Calibrating water depths of Ordovician communities: lithological and ecological controls on depositional gradients in Upper Ordovician strata of southern Ohio and north-central Kentucky, USA

Carlton E. Brett[a], Thomas J. Malgieri[a], James R. Thomka[b], Christopher D. Aucoin[a], Benjamin F. Dattilo[c] and Cameron E. Schwalbach[a]

[a] Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221, USA; brettce@ucmail.uc.edu, malgietj@mail.uc.edu, aucoincd@mail.uc.edu, schwalce@mail.uc.edu
[b] Department of Geosciences, University of Akron, Akron, Ohio 44325, USA; jthomka@uakron.edu
[c] Department of Geoscience, Indiana University-Purdue University-Fort Wayne, Fort Wayne, Indiana 46805, USA; dattilob@ipfw.edu

Received 2 July 2014, accepted 13 October 2014

Abstract. Limestone and shale facies of the Upper Ordovician Grant Lake Formation (Katian: Cincinnatian, Maysvillian) are well exposed in the Cincinnati Arch region of southern Ohio and north-central Kentucky, USA. These rocks record a gradual change in lithofacies and biofacies along a gently northward-sloping ramp. This gradient spans very shallow, olive-gray, platy, laminated dolostones with sparse ostracodes in the south to offshore, nodular, phosphatic, brachiopod-rich limestones and marls in the north. This study uses facies analysis in outcrop to determine paleoenvironmental parameters, particularly those related to water depth (e.g., position of the photic zone and shoreline, relative degree of environmental energy). Within a tightly correlated stratigraphic interval (the Mount Auburn and Straight Creek members of the Grant Lake Formation and the Terrill Member of the Ashlock Formation), we document the occurrence of paleoenvironmental indicators, including desiccation cracks and light-depth indicators, such as red and green algal fossils and oncolites. This permitted recognition of a ramp with an average gradient of 10–20 cm water depth per horizontal kilometer. Thus, shallow subtidal ("lagoonal") deposits in the upramp portion fall within the 1.5–6 m depth range, cross-bedded grainstones representing shoal-type environments fall within the 6–18 m depth range and subtidal, shell-rich deposits in the downramp portion fall within the 20–30 m depth range. These estimates match interpretations of depth independently derived from faunal and sedimentologic evidence that previously suggested a gentle ramp gradient and contribute to ongoing and future high-resolution paleontologic and stratigraphic studies of the Cincinnati Arch region.

Key words: paleobathymetry, Cincinnatian, faunal gradients, microendoliths, water depth.

INTRODUCTION

The problem of absolute depth in ancient depositional environments is a difficult one. While it is commonly possible to determine the relative depth of a given facies or fossil community, it is far more difficult to assign depths in terms of meters below sea level. Given the ecological importance of depth-related facies (Patzkowsky & Holland 2012), it is important to attempt assignment of fossil assemblages to quantitatively defined depth zones. Estimates of absolute depth can be made based upon integrated analysis of a variety of distinctive sedimentary structures related to exposure, indicators of position with respect to shoreline, normal wave base and storm wave base, and evidence of light-related zones (Brett et al. 1993).

In the present study, we attempt to calibrate absolute depths of lithofacies and biofacies in a well-constrained stratigraphic interval in the Upper Ordovician of the classic Cincinnati Arch region of northern Kentucky and southern Ohio, USA. We also determine the orientation and gradient of an ancient, gently dipping carbonate ramp.

GEOLOGIC HISTORY AND DEPOSITIONAL SETTING

Strata assigned to the upper Katian (Cincinnatian: uppermost Maysvillian to lower Richmondian) Mount Auburn Member of the Grant Lake Formation in southwestern Ohio and its lateral equivalents, the Terrill Member of the Ashlock Formation in central Kentucky and the Straight Creek Member of the Grant Lake Limestone (*sensu* Schumacher et al. 1991) of southern Ohio and northern Kentucky, crop out along the periphery of the Cincinnati Arch (Fig. 1). The upper Katian of the Cincinnati Arch region is made up of mixed carbonate

