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Silurian carbonate high-energy deposits of potential tsunami origin: Distinguishing lateral redeposition and time averaging using carbon isotope chemostratigraphy

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Stable carbon isotope curves are used as a precise stratigraphic tool in the Paleozoic, even though they are commonly based on shallow-water carbonate record, characterized by low stratigraphic completeness. Identification of episodes of large-scale redeposition and erosion may improve $\delta^{13}C_{carb}$-based correlations. Here, a series of at least three episodes of high-energy onshore redeposition are described from the Makarivka Member (new unit) of the Ustya Formation from the Homerian (middle Silurian) of Podolia, Ukraine. The Makarivka Member is emplaced within a tidal flat succession. Its most prominent part is divided into a lower polymictic conglomerate of sand- to boulder-sized clasts representing a range of subtidal facies, and an upper heterolithic unit composed of grainstone and mudstone laminae. The aim of the study is to identify the mechanism of deposition of the allochthonous conglomeratic material in this Member. Based on analogies with recent tsunami deposits, the conglomerate is interpreted to reflect the strongest landward-directed current in the tsunami run-up phase, and the heterolith — alternating high-density landward currents, stagnant intervals allowing mud and land-derived debris to settle, and backwash flows. The tsunamite was deposited during an interval of decreasing isotopic values of the Mulde excursion, a global $\delta^{13}C$ excursion reaching +5.2‰ in the studied sections. Clast redeposition in an interval characterized by rapidly changing $\delta^{13}C_{carb}$ offers the opportunity to evaluate the degree of temporal and spatial averaging caused by the tsunami. The clasts in the polymictic conglomerate show scattered $\delta^{13}C_{carb}$ values (−0.3‰ to +2.1‰) compared to homogenous (1.3‰ to 1.6‰) values in the matrix. The presence of clasts characterized by low $\delta^{13}C_{carb}$ values is explained by their decrease with bathymetry rather than erosion of pre-excursion strata, whereas high values characterize material entrained from the sea-floor and strata directly underlying the tsunamite. Close (1.3‰ and 1.5‰) average $\delta^{13}C_{carb}$ values suggest that the matrix of the conglomerate is potentially a product of clast grinding.

1. Introduction

The term "time averaging" is most commonly employed with reference to accumulations that contain fossils mixed over time intervals exceeding the life span of organisms (Kowalewski and Bambach, 2008). Inorganic particles are subject to this process in the same extent as fossils, and in fact every sedimentological record is time-averaged (Kowalewski, 1996). The absolute extent of time averaging in the geological record is difficult to estimate, with the exception of situations where sedimentary particles are themselves carriers of time information (e.g., Kowalewski and Rimstidt, 2003). The process of temporal mixing may affect $\delta^{13}C$-based chemostratigraphic correlations, which – particularly in the Paleozoic – are considered to often provide the highest temporal resolution available (e.g., Cramer et al., 2010a, 2010b; Sadler, 2012). At the same time, the majority of the $\delta^{13}C$ chemostratigraphic record is derived from shallow-water carbonates, which are subject to intensive erosion and redeposition. Recognition of the influence of these processes on carbon isotope curves employed for correlations may help improve these correlations and refine their stratigraphic resolution by constraining the temporal extent of gaps which cannot be evaluated using less sensitive stratigraphic tools such as biostratigraphy.

The present study describes an example of large-scale redeposition of allochthonous material in a shallow-marine carbonate succession of the middle Silurian in Ukraine. Based on the sedimentological documentation presented below, potential mechanisms responsible for the formation of the high-energy deposit belonging to the newly introduced Makarivka Member are discussed. The Makarivka Member was deposited during an interval of lowering isotopic values of the Mulde positive carbon isotope excursion (CIE) and includes a polymictic conglomerate, which contains boulders of various lithologies occurring across the excursion interval. The high rate of $\delta^{13}C_{carb}$ change in a short interval provides an opportunity to evaluate the degree of time averaging, as

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well as its potential effect on the shape of the $\delta^{13}C$ curve and correlations based on it.

