40 Coffee and Posters

10:40 STRUCTURAL INFLUENCE ON DEVONIAN BLACK SHALE DEPOSITION IN SOUTHWESTERN NEW YORK STATE: BASIN ARCHITECTURE DRIVEN BY CRUSTAL SCALE THRUST LOADING TO THE EAST AND TO THE SOUTH/SOUTHEAST
Jacobi, R. D., and Smith, G. J.

11:00 SUMMARIZING A DECADE OF DEVONIAN SUBSURFACE MAPPING IN OHIO BY THE OHIO GEOLOGICAL SURVEY
Waid, C. B. T.

11:20 NORTHWEST THINNING OF FAMENNIAN BEDS IN WESTERN NEW YORK STATE
Vaughan, R. C.

11:40 NEW OBSERVATIONS IN END-DEVONIAN TO BASAL TOURNAISIAN SUCCESSION IN OHIO RELEVANT TO THE NEED FOR RENEWED, DETAILED CHRONOSTRATIGRAPHIC STUDY OF CONTINUOUS OUTCROP SECTIONS.
Baird, G. C., Over, D. J., Hannibal, J. T., McKenzie, S. C., Harper, J. A., and Tesmer, I. H.

12:00 FAMENNIAN TO EARLY TOURNAISIAN DEPOSITIONAL SEQUENCES FROM THE WILLISTON BASIN AND SURROUNDING AREAS, NORTHWESTERN UNITED STATES.
Hogancamp, N. J., Hohman, J. C., Guthrie, J. M., and Rodriguez, A. P.

12:20–1:20 Lunch

Ecological and Evolutionary Studies—Elizabeth Dowding and James Zambito, presiding

1:20 ENVIRONMENTAL STASIS AND VOLATILITY: DRIVERS OF ECOLOGICAL-EVOLUTIONARY PATTERN AND MACROEVOLUTIONARY PROCESS IN THE DEVONIAN APPALACHIAN BASIN
Brett, C. E., Baird, G. C., Bartholomew A., Ivany, L. C., and Zambito, J.

- 1:40 THE CENTRAL ASIAN OROGENIC BELT (WESTERN CHINA AND MONGOLIA) WAS A BIODIVERSITY HOTSPOT IN THE LATE DEVONIAN
Waters, J. A., Waters, J. W., Carmichael, S. K., Königshof, P., Munkhjargal, A. and Gonchigdorj, S.
- 2:00 REVISION OF LATEST SILURIAN–MID-DEVONIAN BRACHIOPOD FAUNAS FROM THE RHENISH MASSIF (GERMANY): STATE OF THE ART AND PERSPECTIVES
Jansen, U.
- 2:20 LATE DEVONIAN CRINOID AND BLASTOID GHOST LINEAGES
McIntosh, G. C.
- 2:40–3:00 Coffee and Posters

Devonian Magnetic Field and Terrestrial Strata—Annique van der Boon and Charles Ver Straeten, presiding

- 3:00 DEVONIAN TERRESTRIAL SYSTEM IN NEW YORK STATE
Ver Straeten C. A.
- 3:20 MAPPING THE MIDDLE AND UPPER DEVONIAN MARINE-NONMARINE TRANSITION IN THE APPALACHIAN BASIN FROM WEST VIRGINIA TO NEW YORK
Doctor, D. H., and Pitts, A. D.
- 3:40 THE QUEST FOR THE DEVONIAN MAGNETIC FIELD: AN UPDATE
van der Boon, A.
- 4:00 Posters
- 4:30 SDS Business Meeting followed by IGCP 652 Business Meeting

31 July 2023 (Monday)

Excursion to Niagara Falls: leader Carlton Brett; meet in Quality Inn Parking Lot at 8:00 a.m.

Excursion to Tioga, Pennsylvania, and Frasnian-Famennian strata: leader Andrew Bush; meet in Quality Inn Parking Lot at 8:15 a.m.

01 August 2023 (Tuesday)—Newton Hall 204 on the Campus of SUNY Geneseo

Devonian Extinctions and geochemistry—Diana Boyer and Nina Wichern, presiding

- 8:20 UPPER DEVONIAN LOWER AND UPPER KELLWASSER EXTINCTION RECORD IN THE SWEETLAND AND GRASSY CREEK SHALES IN THE IOWA BASIN OF CENTRAL NORTH AMERICA
Day, J., and Long, G.

- 8:40 TIMING OF THE LATE DEVONIAN KELLWASSER CRISIS: CYCLOSTRATIGRAPHIC ANALYSIS OF THE JAVA GROUP AT THE WALNUT CREEK SECTION, NEW YORK, USA
Klisiewicz, J. , Wichern N. , Over, D. J., Tuskes, K., Hinnov, L. A., and De Vleeschouwer, D.
- 9:00 GEOCHEMICAL AND SEDIMENTOLOGICAL ANALYSIS OF THE UPPERMOST DEPOSITS OF THE UPPER DEVONIAN HANOVER SHALE IN WESTERN NEW YORK STATE
Blood, D. R., McCallum, S. D., and Douds, A. S. B.
- 9:20 DECIPHERING THE ROLE OF TERRESTRIAL/ATMOSPHERIC INTERACTIONS IN LATE DEVONIAN KELLWASSER BLACK SHALE DEPOSITION: A HIGH-RESOLUTION CYCLOSTRATIGRAPHIC STUDY OF THE WINSENBERG SECTION (RHENISH MASSIF, GERMANY)
Wichern, N. M. A., Bialik, O. M., Nohl, T. , Percival, L. M. E., Kaskes, P., Becker, R. T., and De Vleeschouwer, D.
- 9:40 PYRITE FRAMBOID DISTRIBUTIONS AS INDICATORS OF ANOXIA: CAN WE USE THEM IN SHALLOW WATER ENVIRONMENTS?
Carmichael, S. K., Waters, J. A., and Boyer, D. L.

10:00–10:30 Coffee and Posters

- 10:30 LATE DEVONIAN TO EARLY CARBONIFEROUS INTERVALS (D/C TRANSITIONS) FROM MONGOLIA: INSIGHTS FROM TWO DIFFERENT TERRANES.
Munkhjargal, A., Königshof, P., Waters, J. A., Carmichael, S. K., Gonchigdorj, S., Nazik, A., Crônier, C., Udchachon, M., Thassanapak, H., Roelofs, B., Duckett, K., and Foronda, J.
- 10:50 THE HANGENBERG CRISIS (DEVONIAN-CARBONIFEROUS BOUNDARY) TIMING AND CLIMATIC FORCING (CHANXHE AND ANSEREMME SECTIONS, BELGIUM).
da Silva, A. C., Arts, M., Crucifix, M., Franck, L., Huygh, J., Omar, H., and Denayer, J.
- 11:10 HYDROGRAPHIC AND GEOCHEMICAL EVOLUTION OF THE LATE DEVONIAN EPEIRIC SEAS OF NORTH AMERICA: LINKAGES BETWEEN REDOX, SALINITY, AND BIOTIC CRISES
Gilleaudeau, G. J., Remírez, M. N., Wei, W., Song, Y., Sahoo, S. K., Kaufman, A. J., and Algeo, T. J.
- 11:30 USING $\delta^{13}\text{C}_{\text{TOC}}$ CHEMOSTRATIGRAPHY TO RECOGNIZE DEVONIAN GLOBAL EVENTS IN THE NEW ALBANY SHALE (ILLINOIS BASIN, U.S.A.)
Zambito, J. J., Weldon, A. C., Farbarik, O. B., Bolin, D. L., and McLaughlin, P. I.

11:50–1:30 Lunch

Devonian Events, Cyclic Stratigraphy, and Astrochronology—Faye Higgins and David De Vleeschouwer, presiding

- 1:30 THE KINGSTON RECORD, NEW YORK STATE, U.S.A—A WINDOW TO THE DEVONIAN PALEOCLIMATE AND TO THE DURATION OF PART OF THE EMSIAN.
da Silva, A. C., Brett, C., Bartholomew, A., Ver Straeten, C., Hilgen, F., and Dekkers, M. J.
- 1:50 EXPRESSION OF THE MIDDLE DEVONIAN KAČÁK EPISODE IN THE MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES, CANADA.
Gouwy, S. A.
- 2:10 IMPACT OF GLOBAL EVENTS ON THE DROWNING AND EXTINCTION OF GIVETIAN/FRASNIAN REEFS IN THE NORTHERN RHENISH MASSIF (GERMANY)
Becker, R. T., and Aboussalam, Z. S.
- 2:30 INVESTIGATING THE LINK BETWEEN DEVONIAN ANOXIC EVENTS AND ASTRONOMICAL FORCING
Huygh, J. , Gérard, J., Sablon, S., Crucifix, M., and da Silva, A. C.

2:50–3:20 Coffee and Posters

- 3:20 ASTROCHRONOLOGY OF THE HANOVER FORMATION, LATE DEVONIAN, WESTERN NEW YORK
Higgins, F., Tuskes, K., Otto, C., Over, D. J., Giorgis, S., and Slater, B.

- 3:40 BASIN-WIDE CORRELATION OF ASTRONOMICALLY FORCED CYCLES IN THE FAMENNIAN OHIO SHALE, APPALACHIAN BASIN, OHIO, USA
Hinnov, L. A., Algeo, T. J., and Lisiecki, L. E.
- 4:00 NUMERICAL SIMULATIONS OF THE EFFECTS OF ASTRONOMICAL FORCING ON NUTRIENT SUPPLY AND OXYGEN LEVELS DURING THE DEVONIAN
Crucifix, M., Sablon, L., Gerard, J., Godderis, Y., and da Silva, A.
-

02 August 2023 (Wednesday)

Depart from Quality Inn at 8:00 a.m.

Stop 1: Neid Road Quarry; Silurian Devonian unconformity, Silurian, Lower Devonian, Middle Devonian strata

Stop 2: Fall Brook Glen, Middle-Upper Devonian boundary

Lunch in Geneseo

Stop 3: Taughannock Falls, Middle Devonian

Banquet “under the whale” at Paleontological Research Institution, Museum of the Earth, 1259 Trumansburg Road, Ithaca, New York. Dinner at 7:30 p.m.

Lodging at Quality Inn-Ithaca, 356 Elmira Road, Ithaca, New York

POSTERS – ISC 142

[1] REASSESSING HYDROCARBON VOLUMES OF THE DEVONIAN SHALES IN EASTERN OHIO AT MEMBER-LEVEL SCALE

Danielsen, E. M., Blood, D. R., and Waid, C. B. T.

[2] A REVISED PALAEOGEOGRAPHY FOR THE FRASNIAN-TOURNAISIAN OF ANGARIDA (SIBERIA)

Dowding, E. M., Akulov, N., Torsvik, T. H., and Markussen Marcilly, C.

[3] THE LATEST EIFELIAN-FRASNIAN HORN RIVER GROUP IN THE NORTHERN MACKENZIE MOUNTAINS AND MACKENZIE VALLEY (NW TERRITORIES, CANADA): INTEGRATED STRATIGRAPHY AND SECTION CORRELATION

Gouwy, S. A., Kabanov, P., Chan, W., Hadlari T., and Uyeno, T. T.

[4] VARIABILITY, RELIABILITY, AND SIGNIFICANCE OF BRACHIOPOD $\delta^{18}\text{O}$ VALUES FROM THE MIDDLE DEVONIAN HAMILTON GROUP

Ivany, L. C., Welych-Flanagan, M., and Owens, J. C.

[5] TIMING OF THE LATE DEVONIAN KELLWASSER CRISIS: CYCLOSTRATIGRAPHIC ANALYSIS OF THE JAVA GROUP AT THE WALNUT CREEK SECTION, NEW YORK, USA

Klisiewicz, J. , Wichern N. , Over, D. J., Tuskes, K., Hinnov, L. A., and De Vleeschouwer, D.

[6] UNTANGLING THE LATE DEVONIAN CARBON CYCLE USING COMPOUND SPECIFIC ISOTOPES

Logie, T., Bhattacharya, T., Uveges, B., and Junium, C.

[7] INTEGRATED CONODONT, CARBON ISOTOPE, TRACE ELEMENT, AND SEQUENCE STRATIGRAPHIC DATA FROM THE GIVETIAN-FRASNIAN 'FRASNES EVENT' AND FALSIOVALIS EXCURSION IN IOWA AND NEVADA, USA.

McAdams, N. E. B., Day, J. E., Morgan, D., and Fiorito, A.

[8] DIVERSITY AND BODY SIZE TRENDS OF DACRYOCONARIDS ACROSS THE LATE DEVONIAN PUNCTATA EXCURSION, APPALACHIAN BASIN

Prow, A. N., Yang, Z., Lu, Z., Meehan, K.C., and Payne, J. L.

[9] KEY STRATIGRAPHIC MARKERS IN THE LATE DEVONIAN NORTH AMERICAN SEAWAY: TOWARDS A CHEMOSTRATIGRAPHIC FRAMEWORK FOR CORRELATION IN MUD-DOMINATED BASINS

Remirez, M. N., Gilleaudeau, G. J., Elrick, M., and Algeo, T. J.

[10] A UNIQUE OCCURRENCE OF *SCHIZOPHORIA* (KING, 1850) IN LOWER GIVETIAN STRATA OF EASTERN NY

Sabatino, F., Grippo, A., and Bartholomew, A. B.

[11] GEOLOGIC CROSS SECTION A-A' FROM GENESEE COUNTY, WESTERN NEW YORK, TO LYCOMING COUNTY, NORTH-CENTRAL PENNSYLVANIA, SHOWING THE REGIONAL STRUCTURAL AND STRATIGRAPHIC FRAMEWORK OF THE ALLEGHENY PLATEAU AND VALLEY AND RIDGE PROVINCES IN THE NORTHERN APPALACHIAN BASIN

Trippi, M. H.

[12] INTEGRATED STRATIGRAPHY OF MIDDLE DEVONIAN STRATA IN THE CARGILL TEST #17 CORE (LANSING CORE) OF NEW YORK STATE

Zambito, J. J., Brett, C. E., Da Silva, A.-C., Farbarik, O. B., and Willison M. J.

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

Zambito, J. J., Voice, P. J., Barker-Edwards, T., Giehler, M., Gugino, J., Johnson, I., O'Bryan, H., Quiroz, C., Truong, L., Wiesner, A., and Winget, M.

REGIONAL MUDSTONE DARKENING EFFECT: OVERLOOKED REGIONAL MATURITY MEASURE IN OUTCROP AND CORES

BAIRD, G. C.¹, C. E. BRETT², AND D. R. BLOOD³

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ABSTRACT

Thermal and burial histories of Paleozoic basinal deposits have typically been assessed on the basis of the Conodont Alteration Index (CAI) and Vitrinite Reflectance (%R_v) in organic-rich facies. However, other potential approaches are available that could permit analysis of burial temperatures for a broader range of facies. This paper provides an introduction to two minimally characterized indices applicable to thermal histories of marine low-organic mudrocks: mudrock darkening and fossil color alteration. Mappable patterns of variability in these parameters show a strong correlation with those of CAI, %R_v, and illite crystallinity that suggest that they can provide further useful indicators, when quantitatively calibrated against those parameters.

INTRODUCTION

Tools for assessing regional thermal and burial histories of mudstone and shale deposits for exploration purposes typically include the Color Alteration Index (CAI) of conodonts and the use of Vitrinite Reflectance (%R_v) for microscopic vitrinite inclusions in sedimentary deposits for Devonian and younger deposits. In addition, modified vitrinite reflectance scales have been used for microscopic graptolite fragments and other organic bioclasts in Ordovician and Silurian deposits. Such work is usually directed toward subsurface, organic-rich target facies, as studied in drill cores and well cuttings, including several major surveys within the Appalachian Basin (Epstein et al., 1977; Harris, 1979; Repetski, et al., 2008; East et al., 2012). Because of this, the late diagenetic histories of low Total Organic Carbon (TOC) “non-economic” deposits appear to have been overlooked. Given that non-target facies comprise the bulk of basin deposits and exposed rock, there is contextual scientific value in assessing the alteration histories of these deposits.

In contrast to the above approach, we advance new unconventional whole-rock, maturity parameters from the study of variably carbon-poor mudrock units exposed at the surface and widely available for sampling (Baird and Brett, 1989; Baird et al., 1992). These deposits are mostly marine, gray, fissile to blocky mudstone and argillaceous limestones with variable macrofossil content, which are typically referred to as “gray shale” deposits. However, we document herein that, like the conodont fossils themselves, the marine, gray mudstones and argillaceous limestones are sensitive to thermal alteration and distinctly darken, commonly becoming more

indurated in a regional pattern roughly covariant with changes in CAI (Text-fig. 1). Given that carbon-poor rocks make up the greater bulk of the sedimentary rock record, regional characterization of maturity measures for neritic marine facies in outcrop would be a powerful tool once quantified.

Ordovician and Devonian fossil-rich marine mudstone deposits in southern Ontario and New York display regional patterns of pervasive, within-facies changes in mudstone color value, susceptibility to slaking, hardness, and fossil preservation. These reflect a gradient of late diagenetic thermal alteration linked to basin evolution. These changes, recorded in outcrop, largely track regional trends in CAI data as recorded by studies of subsurface rocks (Weary et al., 2001; Repetski et al., 2008; Text-fig. 1). Repetski et al. (2008) documented eastward maximum conodont alteration index values, ranging from < 2.0 near Buffalo, New York, to > 3.0 in the region between Seneca Lake and Cayuga Lake. The steepest thermal gradient in the region is between the Genesee Valley and Seneca Lake where the mudstone darkening change is also most rapid. Similarly, Repetski et al. (2008) showed a steep eastward increase in mean vitrinite reflectance values from < 0.5 near Buffalo, New York, to a range of 1.5–2.0 in the eastern Finger Lakes region; their findings showed that the dramatic visual changes described herein are linked to rock maturity histories and are relevant to exploration. Moreover, we think that these visual thermal indices exist in foreland basins worldwide.

Attendant with maturity-based darkening of mudstone and loss of fossil color hues are other effects associated with increased depth-of-burial and/or increased heat flow.



Text-fig. 1. Generalized model of thermal maturity color-value parameter matched to conodont alteration index (CAI) and trilobite chromatic hue change.

Immature, noncalcareous, gray mudstone units typically display a blocky, poorly fissile condition in the outcrop, and they often absorb water readily upon exposure, slaking to slopes of mud. Mudstone units buried to greater depths lose this slaking tendency, transforming into darker, harder, and distinctly fissile rock, best described as “shale.” These changes, although pervasive, are beyond the scope of this paper, which focuses on mudstone darkening and macroscopic visual changes in the appearance of fossils.

MATERIAL AND METHODS

This study is based on systematic regional collecting of both Ordovician and Devonian marine mudrock samples across the Lake Ontario and Lake Erie region in New York State and southern Ontario, Canada, over the past 40 years. Outcrops of numerous different rock units were evaluated both visually and through sampling. Dry samples were rewetted to assess slaking tendency relative to heat-of-burial history. The samples figured here are now part of a newly donated Mudstone Thermal Maturity Collection at the Paleontological Research Institution, Ithaca, New York, composed of samples displaying varying levels of thermal color value alteration from spatially widespread localities. These will serve as

potential standards for evaluating regional maturity gradients in given rock units.

MATURATION PROCESS

The ability to determine the thermal maturity of mudstone successions is important because it allows for the prediction and exploitation of hydrocarbon products. Thermal maturation involves the conversion of labile organic matter to bitumen and the generation of natural gas. Oil-prone, Type I/II kerogens (algal material and amorphous organic matter) are converted to residual solid bitumen and hydrocarbons, which are expelled (migrate as a fluid) or are retained. In contrast, gas-prone, refractory, terrestrial Type III/IV kerogen macerals (vitrinite, inertinite) persist to high maturity as indicated by coalification products. These irreversible catagenic changes in organic matter conversion during the maturation process reflect, to a strong degree, the extent and duration of burial-related temperature increases, although other factors, e.g., changing chemistry and pressure at depth, are also relevant (Price and Baker, 1985; Tissot and Welte, 1984).

Conversion of oil-prone kerogens during maturation leads to a great dominance of residual solid bitumen at peak oil/gas thermal maturity, but vitrinite survives as a minor constituent fraction (Hackley and Cardott, 2016). However, there is still much debate over the relative roles that kerogen, bitumen, and thermal maturation play in the development of organic-matter hosted pores (Milliken et al., 2013; Cardott et al., 2015; Lu et al., 2015; Hackley and Cardott, 2016).

The reflectance value of vitrinite has long been used as a primary measure of maturity and sample position relative to the “oil window”; the higher the reflectance, the greater the maturity (Tissot and Welte, 1984; Waples, 1985). However, solid bitumen, which is typically dominant in samples in the oil window, yields lower reflectance levels than vitrinite, giving a false impression of a given sample as being below the oil window if the bitumen is mistaken for vitrinite (Hackley and Ryder, 2021). Source units, e.g., the organic-rich Ohio Shale and Sunbury Shale in eastern Ohio, were initially understood to yield reflectance values below the oil window, leaving the presence of oil in the intervening Berea Sandstone unexplained except for a model of long-distance, westward, up-dip, hydrocarbon migration from deep sources in the Appalachian Basin. Recognition of these lower reflectance values as bitumen instead of vitrinite (Hackley and Ryder, 2021) suggests that the source units under eastern Ohio are indeed within the oil window and, hence, within the region of viable petroleum exploration.

Further, a phenomenon known as vitrinite suppression, in which the measured vitrinite reflectance is less than it should be for a given thermal maturity, is not uncommon in marine shales and can create difficulties in assessing the thermal

maturity of mudrocks (Hutton and Cook, 1980; Price and Baker, 1985; Carr, 2000). Vitrinite suppression can occur in mudrocks rich in marine algal kerogen in which the expulsion of volatiles is restricted in hydrogen-rich vitrinite (Carr, 2000). This phenomenon has been well documented in the Devonian New Albany Shale of the Illinois Basin (Nuccio and Hatch, 1996; Mastalerz et al., 2024).

Although the petroleum industry most commonly utilizes the parameters vitrinite reflectance (VR), miospore coloration, and T_{max} (Rock-eval), maturation science now utilizes an ever-increasing array of component microscopic paleotemperature indices. Maturity-related color changes using both incident reflected light and transmitted light is observed for conodonts, foraminiferans, ostracods, conchostracans, ichthyoliths, acritarchs, miospores, and arthropod cuticle. Temperature sensitive macerals and organic bioliths, examined using incident reflected light, include vitrinite, solid bitumen, graptolite debris, chitinozoans, and scolecodonts (Hartkopf-Fröder et al., 2015). All of these components undergo directional visual thermal alteration, but the continuing challenge is to calibrate each index to a meaningful collective measure of change (see Hartkopf-Fröder et al., 2015, fig. 26, p. 110).

Generally, as organic matter evolves during increasing maturity, it displays increasing aromaticity associated with shifts in visible light absorption from high energy range to lower energy. Generally, this is visually expressed in several indices as a predictable sequence of colors, commencing with light yellow, followed by orange tones at low maturation. At higher maturity, there is a shift to red-brown coloration, followed by dark tones (Hartkopf-Fröder et al., 2015). This is particularly well illustrated by the thermal color sequence in conodonts (Epstein et al., 1977), but is also observed in other indices. Hence, visual macroscopic regional darkening of mudstone in outcrop and cores is herein considered to be the aggregate expression of these changes at microscopic scale.

MACROSCOPIC THERMAL ALTERATION IN MUDROCKS

The regional thermal mudrock darkening phenomenon has been rarely remarked upon as a macroscopic feature by others. McCrossan's (1957) study of subsurface drill cores from the Devonian Ireton Shale of Alberta showed a pervasive darkening of this unit with increased depth; he attributed much of this darkening to increased compression with depth rather than paleoenvironmental changes. Generally, thick stratigraphic sections of fossil-bearing, neritic deposits, within particular facies, display only minor color value variations, but show stepwise regional darkening and lightening trends between sections along inferred lateral thermal gradients. Upper Ordovician mudstone deposits of the Georgian Bay Formation display a southeastward darkening trend from light

gray and green hues at localities near Georgian Bay and west of Toronto, Ontario, to dark gray in the Pulaski Formation in north-central New York (Text-fig. 2). Middle and Upper Devonian deposits display a similar, but more easterly, darkening trend from cratonward sections bordering Lake Erie to strongly altered mudstone and argillaceous limestone units in central and eastern New York (Text-fig. 3). The first thermal alteration parameter, mudstone color darkening, is most noticeable in samples containing 0.2–0.5% TOC, in which the gray-to-black change is of greatest contrast. Where mudrocks have very low organic content (< 0.1 %) or elevated organic values (> 1.0 %), the darkening effect is more subtle, although this remains to be rigorously quantified.

Thermal mudstone darkening is also associated with the loss of colors (chromatic hues), which are well expressed in thermally immature lithologies and fossils in cratonward rock units (Text-figs. 1, 4, 5). Both color values and hues are herein described for certain mudstone and fossil samples using standard codes from the Munsell Color Chart (Munsell Color, 2010; Text-figs. 2–4).

Thermally immature, noncalcareous, light-colored Ordovician and Devonian mudstones commonly display a tendency to readily slake water when rewetted, as is well displayed in the Upper Ordovician Georgian Bay Formation succession north of Toronto and in the Middle Devonian Arkona Formation in southern Ontario where these units weather rapidly to clay slopes in outcrop. Both Ordovician and Devonian units grade southeastward and eastward to a more brittle, slake-resistant state in northern and central New York. This change, along with attendant color darkening, is conspicuous in Middle Devonian mudstones between the Genesee and Seneca Lake valleys in New York; slake-prone mudstone deposits south of Rochester distinctly transform to a darker, more strongly fissile, nonslaking condition across a 65 km distance east of the Rochester meridian (Text-fig. 5). This darkening trend is roughly consistent with eastward increases in thermal rank indicators CAI and %R_o from western to central New York as indicated on thermal maturity maps (Repetski et al., 2008; East et al., 2012).

The southeastward and eastward color darkening and loss of slake-tendency coincides with the loss of variable color hues (chroma) on certain fossils, particularly trilobites. The cuticle of the Middle Devonian trilobite *Eldredgeops* Struve, 1990 in Genesee Valley sections changes from brown in Genesee Valley sections to black in the Cayuga Valley. Similarly, Upper Ordovician trilobite genera dramatically change color basinward from a distinctive light brown in very immature (CAI 1.0) deposits on the midcontinent craton to dark gray and black at Trenton Falls in central New York (CAI 3.5), within the northern Appalachian Basin (Text-fig. 4). Hues quickly become muted to the southeast and eastward within increas-



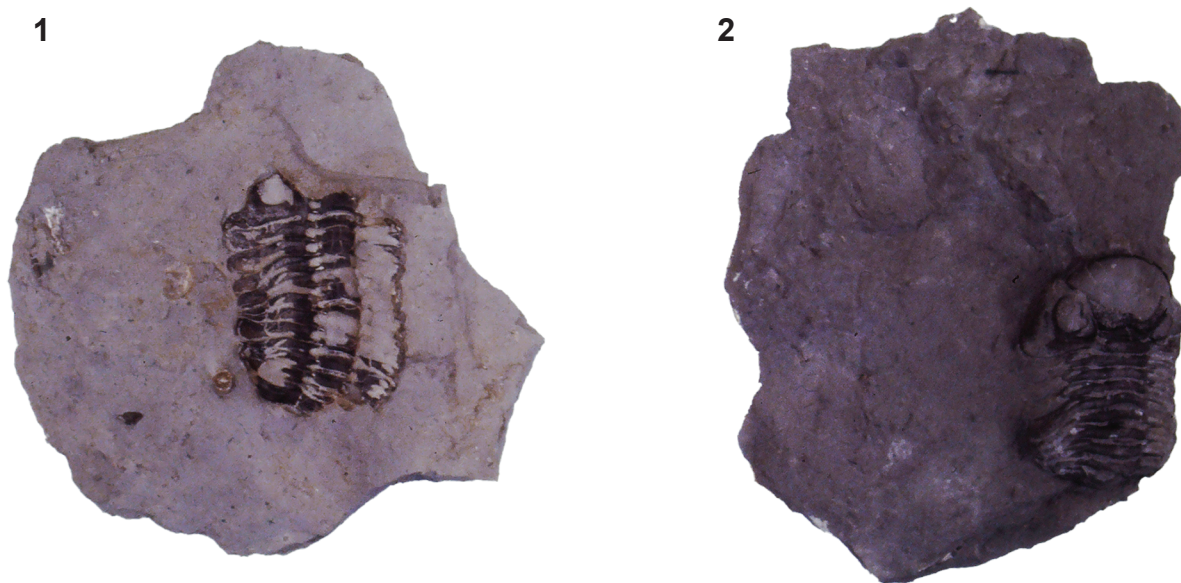
Text-fig. 2. Upper Ordovician (Katian Stage) marine mudstone samples containing nearly identical total organic carbon (TOC) levels, but displaying dramatic thermal maturity contrasts and appearance. Specimens collected at nearly opposite ends of Lake Ontario. **1**, Crinoid stem-bearing mudstone from the thermally immature lower part of Georgian Bay Formation collected along the Humber River, west of Toronto, Ontario, Canada, 43.663039, -79.506514 (5YR 5/1, TOC = 0.1%). **2**, Crinoid stem-bearing shale parting within the overmature Pulaski Formation, collected along the Salmon River at Pulaski in north-central New York State. Richland 7.5' quadrangle at ~43.555531, -76.105709 (N3.5, TOC = 0.2%). Samples submitted as part of new Paleontological Research Institution Mudstone Thermal Maturity Collection. Temporary sample numbers PRI 2826 (1), PRI 2801 (2).

ingly mature rock units, such that only grayscale shades are present on Ordovician fossils at Trenton, Ontario, and on Devonian fossils east of Canandaigua Lake.

In the special case of carbonaceous fossils, graptolites in Ordovician to Lower Devonian deposits display a maturity-related carbon reflectance gradient, which is analogous to the vitrinite reflectance parameter widely used for Devonian and younger rocks (Bertrand and Héroux, 1987; Goodarzi and Norford, 1989). In immature, cratonward rock units, macroscopic graptolite fossils are brownish and black, and they stand out as dark objects on gray shale surfaces. In thermally heated, basinal, Ordovician units, e.g., the Utica Shale, they are commonly expressed as submetallic to brightly reflectant silvery forms, strongly contrasting with a dark background matrix. Much of this reflectance increase from black to bright metallic appears to coincide with CAI rank increase from 3.0 to 4.5.

Middle Devonian marine mudstone deposits in the Arkona area in southern Ontario display light color values

(N6.5–N7), pinkish-brown calcareous fossils, and associated mudstone matrix that slakes readily to clay slopes in outcrop. However, to the east in New York State, equivalent mudrock facies in the Hamilton Group are darker and harder eastward, changing from light gray (N5–N6) color values and less slake-prone condition near Lake Erie, to a dark gray (N3), hard, brittle, slake-resistant character in central New York, with the most pronounced changes taking place across a 65 km-wide area between the Genesee Valley and Seneca Lake (Text-figs. 3, 5). Similarly, there is a southeastward, regional color-value gradient within the Ordovician Black River Group-through-Lorraine Group succession in New York (Simcoe Group–Georgian Bay Formation succession in Ontario); calcareous mudstone in the Middle Ordovician Trenton Group changes from medium to light gray (N5–N6) near Lake Simcoe and Meaford, Ontario north of Toronto, to brittle, hard, and dark (N2.5–N3) strata in northern New York, with the most rapid changes occurring southeast of Peterborough, Ontario.



Text-fig. 3. Two Middle Devonian (Givetian Stage, Jaycox Shale Member) marine mudstone samples from roughly identical, fossiliferous, neritic mid-shelf facies illustrating eastward, maturity-related thermal darkening within the lower part of the Moscow Formation of the upper Hamilton Group succession. **1**, From the Kipp Road Submember of the Deep Run Shale Member (lower part of Moscow Formation) at Jaycox Run, 3.0 km north of Geneseo, Livingston County, in the Genesee Valley, western New York (N5, TOC 0.3%). Geneseo 7.5' quadrangle at ~42.831513, -77.794809. **2**, From the equivalent Kipp Road Submember of the Deep Run Member (lower part of Moscow Formation) in the Seneca Lake Valley, Ontario County, New York (N3, TOC 0.2%). Locality is Benton Run, east of (downstream from) the N-S County Road 6 (Preemption Road) overpass and north of E-W Reed Road on the Stanley 7.5' Quadrangle, 42.793423, -77.001857. Samples submitted as part of new Paleontological Research Institution Mudstone Thermal Maturity Collection. Temporary sample numbers PRI 62 (1), PRI 300 (2).

DISCUSSION

REGIONAL GRADIENTS

The synchronous color-value and fossil color changes could be attributed largely to regional differences in depth-of-burial associated with sediment-filling within the northern Appalachian Basin. In fact, depth-of-burial does account for much, if not most of, observed rock alteration in eastern New York where overburden was greater (Friedman and Sanders, 1982; Miller and Duddy, 1989). However, Weary et al. (2001), who revised the thermal maturity maps of Epstein et al. (1977) and Harris (1979), recognized a steeper west-to-east maturity gradient, indicated by CAI and % R_o levels, across western and central New York. Moreover, the east-west color-value gradient of Middle Devonian units in New York State shows a pattern of abrupt darkening across a narrow belt in the western Finger Lakes region southeast of Rochester, New York, with more modest changes to the east and west (Text-fig. 5). To the east and south of Syracuse, Devonian mudstone deposits remain dark, hard, and brittle, generally tracking CAI and % R_o values as noted by others across a broad belt to the Catskill Front in eastern New York and southward to the Appalachian fold and thrust belt in cen-

tral Pennsylvania (Epstein et al., 1977; Harris, 1979; Repetski et al., 2008). Given that Syracuse is significantly farther to the northwest of the region of inferred maximum Devonian-to-Permian overburden development, episodes of elevated heat flow must have occurred in central New York as a result of one or more additional factors (Johnsson, 1986; Jackson et al., 1988; Weary et al., 2001).

RELATION TO ALLEGHENIAN TECTONICS

Although Paleozoic deposits in central New York State largely escaped the intense compressive deformation associated with the Carboniferous-Permian Alleghenian Orogeny, which is recorded in the nearby Hudson Valley and eastern Pennsylvania regions, there is mounting evidence from numerous independent studies for unexpectedly high temperatures of burial and/or chemical alteration (cf. Jackson et al., 1988; Weary et al., 2001) for deposits up to 320 km (200 mi) northwest of the cratonward limit of the Valley-and-Ridge structural belt.

Oliver (1986) suggested that overpressure due to the stacking of collisional overthrusts during the late Paleozoic Alleghenian Orogeny had forced the injection of hot brines through cratonic rocks within and bordering the Appalachian



Text-fig. 4. Halves of sectioned (spliced) images from two separate trilobites, rematched to show contrasting regional, thermal-burial coloration. Specimen half on the left is *Homotelus bromidensis* from the immature Late Ordovician (Sandbian Stage) Poolville Member of the Bromide Formation at the Criner Hills locality in Oklahoma, Paleontological Research Institution collection specimen PRI 42099; specimen half on the right is *Isotelus gigas* from overmature (Katian Stage) basal Russia Member of the Denley Formation, Trenton Group at Trenton Falls in central New York, Paleontological Research Institution specimen PRI 104032.

Basin. Similarly, Lyons et al. (1989), citing evidence for structural controls on elevated coal rank in Pennsylvania, argued that tectonic processes could have produced elevated illite crystallinity values in central and eastern New York. Karig and Elkins (1986) and Johnsson (1986) both inferred an elevated geothermal gradient in the Finger Lakes region citing unusually high illite crystallinity values as well as anomalous fission-track ages. In addition, inferred late Paleozoic (Alleghenian) remagnetization of carbonate deposits has been attributed to cratonward injection of hot tectonic brines through foreland basin deposits due to the stacking (loading) of thrust sheets (Miller and Kent, 1988; Jackson et al.,

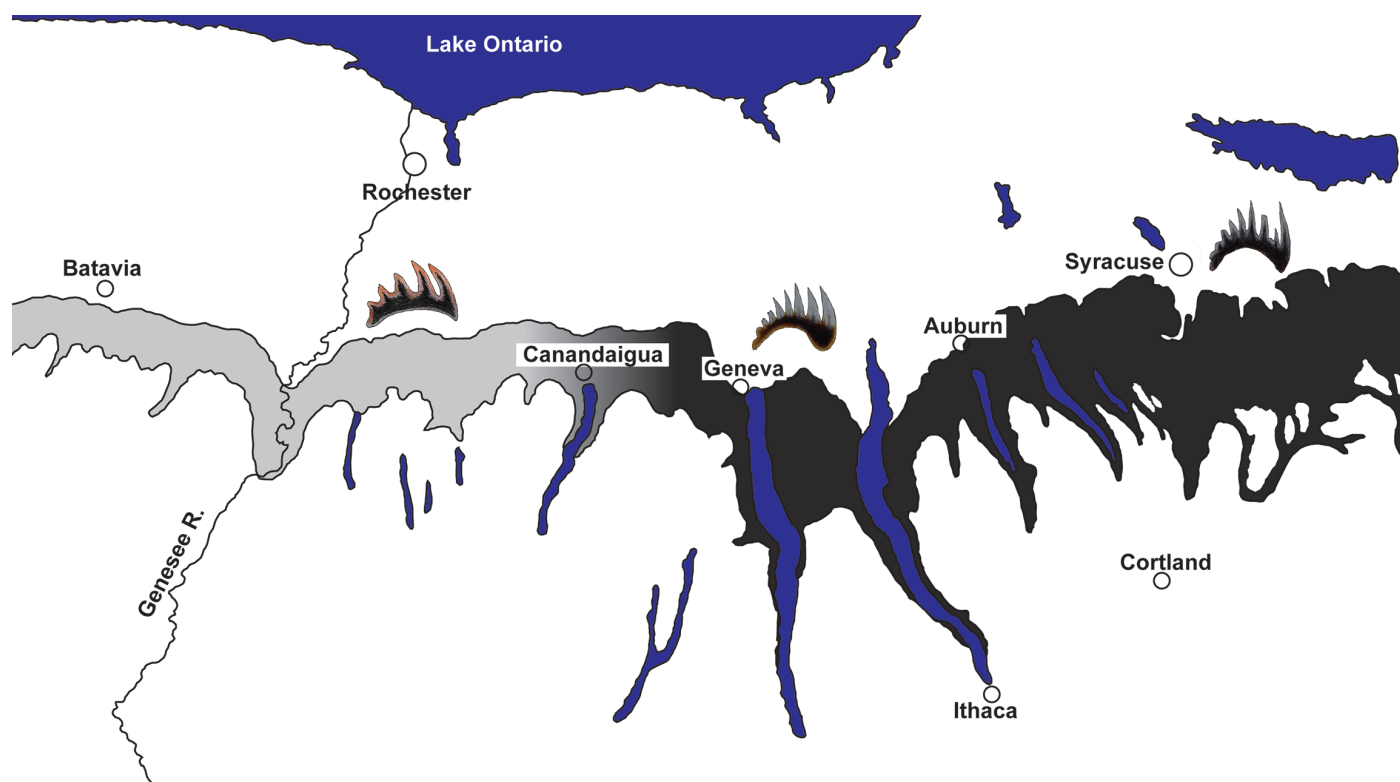
1988). Lower and Middle Devonian carbonate units across New York State show an eastward increase in magnetite authigenesis associated with an inferred invasion of orogenic fluids associated with Alleghenian tectonics (Jackson et al., 1988). This anhysteretic remanent magnetization (ARM) increases abruptly just to the east of the Rochester meridian, and it peaks near Syracuse before dropping to significantly lower levels in eastern New York; this pattern closely parallels Johnsson's (1986) illitization levels across the same area, but it is markedly at variance with CAI levels along the same transect, leading Jackson et al. (1988) to argue that the authigenic magnetization, and also the clay illitization, was due primarily to chemical- (not burial-) controlled processes. The abrupt jump in ARM values eastward from the Rochester meridian is also coincident with corresponding abrupt eastward decreases in Devonian mudstone color values and slake-susceptibility levels as described herein.

MESOZOIC HEAT FLOW

In addition to the above observations, numerous Early Cretaceous kimberlitic dike swarms in the Syracuse-Ithaca area (Miller and Duddy, 1989; Heaman and Kjarsgaard, 2000), suggest the presence of one or several localized post-Paleozoic elevated heat-flow events that affected strata in central New York. Heaman and Kjarsgaard (2000) argued that diachronous, northwest-to-southeastward emplacement of kimberlite intrusions across southern Ontario and central New York from the Triassic to the Cretaceous is the record of the Great Meteor hotspot under the moving North American plate as North America migrated northwestward. In a related analysis, fission track analysis of detrital apatite documented rapid cooling of Lower Devonian rocks under New York as a reflection of a major pulse of Cretaceous erosion (unroofing) (Miller and Duddy, 1989). Present-day elevated geothermal gradients in the eastern Finger Lakes region are also indicated by the presence of sufficiently high (to 70 MW/m²) heat flow, based on two low temperature hydrothermal wells at Auburn, New York (Hodge et al., 1982; Hickman et al., 1985; Karig and Elkins, 1986).

FUTURE RESEARCH

The mudstone and fossil color parameters must be rigidly calibrated to component geochemical rock properties to be meaningful as a thermal history tool. First, future work involves sample-based calibration of color-value determinations for individual samples, TOC, CAI, organic chemistry, and clay mineralogy measures within single samples. More specifically, low maturity mudrock samples could be heated in laboratory settings to simulate heat-of-burial conditions, an approach undertaken earlier by Epstein et al. (1977) in establishing the CAI parameter. Moreover, techniques for assess-



Text-fig. 5. Generalized hand-drafted map of eastward thermal color-value darkening of Middle Devonian Hamilton Group mudstone deposits across western-into-central New York State. Darkening of associated conodonts also shown schematically. Note narrow belt of mudstone-conodont darkening between the Genesee River Valley and Seneca Lake, roughly corresponding to an interval of eastward-increasing $\%R_o$ and CAI values identified by Repetski et al. (2008) and East et al. (2012).

ing TOC, kerogen composition, and measuring maturity via vitrinite reflectance, T_{max} , CAI, as well as thermal alteration of microscopic bioclasts, are currently widely used and published results widely available. This work must be performed, not only upon the samples presented here, but on numerous additional samples along inferred maturity gradients within sedimentary units and across regions to interpolate trends. Determination of CAI and $\%R_o$ levels at numerous low or variable TOC layers in cores and sections in multiple stratigraphic units in the future is essential for formalization (calibration) of the mudstone darkening parameter as an exploration tool as was done earlier for other indices (Héroux et al. 1979; Bertrand and Héroux, 1987).

What is the utility of the recognition of regional mudstone color-value gradients? Because mudstone color and fossil color represent the summation of numerous microscopic indices in any given hand specimen, outcrop, or core segment, these gradients can be evaluated in the context of prior microscopic petrographic work already published by others. In addition, we think that numerous field and subsurface geologists have observed the mudstone darkening effect in respec-

tive rock units but have not reported or discussed it in the literature. Once the regional mudstone color gradient concept becomes more widely known and discussed, sedimentary geologists familiar with specific regions and basins should expand their investigations to include regional mudstone color and fossil color changes as a part of their findings.

Characterization of mudstone color value in outcrop, coupled with CAI and $\%R_o$ at and near borehole sites, is necessary to better constrain both the geothermal gradient and estimated depth to the oil window in cratonward areas. Light-colored, low TOC mudstone beds in shallow core segments within the immature thermozone (CAI 1.0–2.0) interval should generally darken as a long core extends downward into thermally mature and postmature deposits. For example, mature, shallow, Upper Devonian drill-core sections secured in western Pennsylvania, compared to immature, equivalent facies obtained in central Ohio, provide an example of how this downward darkening should appear in comparable facies at depth in the Ohio core. Such thermal depth-related darkening of mudstone is likely a widespread but underreported phenomenon. Again, as noted by Hackley and Ryder (2021),

solid bitumen reflectance can be mistaken for vitrinite, giving a false impression of maturity levels.

Recognition of belts of conspicuous mudstone darkening is particularly relevant to exploration activity in cratonward areas where the oil window intersects the land surface or descends entirely into the subsurface. Because this darkening effect corresponds to the CAI range (1.0–2.5) and %R_o values (0.5–1.4), it corresponds to much, if not most, of the geothermal oil window. Most mudstone darkening occurs over a narrower geothermal range (CAI 1.0–2.0) corresponding to submature deposits yielding biogenic gas as well as the lower part of the oil window (0.5–1.0). As such, mudstone color-value and slakeability patterns are most useful and relevant to exploration in areas along the margins of foreland basins, and for the identification of localized hotspots on the craton (East et al., 2012).

Rigorously characterized and measured regional mudstone color-value and fossil-color gradients would benefit not only the exploration community, but also paleoenvironmental researchers and those assessing late diagenetic preservational changes in the fossil record. Fossils are, as a rule, easier to find and extract from softer, immature rock units with high contrast between the fossils and the matrix. This is particularly true for micropaleontologists who use bulk disaggregation of Paleozoic mudrocks for screening of macrofossils, conodonts, and organic microfossils. Hence, the data presented in this study can help establish predictive gradients of late diagenetic changes affecting certain fossil groups in sedimentary basins worldwide. As noted above, lithologic specimens and associated fossils from key rock units should be archived in museum and state survey collections as macroscopic maturity standards. Similarly, stratigraphers and sedimentologists should be mindful of thermal mudrock darkening for correlation of units and facies. Such darkening can be misunderstood as a paleoenvironmental signal, incorrectly suggesting a transition to deeper, oxygen-deficient conditions (Text-figs. 2, 3). Our results indicate that the regional overprint of late diagenesis on facies could obscure or distort interpretations.

CONCLUSIONS

This paper serves as an introduction to overlooked maturity indices, including mudstone darkening and fossil color changes, applicable to thermal histories and gradients in marine mudrocks. With increased thermal-burial maturity, these changes, paralleling changes in conodont CAI, include:

- Pronounced darkening of mudstone hue.
- Loss of expandable clay (slakeability) and rock hardening.
- Brown-black color to reflectant, metallic gray color-luster in graptolites.
- Brown to black color change in arthropod cuticle.

It is suggested that low maturity mudrock samples should be experimentally heated to simulate heat-of-burial conditions, as undertaken by Epstein et al. (1977) in establishing the CAI parameter. Although many studies have utilized CAI and %R_o in exploration work, these new and readily observable parameters, once formally calibrated, hold great potential for reconciling subsurface petrographic microscopic data to visual macroscopic features in overlying outcrops.

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STRATIGRAPHY, SEDIMENTOLOGY, AND DIAGENESIS OF CENTIMETER-SCALE BLACK SHALE BEDS AND ASSOCIATED STRATA IN THE UPPERMOST DEPOSITS OF THE UPPER DEVONIAN (FAMENNIAN) HANOVER SHALE, WESTERN NEW YORK, USA

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ABSTRACT

The Upper Devonian (Famennian) strata at the top of the Hanover Shale Formation that lies between the Point Gratiot Bed and the overlying Dunkirk Shale Formation is designated as the Beaver Meadow Member. This member is an eastward thickening wedge of gray shale that contains numerous centimeter-scale black shale beds that are classified into two different types based on sedimentological and geochemical characteristics. One type was deposited by the hyperpycnal flow of organic-rich turbidity currents, and the other was deposited as an accumulation of organic-rich mud under an anoxic water column associated with marine transgression. Evidence for hyperpycnal transport includes stratigraphic profiles of Zr/Al that suggest inversely graded sediment is overlain by normally graded sediment. Stable Zr/Al profiles above and below the hyperpycnite beds suggest that they were deposited intermittently during otherwise stable conditions. The black shale beds associated with marine transgression commonly have a detrital lag of insoluble material at their bases. These lags are dominated by pyrite and exhibit excursions in Zr/Al that typically demarcate a bulk shift in the Zr/Al values between the surrounding gray mudstones. The hyperpycnite black shale beds occur nearest to inferred shallower-water facies in the lower part of the Beaver Meadow Member, whereas transgressive black shale beds occur nearer to deeper-water facies in the upper part of the Beaver Meadow Member. We suggest that initial marine transgression flooded fluvial systems and formed shallow water lagoons or estuaries. Organic matter, perhaps in the form of fecal pellets, accumulated in these lagoons and was occasionally transported out to sea during storm events. As transgression continued, internal waves moved along a pycnocline that impinged on the seafloor, producing a detrital lag rich in pyrite that was overlain by organic-rich muds that accumulated under an oxygen-depleted water column. Iron to aluminum ratios in gray mudstones reach local maxima directly below thin black shale beds and decrease downward back to background values centimeters to tens of centimeters below the basal contact with overlying black shale. Abundant pyrite observed in hand samples and determined from X-ray diffraction mineralogy suggests that these Fe/Al profiles correspond with changing volumes of pyrite. The pyrite could have formed in diagenetic fronts of downward diffusing hydrogen sulfide produced by the bacterially mediated sulfate reduction of organic matter in overlying organic-rich muds. Many black shale beds exhibit sharp, often bioturbated, and occasionally undulatory upper contacts with gray shale, suggesting that early diagenetic “burn down” oxidation events invaded underlying sediments and removed organic matter.

INTRODUCTION

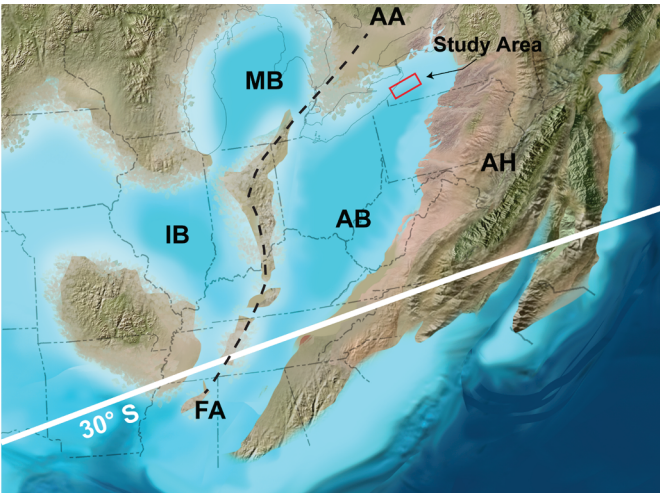
OBJECTIVES

The continued development of unconventional hydrocarbon reservoirs and the recent interest in critical metals has once again drawn attention to successions of organic-rich mudstone in sedimentary basins. Thin, often pyritic, centimeter-scale, organic-rich mudstone interbedded with organic-lean, gray mudstone provide an opportunity to understand both the depositional and diagenetic processes that lead to the accumulation of organic-rich muds at high resolution. Numerous studies of such deposits have been conducted in both modern and ancient settings and several processes have been proposed to explain the accumulation of organic-rich units including periods of increased primary productivity, shifts in the position of the redox boundary, and an influx of allochthonous material in the form of hyperpycnites (Hay et al., 1982; Bond et al., 1992; Lash, 2017).

This study documents the sedimentology, chemostratigraphy, and stratigraphic stacking patterns of numerous centimeter-scale black shale beds in the upper Hanover Shale Formation in western New York State. Cores were collected and studied at numerous outcrop exposures along a 75 km outcrop belt to describe the variation of the black shale beds across a depositional profile to determine the processes responsible for their formation. Key research questions included whether superficially similar black shales were deposited by different depositional or diagenetic processes, and whether they were formed during rapid depositional events or long stable intervals. The results and depositional models discussed herein provide geological concepts that can be used in the exploration and characterization of these beds.

GEOLOGIC SETTING

During the Upper Devonian, sediment accumulated in the northeast-southwest trending Appalachian Basin, cen-

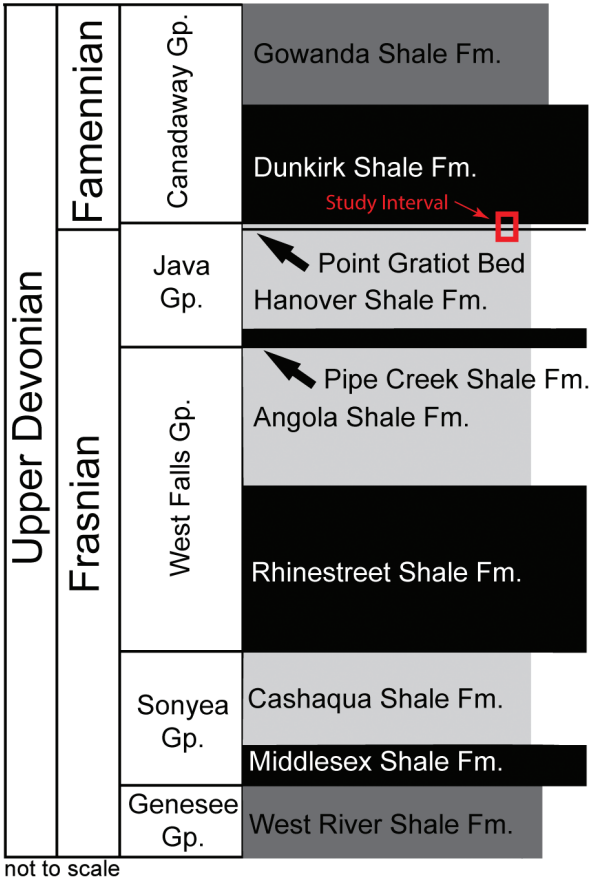


Text-fig. 1. Paleogeographic reconstruction of the Appalachian Basin modified from Blakey (2023). Red box denotes the study area. Base map from R. Blakey, Colorado Plateau Geosystems, used with permission. The Algonquin and Findlay arches are denoted by black dotted lines. AA = Algonquin Arch; AB = Appalachian Basin; AH = Acadian Highlands; FA = Findlay Arch; IB = Illinois Basin; MB = Michigan Basin.

tered at approximately 27° south paleolatitude (Scotese and McKerrow, 1990; Blakey, 2023). The basin was bounded to the east by the Acadian highlands and to the west by the Findlay-Algonquin Arch complex that separated the Appalachian Basin from the Michigan and Illinois basins (Text-fig. 1; Scotese and McKerrow, 1990; Rast and Skehan, 1993; Bose and Bartholomew, 2012; Blakey, 2023). Thick successions of Upper Devonian strata are well exposed and largely undeformed along lakeshore and creek exposures across western New York State. In this portion of the Appalachian Basin the Upper Devonian strata comprises the distal portions of a westward thinning clastic wedge shed from the Devonian Catskill Delta complex toward the southeast (Text-fig. 1; Broadhead et al., 1982; Ettensohn, 1985; de Witt et al., 1993). These distal strata are dominated by interbedded marine mudstones that are either black and organic-rich, or gray and organic-poor which are meters to decameters in thickness. Other less common lithologies include siltstone and limestone beds. Each organic-rich black shale interval represents the initial deposition of cyclical drowning phases of the foreland basin in response to concomitant thrust-induced loading in the Acadian Highlands to the east (Ettensohn, 1985, 1987), eustatic sea-level rise, or some combination of both.

