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Redox-dependent distribution of early macro-organisms: Evidence from the terminal Ediacaran Khatyspyt Formation in Arctic Siberia

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ABSTRACT

The Ediacaran Period witnessed the first appearance of macroscopic animal life in Earth's history. However, the biogeochemical context for the stratigraphic occurrence of early metazoans is largely uncertain, in part due to the dearth of integrated paleobiological and chemostratigraphic datasets. In this study, a comprehensive geochemical analysis was conducted on the fossiliferous Khatyspyt Formation in Arctic Siberia, in order to gain insights into the Ediacaran paleoenvironments. This study was designed to specifically address the relationship between paleoredox conditions and Ediacaran fossil occurrences in the Khatyspyt Formation. Our data reveal a dramatic shift in pyrite sulfur isotope compositions ($\delta^{34}S_{pyrite}$) from ca. −20‰ to ca. 55‰, and this shift is intriguingly associated with the first occurrence of Ediacara-type macrofossils at the studied section, suggesting a possible link between seawater redox conditions and distribution of early macroscopic organisms. Based on multiple lines of sedimentological and geochemical evidence, we propose that the development of oceanic euxinia — which may be widespread in the continental margins due to enhanced oxidative weathering in the terminal Ediacaran Period — may have locally prohibited the colonization of Ediacara-type organisms and resulted in low $\delta^{34}S_{pyrite}$ values in the lower Khatyspyt Formation. In the middle and upper Khatyspyt Formation, progressive secular transition from euxinic to non-euxinic and more habitable conditions may have allowed for the colonization of Ediacara-type and other macro-organisms.

1. Introduction

The Ediacaran Period (ca. 635–541 Ma) holds the answers to key questions related to the origins of the modern Earth system. In particular, Ediacaran strata contain the planet's first unambiguous evidence of macroscopic metazoans and assemblages of “Ediacara-type” fossils (Xiao and Laflamme, 2009). Our present understanding of the origin of animals depends critically on the ability to interpret fossil impressions in siliciclastic sediments made by the Ediacara-type macro-organisms (Gehling, 1999; Narbonne, 2005; Fedonkin et al., 2007) and to document their spatial and temporal distribution (Grazhdankin, 2011, 2014; Narbonne et al., 2014). However, siliciclastic rocks, particularly coarse-grained sandstones, offer limited opportunities for biogeochemical reconstructions of the deep-time record. Fortunately, Ediacara-type macrofossils can also be preserved in carbonate rocks, including the Khatyspyt Formation in Siberia (Fedonkin, 1990; Nagovitsin et al., 2015; Rogov et al., 2015) and the Dengying Formation in South China (Ding and Chen, 1981; Sun, 1986; Xiao et al., 2005; Chen et al., 2014). Chemostratigraphic investigation of these fossiliferous carbonate successions can provide critical geochemical data that complement our understanding from siliciclastic successions.

Ediacaran animals and perhaps Ediacara-type macro-organisms are believed to be oxygen-breathing life forms (Cloud, 1968; Cloud, 1976; Xiao, 2014), therefore a putative rise in atmospheric oxygen during the Ediacaran Period (Derry et al., 1992; Kaufman et al., 1993) may have dictated their evolutionary trajectories and their environmental distribution. Compilations of redox-sensitive proxies at broad timescale suggest a general pattern of rising atmospheric oxygen levels during the

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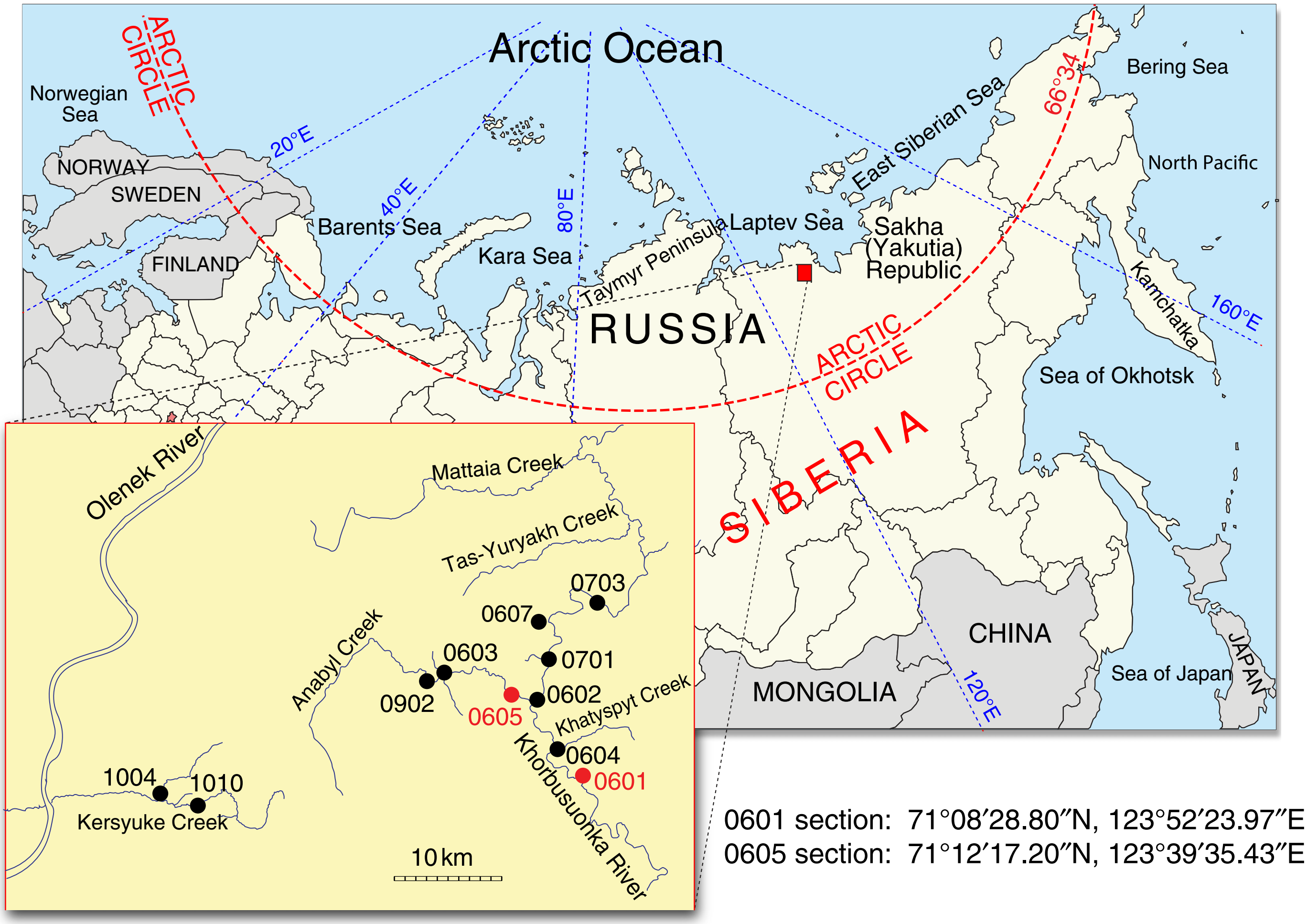