The first aim of the study is to identify the mechanism which has led to redeposition and mixing of clasts representing a variety of lithologies from subtidal facies in the Makarivka Member. Four possibilities are considered: landward transport of clasts by 1) a hurricane or 2) a tsunami, 3) transport of clasts from an uplifted area located landward to the site of deposition, e.g. by a stream flood, and 4) mixing of clasts of different facies and ages in a transgressive lag. The identification of the depositional process is based on the stratigraphic position of the Makarivka Member, on the direction of transport, and on comparison with sedimentary structures observed in modern hurricane and tsunami deposits.

The second aim is to evaluate the scale of time- and space-averaging of $\delta^{13}C_{carb}$ values in the polymictic conglomerate in the Makarivka Member in comparison to the general trend of the $\delta^{13}C_{carb}$ development in the uppermost part of the Mulde CIE, and to use the clasts' $\delta^{13}C_{carb}$ values to identify the point on the Mulde $\delta^{13}C$ curve to which they correspond, and thus the temporal or spatial scale of redeposition.

2. Geological setting

The Silurian succession in Podolia, Ukraine, represents deposits of a carbonate ramp developed in a low-relief epicontinental basin, which stretched during the Silurian along the western shelf of the paleocontinent of Baltica (Figs. 1, 2) from present-day Scandinavia to Moldova (Poprawa et al., 1999). In Podolia, Silurian rocks are exposed in deep canyons of the Dniester River and its tributaries. They comprise a succession starting in the uppermost Llandovery and continuing without major stratigraphic breaks into the Devonian (Nikiforova et al., 1972; Tsegelnyuk et al., 1983; Racki et al., 2012).

2.1. Stratigraphy

Following the lithostratigraphic scheme of Tsegelnyuk et al. (1983) adapted according to the recommendations of the International Commission on Stratigraphy, the Homerian in Podolia is represented by the Ternava, Muksha and Ustya formations of the Yaruga Group (Fig. 3). The Muksha and lowermost Ustya formations record a pronounced (up to +5.2‰) positive carbon isotope excursion (Kaljo et al., 2007; Jarochowska et al., 2014), known as the Mulde excursion, which allows correlations with other regions. It is recorded in the carbonate platform in Gotland (Samtleben et al., 2000; +3.2‰; Calner et al., 2006; +3.8‰; Calner et al., 2012; +2.6‰), Lithuania (Martma et al., 2005; +1.6‰), Latvia and Estonia (Kaljo et al., 1997; Kaljo and Martma, 2006; +4.6‰), in open shelf environments in the subsurface Poland (Porębska et al., 2004; +0.6‰), in the Anglo-Welsh Basin (Corfield et al., 1992; Marshall et al., 2012; +5.5‰), in the peri-Gondwanan Prague Basin (Frýda and Frýdová, 2014; +3.2‰), in the USA (Cramer et al., 2006; +2.6‰) and in Arctic Canada (Noble et al., 2005, 2012; shifts up to +3.4‰). The age of the Mulde CIE has been constrained with $^{206}Pb/^{238}U$ (zircon) dating to 428.45 ± 0.73 Ma to 427.86 ± 0.71 Ma, indicating its duration to be shorter than 1 Myr. (Cramer et al., 2012). Conodont biostratigraphy based on Gotland (Calner and Jeppsson, 2003; Jeppsson and Calner, 2003) indicates that the onset of the excursion is close to the boundary between the *Ozarkodina sagitta sagitta* and the *Ozarkodina bohemica longa* conodont zones, the rising limb of the second peak of the CIE starts within the *Kockelella ortus absidata* conodont zone, and the return of the $\delta^{13}C_{carb}$ values to the baseline level is, depending on the amplitude of the excursion in different sections, placed within this zone or in the following *Ctenognathodus murchisoni* conodont zone. In the Dniester River Valley the end of the excursion falls in the lower part of the Ustya Formation, above the Makarivka Member, indicating its late Homerian age (Jarochowska et al., 2014).