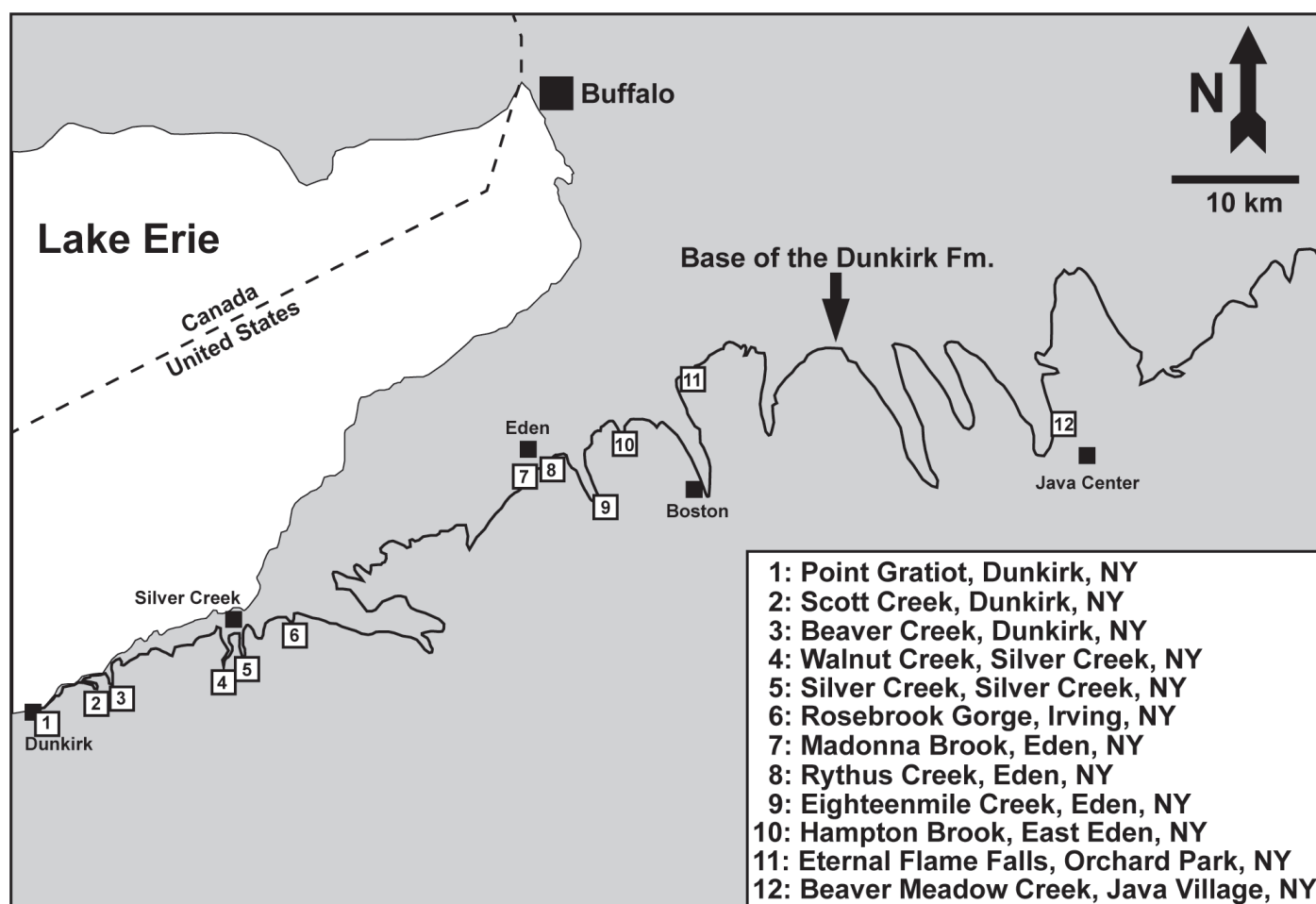
THE HANOVER SHALE FORMATION

This study focuses on strata from the uppermost part of the Hanover Shale Formation of the Java Group that is exposed along an outcrop belt spanning from Dunkirk, New



Text-fig. 2. Generalized stratigraphic column depicting the shale-dominated Upper Devonian strata of western New York State. The studied Hanover Shale section are those deposits occurring between the Point Gratiot Bed and the base of the Dunkirk Shale Formation, indicated by the red box. Black = black shale; light gray = gray shale; dark gray = interbedded black and gray shale.

York to Java Village, New York (Text-figs. 2, 3). The Hanover Shale Formation overlies the hard, organic-rich black shale of the Pipe Creek Formation, which represents deep water facies associated with transgression and, in the Appalachian Basin, is equivalent to the Lower Kellwasser event (Johnson et al., 1985, Over, 1997, Lash, 2017). In the western portion of the study area, the Hanover Shale is approximately 30 meters thick and is dominated by organic-poor, bioturbated gray mudstone. This gray mudstone succession is interrupted in places by siltstone beds or cyclical bundles of thin black shale beds (Lash, 2017; Bush et al., 2017). These black shale bundles have been interpreted to coincide with relative sea-level rise, likely induced by orbital forcing mechanisms, eustatic sea-level rise, tectonism, or some combination thereof (Lash, 2017; Bush et al., 2017). Outside of the study area toward the southeast, the Hanover Shale expands into shallow-water nearshore facies that Bush et al. (2015, 2017, 2023) have cor-



Text-fig. 3. Map of western New York State depicting the outcrop belt of the base of the Dunkirk Shale. Numbered boxes refer to specific outcrops analyzed as part of this study; see Appendix for site information.

related with the Canaseraga Formation based on numerous lines of biostratigraphic evidence. Cyclostratigraphic analyses of the Hanover Shale suggest that the unit was deposited over ~800,000 yr (De Vleeschouwer et al., 2013; Bush et al., 2017; Klisiewicz, 2023).

Near the top of the Hanover Shale Formation is a conspicuous decimeter-scale black shale called the Point Gratiot Bed. This bed represents the Upper Kellwasser Event in western New York, and the top of the bed marks the Frasnian/Famennian boundary (Over, 1997, 2002; Over et al., 2013). Harrington et al. (2021) placed the age of the Frasnian/Famennian boundary at 372.15 ± 0.46 Ma. The previously unnamed gray shale that overlies the Point Gratiot Bed is the uppermost lithological unit within the Hanover Shale Formation and is designated herein as the Beaver Meadow Member. The Beaver Meadow Member represents an eastward thickening wedge of gray shale with numerous thin, centimeter-scale, black shale beds, nodular carbonate horizons, and occasional

siltstone beds. The Beaver Meadow Member is overlain by the Dunkirk Shale Formation of the Canadaway Group and the contact between them in the study area is erosional, often marked by a lag of reworked detrital pyrite with subordinate fish bones, wood debris, and conodonts (Baird and Brett, 1985, 1986a, b; Baird and Lash, 1990; Baird and Brett, 1991). The Dunkirk Shale comprises laminated, organic-rich, silty black shale, with minor gray shale and siltstone beds, and several horizons of carbonate concretions.

METHODS

DATA COLLECTION

Vertical cores were obtained through the Beaver Meadow Member at numerous exposures along the outcrop belt, and these cores span ~1 m above the base of the overlying Dunkirk Shale to 1 m below the Point Gratiot Bed at the base of the member (Text-figs. 1, 3). Vertical BQ-size (41 mm diameter) cores were collected using the Shaw Backpack drill. A

DeWalt 10" 15-amp wet sliding table tile saw with a diamond blade was used to cut cores into 1 cm thick pucks, although some pucks were cut thinner to ensure that samples did not mix lithologies. Core pucks were manually disaggregated and sieved to < 3 mm. Samples were placed in 100 ml Brazilian Agate jars and powdered in an Across International PQ- N04 100 mL x 4 Planetary Ball Mill operating at 600 rpm for 20 min. Powders were hand-pressed into pellets and analyzed by a NITON XL3t GOLDD handheld energy dispersive X-ray fluorescence (EDXRF) spectrometer equipped with a silicon drift detector. Samples were analyzed in a hands-free test stand with the analyzer running for ~150 s.

A subset of these samples was analyzed for total organic carbon (TOC) content and programmed pyrolysis parameters (Espitalié et al., 1977). Samples for TOC analyses were ground to a size that would pass through a 60-mesh (250 μ m) sieve. For each sample, ~0.10 g was treated for a minimum of 2 hr with 15% hydrochloric acid to remove carbonates. The samples were then placed in a LECO crucible and dried at 110°C for at least 1 hr. Upon drying, samples were analyzed with a LECO 600 Carbon Analyzer with detection limits to 0.01 wt% and precision 2–5% of the measured value. Samples selected for TOC analysis were also subjected to programmed pyrolysis. Samples were progressively heated to 550°C. Upon heating, existing hydrocarbon is volatilized and recorded as the S1 peak and measured in mg of hydrocarbon per gram of rock (mg Hc/g rock). As heating progressed, kerogen in the sample was pyrolyzed generating hydrocarbon, which was recorded as the S2 peak and measured in mg Hc/g rock. This process also generated carbon dioxide, which was recorded as the S3 peak and measured in mg CO₂/g of rock. The Hydrogen Index (HI) was calculated using the formula:

$$HI = S2 / TOC \times 100 \quad (1)$$

The Oxygen Index (OI) was calculated using the formula:

$$OI = S3 / TOC \times 100 \quad (2)$$

Semiquantitative mineralogy was assessed by X-ray diffraction following the procedures and methods outlined by Poppe et al. (2001) and Jenkins and Snyder (1996). Randomly oriented samples were scanned with a Bruker AXS D4 Endeavor X-ray diffractometer using copper K-alpha radiation from 5° 2 θ to 70° 2 θ at a step interval of 0.020° and 0.5 s/step. Bulk mineralogy was identified using the MDI Jade software (www.materialsdata.com) and the International Centre for Diffraction Data PDF-4+ database. The reference intensity ratio method was used to determine whole-rock mineralogy.

ELEMENTAL PROXIES TO DETECT CHANGES IN CLASTIC SEDIMENTATION

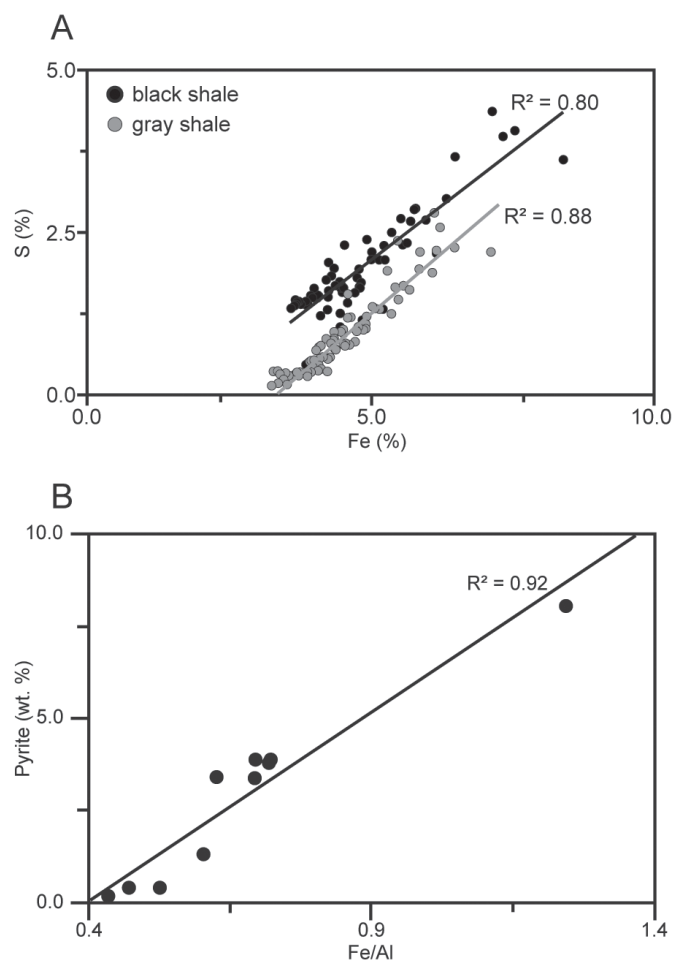
Some portion of most marine sediment is of a detrital provenance, including eolian and fluvial inputs (Calvert and

Pedersen, 2007). Aluminum is the principal conservative proxy for clay mineral flux in fine-grained clastic deposits (Arthur and Dean, 1991; Arthur et al., 1985; Calvert and Pedersen, 2007). As such, it can be used as a normalizing parameter to assess the relative enrichment or depletion of elements. However, care must be taken when using Al to normalize elemental datasets. Van der Weijden (2002) noted several issues with this approach especially when the coefficient of variation (i.e., the standard deviation divided by the mean) of Al is larger relative to that of the element(s) of interest. In such a scenario, variations in Al-normalized data would reflect fluctuations in the amount of Al, and not the element of interest. Therefore, we present Al% alongside element/Al ratios when assessing the nature of vertical profiles through the sections.

Changes in grain size of the detrital flux can be recognized by variations in the abundances of elements associated with the coarser size fraction relative to aluminum (Al), including zirconium (Zr), titanium (Ti), and silicon (Si; Sageman and Lyons, 2004). The Si/Al ratio reflects the ratio of quartz to aluminosilicate minerals and provides a qualitative indication of coarse to fine-grained sediment (Ver Straeten et al., 2011). However, some portion of the Si content can reside in siliceous skeletal remains of sponges, diatoms, and radiolarians, which can accumulate independent of detrital flux, and therefore care should be taken when using the Si/Al ratio (Calvert and Pedersen, 2007). Nondetrital sources of silicon are most easily recognized as steady or increasing Si abundance coupled with decreasing Al. Zirconium and Ti are thought to reside in high density minerals, e.g., zircon, rutile, sphene, and ilmenite (Schütz and Rahn, 1982; Dypvik and Harris, 2001; Calvert and Pedersen, 2007). Therefore Zr/Al and Ti/Al ratios are useful proxies for grain size, and by extension the strength of sediment transport processes (Boyle, 1983; Shimmield and Mowbray, 1991; Schneider et al., 1997; Zabel et al., 1999, 2001). A correlation between trends in Si/Al values with Zr/Al and Ti/Al is another useful indicator that the Si fraction is the result of detrital transport and not aeolian or biogenic in origin.

ELEMENTAL PROXIES TO DETECT CHANGES IN PYRITE VOLUME

Pyrite is a common mineral in sedimentary rock successions that contain organic matter. Bacterially mediated sulfate reduction of labial organic matter produces hydrogen sulfide that in turn combines with reactive iron to form pyrite via a succession of "FeS" species (Berner, 1970, 1984; Tribouillard et al., 2008). The strong correlation between S and Fe in the studied stratigraphic interval suggest that most of the Fe in the section exists as pyrite (Text-fig. 4A), so excursions in Fe/Al are used to represent the sequestering of reactive iron



Text-fig. 4. Crossplots of EDXRF data generated on samples from the Beaver Meadows Member depicting (A) the strong correlation between Fe and S in black and gray shale, and (B) the strong correlation between Fe/Al and pyrite abundance generated from XRD.

as pyrite (Canfield et al., 1996; Raiswell and Canfield, 1998; Lyons et al., 2003; Lyons and Kashgarian, 2005; Lyons and Severmann, 2006). The strong correlation between Fe/Al and pyrite abundance derived from XRD confirms the use of Fe/Al as a robust proxy for pyrite enrichment (Text-fig. 4B).

RESULTS AND INTERPRETATIONS

DESIGNATION OF THE BEAVER MEADOW MEMBER

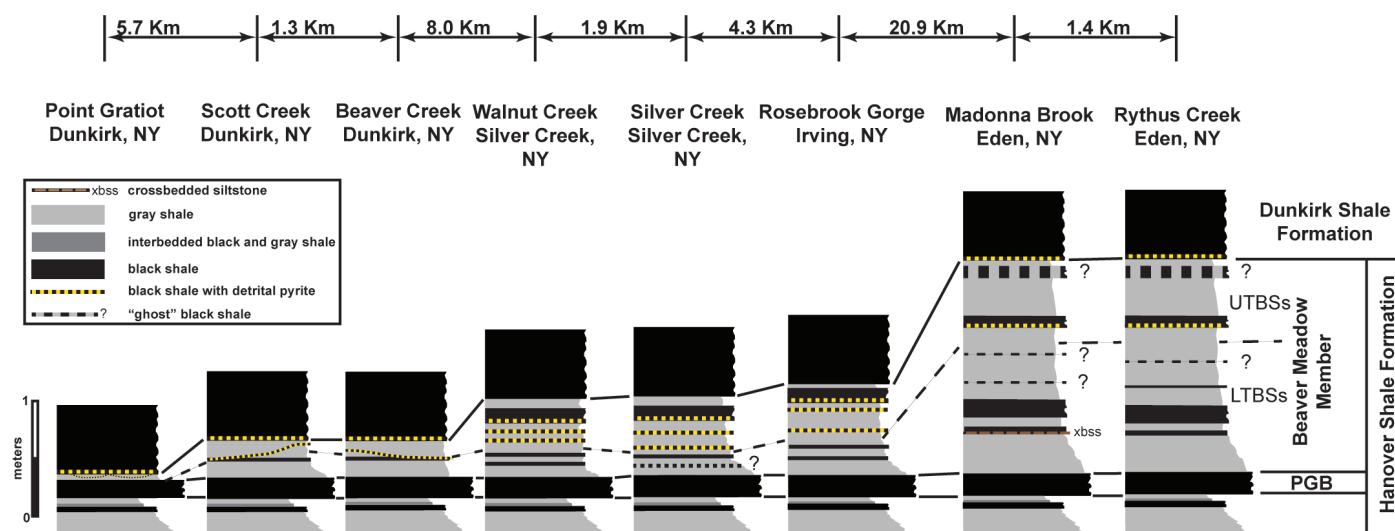
The gray, organic-lean (mean TOC of 0.34 wt. %; $N = 4$) shale unit between the Point Gratiot Bed of the Hanover Shale and the base of the overlying Dunkirk Shale is ~15 cm thick at Point Gratiot, Dunkirk, New York and expands eastward where it is > 4 m thick along Beaver Meadow Creek in Java Village, New York (Text-fig. 3; Baird and Brett, 1991;

Over et al., 2013). Because this lithological unit is easily differentiated from the underlying and overlying units, and it can be mapped across the entire study area, it is formally designated here as the Beaver Meadow Member. The name is derived from the excellent exposure of the member along Beaver Meadow Creek in Java Village, New York where it is dominated by gray, bioturbated mudstone that hosts abundant pyrite-filled burrows, nodules, and concretions, occasional small, centimeter-scale carbonate nodules, and numerous siltstone, and thin black shale beds. The upper 1–10 cm of gray shale that underlies black shale beds is often pyritic and appears darker gray. Of particular interest to our study is the presence of the thin black shale beds (Text-figs. 5, 6). In general, the beds appear to merge westward with the base of the Dunkirk Shale through a combination of sediment starvation and/or erosional overstep (Baird and Lash, 1990; Baird and Brett, 1991). Bed thicknesses are subcentimeter- to decimeter-scale and display sharp contacts with both underlying and overlying gray shale (Text-fig. 6A). Contacts are occasionally bioturbated preserving *Planolites*- and *Chondrites*-type traces (Text-fig. 6B). Some thin black shale beds contain a layer of centimeter-scale pyrite nodules within the bed, or coarse, detrital pyrite at the base (Text-fig. 6C, D).

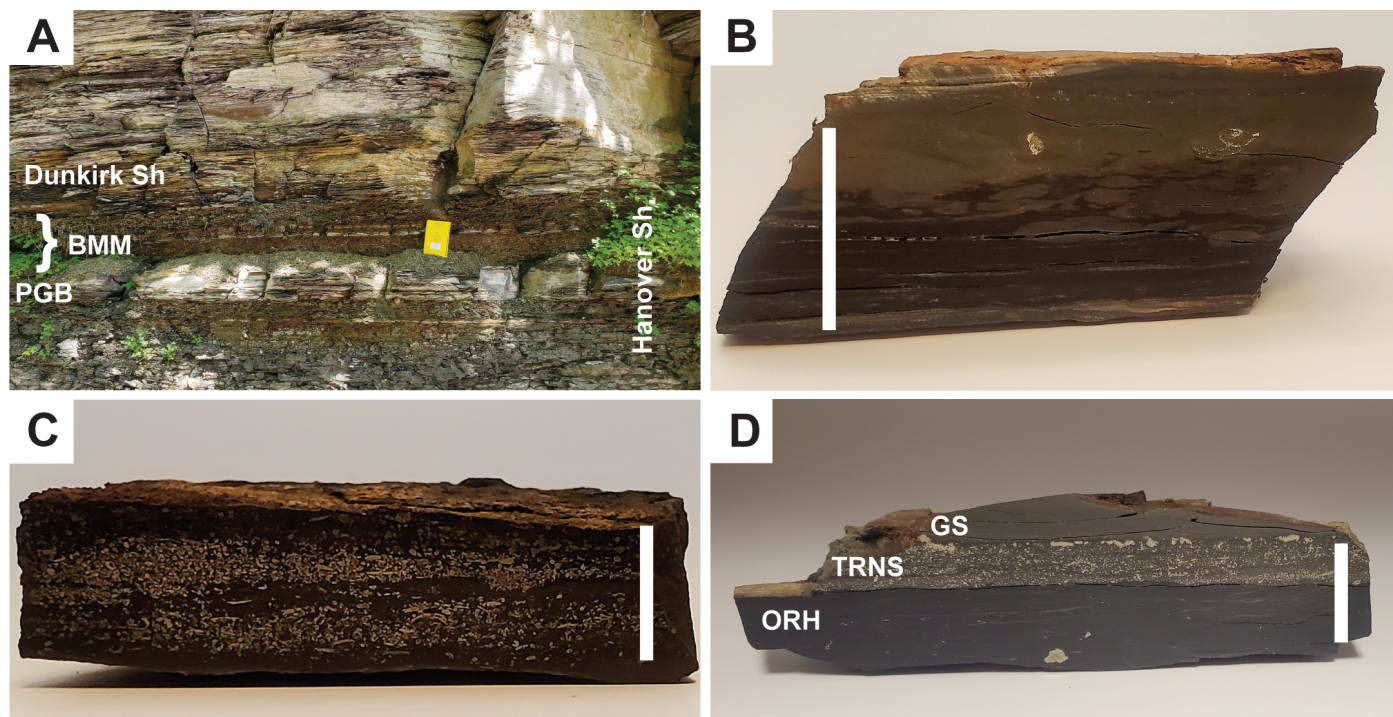
Given the diversity of black shale characteristics observed, two major kinds of black shale can be differentiated, and they are observed in different stratigraphic positions within the Beaver Meadow Member.

LOWER THIN BLACK SHALE BEDS

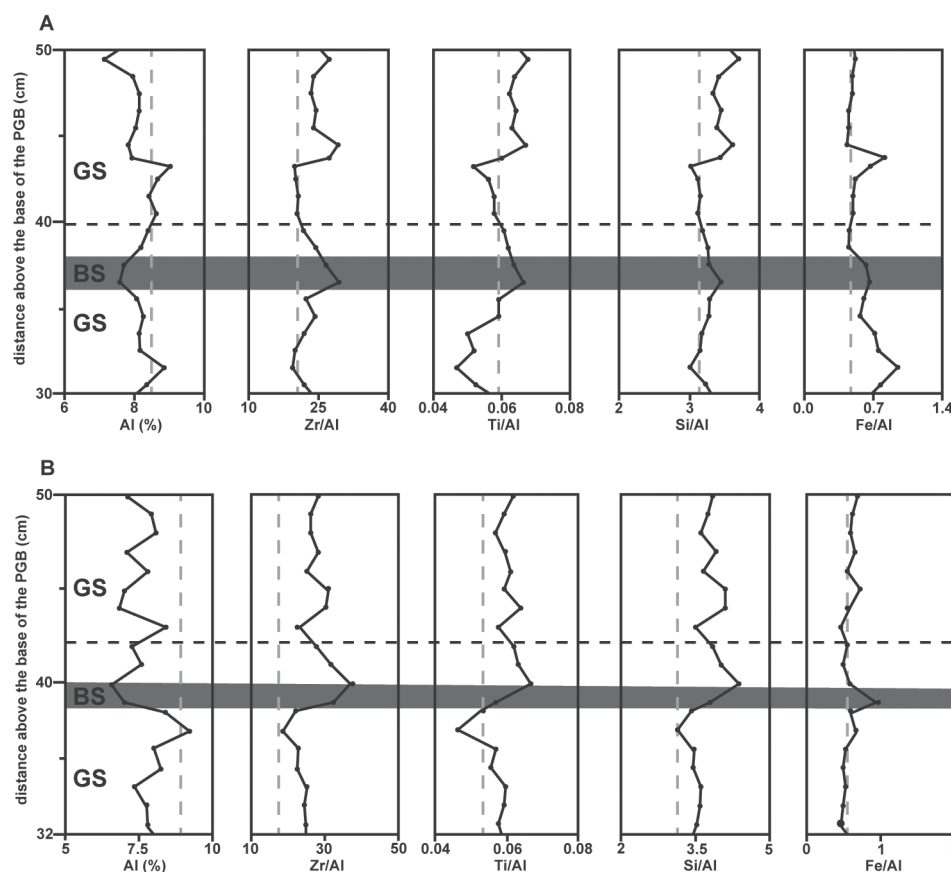
Lithostratigraphy and Chemostratigraphy.—The thin black shale beds occurring lowest in the section (closest to the Point Gratiot Bed) are < 1 cm to a few cm thick, do not contain detrital pyrite or visible pyrite nodules, can have a bioturbated contact with underlying gray shale, and often display sharp, sometimes bioturbated upper contacts with overlying gray shale (Text-figs. 5, 6A, B, D). Stratigraphic profiles of the clastic proxies through these lower black shale beds display some common patterns. Aluminum decreases from the background values observed in the underlying gray shale to a minimum within or just above the top of the black shale, before increasing back to gray-shale background values (Text-fig. 7). Conversely, Zr/Al, Ti/Al, and Si/Al values increase from just below the base of the black shale, reaching a maximum within or just above the top of the black shale, before decreasing to background gray-shale values, in some instances, 3–4 cm above the top of the black shale (Text-fig. 7). The gradually changing trends in the elemental profiles across the sharp upper contact between black and gray shale is a matter of significance discussed later (see “‘burn down’ of black shale beds” section).



Text-fig. 5. Schematic representation of cores cut through various outcrops exposing the Beaver Meadow Member. The dashed correlation lines denote the rough boundary between lower and upper thin black shale beds. “?” indicates the position of a possible “ghost” black shale based on elemental data profiles. LTBSs = lower thin black shales; PGB = Point Gratiot Bed; UTBSs = upper thin black shales.



Text-fig. 6. Images of thin black shale beds occurring within the Beaver Meadow Member: A, Field image of exposure along Beaver Creek, near Dunkirk, New York. The white bracket indicates the stratigraphic interval of the Beaver Meadow Member (BMM). PGB = Point Gratiot Bed. The Beaver Meadow Member is 31 cm thick and contains an organic-rich hyperpycnite and a transgressive black shale with a basal pyrite lag. The transgressive black shale cuts down to the top of the hyperpycnite at the position of the yellow field notebook. The notebook is 17 cm in length. B, Cut and polished hand sample of an organic-rich hyperpycnite recovered from the Beaver Meadow Member exposed along Madonna Brook in Eden, New York. Note the sharp basal contact and bioturbated upper contact. C, Cut and polished hand sample from a transgressive black shale recovered from the Beaver Meadow Member exposed along Scott Creek near Dunkirk, New York. The thin black shale contains abundant detrital pyrite. D, Cut and polished hand sample recovered from the Beaver Meadow Member along Beaver Creek near Dunkirk, New York. An organic-rich hyperpycnite is disconformably overlain by a transgressive black shale, which is composed mostly of detrital pyrite. The transgressive black shale is overlain by bioturbated gray shale. GS = gray shale; ORH = organic-rich hyperpycnite; TRNS = transgressive black shale. Scale bars = 1 cm (C), 2 cm (D), 3 cm (B).



Text-fig. 7. Elemental EDXRF profiles across lower thin black shale beds within the Beaver Meadow Member at (A) Walnut Creek and (B) Rosebrook Gorge. Vertical gray dashed lines represent mean shale values (Wedephol, 1971). Dark gray bars represent the observed thickness of black shale. The horizontal black dashed lines represent the potential pre-burndown thickness of the black shale. See text for discussion. BS = black shale; GS = gray shale.

Depositional Process Interpretations and Discussion.—These profiles indicate couplets of increasingly coarse sediment overlain by increasingly finer sediment delivered to the basin. Dupré et al. (1996) and Zabel et al. (1999) argued that high-density minerals, including zircon, are transported in the thalwegs of river channels, making them prone to mobilization into the ocean during moderate to large flooding events. Similarly, black shales of the Beaver Meadow Member with enrichment of Zr can preserve a record of periodic flood-related discharges of sediment, a depositional process proposed by Lash (2016) for the thin black shale beds within the underlying Rhinestreet Shale (Text-fig. 2) that have similar Zr/Al profiles. Lash (2016) proposed that such deposits could be the result of hyperpycnal flow.

Hyperpycnal flows are defined as outflows from a river mouth with a density greater than the fluid density into which they flow (Bates, 1953; Wright et al., 1986; Mulder and Syvitski, 1995). Ancient hyperpycnal flows are preserved as hyperpycnites and are often relatively silty to sandy (Kneller and Branney, 1995; Mulder and Alexander, 2001; Zavala et al., 2011; Wilson and Schieber, 2014). Soyinka and Slatt (2008) suggested that there should be a stratigraphic record of clay-rich hyperpycnites, but their fine-grain size and lack of sedi-

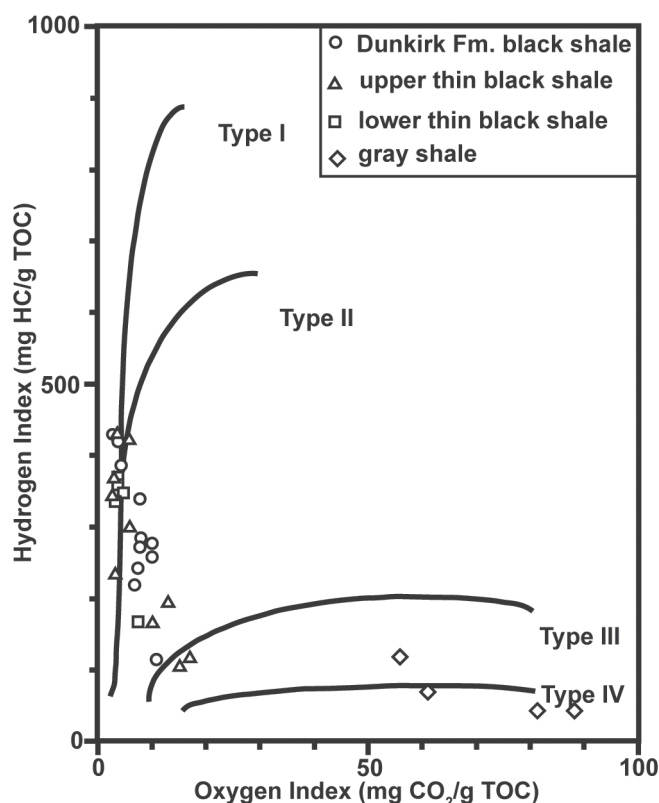
mentary structures can make them more difficult to recognize. Indeed, Brett et al. (2008) and Dattilo et al., (2008, 2012) have argued that the fine-grained nature of mudstone within Ordovician strata of the Cincinnati units in southern Ohio and Indiana has long resulted in their common misinterpretation as background pelagic sediments when they are likely aggregational event beds.

A complete hyperpycnite comprises a coarsening upward unit overlain by a fining-upward unit (Mulder and Syvitski, 1995; Mulder et al., 2001a, b, 2003). This results from the typical hydrographic profile of a flooding river in which the coarsening-upward portion of the sediment reflects the waxing stage of a flood, whereas the fining-upward portion reflects the waning phase (Kneller, 1995; Kneller and Branney, 1995; Mulder et al., 2001a, 2003; Alexander and Mulder, 2002). Stratigraphic trends in Zr/Al, Ti/Al, and Si/Al profiles in the lower black shale beds of the Beaver Meadow Member show an increase followed by a decrease in the amount of Zr, Ti, and Si (Text-fig. 7), likely corresponding with an increase, followed by a decrease in coarser grains that can record the waxing and waning phases of hyperpycnal flow deposition. Over et al. (2013) suggested that similar looking thin black shale beds in the Rhinestreet Shale could represent rapid redeposi-

tion of pelletal organic-rich sediments, and Lash (2016) noted Zr/Al profiles across those thin black shale beds like those observed in this study were the result of hyperpycnal flows.

It is noteworthy that the bases of the inferred hyperpycnites are organic-rich. The mean TOC in the lower black shale beds is 4.04 wt. % (N = 5). The elevated values are similar to the TOC content of the basal meter of the Dunkirk Shale (mean = 3.63 wt. %; N = 11). Hyperpycnal deposits likely contain greater proportions of terrestrial organic matter relative to background marine sediments (Mulder et al., 2003; Nakajima, 2006; Bhattacharya and MacEachern, 2009). Programmed pyrolysis parameters, specifically the hydrogen and oxygen indices (HI and OI, respectively), are often used to characterize the origin of organic matter (Tissot and Welte, 1984). Organic matter with high HI and low OI values are typical of organic matter of marine algal origin (Type I and Type II organic matter), whereas Type III and Type IV organic matter, of terrestrial origin, generally have lower HI and higher OI values (Tissot and Welte, 1984). The HI and OI of organic matter in the inferred hyperpycnites suggests an overwhelming abundance of Type I and II kerogen (Text-fig. 8). A two tailed t-test was run on the HI and OI values of organic matter from the hyperpycnites and the Dunkirk Shale. The p value for the HI and OI (0.661 and 0.053, respectively) fail to reject the null hypothesis that the means are the same at an alpha value of 0.05. This indicates that the organic matter type in the hyperpycnites and the Dunkirk Shale is chemically indistinguishable and does not indicate an increased occurrence of terrestrial organic matter in hyperpycnites that occur in the Beaver Meadow Member.

Another plausible explanation of the organic matter in the hyperpycnites is that they are fecal pellets. A large portion of modern marine sediment is composed of fecal pellets containing undigested organic matter (Porter and Robbins, 1981; Weaver, 1989; Tyson and Pearson, 1991; Turner, 2002; Potter et al., 2005). Fecal pellets can be transported out to sea from nearshore environments during flooding events. Such an explanation has been offered for fecal pellets observed in the Rhinestreet Shale of the Appalachian Basin (Cuomo and Rhoads, 1987). Rapid deposition of fecal pellet-rich sediment has been offered as a mechanism for the formation of similar thin black shale beds in the Rhinestreet Shale (Over et al., 2013; Lash, 2016). Although fecal pellets have not been observed in organic-rich deposits of the Beaver Meadow Member, black shale-hosted elongate bodies comprising framboidal pyrite and euhedral microcrystallites are common (Text-fig. 9). Lash (2016) postulated that similar pyritic bodies contained within the black shale of inferred hyperpycnites from the Rhinestreet Shale could be diagenetic artifacts of fecal pellets. Moreover, Tribouillard et al. (2008) suggested that similar masses of pyrite observed in Jurassic

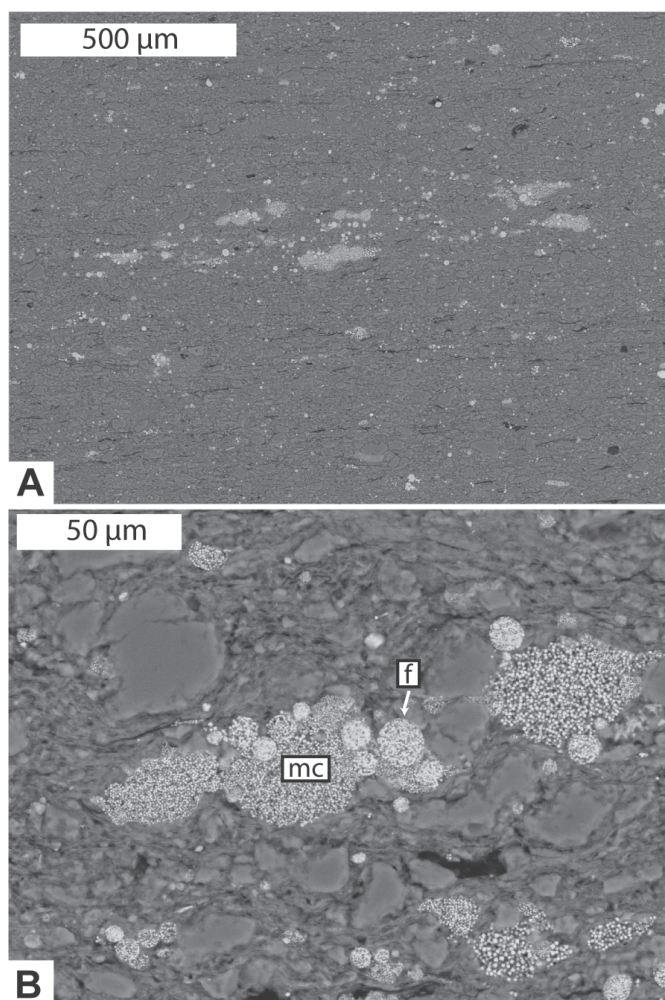


Text-fig. 8. Plot of oxygen vs. hydrogen indices of samples recovered from the Beaver Meadow Member of the Hanover Shale and overlying Dunkirk Shale. Thin black shale units are dominated by Type I/II kerogen of marine algal origin. The organic matter type is largely indistinguishable from black shale of the overlying Dunkirk Shale. Organic matter in the gray shale appears to be dominated by Type III material of terrestrial origin.

limestone and shale were formed within reducing microenvironments resulting from the decay of organic matter within fecal pellets. In this scenario, hydrogen sulfide was produced by bacterially mediated sulfate reduction of organic matter within the fecal pellets (Stockdale et al., 2010). The hydrogen sulfide combined with reactive iron to form pyrite through a series of iron monosulfide intermediates (Berner, 1970, 1984; Tribouillard et al., 2008). Bacterial sulfate reduction occurring relatively early within buried hyperpycnite beds that were enriched with fecal pellets could have formed the elongate framboidal pyrite bodies observed in the Beaver Meadow Member.

UPPER THIN BLACK SHALE BEDS

Lithostratigraphy and Chemostratigraphy.—The upper thin black shale beds, those closer to the base of the Dunkirk Shale, are < 1 cm to a few cm thick and contain nearly continuous pyrite nodules and/or graded, detrital



Text-fig. 9. Backscatter scanning electron micrographs of pyrite masses occurring in inferred organic-rich hyperpycnites in the Beaver Meadow Member of the Hanover Shale. A, Low magnification view showing the abundance of pyritic masses. B, High magnification view of elongate masses composed of framboidal pyrite (f) and euhedral microcrystalline pyrite (mc).

pyrite at their base (Text-figs. 5, 6A, C, D). They show sharp, erosional contacts with the underlying gray mudstone and in some instances can remove the underlying gray mudstone and hyperpycnites (Text-figs. 5, 6D). Examples of these erosive contacts are well expressed near Dunkirk, New York at the Point Gratiot, Beaver Creek, and Scott Creek localities. Two thin black shale beds were observed with clear channel-like geometries that are several meters wide at the Point Gratiot locality (Text-fig. 10). The edges of these thin black shale beds terminate at the base of the Dunkirk Shale, with up to 4 cm of gray shale between the base of the Dunkirk Shale and the top of the thin black shale (Text-fig. 10). Some upper thin

black shale beds do not have an observable pyritic lag but do contain a horizon of nodular and concretionary pyrite near the base. The mean TOC of the upper black shale beds is 3.89 wt. % ($N = 11$). These black shale beds also exhibit sharp upper contacts with overlying gray shale (Text-fig. 6A, D).

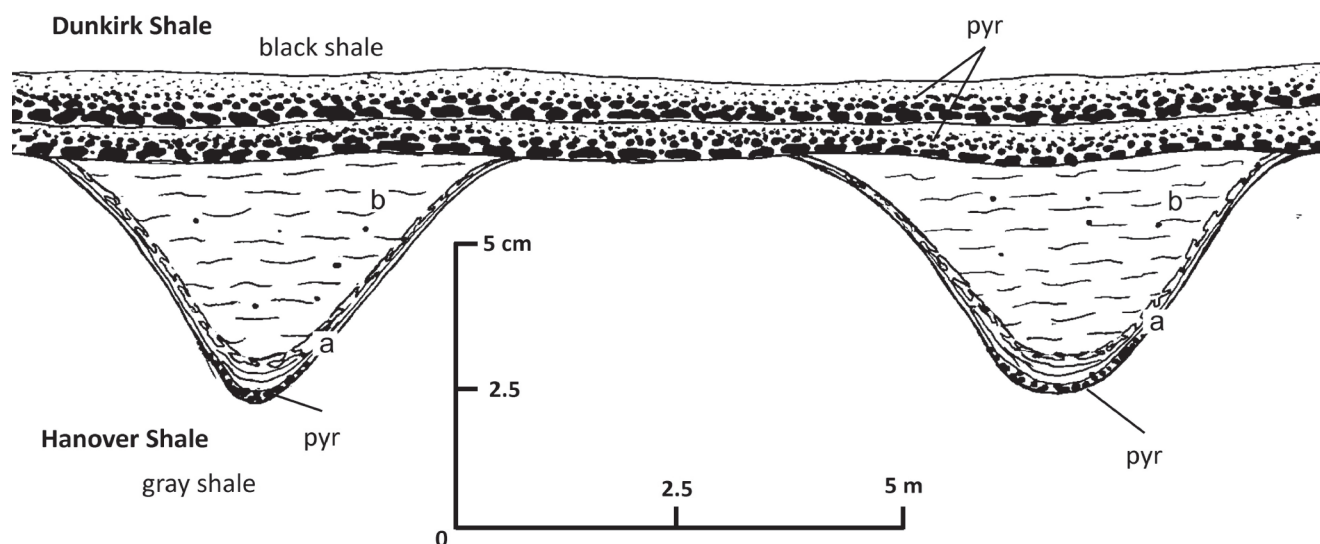
Examination of stratigraphic profiles of the clastic proxies through the upper thin black shale beds reveals consistent patterns (Text-fig. 11). The basal portion of the thin black shale is enriched in Fe relative to the overlying black and gray shale. Aluminum is lowest in the Fe-enriched basal portion and increases into the overlying black shale deposits. Both Zr/Al and Si/Al show significant increases in the base of the black shale, whereas Ti/Al shows a moderate increase. All three of these ratios decrease up section through the black shale.

Depositional Process Interpretations and Discussion.—The channel-like geometry and sharp basal contacts combined with the observed decrease in Al relative to enrichment of Zr, Si, and Ti (Text-fig. 11) imply that the basal portion of the thin black shale is a product of erosion, followed by coarser grain size and increased current energy during deposition. The decrease of Zr/Al , Si/Al , and Ti/Al upward through the thin black shale beds (Text-fig. 11) is consistent with waning current energy. The strong correlation between Zr/Al , Ti/Al , and Si/Al indicates that the Si is largely of detrital origin.

Numerous subaerial and subaqueous processes can generate erosional currents. The presence of erosional lags dominated by pyrite and overlain by black (often anoxic) shale requires a unique combination of depositional and diagenetic circumstances.

First, an energy source is required to erode and transport the sediments. Waves form at the interface between two stably stratified fluids of differing densities when the restoring force of gravity is applied to particles displaced from equilibrium by some force. Oceanic internal waves are common and occur along the interface of stratified water bodies of differing densities (Garrett and Munk, 1979; Munk, 1981; Olbers, 1983). Internal wavelengths are generally much longer than surface wavelengths, and amplitudes can reach meters (Garrett and Munk, 1979; Olbers, 1983).

Second, a physical or chemical event is required to concentrate pyrite and other insoluble materials together into beds. In a series of papers describing detrital pyrite lags overlain by black shale, Baird and Brett (1985, 1986a, b, 1991) and Baird and Lash (1990) noted that in addition to pyrite, lags contain subordinate amounts of other insoluble material, e.g., quartz, apatitic fish teeth and bone material, and carbonized wood. Notably absent were calcite allochems. Indeed, where such pyritic lag material encountered carbonate concretions, the concretions were often partially dissolved (Baird



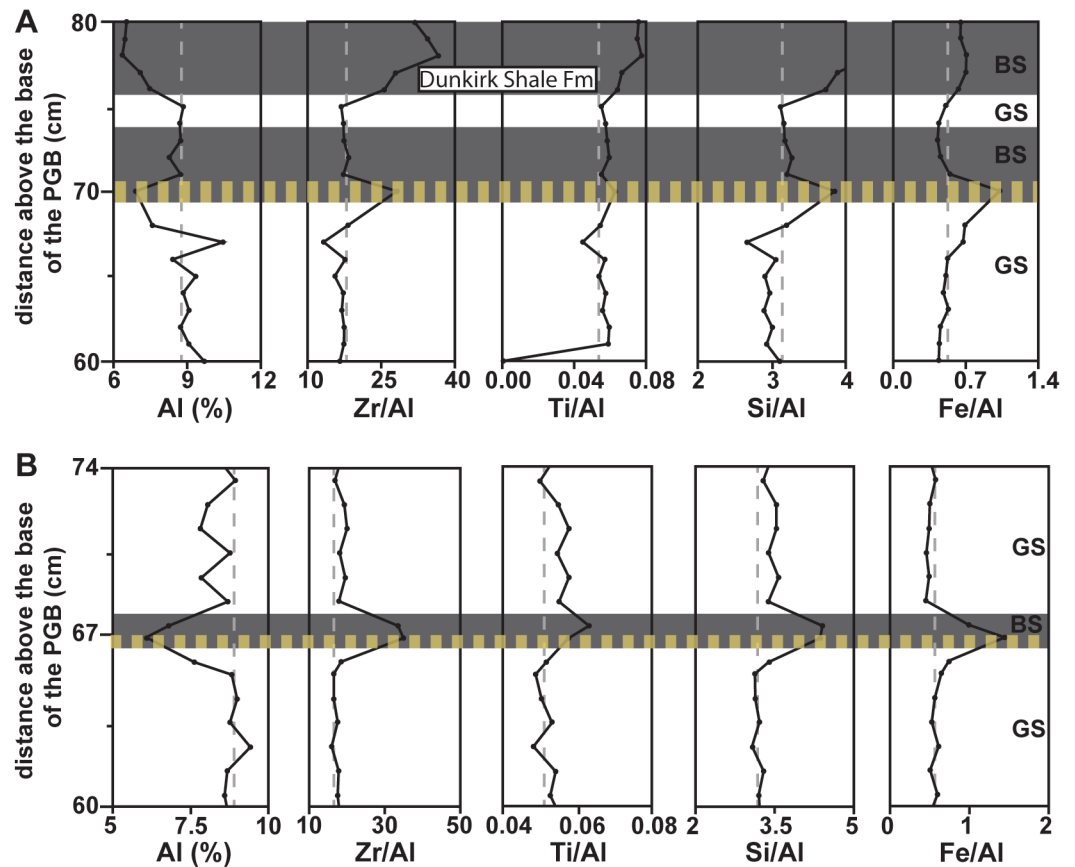
Text-fig. 10. Drawing of inferred upper black shale channels in the Beaver Meadow Member at the base of the Dunkirk Shale at Point Gratiot, Dunkirk, New York. a = black shale; b = gray shale channel fill; pyr = pyrite.

and Brett 1985, 1986a, b, 1991). They argued that sequences of gray shale, overlain by lenticular placer-like lags of pyrite, which are in turn overlain by black shale, represent periods where rising sea level replaced lower density oxygenated waters with anoxic, more acidic, higher density water (Baird and Brett, 1985, 1986a, b, 1991; Baird and Lash, 1990). In this scenario, internal waves moved along a pycnocline, impinged on the sea floor, winnowed away fine material, and concentrated heavier material, e.g., pyrite-filled burrows, concretions, and nodules, hosted by the gray muds into placer-like lag deposits.

Although Zr, Si, and Ti are enriched relative to Al within the pyritic lag and basal black shale intervals (Text-fig. 11), they do not possess the same profile associated with the organic-rich hyperpycnites described previously (Text-fig. 7). Rather, what we interpret as transgressive black shale beds appear as a thin anomaly of elevated Zr, Si, and Ti relative to Al. Moreover, a bulk shift in the baseline values in underlying versus overlying gray shale suggests a change in sediment delivery to the basin before and after black shale deposition (Text-fig. 11B). Increased Zr, Si, and Ti relative to Al in the basal portions of these black shale beds are likely due to erosion induced by increased current energy winnowing away lighter material and leaving behind sediment rich in heavier minerals. The occurrence of nodular pyrite and detrital pyrite lags suggest that the black shale beds are transgressive in nature, and overlie an erosional surface, likely induced by internal waves moving along a pycnocline.

THE DEPOSITIONAL HISTORY AND SEQUENCE STRATIGRAPHY OF THE BEAVER MEADOW MEMBER

It is reasonable to suggest that gray shale of the Beaver Meadow Member accumulated under normal, oxygenated conditions (Text-fig. 12A). The gray shale within this unit is thoroughly bioturbated and although body fossils are rare, they are noted in the eastern portion of the study area (Day and Over, 2002). Lash's (2017) investigation of the Hanover Shale-Dunkirk Shale succession along Walnut Creek found that progradation during deposition of the upper Hanover Shale marked by the occurrence of siltstone beds, ended just below the Point Gratiot Bed at which point transgression began, ultimately leading to deposition of the Dunkirk Shale. As sea level rose, river mouths were likely drowned, creating nearshore estuaries and lagoons that likely accumulated organic matter in a nearshore environment. Occasionally large storms would cause flooding and transport these sediments out into the deeper basin where they were deposited rapidly as an organic-rich hyperpycnite (Text-fig. 12B). As transgression progressed, sea level continued to rise and the pycnocline impinged on the seafloor where internal waves caused subaqueous erosion and winnowing of underlying muds and ultimately the deposition of detrital pyrite lags. The replacement of normal oxygenated water by anoxic water associated with deepening of the basin led to the accumulation of transgressive black shale overtop the pyrite lag (Text-fig. 12C). Transgressive black shale interbedded with bioturbated gray shale could represent minor fluctuations in sea-level and/or



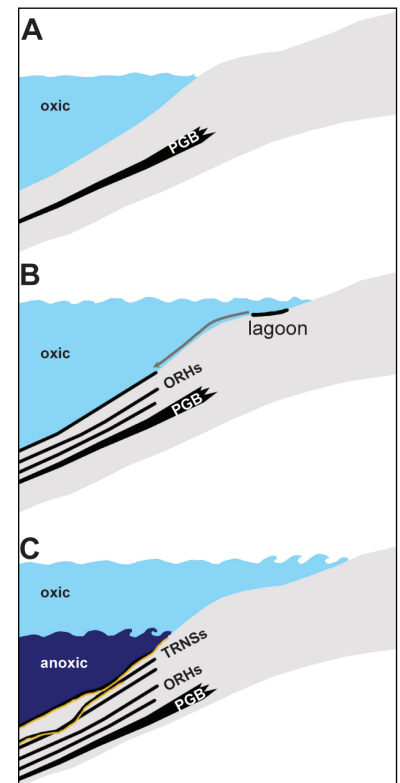
Text-fig. 11. Elemental profiles across upper thin black shale beds within the Beaver Meadow Member at (A) Walnut Creek and (B) Rosebrook Gorge. Vertical gray dashed lines represent mean shale values (Wedepohl, 1971). Dark gray bars represent the observed thickness of black shale. The dashed yellow bars indicate the thickness of detrital pyrite observed in core.

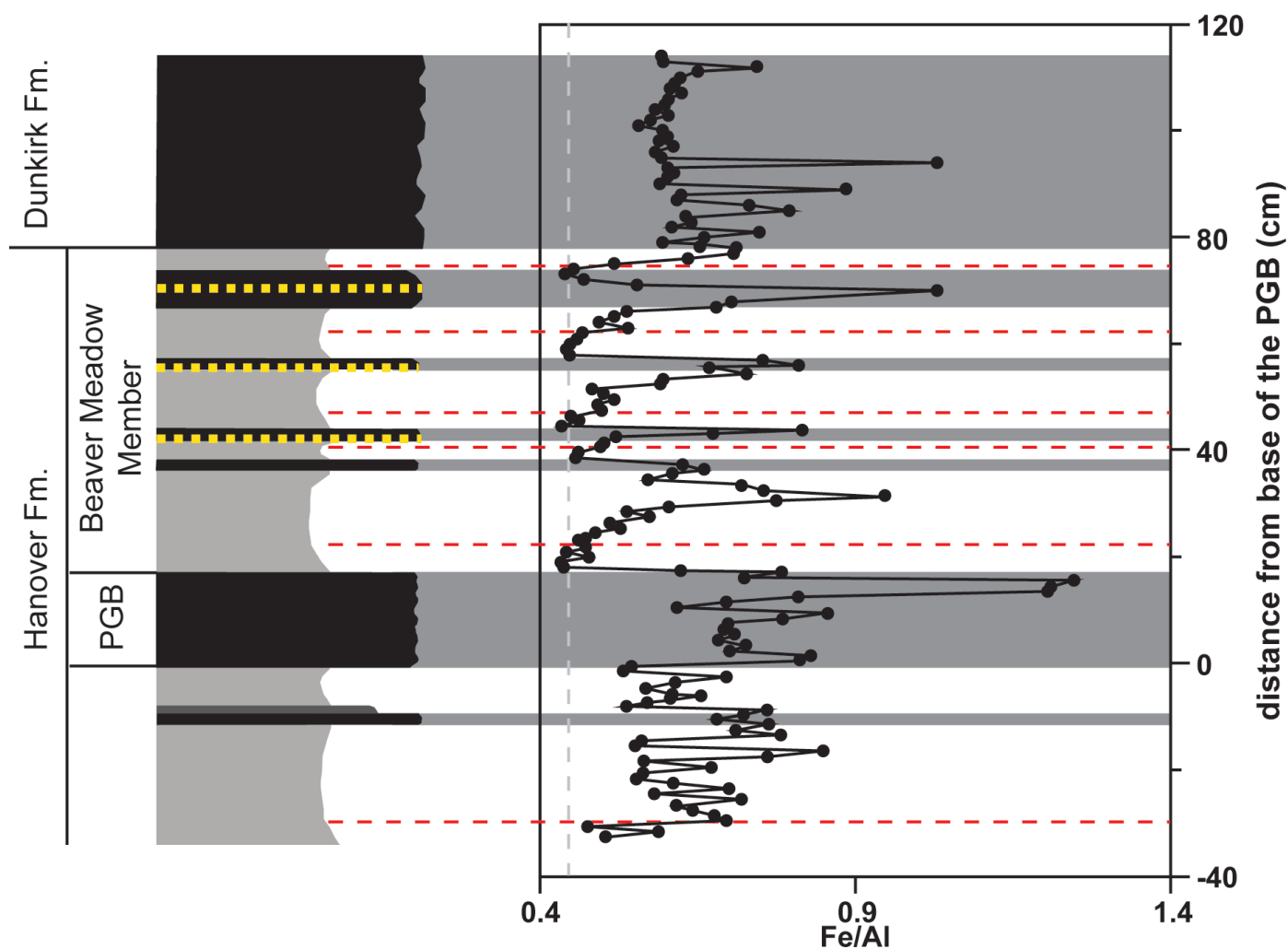
bottom-water oxygenation, perhaps forced by orbital cycles. Whereas organic-rich hyperpycnites could have accumulated in hours or days, transgressive black shales could have accumulated over decades or centuries.

EARLY DIAGENESIS IN THE BEAVER MEADOW MEMBER

Diagenetic Pyrite Enrichment.—Pyrite occurs in numerous submicroscopic to macroscopic forms in the Beaver Meadow Member and associated strata. Microscopic framboidal microcrystalites, framboids, polyframboids, euhedral grains, and pyrite-replaced radiolarian tests have been noted from numerous thin black shales within the Hanover Shale in this study and by others (Blood and Lash, 2004; Lash, 2017), and pyrite-filled burrows, nodules, and erosional lag debris represent the macroscopic portion of pyrite observed in the section. These forms of pyrite result in conspicuous stratigraphic patterns of the Fe/Al profile

Text-fig. 12. Diagrams depicting a model for thin black shale deposition in the Beaver Meadow Member of the Hanover Shale. A, Accumulation of gray, organic-lean mud under oxic to dysoxic conditions. B, Relative sea level rise floods river mouths forming nearshore estuaries and lagoons where organic matter can accumulate. Occasionally, this organic matter is transported out into the basin during storm events as hyperpycnal flows resulting in organic-rich hyperpycnites. C, As transgression progresses, the pycnocline impinges on the seafloor leading to erosion and deposition of pyrite-dominated lag deposits. Anoxic water replaces dysoxic water leading to the deposition of organic-rich muds over the lag deposit. ORHs = organic-rich hyperpycnites; PGB = Point Gratiot Bed; TRNSs = transgressive black shales.





