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Review article

Magnetic susceptibility as a high-resolution correlation tool and as a climatic proxy in Paleozoic rocks – Merits and pitfalls: Examples from the Devonian in Belgium

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A B S T R A C T

Low-field magnetic susceptibility (χ_{in}) measurements are quick and sensitive enabling the creation of high-resolution records; making χ_{in} an attractive correlation tool and a proxy for paleoclimate and paleoenvironments. In geologically young material – foremost in Cenozoic sediments – χ_{in} belongs to the geoscientist's toolkit. However, χ_{in} is a convolved signal and may reflect other processes than the often implicitly inferred depositional conditions. Diagenesis, remagnetization and low-grade metamorphism, can potentially obscure the original, depositional, χ_{in} signal. This aspect is particularly important when interpreting χ_{in} records from Paleozoic rocks.

Here, we review data obtained from a large sample collection of Middle to Upper Devonian sections in Belgium. Comparison of χ_{in} trends with paleoenvironmental indicators (facies) and with detrital input proxies (Zr, Th, Ti, Al) allowed to assess the persistence of depositional trends. Furthermore, the χ_{in} signal was deconvolved into its dominant mineralogical contributions with the help of magnetic-property analysis.

The main results are pointing to a magnetic signal dominated by fine-grained magnetite, of which paleomagnetic analysis indicated a formation during Carboniferous remagnetization. This prompts a potentially strong influence of post-depositional processes and it complicates the interpretation of χ_{in} records in terms of depositional environments. However, in most of the sections, there is a relatively good relationship between χ_{in} trends and facies evolution and between χ_{in} and geochemical proxies for detrital inputs. This indicates that the newly formed magnetite grains would at least partly remain where they are formed, and this allows a relative preservation of the original signal, despite the strong influence of diagenesis. Two sections show a stronger impact of diagenesis, where for about half of these sections, the primary, depositional information is lost.

The Eifelian–Givetian Monts de Baileux section was selected for time-series analysis of the χ_{in} series. The Average Spectral Misfit (ASM) method is applied to explicitly evaluate the null hypothesis of no orbital signal and in this section, there is 99.05% chance that the MS signal is reflecting an orbital imprint.

1. Introduction

Since the 1980s magnetic susceptibility (labeled χ_{in}, χ_{LF}, κ, or MS; in this contribution we opt to use χ_{in}) has been increasingly used in recent sediment records as a paleoclimatic proxy or as a correlation tool (e.g. Kent, 1982; Mead et al., 1986; Thompson et al., 1980; Soreghan et al., 1997; Vanderaveroet et al., 1999). It is

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routinely adopted in the International Ocean Drilling Program (IODP) for correlation purposes since the 1980s as well (e.g. Bloemendal et al., 1988). A close relationship between magnetic susceptibility, lithogenic input and oxygen isotopes led to use χ_{in} as a paleoclimatic indicator (e.g. Curry et al., 1995; Robinson, 1986, 1993). Spectral analysis of χ_{in} records demonstrated the response of the sedimentary system to astronomically driven climate change (e.g. Mead et al., 1986; Shackleton et al., 1999; Boulila et al., 2008; De Vleeschouwer et al., 2012a, 2012b).

While IODP program work often relates to unlithified sediments, magnetic susceptibility measurements were increasingly retrieved from lithified sediments of Mesozoic and Palaeozoic age since the end of the 1990s (e.g. Crick et al., 1997). This technique called magnetosusceptibility event and cyclostratigraphy (MSEC) is claimed to enable establishing intercontinental correlations which are argued to be facies-independent and of a higher resolution than biozones (Ellwood et al., 1999; Crick et al., 2000). Since the beginning of the 21st century, this technique has become more popular and has been used for correlating Paleozoic sediment sequences (Bábek et al., 2007; Bertola et al., 2013; Da Silva and Boulvain, 2010; Da Silva et al., 2009a, 2010; Devleeschouwer et al., 2010; Ellwood et al., 2006, 2007; Hladil, 2002; Hladil et al., 2003; Koptíková, 2011; Koptíková et al., 2010; Racki et al., 2002; Whalen and Day, 2010). The present contribution is carried out under the umbrella of the IGCP-580 (UNESCO, 2009–2013) project, which is dedicated to the "Application of magnetic susceptibility as a paleoclimatic proxy on Paleozoic sedimentary rocks and characterization of the magnetic signal".

