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Llandovery green/grey and black mudrock facies of the northern Holy Cross Mountains (Poland) and their relation to early Silurian sea-level changes and benthic oxygen level

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ABSTRACT

The Llandovery mudrock facies in the northern Holy Cross Mountains reveal lithological variability allowing their interpretation in the context of post-Ordovician climate and sea-level changes in the Caledonian foredeep basin developed along the present SW margin of Baltica. They form a succession up to 50 m thick made up of grey and greenish clayey mudstones interrupted by black shales. The sedimentary and geochemical data (total organic carbon, pyrite framboids and trace metals) clearly show that the black shales document periods of the significant sediment starvation and oxygen- deficient conditions. Their occurrence is confined to the *persculptus–acuminatus*, *vesiculosus*, *cyphus*, *convolutus–sedgwickii*, *turriculatus–crispus*, *crenulata* and *spiralis* graptolite biozones and they can be correlated with post-glacial transgressions. In contrast, the grey and greenish mudstones are interpreted as lithofacies reflecting permanent benthic oxygenation driven by deep-water ventilation during the Aeronian and Telychian regressions supported by sedimentary and geochemical studies, and diameters of pyrite framboids

1. Introduction

It is now widely accepted that the Silurian Period was characterized by remarkable climate and sea-level changes manifested by isotope geochemistry and bioevents (Loydell, 1998; Calner, 2008; Davies et al., 2016). The time interval from the Late Ordovician GICE (Guttenberg Isotope Carbon Event) to the early Wenlock Ireviken event was defined by Page et al. (2007) as the Early Paleozoic Icehouse comprising seven glacial maxima developed at elevated atmospheric CO_2. The short-lived Hirnantian glaciation on Gondwana is the most widely recognized among them (Sheehan, 2001; Brenchley, 2004; Armstrong, 2007; Finnegan et al., 2011); notwithstanding, it is widely accepted that the early Silurian glaciations in South America (Diaz-Marinez and Grahn, 2007) strongly influenced the sedimentary, faunal and geochemical record. The post-glacial sea-level rise contributed to deposition of globally extensive organic-rich black shales in the Llandovery and Wenlock deeper water settings (Loydell, 1998; Lüning et al., 2000; Štorch, 2006; Page et al., 2007; Podhalańska, 2009; Smolarek et al., 2016). Page et al. (2007) postulated that black shales in the latest Ordovician–early Silurian represent post-glacial transgressive deposits drawing down CO_2 in the Early Palaeozoic Icehouse interval.

Factors controlling the preservation of black shales include: primary productivity, bacterial decomposition, redox conditions and bulk sedimentation rate that are strongly dependent on relative sea-level changes and palaeoceanographic conditions (Arthur and Sageman, 1994; Canfield, 1994; Wignall, 1994; Bohacs et al., 2005; Tyson, 2005). Black shales contain many trace elements, which are a useful tool in recognition of redox conditions during the time of their deposition and early diagenesis as well as climatic and palaeoceanographic changes (e.g. Calvert and Pedersen, 1993; Wignall, 1994; Sageman et al., 2003; Algeo, 2004; Algeo and Maynard, 2004; Tribovillard et al., 2006; Perkins et al., 2008).

Here we present multiple data from the northern Holy Cross Mountains (HCM, Poland) where the Llandovery mudrock succession consists of black shales grading upwards into grey and greenish-grey clayey mudstones with subordinate black/dark shale interbeds. Previous studies of these deposits concentrated chiefly on stratigraphical aspects (Tomczyk, 1962; Tomczykowa and Tomczyk, 1976, 2000; Trela and Salwa, 2007). Here we discuss their deposition in the context of post-Ordovician climate and sea-level changes. Stratigraphical and sedimentological studies are supplemented by inorganic geochemistry and measurement of pyrite

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framboid diameters in order to reconstruct the oxygenation history of the studied mudrock succession. Graptolite biozones provide the stratigraphical framework for the temporal correlation of this sedimentary record with the Silurian sea-level curve.

2. Materials and methods

The samples studied were collected from the Llandovery black/dark shales and grey to greenish-grey clayey mudstones, and the uppermost Hirnantian shales and sandy mudstones. They were derived from two cores: Wilków 1 and Dębniak 1 which were drilled in the western and central parts of the northern HCM, respectively, in the late fifties of the 20th century (Figs. 1, 2, 3). We have conducted studies largely on the Wilków 1 drill core, while in the case of the Dębniak 1 well we had only 22 archive samples (from depths of 71.0; 70.3; 69.6; 69.4; 69.3; 69.2; 68.95, 68.9; 68.8; 68.6; 68.45; 68.2; 68.0; 67.7; 67.5; 67.2; 67.0; 66.8; 65.3; 64.5; 64.0–65.0; 62.0 m).

The sedimentological investigation concentrated chiefly on lithology, rock colour, sedimentary structures and ichnofabric. Detailed sedimentological observations were conducted on 100 selected samples cut perpendicular to the bedding surface. Moreover, they were supplemented by examination of 35 thin sections using standard petrographic techniques. To better understand the depositional conditions of the succession investigated we also used basic inorganic geochemical indices (31 samples), including trace element ratios and total organic carbon (TOC) data. Concentrations of trace elements were determined directly on pressed powder pellets by X-ray fluorescence using a Phillips PW 2400 XRF spectrometer, while TOC was analyzed by a Coulomat 702 CS/LI in the Polish Geological Institute-National Research Institute (Warsaw, Poland).