Text-fig. 13. Fe/Al profile across the Beaver Meadow Member and associated strata of the Hanover and Dunkirk Formations. Black and yellow dotted lines in the stratigraphic column indicate the position of pyritic erosional lags and concretion/nodule horizons. The vertical dashed gray line indicates the baseline Fe/Al value of gray shale not enriched in pyrite. The horizontal dashed red lines indicate the base of elevated Fe/Al in gray shale underlying black shale.

through interbedded successions of black and gray shale in the Beaver Meadow Member. The lowest Fe/Al values of 0.43–0.46 are observed in gray shale that directly overlies thin black shale beds. The Fe/Al values increase up-section and reach maximum values ($> \sim 1.0$) at or near the base of thin black shale beds (Text-fig. 13). These Fe/Al profiles occur in gray mudstone underlying both organic-rich hyperpycnites and transgressive black shale. Many gray mudstone units underlying black shale contain visible pyrite in the form of pyrite-filled burrows, concretions, and nodules. Visible pyrite steadily increases up-section toward the base of the black shale beds. Fe/Al values can remain elevated above baseline levels where macroscopic pyrite is not evident suggesting it exists as microscopic to submicroscopic particles.

The association of pyrite in gray shale that underlies black shale units is commonly observed in other Upper Devonian shale units in the Appalachian Basin. Gray mudstone-hosted pyrite is found in sediment underlying black shale beds in the Olentangy Shale, in pyritized goniatite-bearing gray mudstone at the bases of thin black shale beds within the Angola Shale and Hanover Shale, within the uppermost Angola Shale at the base of the organic-rich Pipe Creek Shale, and in gray mudstone underlying the base of both the Point Gratiot Bed and the Dunkirk Shale within the Hanover Shale.

Diagenetic pyrite enrichment of organic-poor sediments underlying organic-rich sediments is well described from modern and ancient environments (e.g., Passier et al., 1996, 1999; Lyons et al., 2003; Jørgenson, et al., 2004; Neretin et

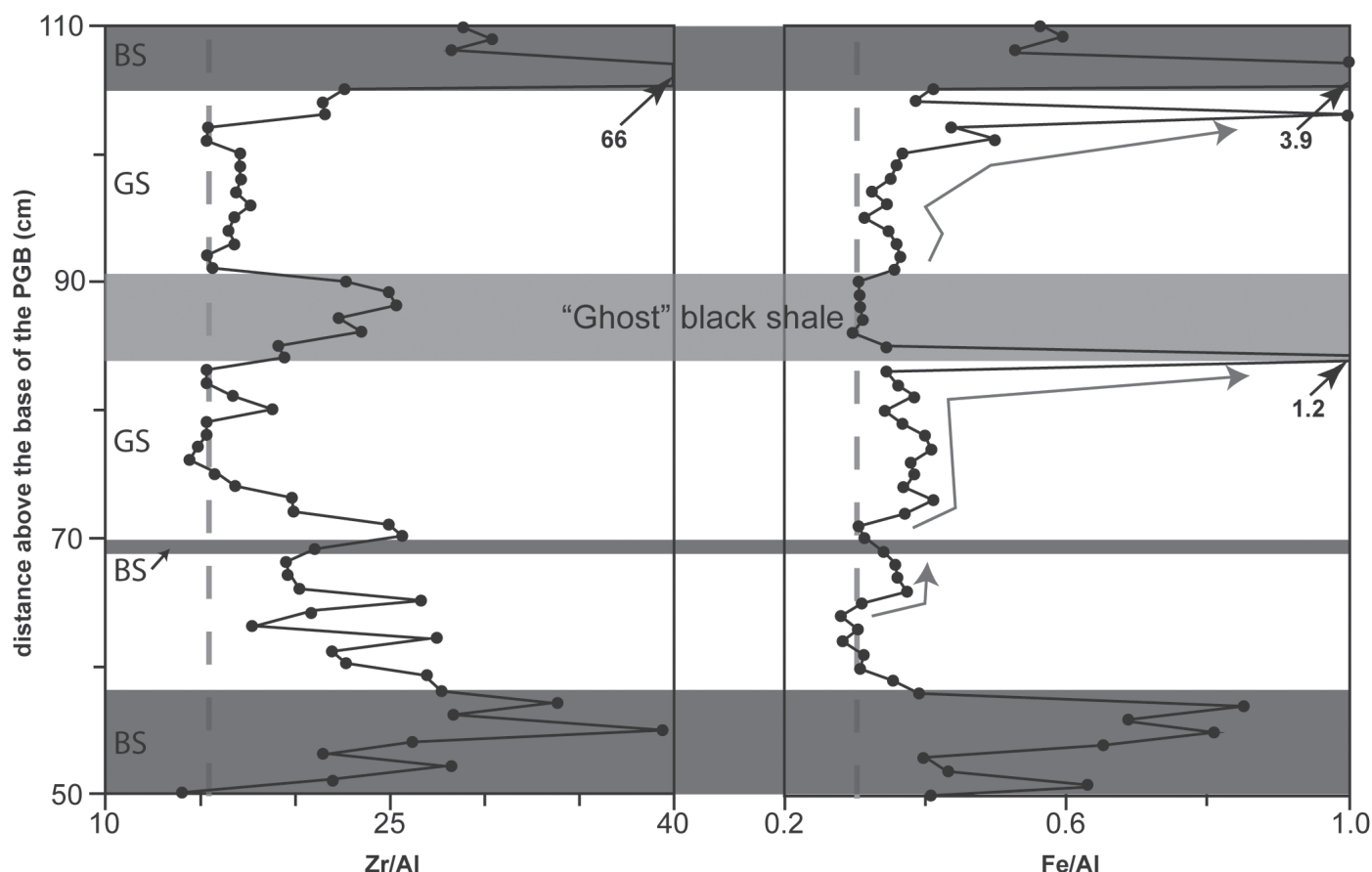
al., 2004; Lash, 2015). Often the rate of bacterially mediated hydrogen sulfide production exceeds the availability of reactive iron in organic-rich strata, and the production of pyrite is Fe-limited (Raiswell and Berner, 1985; Calvert et al., 1991; Lyons and Berner, 1992; Canfield et al., 1996; Lyons, 1997; Raiswell and Canfield, 1998; Wilkin and Arthur, 2001). As a result, excess sulfide diffuses out of the organic-rich sediments into the underlying oxic sediments and reacts with iron initially preserved due to low organic carbon levels (Lyons et al., 2003; Jørgenson, et al., 2004; Neretin et al., 2004). The front of diffusing sulfide advanced to progressively greater depths reflecting the quantity of available sulfide and iron (Lyons et al., 2003). The lower limit of diffusion is marked by an absence of pyrite in the organic-lean sediments.

We suggest that the presence of visible pyrite in the form of gray mudstone-hosted pyrite-filled burrows and nodules is an early diagenetic pyrite forming in isolated anoxic environments produced by decaying organic matter. Such material provides the bulk of initial pyrite incorporated into detrital pyrite lags underlying transgressive black shale beds. Syngenetic and diagenetic production of pyrite framboids and euhedral grains account for elevated Fe/Al and pyrite enrichment observed in organic-rich black shale beds within the Beaver Meadow Member. The pyrite production was limited by the availability of reactive iron within the organic-rich muds, forcing sulfide to diffuse out of beds and into underlying organic-poor sediments where sulfide combined with abundant reactive iron to form pyrite along a downward diffusing sulfide front. Low Fe/Al values of 0.43–0.46 likely represent baseline gray mudstone values that do not contain increased diagenetic pyrite and mark the stratigraphic limit of the downward diffusing sulfide front.

The Fe/Al ratios often record minimum depleted values immediately overlying thin black shale beds (Text-fig. 13) suggesting that the diagenetic pyrite formed quite early. Indeed, Canfield et al. (1996) suggested diagenetic pyrite could form within 2000–3000 yr, and Lash (2015) provided textural evidence in the Upper Devonian Rhinestreet Shale that diagenetic pyrite formed early, prior to the onset of significant compaction. Jørgenson et al. (2004) suggested that sulfide could diffuse upward into overlying deposits, and Lash (2015) provided isotopic evidence for the upward diffusion of sulfide in the Rhinestreet Shale, however, no evidence of upward diffusing sulfide was observed in the Beaver Meadow Member. One possible explanation for the observed patterns of Fe/Al enrichment in the Beaver Meadow Member is that diagenetic pyrite formed very early in the burial history. Excess sulfide was drawn down into underlying gray muds, and not upward into overlying gray mud because it had not yet been deposited. Further research of pyrite sulfur isotopes could better resolve our understanding of the driving mecha-

nisms responsible for pyrite formation in the Beaver Meadow Member and similar units.

“Burn down” of Black Shale Beds.—Although the tops of the thin black shale beds in the Beaver Meadow Member display sharp contacts with the overlying gray shale, there is no evidence of erosion at these contacts except for instances where the erosive base of an overlying transgressive black shale bed had cut down into the underlying black shale bed (Text-figs. 5, 6D). The Zr/Al profiles through the organic-rich hyperpycnites gradually return to baseline values in the overlying gray mudstone indicating gradational deposition from black to gray shale (Text-fig. 7). Similar contacts are noted from hyperpycnites identified in the Rhinestreet Shale (Lash, 2016), and sapropels recovered from the Mediterranean Sea (Colley et al., 1984; De Lange et al., 1989; Thomson et al., 1995; Jung et al., 1997). The upper contacts of thin black shale beds in the Beaver Meadow Member are typically bioturbated, preserving *Planolites*-type burrows filled with gray mudstone (Text-fig. 6B) that were also reported from thin black shale units lower in the Hanover Shale (Lash and Blood, 2006). The sharp contact between black and overlying gray shale is thought to represent the final position of an oxidation front formed when oxygenated water moved downward through the sediment, possibly aided by bioturbation, into anoxic pore waters and removed organic matter and redox sensitive trace metals in a process known as “burn down” that reduces the visible thickness of the original organic-rich layer (Colley and Thompson, 1985; De Lange et al., 1989; Thomson et al., 1993; Higgs et al., 1994; Van Santvoort et al., 1997). Sedimentation rate must exceed the rate of burn down for an organic-rich shale to survive. Mangini et al., (2001) suggested that unless sedimentation rates are less than several cm/kyr, organic-rich layers will survive burn down. However, “ghost” black shale beds are noted with increasing occurrence in more proximal deposits of the Beaver Meadow Member (Text-fig. 5). “Ghost” black shale beds are inferred where upward increasing Fe/Al profiles occur in gray shale where a maximum in Fe/Al occurs near the base of overlying gray shale enriched in clastic sediment proxies, e.g., Zr/Al (Text-fig. 14). The increased presence of “ghost” black shale beds in a proximal direction can reflect increased or prolonged influxes of oxygenated bottom water and burn down rates that exceeded sedimentation rates. Although it is impossible to know the original thickness of thin black shale beds that have been affected by burn down, we can suggest that they could not have exceeded the thickness of the hyperpycnite, or transgressive black shale. The top of the original organic-rich mud is defined by the point at which the Zr/Al values return to the baseline values of the gray shale deposited under normal marine conditions (Text-fig. 7).



Text-fig. 14. Elemental profiles of Zr/Al and Fe/Al across thin black shale beds within the Beaver Meadow Member at Rythus Creek. Vertical gray dashed lines represent baseline gray shale (GS) values. Dark gray bars represent the thickness of present-day black shale (BS). The light gray bar represents the potential thickness of a “ghost” black shale inferred from the Zr/Al and Fe/Al profiles. The dark gray arrows denote the general trend of increasing Fe/Al in gray shale underlying the thin black shales and the inferred “ghost” black shale. The black arrows refer to data points that plot off of the scale. PGB = Point Gratiot Bed.

CONCLUSIONS

The strata overlying the Point Gratiot Bed in the uppermost part of the Hanover Shale Formation is here termed the Beaver Meadow Member. This member is an eastward thickening clastic wedge of gray shale that contains numerous thin black shale beds and records sediment accumulation during transgression. Stratigraphic profiles of elemental data through thin black shale beds suggest that thin black shale beds lower in the Beaver Meadow Member formed by hyperpycnal flow of organic-rich sediments, and thin black shale beds higher in the member represent deposition of transgressive organic-rich sediments. The occurrence of organic-rich hyperpycnites below transgressive black shale demonstrates that lithologically similar looking units could be deposited under markedly different conditions. The hyperpycnites are event beds that could have accumulated in hours or days,

transgressive black shale beds could have accumulated over much longer time spans, perhaps years to centuries. These organic-rich beds and intercalated gray mudstone beds were further modified by several diagenetic processes that impacted the present-day distribution of pyrite and organic matter in the succession. Early authigenic formation of pyrite occurred in the organic-rich sediments and when the local supply of iron was consumed, the hydrogen sulfide diffused downward into underlying, organic-lean sediment where it reacted with iron to form diagenetic pyrite. The lack of evidence for increased pyrite in gray shale directly above black shale beds suggests that those sediments might not have been deposited at the time of the sulfide diffusion. The sharp upper contacts between thin black shales and overlying gray shales likely represents an oxidation front formed during a process referred to as “burn down” that occurs when oxygenated water in-

vades organic-rich sediments and removes their organic material and redox sensitive metals. Clastic and Fe/Al profiles indicate that some black shale beds were completely oxidized by burn down in more proximal settings, leaving behind a present-day gray color.

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APPENDIX: LOCALITY REGISTER

Key localities in this study. This section provides site details for Text-fig. 3 locality map. Latitude and longitude are given in World Geodetic System 1984 standard coordinate system.

(1) Point Gratiot, Dunkirk, New York, lakeshore exposure of the Beaver Meadow Member occurs along the public access Dunkirk Beach and continues north onto private property; 42.49265°, -79.35225°.

(2) Scott Creek, Dunkirk, New York, creek exposure of the Beaver Meadow Member occurs ~10 m northwest of the Werle Road overpass on private property; 42.49806°, -79.28389°.

(3) Beaver Creek, Dunkirk, New York, creek exposure of the Beaver Meadow Member occurs ~10 m northwest of the Newell Road overpass on private property; 42.50300°, -79.26909°.

(4) Walnut Creek, Silver Creek, New York, creek exposure of the Beaver Meadow Member occurs directly under Interstate 90 overpass on public property; 42.51252°, -79.17254°.

(5) Silver Creek, Silver Creek, New York, creek exposure of the Beaver Meadow Member occurs north-northwest of the Interstate 90 overpass on public property; 42.52376°, -79.15587°.

(6) Rosebrook Gorge, Irving, New York, creek exposure of the Beaver Meadow Member occurs at the top of a waterfall directly under the Spear Road overpass on private property; 42.54965°, -79.11611°.

(7) Madonna Brook, Eden, New York, creek exposure of the Beaver Meadow Member occurs in small creek on private property; 42.64299°, -78.89621°.

(8) Rythus Creek, Eden, New York, creek exposure of the Beaver Meadow Member occurs in a deep gully ~70 m west-

southwest of the driveway on private property; 42.54713°, -78.88045°.

(9) Eighteenmile Creek, Eden, New York, creek exposure of the Beaver Meadow Member occurs along the creek running parallel to New Oregon Road on private property; 42.62494°, -78.83800°.

(10) Hampton Brook, East Eden, New York, creek exposure of the Beaver Meadow Member occurs at the top of a waterfall on private property; 42.66741°, -78.81574°.

(11) Eternal Flame Falls, Orchard Park, New York, creek exposure of the Beaver Meadow Member occurs in the Eternal Flame Falls waterfall in Chestnut Ridge Park; 42.70172°, -78.75159°.

(12) Beaver Meadow Creek, Java Village, New York, designated Type Section of the Beaver Meadow Member occurs along the creek ~1 km east of New York State Route 78 on private property; 42.67004°, -78.42942°.

NORTHWEST THINNING OF FAMENNIAN BEDS IN WESTERN NEW YORK STATE: HOW IT ENABLES WIDER RECOGNITION OF THE WEST-DIPPING LAONA SILTSTONE AND POSES QUESTIONS FOR LAKE ERIE AND ADJACENT CANADA

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ABSTRACT

Famennian strata in western New York State south of Buffalo thin to the northwest. Such thinning causes the dip of these beds to rotate progressively westward, thus diverging from the generally southward dip of older Devonian and Silurian strata. The change in dip direction in the shale-dominated interval from the base of the Dunkirk Formation to base of the Laona Formation of the Canadaway Group has hindered geologic recognition of the continuity of beds. In all, the members and formations within this Dunkirk/Laona interval range to 250 m thick, with comparatively few marker beds to aid in lateral correlation. When the thinning demonstrated here by outcrop and well log data is extrapolated northwestward, the beds pinch out within the footprint of Lake Erie. This suggests that the topographic low occupied by the eastern end of the lake was formed mainly by nondeposition rather than erosion.

INTRODUCTION

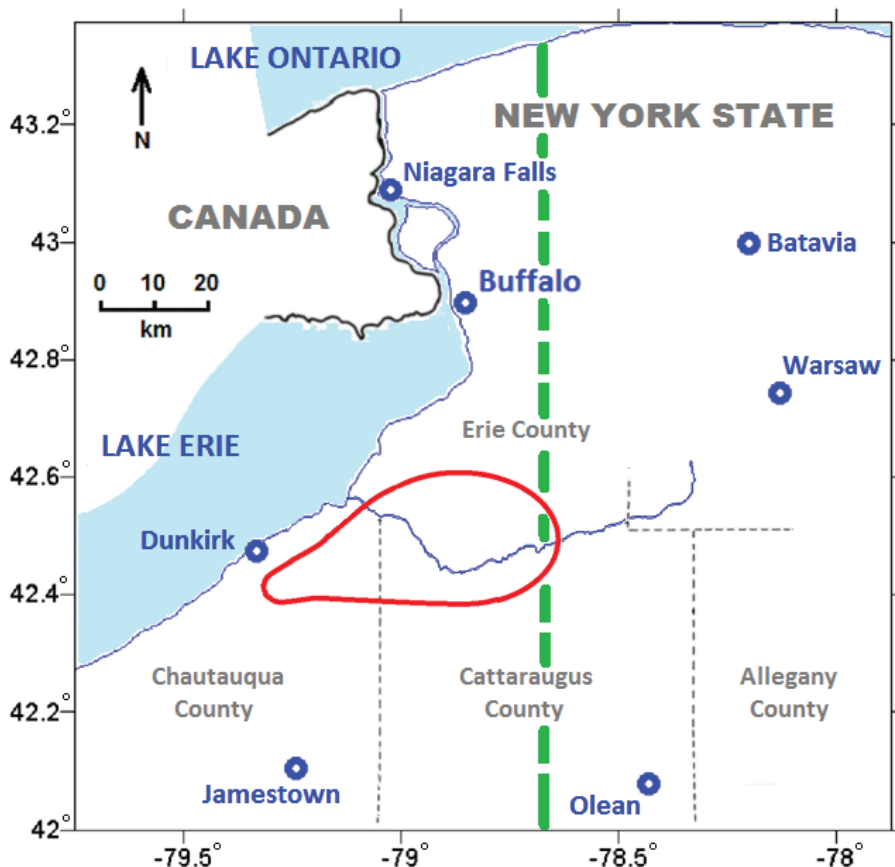
The purpose of this work is to document the dip, thinning, and lateral correlation of lower Famennian strata of the Canadaway Group in southern Erie, northeastern

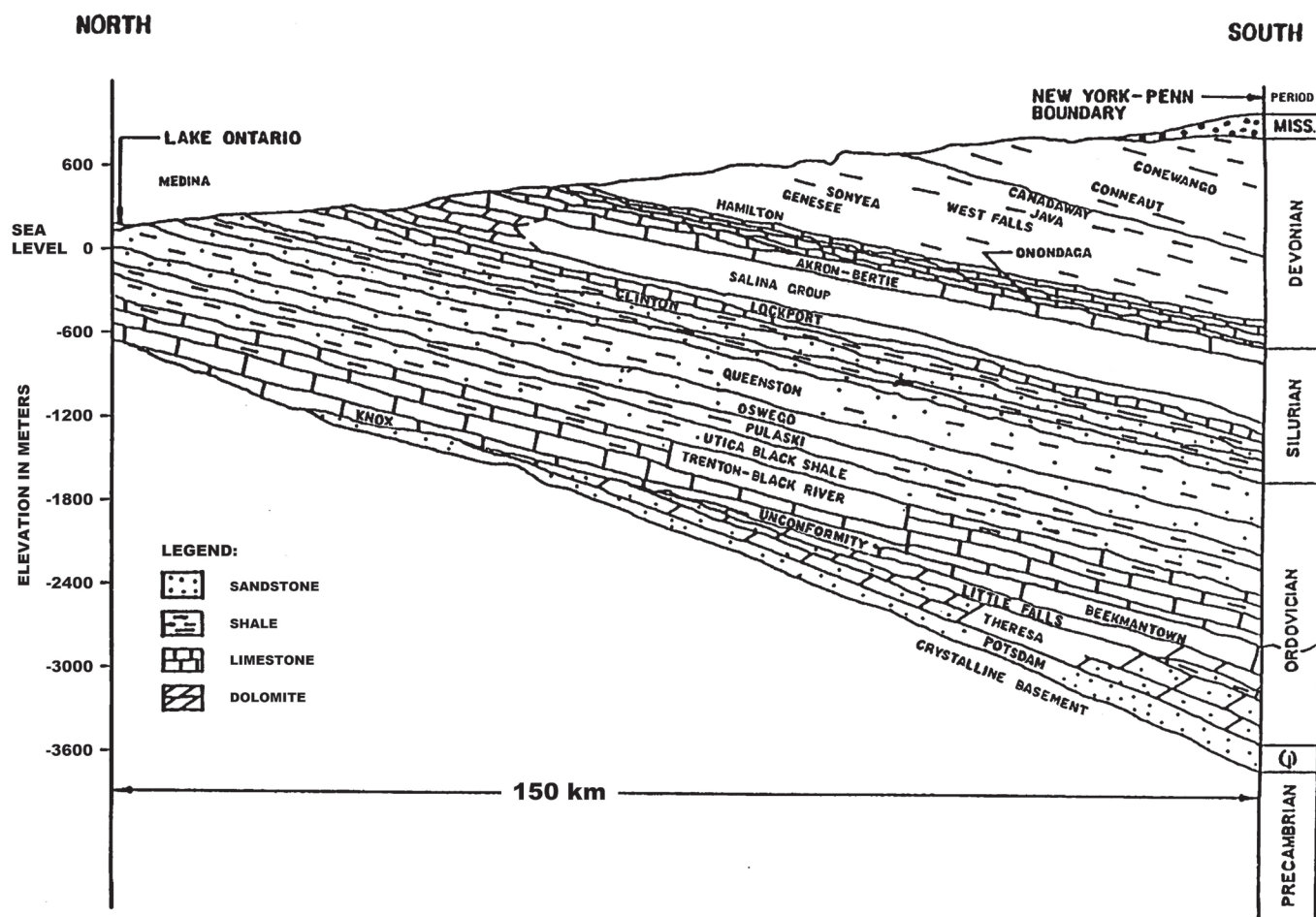
Chautauqua, and northern Cattaraugus counties bisected by Cattaraugus Creek in western New York State (Text-fig. 1). It addresses the Dunkirk/Laona interval from the base of the Dunkirk Formation to the base of the Laona Formation.

The higher Canadaway Group beds, e.g., the Westfield Shale, Shumla Siltstone, and Northeast Shale that were identified above the Laona Formation in Chautauqua County by Tesmer (1963), are not included, nor is the corresponding upper portion of the "Upper Part of Canadaway Formation, Undivided" mapped by Tesmer (1975) in Cattaraugus County. These overlying strata are largely absent from the study area.

Throughout much of western New York, the sedimentary beds are known to dip southward at about one degree or less. As described by Liberty (1981), based partly on the work of Spencer (1891, 1907) and Grabau (1901, 1908, 1920), the various south-dipping beds, particularly the tops and/or north faces of these beds, have been erosion-

Text-fig. 1. Study area (red outline) in western New York State. The dashed green line, extending along $-78^{\circ}40'$ longitude, is the line of section for Text-fig. 2.





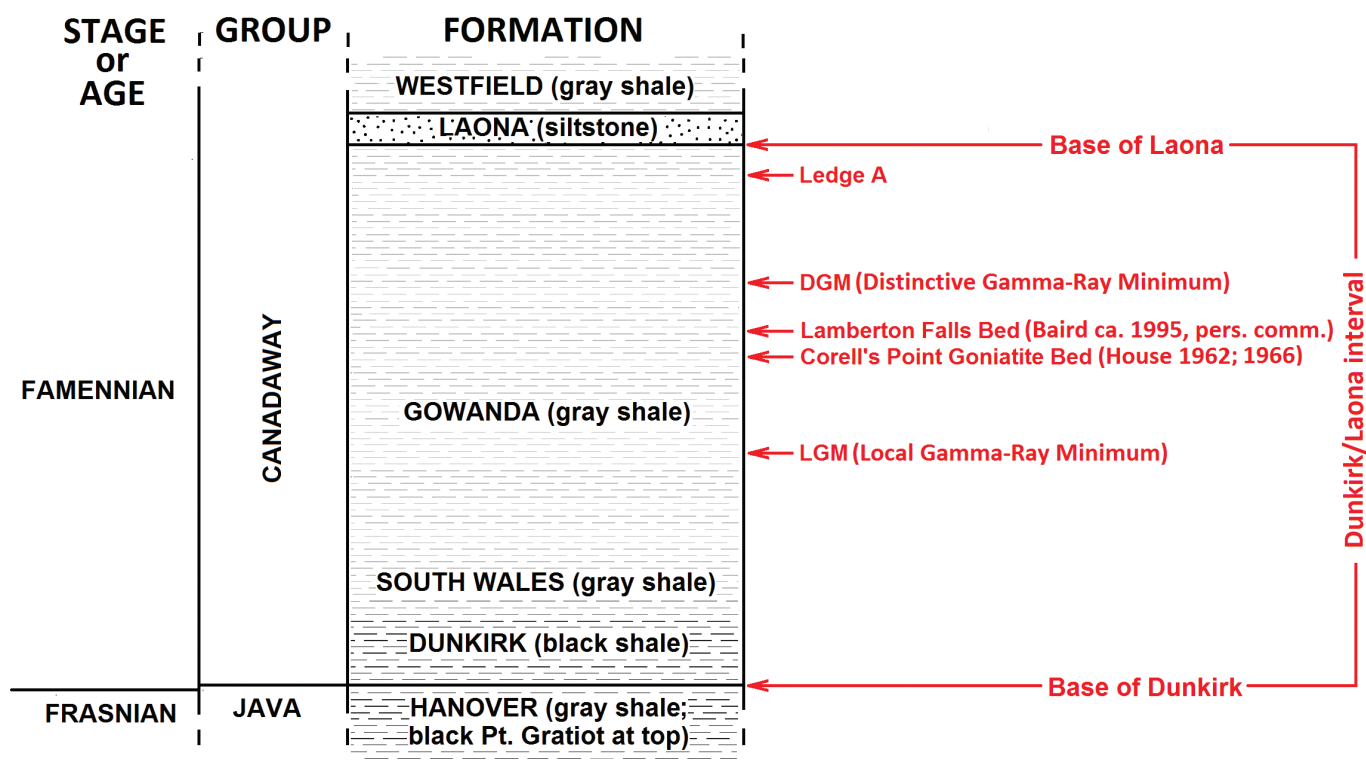
Text-fig. 2. North-south cross section along $-78^{\circ}40'$ longitude, adapted from WVNSCO (1993: fig. 2-3). The line of section is shown by the dashed green line in Text-fig. 1. Note the vertical exaggeration in this cross section.

ally truncated. Such dip and truncation (Text-fig. 2) continue along the $-78^{\circ}40'$ corridor as that line of longitude extends northward across Lake Ontario, reaches the Canadian shore, and passes between Oshawa and Peterborough, Ontario, toward Algonquin Provincial Park. A substantial thickness of sedimentary rock, sometimes termed the Ontario Dome (Grabau, 1920), has thus been removed from the footprint of Lake Ontario and adjacent areas of New York State and Canada over hundreds of millions of years. The lost thickness can be on the order of several thousand feet (Fenneman, 1938) or as much as 7 km (Eyles, 2002).

In the absence of contrary evidence, the well-established southward dip could be assumed to continue upward through the entire section. However, evidence indicates that beds within the Dunkirk/Laona interval thin to the northwest and their direction of dip rotates progressively westward from the base of the Dunkirk Formation upward. Their thickness more than doubles in the study area, ranging from lesser val-

ues near Lake Erie to thicknesses on the order of 250 m at inland locations, with few marker beds previously recognized within the interval (Text-figs. 3, 4).

These Canadaway Group strata are dominated by shales and thin interbedded siltstones of the distal Catskill Delta (Text-fig. 5). Two historical changes in stratigraphic nomenclature should be noted. First, the Canadaway has been upgraded in recent years from formation to group, and its constituent beds, e.g., the Dunkirk, Gowanda, Laona, Westfield, Shumla, and Northeast, have been upgraded from member to formation; compare Baird and Lash (1990) and Baird et al. (2023); see also Smith and Jacobi (2000, 2023). Second, the Dunkirk/Laona interval was formerly called the Perrysburg Formation by Pepper and de Witt (1951) and de Witt and Colton (1953); see also Tesmer (1975). The Perrysburg Formation terminology remains obsolete but is noted here as historical usage.



Text-fig. 3. Stratigraphic column, showing the Dunkirk/Laona interval within which are two existing marker beds (the Corell's Point Goniatile Bed and Lambertton Falls Bed) and three additional marker beds proposed here. These three beds are termed the Local Gamma-Ray Minimum (LGM), Distinctive Gamma-Ray Minimum (DGM), and Ledge A.

Lateral correlation of the base of the Laona Formation and underlying Canadaway Group strata cannot generally be achieved by continuous tracing from one location to another within the study area. This is an inherent complication because this part of the Allegheny Plateau is highly dissected by valleys and gorges where erosion has cut deep grooves into the surviving Famennian beds. In some parts of the study area, the uppermost surviving beds are effectively confined to bedrock "islands."

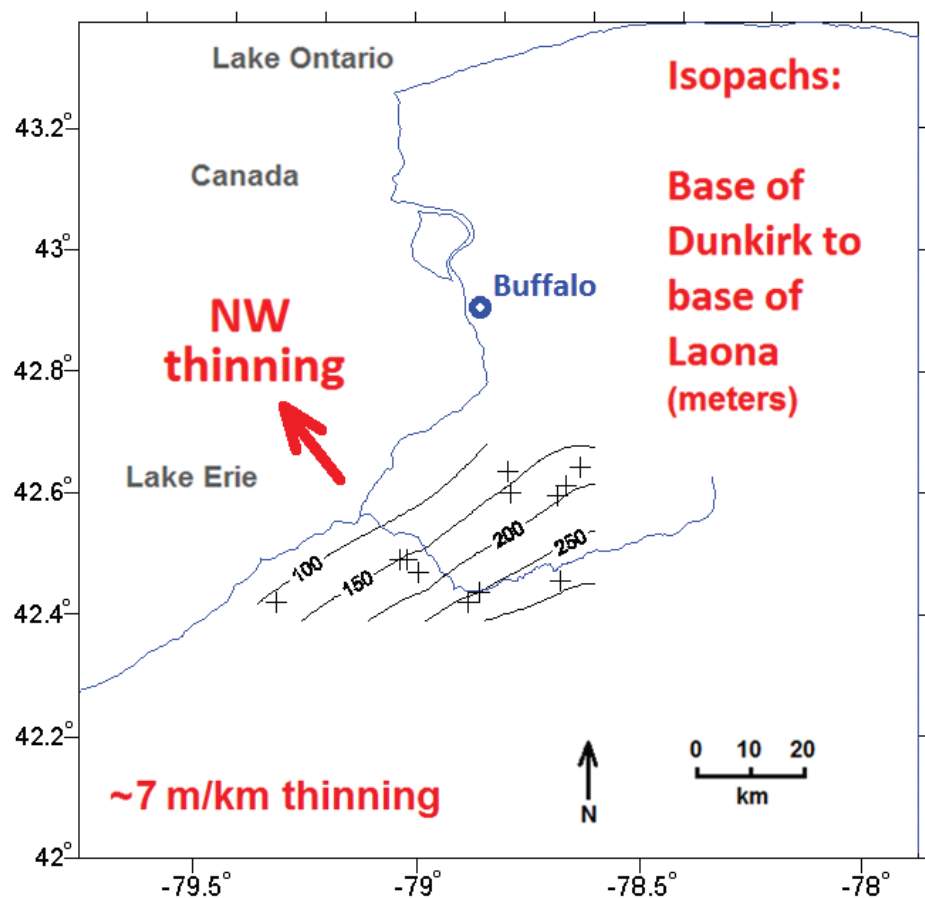
Complete absence of the Canadaway Group north and west of the study area, resulting from some combination of nondeposition and erosion, was recorded by Buehler and Tesmer (1963), Tesmer (1963, 1975), and Pepper and de Witt (1951). The irregular northward extent of the correlative Kettle Point Formation in adjacent Canada was documented by Carter et al. (2019; Text-fig. 6).

HISTORICAL PERSPECTIVE

In describing the bedrock exposed in northern Cattaraugus County, Houghton (1945: p. 107) stated that sandstone beds or lentils interbedded with the shales "are not continuous for any great distance, so that they appear and can be traced for

a few miles, then disappear to be replaced by other lentils at about the same horizon," which in his experience made the identification and correlation of this bedrock "difficult and unsatisfactory." He continued, "All the beds dip southward at the rate of about thirty feet per mile [5.7 m/km]," which is not true with respect to direction.

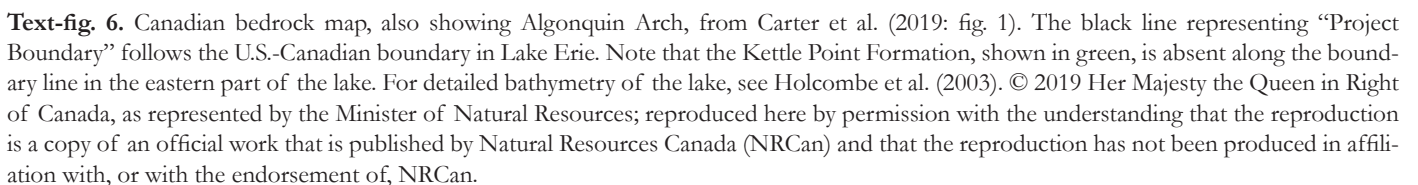
Such erroneous understanding that these beds dip southward will confound any attempt at lateral correlation. Meyers (1999) adhered to the generalization of southward dip and spelled out the unsuccessful quest for a laterally traceable Laona Formation. Van Tyne (1982: 380) similarly stated that "In the present study, we have not been able to trace the Laona eastward from Chautauqua County in the subsurface by the use of gamma ray logs and/or well sample studies." Buehler and Tesmer (1963) and Tesmer (1975) were likewise unable to observe definite exposures of the Laona Formation in Erie County, New York, or at any location in Cattaraugus County east of Perrysburg, New York. In contrast, Finlayson and Ebert (1991) concluded that the Laona Formation crops out in the South Branch of Cattaraugus Creek at an elevation of 980 ft (299 m), but such a low elevation is not reconcilable with this study.



Text-fig. 4. Isopach map of the northwest-thinning interval between the base of the Dunkirk Formation and base of the Laona Formation ("Dunkirk/Laona interval"), with isopachs showing thickness of the interval in meters. Black crosses are data points. Data are from outcrop identification and measurements by the author and Tesmer (1975) and from well-log picks by the author (Supplemental File 1).



Text-fig. 5. Cattaraugus Creek Gorge (known as Zoar Valley) at confluence with South Branch. The entire outcrop seen in the cliff is Gowanda Formation shale, and the vertical exposure here exceeds 100 m. People walking at the base of the cliff for scale appear too small to be discernible. Photo by the author.



County, but no intervening outcrop that would define lateral correlation across the present study area was documented.

Using well logs, Jackson (2022) found that the “Laona and Shumla formations display discontinuity throughout the subsurface; their distributions are irregular, and thicknesses are

mostly controlled by local fault system reactivation” and that “Recognizing these faults in the subsurface aids in small scale, local correlation.” The occurrence of repeated sections from Bass Island thrusting in a few wells northwest of Springville, New York (wells 18270, 21170, 21917, 22603, 22617, and 22676), attests to this, but effects of faults on bed thicknesses are not otherwise evident in the data sets used here.

PURPOSE AND METHODS

The purpose of this study was to reconcile conflicting interpretations of the thinning, dip, and lateral correlation of the Famennian beds that are the uppermost bedrock in parts of western New York State and southern Ontario.

FIELD WORK

Bed elevation in outcrop was determined by running one or more measurement legs with a sighting clinometer and a 100-ft (30-m) tape measure, using the sine of the measured angle to convert the measured hypotenuse to a vertical distance. Each set of measurement legs has been tied to a benchmark or other reference elevation, sometimes using a Cole-Parmer 99770 model EB833 pocket altimeter or a sighting water level (15-m water-filled hose with transparent ends) to span greater distances where no benchmark or other reference elevation was close to the measured outcrop (see Supplemental File 1 for additional information). Repeat measurements, particularly when done with different sets of measurement legs between the same two endpoints, have generally shown agreement within a fraction of a meter. Such agreement has been interpreted as corroborative, whereas disagreement has indicated a need for further measurement. A set of measurements around a 1.8-km closed loop has shown ~1:1000 vertical error (1 unit vertical discrepancy per 1000 units horizontal distance).

Outcrop mapping and other field measurements and interpretations by Buehler and Tesmer (1963), Smith (2002), Smith and Jacobi (2000; 2006b), Tesmer (1957, 1963, 1975), and Van Tyne (1982) served as foundations for this work.

WELL LOGS

Subsurface data published by Van Tyne and Foster (1980), Kreidler (1963), and Richardson (1941), primarily from gamma-ray well logs and drillers’ logs, were supplemented here by picks from paper copies of well logs, completion reports, and associated records acquired from the New York State Department of Environmental Conservation (DEC) in Olean, New York. Logs and associated records are now available in electronic format from the New York State Museum Empire State Organized Geologic Information System, with additional well information available from the DEC

online Mineral Resources Navigator and Searchable Online Database.

Contact picks for key beds from the various well logs are attributed, as shown in Supplemental File 1. The electronically filed spreadsheet for the base of the Dunkirk Formation, for example, shows picks by Van Tyne and Foster (1980) along with many picks made during the course of this work. The latter were made visually by curve matching from one gamma log to another. For the top of the Onondaga Formation, the supporting data could come from a source such as Kreidler (1963), or otherwise from either the gamma log or the driller’s log submitted with the completion report (Supplemental File 1). Ground elevation or other reference elevation for a given log was taken from the most credible source, typically the completion report or log.

THINNING, DIP, AND VECTOR ADDITION

Thinning and dip are not entirely independent of each other. Consider, for example, three sets of values that represent dip of the base of the Dunkirk Formation, dip of the base of the Laona Formation, and thinning of the Canadaway Group from base of the Dunkirk Formation to base of the Laona Formation. Only two of these three sets of values are independent; the other set of values is dependent on the first two. This relationship can be expressed in vector notation. Vectors $\mathbf{V}_1$, $\mathbf{V}_{1.5}$, and $\mathbf{V}_2$ can be used to represent dip of the base of the Dunkirk, thinning of the intervening interval of interest, and dip of the base of the Laona, respectively, such that

$$\mathbf{V}_1 + \mathbf{V}_{1.5} = \mathbf{V}_2 \quad (1)$$

Applying one form of vector notation, each of these three vectors can be expressed as an ordered triple of scalar values x , y , and z , such that:

$$\begin{aligned} \mathbf{V}_1 &= x, y, z_1 \\ \mathbf{V}_{1.5} &= 0, 0, \Delta z \\ \mathbf{V}_2 &= x, y, z_2 \end{aligned} \quad (2)$$

for all points within the xy domain. The horizontal xy plane is oriented with its y -axis pointing north and its x -axis pointing east. The z -axis points vertically upward. For small geographic footprints where thinning or dip can be considered planar, or larger footprints where a planar approximation is adequate, let S_n represent thinning or dip, expressed as a negative gradient such as $S_n = -0.007$ for 7 m/km thinning or dip. Let θ_n represent the azimuth of thinning or dip, measured clockwise from north in the usual manner. (Alternatively, θ_n' could represent the direction of thinning or dip, measured counterclockwise from the positive x -axis, as customary in analytic geometry. In that case, $\sin \theta_n' = \cos \theta_n$ and $\cos \theta_n' =$

$\sin \theta_n$.) The scalar values of z_1 , Δz , and z_2 in Equation 2 can then be expressed in terms of $S_n \sin \theta_n$, etc.

INFERRING THE BASE OF THE DUNKIRK FORMATION

AT A GIVEN LOCATION BASED ON NEARBY WELLS

Picking the base of the Dunkirk Formation from the log of a given well is necessary but not sufficient for establishing the elevation of the contact at some distance from the well. Such circumstances frequently arise where outcrop can be measured at locations not immediately adjacent to a logged well, requiring the base-of-Dunkirk-Formation elevation to be inferred from one or more neighboring wells. In this work, a best-fit plane was constructed for some number of surrounding wells (e.g., best fit by least squares) and the base-of-Dunkirk-Formation elevation was taken from the best-fit plane.

EVIDENCE AND RESULTS

Northwest thinning, and the consequent westward rotation of dip from the base of the Dunkirk Formation upward, are supported by the following lines of evidence. Note the distinction made here between the Dunkirk/Laona interval and various subintervals within that interval.

FIRST LINE OF EVIDENCE:

LOCAL GAMMA-RAY MINIMUM (LGM)

A notable gamma-ray low in the South Wales Formation-Gowanda Formation succession, here termed the Local Gamma-Ray Minimum (LGM), is present on numerous logs of gas wells within the study area. The subinterval between the base of the Dunkirk Formation and the LGM has a consistent northwest (321° azimuth) thinning of ~ 3 m/km (Table 1; Text-fig. 7; Supplemental File 1).

The LGM is stratigraphically lower than the base of the Laona Formation. The Dunkirk/LGM subinterval is thus less than the Dunkirk/Laona interval. Northwest thinning, if projected northwestward, eventually pinches out. The extrapolated pinchout line for the Dunkirk/LGM subinterval lies in the U.S. waters of Lake Erie. It strikes northeastward approximately parallel to, and ~ 7 km offshore from, the New York shore.

SECOND LINE OF EVIDENCE:

DISTINCTIVE GAMMA-RAY MINIMUM (DGM)

Another notable gamma-ray low in the Gowanda Formation, here termed the Distinctive Gamma-Ray Minimum (DGM), is present on the logs of various gas wells within the study area. The subinterval between the base of the Dunkirk Formation and the DGM shows a consistent northwest (322° azimuth) thinning of ~ 4 m/km (Table 2; Text-fig. 7; Supplemental File 1).

The DGM is stratigraphically lower than the base of the Laona Formation and stratigraphically higher than the LGM. The Dunkirk/DGM subinterval is thus thinner than the Dunkirk/Laona interval and thicker than the Dunkirk/LGM subinterval. Its rate of thinning is correspondingly lower than the Dunkirk-Laona rate and higher than the Dunkirk-LGM rate. The extrapolated pinchout line for the Dunkirk/DGM subinterval lies in the Canadian waters of Lake Erie. It strikes northeastward approximately parallel to, and ~ 18 km offshore from, the New York shore.

At least one outcrop bed (red data point in Text-fig. 7) can be correlated with the DGM. This is a thin fossiliferous carbonate bed, essentially a fossil hash, on the order of 10 cm thick, that Robert D. Jacobi and the author observed on 1 September 1996 in the South Branch of Cattaraugus Creek at $\sim 42.3959^\circ$, -78.8890° , 320 m elevation. Although this bed exhibited slickensides in its outcrop on both sides of the creek, brief inspection did not show evidence of substantial offset. The bed, ~ 195 m above the base of the Dunkirk Formation based on nearby wells, was not included in the Table 2 dataset that yielded a planar best fit of ~ 4 m/km thinning at 322° , but is a good match to that plane.

THIRD LINE OF EVIDENCE:

SOUTH BRANCH OUTCROP CORRELATED BY PROJECTION FROM LAONA OUTCROPS IN PERRYSBURG

When three undisputed Laona Formation outcrops in Perrysburg, New York, were projected to the South Branch gorge of Cattaraugus Creek, either of two siltstone outcrops in the South Branch gorge wall became a good candidate for correlation with the Laona Formation.

One of these South Branch outcrop beds provides a better overall correlation than the other, as discussed below. However, regardless of which correlation is adopted, the projection from Perrysburg to the South Branch gorge showed northwest thinning of the Dunkirk/Laona interval.

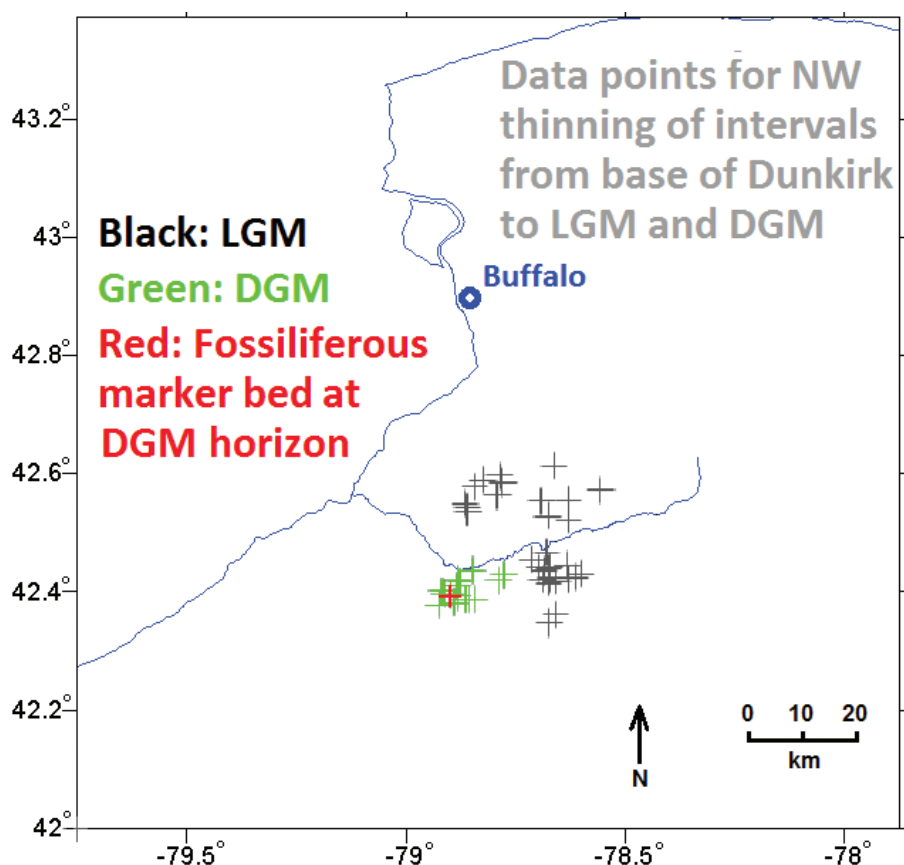
The three Laona Formation outcrops that Tesmer (1975) listed in Perrysburg, New York are located at 42.4905° , -79.0338° ; 42.4895° , -79.0164° ; and 42.4707° , -78.9915° . These outcrops lie essentially on a line, oriented NW-SE, that can be projected northwestward to well 20369 at 42.4957° , -79.0437° and southeastward to the South Branch gorge at 42.4208° , -78.8807° (Text-figs. 8, 9).

The elevation of the base of the Laona Formation, as correlated here between the Perrysburg outcrops and the South Branch gorge, rises to the southeast relative to sea level, and its height above sea level thins to the northwest. It also rises southeastward relative to the base of the Dunkirk Formation, and its height above the base of the Dunkirk Formation thins northwestward, as determined from logs of wells 20369, 16411, 16412, and 10577.

Table 1. Thirty-one gas wells in which the subinterval between the base of the Dunkirk Formation and the Local Gamma-Ray Minimum (LGM) can be observed. This Dunkirk/LGM subinterval exhibits northwest thinning of ~ 3 m/km at 321° . Data are from well-log picks by Van Tyne and Foster (1980) and the author (Supplemental File 1). Well logs are scaled in feet, and the subinterval thickness is shown here in both feet and meters. Well numbers shown here are just the five-digit hole numbers. For full API number, add prefix 31-029- for wells in Erie County (Colden, Sardinia, Concord, North Collins) or 31-009- for wells in Cattaraugus County (Ashford, Ellicottville, East Otto).

Well	Latitude (degrees)	Longitude (degrees)	Base of			
			Dunkirk (ft depth)	LGM (ft depth)	Subinterval thickness	
					(ft)	(m)
Well 17767 in Colden	42.61473	-78.66427	548	281	267	81
Well 19222 in Sardinia	42.57363	-78.55662	892	537	355	108
Well 17768 in Concord	42.55624	-78.63020	737	409	328	100
Well 20905 in Concord	42.55519	-78.69161	834	534	300	91
Well 19209 in Concord	42.52906	-78.67796	730	400	330	101
Well 17735 in Concord	42.52385	-78.62995	655	300	355	108
Well 21181 in Concord	42.58633	-78.77998	421	181	240	73
Well 20745 in North Collins	42.59742	-78.78741	518	285	233	71
Well 15810 in North Collins	42.58972	-78.82526	476	251	225	69
Well 21944 in North Collins	42.56402	-78.79253	682	433	249	76
Well 21887 in North Collins	42.57899	-78.84499	557	333	224	68
Well 21888 in North Collins	42.55094	-78.86617	555	322	233	71
Well 20749 in North Collins	42.54468	-78.86120	561	324	237	72
Well 11723 in Ashford	42.46857	-78.68018	733	360	373	114
Well 20264 in North Collins	42.53737	-78.85985	549	308	241	73
Well 20220 in Ashford	42.45569	-78.71344	747	386	361	110
Well 06740 in Ashford	42.44567	-78.63439	774	353	421	128
Well 21763 in Ashford	42.43103	-78.60089	1295	837	458	140
Well 07196 in Ashford	42.44643	-78.63375	798	377	421	128
Well 21184 in Ashford	42.42622	-78.61442	862	411	451	137
Well 21786 in Ashford	42.44451	-78.67421	1202	808	394	120
Well 21769 in Ashford	42.42347	-78.63065	959	514	445	136
Well 20898 in Ashford	42.44159	-78.69770	942	559	383	117
Well 20787 in Ashford	42.44134	-78.67784	1235	840	395	120
Well 20897 in Ashford	42.43686	-78.68555	1213	820	393	120
Well 20908 in Ashford	42.42277	-78.69096	983	582	401	122
Well 20755 in Ashford	42.42333	-78.67068	1332	918	414	126
Well 21775 in Ashford	42.42004	-78.65771	1400	975	425	130
Well 20907 in Ashford	42.41673	-78.67662	1332	918	414	126
Well 16961 in Ellicottville	42.36282	-78.66036	1614	1140	474	144
Well 17073 in East Otto	42.34852	-78.67448	1765	1288	477	145

Text-fig. 7. Post map of Local Gamma-Ray Minimum (LGM, black) and Distinctive Gamma-Ray Minimum (DGM, green) data points, corresponding to data in Tables 1 and 2, also including the fossiliferous carbonate bed (red) observed at the DGM horizon in outcrop along the South Branch of Cattaraugus Creek near Skinner Hollow.



The South Branch gorge at 42.4208°, -78.8807° exhibits two siltstone intervals, a thick unnamed siltstone packet high on the cliff wall, and also a lower, thinner unnamed siltstone bed (Text-fig. 10). The upper siltstone packet is identified here as the Laona Formation, and the lower, thinner bed is here termed Ledge A.

Three results can be drawn from these two identifications. First, northwest thinning of the Dunkirk/Laona interval along the line of section is ~7 m/km (Text-fig. 8). Second, when extrapolated northwestward the interval pinches out in the waters of Lake Erie, ~8 km off of the New York shore. Third, Ledge A is hereby proposed as a marker bed, with the bed and its proposed type locality defined photographically (Text-fig. 10). The outcrop, high on the South Branch cliff wall, is on privately owned land and not safely accessible on foot, hence the photographic identification.

FOURTH LINE OF EVIDENCE: CORELL'S POINT GONIATITE BED AND LAMBERTON FALLS BED

House (1962, 1966, 1968) and House and Kirchgasser (2008) identified the Corell's Point Goniatite Bed (CPGB) in the South Branch gorge of Cattaraugus Creek at 42.4126°,

-78.8878°, 294 m elevation. This is a regionally recognized marker bed. Immediately upstream, at 42.4116°, -78.8880°, 302 m elevation, is the South Branch waterfall known as Sweetland Falls (Text-fig. 11), which can be correlated to another existing marker bed.

As identified by House (1962), the type locality for the CPGB is at Corell's Point on Lake Erie near Brocton, New York, at 42.3892°, -79.4997°, 174 m elevation, which is ~120 m lower than, and ~50 km due west from, the CPGB exposure in the South Branch gorge of Cattaraugus Creek. The apparent dip of the CPGB at 270° azimuth is thus 120 m/50 km or 2.4 m/km.

A bed at the brink of a small waterfall on Little Canadaway Creek at Lamberton, New York, at 42.4127°, -79.3960°, 210 m elevation, was identified by Baird (ca. 1995, pers. comm., 4 March 1995) as a locally traceable bed, termed the Lamberton Falls Bed, to which the Sweetland Falls bed in the South Branch gorge can be considered equivalent. The informal type locality at Lamberton Falls is ~92 m lower than, and ~42 km due west from, the exposure in the South Branch gorge of Cattaraugus Creek. The apparent dip of the Lamberton Falls Bed at 270° azimuth is thus 92 m/42 km or 2.2 m/km.

Table 2. Fifteen gas wells in which the subinterval between the base of the Dunkirk Formation and the Distinctive Gamma-Ray Minimum (DGM) can be observed. This Dunkirk/DGM subinterval exhibits northwest thinning of ~ 4 m/km at 322° . Data are from well-log picks by the author (Supplemental File 1). Well logs are scaled in feet, and the subinterval thickness is shown here in both feet and meters. Well numbers shown here are just the five-digit hole numbers. For full API number, add prefix 31-009- for these wells, all of which are in Cattaraugus County.