The rationale behind the application of magnetic susceptibility to rocks is similar to that in the case of recent sediments. The underlying line of thinking is that the provenance of magnetic minerals is detrital input. Variations in detrital input are driven by climate, sea level or tectonic changes (the latter leading to long-duration 'base level' changes). The use of χ_{in} records is well appreciated because data acquisition is fast and straightforward, providing the high-resolution data required for climatic studies, correlations and paleoenvironmental research. All iron-bearing minerals – silicates, carbonates, sulfides, or oxides – show a positive response when subjected to a magnetic field (this is the free electron spins tend to line up with the applied field). Depending on whether or not the free electron spins of the iron ions in the mineral behave collectively, the minerals are classed as paramagnetic (non-collective spin behavior, small positive response) or ferromagnetic (collective spin behavior, very large positive response). We speak off paramagnetic or ferromagnetic minerals. Examples of paramagnetic minerals are clay minerals or pyrite, etc.) while examples of ferromagnetic minerals (sensu lato) include magnetite (Fe_3O_4), and the magnetic iron sulfides (greigite (Fe_3S_4) and pyrrhotite (Fe_7S_8)). Minerals that contain only paired electron spins in their structure like quartz or calcite are in magnetic terminology termed diamagnetic and they have a negative response to an applied field. The ferromagnetic minerals often occur only in trace amounts in essentially all rock types but their contribution to a rock's χ_{in}, however, is often significant because of the very high specific susceptibility of these minerals (in comparison with paramagnetic and diamagnetic minerals).

Compared to recent sediments, Paleozoic or younger rocks affected by diagenesis have some additional potential complexities that should be considered when interpreting χ_{in} records. 1) The primary paleoenvironmental setting is often not that well constrained; so the origin of the magnetic minerals is rather poorly constrained as well (e.g. proportion of eolian and riverine input, influence of biological processes during deposition). 2) After deposition, post-depositional transformations can be relatively strong, from the very early diagenesis, to burial, remagnetization and metamorphism (e.g. McCabe and Elmore, 1989; Elmore et al., 1993, 2012; Font et al., 2006, 2012; Rowan et al., 2009). Thus, it was clearly demonstrated that diagenesis can create or destroy magnetic minerals (Channel and McCabe, 1994; Katz et al., 2000; Elmore et al., 2001; Zegers et al., 2003; Zwing et al., 2009). Indeed, the magnetic susceptibility signal can be a convolved expression of detrital, diagenetic and later remagnetization processes; thus, for a meaningful interpretation in terms of paleoenvironment and paleoclimate, the origin of the magnetic susceptibility signal must be fully understood. This implies the untangling of the influence of primary sedimentary processes and secondary processes (i.e. diagenesis, metamorphism, and potential remagnetization). However, only few studies addressed the question of the potential influence of diagenesis and metamorphism on the χ_{in} signal (Schneider et al., 2004; Devleeschouwer et al., 2010; Riquier et al., 2010; Da Silva et al., 2012).

A remagnetization event was described in the carbonate rocks of the Devonian of the Rhenohercynian fold and thrust-belt (Molina Garza and Zijderveld, 1996; Zwing et al., 2002, 2005, 2009; Zegers et al., 2003). However, a clear link between facies and magnetic susceptibility was also highlighted (Da Silva and Boulvain, 2002, 2006), indicating a possible preserved paleoenvironmental signal. Here, we review a decade of research on the χ_{in} signal from the Devonian of Belgium. A compilation of various techniques serves to identify these preserved primary trends; the origin of the magnetic susceptibility signal is evaluated and the influence of remagnetization established. As a first approach, the origin of the magnetic susceptibility signal is assessed by comparing the χ_{in} records with paleoenvironmental proxies, such as facies indicators (Da Silva and Boulvain, 2006). Further elemental analysis is performed on selected sections so that measured χ_{in} patterns can be evaluated against trends of acknowledged detrital elements such as Zr, Rb, Ti and Al. Comparison with facies allows for the determination of an effective link between χ_{in} and depositional environment, while the elemental proxies reflect changes in the source, amount or type of weathering (Tribovillard et al., 2006; Calvert and Pedersen, 2007; Riquier et al., 2010). To help explain the origin of the χ_{in} signal, a more detailed rock-magnetic characterization is performed on selected samples. Measurement of magnetic hysteresis loops enables the distinction of the paramagnetic and diamagnetic contributions to χ_{in}, distinguishing the matrix contribution from the ferromagnetic contribution. With acquisition curves of the isothermal remanent magnetization (IRM) the ferromagnetic minerals are characterized in more detail. This allows to evaluate the influence of diagenesis, remagnetization and (incipient) metamorphism on the χ_{in} signal by comparison with published data. Finally, after an in-depth assessment of the impact of secondary processes on χ_{in} trends, we selected a section where the χ_{in} signal is shown to reflect depositional conditions, for spectral analysis. The imprint of astronomical forcing is discussed.

2. Geological setting

The studied Devonian neritic limestone outcrops from southern Belgium are part of the western zone of the Rhenohercynian fold-and-thrust belt. From the Eifelian until the late Frasnian, southern Belgium was located at 15–20° south of the equator, with a humid tropical climate (Copper, 2002; Joachimski et al., 2009). These conditions favored the expansion of well-developed reef carbonates during this period. The most distal part of the carbonate platform ("southern belt") is located along the southern border of the Dinant Synclinorium (Fig. 1A); what is referred to as the "intermediate belt" is represented in this study by a single section in the Philippeville Anticlinorium. The shallowest facies are exposed along the northern border of the Dinant Synclinorium ("northern