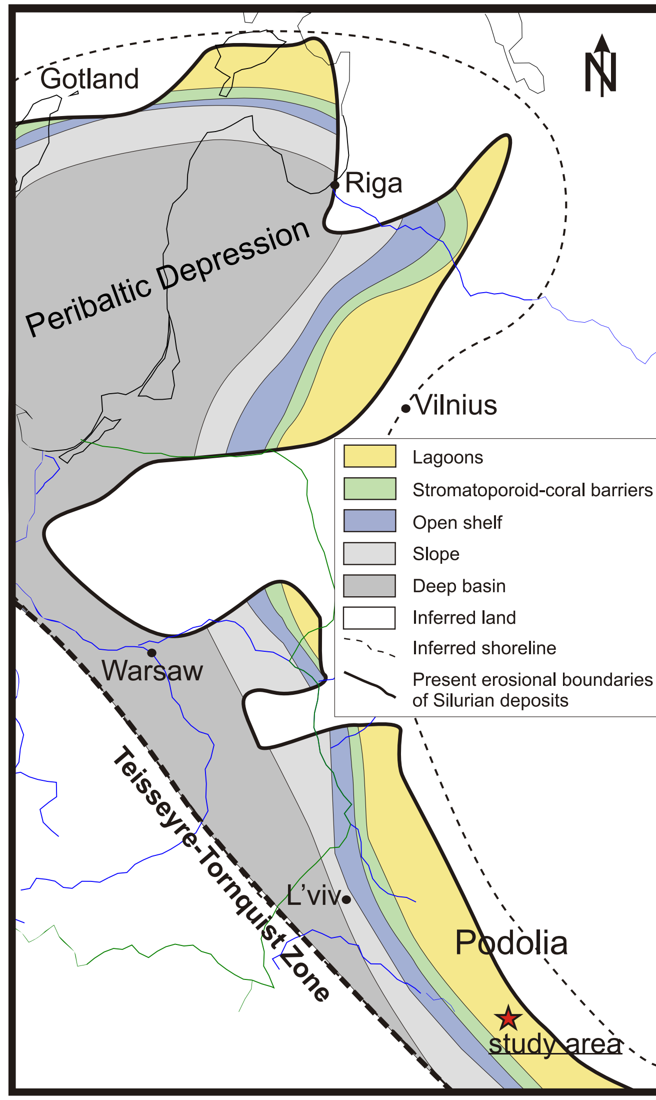

Fig. 1. Paleogeographical map of the Baltic Basin on the shelf of Baltica during the middle Silurian (*Gothograptus nassa* Chron). After Einasto et al. (1986) and Teller (1997).

2.2. Study locations

The Makarivka Member occurs in two aspects: the more complete, proximal with respect to the source of allochthonous material aspect, exposed in the Makarivka section (φ 48°34′13.80″ N, λ 26°44′18.50″ E, Figs. 2, 4A), which is located in the southern bank of the Dniester River, and in a distal, less complete aspect, lacking some of the lithological types present in Makarivka (Sections 4.2.1 and 4.2.2), in the Bagovytsya (φ 48°36′21.00″ N; λ 26°43′45.50″ E) and Muksha 2 (φ 48°35′13.90″ N; λ 26°42′3.90″ E) sections located in valley slope ravines of the northern tributaries of the Dniester River (Figs. 2, 4). The name of the Makarivka Member is derived from the village of Makarivka, Chernivtsi administrative region, western Ukraine. The type locality is a 200-m-long exposure along the southern bank of the Dniester River, located 300 m to the west of the village.

3. Methods

3.1. Sample collection and processing

The Makarivka, Bagovytsya and Muksha 2 sections were logged for the construction of lithological columns (Fig. 5). In Makarivka, individual beds