Well	Latitude (degrees)	Longitude (degrees)	Base of		Subinterval thickness	
			Dunkirk (ft depth)	DGM (ft depth)	(ft)	(m)
Well 16525 in East Otto	42.43040	-78.76779	883	201	682	208
Well 21889 in Otto	42.43760	-78.83876	812	190	622	190
Well 16526 in East Otto	42.42120	-78.78004	878	193	685	209
Well 10577 in Otto	42.41152	-78.87301	1013	382	631	192
Well 22080 in Otto	42.42181	-78.87070	1084	464	620	189
Well 10770 in Otto	42.41779	-78.86683	1151	524	627	191
Well 16964 in Persia	42.40281	-78.90750	982	360	622	190
Well 16965 in Persia	42.40270	-78.90257	972	350	622	190
Well 16963 in Persia	42.39822	-78.90213	994	366	628	191
Well 18786 in Otto	42.39298	-78.87173	1037	378	659	201
Well 18485 in Otto	42.38913	-78.83501	1107	413	694	212
Well 18045 in Otto	42.38885	-78.85247	1179	500	679	207
Well 18046 in Otto	42.38889	-78.84486	1234	553	681	208
Well 16924 in Persia	42.37948	-78.91465	971	325	646	197
Well 18070 in Otto	42.38332	-78.88123	1013	348	665	203

These two apparent dip values of 2.4 and 2.2 m/km for beds over long measurement legs of 50 and 42 km, respectively, are consistent with the dip and thinning in other lines of evidence presented here. Given the westward dip rotation from the base of the Dunkirk Formation upward (Text-figs. 12, 13), both the Corell's Point Goniatite Bed and the Lamberton Falls Bed are likely to be dipping to the southwest. If their average apparent dip at 270° azimuth is 2.3 m/km, this corresponds to a true dip of $2.3\sqrt{2} = 3.3$ m/km toward the southwest (225° azimuth).

FIFTH LINE OF EVIDENCE:

GAMMA-RAY FEATURE CORRELATED TO LEDGE A

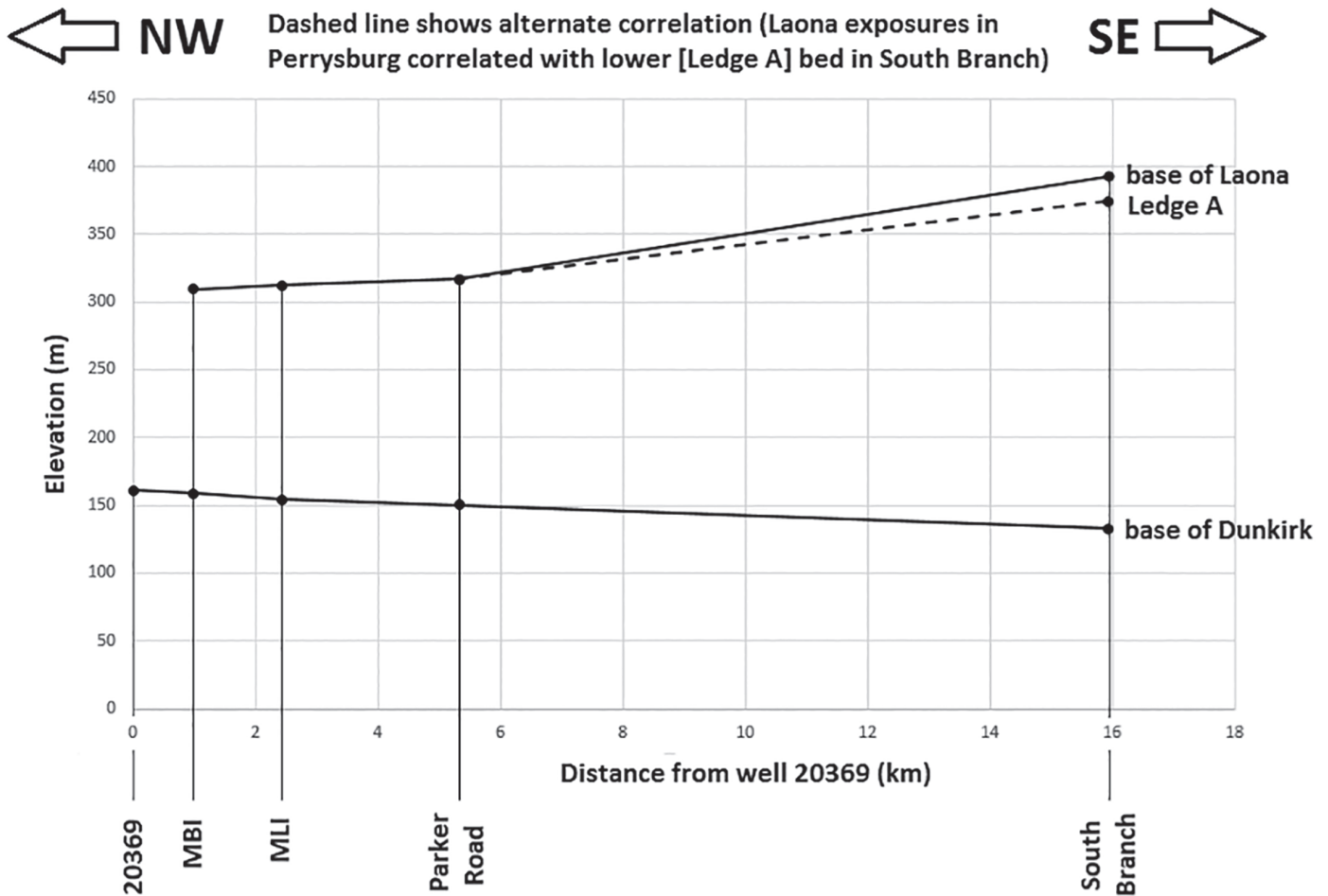
A correlatable gamma-ray feature, different from the LGM and DGM, can be recognized on the logs of seven wells in Ashford and Machias, New York, which lie within the study area. The subinterval between these gamma-ray picks and the base of the Dunkirk Formation shows a consistent northwest thinning of ~ 6 m/km at 337° azimuth. These gamma-ray picks can be correlated with Ledge A, and the subinterval between these picks and the base of the Dunkirk Formation can thus be termed the Dunkirk/Ledge A sub-

interval. Regardless of whether the proposed identification with Ledge A is made, this set of seven data points provides another demonstration of northwest thinning of a subinterval within the Dunkirk/Laona interval (Table 3; Text-fig. 9; Supplemental File 1).

Ledge A is stratigraphically lower than the base of the Laona Formation and stratigraphically higher than the LGM and the DGM. Hence, the Dunkirk/Ledge A subinterval is thinner than the Dunkirk/Laona interval and thicker than either the Dunkirk/LGM subinterval or the Dunkirk/DGM subinterval. Its rate of thinning is correspondingly lower than the Dunkirk-Laona rate and higher than either the Dunkirk-LGM rate or the Dunkirk-DGM rate. The extrapolated pinchout line for the Dunkirk/Ledge A subinterval lies approximately on the U.S.-Canadian boundary line in Lake Erie. It strikes northeastward approximately parallel to, and ~ 10 km offshore from, the New York shore.

FITTING BASE OF LAONA FORMATION TO A REGIONAL NW-THINNING SET OF WELL AND OUTCROP DATA

The base of the Laona Formation has been placed into a regional framework of well and outcrop data points by fit-



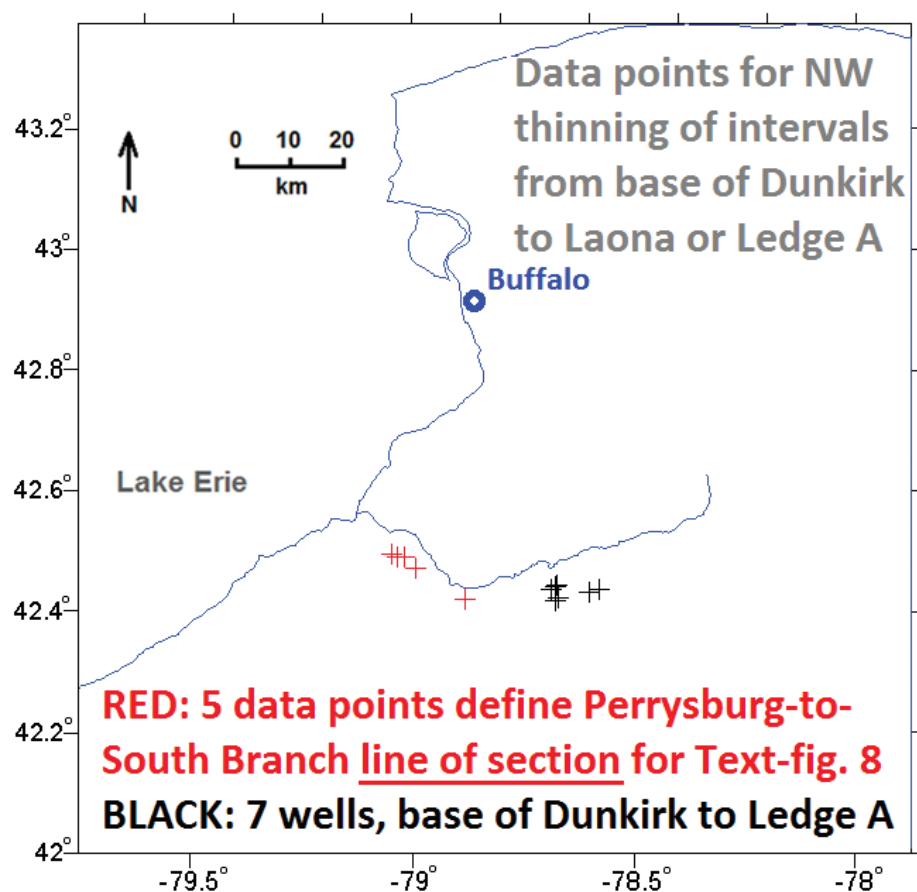
Text-fig. 8. NW-SE cross section, extending from Perrysburg, New York, to the South Branch gorge of Cattaraugus Creek. The line of section passes through the five red data points in Text-fig. 9. The x -axis shows distances from well 20369 in Perrysburg to the Laona Formation outcrops along Mackinaw Road at Big Indian Creek (“MBI”), along Mackinaw Road at Little Indian Creek (“MLI”), and in the ravine at the eastern end of Parker Road, all in Perrysburg; also to the South Branch gorge at 42.4208° , -78.8807° . The y -axis values are for elevation of the base of the Laona Formation (upper solid black line) and elevation of the base of the Dunkirk Formation (lower solid black line). Note the vertical exaggeration in this cross section.

ting the Dunkirk/Laona interval to a set of candidate data points over a broad geographic footprint. In effect, but not necessarily explicitly, the task is to find a function $f(x,y)$ for which directions and magnitudes of dip and thinning are consistent with those demonstrated for subintervals within the Dunkirk/Laona interval. The function should be reasonably smooth, but not necessarily a planar function like those used above for best-fit planes to which subinterval data have been compared.

The data points were termed “candidates” in the sense that each of them, at its location x,y , represents the upward distance Δz from the base of the Dunkirk Formation to the base of a candidate siltstone that could be the Laona Formation. A data point that is a good fit to a reasonably smooth function

$\Delta z = f(x,y)$ is a good candidate; it strengthens the evidence that the candidate siltstone is indeed the Laona Formation.

The results obtained here, using 12 such data points, are shown by the Dunkirk-to-Laona isopach map (Text-fig. 4) and the base-of-Laona-Formation structure contour map (Text-fig. 13; Supplemental File 1). The northwest thinning of this interval is ~ 7 m/km. Such thinning, if extrapolated into Lake Erie, indicates full pinchout of the beds within this interval. Approximately 25 or 30 km inland from the Lake Erie shore, these Famennian strata range up to 250 m thick, yet within the footprint of Lake Erie, they can be projected to zero thickness, with the pinchout line approximately parallel to the New York shore and ~ 10 km offshore.



Text-fig. 9. Post map of seven Ledge A data points from well-log picks by the author (Supplemental File 1), corresponding to data in Table 3, and also showing the five red data points that define the line of section in Text-fig. 8.

FITTING LEDGE A TO A REGIONAL NW-THINNING SET OF WELL AND OUTCROP DATA

Fitting Ledge A to a regional NW-thinning set of well and outcrop data was done in the same manner described above by fitting the Dunkirk/Ledge-A subinterval to another set of candidate data points. Again, the task was to find a function $f(x,y)$ for which directions and magnitudes of dip and thinning are consistent with those demonstrated for subintervals within the Dunkirk/Laona interval. The function should be reasonably smooth but not necessarily planar.

The data points were again termed “candidates” in the sense that each of them, at its location x,y , represents the upward distance Δz from the base of the Dunkirk Formation to a candidate siltstone that could be Ledge A. Data points that fit a reasonably smooth function $\Delta z = f(x,y)$ are good candidates; they strengthen the evidence that the candidate siltstone is indeed Ledge A.

The results, using 23 such data points, are shown by the Dunkirk-to-Ledge-A isopach map (Text-fig. 14) and the Ledge A structure contour map (Text-fig. 15; Supplemental File 1). The northwest thinning of this subinterval is ~ 5 m/km. Such thinning, if extrapolated into Lake Erie, indicates

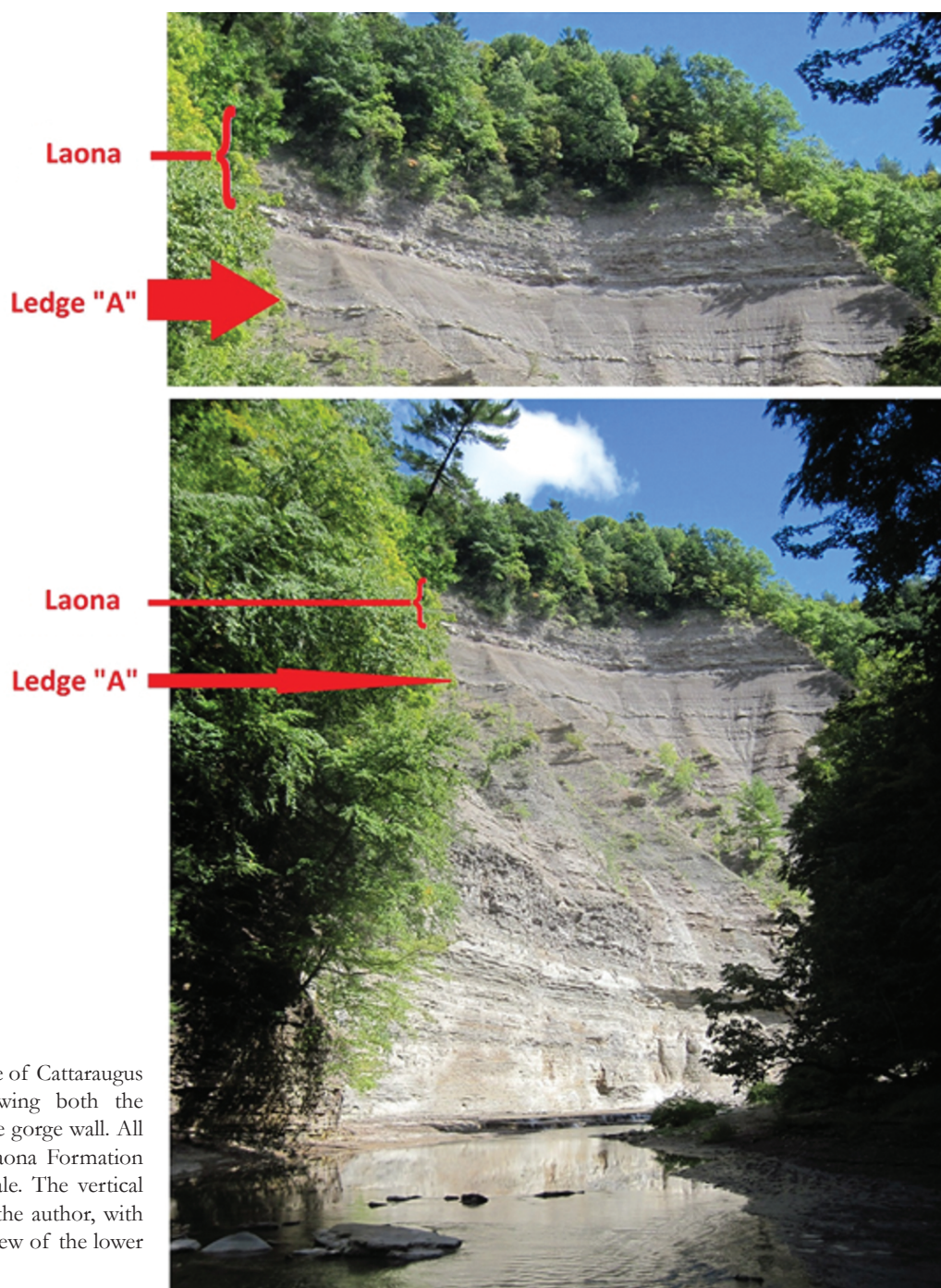
full pinchout of the strata within this subinterval. The pinchout line is approximately parallel to the New York shore, ~ 12 km offshore.

DISCUSSION

Multiple lines of evidence have been presented here to show mutually consistent results for thinning and dip. These lines of evidence differ not only in their geographic footprints, but also their methodologies and sources of possible error.

For example, results for the Dunkirk/LGM and Dunkirk/DGM subintervals were independently derived. Their accuracies, although dependent on well log picks and on an assumption that no missing or repeated sections occur between the picks on a given log, avoided some of the larger uncertainties associated with gas-well and outcrop measurements. The latter include uncertainties in gas-well ground elevations and difficulties of vertical measurements on high cliffs, often compounded by the need to tie outcrop measurements in deep ravines and cliff faces to reliable benchmarks.

Overall, the results are quantitatively consistent, showing northwest thinning on the order of 7 m/km for the



Text-fig. 10. The South Branch gorge of Cattaraugus Creek (42.4208° , -78.8807°), showing both the Laona Formation and Ledge A in the gorge wall. All outcrop shown here beneath the Laona Formation siltstone is Gowanda Formation shale. The vertical exposure exceeds 100 m. Photo by the author, with upper panel providing a magnified view of the lower panel.

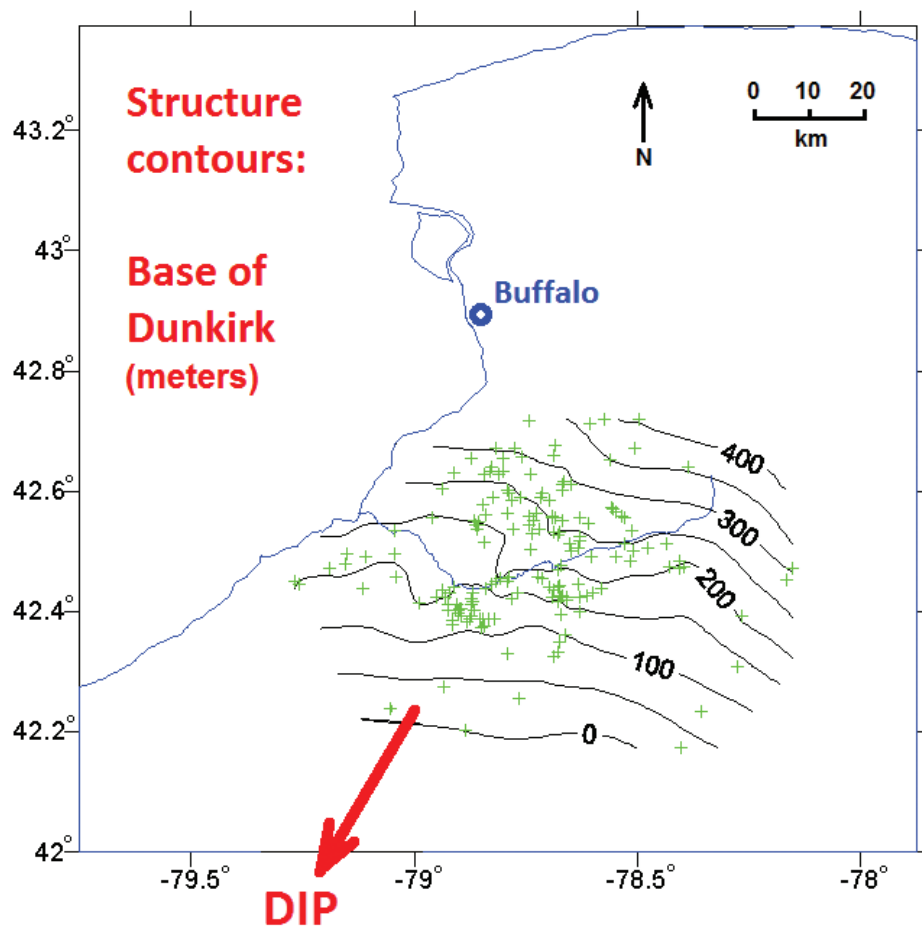
Dunkirk/Laona interval and lesser northwest thinning for its subintervals. The results also show that the subintervals remain in approximately the same proportions to the entire interval, regardless of the overall northwest thinning of the lower Famennian beds.

Northwest thinning, although sometimes observed and noted by others, has not been previously investigated, integrated, and reported in detail. For example, Baird and Lash

(1990: A16), while acknowledging “the possibility that the Laona could be present in northwest Cattaraugus County at a higher elevation than expected on the assumption of uniform southward dip of Devonian strata,” did not ultimately develop this possibility. They noted, citing informal communication with Tesmer, that “no Laona deposit has yet been observed in that area.”



Text-fig. 11. Waterfall known as Sweetland Falls at 42.4116° , -78.8880° on the South Branch of Cattaraugus Creek, immediately upstream of the Corell's Point Goniatile Bed at 42.4126° , -78.8878° , 294 m elevation. The bed at the brink of this fall is an analog of the Lamberton Falls Bed identified by Baird (ca. 1995, pers. comm., 4 March 1995) at 42.4127° , -79.3960° . Photo by the author.



Text-fig. 12. Structure contour map of the SSW-dipping base of the Dunkirk Formation, with elevation above mean sea level in meters. Green crosses are data points. Data are from Buehler and Tesmer (1963), Tesmer (1975), and well-log picks by Van Tyne and Foster (1980) and the author (Supplemental File 1).

Text-fig. 13. Structure contour map of west-dipping base of the Laona Formation, with elevation above mean sea level in meters. Black crosses are data points. Data are from outcrop identification and measurements by Tesmer (1975), Baird and Lash (1990), and the author (Supplemental File 1). The westernmost data point is the lakeside Laona Formation exposure at Barcelona, New York, as identified by Baird and Lash (1990) and others.

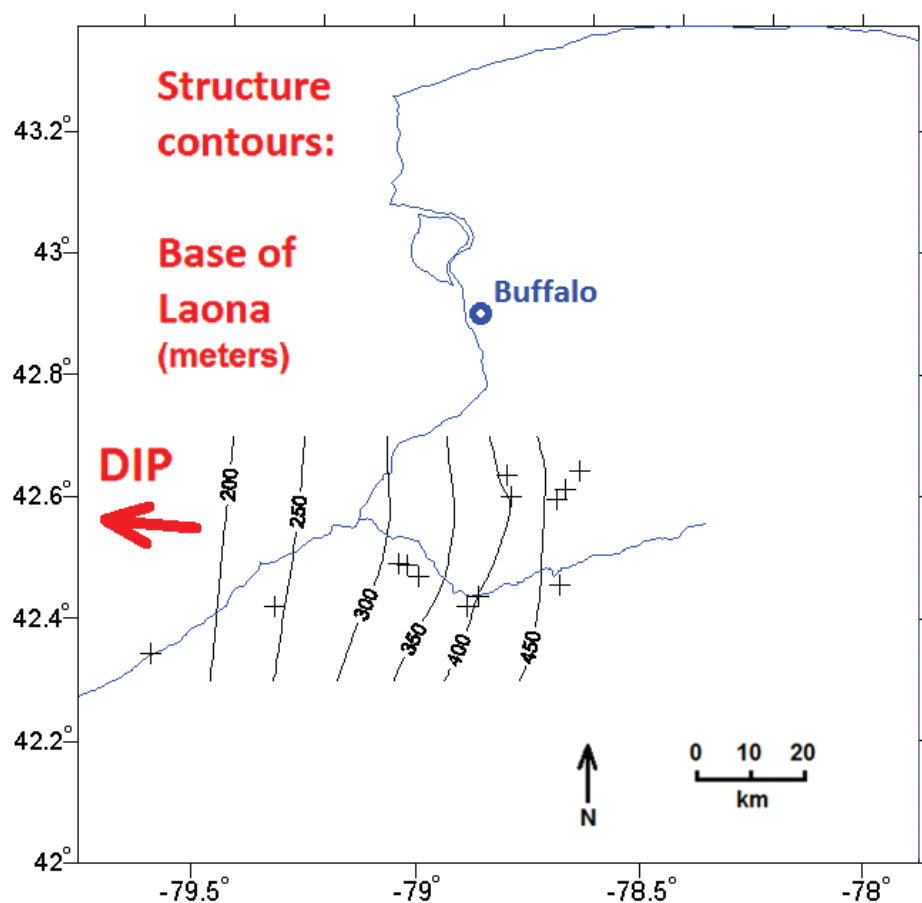
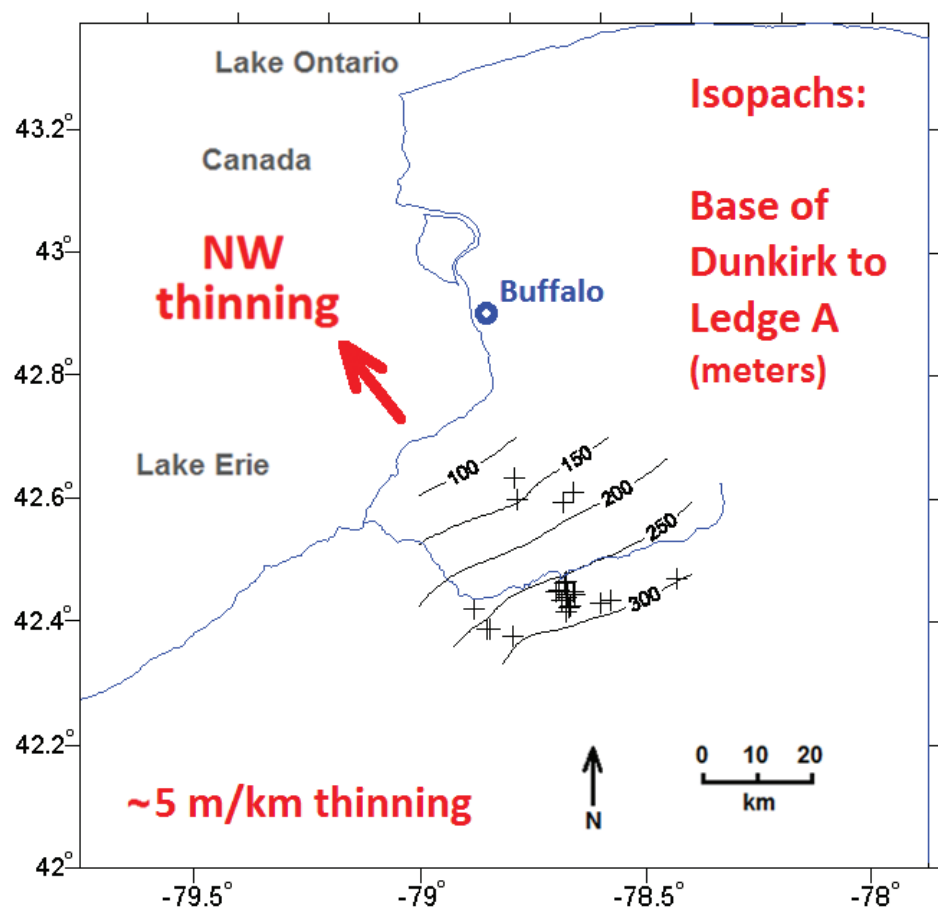


Table 3. Seven gas wells in which the subinterval between the base of the Dunkirk Formation and Ledge A can be observed. This Dunkirk/Ledge A subinterval exhibits northwest thinning of ~ 6 m/km at 337° . Data are from well-log picks by the author (Supplemental File 1). Well logs are scaled in feet, and the subinterval thickness is shown here in both feet and meters. Well numbers shown here are just the five-digit hole numbers. For full API number, add prefix 31-009- for these wells, all of which are in Cattaraugus County.

Well	Latitude (degrees)	Longitude (degrees)	Base of		Subinterval thickness	
			Dunkirk (ft depth)	Ledge A (ft depth)	(ft)	(m)
Well 20907 in Ashford	42.41673	-78.67662	1332	405	927	283
Well 20897 in Ashford	42.43686	-78.68555	1213	329	884	269
Well 20787 in Ashford	42.44134	-78.67784	1235	354	881	269
Well 21786 in Ashford	42.44451	-78.67421	1202	325	877	267
Well 21763 in Ashford	42.43103	-78.60089	1295	350	945	288
Well 20953 in Machias	42.43686	-78.57905	1231	286	945	288
Well 20755 in Ashford	42.42333	-78.67068	1332	415	917	280



Text-fig. 14. Isopach map of northwest-thinning subinterval between the base of the Dunkirk Formation and Ledge A (“Dunkirk/Ledge A subinterval”), with isopachs showing thickness of the subinterval in meters. Black crosses are data points. Data are from outcrop identification and measurements by the author and Tesmer (1975) and from well-log picks by the author (Supplemental File 1).

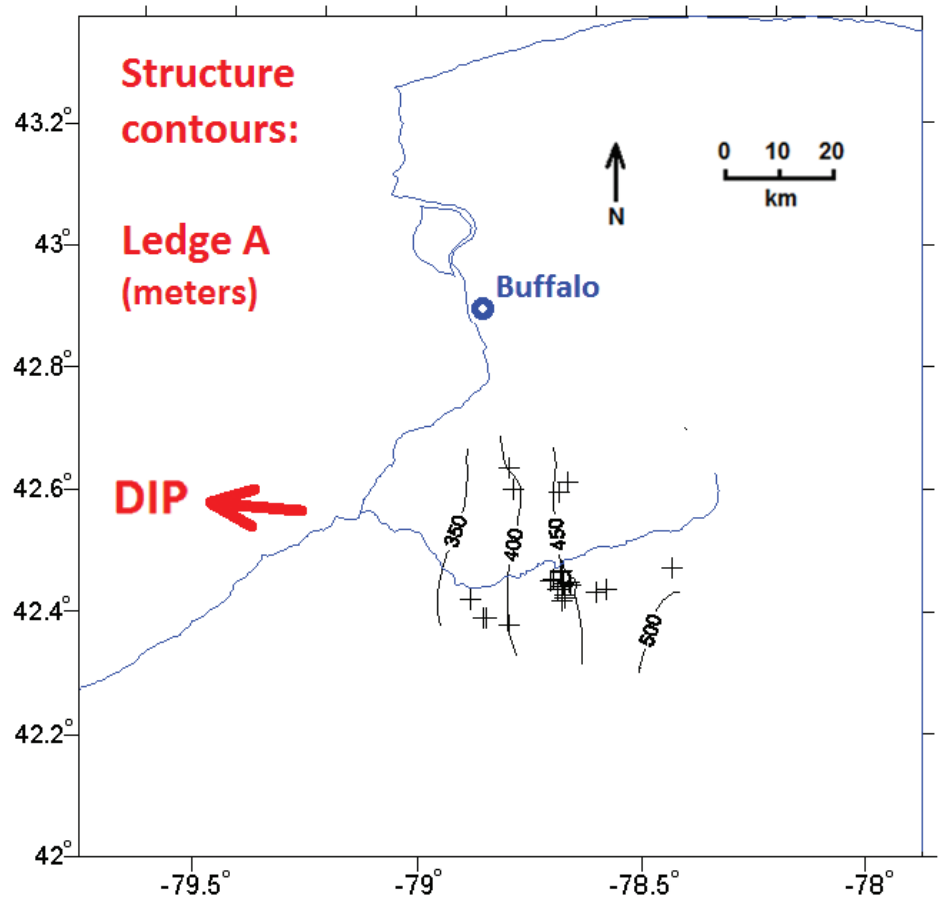
The beds described here merit further investigation of depositional facies, geochemical fingerprinting, radiometric dating, and fossil evidence. Their thicknesses offer both challenges and opportunities. Although no outcrop shows the full 250-m Dunkirk/Laona interval that exists 25 or 30 km inland, two examples of outcrop within the Zoar Valley (Text-figs. 5, 10) exhibit vertical sections of that interval that exceed 100 m, where 40% of the full 250-m sedimentary thickness is exposed. These strata thin to zero when projected onto the footprint of the lake.

Three new marker beds within the Dunkirk/Laona interval—the LGM, DGM, and Ledge A—have been proposed here in addition to the Corell’s Point Goniatile Bed and Lambertson Falls Bed. The DGM, initially identified from well logs, has also been assigned a proposed exposure in outcrop that can serve as its type locality; this is the fossiliferous carbonate bed at $\sim 42.3959^\circ$, -78.8890° , 320 m elevation, in South Branch (Text-fig. 7). The LGM, although currently known only from well logs, can be present and identifiable in outcrop locations like Franklin Gulf in North Collins, New York. Ledge A and its proposed type locality, as described above, are defined photographically high on the South Branch

cliff wall (Text-fig. 10). In future work, “Otto Siltstone Bed” can serve as an enduring, location-based name for Ledge A; likewise “Skinner Hollow Bed” for the DGM.

If this work could be extended further south—despite poorer well control in that direction—a potentially corroborative test would be whether outcrop in the area known as The Narrows, located west of Franklinville, New York, at 42.3372° , -78.4798° , is correlative with the Laona Formation. Such lateral correlation is roughly consistent with the dip and thinning presented here. Another potentially corroborative test involves the identification of the Corell’s Point Goniatile Bed in outcrop in the town of Concord, New York, at 42.5898° , -78.6845° , 393 m elevation. This outcrop location fits the interpretation presented here in terms of continuity and proportionality but would not otherwise be an expected location for the goniatile bed.

As an illustration of how an “expected location for the goniatile bed” is changed by the work set forth here, consider the comment by Baird and Lash (1990: A14) on the CPGB exposure in the South Branch gorge of Cattaraugus Creek. They acknowledged its identification by House (1966, 1968) but suggested that “it occurs at an elevation of 965 feet which



Text-fig. 15. Structure contour map of west-dipping Ledge A, with elevation above mean sea level in meters. Black crosses are data points. Data are from the author's outcrop identification and measurements and his well-log picks (Supplemental File 1).

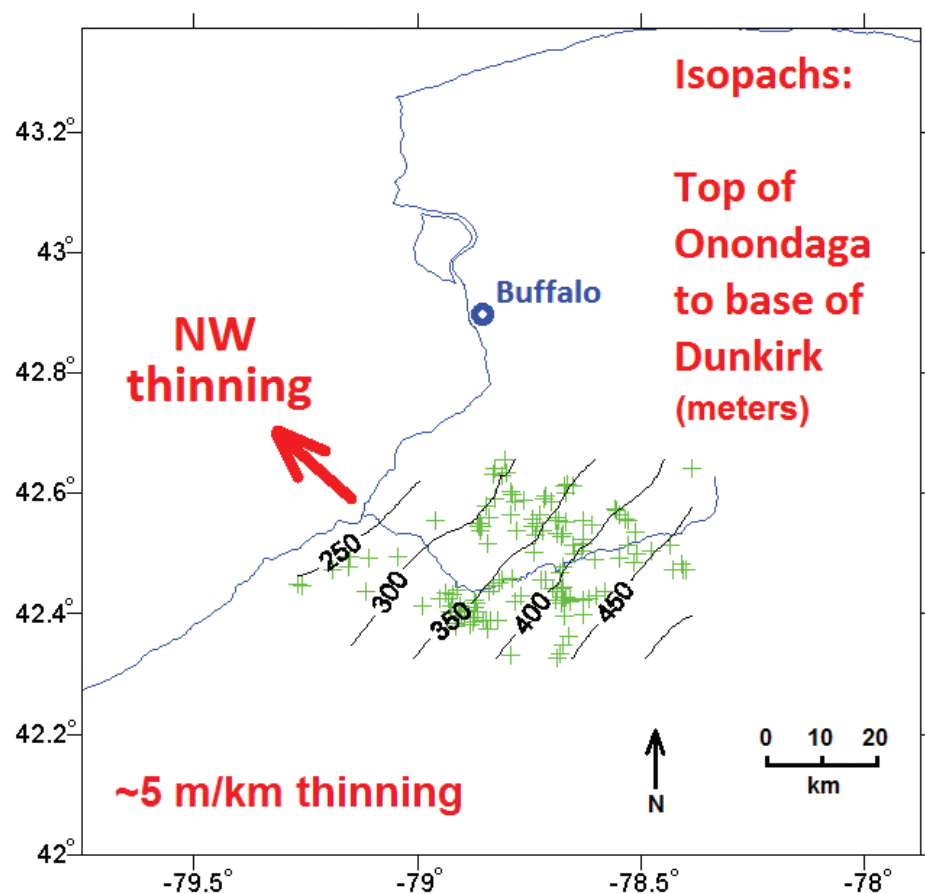
is anomalously high suggesting the possibility of significant structural upwarping of beds southeast of Gowanda [NY].” As set forth above, the elevation of 965 ft (294 m) is not anomalously high but fits the present work very well, with no need to invoke structural upwarping.

The rotation of the dip direction is simply a response to the northwest thinning of the intervening beds, as can be shown either by simple experiment or vector addition. Similar rotation in response to northwest thinning can also be seen in older/deeper Devonian beds. For example, isopachs for the northwest-thinning interval between the top of the Onondaga Formation and the base of the Dunkirk Formation (Text-fig. 16) conform to the abutting lower and upper contacts at the SSE-dipping top of the Onondaga Formation (Text-fig. 17) and SSW-dipping base of the Dunkirk Formation (Text-fig. 12). This is analogous to the isopachs mapped for the northwest-thinning Dunkirk/Laona interval (Text-fig. 4), which conform to the abutting lower and upper contacts at the SSW-dipping base of the Dunkirk Formation (Text-fig. 12) and west-dipping base of the Laona Formation (Text-fig. 13). Although additional work would be needed to determine whether such dip and thinning continue to rotate in

upper Canadaway Group beds above the Laona Formation, a comparison of LGM and Ledge A picks in Tables 1 and 3 for wells 20907, 20897, 20787, 21786, 21763, and 20755 suggests continued rotation (clockwise upward) below the Laona Formation and potentially above it as well.

The work presented here could be locally important as a bridge between the stratigraphic characterizations west of the present study area by Baird and others (Baird and Lash, 1990, Baird et al., 2023) and east of the study area by Smith and Jacobi (2006a, 2023). It could also offer clues to the origin of Lake Erie. Unlike the gradual bedrock lowering along the $-78^{\circ}40'$ transect where the Ontario Dome evolved into Lake Ontario, and where the surviving beds generally pinch out northward due to erosional truncation, the Famennian pinchout in the eastern portion of Lake Erie was apparently the result of depositional northwest thinning. Along the line of full pinchout within the present footprint of Lake Erie, this means that any sediment deposition from the Frasnian-Famennian boundary onward was absent by the time any Laona Formation deposition commenced.

The evidence that bears on the pinchout question is necessarily incomplete. The problem is that the beds comprising



Text-fig. 16. Isopach map of northwest-thinning interval between the top of the Onondaga Formation and the base of the Dunkirk Formation, with isopachs showing thickness of the interval in meters. Green crosses are data points. Data are from Kreidler (1963) and well-log picks by Van Tyne and Foster (1980) and the author (Supplemental File 1).

the interval of interest are entirely or almost entirely gone from the footprint of Lake Erie and the immediate lakeshore area. The evidence—particularly the proportionality of sub-intervals within the Dunkirk/Laona interval—favors depositional pinchout, meaning nondeposition rather than postdepositional erosional removal (Text-fig. 18).

Overall, the available evidence indicates that Lake Erie, at least its eastern end, occupies a bedrock low hundreds of millions of years old, subsequently deepened by glacial action but originally a Famennian nondepositional feature. The Algonquin Arch, unless too distant, likely played a role in such pinchout of strata.

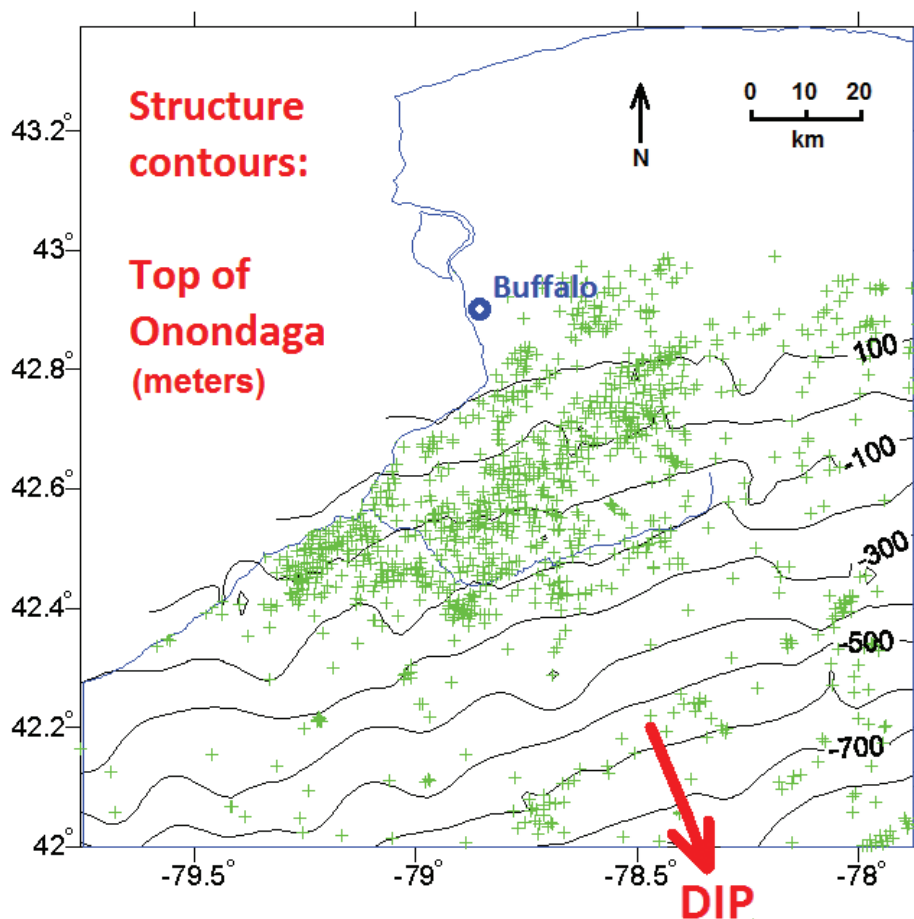
RELATION TO ONTARIO, PENNSYLVANIA, AND OHIO

The thinning and termination of lower Famennian strata in the area now covered by Lake Erie could also tie into the Appalachian and Michigan Basins and the bedrock geology—including configuration of the Algonquin Arch and Niagara Escarpment—on the Canadian side of Lake Erie.

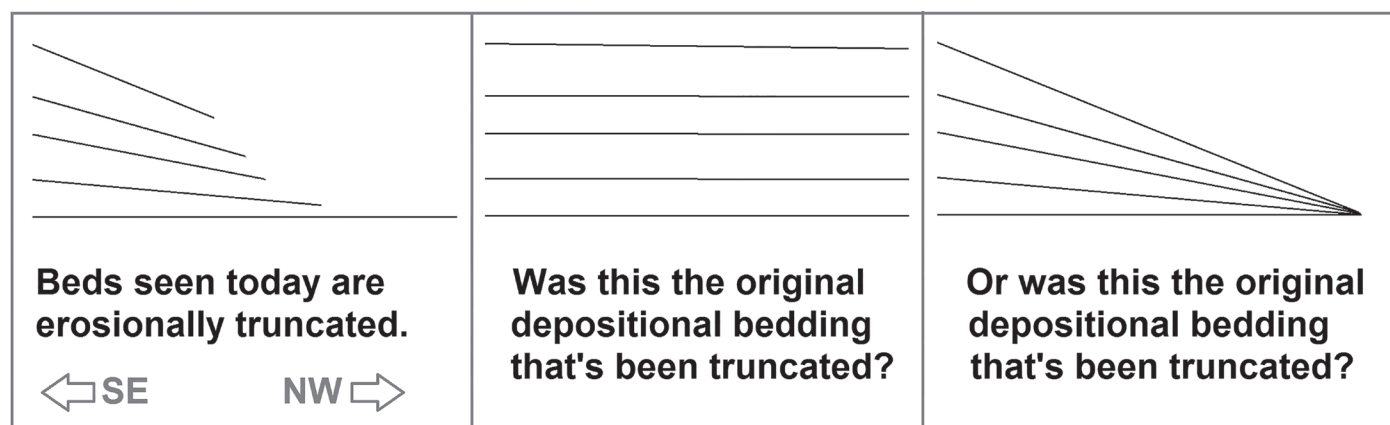
Recent mapping shows the zigzag connection between lower Famennian beds on the south (U.S.) shore of Lake

Erie and those on the north (Canadian) shore (Carter et al., 2019; Text-fig. 6). Although Hamblin (2010) placed the Kettle Point Formation immediately below the Frasnian-Famennian boundary, Bingham-Kosłowski (2015) showed the boundary lying within the Kettle Point Formation, and Kendall et al. (2020) demonstrated a more precise placement of the boundary within the formation. Thus, the Kettle Point is substantially correlative with the Dunkirk/Laona interval discussed here.

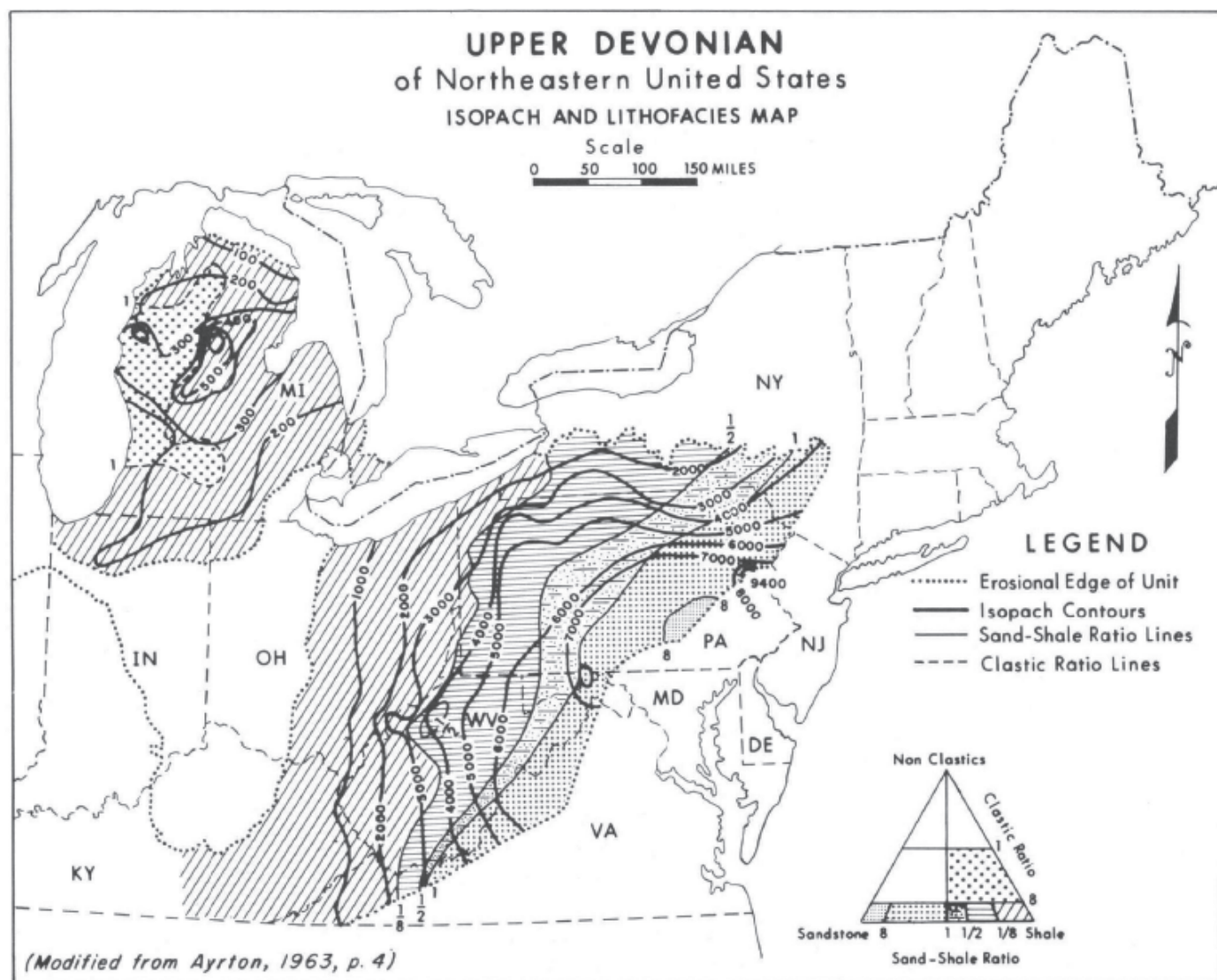
Sevon (1985), from Ayrton (1963), mapped Upper Devonian strata, along with their isopachs, and the narrow connection between the Appalachian and Michigan Basins via the Chatham Sag, through which the Kettle Point Formation runs northward (Text-fig. 19). The configuration of the Upper Devonian isopachs along the Lake Erie shore—not only in New York but Pennsylvania and part of Ohio as well—demonstrates that the general trends in western New York State, particularly northwest thinning and pinchout, extend beyond the study area. The Upper Devonian thicknesses represented by the isopachs running generally parallel to the shore are noteworthy. When extrapolated northwestward, they thin to zero in, or nearly within, the footprint of Lake Erie.



Text-fig. 17. Structure contour map of the SSE-dipping top of the Onondaga Formation, with elevation above mean sea level in meters. Green crosses are data points. Data are from Kreidler (1963), Richardson (1941), and well-log picks by the author (Supplemental File 1).



Text-fig. 18. Schematic cross sections of a generalized stratigraphic interval with subintervals within it. The left panel shows erosionally truncated beds, analogous to the truncation along the lake plain of Lake Erie. Specifically, the left panel shows the surviving beds converging relatively uniformly toward zero thickness. The center and right panels show two possible configurations of the beds as deposited. The right panel, in which beds exhibit northwest depositional thinning and pinchout, is a better fit for the erosionally truncated Famennian beds discussed here. Note the vertical exaggeration in these cross sections.



Text-fig. 19. Isopach and lithofacies map of the Upper Devonian, northeastern U.S. and adjacent Canada, from Sevon (1985: fig. 1) as adapted by him from Ayrton (1963). © 1985 The Geological Society of America, Inc., unless within scope of government employee exemption, and reproduced here under 'Fair Use' permission.

CONCLUSION

Northwest thinning of Famennian strata within the Canadaway Group, particularly in the interval between the base of the Dunkirk Formation and the base of the Laona Formation, and the lesser northwest thinning of its subintervals, have two implications. First, such thinning has affected the bedrock dip directions as they now exist by causing the southward regional dip of the older beds to swing westward during the Famennian. The resulting westward dip has confounded prior efforts to trace and correlate beds such as the Laona Formation. Second, when such thinning is projected

northwestward, the strata pinch out within the footprint of Lake Erie, implying that the bathymetry of the lake, especially the relatively deep eastern end, is due primarily to nondeposition rather than erosion.

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ABSTRACTS

ORAL

DEVONIAN CONODONT STRATIGRAPHY AND FACIES DEVELOPMENT OF THE AZROU REGION
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The Moroccan Meseta represents the northwestern margin of Gondwana that was strongly tectonized in the Carboniferous during the main Variscan orogeny, in continuation of the southern European Variscides. In the Devonian, the region was a subtropical archipelago with reefs, subdivided by synsedimentary, Eovariscan block faulting into a complex mosaic of basins and rises. Investigation of their individual facies histories, stratigraphy and faunas was the topic of a joint DFG-CNRST Maroc project. Results on various regions have been published in two recent monographs [1, 2] and this contribution is part of a third volume that has a focus in the eastern part of the Western Meseta.

The Azrou region belongs to a Variscan nappe that was transported westward in the Viséan. This resulted in a strong tectonization that affected the preservation of fossils. For example, a fair amount of conodonts shows weak to strong plastic deformation, and macrofauna is difficult to extract from folded, partly cleaved, and strongly diagenetically overprinted limestones. However, a high-resolution reconstruction of facies developments is possible by combined conodont and microfacies investigations. This commenced with a pioneer study by G. Bohrmann and G. Fischer [3] and is refined by our new data.

Three different Devonian successions exposed in various erosional windows below a cover of Mesozoic sediments and Quaternary volcanics have been recognized in the Azrou region. Measured and sampled outcrops represent individual nappes and tectonic slices overthrust onto Ordovician and thin Silurian siliciclastics. In the whole region, the Lochkovian/main Pragian is represented by silty shales to fine sandstones with dacryoconarids, trilobite debris, and rare *Pleurodictyum*.

NW Succession: It is represented ~4 km NNW of downtown Azrou by a thick section exposed on the slope just north of a convenient new auberge with swimming pool. The lower part are up to 150 m thick, light-gray calcareous shales assigned to the Bab-al-Ari Formation. Thin, dark-gray, fine-grained crinoidal limestones ~7 m below the top yielded a *Belodella* fauna with a single, poorly preserved *Icriodus ?ultimus*, which indicates an Emsian age. Previous records from the unit [3] include typical lower Emsian icriodids. The subsequent, massive, light-gray flaser limestones of the Azrou

Formation include a strange jump from the *bilatericrescens/excavatus* Zones at the base to Eifelian faunas still in the lower part. The upper Emsian seems missing due to nondeposition. In the upper part, there are basal middle Givetian conodonts with *I. difficilis*. The Azrou Formation is capped by a lenticular to massive flat pebble breccia with tabulate, solitary and colonial rugose corals (*Phillipsastrea*). It forms the base of the Bou Ighial Formation. The reworking of a near-by biostrome occurred in the upper part of FZ 3 (*Ancyrodella africana* Zone). Laterally, reef debris limestones have been dated as *ansatus* Zone [3] suggesting that the biostrome had a middle Givetian age.

Approximately 2.5 km to the north, thick-bedded limestones grade into a succession of breccia beds that still fall in the middle Givetian, showing an early onset of synsedimentary uplift and re-deposition.

Bou Ighial: There is a marked, high ridge in the middle of Azrou, which lower part is occupied first by silty greenish shales, then by calcareous gray shales of the Bab-al-Ari Formation. In the western part, the first limestones of the Azrou Formation yielded among a flood of *Belodella* and unknown *Polygnathus* resembling Eifelian forms. Flaser limestones grade into and alternate with brecciated limestones with lower/middle Givetian conodonts. At short distance, this brecciated Bou Ighial Formation truncates into the Lower Devonian shales. Near the base, *Linguipolygnathus linguiformis* is mixed with top-Givetian taxa, such as *Po. paradecorosus* and *Po. dengleri dengleri*. Several meters higher, weakly tectonized, platy limestones yielded a lower Frasnian fauna with *Ad. africana* (upper FZ 3). Following a thick shale interval, there is a thick upper conglomerate/breccia succession alternating with laminated dark-gray shales. The succession yielded *Scaphignathus velifer leptus*, *Sc. velifer velifer*, *Palmatolepis marginifera duplicata*, *Pa. perlobata schindewolfi*, *Po. fallax*, and others. This proves a second prolonged interval of Eovariscan uplift and erosion of parts of a deep neritic/shallow pelagial platform in the middle Famennian. There are numerous Givetian and Frasnian reworked conodonts, including possibly new forms that could be from any of the three stages. A distinctive feature is the rarity of middle/upper Frasnian and lower Famennian palmatolepids. We assume that there was nondeposition or extreme condensation at that time.

Bab-el-Ari: A different succession ranging from the Lochkovian/Pragian to the uppermost Famennian is exposed at the isolated Bab-el-Ari hill ~3 km northeast of the Bou Ighial. Above ~50 m silty and sandy shales, gray calcareous shales of the lower Bab-al-Ari Formation are interrupted by a ~10 m thick unit (local Member 2) of coarse crinoidal limestones. It yielded near the base a rich fauna with dominant *Belodella* and common *Caudicriodus claudiae*, a typical Pragian species. Member 3, the ~75 m thick upper calcareous shales, are not dated but thin lenticular limestones at the base of the Azrou Formation yielded a lower Emsian fauna with *Latericriodus multicostatus* and *Lat. gracilis*. As previously advocated [3], we suspect that the upper Emsian is missing again. Approximately 15 m higher, micritic flaser limestones yielded only *Belodella*, but 23–25 m higher, there are middle Givetian faunas that reach to the formation top.

