The Ordovician Magnetostratigraphy and Cyclostratigraphy: A Review

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Citation: Dai et al., 2019. The Ordovician Magnetostratigraphy and Cyclostratigraphy: A Review. *Acta Geologica Sinica* (English Edition), 93 (supp. 1): 94-97

The study of magnetostratigraphy and cyclostratigraphy in the last two decades has provided a great deal of opportunities to improve the geologic time scale. The Cenozoic and Mesozoic geologic timescale have been well calibrated (Gradstein et al., 2012; Ogg et al, 2012; Cohen et al., 2018). However, for the Paleozoic era the uncertainty over boundary ages are still very large. The reasons include that the geomagnetic polarity timescale prior to the Middle Jurassic have been pending due to the absence of oceanic anomalies (Opdyke and Channell, 1996; Ogg, 2012), and the robust theoretical astronomical model has not been setup for the Paleozoic (Hinnov and Hilgen, 2012). On the other hand, the Primary (characteristic remnant) magnetization or orbital signals are difficult to isolate in the Paleozoic rocks. Due to the outstanding glacial-interglacial climatic changes and mass radiation and extinction in the Ordovician, the studies for Ordovician magnetostratigraphy and cyclostratigraphy are more abundant in the Early Paleozoic. Here we give an overview of the research progress in Ordovician magnetostratigraphy and cyclostratigraphy.

The magnetostratigraphy of Ordovician has been rare till now. Earlier research were largely conducted in Europe (Torsvik et al., 1991;Trench et al., 1991; Smethurst et al., 1998; Pavlov and Gallet, 2005; Schätz et al., 2006; Pavlov et al., 2012; Grappone et al., 2017) and Siberia (Torsvik et al., 1995; Gallet et al., 1996a; Pavlov et al., 1998, 2008, 2012, 2017; Rodionov et al., 2003), and few in America (Ellwood et al., 2007), Australia (Ripperdan and Kirschvink, 1992) and China (Fang et al., 1990; Ripperdan et al., 1993; Huang et al., 1996, 1999; Yang et al., 1998, 2002). These studies focus on two issues. One is natural remnant magnetization (NRM) behavior and/or remagnetization, another is Ordovician geomagnetic polarity timescale. With respect to the NRM behavior, most research reveals that there were two or three NRM components. But only one is characteristic remnant magnetization (ChRM), mostly carried by mainly magnetite and/or hematite (e.g., Pavlov et al., 2008), which was characteristic of antipodal reversed polarity (e.g., Fang et al., 1990; Huang et al., 1996, 1999; Smethurst et al., 1998; Rodionov et al., 2003). While other (s) was (were) secondary NRM (Fang et al., 1990; Torsvik et al., 1991; Ripperdan and Kirschvink, 1992; Huang et al., 1996, 1999; Gallet et al.,1996; Pavlov et al., 1998; Rodionov et al., 2003; Grappone et al., 2017), originated from remagnetization (e.g. Fang et al., 1990, Huang et al., 1996; Smethurst et al., 1998).

The onset of Ordovician geomagnetic polarity zones has been long-term attention. Firstly, Khramov et al. (1965) and Rodionov (1966) investigated the magnetozones in Cambrian - Ordovician strata at the Moyero river section, Siberia. Then Torsvik et al. (1991) recognized three reversed (SE, down) and three normal (NW, up) antipodal polarity intervals within Baltoscandian Ordovician carbonates. Trench et al (1991) studied the magnetostratigraphy of the Baltic and South Siberian platform, and firstly found a long geomagnetic polarity zone which is dominated by reversed polarity during the Early Ordovician (Tremadoc-Llanvirn), succeeded by a predominantly normal polarity field in later Ordovician (Llandeilo Ashgill). This is the start of the Moyero reversed superchron. After that, more studies came out from Siberian and other sites for the composition of the Ordovician geomagnetic polarity zones. In Australia, Ripperdan and Kirschvink (1992) sampled a section of 1000m thick of Ordovician strata, and got more polarity zones than in previous works, i.e. four couplets of normal-reversal polarity zones. In Northeast China, Ripperdan et al (1993) reported more normal - reversed polarity zones couplets from the Cambrian-Ordovician Boundary section at Xiaoyangqiao, Jilin province, equivalent to major portions of the Australian sequence. In the North China Block, Yang et al (1998, 2002) also documented the early Ordovician (Tremadoc) mixed polarity zones and the Middle Ordovician long-term reversed polarity zone. These studies demonstrated that there was a long-term reversed polarity zone