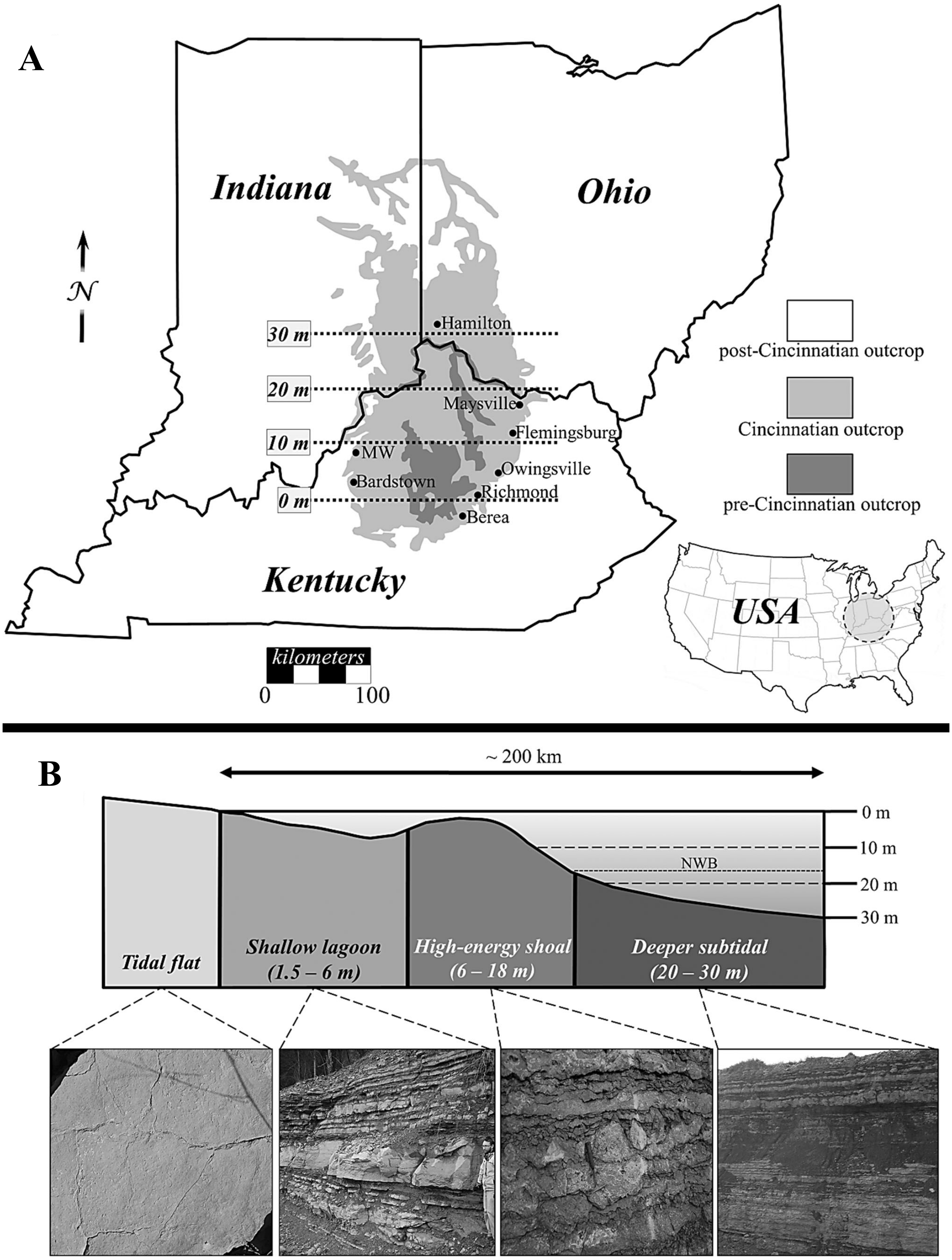

Fig. 1. Paleobathymetry of an Upper Ordovician ramp in the Cincinnati Arch region. **A**, map showing the distribution of the Ordovician outcrop, localities mentioned in the text and approximate inferred depths below the sediment–water interface. The 0-m line marks the northernmost occurrence of desiccation cracks, the 10-m line marks the northernmost occurrence of micritic, pale green mudstones, the 20-m line marks the northernmost occurrence of oncoids and abundant algae. "MW" = Mt Washington. **B**, idealized cross-section of the ramp showing lateral lithofacies relationships. Shoal topography is exaggerated, although some areas may have built up locally to a few meters in height. Insets show examples of certain aspects of lithofacies. Note the desiccation cracks in the dolomitic mudstone associated with the tidal flat facies, the carbonate–dark shale rhythms in the lagoon facies, the large stromatoporoids in the shoal facies and the muddy wackestones and shelly packstones of the shelf facies. "NWB" = normal wave base.

and siliciclastic rocks that accumulated in the distal portion of the Taconic foreland basin. Most strata accumulated along a north-sloping ramp known as the Lexington Platform (Cressman 1973). This ramp contains lithofacies ranging from shallow peritidal deposits in the southern depositional limit to shoal and outer ramp deposits in the north. Siliciclastic sediments were derived from tectonic source areas to the east that were uplifted during the Taconic Orogeny. Carbonates accumulated largely in situ, with micritic wackestones in shallow-water areas, skeletal, oncoid- and stromatoporoid-bearing grainstone facies in mid-ramp settings and muddy, nodular, brachiopod-dominated packstones with minor grainstone beds in areas below normal wave base to the north.

