Calibrating Water Depths of Ordovician Communities: Ecological Controls on Depositional Gradients in Upper Ordovician Strata of Southern Ohio and North-Central Kentucky, USA

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Calibrating water depths of a Late Ordovician ramp, southern Ohio and north-central Kentucky. USA

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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 determine depths in terms of meters below sea level. Given the ecological importance of depth-related facies (Patzkowsky and 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 a variety of distinctive sedimentary structures related to exposure, and position with respect to shoreline, normal and storm wave base or evidence of light-related zones (Brett et al., 1993). In the present study we attempt to calibrate absolute depths of litho- and biofacies in a well-constrained stratigraphic interval in the Upper Ordovician of the classic Cincinnati Arch region of northern Kentucky and southern Ohio. We also determine the orientation and gradient of an ancient gently dipping carbonate ramp.

Strata assigned to the upper Katian (uppermost Maysvillian to lower Richmondian) Mount Auburn Member in southern Ohio and northern Kentucky and the laterally equivalent Terrill Member of the Ashlock Formation of central Kentucky crop out along the periphery of the Cincinnati Arch, an eroded Late Paleozoic intracratonic uplift.

The Mount Auburn and Terrill members comprise mixed siliciclastic and carbonate rocks deposited in the Taconic foreland basin. These sediments accumulated along a gently north-sloping ramp from shallow peritidal facies in the south to shoal and deeper ramp environments in the north. Siliciclastic sediments were derived from tectonic source areas uplifted in the Vermonian tectophase of the Taconic Orogeny. Locally derived carbonates were micritic wackestones in the shallow water areas and skeletal, ooid-and stromatoporoid-bearing grainstone facies in middle ramp, through muddy, nodular, brachiopod dominated packstones with occasional grainstones in areas below wavebase to the north.

Limestone and shale facies of the Grant Lake Formation (Upper Ordovician; Katian; Maysvillian) in the Cincinnati Arch of southern Ohio and north central Kentucky document gradual change in litho- and biofacies from offshore, nodular, phosphatic, brachiopod-rich limestones and marls to very shallow olive gray platy, laminated dolostones with desiccation cracks and sparse ostracodes, southward along a gently sloping ramp. 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, and environmental energy). Within the tightly correlated stratigraphic interval of the Mount Auburn Member and coeval Terrill Member, we document the occurrence of sedimentological indicators, including desiccation cracks, and light-depth indicators, such as red and green algal bodies and, especially microendolithic trace fossils, and oncolites.

The Mount Auburn Member (Grant Lake Formation) and its lateral equivalents in the Terrill Member (Ashlock Formation) was chosen because: a) regional stratigraphic correlations were constrained to a decimeter-scale, using a combination of key surfaces, marker beds and faunal epiboles in closely spaced outcrops along both sides of the Cincinnati Arch; and b) it extends laterally from desiccation-cracked shaly dolomitic facies to nodular, fossiliferous facies representing environments
below normal wave base that had been previously examined for microendoliths, traces of light-sensitive endolithic cyanobacteria and green and red algae (Vogel and Brett, 2009). To do this we need to establish three points of references: a) depositional strike, the orientation of facies belts relative to shoreline; b) position of the shoreline; c) depth of deepest water facies. Once the depth of two end-members was established along depositional dip, we utilize this information to determine the water depth gradient, interpolating depths for intermediate localities, assuming a homoclinal ramp.

The position of the paleoshoreline 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. The northernmost appearance of desiccation cracks in age-equivalent rocks, recording tidal flat facies (Terrill Member), just north of Richmond, Kentucky constrains the position of the contemporary shoreline and allows for the first semi-quantitative assessment of the slope of the Ordovician seafloor at this time.

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 shells of brachiopods obtained from Hamilton, OH. Vogel and Brett (2009) recognized a series of microendoliths related to the modern Fasciculus dactylus-Palaeoconchoelis ichnofacies. These include diverse microborings of green algae and cyanobacteria indicative of Shallow Euphotic Zone III (SEZIII). Moreover, these facies appear to pass both laterally and vertically into Rafinesquina-dominated brachiopod facies with microendoliths that suggest a deeper euphotic position.

The maximum (daytime) depths of light-influenced zones are dependent upon latitude as well as water clarity. As noted, the Mount Auburn Formation of southern Ohio was probably deposited in the subtropics at about 25°S. Therefore, we utilized data on the depth range of the SEZIII for the analogous latitude (25°N) in the modern Bahamas to estimate the water depth. Based upon their detailed studies of microendoliths in modern carbonates, Glaub et al. (2002) indicate a range of depths from about 30 to 80 m (depending upon water turbidity) for the base of SEZIII in the Bahamas. The maximum base of this zone in more turbid, subtropical waters off Mauritania, at 19°N is also about 30 m (Glaub et al., 2002). Given that Ordovician seas were receiving siliciclastic sediments from the Taconic Orogeny, shallower end-member, 30 m, is most plausible.