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between late Early and Middle Ordovician. However, Channell et al (1996) argued against this and proposed an alternative frame for the Ordovician geomagnetic polarity zones, the difference is that there are several short normal polarity zones within the long-term reversed polarity zone. The latest data from Siberia and Europe confirmed the work of Trench et al. (1991). For example, Schätz et al. (2006) demonstrated that the Upper Ordovician has alternating normal and reversed polarity zones. Pavlov et al. (2005, 2012, 2017) corroborated the occurrence of a long reversed magnetic polarity interval during the Ordovician, and formally named it the Moyero reversed superchron. Pavlov et al. (2005) finally built up a reasonable geomagnetic polarity zones for Early Ordovician thorough early Late Ordovician, composed of the Ordovician-Cambrian boundary series in the early Tremadocian (485.4 Ma-480 Ma), the Moyero reversed superchron from late Tremadocian to late Darriwilian (480 Ma-460.5 Ma), the Sandbian-early Katian mixed polarity interval (460.5 Ma-449 Ma), and the Hirnantian-Late Katian normal polarity zone at the top (Ogg, 2012). This geomagnetic polarity timescale for Ordovician, in particular the definition and duration of the Moyero reversed superchron (Pavlov and Gallet, 2005; Ogg, 2012; Grappone et al., 2017), has a great significance for the study of Ordovician magnetostratigraphy.

Cyclostratigraphy studies largely conducted out over North America, Europe, Africa and East Asia. From 1990s to the beginning of this century, the research focused on identifying Milankovitch cycles in the Ordovician strata and tried to setup an astronomical timescale, but most of them lacked high-precision geochronological data constraints. In North America, the remarkable sedimentary cycles in the Lower Ordovician strata in the Diablo platform, Texas, USA, was considered by Goldhammer et al. (1993) as the Milankovich cycle overprinted. Gong and Droser (2001) identified a short-eccentricity 100ka sedimentary cycle in the low-middle Ordovician in the western Utah, USA. Long (2007) identified eccentricity cycles of 100 kyr or 400 kyr in the Late Ordovician-Early Silurian carbonate layer on the island of Anticosti, Québec, Canada. Elrick et al. (2013) measured the $\delta^{18}O$ values of conodont and found out orbital-scale climatic fluctuations in a couple of Late Ordovician sections in Lexington, Kentucky, USA, and in the Anticosti Island, Québec, Canada. In western Australia, using the elemental geochemical data, Williams (1991) isolated the eccentricity and precession cycle from the Late Ordovician-Early Silurian clastic-carbonate-salt rock in the Canning Basin. In Africa, Sutcliffe et al. (2000) proposed that the Late Ordovician glaciations and mass extinction are controlled by the short eccentricity cycles, he also gave an estimation of the first extinction event in the Late Ordovician as about 0.3 Ma. In southern Siberia Rodionov et al. (2003) recognized cyclicities of short eccentricity (125 kyr), obliquity (27.9 kyr), and precession (17.82 kyr and 16.35 kyr) from the magnetic susceptibility data of the Ordovician strata on the Krivaya Luka section, and estimated the duration of the Volginsky fossil zone and the strata on the section as 1Ma and 1.2 Ma, respectively. In Tarim, NW China, Zhao et al. (2010) found the sixth- (meter-scale), fifth- and fourth-order cycles from the well logging data of the carbonate rocks of the Upper Ordovician Lianglitage Formation, and thought these cycles correspond respectively to precession, short - and long - eccentricity cycles. Furthermore, Zhang et al. (2011) distinguished an obliquity cycle (37kyr) in the Lower Ordovician Yingshan Formation in the center of Tarim, and estimated a duration for this formation as about 4.92Ma. In the North China, Ma et al. (2016) found out the long eccentricities of 405kyr and short-eccentricity of 90kyr based on the analysis of the Fe/Ca and Ti/Ca ratios of the Lower Ordovician Liangjiashan formation in Qinhuangdao, Hebei Province. Also, according to the long eccentricity cyclicity, the float astronomical age of the Liangjiashan was estimated at 6.2 Myr (Ma et al., 2016). In North Korea, the meter-scale sedimentary cycles of the Lower Ordovician Dumugol Formation may correspond to short eccentricity cycles (Kim and Lee, 1998).