The Bou Ighial Formation characterized by recurrent Eovariscan reworking consists in the main section of alternating shales and thin conglomerate layers, first with conodonts

of the *marginifera* Zone. Approximately 30 m higher, a thick conglomerate contains reworked Givetian reef fauna, which is restricted to this marker unit. The next hill to the north differs in a lower conglomerate with reworked sandstone blocks and a middle Frasnian conodont fauna (FZ 6 with *Ad. lobata*). It is overlain by ~20 m of thin sandstones and siltstone, a unit that was obviously cut out laterally by erosion before the basal middle Famennian transgression. In the northern section, lateral section, the main Bou Ighial Formation falls in the *marginifera* to *velifer* Zones, occasionally with reworked Givetian and Frasnian taxa). Near the top, where limestones become sparse and thin, there is a record [3] of *Bispathodus ultimus*, suggesting long phases of nondeposition and condensation.

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ORAL

**NEW OBSERVATIONS IN END-DEVONIAN TO BASAL TOURNAISIAN SUCCESSION IN OHIO
RELEVANT TO THE NEED FOR RENEWED, DETAILED CHRONOSTRATIGRAPHIC STUDY OF
CONTINUOUS OUTCROP SECTIONS**

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Much of what we have learned about the nature and timing of key end-Devonian events (Dasberg transgression, Hangenberg biocrises) has come from very detailed zonal studies of “old world” outcrops in Europe and North Africa, which are largely developed in condensed sections recording offshore pelagic conditions. In contrast, Ohio and northwestern Pennsylvania offer numerous accessible sections, which are developed in thicker, variably neritic, and sometimes enigmatic facies. Physical mapping by the present authors has led to the discovery of many new sections. Moreover, additional work by others has revealed direct and indirect evidence of end-Devonian glacial events in the northern Appalachian Basin region. However, the relative paucity of detailed biostratigraphic work on these strata leaves a great many unanswered questions concerning the timing of these and other events.

Re-examination of the upper Famennian succession in Ohio has confirmed earlier work suggesting that sections in central and southern Ohio record relatively offshore, marine to marginally marine conditions. In particular, these sections suggest that deposition was largely continuous during much of the end-Devonian biocrisis interval. West of Cleveland, Ohio, the basal contact of the black, basinal Cleveland Shale with the underlying gray Chagrin Shale grades basinward from a prominent drowning surface disconformity to depositional conformity. More significantly, the base-Bedford

Formation disconformity capping the Cleveland Shale across the Cleveland metropolitan area and across northeastern Ohio, similarly becomes gradational westward. This contact is distinctly conformable from the vicinity of Amherst in northwest-central Ohio southwestward to Columbus in central Ohio. This deposition continuity provides an opportunity to secure an unbroken record of the conodont, palynomorph, and ammonoid successions from the basinal upper Chagrin and Cleveland Shale successions, upward to, and possibly through, the enigmatic middle (red) Bedford succession, into the minimally studied marine, uppermost gray Bedford interval at Columbus. Such work should eventually lead to confident recognition of the key global Hangenberg markers, *Hangenberg black shale*, *Hangenberg gray shale*, and *Hangenberg sandstone* expressed locally in basinal to nearshore facies.

The presence of unusual lithofacies (“barren” red Bedford and succeeding Berea Sandstone) in the Ohio late Famennian section as well as evidence of glacial and/or peri-glacial deposits in eastern Pennsylvania, Maryland, and Kentucky, suggest that these distinctive deposits should allow a connection between successive lithologic events and likely causal factors. Hence, detailed future biostratigraphic and chemostratigraphic studies, particularly in the upper Cleveland Shale to basal Berea Sandstone interval, in multiple long sections, offers great promise in unraveling the succession of end-Devonian events.

ORAL

MARINE STRATA OF THE MIDDLE AND UPPER HAMILTON GROUP (MIDDLE DEVONIAN, LOWER GIVETIAN), EASTERN OUTCROP BELT IN NEW YORK STATE

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Background: The -74.75° West meridian marks roughly the eastern limit, in both the northern and southern outcrop belts, of fully marine facies of the Hamilton Group (Fig. 1), with the transition to terrestrial facies occurring progressively lower in the section as one moves eastward. Lower Givetian strata east of this line present a challenging puzzle compared to equivalent strata to the west in New York State. As opposed to the more-well understood strata to the west, strata in this region: (1) have overall less abundant and complete exposure; (2) preserve relatively varied facies that in places change laterally over short geographic distances; (3) are generally thicker (in some cases over two orders of magnitude thicker compared to correlative intervals in western New York State) with less vertical heterogeneity and more gradational facies changes within the vertical succession; (4) further complicating matters are in which in shallow-water, shoreface sandstone packages it can be difficult to correlate between sections due to a lack of intermingled contrasting lithologies (i.e., dark shales); and finally (5) some levels contain anomalous faunal elements when compared to the standard list of taxa for the Hamilton interval.

A significant problem related to the homogeneity of nearshore facies is the paucity of recognition of distinct, correlative marker units. This has resulted in a lack of identity of the key position of strata correlative with the base of the Skaneateles and Ludlowville formations, the Mottville and Centerfield members, in Schoharie, Albany, Greene, and Ulster counties, in the eastern outcrop belt. All of this is also complicated by the greater overall thickness and greater degree of cover of the strata, as well as a lack clear biostratigraphic data. Furthermore, very few workers have attempted to carry out stratigraphic and paleontologic studies within this region over the last 150 years, as opposed to the myriad of studies carried out in western and central New York State on age-equivalent strata.

Results: Our own fieldwork, combined with the interpreted findings of previous workers, has allowed us to: (1) correlate basal Skaneateles Formation strata of the Mottville interval in central New York further eastward into the Schoharie Valley region (Fig. 2); (2) establish tentative correlations between coral-rich strata in eastern Schoharie County and western Albany County and the Mottville Member interval to the west (Fig. 2); (3) redefine the boundary of the

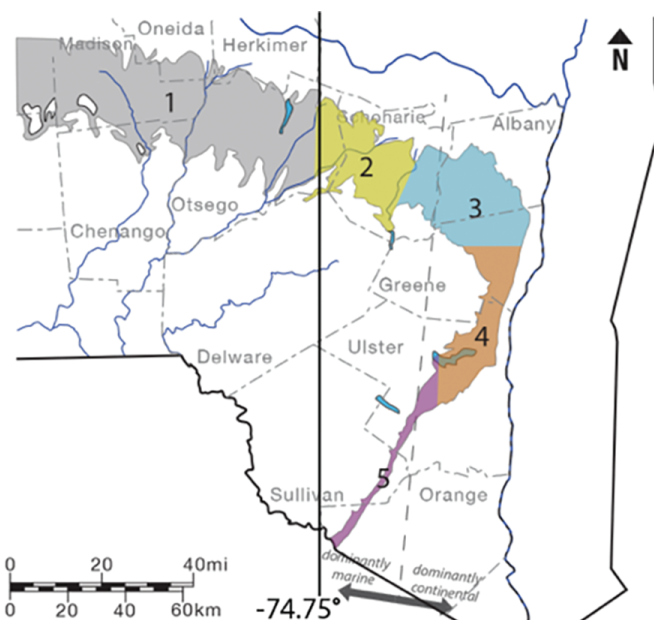


Figure 1. Location map for eastern New York State showing major regions of study showing -74.75° West meridian.

Mount Marion and Panther Mountain formations proximal to the base of the Mottville correlative interval, narrowing this down stratigraphically in eastern sections (Fig. 2); (4) identify two distinct intervals rich in the anomalous brachiopod *Schizophoria* (King, 1850) in southwestern Albany County, northwestern Greene County, and northern to central Ulster County (Fig. 2); (5) gain a better understanding of the stratigraphic distribution of conglomerate intervals in the interval of the upper Mount Marion Formation and to some degree the lower Panther Mountain Formation; and (6) identify the lowest level of marginal marine/terrestrial facies within the Hamilton Group as occurring within the upper Marcellus interval in Greene County.

In the process of our work, we have also come to a more resolved view of the stratigraphic and geographic location of the lowest (oldest) position of the transition between marine and terrestrial environments within the Middle Devonian strata across this region. In the area between the Schoharie Valley and Otsego County (region 2 in Fig. 1), this transi-

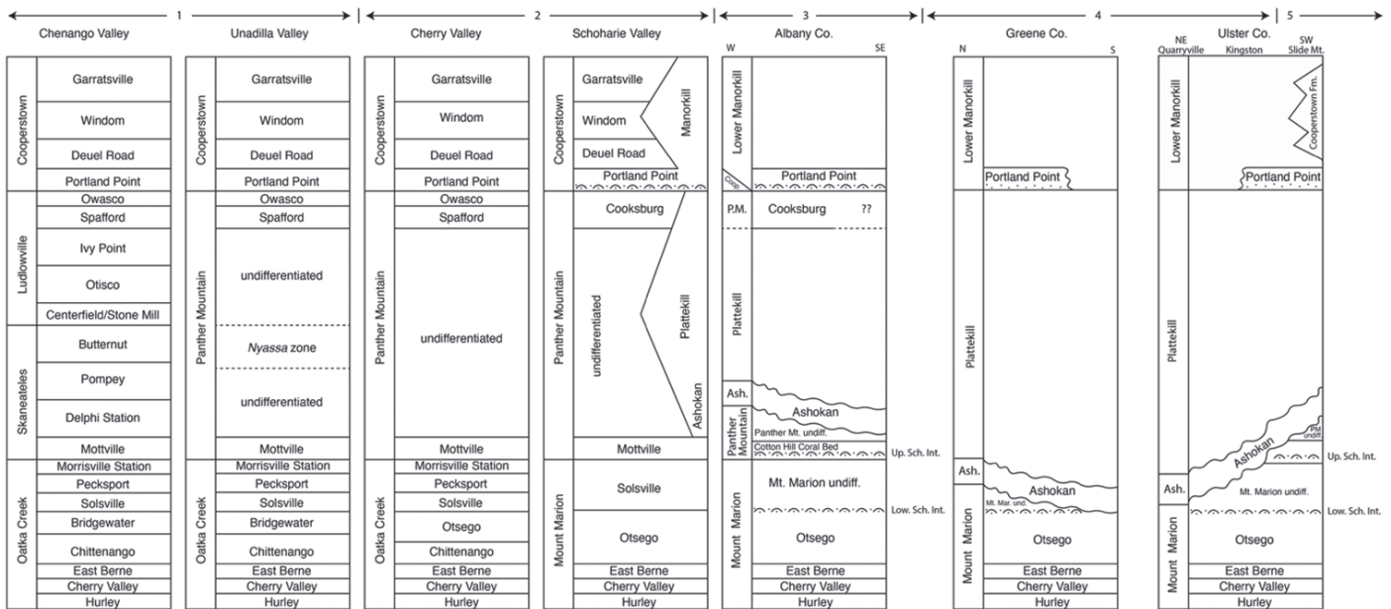


Figure 2. Stratigraphic columns for the various regions of study. Ash. = Ashokan; Coop. = Cooperstown; Mt. Mar. = Mount Marion; PM = Panther Mountain; Sch. Int. = *Schizophoria* interval; undiff. = undifferentiated.

tion takes place within the upper Panther Mountain interval. In the area of eastern Schoharie County and southwestern Albany County (region 3 in Fig. 1), this transition takes place within the lower Panther Mountain interval. In central Greene County southward into Ulster County (region 4 in Fig. 1), this transition takes place within the upper portion of the Mount Marion Formation. Finally, in the region through southwestern Ulster through western Orange County in the southern outcrop belt (region 5 in Fig. 1), this transition again rises up through the formations getting back to totally marine strata extending through the entire Hamilton Group inter-

val around Port Jervis in western Orange County near the -74.75° West meridian.

Additionally, we have been able to further resolve the stratigraphic position of tongues of marine strata that extend eastward into areas dominated by terrestrial facies. Thus far, we have identified intervals interpreted by us to be at the base of both the Panther Mountain and Cooperstown formations that preserve thin tongues of marine facies characterized by stenotypic marine fauna including brachiopods, bivalves, and echinoderms sandwiched between thicker packages of strata preserving transitional to fully terrestrial facies.

ORAL

IMPACT OF GLOBAL EVENTS ON THE DROWNING AND EXTINCTION OF GIVETIAN/FRASNIAN REEFS IN THE NORTHERN RHENISH MASSIF (GERMANY)

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Introduction: There are numerous Givetian and Frasnian reefs in the Rhenish Massif, which have been quarried in partly huge quarries or which have been explored by fully cored bore holes in conjunction with the mining operations or during the search for metalliferous deposits. In the northern Rhenish Massif, from the Aachen region in the southwest to the Brilon and Messinghausen reefs in the northeast, there are ten larger and some small-sized biostromes and bioherms that grew on the southern shelf of the Old Red Continent in times of reduced siliciclastic delivery from the eroding Caledonian orogen.

After a first period during the initial geological mapping in the early 20th century, and a second period in the 1960s/1970s, research slowed down and modern microfacies and high-resolution biostratigraphic data were published only in a few cases. In the last 20 years, the Devonian Münster Group, in close cooperation with the Geological Survey/Service at Münster (M. Piecha, D. Juch, J. Drozdowski, S. Hartenfels, S. Stichling, S. Becker), investigated numerous outcrops of nine reefs but research is continuing. Our studies, which included numerous B.Sc. and M.Sc. theses, benefitted much from the good cooperation and partial financial support by the Lhoist Germany Rheinkalk GmbH. They provided access to active quarries and core material. Our work had a wide range of goals, from geological mapping, to reef microfacies types, palaeoecology, microbial carbonates, and initial phases and their microfaunas [1] to diagenesis in the context of their geothermal potential, reefal detritus, sedimentary geochemistry, and post-reefal facies history. The identification of reef builders by A. May (Unna) was crucial. We had a strong focus on conodont or ammonoid dating of the locally very different drowning and final extinction phases and their potential correlation with the well-known global events as a possible trigger.

The Walheim Reef Complex lies in the Inde Syncline of the Aachen region. A deepening interval marked by dark gray marls with the last dechenellid trilobites and just below the extinction of *Stringocephalus* has been roughly correlated with the Taghanic Transgression. The reef survived into the lower Frasnian, where it was drowned a second time in the course of the Timan Event (high in FZ 3). It recovered once more and a final coral garden biostrome fell victim to the *semichatovae* Transgression.

The similar but older (uppermost Givetian) biostrome of Hofermühle South (northern Velbert Anticline) was sharply

interrupted by a black shale that represents probably the main pulse of the Frasnian Event. In the northern reef, thin detrital limestones at the base of a unnamed siliciclastic unit yielded middle Frasnian conodonts. Because coarse conglomerates are already intercalated in the lower Frasnian, the Hofermühle Reef is regionally exceptional because it seems to have been suffocated by the spread of clastic wedges from a small island (now in the subsurface) to the north.

In the upper Frasnian, a crinoidal-microbial (stromatolitic) carbonate platform with subordinate corals and stromatopores was re-established. It ranges right to a unique angular unconformity at the Frasnian-Famennian boundary that was temporarily exposed at Hülsbeck.

Just a few kilometers to the east, the very different and thick Wülfrath Reef Complex started to grow with the same basal Frasnian transgression that almost killed the adjacent Hofermühle Reef. The Rohdenhaus bioherm was drowned by the *semichatovae* Transgression and turned into a extensive deeper-water microbial platform with rare corals, the youngest Devonian reef body of all the Rhenish Massif. The Upper Kellwasser Event led to a sharp termination of the last *Stromatactis* layers, followed by a marked unconformity that reflects the major F-F boundary tectonic event of the region [2]. The Upper Kellwasser platform flooding and F-F tectonism are expressed at the southern end of the Wülfrath Reef, at Schlupkothen, by a thin black homoctenite overlying thick microbialites and a basal Famennian reworking unit with cross-bedding and megaripples.

At the southern limb of the Velbert Anticline, the Neanderthal Reef, famous for its ancient cave man, has hardly been studied. A black shale overlying back-reef *Amphipora* limestones yielded an *Acanthocyathia* fauna that proves a lower Frasnian age. It suggests terminal reef drowning by the Frasnian Event, similar as at Hofermühle. New data from the Wuppertal region (Hahnenfurt railway station) show that this is also true for the Dornap Reef but huge allochthonous reef blocks reoccur much higher in the Voßbeck Quarry.

The Hagen-Balve Reef Complex extends for more than 20 km in west-east direction along the northern margin of the Remscheid-Altena Anticline. The lower/middle Givetian reaches a thickness of up to 1 km at its eastern end. In the western Hagen-Hohenlimburg region, the bioherm drowned during the Taghanic Events [3] and was abruptly covered by hypoxic shales and turbidites (Flinz facies). But the retro- and

then prograding reef margin shed coarse reefal debris northward until the basal Frasnian. In the eastern Hönne Valley, the Frasnian Events caused a major transformation from a thick, fast-growing bioherm into a condensed open coral garden. The platform remained in the lower photic Zone; there is no basinal Flinz facies. A last, short coral biostrome recovery occurred before the Middlesex Transgression [4].

From the Hagen-Balve Reef to the east, some work has started on the poorly known, lower Givetian, biostromal *Sparganophyllum* Limestone, which is sandwiched between pelagic shales. Further eastward, the large Brilon Reef has been subject of a voluminous monograph by J. Brinkmann and D. Stoppel which has been in print several years.

In the eastern Sauerland, we focused on the Messinghausen Atoll, which clear separation from the Brilon Reef has partly been overlooked in previous studies. The atoll talus at Beringhauser Tunnel is famous for its conodont-dated colonial Rugosa [5]. We analyzed the carbon isotope stratigra-

phy in search of the positive excursions of the Timan and Middlesex Events. The latter is developed in distal reefal debris facies at Padberg [6].

In summary, almost all regional reef drowning and extinction phases can be aligned with global transgressive or anoxic events

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ORAL

GEOCHEMICAL AND SEDIMENTOLOGICAL ANALYSIS OF THE UPPERMOST DEPOSITS OF THE UPPER DEVONIAN HANOVER SHALE IN WESTERN NEW YORK STATE

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Introduction: The Upper Devonian shale succession of western New York State is notable for thick accumulations of interbedded black and gray shale. Many of the gray shale units contain numerous packages of thin black shale beds (TBSs). Such beds depict sharp basal contacts with underlying gray shale, upper contacts are sharp, often undulatory, and in some cases, bioturbated with planolites-type burrows. In effort to understand the depositional and diagenetic story behind these TBSs, we conducted a detailed analysis of the uppermost beds of the Upper Devonian Hanover Shale in a series of lakeshore and creek exposures in Chautauqua, Erie, and Wyoming counties.

Stratigraphic Setting: The Hanover Shale in western New York comprises gray, bioturbated mudstone, with numerous packages of TBSs, occasional carbonate concretion horizons and siltstone beds. Near the top of the unit, a conspicuous black shale, the Point Gratiot Bed, marks the culmination of the Upper Devonian Mass Extinction event. Overlying the Point Gratiot Bed is an eastward-thickening wedge of gray to silty gray shale, occasional nodular carbonate, and an eastward increasing occurrence of TBSs. This wedge of shale, here termed the Beaver Meadow Beds, thickens from 15 cm at its western most exposure at Pt. Gratiot, NY, to over 8 m along Beaver Meadow Creek in Java Village, NY, a distance of ~75 kms. The Dunkirk Shale unconformably overlies the Beaver Meadow Beds, and the basal contact is often marked by the presence of a detrital pyrite lag.

Methods: A 41 mm diameter continuous core of outcrop sections was collected using Shaw Backpack drill. Cores were collected from ~1 m above the contact with the overlying Dunkirk Shale to ~1 m below the base of the Point Gratiot Bed. Cores were cleaned and cut into 1 cm "pucks" using a Dewalt 10" high-capacity wet tile saw. Pucks were disaggregated and powdered using an Across International PQ-NO4 100ml x 4 Planetary Ball Mill. The Powders were compressed into 32 mm diameter sample cups and analyzed by a Niton XL3t GOLDD+ X-Ray Fluorescence analyzer.

Results: Zirconium/Aluminum (Zr/Al) profiles through the Beaver Meadow Beds reveal distinct trends through TBSs. Thin black shale beds in the bottom of the Beaver Meadow sections, referred to as Type 1 black shales, show asymmetric to symmetric Zr/Al profiles where Zr/Al sharply increase at the base of the black shale from underlying gray shale values, achieve a maximum within the black shale, and gradually re-

turn to baseline gray shale values. It is noteworthy that the Zr/Al profiles often remain elevated, and do not return to background gray shale values for some distance above the top of the black shale. Thin black shale beds higher in the Beaver Meadow Beds, Type 2 black shales, display markedly different Zr/Al profiles. Gray shales underlying these beds demonstrate a largely uniform Zr/Al profile which is interrupted by an increase in Zr/Al associated with the thin black shale. The Zr/Al values generally return to a consistent baseline in the gray shale overlying the TBS, however, the Zr/Al values are often greater or less than those of the gray shale underlying the TBS. It is noteworthy that unlike the Type 1 black shale beds lower in the section, the Type 2 black shale beds are often accompanied by a detrital pyrite lag. In all sections examined, Type 2 thin black shale beds always occur above Type 1 black shale beds.

Gray shale underlying both types of thin black shale beds contain abundant pyrite in the form of pyritized worm burrows, nodules, and concretions. The size and occurrence of pyrite generally decreases down section from the contact between the base of the black shale and the underlying gray shale. Iron/Al (Fe/Al) profiles through these intervals show a similar pattern where Fe/Al values achieve a maximum within the black shale, or at its base. The Fe/Al values remain elevated decreasing to background gray shale values some distance below the TBS. Indeed, Fe/Al ratios are highest in the gray shale where macroscopic pyrite is present.

Discussion: The Zr/Al profiles through Type 1 TBSs are consistent with their deposition as hyperpynites. The increasing Zr/Al reflects increased energy during the flood stages of river systems transporting sediment to the sea, whereas the decreasing Zr/Al profile reflects the waning stage of the flood. Moreover, pyrite masses found within these deposits could represent fossilized fecal pellets of organic matter that accumulated in a nearshore estuary or lagoon. We interpret Type 2 TBSs as transgressive black shales. As sea level rose, the pycnocline impinged on the seafloor, eroding underlying gray muds and leaving behind placer-like lags of detrital pyrite. Continued sea-level rise led to the deposition of organic-rich black muds over pyrite lag. Subsequent sea-level drop resulted in the renewed deposition of gray muds, often under different depositional conditions as evinced by the different Zr/Al baselines.

The Fe/Al profiles are interpreted to reflect fossilized

hydrogen sulfide fronts diffusing into underlying gray muds. Bacterial sulfate reduction of organic matter within the black muds consumed the local supply of reactive iron long before the production of hydrogen sulfide ended. Whereas much of the hydrogen sulfide likely diffused into the overlying water column, some portion of it diffused into underlying sediment. Here, the hydrogen sulfide scavenged reactive iron to form nodular and concretionary pyrite. Decreasing Fe/Al values down section from the base of thin black shales, and the notable decrease in the size and occurrence of visible pyrite point to the slowing and eventual arrestment of downward diffusing hydrogen sulfide.

Finally, the sharp upper contacts of these thin black shales warrant explanation. Elevated Zr/Al profiles some distance above the tops of the hyperpycnites suggests that the present-day thickness of a TBS might not represent original depositional thickness. Oxygen, aided by bioturbation, could have

diffused downward into the TBS, oxidizing organic matter, and remobilizing redox sensitive trace elements in a process known as “burn-down.”

Summary: In sum, the Beaver Meadow Beds represent deposition during transgression. Rising sea-level flooded nearshore river mouths creating estuaries and lagoons where organic matter accumulated. Occasional storms flushed this material out to the deeper basin where it was deposited as hyperpycnites. Continued sea-level rise led to the deposition of transgressive black shale. Minor changes in sea level led to numerous transgressive black shale/gray shale cycles before transgression culminated in deposition of the overlying Dunkirk Shale. After deposition, excess hydrogen sulfide diffused out of organic-rich muds into underlying gray shale forming abundant pyrite. The return of (dys?)oxic water and deposition of gray muds over black shales led to burn-down likely aided by bioturbation.

ORAL

ECOLOGICAL-EVOLUTIONARY PATTERNS AND PROCESSES IN THE DEVONIAN OF THE APPALACHIAN BASIN

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Introduction: The well-preserved Devonian record of the Appalachian Basin in eastern North America has proven a natural laboratory for the study of evolutionary paleoecology. Edredge and Gould's seminal hypothesis of punctuated equilibrium within species lineages [1] was based in large measure on Devonian phacopid trilobites from New York. At nearly the same time, two papers on faunal associations in the Middle-Upper Devonian in New York [2, 3] provided exemplars of the community paleoecology approach. Brett and Baird [4] attempted to bridge evolutionary and ecological approaches in mid-Paleozoic faunas with a special focus on the rich fossil assemblages of New York State.

Coordinated Stasis: The pattern of Coordinated Stasis [4] describes morphological and ecological stability in basin-wide faunas over extended intervals of geologic time (10^5 – 10^6 yr) with original examples from the Silurian-Devonian marine faunas of eastern North America. These "ecological-evolutionary subunits" (EESUs) are separated by episodes of rapid faunal change. For example, the most studied of these units, the Middle Devonian Hamilton fauna of New York, shows a high degree of persistence of both species (~80%) and biofacies through the majority of the Givetian Stage [5]. The absence of significant morphological change in a majority of lineages over long time intervals and across their biogeographic ranges indicates that phyletic change is negligible during most of geologic time and morphological stasis prevails. A combination of stabilizing selection, habitat tracking, and incumbency likely maintains morphological stasis during these times, despite significant oscillations in sea level and environmental shift.

EE subunits also display a strong degree of ecological stasis [5, 6]. Biofacies and gradients of faunal distribution are relatively stable in terms of overall species composition, richness, and guild structure, although there are frequent short term fluctuations in relative abundance and some short-lived proliferations or incursions of a few species (epiboles). Despite geographic shifts in faunal associations over 100s of km during 4th order ($\sim 10^5$ yr) cycles of relative sea-level change, faunal associations/gradients appear to track shifts in environment with considerable fidelity. In addition, there are predictable changes in the areal extent of particular commu-

nities or biofacies during transgressive-regressive cycles. For example, during times of regression and sediment progradation, high diversity, coral-rich biofacies adapted to shallow shelf, clean-water environments, can contract along depositional strike to a small fraction ($< 1/4$) of their most expansive distribution during times of transgression and associated offshore siliciclastic starvation. Yet, again, despite these strong changes in geographic distribution, there appears to be minimal change in the ecological properties of the biofacies. These patterns do not necessarily require ecological locking [7], but minimally they indicate that species tend to maintain the same fundamental niche; i.e., there is little niche modification or evolution during EE subunits [8].

A further important aspect of the pattern is coordinated faunal turnovers that include extinction, migration, and speciation, as well as ecological reorganization. In many cases, these changes can be constrained to portions of small scale cycles, typically late transgressions to early highstands, representing intervals of time on the order of 10^3 – 10^4 yr. They appear to record times of climatic instability and can be characterized by rapid fluctuation of biogeographic boundaries, akin to Vrba's Turnover Pulse model [9]. It should be noted that these times of rapid fluctuation bound relatively stable intervals (EESUs) that can span from $< 100,000$ to several million years. For example, the Givetian in the Appalachian Basin shows high volatility at the stage level. However, it contains the remarkably stable Hamilton fauna, which persisted for > 3 million years, even though it is bracketed by the short-lived Stony Hollow (below) and Lower Tully (above) EESUs [10].

Volatility and Faunal Turnover: Newly developing high-resolution chronostratigraphy for the Devonian reveals the environmental framework within which long-term stasis and rapid evolutionary and ecological change occurs. EESUs persist longest during intervals, such as the Emsian Stage, of comparatively low-amplitude variation in climate, sea level, and the carbon cycle, as reflected in stable isotope records [11]. In contrast, intervals such as the late Eifelian to Frasnian show a much higher degree of environmental volatility. Such intervals of comparatively abrupt, clustered fluctuations in climate, often associated with hypoxia and sea-level rise, could drive regional or global benthic assemblage turnovers, migra-

tions, and speciation. Associated conodont and ammonoid biozonal durations are short during volatile intervals, suggesting similar evolutionary and biogeographic responses in the nekton as well. These patterns indicate that volatility in the global ocean-climate system is a primary driver of macroevolution, at least during the Devonian Period, although the ultimate causes of alternating intervals of environmental volatility and prolonged stable times remain unclear.

Fertile areas for future inquiry include both (a) further tests of the association of patterns of faunal stasis and turnover, with more detailed records of environmental change, and (b) tests of the generality of the patterns of stability and change observed in other time intervals and environmental settings. It will be important, going forward, to document the relative stability as well as the timing and severity of faunal

turnovers in post-Paleozoic assemblages to determine whether or not coordinated stasis signals persist into the age of higher diversity, metabolically enabled, benthic associations.

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ORAL

PYRITE FRAMBOID DISTRIBUTIONS AS INDICATORS OF ANOXIA: CAN WE USE THEM IN SHALLOW WATER ENVIRONMENTS?

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Depending on the environment of deposition, stratigraphic intervals that are associated with marine anoxic events can be exhibited as a black-shale sequence, an organic-rich carbonate sequence, an organic-poor carbonate sequence, a turbidite sequence, or a shallow-water nearshore sediment sequence. In the sediments that do not display obvious visual evidence of anoxia in the field (i.e., black shale layers), multiple ichnological, geochemical, mineralogical, and isotopic proxies can be used to infer the presence or absence of anoxia. Most of these proxies provide a binary “presence vs. absence” indicator of anoxia; however, pyrite framboid distributions and the amount of bioturbation are both ways that the relative severity of oxygen stress can be assessed in the rock record.

In the absence of obvious trace-fossil evidence, pyrite framboid distributions become the primary way to measure the degree of anoxia. Pyrite framboids are aggregated microcrystalline pyrite spheres that appear similar to raspberries under scanning electron microscopy (Fig. 1). The size and shape of these individual framboids are functions of the degree of anoxia in the marine water column. To assess the severity of anoxia, pyrite framboids are counted and their diameters are measured using scanning electron microscopy, and the diameters are plotted in a histogram (Fig. 2). Based on studies in modern reduced oxygen settings, a histogram with framboids clustered in the 3–5 μm range indicates a euxinic water column (where anoxia is so severe that free H_2S is present), anoxia is represented by pyrite framboids primarily $\sim 5 \mu\text{m}$ or less, but with a wider size distribution. Dysoxic/suboxic conditions result in pyrite framboid distributions where the size range is far greater (from 5–10 μm , with some framboids up to 20+ μm in diameter) [1]. If there are no framboids present, the water column is likely oxygenated.

In our research, pyrite framboid distributions have proven useful in detecting and assessing the severity of anoxia in both the Kellwasser and Hangenberg Events in sections around the globe that lack black shales. Their utility can be complicated by the presence of framboid-filled burrows that are invisible at the hand sample scale (Fig. 3). Framboid-filled burrows reflect anoxic conditions within the burrow itself due to microbial sulfate reduction of organic waste material trapped in the burrow, and do not reflect the overall level of oxygenation in the water column.

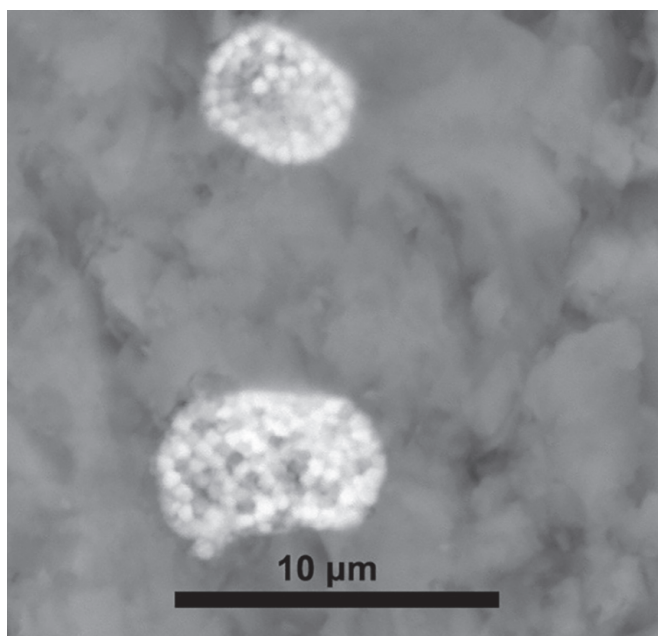


Figure 1. Pyrite framboids in a clay, quartz, and albite-rich sediment (modified from [2]).

In cases where the only framboids that are present are within burrows, the water column is likely fully oxygenated. In cases where framboids are not in burrows but are scattered individually throughout the sample, the pyrite size distribution histograms can be used to assess the severity of oxygen loss. In cases where there are both individual framboids throughout the sample, as well as framboids within burrows, care must be taken to eliminate the framboids within the burrows from the size distribution analysis. As demonstrated by the bioturbation index, burrows can be present even in sediments with reduced oxygen levels, so samples with framboid-filled burrows cannot be discounted when assessing sediment packages for signatures of anoxia.

Most studies of ocean anoxia using pyrite framboid distributions have been focused on deeper water environments and the assessment using these distributions was relatively straightforward, where the severity of anoxia corresponded to known ocean anoxia events. Our research on the Kellwasser

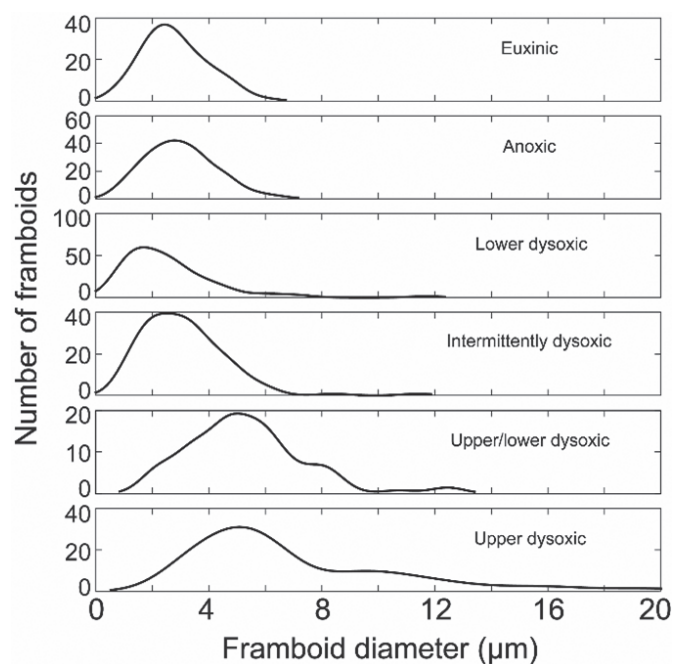


Figure 2. Pyrite framboid distributions showing the degrees of oxygen stress severity, based on histogram shape [3].

and Hangenberg Events spans both deep- and shallow-water sections in a variety of paleoenvironments, from shallow- to deep-water carbonates, mudstones in tectonic and foreland basins, and open ocean volcanic island arc settings at a variety of depths. Like previous studies, our assessment of anoxia using pyrite framboid distributions in deeper water sections

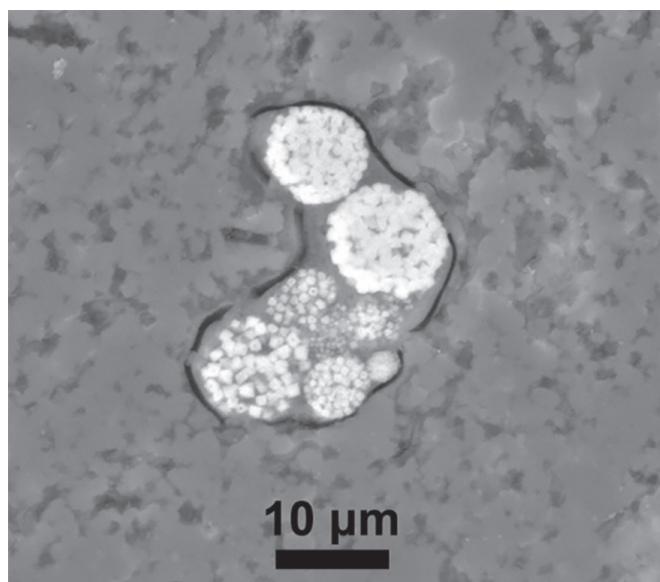


Figure 3. Framboids in burrows (modified from [2])

was relatively straightforward and corresponded to both the expected stratigraphic interval of anoxia as well as other geochemical and isotopic proxies. In contrast, our ongoing assessment of anoxia in shallower water environments shows a far more complex picture and might reflect local conditions rather than global conditions.

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ORAL

NUMERICAL SIMULATIONS OF THE EFFECTS OF ASTRONOMICAL FORCING ON NUTRIENT SUPPLY AND OXYGEN LEVELS DURING THE DEVONIAN

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Declining oxygen levels in the ocean since the middle of the 20th century have been linked to increasing temperatures, CO₂ concentrations, and nutrient inputs. In the geological past, numerous oceanic anoxic events have occurred under similar conditions. These events, during which dissolved oxygen in the ocean drops to potentially harmful levels, can have serious consequences for marine life and can also alter the geochemistry of the ocean.

The 60-million-year Devonian stage was the theater of at least 29 identified anoxic events [1], marked most of the time by the deposition of black shales, associated with carbon isotopic excursion. It is understood that concurrent trends in CO₂ and silicate weathering during the Devonian Period have generated a context prone to ocean anoxia. On the other hand, there is growing evidence that their periodic recurrences in sedimentary records might have been influenced by astronomical forcing, such as changes in Earth's axis rotation and orbit geometry [2, 3].

In the umbrella project WarmAnoxia, we combine climate models and geological observations to explore and test proposals linking astronomical forcing to Devonian anoxia. Through this presentation, we focus specifically on the hypothesis that astronomical forcing influenced precipitation and temperature patterns in a way that significantly modified

soil weathering dynamics, with enough effects on nutrient fluxes toward the ocean to promote oceanic anoxia.

To test this proposal, we performed 81 experiments with the global atmosphere-slab model HadSM3. Experiments have been designed to span the range of astronomical forcing and CO₂ concentrations experienced during the Devonian. The output was used to calibrate an emulator. With the latter, we estimate the transient evolutions of temperature and precipitation over 5-million-year periods, for which we assumed both simplified and realistic astronomical forcing scenarios. In turn, these transient evolutions force the GEOCLIM model [4], which simulates soil dynamics, estimates nutrient fluxes from the continents to the oceans, and the response on the oceanic chemistry and atmospheric oxygen levels.

The presentation also highlights progress in the simulation of deep ocean dynamics during the Devonian, using the model of intermediate complexity cGENIE.

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POSTER

REASSESSING HYDROCARBON VOLUMES OF THE DEVONIAN SHALES IN EASTERN OHIO AT MEMBER-LEVEL SCALE

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Background: Middle and Upper Devonian siliciclastic rocks exposed in a north-to-south trending outcrop belt through central Ohio and along Lake Erie were deposited on the western edge of the Appalachian Basin during the Acadian Orogeny. These units are composed of mostly shales and mudstones with minor carbonates, siltstones, and sandstones that range from the top of the Middle Devonian limestones (e.g., Columbus and Onondaga limestones) through the upper Famennian Bedford Shale and Berea Sandstone (Fig. 1). From the westernmost part of the outcrop, where the Middle to Upper Devonian succession can be as thin as 500 ft (~150 m), these rocks dip eastward into the subsurface and expand to almost 4,000 ft thick (> 1,200 m) at the eastern border of the state.

Many parts of the shale units in this succession are organic-rich and hydrocarbon bearing. In Ohio, these include the Marcellus Shale, Rhinestreet Member of the West Falls Formation, lower part of the Huron Member of the Ohio Shale, and Cleveland Member of the Ohio Shale. Several studies were conducted between the 1970s and the 1990s to assess the hydrocarbon resource potential of these organic-rich shale units across the Appalachian Basin. The advent of unconventional drilling technology and the potential for CO₂ sequestration in organic-rich rocks spurred further research on these units over the past decade. This has resulted in a large quantity of data being produced for these shale units in Ohio, although few studies have been done at the formation or member-level scale. The goals of this project are to compile the disparate data from several past projects into a curated dataset, and to use the dataset to produce a general estimate of hydrocarbon resource volumes for the Devonian shale units within Ohio.

Assessment Methods: The Rhinestreet Member and lower Huron Member are the initial focus of this study because they are the most extensive and organic rich of the Devonian shale units in Ohio [1, 2]. Waid [3] developed a stratigraphic framework for these units in the subsurface using > 800 geophysical well logs across the eastern half of Ohio. Two sequences in the lower Huron were identified and correlated across the study area, which helped us assess the lower Huron at a finer stratigraphic resolution as it reaches thicknesses over 1,000 ft (~300 m) in the easternmost part of the state. Thickness was

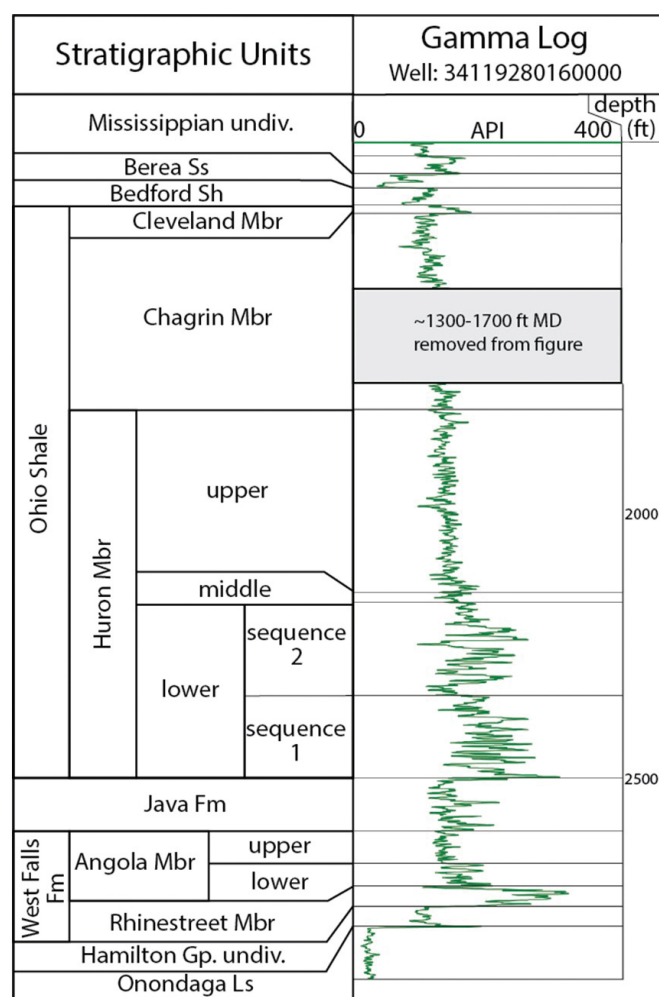


Figure 1. Typical gamma-ray log from Muskingum County showing stratigraphic nomenclature for the Middle and Upper Devonian interval in eastern Ohio.

mapped for each sequence in the lower Huron and for the Rhinestreet.

To initially assess the Rhinestreet and lower Huron for hydrocarbons, total organic carbon (TOC) content and thermal maturity of each unit were mapped across eastern Ohio. TOC

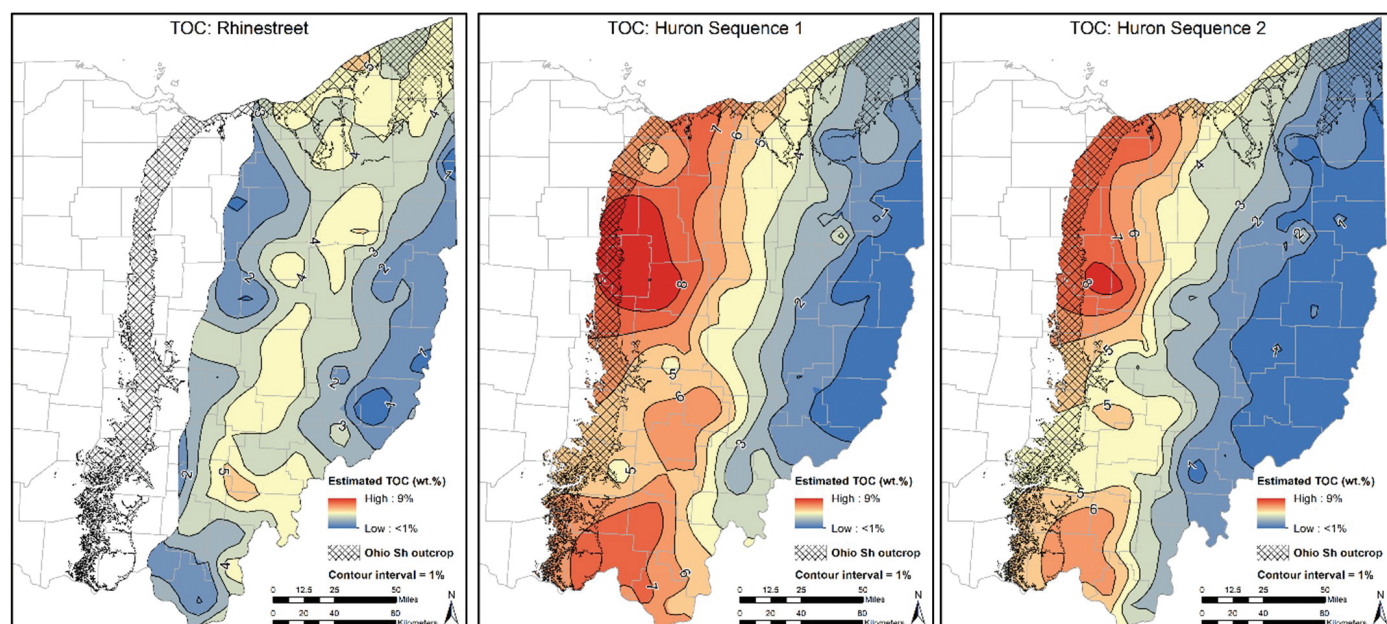


Figure 2. Average estimated total organic carbon (TOC) content in weight percent for the Rhinestreet Member of the West Falls Formation and for sequences one and two of the lower Huron Member of the Ohio Shale (see Fig. 1 for sequence definition). The relationship between measured TOC from five cores and their associated gamma-ray and density logs defined the equation used to estimate TOC from geophysical logs in 175 wells across the eastern half of Ohio.

measurements from Devonian cores in Ohio have a limited spatial resolution, so to achieve a more even data distribution across the study area we used digital geophysical logs to estimate TOC. Measured TOC data from cores sampled in previous studies (e.g., [4, 5]) were used to determine the relationship between measured TOC and gamma-ray and density log responses. The resulting equation ($R^2 = 0.65$) was applied to 175 wells across the study area. The average TOC values estimated for each unit were mapped for the Rhinestreet and both lower Huron sequences (Fig. 2).

Thermal maturity was assessed using vitrinite reflectance and Tmax data from programmed pyrolysis. Data collected from both cores and cuttings were compiled from previous studies (e.g., [4, 6]). Approximately 2,000 samples of either measured vitrinite reflectance or Tmax were found to have

been collected through most of the Devonian shale units in 72 wells. This sample size provides adequate coverage across eastern Ohio. The resulting thermal maturity map was used to determine the extent of the oil window in Ohio. Within the oil window, density logs were used to estimate the porosity of the units. Potential oil volumes were calculated using the estimated porosity and unit thickness maps.

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ORAL

THE HANGENBERG CRISIS (DEVONIAN-CARBONIFEROUS BOUNDARY) TIMING AND CLIMATIC FORCING (CHANXHE AND ANSEREMME SECTIONS, BELGIUM)Da Silva, A. C.,¹ Arts, M.,¹ Crucifix, M.,² Franck, L.,¹ Huygh, J.,¹ Omar, H.,¹ and Denayer, J.¹

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The Hangenberg Crisis, at the Devonian-Carboniferous Boundary, severely affected the marine realm. The crisis is characterized by several events associated with change in the sedimentation and biotic extinctions and turnovers. The Hangenberg Black Shale event that recorded the extinction peak in the pelagic realm corresponds to a widespread development of oceanic anoxia and/or dysoxia. The Hangenberg Sandstone event is associated with an extinction of neritic fauna in shallow-water settings, including the final demise of several classical Devonian faunas (stromatoporoids, quasien-dothyrid foraminifers, placoderms, etc.). The succession of these events is nowadays explained by a combination of sea-level fluctuations (third order transgressive sequence, out-of-sequence regression) and global climatic changes. Through the identification of Milankovitch cycles in the Chanxhe and Anseremme records, we aim at getting a better understanding of the timing and orbital forcing of the different events of the Hangenberg Crisis in shallow-water settings.

The sedimentary record of the interval of interest at Chanxhe is composed of 16 m of alternating decimeter-thick carbonate beds with shaly siltstones, which displays a clear cyclicity. The carbonate-siliciclastic alternations (~0.8 m) are bundled into larger cycles (~5 m) which are separated by intervals dominated by the shaly facies. This is followed by 11 m of carbonate-dominated lithology with thin shale layers displaying a less clear cyclicity with ~3 m thick cycles. Then the equivalent of the Hangenberg dark shales is recorded as

two dark shaly intervals separated by a carbonate bed. After the Hangenberg dark shales, the section displays carbonates, with the Devonian Carboniferous boundary in massive carbonates 7 m above the top of the black shales. The Record at Anseremme, is characterized carbonate-siliciclastic alternations (~0.8 m) bundled into larger cycles (~5 m) and the lithology remains much more stable. Samples have been collected along these records every 10 cm, which were measured by the portable X-Ray Fluorescence device (Tracer 5, Bruker) and magnetic susceptibility with a selection of samples for carbon isotopes. Spectral analysis is applied on Ca and Al, to identify the main cyclicity in the record. The 0.8 m thick limestone/shale alternations are clearly recorded in the Ca and Al records and are associated with precession cycles (18 kyr), whereas the 5 m cycles are associated with short eccentricity (100 kyr). Prior to the Hangenberg anoxic events, the 100 kyr cycles became less clear and shorter (~3 m) which is interpreted as a long-term (equivalent to 2.4 Myr) minimum eccentricity. During and after the Hangenberg, the cyclicity returns. Severe anoxic events, e.g., the Oceanic Anoxic Event II in the Cretaceous, as well as the upper Kellwasser Devonian anoxic event, have been associated with long term eccentricity minima. It is essential to better understand the mechanism behind the astronomical forcing and anoxia expansion, and the identification of the long-term minima through the geologic time scale is key to better understand the climate forcing.

ORAL

THE KINGSTON RECORD, NEW YORK STATE, U.S.A.—A WINDOW TO THE DEVONIAN PALEOCLIMATE AND TO THE DURATION OF PART OF THE EMSIANDa Silva, A. C.,¹ Brett, C.,² Bartholomew, A.,³ Ver Straeten, C.,⁴ Hilgen, F.,⁵ and Dekkers, M. J.⁵

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The Emsian is among the Devonian stages with the least U-Pb constraints, together with the Givetian. These two stages are classically used as an adjustment variable for the Devonian time scale and they are stretched or squeezed depending on the new age constraints obtained for other stages. Indeed, the duration of the Emsian swung between ~4 Myr (Harland et al., 1990) and ~17 Myr (Kaufmann, 2006). So, any new constraints on its duration is essential. We introduce the Kingston record in New York State (U.S.A.), which goes through part of the Schoharie Formation. It is characterized by exceptional Milankovitch forcing color patterns visible at the outcrop. It is a window through the paleoclimate of the Devonian, as well as a precise chronometer part of the Emsian. We propose high resolution portable XRF measurements, magnetic susceptibility, spectrophotometry, and carbon isotope for the Kingston record. At the outcrop scale,

three main types of cyclicities can be identified with the smallest cycle corresponding to dark-light beige alternations. Five to seven of those alternations occur between distinctive light white to orange beds. Four of these medial-scale cycles then bundle into larger scale cycles. So, there is a ratio of ~24:4:1 between these cycles, which fits well with the ratio between precession, short eccentricity and long eccentricity for the Devonian (23.6:4:1). These cycles are clearly recorded also in the PXRF records, as well as magnetic susceptibility, but they are less clear into the spectrophotometry record and carbon isotopes. This allows transformation of the record from the distance domain into the time domain. It also includes a maxima long term eccentricity (today 2.4 Myr) in the middle of the record, marked by the best development of cyclicity. We also propose to use these data as constraints for the duration of the precession cycle in the Devonian.

ORAL

UPPER DEVONIAN LOWER AND UPPER KELLWASSER EXTINCTION RECORD IN THE SWEETLAND AND GRASSY CREEK SHALES IN THE IOWA BASIN OF CENTRAL NORTH AMERICA

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Introduction: The Sweetland Creek and lower Grassy Creek shales in Muscatine County in eastern Iowa comprise a condensed deep ramp succession of hemipelagic shales and mudstones that accumulated seaward of the Lime Creek Formation carbonate platform that transitions into the western Illinois Basin (Fig. 1) [1, 2]. These facies are equivalents to the Selmier Shale Member of the New Albany Shale in the adjacent Illinois Basin, although they differ in that they are thermally pristine as indicated by conodont CAI values of 1 [1, 2, 3]. Continuous sampling in 2016–2020 of the

type section of the Sweetland Creek Shale and overlying Grassy Creek Shale (Fig. 2) yield conodont faunas of spanning Frasnian Zones 11 and 12, Subzones 13a–13c, and the Lower Famennian *Palmatolepis subperlobata* to *Pa. triangularis* Zones. Species LADs and FADs clearly identify the Lower and Upper Kellwasser extinction (LKE and UKE) intervals.