METHODS

Our approach to reconstructing absolute depths along the ramp involved first establishing a precisely correlated, thin stratigraphic interval (10–20 m thick) and then identifying benchmark positions at which the depth range could be reasonably well-constrained. The Mount Auburn Member of the Grant Lake Formation and its lateral equivalents in the Terrill Member of the Ashlock Formation was chosen because: 1) regional stratigraphic correlations were constrained to decimeter scale using a combination of key surfaces and marker beds (e.g., hardgrounds, erosional surfaces, major lithofacies offsets), as well as faunal epiboles in closely spaced outcrops along both sides of the Cincinnati Arch and 2) this interval extends laterally from desiccation-cracked, shaly facies to nodular, fossiliferous facies representing environments below normal wave-base that have been previously examined for microendoliths, traces of light-sensitive endolithic cyanobacteria and green and red algae (Vogel & Brett 2009). To reconstruct our absolute depth gradient, we needed to establish three points of reference: 1) depositional strike, the orientation of facies belts relative to shoreline, which allowed determination of depositional dip, the direction of most rapid change in depth-related facies components, 2) position of the shoreline and 3) depth of the deepest-water facies. Once the depth of two end-members was established along depositional dip, we utilized this information to determine the water depth gradient, interpolating depths for intermediate localities. For this initial methodological test case, we assumed a homoclinal ramp beyond the tidal flat facies and into deeper environments. This assumption was supported by the evidence in this study, but more complex ramp geometries can be inserted into future analyses if data do not match interpreted depth patterns.

FACIES AND DEPOSITIONAL ENVIRONMENTS

The position of the paleo-shoreline was identified by the appearance of desiccation cracks in the lower Terrill Member. This was identified as the supratidal zone where carbonate mud-flats were exposed to alternating episodes of wetting and more prolonged drying; hence, this represents a setting above average sea level, assuming a microtidal coast, typical of most epicontinental seas (Allison & Wells 2006). The northernmost appearance of desiccation cracks in age-equivalent rocks, recording tidal flat facies (Terrill Member), occurs just north of Richmond, Kentucky, and constrains the position of the shoreline (Fig. 1A). The width of the mudcracked, argillaceous mudstone facies, approximately 20 km, gives a sense of the width of the supratidal zone during deposition of this interval. In general, desiccation cracks range from small, vaguely defined polygons in northernmost crack-bearing outcrops to larger prism cracks in outcrops to the south (Fig. 1B).

These facies pass laterally northward into heavily bioturbated, pale green, argillaceous, micrite facies that carry in situ lingulid brachiopods and mollusks; these are inferred to record shallow lagoonal settings. The presence of carbonized dasyclad algae suggests water depths <15 m (Brett et al. 1993). Such facies pass abruptly into skeletal packstones and grainstones, mapped locally as either the Straight Creek Member of the Grant Lake Limestone or the Mount Auburn Member of the Grant Lake Formation (Schumacher et al. 1991), which can contain abundant oncoids and stromatoporoids (*Labechia*) up to 1 m in diameter (Fig. 1B). Evidence of strong winnowing and reworking of grains suggests a high-energy shoal environment. The deepest-water environments of the studied transect, exposed near Hamilton, Ohio, comprise nodular-bedded, phosphatic limestone facies (Fig. 1B) dominated faunally by the robust orthid brachiopod *Vinlandostrophia ponderosa*. Sediments of these facies were deposited below normal wave base but within the shallow euphotic zone, as indicated by the presence of cyclocrinitid green algae (Beadle & Johnson 1986).

The approximate depth of some of the more distal (northernmost) sections of the Mount Auburn Member was established more precisely based on recent study of microendoliths in brachiopod shells obtained from Hamilton, Ohio. Vogel & Brett (2009) recognized a series of microendoliths related to the modern *Fascichnus dactylus–Palaeoconchocelis* ichnofacies. These include diverse microborings attributable to green algae and cyanobacteria; these photoautotrophs indicate a relatively strong light source, suggestive of shallow euphotic zone III (e.g., Vogel et al. 1995). This interpretation is strongly supported by the presence of several ichnogenera that have persisted to the modern with very little morphologic change.