Assuming a shoreline north Richmond, KY (northernmost desiccation cracks) and a depth of ~30 m at Hamilton, OH, about 200 km to the north, we reconstruct a very gentle ramp with a gradient of about 15 cm/km water depth increase in a northward direction. Assuming a uniform gradient, the depths of the bioturbated, micritic limestones, representing intertidal to shallow subtidal (“lagoonal”) environments in the Terrill Member, exposed about 10 to 40 km to the north of Richmond would be about 1.5 to 6 m. The cross-bedded skeletal, oncolitic grainstone facies, present in outcrops between 40 and 120 km to the north, would represent depths of 6 to 18 m in reasonable accord with estimates of normal wave base in epeiric seas (5–15 m). Nodular, Vinlandostrophia facies represent deeper subtidal settings, ranging from 20 to 30 m.

The Terrill Member at its type locality in central Kentucky appears to form the base of a deepening upward, retrogradational succession. The mudcracked Terrill is abruptly but conformably overlain by fenestral micritic wackestone facies and gastropod-ostracode rich wackestones (Sunset Member) that give way gradationally upward into oncolitic to nodular Vinlandostrophia-rich facies of the Reba Member. Based on similarities of this facies those of the mid-ramp we estimate overall deepening to be on the order of 20 m. Assuming a constant ramp gradient during this deepening, we further calculate that Rafinesquina-rich packstones of the Arnhem Formation at Hamilton, OH, equivalent to the Reba Member, represent depths of about 50 m, still within the deeper portion of the
euphotic zone as indicated by microendoliths.

This approach promises to unlock the relative and absolute depths of facies and benthic assemblages; ideally faunal associations, quantified using gradient analyses, such as detrended correspondence analysis (see Patzkowsky and Holland, 2012), can be calibrated to absolute depth ranges. By determining such ecological parameters, this study provides a better understanding of paleogeography and environments during a time of important ecological change.

References
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Extended Summary

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Explanations of cover photos:
Cover: upper—a ventral internal mould of brachiopod Saurorthis sp. (x15) from the Shihtien Fm (Darriwillian, Middle Ordovician) of Laojianshan, Baoshan; down—graptolite Lithograptus glomeratus Ni (x5) from the lower Jenhochiao Fm (upper Aeronian, middle Llandovery) of the same section as above.
Rock cover: a complete specimen of Anomalocaris saras (~17cm) from the lower Yu’anshan Mb of the Heilinpu Fm (Cambrian Stage 3) of Maotianshan, Chengjiang, eastern Yunnan.

Preface

IGCP Project 591 is dedicated to investigating the "Early to Middle Paleozoic Revolution". Indeed, the geological interval from Cambrian to Devonian was full of revolutionary events, both in the organic and inorganic realms, and their interactions triggering the macroevolution of Earth ecosystems as well as the solid Earth itself. The well known Cambrian Explosion, the first macroevolutionary radiation of ecosystem, comprises several episodes from its prologue (represented by the Ediacara Biota), through the first (the Small Shelly Fauna) and the main stages (the Chengjiang Biota) to the epilogue (the Burgess Shale Fauna, the Kaili Fauna etc.). The great Ordovician biodiversification event (GOBE), i.e. the Ordovician radiation, spanned tens of million years, highlighted by several diversity acmes, and established the basic framework of the Paleozoic Evolutionary Fauna that dominated the marine ecosystems for more than 290 Ma. The end-Ordovician mass extinction was the first catastrophic event in life history. It is now known not to be ranked as one of the Big Five, and the marine ecosystem did not collapse at all during this mass extinction. None of these major biotic events are regional in scale, not to say local, although all of them were closely related with local, regional and global tectonic movements, paleogeographic and paleoclimatic changes and apparently some sedimentary innovations (e.g. the Substrate Revolution in Cambrian and Ordovician), as well as some other geological activities such as volcanic eruptions, comets collisions, Milankovich cycles, etc. To investigate these Early to Middle Paleozoic revolutionary events and their dynamics, geoscientists in the world need a common language, i.e. the GSSPs and the establishment of regional and global chronostratigraphic frameworks, which have been some of the major tasks of each Subcommission of ICS for several decades.

On behalf of the Organizing Committee, we would like to take this opportunity to thank all 151 experts who have co-authored the 66 abstracts, summaries and extended summaries in this Extended Summary volume for this meeting. The scope of these papers covers all the above-mentioned topics dealing with the Early to Middle Paleozoic revolutionary events and their triggering factors. Among the 151 contributors, nearly half of them are graduate students or young researchers who brought great vitality to this meeting as well as the IGCP Project. We also want to thank the three keynote speakers, Michael Melchin (ISSS), David Harper (ISOS) and Loren Babcock (ISCs), who prepared both extended summaries and reviewed presentations for this meeting.

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Zhan Renbin and Huang Bing
On behalf of the Organizing Committee
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