Frasnian Zone 11: A diverse fauna, first reported from two samples in 1992 [4] from the basal 50 cm shale, complemented by three new samples collected in 2020, includes: *Palmatolepis semichatovae*, *Pa. provera*, *Pa. kireevae*, *Ancryodella ha-*

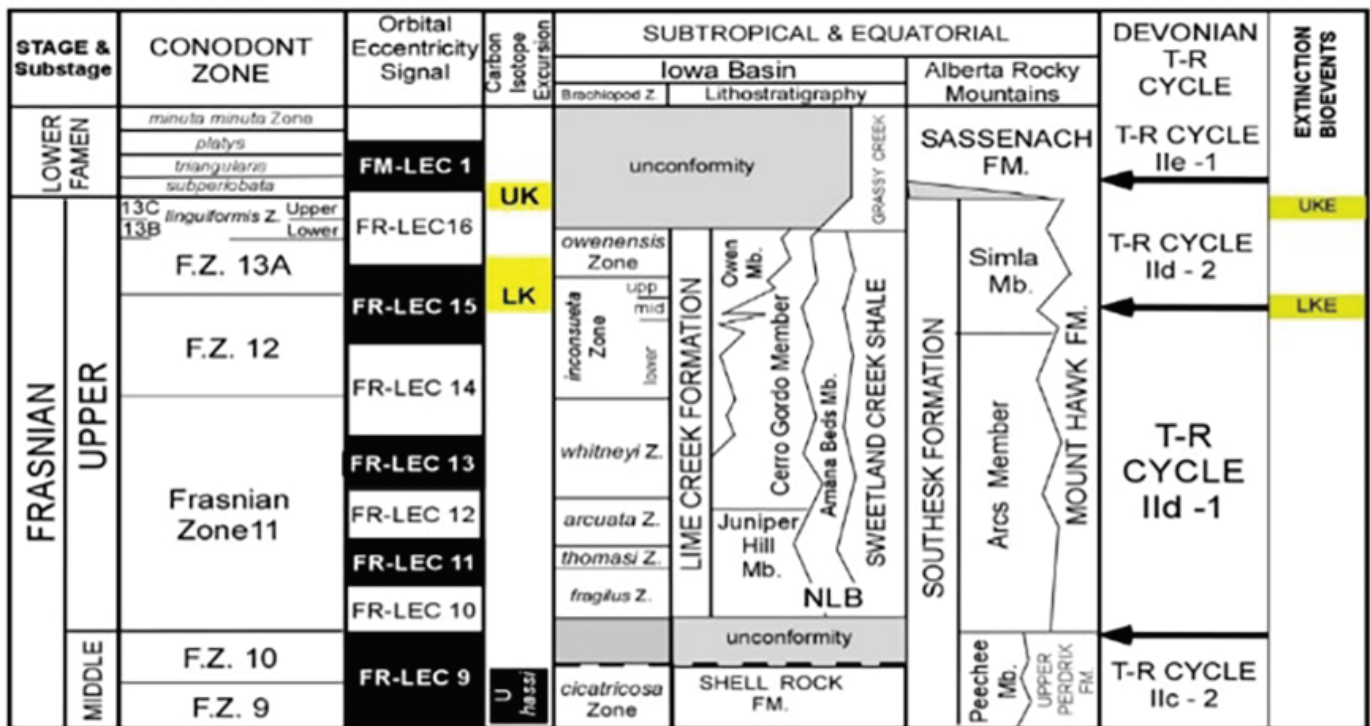


Figure 1. Chronostratigraphy of the Late Devonian (Middle Frasnian to Early Famennian) strata of the Iowa Basin. See Devonian lithostratigraphy by [4, 5, 1]. Qualitative Euramerica Devonian eustatic T-R cycles by [6, 3]; Late Frasnian subdivisions proposed by [7]. Upper Devonian (Frasnian) conodont biostratigraphy follows [8], and the Famennian global standard zonation [9]. Devonian brachiopod biostratigraphy from Day [1]. Magnetic Susceptibility Cyclostratigraphy for the Late Frasnian and Early Famennian from [10, 11, 12]. Fm. = Formation; FM-LEC = Famennian Long Eccentricity Cycle; FR-LEC = Frasnian Long Eccentricity Cycle; LKE = Lower Kellwasser Event; Mb. = Member; NLB = North Liberty Beds; UKE = Upper Kellwasser Event. Modified from [1]: fig. 3.

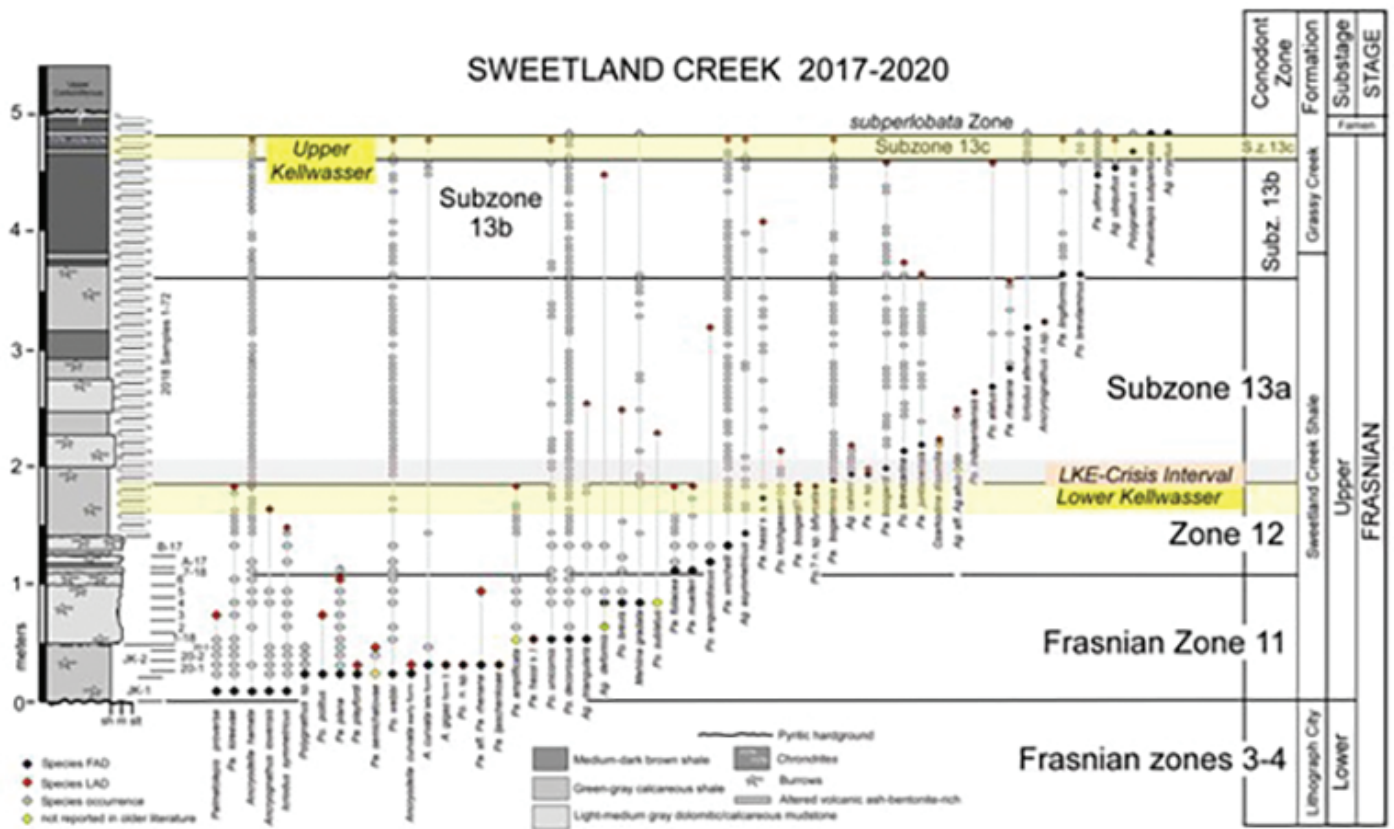


Figure 2. Type section of the Sweetland Creek Shale exposed on Sweetland Creek, Muscatine County, Iowa in June 2016–2021 (see location by [1, 13, 14]; appendix 1 of [8]: 28). Composite of lower two samples reported by Klapper in [3]: 132, fig. 2), new samples collected by Day in 2017 (A-17, B-17), 2018 (1-18 to 7-18, SC-1 to SC-80), and 2020 (20-1 to 20-3). Frasnian and Famennian conodont zonal boundaries and Lower and Upper Kellwasser Extinction interval (LKE and UKE) positions based species FADs and LADs. Numbered Zones 3, 4, 11, 12, 13a, 13b, and 13c are Frasnian Zones or Subzones of [8]. Early Famennian zones: sup = *Palmatolepis subperlobata*, follow the current usage [9].

mata, *Ancryognathus iowensis*, *Icriodus symmetricus*, *Pa. ljaschenkoae*, *Pa. plana*, *Pa. playfordi*, *Pa. aff. Pa. rhenana*, *A. gigas* form 3, *A. curvata* early form, and *A. curvata* late form. The lower 20 cm of the “siltstone” is marked by additional FADs of *Pa. amplificata*, *Pa. bassi* s.l., *Polygnathus unicornis*, *P. webbi*, *P. decorosus*, and *Ag. triangularis*. Additional stepped FADs of *Ancryognathus? deformis*, *P. politus*, *P. brevis*, *P. sublatius*, and *Mehlina gradata* occur in the overlying 30 cm of the “siltstone” (Fig. 2).

Frasnian Zone 12: The lowest occurrence of *Pa. foliacea* with *Pa. rehnana* identifies the base of Zone 12 in the upper 5 cm of the “siltstone” above a prominent pyritic hardground. Above the “siltstone”-capping hardground, *Pa. winchelli* and *Ag. asymmetricus* have their FADs in the lower Zone 12 interval.

Frasnian Subzone 13a: The base of Frasnian subzone 13a is 185 cm above the base of the Sweetland Creek Shale, identified by the FAD of *Pa. bogartensis*, with FADs of *Pa. bassi* s.s., *Ag. calvini*, *Ag. sp. aff. Ag. altus*, *P. alatus*, *P. brevicarina*, and *Ozarkodina dissimilis* low in Subzone 13a. In Iowa, *Ag. calvini* is restricted to a 35 cm interval low in Subzone 13a. Its LAD

high in Frasnian Subzone 13b to lower 13c in southern New Mexico.

Lower Kellwasser Extinction and Crisis Interval: The LKE is marked by the LADs of *Pa. kireevae*, *Pa. amplificata*, *Pa. foliacea*, and *Pa. muelleri*. The LKE interval is 45 cm thick spanning the upper part of Frasnian Zone 12 and extending into the lower part of Frasnian Subzone 13a in the Sweetland Creek Shale with the onset denoted by the occurrences of pathogenic (teratological) *Ag. asymmetricus*, with pathogenic specimens of *Ag. aff. Ag. altus*, *P. decorosus*, and *Palmatolepis winchelli?*, and *Pa. n. sp.* defining the LKE crisis interval in the lower 30 cm of Subzone 13a.

Frasnian Subzones 13b–c and the Upper Kellwasser Extinction Interval: The FAD of *Pa. linguiformis* defines the base of Subzone 13b. The onset of the UKE is marked by LADs of *Pa. boogardi* 5 cm below, and *P. alatus* immediately below the first K-bentonite bed in the lower Grassy Creek Shale. Extinctions of most typical Frasnian conodont taxa characterize the 15 cm thick UKE crisis interval (Frasnian Subzone 13c) with species LADs of surviving typical Frasnian con-

odont taxa immediately below the second K-bentonite bed in the Grassy Creek.

Earliest Famennian: Frasnian survivors (*P. decorosus*) and FADS of *Pa. subperlobata* and *Ancyrognathus cryptus* early form denote the position the lowermost Famennian and F-F boundary at the base of the second K-bentonite bed in the Grassy Creek Shale at this location. Famennian conodont zonal boundaries and Lower and Upper Kellwasser Extinction interval (LKE and UKE) positions based species FADs and LADs. Numbered Zones 3, 4, 11, 12, 13a, 13b, and 13c are Frasnian Zones or Subzones of [8].

Early Famennian zones: sup = *Palmatolepis subperlobata*, follow the current usage [9].

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ORAL

MAPPING THE MIDDLE AND UPPER DEVONIAN MARINE-NONMARINE TRANSITION IN THE APPALACHIAN BASIN FROM WEST VIRGINIA TO NEW YORK

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Introduction: Middle and Upper Devonian strata representing the transition from the marine to nonmarine environment in the Appalachian Basin have proven to be problematic for consistent geologic mapping and stratigraphic correlation for decades. The units that represent this environment include the Foreknobs Formation in West Virginia, Virginia, and Maryland, and the Irish Valley Member of the Catskill Formation in central and northeastern Pennsylvania; strata representative of this transition have yet to be consistently mapped within north-central Pennsylvania and south-central New York. In central and northeastern Pennsylvania, these strata are generally included within the lower part of the Catskill Formation. In south-central New York near Binghamton, these strata have been placed within the West Falls Group, but formation-level units have yet to be formally defined. Further to the east near Wurtsboro, New York, these strata have been placed either within the Oneonta Formation of the Genesee Group or in the upper part of the Hamilton Group [1].

Approach: To achieve better consistency in the identification and mapping of these transitional units, we recommend revising existing stratigraphy to formally define the intercalated marine, marginal marine, and nonmarine strata into a separate formational lithostratigraphic unit. Over the course of a decade, the authors have traced this interval of transitional strata from southeastern West Virginia to north-central New York and have established criteria that can be used for consistently identifying a basal formational contact; namely, the first mappable occurrence of either a quartz-rich sandstone package containing rounded quartz pebbles or a series of conglomeratic beds that transition up section from interbedded, fossiliferous sandstone, siltstone, and shale. The quartz-rich sandstone package can be fossiliferous, but can be differentiated from sands lower in the stratigraphy by the greater abundance of quartz in the sand fraction. The presence of rounded quartz pebbles in high-angle cross-bedded sands, mud rip-up clasts, fossil hash beds within sandstones, and other indicators of nearshore storm and wave action all aid in identification of this unit. The first appearance of pebble-sized quartz clasts likely indicates the arrival of deltaic and shoreline-derived detrital sediments into the basin [2]. The ultimate absence of marine fossils intercalated with terrestrial sediments indicates the gradational upper contact with fully terrestrial strata.

This approach has been proven successful for reconciling numerous offsets within previously published geologic maps in the stratigraphic interval formerly represented by the Greenland Gap Group (Foreknobs and Scherr formations) in West Virginia and Virginia. Recent revisions to the Greenland Gap Group resulted in abandonment of the Scherr Formation and Mallow Member of the Foreknobs Formation. These strata are proposed to be placed within an informal upper member of the underlying Brallier Formation, and the base of the Foreknobs Formation is revised as being coincident with the base of the Briery Gap Sandstone Member of the formation [3].

Challenges: A primary challenge to implementing these stratigraphic changes northward is that the thickness of this interval greatly increases in central Pennsylvania and southern New York, making the heterolithic nature of the marine-nonmarine transitional interval more pronounced and more difficult to map with consistency. However, recent mapping in central Pennsylvania and southern New York has revealed that the first occurrence of quartz pebbles into marine strata can be used to identify the base of the marine-nonmarine transition. A second challenge for correlation is the time-transgressive nature of this transitional interval as it becomes younger from east to west, and from northeast to southwest [2, 4].

Sequence Stratigraphic Framework: The diachroneity of the marine-nonmarine transition means that the strata comprising these lithostratigraphic units will necessarily change in both time and space. However, the sensitivity of the transitional unit to base-level changes provides variably resistant topographic expressions that, when combined with advancements in lidar-derived, high-resolution topography, has allowed for the regional mapping of major surfaces and the construction of a basin-wide sequence stratigraphic framework for the interval. In this manner, we have traced two major third-order cycles within the Foreknobs and Irish Valley from West Virginia into central Pennsylvania. In the Foreknobs Formation, two major base-level low stands are represented by the Briery Gap and Pound Sandstone Members in West Virginia, Virginia, Maryland, and into south-central Pennsylvania. Near Raystown Lake, Pennsylvania, the Briery Gap and Pound Sandstone Members have been shown to be equivalent to the informal Allegrippis sandstone and Saxton conglomerate members [4], respectively. Within the Irish Val-

ley Member of the Catskill Formation at Selinsgrove, Pennsylvania, two sea-level lowstands are separated by a distinct sea-level highstand; however, intermeditate proposed fourth- and fifth-order parasequences [5] are not definitively traceable across the extent of the basin. Work is ongoing to trace the third-order cycles through northeastern Pennsylvania into southeastern New York.

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POSTER

A REVISED PALAEOGEOGRAPHY FOR THE FRASNIAN-TOURNAISIAN OF ANGARIDA (SIBERIA)

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Introduction: During the Devonian, Angarida was a large and semi-isolated continent within the warm, arid zones of the northern hemisphere. In the Late Devonian, the Viluy-Yakutsk Large Igneous Province (V-Y LIP) had two active phases and dramatically altered the physical and chemical environment of both the terrestrial and the marine systems. Using fossils and facies, a revised paleogeography of Frasnian to Tournaisian Angarida was reconstructed using GPlates [1] to map the changing terrain of the continent. Plate polygons were sourced from Torsvik and Cocks [2]. Both GEOCABSULFvolv [3] COPSE [4] with methods outlined by Marcilly et al. [5] were used to model changes in weathering, carbon, and climate based upon the revised paleogeography.

Results indicate an increased availability of terrestrial environments between the Frasnian and Tournaisian. The new paleogeography also records the changing deposition of evaporites, and highlights alterations in terrestrial weathering. The alteration of terrestrial habitat availability has importance for the colonisation of Angarida by land plants, for changing weathering regimes, and their follow on effects on climate [6]. This revised paleogeography is also the stage for the activity of the V-Y LIP, allowing local and regional study of its biotic impact with a view toward the global Late Devonian Biocrises.

The presented revision of the Frasnian-Tournaisian paleogeography of Angarida is part of an ongoing project



Figure 1. An example of the revised paleogeography for Angarida highlighting added data for a 360 Ma time slice.

aimed at studying the impact of Large Igneous Provinces on local to regional scales and over short time intervals.

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ORAL

HYDROGRAPHIC AND GEOCHEMICAL EVOLUTION OF THE LATE DEVONIAN EPEIRIC SEAS OF NORTH AMERICA: LINKAGES BETWEEN REDOX, SALINITY, AND BIOTIC CRISESGilleaudeau, G. J.,¹ Remírez, M. N.,¹ Wei, W.,² Song, Y.,³ Sahoo, S. K.,⁴ Kaufman, A. J.,⁵ and Algeo, T. J.⁶

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Introduction: The Late Devonian marks a major transition in Earth history when the expansion of rooted land plants led to a cascade of effects, including enhanced terrestrial weathering and oceanic nutrient delivery, expanded anoxia in epeiric seas, organic carbon burial that drove a decline in pCO₂ and a rise in pO₂, and the transition to the Late Paleozoic Ice Age. The Late Devonian was also characterized by a series of major extinction events, the two largest of which were the Kellwasser Events near the Frasnian-Famennian boundary and the Hangenberg Event just prior to the Devonian-Carboniferous boundary. In this study, we present new information on the hydrographic and geochemical conditions that accompanied these important events in the widespread epeiric seas of North America. Specifically, we present new proxy data for redox and salinity through the Famennian in six cores from the Appalachian Basin (Ohio and Kentucky), three cores from the Illinois Basin (Indiana, Illinois, and Tennessee), and two cores from the Williston Basin (North Dakota). These data elucidate the environmental conditions that fostered dynamic biotic changes through the Famennian.

Redox and hydrographic conditions: In the lower Cleveland Shale of the Appalachian Basin, iron speciation indicates a gradient from intermittently oxic conditions at the most proximal site, to persistently anoxic and periodically ferruginous conditions in the deep basin center, to persistently euxinic conditions approaching the Cumberland Sill. Mo/TOC (units of ppm/wt%) is consistently between ~13 and 18, indicating a moderate degree of basin restriction. In the upper Cleveland Shale, however, iron speciation, trace metal abundances, and pyrite sulfur isotopes indicate expansion of euxinia to all six cores, accompanied by a pronounced pattern of Mo and U drawdown from north to south. Mo/TOC averages ~19 in the most proximal core but progressively decreases to ~3 in the southernmost cores, indicating highly restricted conditions. These data suggest that the lower and upper Cleveland Shale represent distinct intervals in the hydrographic evolution of the Appalachian Basin. The Upper Cleveland Shale, which records maximum euxinic expansion across the basin and potentially in the photic zone, might record the Hangenberg (or Dasberg) Event, suggesting that euxinic expansion in shallow water was an important kill mechanism during the Late Devonian mass extinction.

In the New Albany Shale of the Illinois Basin, a major transgression at the base of the Famennian was accompanied by an expansion of basinal anoxia, which biostratigraphy relates to the Upper Kellwasser Event. The mid-Famennian is also characterized by broad transgression and anoxic expansion, which could be related to the Enkeberg Event. Mo/TOC is between ~10 and 13 in the Illinois Basin throughout the Famennian, indicating a moderate degree of basin restriction.

In the Lower Bakken Shale of the Williston Basin, three progressive pulses of marine transgression and euxinic expansion can be directly related to the Annulata, Dasberg, and Hangenberg events, with maximum onlapping of euxinia onto the shallow basin margins occurring during the Hangenberg Event. In addition to the two cores we investigated for a full suite of geochemical proxies, this interpretation is aided by a compilation of XRF trace metal data from 90 cores (~11,000 data points) across the entire Williston Basin. This dataset allows for a four-dimensional reconstruction of basin redox, which clearly shows euxinic waters shoaling and onlapping the basin margins during the Hangenberg Event. Strong trace metal enrichments during the Hangenberg Event and Mo/TOC ratios consistently > 20 indicate strong connection of the Williston Basin with the open ocean.

Paleosalinity conditions: We also used the B/Ga ratio to investigate paleosalinity in these ancient epeiric seas, with B/Ga shown to effectively delineate freshwater, brackish, and marine conditions in modern sediments. In the Appalachian Basin, these data record a pronounced gradient from brackish conditions proximal to the Catskill Delta to fully marine conditions in the basin interior. This trend is interrupted by a shift back to brackish salinity in the southernmost core, which was deposited in shallow waters atop the Cumberland Sill. In addition, there are strong relationships between paleosalinity, detrital sediment input, and redox indicators, e.g., TOC, Mo, and U in the cores proximal to the Catskill Delta, indicating that freshwater input promoted bottom-water oxygenation.

In the Illinois Basin, the Famennian was characterized by brackish conditions in shallow water near the Cumberland Sill and fully marine conditions in the basin interior. Interestingly, salinity was uniformly higher in the Illinois Basin during the preceding Frasnian interval when the basin was more restrict-

ed, followed by a reduction in salinity across the Frasnian-Famennian boundary.

In the Williston Basin, however, the Lower Bakken Shale records exceptionally high B/Ga ratios consistent with deposition under hypersaline conditions. Hypersalinity is also evidenced by abundant evaporites in the Frasnian, and might have been promoted by arid climatic conditions and high evaporation rates in this paleo-subtropical setting.

Conclusions: Ultimately, our data reveal that the Upper Devonian black shales of North America were deposited under a remarkable variety of hydrographic, redox, and salinity conditions across time and space. Pulses of anoxia and/

or euxinia in all three basins can be confidently linked to biotic crises that witnessed widespread devastation of marine ecosystems, including the Hangenberg Event. Our future work will aim to identify synchronous changes in sea level, watermass chemistry, and extinction across all major Upper Devonian black shale units of North America using refined bio- and chemostratigraphy, as well as Re-Os geochronology. We also seek to tie events in the marine realm with synchronous changes in terrestrial environments through investigation of coeval terrestrial sections in the Appalachian hinterland.

POSTER

THE LATEST EIFELIAN-FRASNIAN HORN RIVER GROUP IN THE NORTHERN MACKENZIE MOUNTAINS AND MACKENZIE VALLEY (NW TERRITORIES, CANADA): INTEGRATED STRATIGRAPHY AND SECTION CORRELATION

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Introduction: The latest Eifelian to early Late Frasnian in the Mackenzie Mountains and Mackenzie Valley is represented by the Horn River Group, a deposit of mainly dark gray and black shales (Hare Indian and Canol formations) and localized platform and reefal limestones (Ramparts Formation). The Group overlies the Eifelian Hume Formation and is overlain by the Frasnian-Famennian Imperial Formation. Lateral variations in facies and thickness of the Horn River Group are described in terms of Givetian-Frasnian paleogeographic zones recognized from SW to NW within the study area (Fig. 1): the southern off-bank zone (SOB), the bank-and-trough zone (BAT), and the western off-bank zone (WOB).

The sharp onlap of the Hare Indian black shales (Bluefish Mb) upon the Hume limestone records the spread of anoxic/dysoxic waters over the shallow-water carbonate shelf in the latest Eifelian-earliest Givetian. The gradational shift to the gray shales of the Bell Creek Mb in the BAT area and to the gray and dark gray shales of the Francis Creek and Prohibition Cr members respectively in the SOB area occurred in the

Early Givetian, representing a shift from anoxic to more oxic conditions in a marginal basin setting. Deposition of these gray calcisiltites of the Hare Indian Formation is interpreted as progradation of a clastic wedge that filled into the basin. Reflecting attenuation of siliciclastic influx, the Hare Indian clastics grade upward and partly laterally into an alternation of calcareous shales and limestones before the establishment of small carbonate platforms or banks (Ramparts Formation) on top of the clastic wedge. On these carbonate banks, a reefal facies (Kee scarp Mb) developed locally. Reef debris accumulated locally on reef flanks and toes (referred to as the Allochthonous limestone beds). The Hare Indian and Ramparts deposits are blanketed by the dark siliceous Canol shale that again represents deeper anoxic/dysoxic conditions [1].

Biostratigraphy (Fig. 1): Conodont research in the study area began in the early 1970s by T. Uyeno [2] and was continued over the years by several other researchers. The state-of-the-art conodont biostratigraphy in the Mackenzie Mountains

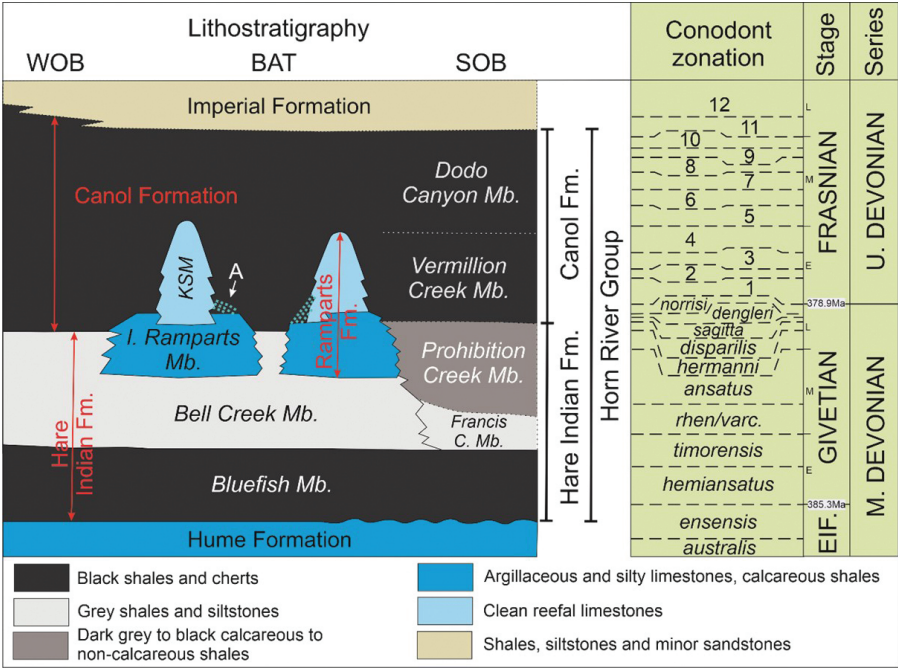


Figure 1. Chronostratigraphic diagram of the Horn River Group in the Mackenzie Mountains and Mackenzie Valley. Paleogeographic areas: WOB: western off-bank area; BAT: bank and trough area; SOB: southern off-bank area; KSM: Kee scarp Member, A: Allochthonous limestone beds; Francis C.: Francis Creek; Mb: Member; Fm.: Formation; E.: Early; M.: Middle; L.: Late. Figure modified from earlier publications [1, 4].

was published in 2022 [3] based on new field samples combined with archival collection material. Conodont faunas indicate a late Eifelian age (*ensensis* Zone) for the base of the Horn River Group. The Bluefish Mb straddles the Eifelian-Givetian boundary and changes into the Bell Creek Mb during the Early Givetian (*timorensis* Zone). In the Middle Givetian (*ansatus* Zone), carbonate banks of the Ramparts Formation start to develop on the Bell Creek Mb. These banks persist until the latest Givetian (*norrisi* Zone) and are locally topped by carbonate reefs that drowned in the late Early Frasnian (Zone 4). The Canol Formation covers the entire area from the Late Givetian until the early Late Frasnian (Zones 11–12) when it grades into the Imperial Formation.

Correlations: Several outcrop sections and cores, measured and sampled along the northern Mackenzie Mountain front and in the Mackenzie Plain, are correlated using a combination of gamma-ray measurements, lithostratigraphy, and chemostratigraphy for the lithostratigraphic correlation and biostratigraphy combined with anoxic event stratigraphy for the chronostratigraphic correlation creating a WNW-ESE profile along the northern Mackenzie Mountain front and a

NE-SW profile through the Mackenzie Valley. The sections represent the BAT, WOB, and SOB paleogeographic areas [4]. The resulting correlations show a synchronous drowning of the Hume platform in the entire area, with no significant hiatus between the Hume and Hare Indian formations. The Ramparts carbonate banks seem to develop simultaneously whereas there is a suggestion of different timing for the drowning of the Kee Scarp reefs [5]. The lower part of the Canol Formation is locally time-equivalent of the upper part of the Ramparts Platform Mb. The Canol Formation continued to be deposited during reef growth and after drowning of the reefs. There is no evidence of a pre-Canol unconformity or hiatus.

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ORAL

EXPRESSION OF THE MIDDLE DEVONIAN KAČÁK EPISODE IN THE MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES, CANADA

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In the Mackenzie Mountains (NW Territories, Canada), the Kačák Episode interval situated close to the Late Eifelian-Early Givetian boundary is characterized by a sharp facies change due to a hypoxic perturbation. The open-shelf limestone of the Hume Formation is overlain by the fine black calcareous shales of the Bluefish Member (Hare Indian Formation). This interval was studied in six sections along the northern Mackenzie Mountain front.

Conodont faunas from the Hume Formation place its main part in the Eifelian *kockelianus* Zone. The initial onset of the black shales took place in the Eifelian *ensensis* Zone, suggested by the appearance of the brachiopod *Eliorhynchus castanea* in the uppermost 3 m of the Hume Formation. The first Givetian conodont fauna was identified at 7.5 m above the base of the Bluefish Member.

The global Kačák Episode represents a polyphased biotic crisis, usually associated with a transgression, with a first phase indicated by a sharp turnover in conodont fauna and facies: a sudden onset of dark *otomari* shales in the hemipelagic to pelagic realms (*otomari* event), and a second phase (Kačák

event s.s.) coinciding with the Eifelian-Givetian boundary.

The Hume-Hare Indian formations transition is generally interpreted as a deepening event and the sharp contact between the two formations as a drowning surface. *Nowakia* sp. cf. *otomari* appears in the uppermost meter of the Hume Formation. This *otomari* event coincides here with an innovation in conodont fauna: new taxa and new morphotypes appear in the top of the Hume Formation, right below the onset of the black shales. The Eifelian-Givetian boundary (and the Kačák event s.s.) cannot be accurately situated in the sections, due to the lack of the index taxon *Polygnathus hemiansatus*.

Based on stable oxygen isotope analysis on conodont apatite of monogeneric assemblages, this innovation coincides with a sign the Hume Formation and lowermost few meters of the Bluefish Member. If no change in salinity were assumed, this shift would suggest a warming of the paleo-ocean surface waters that might have promoted the innovation and could have induced a reduction in oxygenation of the lower part of the water column in combination with a sea-level rise.

ORAL

ASTROCHRONOLOGY OF THE HANOVER FORMATION, LATE DEVONIAN, WESTERN NEW YORK

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The Hanover Formation in western New York State is predominantly composed of interbedded bioturbated light-gray silty shales and dark-gray organic-rich silty shales. These shales were deposited in a prodeltaic deep shelf-to-basin setting on the northeastern margin of the Appalachian Basin. Within this area, the Hanover Formation is framed by the distinct biostratigraphically constrained Pipe Creek Formation, which is equivalent to the Lower Kellwasser interval, and the Pt. Gratiot Bed, which is equivalent to the Upper Kellwasser interval, below the thick and distinct black shales of the Dunkirk Formation. Radiometric dates indicate that the 32 m thick strata of the Pipe Creek and Hanover Formation represent ~800,000 years, where the eccentricity, obliquity, and precession oscillations are visible as packages in decimeter to meter-thick couplets of black and light-gray shales. Two 4.69 m and 2.15 m intervals of the Hanover Formation obtained from the West Valley NX-1 core (API#31-009-06740-00-00)

were sampled continuously at 1 cm intervals for magnetic susceptibility (MS). An astrochronologic timescale reconstruction with any statistical significance was not feasible on either of the West Valley core segments because neither were long enough to preserve an eccentricity cycle that could be used as a geochronometer. Using a third MS series encompassing the entire Hanover Formation along Walnut Creek near the Village of Silver Creek, New York, there was the opportunity to create a significant astrochronology for the Hanover Formation to which the West Valley core intervals could be tuned. Using the MATLAB package Acycle, the Walnut Creek dataset was analyzed with sedimentation rate estimators, multiple methods of spectral analysis, filtering, and age scale tuning (Fig. 1). From this, a timescale of $822,922 \pm 250$ yr was produced for the entire Hanover Formation, which is comparable to the age date derived from radiometric dating. The tuning of the core segments produced age scales of 143,101

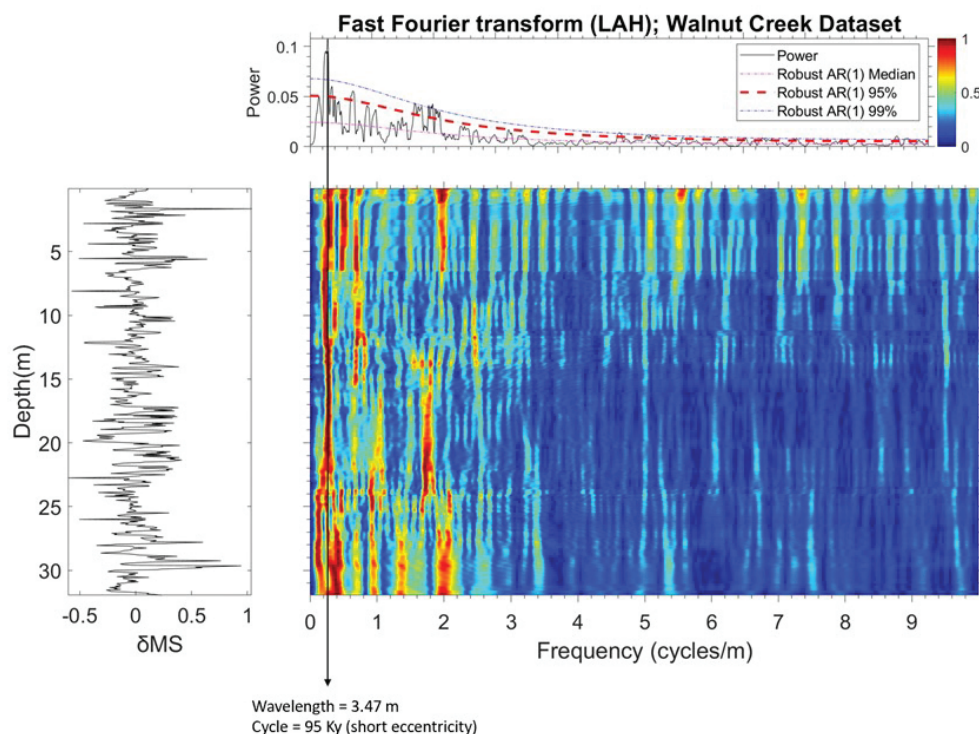


Figure 1. Evolutionary fast Fourier transform (FFT) of the linearly detrended δ MS series from the Hanover Formation section on Walnut Creek with a sliding window at 11.18 m with a step of 0.05 m. The 2π MTM plot is shown above the evolutionary plot and is correlated to the plot by frequency (cycles/m) along the x-axis. The linearly detrended δ MS plot on the left side of the figure is correlated to the evolutionary plot by depth (m) along the y-axis. This plot shows how the spectral power of the Walnut Creek δ MS series varies through depth and time due to changes in sedimentation rate. The gradient color bar correlates to spectral power, with dark blue showing no power, and dark red showing high power. The black arrow going through power spectrum at a frequency of 0.2795 cycle/m corresponds to the short eccentricity cycle, which is presenting high spectral power and shows little variance throughout the section.

± 250 yr for core segment #1 and an age scale of $71,456 \pm 250$ yr for core segment #2. Due to the high-resolution sampling interval of the core segments, the 2π multitaper method spectral analysis plots from both segments showed the presence of fine-scale climatic cycles with a statistical confidence above 95%. A 7–8 ky cycle was interpreted to be the result of combination tones of Milankovitch cycles, a 2.6 ky cycle was interpreted to be the Hallstatt cycle, a 1.5 ky cycle

was interpreted to be Dansgaard-Oeschger variations, and a 900-yr cycle is interpreted to be the Eddy cycle (Fig. 2). This astrochronology of the Hanover Formation creates a high-precision timescale that could be used to help pinpoint the timing of environmental/evolutional events, and the identification of known cycles within the West Valley Core intervals aids in demonstrating the origin and persistence of millennial and centennial-scale cycles during the Late Devonian.

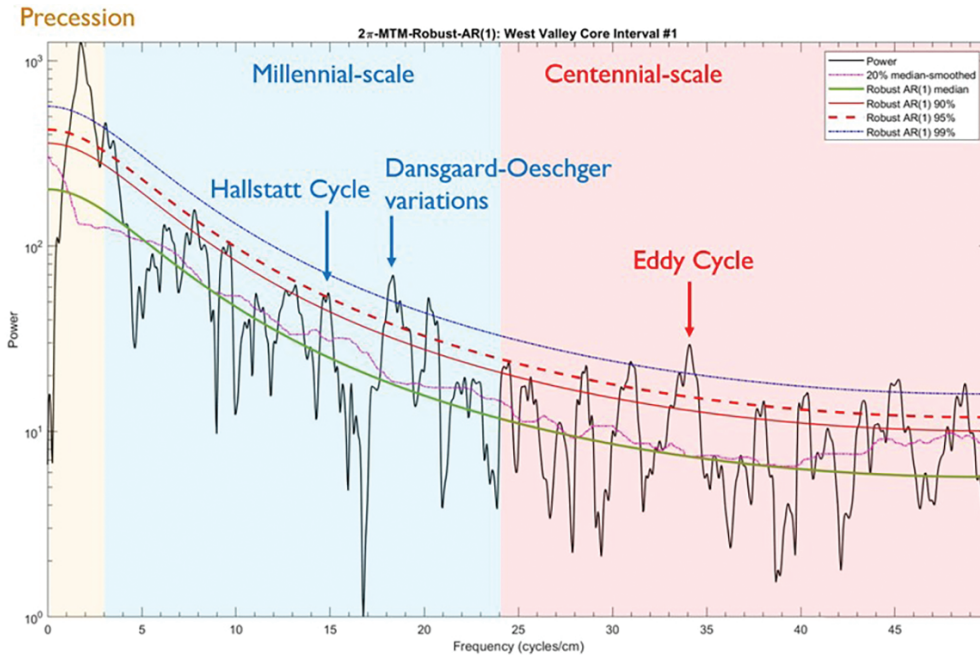


Figure 2. Annotated 2π MTM spectral analysis of West Valley core interval #1 δMS series showing the length of the cycles detected and known cycles that are interpreted to be present. Cycles present within the yellow panel are precession, cycles present within blue are millennial-scale, and cycles present within red are centennial-scale. The Hallstatt cycle occurs within the millennial scale cycles panel at a wavelength of 0.104 m and a confidence level of 95%. Dansgaard-Oeschger variations occur within the millennial-scale panel at a wavelength of 0.055 m and a confidence level above 99%. The Eddy cycle occurs within the centennial-scale panel with a wavelength of 0.035 m and a confidence level above 99%.

ORAL

BASIN-WIDE CORRELATION OF ASTRONOMICALLY FORCED CYCLES IN THE FAMENNIAN OHIO SHALE, APPALACHIAN BASIN, OHIO, USA

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Introduction: The Upper Devonian Ohio Shale of the Appalachian Basin, USA exhibits pervasive decimeter (dm)-scale cyclicity, with organic-rich layers linked to reduced siliciclastic influx and organic-poor layers to increased siliciclastic influx, and a time scale that is on the order of the climatic precession cycle (~20-kyr). The formation consists of five members: Lower Huron, Middle Huron, Upper Huron, Three Lick Bed, and Cleveland. In the state of Ohio, toward the north, the Chagrin Shale replaces the Middle and Upper Huron members; here, starting at the base of the Middle

Huron Member (Chagrin Shale), an extended interval of relatively uniform sedimentary cyclicity provides strong evidence for astronomical forcing frequencies [1]. This raises the prospect for addressing multiple geological problems at once: (1) the paleoclimate-sediment response of late Devonian black shales to astronomical forcing; (2) late Devonian precession rate and rotation rate of the Earth, and Earth-Moon distance; (3) correlation of Ohio Shale members across the Appalachian Basin; and (4) development of an astrochronological framework for the Ohio Shale.

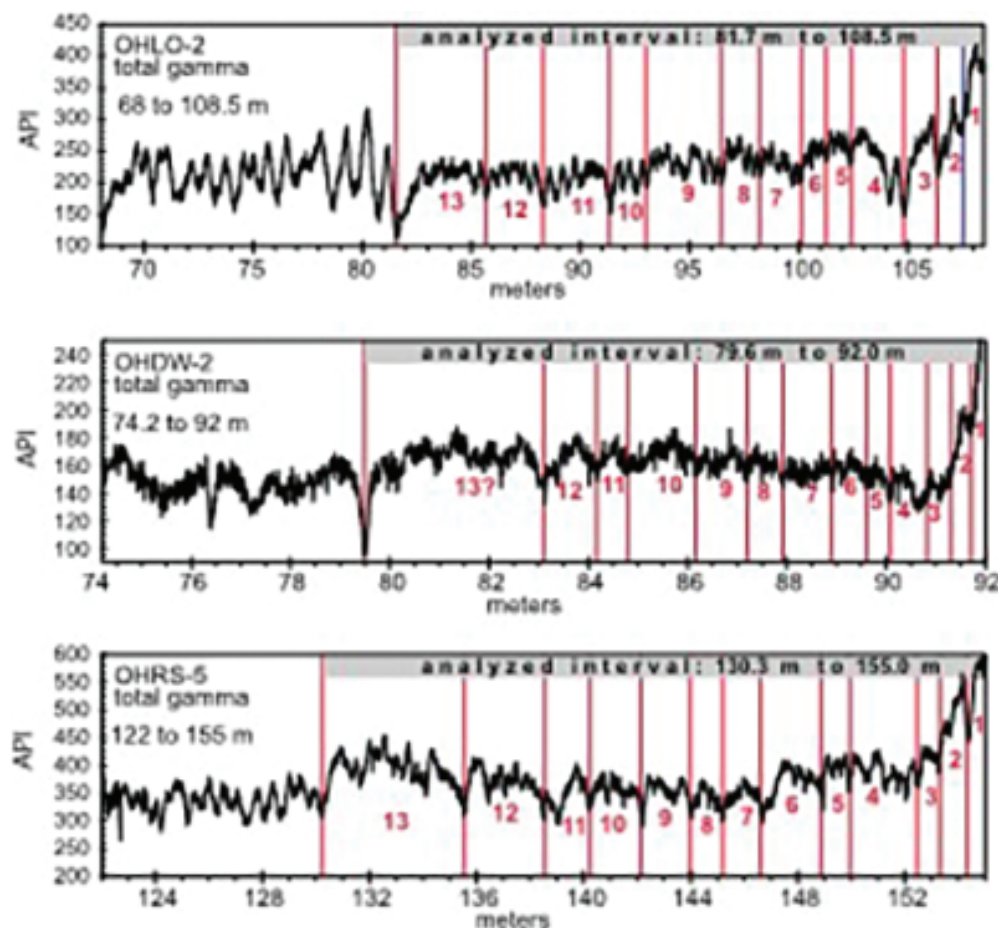


Figure 1. UHR-SGR logs of total gamma ray for three drillcores (OHLO-2, OHDW-2, and OHRS-5) through the Middle Huron Member (lower Chagrin Shale) of the Ohio Shale, Appalachian Basin, Ohio, USA. Measurement spacing is < 1 mm; stratigraphic up is toward the left. The base of the illustrated interval is imprecisely assigned to the base of the (new) *gracilis* conodont Zone [2, 3]. The shaded “analyzed interval” for each of the three logs exhibits 13 bundles of dm-scale cycles; the top of Bundle 13 is marked by a GR minimum, and followed by a distinct change in cycling wavelength and pattern.

Data: Ultra-high-resolution spectral gamma ray (UHR-SGR) logging with < 1 mm measurement spacing [1] was used to measure U (organic matter and phosphate), Th (clay minerals), and K (potassium feldspar) through the Ohio Shale in three drillcores, from north to south: OHLO-2 (Lorraine Co.), OHDW-2 (Delaware Co.), and OHRS-5 (Ross Co.). Starting from the base of the Middle Huron Member, a succession of 13 m-scale “bundles” of dm-scale cycles characterizes the total GR log for the Middle Huron Member in OHRS-5 and OHDW-2, and the lower Chagrin Shale in OHLO-2 (Fig. 1).

Methods: Statistical correlation. The “analyzed interval” of each UHR-SGR log was correlated to those of the other two logs using a hidden Markov model correlation technique with error estimation (borrowed from DNA sequencing methods), HMM-Match [4]. The goal was to determine how well the dm-scale cycles in the 13 bundles correlate among the three logs.

Astrochronology. OHLO-2 provides the thickest (26.8 m; thus potentially highest-resolution) record of the analyzed interval, and so it was analyzed for the presence of astronomical frequencies using spectral analysis, method of ratios, time optimization, and minimal tuning [5, 6]. The reconstructed astrochronology for OHLO-2 was then propagated into the other two correlated logs (OHDW-2 and OHRS-5).

Results: Statistical correlation. HMM-Match was performed on the UHR-SGR logs: (1) OHLO-2 vs. OHDW-2, (2) OHLO-2 vs. OHRS-5, and (3) OHDW-2 vs. OHRS-5. All three logs show excellent matches with one another, with errors (95% uncertainty) on the order of a few cm except in a few isolated m-long intervals where they expand up to ~ 45 cm, indicating uncertainty over a single dm-scale cycle.

Astrochronology. The stratigraphic spectrum of OHLO-2 shows primary power in a band centered at a 3-m wave-

length, and secondary power at peaks centered on a ~ 0.6 -m wavelength; the ratio, $3\text{ m}/0.6\text{ m} = 5:1$ is suggestive of the orbital eccentricity:climatic precession ratio, i.e., 100 kyr:20 kyr. Time optimization is applied to support this interpretation. Spectrograms indicate a 5-m-long interval in which frequencies shift to significantly higher values; minimal tuning is applied to estimate the sediment accumulation rates responsible for this shift. The reconstructed astrochronology from these estimated sediment accumulation rates was transferred to the other two logs via the correlations established above.

Summary: This study presents evidence for astronomical forcing of the Famennian Ohio Shale, Appalachian Basin, USA with a shift in the climatic precession frequency band to a value that is higher than present-day (although lower than expected for ~ 370 Ma), corresponding to a shorter precession period and indicative of faster Earth rotation. Hidden Markov model matching reveals a high degree of correlation of the depositional cyclicity throughout the Middle Huron Member (lower Chagrin Shale) across a 250-km north-south transect of ultrahigh resolution gamma ray logs from three drillcores (OHLO-2, OHDW-2, and OHRS-5). The results provide a detailed (~ 20 -kyr resolution) ~ 0.9 -Myr-long numerical time grid across the Appalachian Basin for the Middle Huron Member. This includes the (new) *gracilis* and *marginifera* conodont zones, which can be used to project the time grid globally.

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ORAL

FAMENNIAN TO EARLY TOURNAISIAN DEPOSITIONAL SEQUENCES FROM THE WILLISTON BASIN AND SURROUNDING AREAS, NORTHWESTERN UNITED STATES

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Introduction: The Farnennian to Early Tournaisian comprises the Bakken and Three Forks formations in the subsurface Williston Basin of northwestern North Dakota [1, 2]. The Bakken-Three Forks interval comprises mixed siliciclastic, carbonate, evaporite, and organic black shale lithologies that represent a diverse array of depositional environments [1, 2]. This interval lies between two thick, marine, carbonate units, the underlying Devonian Jefferson Group and the

overlying Mississippian Madison Group. The Bakken-Three Forks interval is subdivided into ten depositional sequences with four Three Forks sequences characterized by carbonates and evaporites overlain by six Bakken sequences characterized by three siltstone-dominated sequences and three shale-dominated sequences [3]. Each sequence is bound by regionally extensive unconformities and contains distinctive lithological characteristics indicative of different depositional settings [3, 4].

Geological Sequences: The four Three Forks sequences contain dolomitic tidal flat, coastal plain, and evaporite deposits [3, 4, 5]. The basal part of the Bakken includes the lower Pronghorn sequence that is composed of open marine shoreface siltstones, shales, and offshore fossiliferous limestone deposits [3, 4, 6]. The upper Pronghorn sequence is a restricted marine, bioturbated siltstone to low organic-bearing shale [3, 4, 6]. The Lower Bakken sequence is rich in pyritic, marine, organic-bearing shale [3, 4, 7]. The Middle Bakken is composed of two sequences that both comprises a mixed siliciclastic to carbonate marine shoreface setting [3, 4, 8]. The Upper Bakken sequence includes pyritic to calcareous organic-bearing shale [3, 4, 9, 10]. Thinning of the sequences is related to onlap at the base during sedimentation, or truncation at the top during subaerial exposure and erosion between sequences [3, 4] (Fig. 1).

Biostratigraphy: Biostratigraphic data comes from a mixture of literature and private sampling collections collected from the Williston Basin of North Dakota [4] and South Dakota [11], the Sappington Basin in Montana and Wyoming [12, 13, 14], and the South Alberta Basin [15, 16]. Data

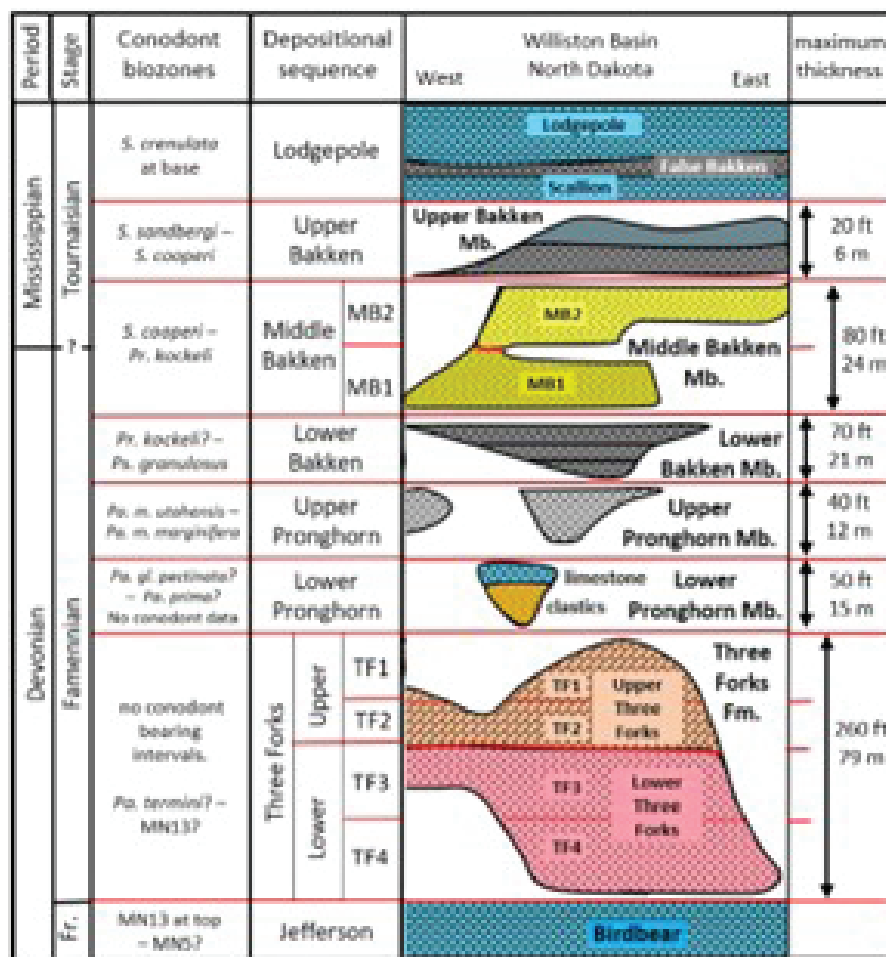


Figure 1. Composite stratigraphy of the Williston Basin showing the changes in thickness from west to east for each depositional sequence.

Sappington Basin MT WY		South Alberta Basin CA		Williston Basin ND		Black Hills SD	
Lodgepole Formation		Lodgepole Fm.		Lodgepole Fm.	undiff.	Pahasapa Formation	
		Banff Fm.	upper black shale unit		False Bakken Shale		
			limestone unit		Scallion Limestone		
Sappington Fm.	Upper Sappington Mb.	Banff Fm.	lower black shale unit	Lodgepole Fm.	Upper Bakken Mb.	Englewood Formation	Mickelson Mb.
	Middle Sappington Mb.		upper siltstone unit		Middle Bakken Mb.		
	Lower Sappington Mb.		lower black shale unit		Lower Bakken Mb.		Griffis Canyon Mb.
Three Forks Fm.	Trident	Big Valley Fm.	Upper Pronghorn Mb.	Lower Pronghorn Mb.			Little Crow Mb.
	Knoll						Crook City Mb.
	Logan Gulch Mb.	Palliser Fm.	Three Forks Fm.				

Figure 2. Stratigraphic correlation table of lithological units from the Williston Basin and the surrounding areas. CA = Canada, Fm. = Formation, ND = North Dakota, Mb. = Member, MT = Montana, SD = South Dakota, WY = Wyoming.

from all of these study areas are used to determine the age of each sequence and justify the correlation of lithological units between these depocenters (Fig. 2).

Summary: Each sequence contains its own unique facies successions, sequence stratigraphic architecture, and depositional environments. The varying depositional environments between the sequences shows that the region was under different environmental and climate conditions at different times throughout the Famennian and Early Tournaisian. Correlation of lithological units across the major bounding sequence boundaries is not supported by the regional stratigraphic mapping or biostratigraphy and depositional models invoking these correlations should be abandoned. Future detailed biostratigraphic sampling will refine the upper and lower age boundaries for each sequence and further aid in interbasinal correlations.

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ORAL

INVESTIGATING THE LINK BETWEEN DEVONIAN ANOXIC EVENTS AND ASTRONOMICAL FORCING

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The Devonian geological record bears evidence of numerous regional-to-global anoxic events. Even though some of these events are believed to have had a limited impact on the biosphere (e.g., shifts in biodiversity, decimation of specific ecosystems), the Kellwasser Event (Frasnian-Famennian boundary) and the Hangenberg Event (Devonian-Carboniferous boundary) are linked to major extinction episodes. Commonly, these anoxic events are characterized by a positive carbon isotope excursion (CIE) and are often expressed as organic-rich black shales interbedded in carbonate-rich sediment. Yet, absence of a positive CIE and expression of anoxic events as an unconformity, facies change, or hiatus have been reported as well, i.e., the expression of anoxic events is variable and depends on the paleoenvironment and paleogeography.

Even though a consensus on the mechanisms behind these events has not yet been reached, clues have been uncovered that suggest a link between the pacing of ocean anoxia and astronomical forcing (2.4 Myr eccentricity nodes) for the Kellwasser Event. It is the main goal of the 'WarmAnoxia' project to investigate the potential link between ocean anoxia and astronomical forcing and—if identified—what their

phase relationship is and which mechanisms are driving the development of ocean anoxia.

In the scope of the 'WarmAnoxia' project, existing geological records covering nearly the entire Devonian (except the Frasnian stage) will be re-evaluated and complemented by new observations of the Lansing Core, NY (USA) and the Oued Ferkla section (Morocco). The stratigraphic position of the anoxic events will be constrained by evaluating the existing biostratigraphic framework and geochemical composition of the sedimentary record (elemental composition, carbon isotope record). Using cyclostratigraphy, these anoxic events will then be located in a well-constrained temporal framework and their duration and position relative to astronomical forcing nodes (i.e., 2.4 Myr eccentricity minima or maxima) will be investigated. Only then will it be possible to attempt consolidating formulated hypotheses with scenarios provided by numerical modeling. This way, it will be investigated which complex multicausal factors can be associated with Devonian anoxic events, which role astronomical forcing plays in their pacing, and whether the 2.4-Myr eccentricity nodes act as a window of opportunity or rather the decisive trigger.