In addition, to reconstruct the palaeoredox environmental conditions, measurement of pyrite framboid diameters was applied to 14 samples collected from the Llandovery mudstones and shales. Small chips taken from the samples were polished and framboid diameters were then measured in back-scattered electron (BSE) mode using a Philips XL30 Environmental Scanning Electron Microscope (ESEM) housed at the University of Silesia (Sosnowiec, Poland), with framboid diameters being measured in μm by the ESEM internal measuring device. At least 100 framboids were measured from each sample — minimum, maximum and mean values for framboid diameters were determined and standard deviations were calculated. In the case of framboid diameters measured on the Aeronian and Telychian samples, the data have been illustrated as box and whisker plots, while for the Rhuddanian samples we used histograms to demonstrate better the frequency of framboid diameters. Biomarker palaeoenvironmental proxies were not measured in this study because of the high organic matter maturity of rocks from the northern HCM (Smolarek et al., 2014).

We have re-examined graptolites from the Dębniak 1 well using the archive samples from the depths of 62.0; 64.0–65.0; 64.5; 65.3; 66.8; 76.2; 67.5; 67.7; 68.2; 68.45; 68.6; 68.8; 68.9; 68.95; 69.2; 69.3; 69.4; 70.3 m. Their preservation state is very poor and therefore their taxonomic identification and graphic documentation are difficult or even impossible in a few cases. However, the recognized graptolites provide limited but essential stratigraphic resolution for the considered section. They were observed using a stereo microscope Olympus SZX 12 equipped with a photo camera OM-4Ti.

3. General background and stratigraphy

The northern HCM – traditionally called the Łysogóry Unit (Dadlez et al., 1994) – is separated by the Holy Cross Fault from the Małopolska Block to the south (Fig. 1). The northern segment of the HCM is supposed to be a passive margin of Baltica (Dadlez et al., 1994); however, there are suggestions of a Gondwanan provenance (Belka et al., 2000; Valverde-Vaquero et al., 2000). Given existing palaeontological and palaeomagnetic data, however, it is clear that in the Early Palaeozoic the Łysogóry Unit was part of SW peri-Baltica (Cocks, 2002; Nawrocki et al., 2007).

The Silurian System in the Łysogóry Unit consists of Rhuddanian (early Llandovery) – Gorstian (early Ludlow) mudrock facies (up to 200 m thick) which are overlain by a continuous succession up to 2000 m thick of late Ludlow to Lochkovian greywacke sandstones, mudstones and carbonates (Kozłowski, 2008) filling the foredeep basin that extended along the present SW margin of Baltica (Poprawa, 2006; Narkiewicz, 2002).

The Llandovery mudrock succession (up to 50 m thick) is represented by Rhuddanian black shales of the Zbrza Member that belongs to the Bardo Formation (Fig. 2; Trela and Salwa, 2007) and the Aeronian-Telychian grey to greenish-grey claystones to clayey mudstones divided into informal lithostratigraphic units called the Dębniak and Ciekoty Beds (Figs. 2, 3; Tomczyk, 1962; Deczkowski and Tomczyk, 1969). The Zbrza Member forms a relatively thin interval (up to 3 m thick) dated by graptolites of the *persculptus*–

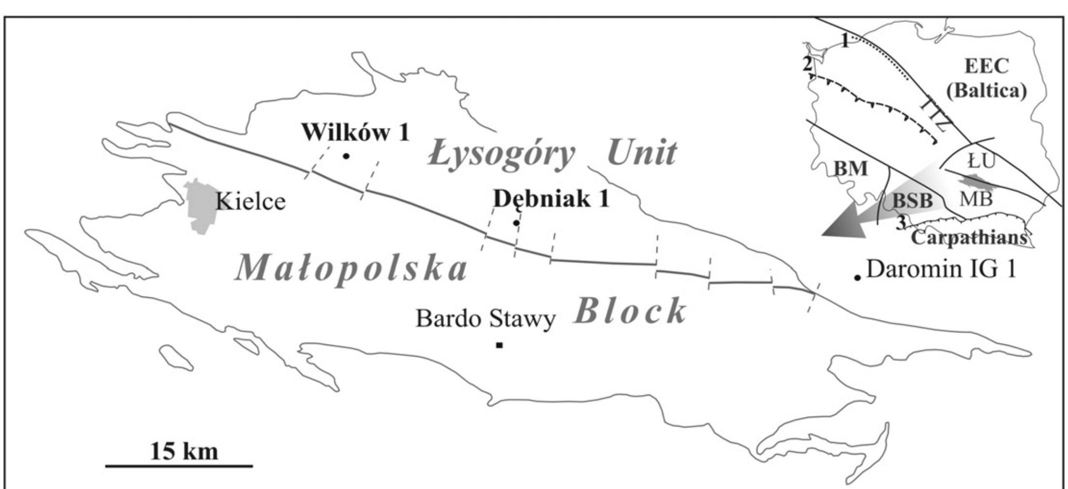

Fig. 1. Location of the Wilków 1 and Dębniak 1 wells in the Holy Cross Mountains. BM – Bohemian Massif, BSB – Bruno-Silesian Block, EEC — East-European Craton, MB — Małopolska Block, ŁU — Łysogóry Unit, 1 — Caledonian front, 2 — Variscan front, 3 — Alpine front.