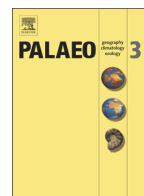




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Investigating the duration and termination of the Early Paleozoic Moyero Reversed Polarity Superchron: Middle Ordovician paleomagnetism from Estonia

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ABSTRACT

Flat-lying Early and Middle Ordovician limestones exposed along the northern margin of Estonia provide key insights into the early Paleozoic biosphere and climatic history of the Baltic Platform and potentially offer a site for calibrating the duration of the proposed Moyero Reversed Polarity Superchron (MRPS). Past paleomagnetic analyses on these rocks have been focused primarily on determining paleomagnetic pole positions and have been hampered by relatively weak remanent magnetizations. We therefore applied techniques of the Rock and Paleomagnetic Instrument Development (RAPID) consortium using thin-walled, low-noise quartz glass sample holders on an automatic system to enhance magnetostratigraphic resolution. Our results, based on over 400 oriented core samples spanning the stratigraphic interval from the Volkhov Stage, into the Uhaku Stage (Dapingian and Darriwillian, Middle Ordovician), expand upon the results of previous work. We isolated a stable characteristic magnetization of reversed polarity and the presence of an interval of magnetically Reversed polarity lasting into the Middle Ordovician. The interval begins in the Dapingian and is interrupted by a short normal period in the mid-Darriwillian (concurrent with the *Yangtzeplacognathus protoramosus* conodont Subzone) before returning to Reversed polarity. In addition, we recognize a magnetic overprint of apparent normal polarity held in antiferromagnetic phases.

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1. Introduction

Ever since their discovery nearly 50 years ago, geomagnetic superchrons have been a puzzle for the geophysical community. Although there have only been a few during Phanerozoic time, Driscoll and Evans (2016) recently proposed multiple superchrons during the Proterozoic. Biggin et al. (2012) suggested that superchrons are the result of low heat flow at the Core Mantle Boundary (CMB), which causes low dynamo activity, and that they are generally separated by 180–190 Myr. According to Courtillot and Olson (2007), one potential process for ending a superchron is via the generation of a superplume at the bottom of the mantle, followed by the eruption of a large igneous province (LIP) 10–20 Myr later. However, this theory is unable to

explain the Middle Cretaceous LIP activity and recent modelling favors a longer plume rise-time of 20–50 Myr (Biggin et al., 2012).

The two well-studied superchrons are the Cretaceous Normal Polarity Superchron (CNPS) (Helsley and Steiner, 1969) and the Kiaman Reversed Polarity Superchron (KRPS) (Irving and Parry, 1963; Kirschvink et al., 2015; McMahon and Strangway, 1968), both of which were followed a few million years later by LIPs. A third Phanerozoic superchron, during the Ordovician, was proposed as a consequence of the polarity bias study conducted in Algeo (1996). Gallet and Pavlov (1996) sampled the Moyero River section in northwestern Siberia and found further magnetostratigraphic evidence for a superchron, with a possible link to the end-Ordovician mass extinction event. They demonstrated a long period of reversed polarity from the Lower Ordovician through to the Middle Ordovician, covering the entire 15 Myr Arenig Siberian stage. Pavlov and Gallet (1998) confirmed the absence of reversals during the Llanvirn. The length has subsequently been revised upward to ~20 Myr (Pavlov and Gallet, 2005; Pavlov et al., 2012). Of the Phanerozoic superchrons, the Moyero Reversed Polarity Superchron (MRPS) is the least-well understood and demands further study.

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The type locality of the MRPS is the Moyero River region in Siberia, where epicontinental sedimentary rocks of the early Paleozoic occur. With regards to the Ordovician stratigraphy in that area, sedimentary gaps cannot be excluded and the Ordovician/Silurian boundary is in hiatus as well (Gallet and Pavlov, 1996). The precise duration of this superchron has not yet been calibrated by conodont biostratigraphy that, with graptolites, form the bases of intercontinental correlation for Ordovician time.

Paleomagnetism studies of Fennoscandian Ordovician limestone have been of interest for nearly 40 years. Claesson (1978) first found a stable bulk magnetization (pole position: Lat = 30° N, Long = 46° E, $\alpha_{95} = 2.2^\circ$) in Swedish limestone, with evidence of secondary components complications. Khramov and Iosifidi (2009) found a similar pole position (Lat = 18° N, Long = 55° E, $\text{dp/dm} = 5/7^\circ$), in exposed lower Ordovician limestones along the Narva River, which flows into the Baltic Sea.

Several studies in the last decade in Estonia in the Lower and Middle Ordovician have consistently found reverse polarity components and poles (e.g. Preeden et al. (2008), Plado et al. (2010), and Plado et al. (2016b)). Plado et al. (2010) studied Lower to Middle Ordovician strata in Estonia and found a reverse polarity primary component (pole position: Lat = 11.4° N, Long = 39.1° E, $\alpha_{95} = 6.7^\circ$), which confirmed the Baltic plate's southern hemisphere location during the proposed time of the MRPS. These studies only show evidence of normal polarity in a high-temperature secondary component, of apparent younger age. Further study in this area is necessary to determine if a normal polarity synsedimentary magnetozone was recorded in the local stratigraphy. Our goal is to find this magnetozone and determine if the normal period that ended the MRPS exists in Estonian stratigraphy, which contains numerous conodont and graptolite zones for global correlation (Fig. 1). We further aim to determine if the normal period is short, as reported in Pavlov and Gallet (1998), or of comparable length, as reported in Algeo (1996). Previous studies suggest that a normal polarity magnetozone should be present near the border between the *Pygodus anserinus* and *Pygodus serra* Zones and a reverse magnetozone in all the others.