As noted, the Mount Auburn Member in southern Ohio was deposited in the subtropics, at about 25° S (Scotese & McKerrow 1990). Therefore, we utilized data on the depth range of the shallow euphotic zone for the analogous latitude in the modern Bahamas to estimate absolute water depths. Glaub et al. (2002) indicated a range of depths (varying depending upon water clarity) for the base of the shallow euphotic zone based upon detailed studies of microendoliths in carbonate substrata. This depth range is from approximately 5 m to 30 or 50 m at deepest. Given that Ordovician seas were likely more turbid due to the presence of siliciclastic mud derived from the Taconic Orogen, the shallower end-member of 30 m seems most plausible for this study.

RAMP GRADIENTS AND DEPTHS OF FACIES

Assuming a shoreline north of Richmond, Kentucky (the northernmost location of desiccation cracks), and a depth of ~30 m at Hamilton, Ohio, about 200 km to the north, we reconstruct a very gentle ramp with a gradient of 10–20 cm of water depth increase per kilometer in a northward direction (Fig. 1). Assuming a uniform gradient of 15 cm per kilometer, the depth of the bioturbated, micritic limestones representing intertidal to shallow subtidal ("lagoonal") environments of the Terrill Member, exposed about 10–40 km to the north of Richmond, would be roughly 1.5–6 m. The cross-bedded, skeletal, oncolitic grainstone facies, present in outcrops between 40 and 120 km to the north of Richmond, would represent depths of 6–18 m, in reasonable accord with estimates of normal wave base in epeiric seas (5–15 m; Brett et al. 1993). As shown in Fig. 1B, the shoal perhaps could have had locally developed as an elevated skeletal buildup a few meters deep. The nodular, shelly *Vinlandostrophia*-bearing facies represent deeper subtidal settings, ranging from 20 to 30 m (Fig. 1). Oncolitic to nodular, brachiopod-rich facies of the Reba Member overlie the mudcracked Terrill Member in its type locality, and we calculate this deepening to be on the order of 20 m. Assuming a constant ramp gradient during this deepening, we may calculate that *Rafinesquina*-rich packstones of the Arnheim Formation at Hamilton, Ohio, equivalent to the Reba Member, represent depths of around 50 m.

This approach promises to further unlock the relative and absolute depths of lithofacies and benthic assemblages in Paleozoic marine environments. Coupled with the established practice of analyzing tempestite proximality trends (e.g., Aigner & Reineck 1982; Aigner 1985; Brett et al. 1986; Baarli 1988; Easthouse & Driese 1988), the paleobathymetry of epeiric seas can be determined with greater resolution. Ideally, faunal associations, quantified using gradient analysis such as detrended correspondence analysis (see Holland & Patzkowsky 2007; Patzkowsky & Holland 2012), can be calibrated to absolute depth ranges. By determining such ecological parameters, this study provides a better understanding of paleogeography and environmnents during a time of important ecological change (e.g., Holland & Patzkowsky 1996, 2007).

CONCLUSIONS

The Upper Ordovician (Katian) Mount Auburn Member of the Grant Lake Limestone and lateral equivalents in the Cincinnati Arch region comprise a gentle, tidal flat-fringed, northward-dipping ramp on the distal margin of the Taconic foreland basin. This ramp spans lithofacies that range from desiccation crack-bearing, silty, dolomitic carbonates in the south to cross-bedded skeletal grainstones further north, to brachiopod-rich offshore packstones in the deepest part of the transect. The presence of desiccation cracks marks the position of the paleoshoreline, and algal fossils and microendoliths constrain the depth ranges for more downramp deposits. Assuming a uniform gradient, this ramp displays a rate of change of 10–20 cm per kilometer; this estimate places shallow peritidal facies in the range of one to a few meters of depth, with shoal-type grainstones within normal wave base and offshore shell-rich deposits at approximately 30 m of depth. These interpretations fit with sedimentologic, paleoecologic, taphonomic and ichnologic evidence for depth-related paleoenvironmental parameters. The approach adopted herein is suggested as an important supplement to other techniques used to infer paleodepth and, moreover, an approach that shows considerable promise for elucidating changes in ramp geometry and calibrating eustatic sea-level changes.