POSTER

VARIABILITY, RELIABILITY, AND SIGNIFICANCE OF BRACHIOPOD $\delta^{18}\text{O}$ VALUES FROM THE MIDDLE DEVONIAN HAMILTON GROUP

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Introduction: Paleotemperatures, glacial regime, and salinity are among the factors that remain mysterious in the Middle Devonian. Stable oxygen isotope values of brachiopod shell calcite hold the promise to resolve some of these uncertainties and reveal benthic paleoenvironmental conditions if their own integrity can be established. Simpler collection and larger specimen sizes offer advantages over conodonts, but their mineralogy and microtextures make them more susceptible to diagenetic alteration. Assessing variation in shell $\delta^{18}\text{O}$ values across a range of spatiotemporal scales could help shed light on the sources of that variation and their potential to retain original compositions.

Methodological Approach: Shells of the impunctate brachiopods *Mucrospirifer* and *Spinocyrtia* with visually well-preserved calcite were collected from multiple localities in the Marcellus, Ludlowville, and Moscow formations, spanning the Middle Devonian Hamilton Group in Central New York. Fresh surfaces of all shells were revealed via crushing or abrasion, and subsamples of clean shell calcite were collected using tweezers or a hand-held dental drill. The interior of the heavily calcified hinge region was targeted for sampling whenever possible. Preservation of shell microtextures was assessed with scanning electron microscopy on the JEOL Neoscope II at SU and the potential for secondary/diagenetic calcite was evaluated with Fe and Mn concentrations of shell subsamples done on the ICP-MS at SUNY-ESF. Stable oxygen and carbon isotope analyses of shell subsamples were performed at the University of Michigan Stable Isotope Lab and the Northern Illinois University Stable Isotope Laboratory. Fossil shell textures are compared to those from modern brachiopods collected off of the coast of Argentina, and elemental data are compared to published data on modern brachiopod shells from Brand et al. [1].

We explore variation in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, Mn and Fe concentrations, and shell microtextures within and among shells, within and among localities, and within and among formations. The Cascade outcrop of the Ludlowville Formation was intensely sampled with decimeter-scale stratigraphic resolution to test for variation across putative fifth-order (20–100 ky) depositional cycles. Individual shells were subsampled along the growth axis to reveal variability within a single shell over an individual's lifespan. This multiscale approach has the potential to disentangle issues of preservation from real on-

togenetic and paleoenvironmental variation on subannual to mega-annual scales.

Initial Results: SEM imagery reveals frequent retention of shell microtextures with very high fidelity. Individual crystal edges are generally sharp and clean, comparable to the micro- and macroscale textural features seen in modern brachiopod shell. Evidence for minor dissolution is occasionally seen on the surfaces of fibers. A very few images reveal what might be secondary calcite precipitating on fiber surfaces. Shell Mn and Fe concentrations nearly all fall within the range of values documented from living brachiopods [1], if on the higher end of that range.

As found by prior workers [2], $\delta^{18}\text{O}$ values of Hamilton Group brachiopods overall are disconcertingly low, ranging from ~ -4.0 to -11.0 per mil. $\delta^{13}\text{C}$ values generally fall between $+1$ and $+3$ per mil and do not correlate with $\delta^{18}\text{O}$. Localities within the Moscow are distinct, as are data from the three formations. Samples with low $\delta^{18}\text{O}$ values do not exhibit Fe or Mn concentrations outside the range of modern shells, and the several fossil samples with significantly elevated Fe or Mn span the full range of $\delta^{18}\text{O}$ values. Diagenetic cement from the Moscow Formation at Geer Road, the Marcellus Formation at Swamp Road, and published whole-rock values from the Marcellus Formation [3] are 2 per mil or more lower in $\delta^{18}\text{O}$ than all brachiopod analyses from the Marcellus and Moscow formations. Geer Road cement additionally plots well above and outside the range of modern brachiopod shells for both Mn and Fe.

Samples collected from the Ludlowville at Cascade generally yield lower $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values than those from the Marcellus and Moscow formations. Samples from within an individual horizon often span the full range of values seen across the whole section. Consistently low $\delta^{18}\text{O}$ (~ -5.5 to -11.0 per mil) and low and more variable $\delta^{13}\text{C}$ ($\sim +3$ to -6 per mil) suggest a greater potential for alteration, with low values converging on the diagenetic end member. These samples were picked from crushed shell fragments or drilled from freshly abraded shell exteriors rather than drilled from shell cross sections. The data from Cascade suggest that either this site was cryptically altered in ways not observed by SEM, or that these methods, especially the exterior drilling method, are susceptible to incorporation of secondary calcite.

Oxygen isotope values from ontogenetic profiles collected from Marcellus Shale *Spinocyrtia* span the full range of values exhibited by bulk-shell values from multiple individuals. $\delta^{13}\text{C}$ values suggest the presence of at least four 'cycles' across 43 mm of shell growth, but these are not mirrored in $\delta^{18}\text{O}$ and so their significance has yet to be established. Transects across polished-shell cross sections using laser-ablation ICP-MS are pending and could shed more light on the significance of ontogenetic variation. If Fe and Mn are low and do not covary with $\delta^{18}\text{O}$, then we might conclude that stable isotope variation along the growth profile is more likely to reflect original sub- and interannual environmental variation.

Preliminary Assessment: These initial data suggest that, minimally, Hamilton Group brachiopod calcite is geochemically distinct from clearly diagenetic precipitates when collected from within heavily calcified shell cross sections. Shell textures and Mn and Fe concentrations are comparable to those seen in modern shell. *En toto*, samples with more typically 'marine' $\delta^{13}\text{C}$ values (+2 to +3 per mil) span a range of

$\delta^{18}\text{O}$ values (-4 to -9 per mil), samples with $\delta^{13}\text{C}$ values < 2 have lower $\delta^{18}\text{O}$ values (-7 to -10 per mil), and at $\delta^{13}\text{C}$ values < -2 per mil, $\delta^{18}\text{O}$ variability decreases and centers around -8.5 per mil. This suggests mixing reflecting the increasing incorporation of diagenetic carbonate, derived from interaction with meteoric water, in brachiopod shell, with $\delta^{18}\text{O}$ affected first and $\delta^{13}\text{C}$ only beginning to shift with higher water:rock ratios [4]. Nevertheless, even presumably altered brachiopod shell retains primary microtextures. Whether this mixing line begins at original shell compositions or even the most positive $\delta^{18}\text{O}$ values are already depleted relative to original values remains to be seen.

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ORAL

**STRUCTURAL INFLUENCE ON DEVONIAN BLACK SHALE DEPOSITION IN SOUTHWESTERN
NEW YORK STATE: BASIN ARCHITECTURE DRIVEN BY CRUSTAL SCALE THRUST
LOADING TO THE EAST AND TO THE SOUTH/SOUTHEAST**

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Isochore maps of Devonian black shales and a limestone in southwestern New York State and northwestern Pennsylvania that were constructed in 2009 [1] show a startling spatial coincidence between sharp gradients in isochore thickness and trends of structural features (faults and folds) that were proposed in 2002 [2]. The isochore thicknesses of the Marcellus, Genesee, Middlesex, Rhinestreet, and Tully formations are based on between 1572 and 4680 well logs.

Two sets of structural systems apparently influenced the deposition of these units and the basin architecture: (1) northerly-striking fault systems and (2) an arcuate (in map-view) structural system that includes northeasterly-striking faults and folds with less dominant orthogonal faults. The arcuate trends overprint the northerly-striking trends, and dominate in the southern part of the area of interest, whereas the northerly-striking trends are dominant in the north.

The northerly-striking syndepositional faults are reactivated Grenvillian fault systems. Although some of the northerly trending thickness gradients are gradual, sharp breaks in thickness across known fault locations suggest that at least some of the syndepositional faults extended to the surface or near surface at the time of deposition (e.g., the abrupt changes in Tully thickness across the Clarendon Linden Fault System).

Reactivation of the northerly-striking faults reflect a thrust load to the east of the Catskill Delta Complex. There, (neo) Acadian metamorphic infrastructure developed during growth of an altiplano that was associated with crustal-scale thrusts with westward transport [3], e.g., the Green Mountain and Berkshire massifs. Recent Ar/Ar dates on these thrusts [4] show that they were generally active during the time of the black shale and limestone deposition. Only one isochore black shale map—the Middlesex—does not display norther-

ly-striking trends, and significantly, the altiplano thrusts do not appear to have been active at the time of Middlesex black shale deposition.

For the arcuate structural system, 2D and 3D seismic reflection data display growth faults at the Precambrian/Cambrian (pC/C) contact that indicate the faults were active in Iapetan opening and Rome Trough time. Structurally disturbed zones of the arcuate set are aligned upsection from the pC/C contact to even above the Silurian salt section. Seismic reflection data and well log analyses suggest that the arcuate fault systems were reactivated during Taconic, Salinic and Neocadian orogenies (and probably more recently).

Well log and seismic data show that black shales onlap and thin against salt-cored anticlines and infill local structural lows (e.g., Marcellus infilling Onondaga structural lows).

Thrust loads to the south and southeast, e.g., reactivation of the Blue Ridge thrust, probably account for the general subsidence to the southeast with the ensuant arcuate structural system development. Thrust loads both to the east and southeast with consequent basin subsidence led to a complicated basin architecture of intersecting northerly-striking faults and arcuate faults and folds. The subsidence accompanied by fault and fold growth were important drivers that strongly influenced the extent and thickness of the Devonian black shale deposition, in addition to the usual suspects, including eustatic sea level and sediment supply.

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ORAL

REVISION OF LATEST SILURIAN – MID-DEVONIAN BRACHIOPOD FAUNAS FROM THE RHENISH MASSIF (GERMANY): STATE OF THE ART AND PERSPECTIVES

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Introduction: The long-term taxonomic revision of latest Silurian (Prídolí) to early Mid-Devonian (Eifelian) brachiopods from the Rhenish Massif has resulted in numerous new implications on their phylogeny, biostratigraphy, paleoecology, and paleobiogeography [1, 2, 3, and work in progr.]. At least 220 species are presently known from the area, and many of these are currently still under revision. In addition, a number of new genera and species have already been or will be introduced. One of the future aims is the reconstruction of the changing brachiopod biotopes in space and time.

Taxonomy: There are important taxonomic novelties concerning some Rhenish strophomenides, orthides, and spiriferides; several taxa will even be accommodated in other families. Lingulides and craniides are now included as well.

Biostratigraphy: As an indispensable prerequisite, a predominantly brachiopod-based biostratigraphic framework is established, enabling the reconstruction of spatiotemporal developments of faunas, paleoenvironments, and paleobiogeographic relations. The two-fold brachiopod biozonation consists of 25 spiriferide taxon range zones (plus subzones) and 20 brachiopod assemblage zones ('faunal zones'), allowing well-constricted regional and supraregional correlations—including regions in western Europe and North Africa formerly belonging to North Gondwana. With respect to the future redefinition of a basal Emsian GSSP, the international correlation of the traditional basal Emsian boundary in the Rhenish type region is one subject presently focused on. Although it is very difficult to pinpoint the boundary in any of the very thick Rhenish sequences, approximate levels can be indicated. The boundary in the Rhenish Massif is distinctly older than the boundary commonly indicated in the Ardennes.

Facies and paleoenvironment: The prevailing siliciclastic-neritic 'rhenotypic' facies reflects a broad spectrum of shallow-marine, tropical shelf paleoenvironments with diverse brachiopod faunas. The 'eurhenotypic facies' is characterized by rich turbidicolous (turbid-water tolerating) faunas of the open shelf; proximal, medial, and distal variations of this facies show faunal change and increasing diversity along a depth gradient from lower intertidal to middle subtidal settings, at estimated water-depths ranging from 5–60 m. The 'pararhenotypic facies' shows low-diversity lingu- lide-terebratulide brachiopod faunas of marginal-marine paleoenvironments with changeable conditions in the inter-

tidal. The 'allorhenotypic facies' is marked by rich claricolous ($\pm$ clear water requiring) brachiopod faunas that inhabited shallow to moderately deep subtidal settings with mixed calcareous-siliciclastic sedimentation. The spatial distribution of brachiopod assemblages is dependent on various factors, e.g., substrate conditions, turbidity, hydrodynamic energy, and salinity. Currently the rhenotypic facies concept is compared with Boucot's concept of Benthic Assemblages [5]. A depth-depending succession of assemblages is reconstructed, including estimated absolute water depths. It is also attempted to analyse/quantify the composition of selected Rhenish faunas and the ecospace utilization. The distal eurhenotypic fauna at Daleiden (upper Emsian, Eifel region), for example, is dominated by brachiopods ('brachiopodetum'). It includes a high quantity of surficially living, nonmotile suspension-feeders showing calm, nutrient-rich biotopes and little disturbance by burrowing animals ('bull-doizing').

Stratigraphic succession of brachiopod faunas: The Rhenish brachiopod 'faunas' (in an ecological-evolutionary sense) occur in stratigraphically successive intervals with more or less consistent taxonomic composition, but they are also represented by different 'communities' within these intervals. The faunas are named by key spiriferide species, including (in stratigraphic order) *Quadrifarius dumontianus*, *Howellella mercurii*, *Acrospirifer primaevus*, *Arduspirifer antecessens*, *Euryspirifer paradoxus*, and *Paraspirifer cultrijugatus*. Each of these faunas is separated from the under- and overlying one by events characterized by marked faunal turnover. Rapid eustatic sea-level fluctuations and regional changes in crustal subsidence and sedimentation rates caused shelf-wide or more regional changes in the paleoenvironment that led to emigration or extinction of substantial parts of a brachiopod fauna. Thereafter, with onset of more suitable conditions, a largely new fauna could immigrate. A longer perturbation is the 'Rhenish Gap', representing a 6–8 myr lasting interval of a facies largely unsuitable for brachiopods, ranging from the late Lochkovian to early Pragian; it has largely been neglected or underestimated in biostratigraphic correlation and paleobiogeographic studies.

Paleobiogeography: The project includes side-by-side comparisons of brachiopods on a world-wide scale, with a focus on western European and North African faunas. Brachiopod-based paleobiogeographic patterns are largely consistent with currently accepted geodynamic reconstruc-

tions for the Silurian–early Middle Devonian that distinguish Laurussia in the north and North Gondwana in the south separated by the Rheic Ocean; a ‘Rhenish Province’ is distinguished from a ‘North Gondwanan Province’, together representing a ‘Maghrebo-European Realm’ [3, 4]. Differences between northern (‘Avalonian’) and southern (‘North Gondwanan’) faunas are distinct in the Pridoli–early Emsian, but often caused or augmented by different facies developments; differences generally diminished in the Middle Devonian, corresponding to narrowing of the Rheic Ocean.

Concluding remarks and perspectives: It is concluded that brachiopod-based stratigraphic correlations, paleoecological studies, and paleobiogeographic reconstructions must consider a complex set of problems referred to the paleoecology of these facies-sensitive fossils, taxonomic bias, questions of origination, extinction and migration, and variable rates of

evolution in different brachiopod stocks. Brachiopod-based biostratigraphy, paleoecology, and paleobiogeography still suffer from a lack of taxonomic standardization. In addition, it is problematic to use genera as proxies for species—a widespread practice lacking a theoretical basis. Age differences between allegedly coeval faunas have often been underestimated. There is still much to do as regards species-level taxonomy and side-by-side comparison of faunas on the worldwide scale.

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POSTER and ORAL

TIMING OF THE LATE DEVONIAN KELLWASSER CRISIS: CYCLOSTRATIGRAPHIC ANALYSIS OF THE JAVA GROUP AT THE WALNUT CREEK SECTION, NEW YORK, USA

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Introduction: The Kellwasser Crisis represents one of the big five mass extinction events in Earth's history. In many places in Europe and North America, it is characterized by successions of black shales in the lithologies of the late Frasnian and early Famennian, punctuated by two thick black shales known as the Lower and Upper Kellwasser events. These black shales indicate rapid changes from oxic to anoxic marine conditions. The driving mechanisms and the timing of the Kellwasser Crisis remain a matter of debate.

Previous Devonian astrochronology: U-Pb dating of zircon crystals from a bentonite layer in uppermost-Frasnian sediments from Steinbruch Schmidt, Germany yielded an age of 372.36 ± 0.053 Ma for the Frasnian-Famennian boundary [1]. Astrochronological studies offered a new perspective on the exact timing and pacing of the Frasnian-Famennian extinctions [2, 3]. By correlating magnetic susceptibility data to astronomical cycles, the duration of the interval between the Lower and Upper Kellwasser events was estimated to be 600 kyr. The inferred astrochronology suggests that there was an orbital eccentricity minimum at the onset of the Upper Kellwasser event, which reduced seasonal extremes. A few tens of thousands of years later, this orbital eccentricity minimum was succeeded by a fast change to an orbital eccentricity maximum and increased climate variability. The hypothesis that an orbital eccentricity minimum led to a stable climate with low action from orbital precession forcing will be tested with a cyclostratigraphic analysis of the Java Group strata at the Walnut Creek section (New York, USA) which spans the Lower-Upper Kellwasser events.

Lithology and Methods: Samples were taken from a 32 m thick cyclic sedimentary section from basin to prodeltaic sediments at Walnut Creek, New York, USA, which spans a series of key Frasnian extinction pulses, in the Pipe Creek Shale and Hanover Shale of the Java Group [4]. The strata consist of gray shales, with interbedded mudstones, carbonates, and black shales. The section was sampled at 5 cm-scale resolution ($N = 639$) and a magnetic susceptibility stratigraphic-series has been established. This series will be compared with XRF geochemistry results. Cyclostratigraphic analysis of this multiproxy dataset will be used to construct a floating astrochronology, that can be linked to other investigation sites in North America [5]. Principal component analysis will be used to identify environmental proxies based on their fluctuation patterns and rates. These paleoenvironmental proxies will be used to determine and quantify changes in detrital input, redox conditions, and organic productivity at a high-resolution precession-timescale to characterize depositional dynamics.

Through this investigation of the pacing and timing of paleoenvironmental proxy concentrations, this study contributes significantly to understanding the origins of the Kellwasser Crisis.

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POSTER

UNTANGLING THE LATE DEVONIAN CARBON CYCLE USING COMPOUND SPECIFIC ISOTOPES

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Introduction: The Late Devonian Kellwasser Events were periods of global anoxia and enhanced carbon burial in marine basins and are associated with a major perturbation to the carbon cycle. The burial of massive quantities of isotopically light carbon in marine settings caused a significant CO₂ drawdown, which is recorded by a positive carbon isotope excursion [1]. However, in the Appalachian Basin, a regional initial negative isotope excursion is superimposed over the global signal [2]. There are multiple potential environmental and ecological reasons for this mismatch. These include, but are not limited to, mixing of terrestrial and organic matter, environmental pressures affecting the marine primary producer community, ecological overturn, or secondary carbon sources. Because each of these factors can create identical bulk organic carbon $\delta^{13}\text{C}$ records, additional tools must be used to understand the cause of the regional carbon cycle variability.

Compound specific isotopes are used to analyze the isotopic change within certain molecular fossils, or biomarkers, with known precursors. This can provide information on the type of organism that produced the biomarkers. For example, pristane and phytane record the average isotopic values of most marine primary producers (algae, cyanobacteria, etc.), but are not directly affected by terrestrial matter or methanotrophic bacteria. Long chain n-alkanes provide information about terrestrial plants, but not marine organisms [3]. Comparing the specific behavior of these groups to the over-

all organic carbon average can be used to identify the biological groups responsible for the difference between regional and global carbon isotope trends. Once this is established, it can be used to determine the environmental and ecological mechanisms that caused the observed behavior

Initial data through the Lower Kellwasser Event and overlying shales show that the unique regional signal observed in the total organic carbon record was not caused by the marine primary producer community. In fact, at each transition from gray to black shale, there are opposite trends observed between the phytane isotope data and bulk organic isotope data. Furthermore, the concentration of terrestrial organic matter does not change significantly throughout the measured samples, so the transport of organic matter from land is not likely to explain the observed carbon isotope trend. The cause of the regional excursion could instead be an expansion of methanogenic consumers or sulfur reducing bacteria in the microbial ecosystem, or environmental mechanisms relating to the recycling of carbon within the basin. These other hypotheses are further tested using the isotopes of medium and long chain n-alkanes.

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POSTER

**INTEGRATED CONODONT, CARBON ISOTOPE, TRACE ELEMENT, AND SEQUENCE
STRATIGRAPHIC DATA FROM THE GIVETIAN-FRASNIAN 'FRASNES EVENT' AND FALSIOVALIS
EXCURSION IN IOWA AND NEVADA, USA**

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Introduction: The Devonian is characterized by a series of global events and crises that variably combine extinctions, positive carbon isotope excursions, and intervals of black shale deposition [1, 2]. These events are often considered to represent rapid eustatic deepening and hypoxia or anoxia, although geochemical data for redox conditions is not available for the majority of events. The Givetian-Frasnian 'Frasnes' Event (or Crisis), a second-order mass extinction, is stratigraphically proximal to the *falsiovalis* positive carbon isotope excursion and up to three black shale intervals [3]. Like other Devonian biogeochemical events with all three components, it could represent a Paleozoic Oceanic Anoxic Event (OAE), but the order and timing of the signals is not well constrained due to the lack of high resolution integrated datasets.

Integrated data from Nevada, USA, is the first to combine conodont biostratigraphy, carbon isotope chemostratigraphy, major and trace element chemostratigraphy via portable X-ray fluorescence analysis, and sequence stratigraphy to characterize the Givetian-Frasnian boundary and the Frasnian and *falsiovalis* biogeochemical event in a carbonate dominated section. Additional data from Iowa are correlated using bio- and sequence stratigraphy.

The Givetian-Frasnian boundary in both areas occurs in shallow water biofacies dominated by species of *Polygnathus*, *Icriodus*, and *Pandorinella insita*, which do not allow for precise placement of the boundary due to the inability to identify *Ancyrodella*-based Frasnian biozones. Correlation is improved

by sequence stratigraphy in both locations and the identification of global Devonian transgressive-regressive (T-R) cycle boundaries.

In Nevada and Iowa, the onset of the carbon isotope excursion closely follows the base of T-R Cycle IIb-1. It occurs very low in the *P. insita* faunal zone in Iowa, but cannot be further constrained to a conodont biozone in Nevada. In Nevada, the excursion is preceded by a thin anoxic black shale facies that could represent a late Givetian black shale horizon of the Frasnian Crisis. The excursion is also followed by anoxic black shales that likely represent a Frasnian phase of the crisis. In both areas, the presence of Frasnian Montagne Noir zones 2–4 conodont species constrains the age of the top of the crisis and excursion interval.

Correlation of the Iowa data with the Waterways Formation of Alberta, Canada, suggests that the excursion likely begins in the latest Givetian *Skeletognathus norrisi* Zone and reaches peak values in MN Zone 1. The combined datasets suggest that deepening pulses and expansions of anoxic shale facies both preceded and succeeded the *falsiovalis* excursion, but that normal marine conditions occurred during the excursion. Additional data are needed to test whether the same sequence of events is present in other localities.

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ORAL

LATE DEVONIAN CRINOID AND BLASTOID GHOST LINEAGES

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Introduction: A brief review of Late Devonian crinoids and blastoids, based on more recent research, is somewhat in order given this year marks the centenary anniversary of Winifred Goldring's (1923) *Devonian Crinoids of New York* [1]. A good deal of research on Devonian crinoids and blastoids has taken place since that time and review of the broad outlines of their diversity and taxonomic change through the interval is timely.

The origins of many Mississippian crinoid and blastoid clades can be traced back to the Early Devonian (Emsian) of Germany [2] and Spain [3] as well as the Middle Devonian (Eifelian and Givetian) of eastern and central North America. After reaching a peak in diversity during the Middle Devonian (e.g., 38 species in the Dock Street Clay of Michigan [*P. rhenanus*/*P. varcus* zones]; 46 species in the Kashong fauna [*P. ansatus* zone] of New York), there is a marked reduction in crinoid and blastoid diversity beginning in the late Givetian (*S. bermanni* and *K. disparilis* zones) of Iowa, Wisconsin, New Mexico, and Michigan following the Taghanic event. A majority of Middle Devonian crinoid and blastoid clades are to date absent during the Frasnian and Famennian.

Crinoids are often at times abundant during the Frasnian although crinoid faunas are generally lacking in diversity. The camerate crinoid genera *Melocrinites* and "*Hexacrinites*" are cosmopolitan and can be abundant in the Frasnian of North America, western Europe, and Australia and strongly dominate most assemblages. Both of these genera are characterized by complex arm patterns evolved to maximize the capture fine zoo- and phytoplankton. *Arthroacantha*, possessing a more conventional camerate arm structure, is also cosmopolitan, ranging over the same regions. The moveable spines that characterize this genus show a marked increase in size over time during the Frasnian. All three of these common Frasnian camerate genera go extinct at the end Frasnian Upper Kellwasser event.

The glossocrinid cladids [4] are widespread in North America during the Frasnian but are extinct by the end of the stage. Although sustaining losses in the late Givetian, the cladid scytalocrinid and decadocrinid crinoid clades are cosmopolitan, increasingly morphologically diverse, and often common throughout the Frasnian and Famennian.

In contrast to the disparid anamesocrinids, the synbathocrinids and calceocrinids, although obviously extant, are absent in all known crinoid faunas during the Frasnian. Flexible crinoid clades appear to have been largely unaffected during

the Frasnian, although this subclass is need of more detailed review.

Frasnian blastoids are exceptionally rare. The author is only aware of 13 blastoid specimens; two individuals from the Sly Gap of New Mexico and 11 specimens from the Virgin Hills Formation of Australia [5].

Rare and low diversity of crinoid faunas are known from the Famennian of Montana (Sappington Formation that also preserves the only reported North American Famennian blastoid genus), Nevada (Pilot Formation), New Mexico (Box Member of the Percha Formation), New York (Alfred Shale, Gowanda, and Chadakoin formations), and Colorado (Broken Rib Member of the Dyer Formation). Crinoids and blastoids increased in abundance and diversity in the Famennian of western Europe, Mongolia [6], and western China before becoming greatly reduced by the Hangenberg event. Relatively scarce in the earliest Tournaisian, diverse and abundant crinoid and blastoid faunas only reappear in the Late Tournaisian (upper *S. crenulata* to *P. communis carina* zones) of North America and western Europe, ushering in the "Age of Crinoids" [7]. It is particularly notable that many of the crinoid and blastoid genera that appear in the Tournaisian are representatives of clades that have no record for much or all of the Frasnian to Famennian interval.

Chronologically, many of the missing clades are absent for over 25 million years. A regional example is the Late Tournaisian (*S. quadruplicata*/*S. crenulata* zone) Meadville Shale crinoid fauna from northern Ohio [8], located < 400 km from western New York, that contains 11 species of camerate, cladid, and disparid crinoids derived from Middle Devonian clades. Examples of these "missing crinoid clades" include: the cladid atelestocrinids, goniocrinids, pellicrinids, and botryocrinids; the camerate gilbertsocrinids, megistocrinids, platycrinids, and eretmocrinids; and the disparid synbathocrinids and calceocrinids.

The underlying cause of Late Devonian ghost crinoid clades is presently unknown. Environmental conditions at presently reported Late Devonian localities were clearly not favorable to the majority of Middle Devonian derived clades. The cosmopolitan Frasnian camerate taxa discovered to date were extinguished by the Hangenberg extinction event, only to be eventually replaced by the descendants of Middle Devonian taxa millions of years later. It is possible that the crinoids survive only elsewhere in unpreserved depositional settings, possibly including deep-sea environments. The lack

of taphonomic preservational conditions, critical for identifying most crinoids, could offer a possible explanation. Additionally, the challenge of discovering crinoids in the massive Frasnian sandstone and siltstone beds of New York and similar Upper Devonian facies elsewhere could provide a partial explanation. Finally, it is also possible that “stealth” Middle Devonian taxa were present in very low numbers at known localities and simply were either not preserved or are as yet to be discovered.

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ORAL

LATE DEVONIAN TO EARLY CARBONIFEROUS INTERVALS (D/C TRANSITIONS) FROM MONGOLIA: INSIGHTS FROM TWO DIFFERENT TERRANES

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The Central Asian Orogenic Belt (CAOB) is the world's largest Paleozoic accretionary orogenic belt, which has evolved over 800 million years from Neoproterozoic time until the Cenozoic. Mongolia lies in the center of the CAOB, which is composed of a large number of different terranes. Mongolia is divided into a northern and southern domain by a Main Mongolian Lineament. Mid-Paleozoic deposits cover a huge area south of this lineament. In the frame of a several years-lasting collaboration undertaken by a working group of IGCP 580 and IGCP 596, three different Devonian/Carboniferous intervals have been studied in western and southern Mongolia.

The Hushoot Shiveetiin Gol site is located in Baruunhuurai Terrane of the Central Asian Orogenic Belt (CAOB), which ranges from the Famennian to the Lower Mississippian and is composed of primarily siliciclastic rocks including thin layers of calcareous rocks and volcanoclastics. Conodont biostratigraphy of the section ranges from the *Palmatolepis minuta minuta* conodont Zone to at least the *Palmatolepis rugosa trachytera* Zone. Due to the facies setting, hiatuses of several conodont

zones occur. Nevertheless, due to lithological comparisons with other sections in the vicinity it seems likely that thick sandstones in the uppermost part of the section represent the Lower Mississippian rocks. Eight facies types were recognized in the Hushoot Shiveetiin Gol site, which ranges from shallow intertidal to open marine palaeoenvironments. The facies setting was characterized by coeval subaerial volcanism resulting in numerous pyroclastic deposits. The depositional environments and intense volcanic activity at the section limited the stratigraphic distribution, abundance, and diversity of many faunal elements, such as brachiopods and microvertebrates. The latter ones show low diversity, yet are abundant in distinct layers of the section, whereas ostracods are very abundant and diverse through many parts of the section. The diverse ostracode assemblage of this section is remarkable.

Deposits of the Devonian/Carboniferous transition of the Bayankhoshuu Ruins section in southern Mongolia likely occurred on either the Mandalovoo or Gurvansayhan Terrane. In contrast to the western section, this section exposes mainly deep-water (hemipelagic and pelagic) deposits

composed of limestones, siltstones, and chert. The marine sedimentary succession is interjected by volcanic rocks, basaltic lava, and volcanoclastic bentonite and tuff of remarkable thickness. Shallow-water sediments are less frequent. It is interesting to note that the intense volcanic activities were observed starting in the Givetian, through the entire Frasnian and Famennian. Evidence of both subaerial and submarine volcanism occurs by several meters of thickness pyroclastic ash and pillow basalt, and the section has experienced greenschist-facies metamorphism and hydrothermal alteration [5] which is consistent with the tectonic setting of an island arc with intensive volcanic activity during Middle-Late Devonian. The overall facies suggest an island arc setting with intensive volcanic activity during Middle-Late Devonian. Prolonged volcanic activity particularly in the Late Devonian is reported from many places around the world and has been suggested to be a driver of ecological collapse at the D/C boundary (e.g., [1, 2, 3, 4]). The stratigraphy of the Bayankhoshuu Ruins section was improved based on a few findings of radiolarians and conodonts, but more data are necessary for a better biostratigraphic record.

In the summer of 2022, the working group measured the two Mid-Paleozoic sections in detail in the Shinejinst region of

southern Mongolia. We have found a number of new things, e.g., coral/stromatoporoid biostroms and bivalve biostroms in Early Devonian, and mapped ~50 volcanoclastic layers in Middle-Late Devonian. The talk aims to contribute to a better understanding of Paleozoic rocks within the critical period of Earth's history around the D/C boundary in different facies settings. Furthermore, we present new sedimentological and biostratigraphical data within the Paleozoic Terrane scheme for Mongolia, an area for which few details are known so far in terms of biostratigraphy and sedimentology.

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POSTER

DIVERSITY AND BODY SIZE TRENDS OF DACRYOCONARIDS ACROSS THE LATE DEVONIAN PUNCTATA EXCURSION, APPALACHIAN BASIN

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Introduction: Dacryoconarids are an extinct group of marine microfossils that were abundant and globally distributed during the Devonian Period. Climate instability during the Late Devonian caused a sharp decline in their diversity and eventual extinction in the early Frasnian stage (~383–375 Ma) [1, 2]. Dacryoconarids exhibited concomitant body size reductions [3], however, it is not certain if this was due to abiotic factors related to environmental degradation driving a true reduction in size (Lilliput effect) or biological reorganization favoring smaller species. This study examines the diversity and size dynamics of dacryoconarids in the northern Appalachian Basin across the globally recognized *punctata* positive carbon isotope excursion during the Frasnian [4]. The adult conch and embryonic chamber volumes of dacryoconarids were measured from consecutive shale-bearing units representing the upper Moscow through West Falls groups at Eighteen Mile Creek in New York.

Results: The family Nowakiidae exhibited slowly declining relative abundance through the late Givetian becoming very rare in the Frasnian. The family becomes locally extirpated prior to the *punctata* event and makes a brief reappearance after the termination of the excursion. The families Striatostyliolina and Styliolina co-occur throughout. Dacryoconarids altogether disappear at the Rhinestreet-Angola contact and exhibit a brief last occurrence several me-

ters up in a narrow window of the Angola shale. Some of the stratigraphic size variations in bulb volume can be explained by diversity, however, a statistically significant reduction in both growth stages coincident with the onset of a negative carbon isotope excursion superimposed on the *punctata* event suggests a causal mechanism. Microtektites in this interval indicate a volcanic origin of depleted carbon and a possible environmental driver. The gradual decline in the assemblage scale adult body size through the early Frasnian is consistent with warming trends at similar paleolatitudes inferred from oxygen isotope trends derived from conodont apatite [5]. This suggests a potential thermally driven mechanism, such as the Temperature Size Rule [6], behind declining body sizes. Other geochemical proxy evidence for productivity and anoxia in the Appalachian Basin [4, 7] are being explored as additional drivers of the observed changes.

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POSTER

KEY STRATIGRAPHIC MARKERS IN THE LATE DEVONIAN NORTH AMERICAN SEAWAY: TOWARD A CHEMOSTRATIGRAPHIC FRAMEWORK FOR CORRELATION IN MUD-DOMINATED BASINSRemirez, M. N.,¹ Gilleaudeau, G. J.,¹ Elrick, M.,² Algeo, T. J.^{3,4,5}

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Introduction: Throughout many ancient intervals of greenhouse climates and resulting high sea levels, stable cratons were flooded, leading to the formation of large shallow epeiric seas. Although modern analogues of these settings are rare, they constitute a significant proportion of the preserved sedimentary record, providing valuable insight into Earth's history prior to the Jurassic Period. Therefore, the reconstruction of fundamental characteristics of ancient epeiric seas, including depth, bathymetry, hydrography, restriction, water circulation, watermass chemistry, redox, and salinity, is crucial to understand the environmental context of many ancient sedimentary deposits. Such reconstructions are critical for enhancing our knowledge of Earth's environmental history and advancing the field of sedimentary geology, but also is crucial for a broad and deep understanding of life's evolution. Epeiric seas often comprise large areas dominated by mudrocks with limited facies diversity, rendering traditional techniques like conventional lithosequence stratigraphy challenging to apply. The lack of proper sequence stratigraphic context as well as limited biostratigraphic control hinder our ability to correlate mud-dominated epeiric sea deposits. In the present contribution, we provide a detailed geochemical (Zr, Zr/Rb, Mo, and U) and sedimentological characterization of six cores from the Illinois Basin that allowed us to establish a sequence stratigraphic and basin evolution model that we correlated to 50 wells across the basin using gamma-ray logs. From this model, we extrapolated the key stratigraphic markers to ten cores and outcrops from the Upper Devonian Appalachian, Iowa, Anadarko, and Permian basins, which allowed us to define evolutionary patterns for each basin. This craton-wide integration creates identifiable and correlatable stratigraphic markers that allows for the correlation of epeiric sea deposits that can be used for climatic and paleoenvironmental reconstructions.

Illinois Basin model and extrapolation: Our results suggest that during the Late Devonian, Illinois Basin mudrocks were deposited in three overlapping stages (one aggradational-progradational, one progradational, and one retrogradational sequence). Upon initial flooding of the basin at the base of the Stage I, the Frasnian interval was characterized

by highstand deposits in a restricted basin with a relatively steep bathymetric gradient. A second transgression (Stage II) was then recorded immediately following the Frasnian-Famennian boundary (FFB), followed by a second stage of highstand deposits in a broader, shallow epeiric sea. Lastly, the mid-Famennian interval (Stage III) was characterized by progressive sea-level rise (a third transgression) and the full inundation of the basin, which continued to nearly the top of the sequence. Furthermore, we identify four anoxic pulses characterized by increase in redox proxy enrichment factors and increases in API units in gamma-ray signals during deposition of the Upper Devonian mudrocks: the first upon initial flooding of the basin in the Frasnian, a second in the middle of the Frasnian (Stage I) likely not associated with sea-level change, the third upon sea-level rise immediately following the FFB, and the fourth within a general retrogradational context in the mid-Famennian. These key markers were also recognized in the adjacent Iowa and Appalachian basins, and a similar reconstruction was made. More broadly, in the Anadarko and Permian basins, we identified the key markers but the general trends are slightly different which, nevertheless, was not an obstacle for correlation. The recorded trends provide evidence for substantial eustatic fluctuations controlling the sequence stratigraphic architecture and development of anoxia in the Late Devonian epicratonic basins of North America.

Paleoenvironmental reconstructions based on chemostratigraphic correlations: Based on a detailed facies association analysis, we reconstructed the environmental variations across four time slices using described correlations across the North American Seaway, demonstrating that the development of anoxic conditions is restricted to certain time intervals. Moreover, we showed significant variation in the mud-size components of different mudrocks across the basins, which highlights the importance of unravelling the origin of the sediments for a better understanding of the sedimentary processes involved in mud delivery in large ancient epeiric seas. Finally, we were also able to tie some of the anoxic pulses to key biotic crises of the Late Devonian, e.g., the Rhinestreet, Upper Kellwasser, and Enkeberg events. Overall,

this study provides a novel and integrated chemostratigraphic framework for the Late Devonian North American Seaway and will serve as an example of using key geochemical signals

for correlation and paleogeographic reconstruction in ancient mud-dominated epicritic seas.

POSTER

A UNIQUE OCCURRENCE OF SCHIZOPHORIA (KING, 1850) IN LOWER GIVETIAN STRATA OF EASTERN NY

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A unique occurrence of the brachiopod *Schizophoria* King, 1850 occurs at several localities in the lower Givetian strata in eastern NYS [1]. A preliminary examination of the brachiopod was undertaken to attempt to determine what species are present in eastern New York. Goldring [2, 3] listed *Schizophoria* cf. *striatula* (Girty, 1900) from Albany and Greene counties. From this, we examined descriptions of *Schizophoria striatula* from various occurrences in eastern North America. Some occurrences for this species were reported from Upper Devonian strata [4] in the Appalachian Basin. Middle Devonian reports of *Schizophoria* are most abundant from the Michigan Basin. Stewart [5] reported this species, along with a smaller variant she named *S. striatula* var. *parvum* (Stewart, 1927), from the Silica Shale of northwestern Ohio. *Schizophoria striatula* was also reported from the Illinois Basin by Kindle [6] who listed this species from the Sellersburg Limestone of southern Indiana, possibly from the Eifelian Stony Hollow-equivalent Speeds Member. A single report of this species from Middle Devonian strata of the Appalachian Basin was made by Prosser et al. [7] from rather poorly preserved material from the Romney Formation in Maryland, which is also possibly from Eifelian Stony Hollow-equivalent strata of the Purcell Member.

Imbrie [8] made a thorough study of Middle Devonian brachiopods from the Michigan Basin, specifically from northern Michigan and northwestern Ohio. In that work, Imbrie redescribed Stewart's specimens of *Schizophoria striatula* and *S. striatula* var. *parvum* from the Silica Formation as a new species, *S. ferronensis* (Imbrie, 1959), aligning these specimens with those he collected from coeval strata of the Ferron Point Formation of northeastern Michigan. Imbrie [8] also redescribed *S. striatula* var. *traversensis* (Grabau, 1931–1933), originally described by Grabau [9] from the Middle Devonian Genshaw Formation of northeastern Michigan as the species *S. traversensis* (Imbrie, 1959). Kesling and Chilman [10] reported *S. ferronensis* from the Silica Shale at several localities in northwestern Ohio and southeastern Michigan, noting that specimens are found in the lowermost portions of the forma-

tion and in a bioherm in the upper portion of the formation.

Stigall Rode [11] conducted the most recent examination of species of the genus *Schizophoria* from the Devonian of eastern North America. In this work, she synonymized various species of *Schizophoria* along with redescribing various forms from across the Iowa, Illinois, Michigan, and Appalachian basins. In this report, Stigall Rode mentioned *S. striatula* in a discussion on the paleoecology of *Schizophoria* but did not list it as a recognized species in her list of the genus, though she did include *S. ferronensis* and *S. traversensis*. Recent correspondence with Alycia Stigall indicates that the omission of *S. striatula* from the species list of *Schizophoria* from eastern North America was the result of too few specimens having been examined during the study and that *S. striatula* is still viewed as a valid species of *Schizophoria*.

Due to a lack of specific details of the morphology of *Schizophoria striatula*, being unable to examine the type material or find detailed descriptions, we have made a comparison to the detailed morphology described by Imbrie [8] for the two major species erected from this species from coeval strata in the Michigan Basin. We collected specimens *Schizophoria* from near Westerlo in Albany County and Lapla in Ulster County from what we interpret to be the upper *Schizophoria* fauna interval. Our correlations indicate that the *Schizophoria*-bearing strata in eastern New York are from: (1) upper Mount Marion strata correlative with the regression of the Solsville Member in central New York—lower *Schizophoria* fauna interval; and (2) strata in the interval proximal to basal Panther Mountain strata coeval with the regression to initial transgression associated with the Morrisville Station to Mottville members of the Oatka Creek and Skaneateles formations, respectively—upper *Schizophoria* fauna interval. In relation to the specific stratigraphic level of the Michigan Basin specimens to which comparisons were made, current understanding indicates that the basal strata of the Silica Formation in northwestern Ohio and southeastern Michigan correlate to the basal Panther Mountain Mottville-equivalent interval and specimens from the Ferron Point and Genshaw formations in

northeastern Michigan are correlative to lower Skaneateles/lower Panther Mountain strata [12]. Because no other occurrences of *Schizophoria* are known from eastern North America in strata equivalent to the Oatka Creek-Mount Marion interval, we are only able to make comparison to specimens from Skaneateles-Panther Mountain equivalent strata.

We measured specimens of *Schizophoria* from the upper *Schizophoria* fauna interval in eastern New York from Lapla in Ulster County for width, length, and number of ribs per given width on the exterior of the shells for comparison with descriptions from Imbrie [8] and Stigall Rode [11] of *S. ferronensis* and *S. traversensis* from the Michigan Basin. From the data, it appears that specimens of *Schizophoria* from eastern New York from the upper *Schizophoria* fauna interval are rather large overall, with some variation in size from ~30 mm to > 40 mm in width, and all specimens examined have the same number of exterior ribs/mm, no matter of size of the specimen. Comparing this data to the descriptions of coeval Middle Devonian *Schizophoria* from the Michigan Basin, it seems as though our eastern New York specimens are either in between *S. ferronensis* and *S. traversensis* in size or about the same size as *S. traversensis*. However, they have distinctly fewer external fine ribs than those found in Michigan Basin spe-

cies. We also note that our large specimens are very similar in description to those of *S. striatula* from Clarke and Schwartz [4] from the Upper Devonian of Maryland. Based on these differences it does not seem possible to assign our specimens to either *S. ferronensis* or *S. traversensis*. As our specimens most closely resemble *S. striatula* from the Upper Devonian of Maryland, we will deem it best to refer *Schizophoria* from the Middle Devonian of eastern New York to *Schizophoria* cf. *striatula* as per the nomenclature of Goldring [2, 3] until such time as an examination of specimens assigned to *S. striatula* can be examined.

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ORAL

BASAL EMSIAN GSSP—POSSIBILITIES IN THE PRAGUE SYNFORM

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Introduction: The basal Emsian GSSP defined in the Zinzil'ban Gorge in the Kitab State Geological Reserve (South Tien-Shan, Uzbekistan) is based on FAD of conodont *Polygnathus kitabicus* Yolkin et al. [1]. According to subsequent detailed correlations with Mauro-Ibero-Armorican, Rheno-Ardennan, and Barrandian faunas, it lies far below the base of the classical Emsian in German sense [2]. At the same time, the current GSSP correlates with a level in the lower half of the Praha Formation [2, 3]. But, the Pragian Stage has been originally devised to correspond entirely to well lithologically and biostratigraphically confined Praha Formation (i.e. “the original Pragian”), and, similarly as the Lochkovian Stage, it has been defined in the Prague Synform (Barrandian area, Czechia) (see e.g., [4]). These traditional Bohemian (Hercynian) stages represent classical megasequences which are characterized by significant environmental turnovers, e.g., [5, 6, 7]. Historically, P. Carls and J. I. Valenzuela-Ríos demonstrated (in materials submitted to the Subcommittee on Devonian Stratigraphy—SDS/ICS) that the present boundary GSSP is much older than the formerly used German Siegenian-Emsian boundary and, that it correlates with middle parts of the traditional Early Siegenian (= approximately lower part of the Praha Formation). According to conodonts, the present GSSP corresponds to the middle of F.I. 5 in Nevada [8], which is close to faunal horizon COP II 295' [9]. This horizon coincides with the highstand of global T-pulse Ia and is older than T-pulse Ib of [10], e.g., [2, 11, 12]. These arguments started a long discussion and doubts concerning the current basal Emsian GSSP, but following attempts to find a new appropriate level by repeated resamplings for GSSP redefinition in the Zinzil'ban Gorge section did not yield promising results. In 2019, the SDS decided to search for alternative section for the replacement of the basal Emsian GSSP. The most promising candidates seem to be located in the Spanish Central Pyrenees and in the Prague Synform.

Prague Synform: Lower Devonian successions in the Prague Synform were extensively studied for conodont biostratigraphy as well as paleontological, sedimentological, geochemical, and petrophysical record, e.g., [4, 6, 7, 13, 14, [5] and references therein. [13] summarized the conodont data from the Early Devonian from the Prague Synform and provided the most recent conodont zonation in this area. They proposed the *gracilis* Event as the alternative marker approxi-

mately corresponding to the traditional boundary between originally defined Pragian and Emsian stages. The team concentrated on the Pragian-Emsian sections in the Prague Synform to obtain large biostratigraphical, geochemical, and petrophysical datasets. The Bohemian Graptolite Event (BGE) is a representative correlation horizon in the upper parts of the Praha Formation with a great potential for future redefinition of the Basal Emsian global stratotype (GSSP) also because of close entries of conodont taxa *Polygnathus excavatus excavatus* Carls & Gandl and *Latericriodus bilatericrescens gracilis* Bultynck, which might be critical for potential definition of new basal Emsian GSSP.

Sections and data: With regard to presence of the BGE with good accessibility and diverse sedimentology, the most eligible are Pod Barrandovem, Mramorka Quarry, and Požár 3 Quarry sections. These sections were sampled for microfacies study and faunal content: conodont samples in dense intervals, sampling of available microfauna and macrofauna, samples for magnetic susceptibility logs, samples for isotopes $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, samples for INAA geochemical analyses and GRS measurements. In some sections, we also used previously obtained data (from MS and GRS). The microfacies study of the Mramorka section showed an increased dolomitization in studied interval of the uppermost part of the Praha Formation. New conodont material obtained enabled more precise recognition of the *steinachensis beta* – *brunsvicensis*, *brunsvicensis* – *celtibericus* and *celtibericus* – *gracilis/excavatus* zones. Bulk carbonate samples from the Mramorka, Požár-3, and Pod Barrandovem sections have $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in the range of -10.45 to -2.08‰ V-PDB and -1.43 to 2.43‰ V-PDB (N = 175), respectively. The $\delta^{13}\text{C}$ values show a marked increase within and/or close above the BGE interval in the Mramorka and Požár 3 sections. The isotope record also correlates with the estimated BGE equivalent in the Pod Barrandovem section. GRS measurements have been already evaluated in all three studied sections and MS samples have been measured. The contents of radionuclides 40K (expressed in %), ^{238}U , ^{232}Th (expressed in ppm) and total natural gamma-ray (tot eU expressed in ppm) were determined. The studied sections show similar GRS patterns around the BGE. The most promising section for the prospective GSSP redefinition will be presented.

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POSTER

GEOLOGIC CROSS SECTION A-A' FROM GENESEE COUNTY, WESTERN NEW YORK, TO LYCOMING COUNTY, NORTH-CENTRAL PENNSYLVANIA, SHOWING THE REGIONAL STRUCTURAL AND STRATIGRAPHIC FRAMEWORK OF THE ALLEGHENY PLATEAU AND VALLEY AND RIDGE PROVINCES IN THE NORTHERN APPALACHIAN BASIN

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Introduction: In 2019, the U.S. Geological Survey (USGS) published geologic cross section A-A' that runs from northwest to southeast from Genesee County in western New York, through Livingston and Steuben Counties in New York, Tioga, Potter, and Clinton counties in Pennsylvania, and ends in Lycoming County in north-central Pennsylvania. It is the fifth in a series of USGS Appalachian Basin geologic cross sections. This geologic cross section is 176 mi (283 km) long, running semiperpendicular to the structural trend of the Appalachian Mountains. Stratigraphic correlations between ten wells were based on gamma-ray well logs, core, and mud log records. Previously published geologic cross sections, stratigraphic correlation charts, and exploration reports for oil, gas, and coal were also used to interpret the structural and stratigraphic relationships of the study area. Several new cross sections in this series are currently under construction for locations in Alabama.

Cross section A-A' displays several important structural features including: (1) crystalline basement rocks in a homocli-

nal ramp that dips gently from the interior craton to the external margin of the fold-and-thrust belt, (2) normal faulting of crystalline basement rocks in the Rome trough and adjacent horst blocks, (3) numerous normal faults that extend from basement rocks up through Paleozoic rocks and were reactivated at least once during the Paleozoic to produce renewed subsidence and (or) small-scale inversion, and (4) large-scale thrust faults with basal detachment in Silurian, Ordovician, and Cambrian strata, and associated ramp foreland-vergent thrust faults that extend northwestward from Pennsylvania into New York. The cross section provides information about the structural and stratigraphic framework that can be used for exploration of energy resources (e.g., coal-bed methane in Pennsylvanian coal beds, and shale gas in the Ordovician Utica Shale and Devonian Marcellus, Rhinestreet, Dunkirk, and other shales); potential CO₂ storage reservoirs in sandstone, salt, and carbonate formations; and the dynamics of fluid flow in the northern Appalachian Basin.

ORAL

THE QUEST FOR THE DEVONIAN MAGNETIC FIELD: AN UPDATE

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The search for high-quality Devonian paleomagnetic data has been occupying paleomagnetists for nearly half a century, but acquiring accurate data from this time period remains problematic to this day. The lack of data has been traditionally interpreted as caused by pervasive overprinting during the late Carboniferous to Permian. Overprinting is indeed a common problem, but an overprinting mechanism is sometimes lacking. The absence of high quality paleomagnetic data in this time period prevents the understanding of the behavior of Earth's magnetic field in this key interval for Earth evolution, and hampers the use of paleomagnetism as a tool for dating and correlation. A recurring observation in Devonian paleomagnetism is that magnetizations are often extremely weak, sometimes below the sensitivity limits of traditional magnetometers. This makes them effectively un-

measurable with standard techniques. I hypothesise that scarcity of Devonian paleomagnetic data does not reflect a lack of dedicated effort or community interest, but is an intrinsic manifestation of a significant natural process not yet clearly identified or adequately understood.

Measurements of the strength of Earth's magnetic field show that the Devonian magnetic field was likely as weak as that of the Ediacaran. A weak magnetic field might have poorly protected Earth's atmosphere, and in this way could have influenced the biosphere. The drivers behind a weak field in the Devonian are still poorly understood, and more data are urgently needed. I will give an overview of the present status of paleomagnetism research in the Devonian, the hypotheses that are currently being investigated and outline the challenges for the coming years.

ORAL

NORTHWEST THINNING OF FAMENNIAN BEDS IN WESTERN NEW YORK STATE

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Famennian beds south of Buffalo in western New York State thin to the northwest and dip generally westward, unlike the older Devonian and Silurian beds in New York that dip generally southward. The unexpected shift in dip direction of these Famennian beds, particularly the interval from base of the Dunkirk Member to base of the Laona Member (both within the Canadaway Formation), has hindered geologic recognition of the continuity of beds such as the Laona that lie above the Dunkirk. The shift in dip direction is neither abrupt nor lacking in explanation; it's an inevitable geometric result of stacking northwest-thinning beds onto the older/deeper Devonian and Silurian beds that dip southward. The northwest thinning, in turn, is clearly demonstrated by outcrop and well log data but not fully understood; it needs further investigation.

The present study area, wherein the Famennian beds thin to the northwest and dip generally westward, spans southern Erie County, northern Cattaraugus County, and northeastern Chautauqua County, New York. North of this study area, the Famennian beds have either pinched out or been erosionally removed. In other directions, the trends described here are not yet fully investigated. The study area itself is part of the Allegheny Plateau, highly dissected by valleys and gorges wherein the Famennian beds have been erosionally removed.

Evidence: Outcrop in the South Branch gorge of Cattaraugus Creek provides key evidence that the Laona Member continues farther east than [1, 2, 3] and others have recognized. Despite their assumption that the Laona dips southward and their conclusion that the Laona cannot be reliably traced east of Perrysburg, New York, they possessed at least part of the evidence that shows otherwise. Buehler & Tesmer's three main Laona outcrops in Perrysburg (42.4905°, 79.0338°; 42.4895°, 79.0164°; 42.4707°, 78.9915°) lie essentially on a line that can be projected southeastward to the South Branch gorge (42.4208°, 78.8807°) where the Laona, unrecognized by them, is found high on the cliff wall (Fig. 1). Such southeastward projection of elevation above sea level (or elevation above base of the Dunkirk, as inferred from well logs such as 31-009-20369) confirms the northwest thinning and points to the approximate Laona elevation near the top of the South Branch gorge wall.