The Ordovician strata exposed around the Gulf of Finland are minimally tectonized, which makes the area easier to sample and simpler to study the full stratigraphy of Middle Ordovician time and better resolve the known temporal boundaries of the superchron (Plado et al., 2010; Smethurst et al., 1998). In terms of paleomagnetism, however, the site is non-ideal. Previous studies of these rocks showed that they generally had very low magnetic moments and contained multiple magnetic minerals (maghemite, magnetite, and hematite), which made the demagnetization analysis more complex (Mertanen, 2006; Preeden et al., 2009). However, new technological developments have allowed measurement sensitivity to approach the machine noise of the SQUID magnetometer system (Kirschvink et al., 2015). When coupled with proper specimen handling to reduce magnetic noise from drilling and handling in lab, we can measure paleomagnetism from specimens too weak to be accurately measured previously, and gain extensive insight into the history of the magnetic field throughout Earth's history. The end of the MRPS by Gallet and Pavlov (1996), is a brief short normal period, which necessitated sampling intervals of 2–5 cm in order to detect it.

2. Geological setting

2.1. Tectono-sedimentary background

Estonia is located in the central part of the Baltica paleocontinent, which encompasses a major portion of northern Europe. Flat-lying terrigenous and carbonate sedimentary rocks, ranging from Ediacaran to Devonian age, cover the Archean-Proterozoic crystalline basement of the Baltic platform. These carbonate and fine siliciclastic sediments accumulated in the northern part of the Paleo-Baltic basin, which extends

from Norway to the Ural Mountains in the East and from the Finnish lowland to the Trans European (Tornquist) Suture Zone in the South. Recent studies on detrital zircons from local sandstones clarified that the main provenance of terrigenous clastics is located in the East and the South (Isozaki et al., 2014; Poldvere et al., 2014). By the end of the Ordovician, the Baltica paleocontinent had amalgamated with Avalonia and merged with Laurentia in the middle Silurian. The collision of Baltica and Laurentia led to the Caledonian orogeny in the western periphery of Paleo-Baltic basin, but only had a negligible tectonic influence on the Estonian area.

Both the Cambrian and Devonian siliciclastic rocks as well as Ordovician–Silurian carbonate rocks are unmetamorphosed and undeformed, as they have never been deeply buried or tectonized. The Ordovician succession of mostly carbonate rocks outcrops only in northern Estonia with particular exposures along highly-weathered sheer seacoast cliffs (known as the Baltic Klint) as well as in several inland quarries, containing significantly less weathered rocks. The bedrock dips only 8°–15° (0.13°–0.25°) to the South throughout Estonia, excluding small-scale local deformations (Preeden et al., 2008). The horizontal bedding precludes the use of the usual paleomagnetic tilt test to deduce the timing of magnetic overprints (Enkin, 2003).

2.2. Middle Ordovician stages studied

Estonia's Ordovician sequence is mostly complete and has a thickness ranging from 70 to 180 m (Meidla et al., 2014). The Middle Ordovician is composed of several sedimentary units described as local stages: Volkov, Kunda, Aseri, Lasnamägi, and Uhaku in ascending order (Bauert et al., 2014; Plado et al., 2010; Smethurst et al., 1998). In northwestern Estonia, the Kunda stage records a meteoritic shower event on the Island of Osmussaar (Alwmark et al., 2010).

The base of the MRPS is rather loosely constrained to start during Tremodocian time (Lower Ordovician) (Fig. 5 in Pavlov and Gallet, 2005). The superchron continued to the late Darriwilian, terminating near the *Hustedograptus teretiusculus* graptolite Zone, during the Middle Llandeilo (Pavlov and Gallet, 1998). According to Hounslow (2016), the end of the superchron appeared to have been followed by an initial fast restart of reversal rates. A stratigraphic framework coupled with magnetic susceptibilities was put together by Plado et al. (2016a), through surveys of the Pakri Peninsula (Middle Ordovician: upper Dapingian–upper Darriwilian). Limestone is the predominant lithology from the localities investigated, but it varies in composition depending on the stage. According to Meidla et al. (2014), the Ordovician limestones formed from cold-water carbonates, which were deposited in a shallow marine basin. Initially, the basins were rather sediment-starved, but the sedimentation rates increase upwards through the Ordovician succession.

The Volkhov stage is the oldest studied unit and straddles the Dapingian–Darriwilian boundary (Plado et al., 2010). This stage consists of glauconitic limestone, which has undergone partial to full dolomitization (Hints et al., 2012). The Kunda stage in northwestern Estonia consists of sandy limestone with kerogene and dolostone inclusions (Hints, 2014; Hints et al., 2012). The Aseri stage in northern Estonia consists primarily of biomicritic limestone, containing fine grain particles with abundant ferriferous ooids (Bauert et al., 2014; Hints, 2014). The overlying Lasnamägi Stage is characterized by slightly argillaceous biomicritic limestones which are occasionally dolomitized. Uhaku is the youngest stage studied, and its lower part in the study area is composed of very fine-grained, clay-poor limestone while moderately to highly argillaceous limestone prevails in the upper part (Bauert et al., 2014; Plado et al., 2010).

2.3. Biostratigraphy

Conodonts are the best biostratigraphic markers for the Middle Ordovician of the Baltic Platform (Fig. 1), though the limestone in the

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