Recently, with the progress of high-precision dating techniques and exploration of a variety of paleoclimatic proxies, the establishment of a high accuracy astronomical timescale is possible. Svensen et al. (2015) measured the magnetic susceptibility of the shale in the Upper Ordovician Arnestad Formation in the Vollen of Oslo, Norway. Combined with the high precision U-Pb age of tuff interlayers, he interpreted the sedimentary cycles of 1 m and 0.28 m thick as short-eccentricity of 109 kyr and obiquity of 30.3 kyr, and estimated the duration of the 7 meter thick strata as 766 kyr, and the Sandbian/Katian boundary age as 451.88 Ma± 0.37 Ma. Fang et al. (2016) recognized the short-eccentricity, obliquity and precession cycles in the 34-m-thick strata of the Upper Ordovician Lower Pingliang Formation in the southwestern Ordos, North China, based on the lithology and magnetic susceptibility values. These cyclicities featured in stratigraphic thickness (equivalent age) of 85.5-124 cm (95kyr), 23-38 cm (35.3kyr and 30.6kyr) and 15-27 cm (19.6kyr and 16.3kyr), respectively. The measured stratigraphic interval was estimated to be about 3.38 Myr or 3.22Myr. Zhong et al. (2018) conducted high-resolution magnetic susceptibility measurement on the Middle Ordovician rocks on the Huangnitang section and a corenearby in Zhejiang Province, South China, and found Milankovitch cycles of 405 kyr, 101–135 kyr, 31–34 kyr, and15.8–21.3 kyr, and estimated the durations ofthe Darriwilian and Dapingian stages as8.38 ± 0.4 Myr and 1.97 ± 0.7 Myr, respectively. The duration of the Darriwilian stage is very close to the estimation by Gradstein et al. (2012), but the Dapingian stage is much shorter than estimation by Gradstein et al. (2012).

Those researches show that cyclicity is remarkable in the Ordovician sedimentary rocks and their formation was controlled or affected by the sedimentary process and paleoclimatic change, which indicates an outstanding overprinted orbital cyclicity. For example, the glaciation in the high latitudes during the Late Ordovician was controlled by the obliquity of the earth's axis and atmospheric CO_2 (Herringmann et al., 2003). Also, this phenomenon has no difference in both low- and high-latitudes regions, for instance, Ghienne et al. (2014) compared the Late Ordovician sedimentary records in low- and high-latitudes regions and found that the Late Ordovician glacial cycles may have super long obliquity periods of 1.2 Myr. On the other hand, Milankovitch cycles recorded in the Ordovician strata include long and short eccentricity, obliquity, and precession cycles, but the length of these cycles varied greatly across regions. Moreover, only the long eccentricity has been used to establish floating astronomical time scales. At the same time, theoretical astronomical orbital parameter models (Laskar et al., 2011; Wu et al., 2011, 2017) and high-precision geochronology (including radioisotope dating and magnetic stratigraphy) are lacking. Finally, since the proxies employed are different in the manifestation and the mechanism, their sensitivity to the cyclicity and the reliability of research outcomes have not been systematically evaluated. All these seriously restricts the study of high-precision astronomical time scale of Ordovician.

Key words: magnetostratigraphy, geomagnetic polarity timescale, cyclostratigraphy, geologic timescale, Ordovician

Acknowledgments: This work is supported by the Fundamental Research Funds for the Central Universities (Grant No. lzujbky-2017-k27) and contributed to IGCP 652.

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