Fig. 1. Map showing measured sections of the Khatyspyt Formation (including the studied 0601 and 0605 sections marked as red dots) along the Khorbusuonka River in the Olenek Uplift, northeastern Siberia, Republic of Sakha, Russia.

late Proterozoic (Kah et al., 2004; Canfield et al., 2007; Kump, 2008; Kah and Bartley, 2011; Shields-Zhou and Och, 2011; Lyons et al., 2014; Planavsky et al., 2014; Liu et al., 2016), although oceanic anoxia has also been argued to remain persistent in many parts of the ocean even in the Ediacaran Period (Canfield et al., 2008; Sperling et al., 2015c; Reinhard et al., 2016; Sahoo et al., 2016). In addition, individual case studies on integrative chemostratigraphy and biostratigraphy of the terminal Ediacaran strata, including the Blueflower Formation in NW Canada (Johnston et al., 2013; Macdonald et al., 2013; Sperling et al., 2015a), the Nama Group in Namibia (Hall et al., 2013; Darroch et al., 2015; Wood et al., 2015), and the Dengying Formation in South China (Duda et al., 2014; Cui et al., 2016a) reveal dynamic redox histories in these depositional basins, suggesting a complex relationship between the emergence of macrometazoans and the putative Ediacaran oxygenation. To further test the various hypotheses about the relationship between the rise of animals and atmospheric oxygen levels, we carried out an integrative investigation of the terminal Ediacaran Khatyspyt Formation in northern Siberia, which contains a moderate diversity of Ediacara-type macrofossils and abundant carbonate rocks for chemostratigraphic analysis (Knoll et al., 1995; Pelechaty et al., 1996a). The goal of this study is to assess the effect of redox conditions on the distribution of early macro-organisms — particularly Ediacara-type macro-organisms — in the Khatyspyt Formation, using carbon, oxygen, sulfur, and strontium isotopes, as well as trace element concentrations.

2. Geological background

2.1. Lithostratigraphy

The fossiliferous Khatyspyt Formation is well exposed along the right-hand side tributaries of the Olenek River (i.e., the Khorbusuonka and Kersyuke rivers) that drains the Olenek Uplift in the northeastern part of the Siberian platform, Republic of Sakha, Russia (Figs. 1 and 2A) (Nagovitsin et al., 2015). Sedimentological observations from the studied Khatyspyt interval (0–130 m in Fig. 3) suggest an overall shelf marine environment with relatively deeper water depth compared with the Maastakh Formation and the overlying Turkut Formation. The lowermost Khatyspyt Formation is dominated by thick packages of intraclastic limestone occurring as channelized bodies up to 7 m in thickness, with abundant tilted angular intraclasts (Fig. 2B) and soft-sediment deformation structures (Fig. 2C), and are laterally persistent over tens to hundreds of meters. The majority of this formation consists of finely laminated medium-bedded limestone with occasional small cross beddings (Fig. 2D). The succession also includes intervals of alternating thin layers of limestone and shale (Fig. 2E), abundant carbonaceous compressions preserved on the bedding planes (Fig. 2F), packages of thin-bedded (Fig. 2G) and thick-bedded limestone (Fig. 2H). The latter often show wavy bedding (Fig. 2J). Finely laminated limestones (Fig. 2I) sometimes contain dense assemblage of *Nenoxites* fossils, which were initially regarded as meniscate trace fossils