Acknowledgments. This study was funded by NSF EAR0819820 to CEB and Dry Dredgers Paleontological Research Awards to JRT and CDA. Discussions with Kyle Hartshorn (Dry Dredgers) and Thomas J. Schramm (Louisiana State University) improved our understanding of the studied interval. Previous versions of this article benefitted from the constructive reviews provided by Mats Eriksson (Lund University) and Patrick I. McLaughlin (Wisconsin Geological and Natural History Survey). This is a contribution to the International Geoscience Programme (IGCP) Project No. 591 "The Early to Middle Palaeozoic Revolution".

REFERENCES

Aigner, T. 1985. Storm depositional systems: dynamic stratigraphy in modern and ancient shallow-marine sequences. *Lecture Notes in Earth Sciences*, **3**, 1–174.

Aigner, T. & Reineck, H.-E. 1982. Proximality trends in modern storm sands from the Helgoland Bight (North Sea) and their implications for basin analysis. *Senckenbergiana Maritima*, **14**, 183–215.

Allison, P. A. & Wells, M. R. 2006. Circulation in large epicontinental seas: what is different and why? *PALAIOS*, **21**, 513–515.

Baarli, B. G. 1988. Bathymetric co-ordination of proximality trends and level bottom communities: a case study from the Lower Silurian of Norway. *PALAIOS*, **3**, 577–587.

Beadle, S. C. & Johnson, M. E. 1986. Palaeoecology of Silurian cyclocrinitid algae. *Palaeontology*, **29**, 585–601.

Brett, C. E., Baird, G. C. & Speyer, S. E. 1986. Storm-generated sedimentary units: tempestite proximality and event stratification in the Middle Devonian Hamilton Group of New York. In *Dynamic Stratigraphy and Depositional Environments of the Hamilton Group (Middle Devonian) in New York State* (Brett, C. E., ed.), *New York State Museum Bulletin*, **457**, 129–156.

Brett, C. E., Boucot, A. J. & Jones, B. 1993. Absolute depths of Silurian benthic assemblages. *Lethaia*, **26**, 25–40.

Cressman, E. R. 1973. Lithostratigraphy and depositional environments of the Lexington Limestone (Ordovician) of central Kentucky. *United States Geological Survey Professional Paper*, **768**, 1–61.

Easthouse, K. A. & Driese, S. G. 1988. Paleobathymetry of a Silurian shelf system: application of proximality trends and trace-fossil distributions. *PALAIOS*, **3**, 473–486.

Glaub, I., Gektidis, M. & Vogel, K. 2002. Microboring from different North Atlantic shelf areas – variability of the euphotic zone extension and implications for paleodepth estimates. *Courier Forschunginstitut Senckenberg*, **237**, 25–37.

Holland, S. M. & Patzkowsky, M. E. 1996. Sequence stratigraphy and long-term lithologic change in the Middle and Upper Ordovician of the eastern United States. In *Paleozoic Sequence Stratigraphy: Views from the North American Craton* (Witzke, B. J., Ludvigsen, G. A. & Day, J. E., eds), *Geological Society of America Special Paper*, **306**, 117–130.

Holland, S. M. & Patzkowsky, M. E. 2007. Gradient ecology of a biotic invasion: biofacies of the type Cincinnatian Series (Upper Ordovician), Cincinnati, Ohio region, USA. *PALAIOS*, **22**, 392–407.

Patzkowsky, M. E. & Holland, S. M. 2012. *Stratigraphic Paleobiology: Understanding the Distribution of Fossil Taxa in Time and Space*. University of Chicago Press, Chicago, 256 pp.

Schumacher, G. A., Swinford, E. & Shrake, D. L. 1991. Lithostratigraphy of the Grant Lake Limestone and Grant Lake Formation (Upper Ordovician) in southwestern Ohio. *Ohio Journal of Science*, **91**, 56–68.

Scotese, C. R. & McKerrow, W. S. 1990. Revised world maps and introduction. In *Palaeozoic Palaeogeography and Biogeography* (McKerrow, W. S. & Scotese, C. R., eds), *Geological Society of London Memoirs*, **12**, 1–21.

Vogel, K. & Brett, C. E. 2009. Record of microendoliths in different facies of the Upper Ordovician in the Cincinnati Arch region, USA: the early history of light-related microendolithic zonation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **281**, 1–24.

Vogel, K., Bundschuh, M., Glaub, I., Hofmann, K., Radtke, G. & Schmidt, H. 1995. Hard substrate ichnocoenoses and their relation to light intensity and marine bathymetry. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, **195**, 46–91.