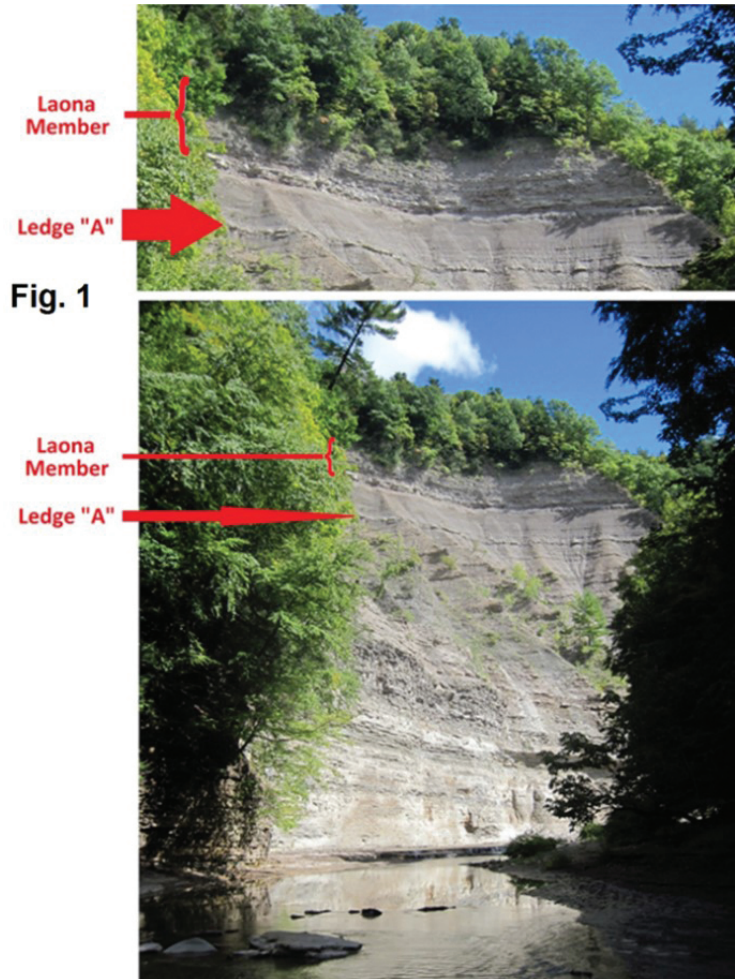
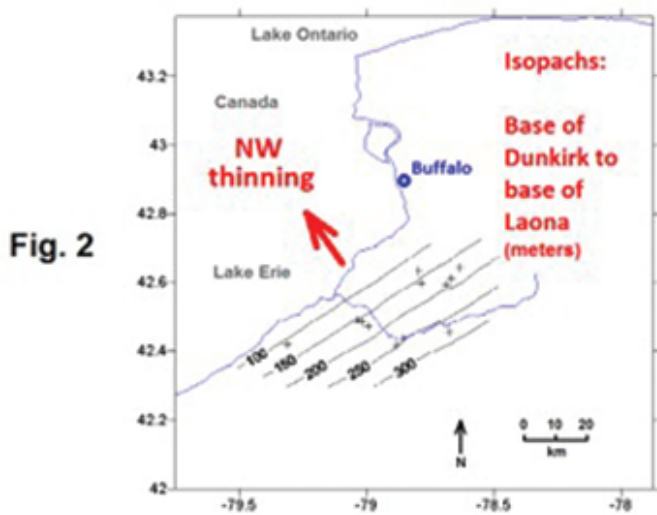


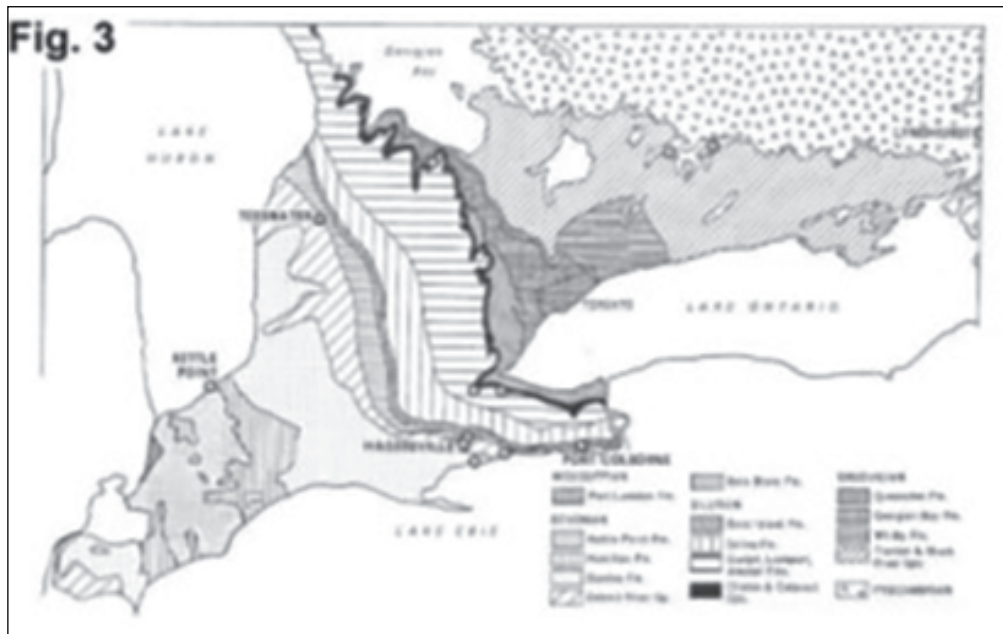
Fig. 1

Additional evidence within the same gorge comes from both the identification by [4] of the Corell's Point Goniatile Bed at 42.4126°, 78.8878°, 294 m elevation, and, immediately upstream, the brink of the South Branch waterfall, which is an analog of the Lamberton Falls Bed identified by Baird. Eastward projections from their respective type localities show substantial thickening consistent with the overall northwest thinning of these Famennian beds. Far more evidence of northwest thinning is found in well logs.

Results: Fig. 2 shows isopachs of the interval between base of the Dunkirk and base of the Laona. Detailed listings of the data points cannot be presented here due to space



limitations. Note the northwestern thinning of ~ 7 m/km shown by the isopachs. Such thinning, if projected into Lake Erie, shows full pinchout of the beds between the base of the Dunkirk and base of the Laona. Approximately 30 km inland, these Famennian beds range up to 250 m thick, yet within the footprint of the present-day lake, they apparently thin to zero. Does this mean that the eastern basin of Lake Erie is at least partly a nondepositional feature rather than an erosional feature? A direct answer is difficult because the beds in question are entirely or almost entirely gone, due to nondeposition and/or erosion, from the footprint of the lake and immediate lakeshore area. Indirect evidence, as in Fig. 2, might thus be helpful.



The work summarized here has generated many measured sections within the study area. The work is locally important as a bridge between the stratigraphic characterizations west of the present study area by Baird and east of the study area by Jacobi. Within the study area, additional work on depositional facies, geochemical and radiometric correlations, and conodonts and other fossil evidence would be useful.

In addition to its local importance, the work presented here could be of broader interest in understanding the Appalachian and Michigan basins, the origin of Lake Erie, and the bedrock geology—including configuration of the Niagara Escarpment—on the Canadian side of Lake Erie. The stratigraphic/structural patterns in Fig. 3, adapted from [5], are certainly influenced by the Algonquin Arch, and flexure of this arch could relate as well to the northwestern thinning found within the present study area.

Conclusion and potential tests: The work presented here sets forth a reinterpretation of the Famennian stratigraphy within the study area. If tests are needed to demonstrate its validity, one such test involves the “Ledge A” siltstone bed shown in Fig. 1. This bed exhibits lateral continuity across the study area while remaining a proportionate distance below the Laona. Similarly, the author’s identification of the Corell’s Point Goniatile Bed at $\sim 42.5898^\circ$, 78.6845° , 393 m elevation, fits the reinterpretation in terms of continuity and proportionality but would not otherwise be an expected location for the goniatile bed. Overall, the reinterpretation’s recognition of northwestern thinning leads to the various local effects and regional implications described here.

References: [1] Buehler, E. J., and Tesmer, I. H. (1963) *Bull. Buffalo Soc. Nat. Sci. (BBSNS)*, 21. [2] Tesmer, I. H. (1975) *BBSNS*, 27. [3] Meyers, M. J. (1999) *NYSGA Guidebook*, F2–F6. [4] House, M. R. (1967), in Oswald, D. H. ed., *Intl. Symp. on Devonian System*, 1066. [5] Roberts, A. (1988) *BBSNS*, 33, 284.

ORAL

THE DEVONIAN TERRESTRIAL SYSTEM IN NEW YORK STATE

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Late 18th to early 19th century reports on the rocks of the Catskill Mountains in eastern New York were followed by over 180 years of scattered geological and paleobiological studies of the Devonian terrestrial succession, in the state and up and down eastern North America. Yet, nearly 230 years later these estimated ~2.4 km (1.5 mi) thick, homogenous strata of the Catskills region in New York largely remain an unknown frontier [1].

The Catskills terrestrial succession is lower Givetian (upper Marcellus-correlative) to an unknown position in the (upper?) Frasnian. Strata are fluvial-dominated, chiefly characterized by sandstones and shales and mudstones, largely deposited in fluvial channels and flood plains, respectively. Conglomerate increases upward through the succession. Relatively rare CaCO_3 occurs as cement locally, as small nodules which locally amalgamate to form hardpan limestones, and rare freshwater lacustrine/palustrine limestones. Shales range in color from black to dark gray, green, and red, largely reflecting deposition on flood plains in wetlands, and below or above Devonian water tables, respectively. Paleosols are common, sometimes with a pattern of alternating vertic and nonvertic soil development. The overall 2.4 km (1.5 mi) thick Catskill succession appears, low to high, to represent a marine-terrestrial transition zone, and lower to perhaps mid-alluvial plain deposition. Overlying strata deposited during the Devonian are eroded.

Devonian terrestrial research in New York during the last century resulted in two different stratigraphic frameworks. The first, by George Chadwick (1930s–1940s), focused on the Catskill Front to the vicinity of Slide Mountain, highest peak in the Catskills. The second, by Rickard and Fletcher in the 1960s to mid-1970s, attempted to create a broader, more geographically inclusive chronostratigraphic nomenclature throughout the entire Catskills outcrop belt. Recent work indicates that in the field, this latter model, based on thick lithosomes of red and gray rocks and conglomerates, is problematic. It can be seen as representing a “second draft” stratigraphic framework, in need of additional work and refinement. At this time, however, too little remains known to better ground the existing stratigraphy, or to propose a well-grounded alternate stratigraphic framework for the Catskills succession.

Other major foci in the Devonian terrestrial of New York include paleobotany (1950s–today), petrography (1960s–1980s), fluvial systems (1970s–1990s), and terrestrial arthropods (1980s–2000s). Broader paleobiological studies, in part associated with the Red Hill site in northern Pennsylvania,

burgeoned in the 1990s and continue today. Recent Catskills terrestrial research of impact is perhaps largely paleobiological and includes the first complete *Eospermatopteris* (“Gilboa”) tree, mapping of two well-preserved forest floors at Cairo and Gilboa (the former is currently the oldest known fossil forest globally), and increasing research on paleosols.

Difficulties in the research of Devonian terrestrial strata in New York include: (1) the lateral discontinuity of terrestrial facies and the lack of documented, distinctive marker beds for correlation; (2) little biostratigraphic and geochronologic control; (3) extensive cover in sometimes rugged terrain; (4) too few researchers; and (5) a need for greater cross-disciplinary perspectives and communication.

The purpose of recent and ongoing research by the author is multifold. First to systematically gather various data, e.g., event deposits, petrography, detrital zircon dating, and palynological biostratigraphy, top to bottom through the succession, initially in the classic Catskill Front to the vicinity of Slide Mountain, in the “Slide Mountain Wilderness” of the large “Catskill Park.” Second within that succession, to better document depositional history, provenance, and biostratigraphy, and to know the succession more closely. Through this, the larger goal is to test the existing stratigraphic framework and try to ground that stratigraphy in the regional rock record better, or to develop a new stratigraphic framework.

Key issues that remain largely unresolved in Devonian terrestrial strata of New York include: (1) lack of a well-tested, viable, and correlatable stratigraphic framework; (2) a general lack of chronostratigraphic data from palynological/micro-vertebrate biostratigraphy and radiometric ages from altered air fall volcanic tephra beds; and (3) no systematic documentation of the vertical Catskill succession. New advances in numbers 1 and 2 include the introduction of rotatable 3D lidar technology, which penetrates through forest cover and thin soils to show bedrock features, permitting lateral correlation of layers mountain to mountain. In addition, the author has begun to recognize altered air fall volcanic tephra in terrestrial strata; a new project of dating will help to constrain ages of the strata. Other future studies could include lateral, interstate/province comparisons of variations in provenance/drainage evolution along the Acadian (Acadian-Neocadian) Foreland Basin and its subbasin known as the Appalachian Basin, via petrography, detrital mineral dating, and other methods.

Reference: Ver Straeten, C. A. (2023) *Bull. Amer. Pal.*, 407–408.

ORAL

THE DEVONIAN IN NEW YORK AND NORTH AMERICA/LAURENTIA

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Devonian strata in New York State comprised the standard North America section for over 100 years. They remain a significant regional to global reference for correlation and research. Since publication of Rickard's [1] New York Devonian correlation chart, various higher-resolution stratigraphic analyses have been employed, sometimes at bed-by-bed scale. These include sequence-, bio-, event-, chemo-, and other stratigraphic approaches, along with increasingly finer-resolution geochronologic dating of airfall volcanic tephra. Results have led to many new interpretations and insights of the succession.

This talk, based on [1], briefly examines the Devonian in North America ("Laurentia") and New York State. The former includes the United States, Canada, Mexico, and Central America. Devonian history of the continent includes sedimentary aspects, paleobiology, orogenesis, metamorphism, silicic igneous activity, exotic terranes of Mexico and Central America, and Appalachian/eastern Americas Realm faunas that extended into South America.

Devonian strata are widespread around the ancient continent "Laurentia." At that time, the equator was positioned over Laurentia, with New York State and the Appalachian region somewhat north of 30°S latitude. Shallow epicontinental seas covered large but varying portions of the continent over the period. Mountain belts formed on the eastern, northern, and western margins of Laurentia, due to plate tectonic collisions with smaller continental masses/exotic terranes +/- a volcanic island arc.

Through the Early to Middle Devonian, seas in western and eastern Laurentia were separated by a "transcontinental arch," and had distinctly different marine faunas. In the latest Middle Devonian, sea level transgressed over the land barrier of the Laurentian Transcontinental Arch and the Canadian Shield, and those marine faunas mixed, leading to a more global cosmopolitan fauna in the Late Devonian. Anomalous, Early and Middle Devonian Laurentian shallow marine faunas are found in Devonian rocks in Central and South America, which were part of the southern Gondwana continent, interpreted by some to be separated from Laurentia by oceanic water depths at that time.

During the Devonian, eastern Laurentia was an active tectonic margin, related to continent-continent collisions with various terranes/smaller continental masses. The Caledonian, Acadian, and Neocadian orogenies resulted in compressional and some transpressional tectonics, and the uplift of an

extensive mountain belt from eastern Greenland to Alabama and Georgia. Crustal loading of the mountain belt led to subsidence and formation of a retroarc Acadian-Neocadian Foreland Basin. Initially the basin was filled with marine waters. However, massive volumes of synorogenic sediments from the orogen gradually overfilled the basin to above sea level. The resulting lands were the site of some of the earliest forests on Earth, preserved at several sites in New York State, and early forest ecosystems.

Large-scale deformation, seismic activity, and metamorphism in the mountain belt were accompanied by igneous processes, including explosive eruption of felsic volcanic ash and other material, collectively termed "tephra." These explosive Devonian eruptions sent volcanic tephra high into the atmosphere, and easterly winds spread airfall volcanic "tephra layers" across the eastern United States.

Devonian rocks in New York occur at or just below the surface across ~40% of the state (~50,500 km²/19,500 mi²). The strata are generally undeformed and gently dipping, and while often covered by soil, glacial sediments, and vegetative cover, they are visible in natural and man-made exposures. Three relatively thin intervals of carbonates are accompanied by eastward thickening wedges of synorogenic mudrocks, sandstones, and minor conglomerates.

The history of geological and paleontological observation and study of the Devonian in New York began in the late 18th century. The first professional geologists appeared in the early 19th century. Since the advent of the first geological survey of New York State in 1836, the Devonian Period (nearly termed the "Erian Period" for New York's Devonian-age rocks) has been the focus of a great volume of research that continues today.

Strata from all seven stages of the Devonian are preserved in New York, with erosional gaps of small to major significance. In addition to a range of marine facies, nearly one quarter of the entire area of Devonian bedrock in New York was deposited in terrestrial settings. These strata feature the fossils of Earth's oldest known forest ecosystems.

Beginning with the work of James Hall, stratigraphic philosophy in New York has evolved toward a hybrid classification, wherein groups, formations, and bed-level units are largely time-rock/allostratigraphic to occasionally chronostratigraphic, with lithostratigraphy often ascribed to member-level divisions (e.g., Pragian to Givetian strata, middle Lower to upper Middle Devonian). In some intervals, e.g.,

Frasnian strata (lower Upper Devonian), group-level units are time-rock units, and formation-level units within groups are largely lithostratigraphic.

Forty-eight years of research since Rickard's [1] New York Devonian correlation chart permits development of a new, more refined chart (forthcoming), and also permits a

new synthesis of Devonian rocks and fossils in New York, presented in this work of 12 chapters, with additional digital appendices.

References: [1] Rickard, L. V. (1975) New York State Museum, Map and Chart, 24, 1–6, 4 pls. [2] Ver Straeten, C. A. (2023) *Bull. Amer. Pal.*, 403/404, 11–102.

ORAL

SUMMARIZING A DECADE OF DEVONIAN SUBSURFACE MAPPING IN OHIO BY THE OHIO GEOLOGICAL SURVEY

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Introduction: Over the past decade, the Ohio Geological Survey (OGS) extensively remapped the Devonian interval in the Appalachian Basin (eastern) part of the state, research primarily driven by governmental projects assessing the region for carbon sequestration and CO₂ enhanced oil recovery potential. Products of this past work include subsurface maps, cross sections, and curated well log datasets, among other items. In the first part of my talk, I will provide a brief overview of map and subsurface data products available through the OGS (Table 1; inset map in Fig. 1). The second

part of the talk will focus on the lower part of the Huron Member of the Ohio Shale.

Mapping depositional cycles in the lower Huron Shale: The lower Huron consists of repetitively-stacked black and gray shale. These cyclic lithological changes correspond closely to gamma-ray cycles and bulk density variation on geophysical logs (Fig. 1). Eight of these gamma/bulk density cycles can be correlated across the eastern half of Ohio, and were picked in 789 wells across eastern Ohio. Structure and isochore maps for each cycle were created using Kriging and hand-contouring.

The lower Huron represents 2.95–3.6 myr, so the duration of each of the eight cycles likely represents no more than 450 kyr [1]. Therefore maps of these cycles capture extremely precise time slices across a large geographic area, and can be useful for determining the timing of basin structure changes. Reorientation of depositional strike beginning in Huron cycle 3 indicate reactivation of faults associated with the proto-Cambridge Arch and the Akron Magnetic Boundary (#s 1 and 2 on Fig. 1 inset map, respectively). Additionally, a consistent thin zone present in all but one cycle between the Smith Township, Suffield, Akron, and Highlandtown fault systems (#3 and 4 on Fig. 1) could also indicate local-scale structural influence, but further mapping is required to determine the impact of those fault systems.

References: [1] Waid C. B. T. (2018) OGS GN-13, 18 p. [2] Hull, D. N. (1990; rev. 2000 by Larsen, G. E. and 2004 by Slucher, E. M.) *Generalized Column of Bedrock Units in Ohio*, 1 p. [3] Boswell, R. M., and Pool, S. E. (2018) *WVGES* RI-35, 47 p.

Table 1. Devonian maps available from the Ohio Geological Survey.

Unit	Structure	Inochore	Publication
Berea Sandstone	Y	N	PG-5C
Cleveland Shale	Y	Y	PG-6A (structure) PG-6B (isopach)
Chagrin Shale	Y	Y	PG-6A (structure) PG-6B (isopach)
upper Huron Shale	Y	Y	PG-6A (structure) PG-6B (isopach)
middle Huron Shale	Y	Y	PG-6A (structure) PG-6B (isopach)
lower Huron Shale	Y	Y	PG-6A (structure) PG-6B (isopach)
Individual depositional cycles (1-8) in lower Huron Shale	Y	Y	OFM 314–321 (structure) OFM 328–335 (isochore)
Java Formation	Y	Y	OFM 313 (structure) OFM 327 (isochore)
upper Angola Member	Y	Y	OFM 312 (structure) OFM 326 (isochore)
lower Angola Member	Y	Y	OFM 311 (structure) OFM 325 (isochore)
Rhinestreet Member	Y	Y	OFM 310 (structure) OFM 324 (isochore)
Sonyea Formation	Y	Y	OFM 309 (structure) OFM 323 (isochore)
Genesee Formation	Y	Y	OFM 308 (structure) OFM 322 (isochore)
Onondaga Limestone	Y	Y	PG-5B (structure) OFM 360 (isochore)
Oriskany Sandstone	Y	Y	OFM 354 (structure) OFM 359 (isopach)
Helderberg Group	Y	Y	OFM 353 (structure) OFM 358 (isopach)

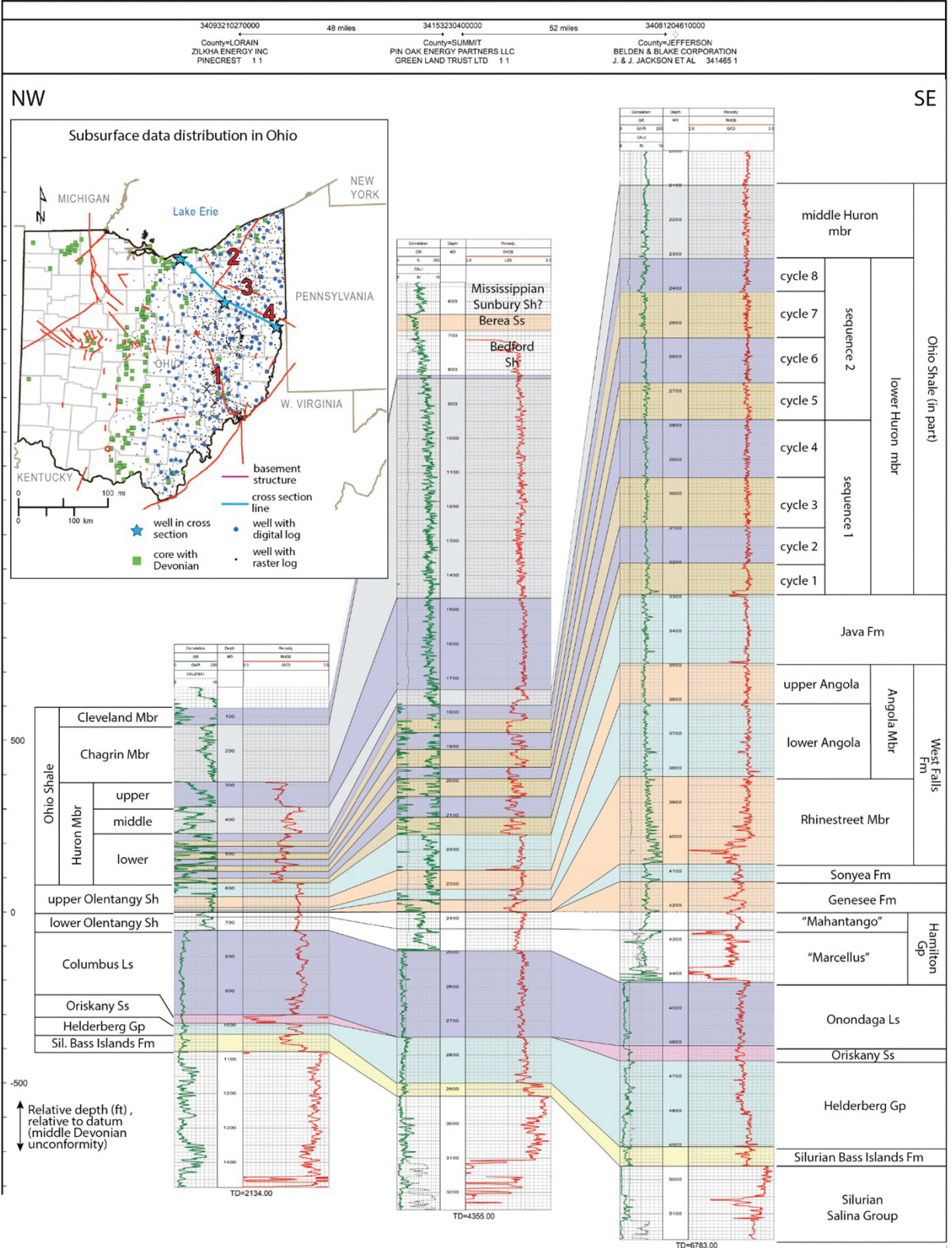


Figure 1. Example cross section showing the Devonian of northeastern Ohio. Color fill indicates units mapped by the OGS. Different colors are used to make correlations easier to distinguish. Stratigraphic terminology based on OGS[1,2] and WVG-ES[3] correlations. Red numbers on inset map referenced in abstract text.

ORAL

THE CENTRAL ASIAN OROGENIC BELT (WESTERN CHINA AND MONGOLIA) WAS A BIODIVERSITY HOTSPOT IN THE LATE DEVONIAN

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Extinction events at the end of the Givetian, Frasnian, and Famennian devastated tropical marine ecosystems and rank in the top ten in taxonomic and ecological severity. The close stratigraphic association between the extinction events and anoxic events, particularly the Kellwasser Anoxic Events and the Hangenberg Anoxic Event, supports a link between oceanographic anoxia and extinction in the Middle and Late Devonian. Faunas from the Central Asian Orogenic Belt (CAOB) demonstrate that central Asia acted as a refugium for marine organisms in the Late Devonian, became a diversity hotspot in the Famennian, and a center of radiation for marine life prominent in the Mississippian.

The CAOB is a Palaeozoic accretionary orogenic belt, which extends from Kazakhstan in the west, through Kyrgyzstan, Uzbekistan, northwestern China, the Altai-Sayan region and Transbaikalia in Russia, Mongolia, and northeastern China to the Russian Far East. The accretionary system includes oceanic island arcs, fragments of Precambrian microcontinents, and collisional and postcollisional complexes as well as continental margin arc terranes.

Late Devonian sediments in Xinjiang Province, China, are part of an accretionary wedge deposited on a Marianas Island type island arc complex and are well exposed at the Boulongour Reservoir and other localities in the vicinity of Hoxtolgay. These are among the very few Famennian localities in the world with richly fossiliferous sedimentary rocks deposited in a shallow marine setting.

The Late Devonian sequence near Hoxtolgay is characterized by an abundant and diversified fossil flora and fauna consisting of acritarchs, spores, radiolarians, sponges, corals, trilobites, ostracods, gastropods, cephalopods, brachiopods, bryozoans, echinoderms (blastoids and crinoids), conodonts, and fish teeth. The biota was very diverse (> 198 genera and 285 species), acted as a refugium for some elements of the fauna, and as a hotspot for rediversification of Famennian and Mississippian marine ecosystems.

Two benthic groups that define the Mississippian are the bryozoans and echinoderms. Crinoids reached their high-

est diversity and abundance in the Mississippian, which has been called the Age of Crinoids. During the Mississippian, crinoids dominated carbonate depositional systems, producing regional encrinites tens of meters thick, extending over hundreds of km². Bryozoans were also abundant and diverse. Bryozoans and echinoderms underwent extensive changes in faunal composition and diversity in the Devonian. Both suffered more significant extinction at the Taghanic Event and Givetian-Frasnian boundary than either at the Frasnian-Famennian boundary or at the Devonian-Carboniferous boundary. Both bryozoans and echinoderms show patterns of significant global rebound in the Famennian. Data suggest that the CAOB was a biodiversity hotspot for both groups.

Biodiversity hotspots are important for understanding how areas of high species richness form, but disentangling the processes that produce them is difficult. Four hypotheses can be offered to explain the biodiversity hotspot in the CAOB. The center-of-origin hypothesis states that more new species originated in the CAOB than surrounding regions. The center-of-accumulation hypothesis states that lineages originating elsewhere preferentially colonized the CAOB. The center-of-overlap hypothesis states that species have widespread ranges that overlap in the CAOB. The center-of-survival hypothesis states that lineages in the CAOB experienced less extinction than those in surrounding regions. These four hypotheses differ in the biogeographic origin of species (within the CAOB, elsewhere, or no prediction), and in the processes ultimately responsible for high richness in the CAOB (colonization, speciation, or extinction).

Differentiating among these hypotheses requires more data than is currently available because the CAOB has not been studied with the intensity of North America or Europe. The CAOB in the Devonian was an amalgam of actively volcanic islands surrounded by oceans with diverse marine ecosystems similar to modern Indonesia.

Recent collections from the Devonian terranes in Mongolia support the hypothesis that the Famennian diversity hotspot extended beyond the arc complexes in Xinjiang Prov-

ince. Lower Devonian coral stromatoporoid biostromes are present at Shine Jinst in the Mandalovoo Terrane, although ongoing volcanic activity limited their geographic and stratigraphic success. Relatively diverse echinoderm communities in the same section document their presence prior to the Middle and Late Devonian extinction events. Sparse collections from Shine Jinst document the presence of survivor Famennian echinoderm communities. The Hushoot Shiveetiin Gol locality in Baruunhuurai Terrane yielded a relatively abundant and diverse Famennian echinoderm community that has

many genera in common with localities in Xinjiang Province, but endemic genera as well.

Echinoderm communities in the CAOB contain taxa that derived from Devonian lineages. However, many taxa represent the oldest members of their lineage and seem to form the basis of the dramatic increase in echinoderm diversity seen in the Mississippian. Although admittedly based on limited data, our current feeling is that the center-of-origin hypothesis best explains the echinoderm communities in the CAOB.

ORAL

DECIPHERING THE ROLE OF TERRESTRIAL/ATMOSPHERIC INTERACTIONS IN LATE DEVONIAN KELLWASSER BLACK SHALE DEPOSITION: A HIGH-RESOLUTION CYCLOSTRATIGRAPHIC STUDY OF THE WINSENBERG SECTION (RHENISH MASSIF, GERMANY)

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The Late Devonian oceans were susceptible to the development of anoxic conditions, as evidenced by repeated widespread organic-rich shale deposition. Understanding how these anoxic facies were deposited will provide insight into Devonian climatic modes. To this end, we constructed a high-resolution cyclostratigraphic model based on portable XRF-generated elemental ratio records from a Frasnian-Famennian (~372 Ma) black shale section. These black shales are associated with the Kellwasser Crisis, one of the largest mass extinctions of the Phanerozoic, which is not fully understood to this day. The studied section at Winsenberg is located in the Rhenish Massif in Germany and represents a basinal setting at southern low paleolatitudes. Spectral analysis was carried out on the SiO₂/CaO ratios generated by XRF, which is interpreted as the detrital (distal) vs carbonaceous (local) input. The resulting astrochronology suggests a duration of ~1 Myr from the base of the Lower Kellwasser black shale to the F-F boundary at the top of the Upper Kellwasser level, or ~900 kyr between the starting points of both $\delta^{13}\text{C}$ excursions. This corresponds to an average sedimentation rate of 0.9 cm/kyr. Both the Lower and Upper Kellwasser shales occur at the onset of a 405 kyr eccentricity cycle. We further interpret the TiO₂/Al₂O₃ record as a riverine runoff signal, because titanium is associated with the coarse-grained fraction, and K₂O/Al₂O₃ as a chemical weathering signal, because potassium is leached easier than aluminium. Both tuned records exhibit eccentricity-modulated precession cycles. The riverine runoff response on precessional and 100 kyr eccentricity timescales is linked to wet/dry cycles controlled by monsoonal climate variations. The chemical weathering signal is antiphased with runoff on these timescales, which can be explained by additional controls (sea-level fluctuations, temperature, mechanical weathering in the hinterland). On 405 kyr timescales, longer wet and dry periods are observed in both riverine runoff

record and chemical weathering signals, which are in-phase on these timescales. Both Kellwasser intervals occur within more arid, but also more fluctuating, climates. In between the two black shales, a stable, humid climate developed. The humidity is evidenced by high runoff rates and high chemical weathering rates, and corroborated by high kaolinite content from XRD analysis. Relatively low variability in all proxy records indicates stable conditions. A long stable, humid period paced by 405 kyr eccentricity that occurs just prior to the Upper Kellwasser event is in line with the ‘eccentricity-minimum hypothesis’ for the Crisis, as postulated by [1]. This hypothesis states that a 2.4 Myr eccentricity node prior to the Upper Kellwasser resulted in the prolonged absence of seasonal extremes, allowing for the build-up of nutrient-rich regoliths on the land that were subsequently eroded away as the Earth came out of the eccentricity minimum and the hydrological cycle intensified once again. This sudden nutrient influx would have led to eutrophication and subsequent anoxia (a ‘top-down’ mechanism for anoxia). The current study suggests an orbital control on the timing of the Kellwasser Crisis. Because Devonian carbon-cycle perturbations did not occur exactly every 2.4 Myr, there must be additional or underlying control mechanisms. Seed plant evolution is a potential candidate of one such mechanism for the Kellwasser Crisis: the timing is consistent and fits with a terrestrial source of nutrients linked to enhanced weathering that is observed at Winsenberg. The influence of widespread volcanism, however, cannot be discounted. Further research will investigate whether this relationship between orbital configuration, Devonian climate, and widespread anoxia holds for subsequent Late Devonian carbon cycle perturbations.

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ORAL

USING $\delta^{13}\text{C}_{\text{TOC}}$ CHEMOSTRATIGRAPHY TO RECOGNIZE DEVONIAN GLOBAL EVENTS IN THE NEW ALBANY SHALE (ILLINOIS BASIN, USA)

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Introduction: A defining feature of the Devonian is repeated global extinctions of varying magnitude [1, 2]. Because these extinctions manifest differently at regional scales, and are studied at varying temporal resolutions and using different techniques (e.g., paleobiology, stratigraphy, geochemistry, etc.), the Devonian literature of these named extinctions applies terms ‘crisis’ and ‘event’ (both sometimes with the prefix bio-) interchangeably when describing these extinctions [1, 2, 3]. Seeking a meaningful consistency for extinction terminology, Walliser [3, see also 4], proposed the hierarchical scheme that multibiozone crises are comprised of (typically) intra-biozone events that could include black shale deposition, sea-level change, carbon-cycle fluctuations, and/or extinction.

Interdisciplinary studies at stratigraphically high-resolution are crucial for applying this ‘events-within-crisis’ framework to understanding the nuances of extinctions globally and regionally. Carbon isotope stratigraphy is a key, and complementary, tool for this approach because carbon-cycle perturbations (excursions) tend to occur within a single biozone or at biozonal boundaries and this tool also serves as a proxy for extinction-causing climate change [e.g., 5].

In carbonate dominated successions, inorganic carbonate carbon isotopes ($\delta^{13}\text{C}_{\text{CARB}}$) provide a relatively reliable record of seawater isotopic composition; organic carbon isotopes ($\delta^{13}\text{C}_{\text{TOC}}$) can also be utilized if some organic matter is present [6, 7]. In contrast, many marine stratigraphic successions of extinctions contain carbonate-poor black shale, and are therefore often not applicable for inorganic carbonate carbon isotopic analysis [e.g., 7]. This can be problematic because the isotopic composition of organic matter at the regional scale is derived from marine sources as well as dissolved and particulate terrestrial organic matter fluxed to marine settings via rivers [8]. In the Devonian, when forests were evolving and progressively colonizing upland settings, terrestrial organic matter and nutrient flux to the marine realm were likely exceptionally variable both temporally and spatially [9].

This study, focused on the black, organic-rich New Albany Shale from eastern Illinois Basin drill cores, combines $\delta^{13}\text{C}_{\text{TOC}}$ analysis of bulk organic matter with elemental proxies for detrital input (Si, Ti, Zr, and K, each plotted as concentrations or standardized to Al; Si serves as a proxy for quartz sand and silt, Ti and Zr proxies for silt, and K a proxy for clay).

In the Devonian greenhouse world, terrestrial organic matter was isotopically heavier (more positive) than marine organic matter [10, 11]. Because terrestrial organic matter and detrital input would both flux to marine settings via rivers, a similar trend in $\delta^{13}\text{C}_{\text{TOC}}$ and detrital input proxies would suggest that the $\delta^{13}\text{C}_{\text{TOC}}$ pattern is recording local changes in marine vs terrestrial organic matter (assuming marine organic matter production and preservation are relatively constant; Fig. 1). Correspondingly, when there is no change in detrital input or when $\delta^{13}\text{C}_{\text{TOC}}$ and detrital proxy trends are opposite, any $\delta^{13}\text{C}_{\text{TOC}}$ trends observed could represent global carbon cycles changes. Combining $\delta^{13}\text{C}_{\text{TOC}}$ analysis of bulk organic matter with elemental proxies for detrital input can therefore be a useful tool for interpreting a $\delta^{13}\text{C}_{\text{TOC}}$ stratigraphic profile in the absence of $\delta^{13}\text{C}_{\text{CARB}}$ data. Confidence in global carbon cycle trends interpreted from $\delta^{13}\text{C}_{\text{TOC}}$ is strengthened when biostratigraphic data is also available, although retrieving conodonts from siliciclastic facies is challenging [7, 12].

Results: A transect of four cores along the eastern Illinois Basin was examined, focusing on late Givetian through early Famennian strata of the New Albany Shale; this interval contains notably high environmental and paleobiological volatility and frequent carbon cycle perturbations [1, 13]. As far as siliciclastic dominated intervals are concerned, there is relatively good biostratigraphic control for this succession [12, 14].

Under the assumptions of the simplified model presented in Fig. 1, $\delta^{13}\text{C}_{\text{TOC}}$ trends were interpreted in the context of detrital input proxy data. In all four cores studied, aspects of the repeated carbon isotope excursion events associated with the Frasnian Crisis were observed in the Blocher Member, although in some cores, it is unclear if the carbon isotope excursions observed were instead associated with the Middlesex and Rhinestreet events due to limited biostratigraphic control. In the overlying Selmier Member, the semichatovae and Lower Kellwasser Events are recognized in the $\delta^{13}\text{C}_{\text{TOC}}$ data, with the Upper Kellwasser Event identified at the base of the overlying Morgan Trail Member.

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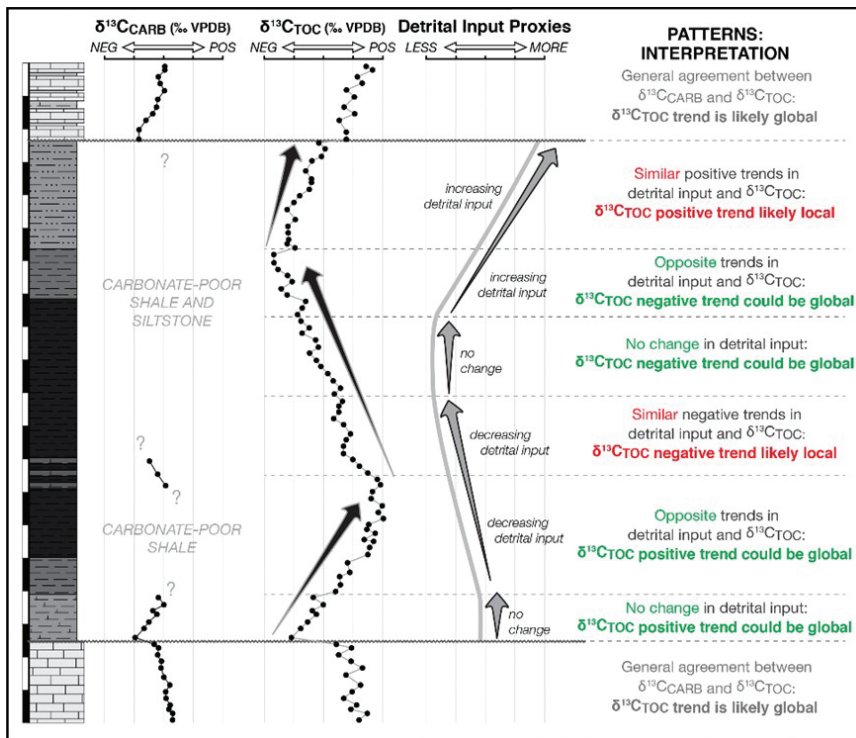


Figure 1: Schematic model for interpreting $\delta^{13}\text{C}_{\text{TOC}}$ trends in the context of detrital input proxies. Red patterns and interpretations indicate scenarios when local terrestrial versus marine organic matter processes are likely controlling the $\delta^{13}\text{C}_{\text{TOC}}$ trend and therefore comparison with global patterns should be avoided. Green patterns and interpretations indicate scenarios when $\delta^{13}\text{C}_{\text{TOC}}$ trends are not related to local terrestrial versus marine organic matter processes and therefore comparison with global patterns can proceed.

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POSTER

INTEGRATED STRATIGRAPHY OF MIDDLE DEVONIAN STRATA IN THE CARGILL TEST #17 CORE (LANSING CORE) OF NEW YORK STATE

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Introduction: The Middle Devonian of New York State is an iconic succession in North America that has contributed key concepts in stratigraphy, sedimentary geology, tectonism, paleoecology, and evolution [e.g., 1–4]. Despite the vast body of previous work, the Middle Devonian of New York is rather poorly constrained chronostratigraphically owing to the relative rarity of conodonts and goniatites. This succession, from oldest to youngest, includes the Onondaga Formation, Hamilton Group, Tully Formation, and the lower portion of the Genesee Group. Within these strata, the Chotec Event has been recognized in the Onondaga Formation [5], the Kačák Crisis and the preceding Bakoven and Stony Hollow Events recorded within the black shale-dominated Marcellus subgroup of the Hamilton [6], and the Taghanic Crisis observed in the Tully Formation and immediately sub- and suprajacent strata [7]. The *pumilio* Events, which are estimated to have occurred during deposition of the upper part of the Hamilton Group, are currently unidentified.

This Study: We have recently undertaken an integrated stratigraphic study of the Cargill Test Core #17 (more commonly known as the Lansing Core) with the goal of better constraining the chronostratigraphy of the Middle Devonian of New York State. This core was drilled in the central New York State town of Lansing (just north of Ithaca), Tompkins County. This drill core provides a nearly continuous record of the entire Eifelian and Givetian stage interval in ~457 m (~1500 ft) of mainly fossiliferous gray mudstone to black laminated shale, with lesser siltstone and limestone facies.

The Lansing Core is located in a depositional setting conducive for this chronostratigraphic project. The core is relatively proximal in the basin so that the overall succession is not condensed and major intervals are not removed by unconformities as seen in more basinward cores [8], yet it is distal enough that carbonate cements conducive for isotopic analysis appear to be present throughout most of the succession. Although some previous studies of the core have been

undertaken, including sedimentological [e.g., 9] and carbon isotope stratigraphy through the Taghanic Crisis [10], the majority of this core has not been studied.

To date, the core has been lithostratigraphically described at a decimeter-scale. A high-resolution magnetic susceptibility dataset has been collected at 1 ft intervals (~1500 analyses) and a total of ~900 sample powders obtained for elemental and isotopic analysis.

Preliminary results indicate that nearly all litho- and allostrostratigraphic units identified in outcrop can be recognized in the core, although there are notable differences in thickness (e.g., Skaneateles Formation is nearly twice as thick as thickest outcrop successions to the north). Much of the core is highly fossiliferous and many of the distinctive epiboles and marker beds have been recognized. Magnetic susceptibility indicates the presence of cyclic alternation at the scale of meters and decameters.

Current and future work includes collection of a cm-scale spectral gamma log as well as carbonate carbon isotopic and pXRF elemental analysis of sample powders. This combined data set will then be used for cyclostratigraphic analysis to identify orbital cycles (precession, obliquity, eccentricity) and to build an astrochronological time scale, allowing the estimation of the pace and duration of the succession of events.

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POSTER

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

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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 CO₂-drawdown due to the evolution of forests during the Middle–Late Devonian (e.g., [1]). 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 glacioeustatic sea-level dynamics operated during the Middle Devonian [2, 3], only Late and end-Devonian evidence for glaciation has been documented [4]. 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 [5–7], especially within the context of local environmental change and tectonics [8, 9].

This Study: We are currently focused on recognizing these events, and reconstructing the environmental change associated with them, in Middle Givetian through Lower Famennian strata of the Michigan Basin. The Michigan Basin is one of four depocenters in the northeastern and upper midwestern United States. 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; 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 [5, 6]. 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 [8]. Conversely, the Middle–Upper Devonian transition from Traverse Group shallow marine carbonates to the Antrim Formation anoxic black shale in the Michigan Basin is unlikely the result of continental-margin tectonism, and more accurately reflects the signal of global environmental change.

The Michigan Basin Devonian succession has a long history of lithostratigraphic study and basin-wide correlation, although 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 [10, and references therein; 11, 12]. Furthermore, Michigan Basin type-section outcrops are rare, stratigraphically short, and generally lack exposure of formation and member contacts. However, a variety of cores exist as a result of active oil and gas exploration [12]; this project is therefore focused 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.

This study is being undertaken through the Keck Geology Consortium, a multicollaboration focused on enriching undergraduate education through development of high-quality research experiences. Potential student research projects as part of this study include sedimentological and microfacies analysis, lithostratigraphy, chemostratigraphy (pXRF, carbon isotopes), magnetic susceptibility stratigraphy, and reconstructing diagenetic history and basin evolution.

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INDEX

- Acadian Highlands 24, 133
 Acadian Orogeny 81
 Acadian-Neoacadian Foreland Basin 122, 123
 Albany County, New York 5, 70, 71, 114
 Alfred Shale Formation 109
 Algonquin Arch 121
 Alleghenian Orogeny 17, 18
 Angarida 10, 89
 Angola Shale Formation 35, 112, 125
 anoxic sediments 9, 23, 31–33, 35, 73, 78–80, 83, 90–93, 100, 106–108, 113, 127, 129, 133
 Appalachian Basin 7, 8, 10, 11, 13–15, 17, 23, 30, 34, 60, 69, 76, 81, 88, 90, 94, 96, 97, 107, 110, 112–114, 118
 Appalachian fold and thrust belt 17, 91, 118, 121–123, 125, 133
 astrochronology 9, 94, 95, 97, 106, 129
 Avalonian fauna 105
 Azrou Formation 67, 68
 Azrou region 7, 67
- Bab-al-Ari Formation 68
 Bakken Formation 90, 91, 98
 Baruunhuurai Terrane 110, 128
 Beaver Meadow Beds 74, 75
 Beaver Meadow Member 23, 25, 27–30, 32–36, 40, 41
 Bedford Shale Formation 69, 81
 Bell Creek Member 92, 93
 bentonite, K 86, 87, 106, 111
 Berea Sandstone Formation 14, 69, 81, 125
Bispathodus ultimus 68
 black shale 3, 6, 7, 9, 11, 23–25, 27–37, 69, 72, 74, 75, 78, 80, 83, 91–94, 96, 98, 100, 103, 106–108, 129, 130, 132, 133
 Bluefish Member 1, 93
 Bohemian Graptolite Event 116
 Bou Ighial Formation 67, 68
 Box Member 109
 Brallier Formation 88
 Briery Gap Sandstone Member 88
 Broken Rib Member 109
 Bromide Formation 18
 burn down oxidation 23, 27, 35–37
- Canadaway Group 25, 43–45, 48, 59, 62, 120
 Canadian Shield 120
 Canol Formation 92, 93
 Carbon isotope excursion 11, 73, 83, 84, 100, 101, 107, 108, 112, 130, 132, 133
 Catskill Delta 24, 44, 90, 104
 Catskill Formation 88, 89
 Catskill Front 122
 Cattaraugus County, New York 43, 45, 47, 50, 57, 120
 Cattaraugus Creek 43, 45, 46, 49, 51, 53, 55, 56, 58, 120
 Central Asian Orogenic Belt 8, 110, 127
 Chadakoin Formation 109
 Chagrin Shale Member 69, 96, 97, 125
 Chatham Sag 60
 Chautauqua County, New York 43, 45, 47, 74, 120
 Chotec Event 132
 Clarendon Linden Fault System 103
 Cleveland Shale Member 69, 81, 90, 96, 125
 Columbus Limestone Formation 81
 conodont color alteration (CAI) index 13–20, 85
 coordinated stasis 76, 77
- Corell's Point Goniatile Bed 45, 51, 52, 56, 58, 120, 121
 Cumberland Sill 90
 cyclostratigraphy 5, 85, 100
- dacryoconarids 11, 67, 112
 Dansgaard-Oeschger variations 95
 Dasberg 69, 90
 diagenesis 20, 23, 33, 72
 Deep Run Shale Member 17
 Denley Formation 18
 Dock Street Clay 109
 Dunkirk Shale Formation 23–25, 27, 28, 30–34, 43–46, 48–50, 52–60, 62, 74, 75, 94, 118, 120, 121
 Dyer Formation 109
- ecological stasis 76
 Eddy cycle 95
 Eifelian 10, 67, 76, 92, 93, 104, 109, 114, 132
 Eifelian-Givetian boundary 93
 Emsian 7, 9, 67, 68, 76, 84, 104, 105, 109, 116
 energy dispersive X-ray fluorescence 26
 Enkeberg Event 90, 113
 epiboles 76, 132
 Erie County, New York 43, 45, 50, 74, 120
- Famennian 3, 6–8, 10, 23, 25, 43, 45, 48, 53, 55, 59–62, 67–69, 72, 81, 85–87, 90–92, 96–100, 106, 109–111, 113, 120, 121, 127–130, 133
 Fe, Fe/Al ratios 23, 26, 27, 31, 33–36, 74, 75, 101, 102
 Ferron Point Formation 114
 Foreknobs Formation 88
 Francis Creek Member 92
 Frasnian Crisis/Event 11, 72, 73, 108, 130
 Frasnian 9–11, 67, 68, 72, 73, 76, 85–87, 89–93, 100, 106, 108–113, 122, 124, 127, 129
 Frasnian-Famennian boundary 6, 8, 25, 59, 60, 72, 90–92, 100, 106, 113, 127
- Genesee County, New York 11, 118
 Genesee Group 88, 132
 Genesee Formation 125
 Genshaw Formation 114
 Georgian Bay Formation 15, 16
 Givetian 7, 9, 11, 17, 67, 68, 70, 72, 73, 76, 84, 92, 93, 108, 109, 111, 112, 114, 122, 123, 127, 130, 132, 133
 Givetian-Frasnian boundary 108, 127
 Gowanda Formation 44, 46, 49, 55, 59, 109
 Grassy Creek Shale Formation 8, 85–87
 Greene County, New York 70, 71, 114
 greenhouse world 113, 130
 Greenland Gap Group 88
- Hagen-Balve Reef Complex 72, 73
 Hallstatt cycle 95
 Hamilton fauna 76
 Hamilton Group 7, 10, 16, 17, 19, 70, 71, 88, 101, 102, 132
 Hangenberg Crisis/Event 9, 69, 79, 83, 90, 91, 100, 109, 127
 Hanover Shale Formation 3, 9, 23–25, 27, 30–36, 74, 94, 95, 106
 Hare Indian Formation 92, 93
 Highlandtown fault system 125
 Hofermühle Reef 72
 Horn River Group 92, 93
 Hume Member (Northwest Territory, Canada) 92, 93

- Huron Member 81, 82, 96, 97, 125
 hyperpycnal flow 23, 29, 30, 33, 36
 hyperpycnite 23, 28–36, 74, 75

 Illinois Basin 9, 15, 24, 85, 90, 113, 114, 130
 internal waves 23, 31, 32
 Iowa Basin 8, 85, 113, 114
 Ireton Shale Formation 15
 Irish Valley Member 88
 Java Group 9, 10, 24, 106, 125
 Jaycox Shale Member 17

 Kačák Episode/Event 9, 93, 132
 Kashong fauna 109
 K-bentonite (see bentonite)
 Kellwasser Crisis/Event(s) Lower/Upper 6, 8–10, 24, 25, 72, 78, 83, 85–87, 90, 94, 100, 106, 107, 109, 113, 127, 129, 130
 kerogen 14, 15, 19, 26, 30
 Kettle Point Formation 45, 47, 60

 Lake Erie 14–16, 43, 44, 47, 49, 51–54, 59–62, 81, 121
 Lamberton Falls Bed 45, 51, 52, 56, 58, 120
 Laona Formation 3, 43–49, 51–55, 57–60, 62, 120, 121
 Late Devonian Biocrises (see Hangenberg)
 Laurentian Transcontinental Arch 123
 Lilliput effect 112
 Lime Creek Formation 85
 Livingston County, New York 5, 17, 118
 Ludlowville Formation 70, 101

 Mackenzie Mountains 9, 10, 92, 93
 Maghrebo-European Realm 105
 magnetic susceptibility 83–85, 94, 106, 116, 132, 133
 Mallow Member 88
 Mandaloochee Terrane 110, 128
 Marcellus Shale Formation/subgroup 70, 81, 101–103, 118, 122, 132
 marine transgression 23, 24, 32, 33, 36, 68, 69, 72, 73, 75, 76, 90, 93, 113, 114
 Meadville Shale Formation 109
 Messinghausen Atoll 72, 73
 Michigan Basin 11, 24, 60, 114, 115, 121, 133
 Middlesex Formation 103
 Middlesex Event/Transgression 6, 73, 130
 Milankovitch cycles 5, 83, 84, 95
 Mo, Mo/TOC 90, 113
 Morgan Trail Member 130
 Moroccan Meseta 7, 67
 Morrisville Station Member 114
 Moscow Formation 17, 101, 112
 Mottville Member 70, 114
 Mount Marion Formation 70, 71, 114, 115
 mudstone thermal maturity 14, 16, 17
 Muscatine County, Iowa 85, 86

 Neanderthal Reef 72
 Neoacadian Orogeny 103, 123
 New Albany Shale 9, 15, 85, 90, 130
 Niagara Escarpment 60, 121
 North Gondwana 104, 105

 Oatka Creek Formation 114, 115
 oceanic anoxic event 80, 83, 108
 Ohio Shale Formation 10, 14, 81, 82, 96, 97, 125
 Onondaga Limestone Formation 48, 59–61, 81, 103, 125, 132

 Ontario County, New York 17
 Orange County, New York 71
otomari Event 93
 Otsego County, New York 70

 paleosols 122
 Panther Mountain 71
 Panther Mountain Formation 70, 71, 114, 115
 Percha Formation 109
 Pilot Formation 109
 Pipe Creek Formation 24, 34, 94, 106
 Point Gratiot Bed 23–25, 27, 28, 32–34, 36, 40, 74
 Pound Sandstone Member 88
 Prague Synform 7, 116
 Praha Formation 116
 Prohibition Creek Member 92
 Pulaski Formation 15, 16
punctata Event/positive carbon isotope excursion 11, 112
 pycnocline 23, 32, 33, 74
 pyrite, pyrite lag deposits 9, 23, 25–28, 30–36, 74, 75, 78, 79, 90

 Ramparts Formation 92, 93
 Rheic Ocean 105
 Rhenish Massif 8, 9, 72, 104, 129
 Rhenish Province 105
 Rhinestreet Event 6, 130
 Rhinestreet Shale Formation 29, 30, 35, 112, 113, 118, 125
 Romney Formation 114

 Scherr Formation 88
 Schoharie County, New York 70, 71
 Schoharie Formation 84
 Sellersburg Limestone 114
 Selmer Shale Member 85, 130
semichatovae Event/Transgression 72, 130
 Silica Shale Formation 114
 Skaneateles Limestone Formation 70, 114, 115, 132
 Sly Gap Formation 109
 Solville Member 114
 Speeds Member 114
 Steuben County, New York 118
 Striatostyliolina 112
 Styliolina 112
 Sweetland Creek Shale Formation 85, 86

 Taghanic Crisis/Event/Transgression 72, 109, 127, 132
 Three Forks Formation 98
 Three Lick Bed 96
 Tompkins County, New York 132
 Tournaisian 7, 10, 69, 89, 98, 99, 109
 Tully Formation 76, 103, 132

 Ulster County, New York 70, 71, 114, 115
 Viluy-Yakutsk Large Igneous Province 89
 Virgin Hills Formation 109
 vitrinite reflectance 13–16, 19, 20, 82

 Walheim Reef Complex 72
 West Falls Formation 81, 82, 88, 112
 Williston Basin 7, 90, 91, 98, 99
 Wülfrath Reef Complex 72

 Zoar Valley 46, 58
 Zr, Zr/Al, Zr/Rb profiles 23, 26, 27, 29–32, 35, 36, 74, 75, 113, 130



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