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Micro- and nanobands in late Archean and Palaeoproterozoic banded-iron formations as possible mineral records of annual and diurnal depositions

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ABSTRACT

The microbands in Precambrian banded-iron formations (BIFs) have been conjectured to record annual or even diurnal depositions. However, these bands have rarely been observed in high resolution at their true (micro) scale. Here, I suggest that nanobands of fine-grained hematite represent possible diurnal depositions and that microbands of chert/jasper represent possible annual depositions in three sets of BIFs: 2460-Myr BIFs from the Kuruman Iron Formation, Transvaal Supergroup of South Africa; 2480-Myr BIFs from the Dales Gorge Member of the Brockman Iron Formation, Western Australia; and 2728-Myr BIFs from the Hunter Mine Group, Abitibi Greenstone Belt, Canada. Observations made using scanning electron microscopy indicate that hematite and chert were syngenetic, and that there was a hiatus between their precipitation and the genesis of the remainder of the minerals containing structural Fe(II). Spindle-like grains of hematite, monocrystals of magnetite, and ferro-dolomite formed microbands of ∼30–70 μm in thickness, which appear cyclically in the matrix of the chert. Neither the band-bound magnetite and dolomite nor the linear formations of the hematite spindles represent annual depositions due to their diagenetic features. The thinnest microbands (∼3–∼12 μm) were observed in the chert and jasper, and indicate depositional rates of 6.6–22.2 m/Myr in the BIFs. These rates are consistent with the integrated deposition rates calculated by geochronologic methods for the BIFs, if annual deposition is assumed. The ∼26-nm nanobands observed only in hematite grains reflect an annual deposition of ∼18.6 μm, or ∼18.6 m/Myr, which is also consistent with the depositional rate calculated by geochronologic methods. It is tentatively suggested that these ∼26-nm nanobands were formed from the diurnal precipitation of Fe(III) resulting from the circadian metabolism of Fe(II)-oxidizing or oxygen-evolving photosynthetic microorganisms, which slowed down the rise of atmospheric oxygen. The diurnal precipitation of Fe(III) as hematite and the annual deposition of silica as chert/jasper in the BIFs provide internal clocks that may facilitate the examination of short-term processes, such as ecological, oceanographic and climatic cycles, that are recorded by the mineral or chemical compositions of BIFs.

1. Introduction

Banded-iron formations (BIF) are the result of chemical depositions that occurred at one particular stage in Earth's evolution (3.8–1.8 Ga, Krapež et al., 2003; Klein, 2005), and are characterized by the dichotomous sedimentation of rough, silica-rich and iron-rich bands with hierarchical thicknesses and mineral structures. The fascinating question of how these bands were formed has received several highly controversial answers. Macrobands, mesobands and microbands are three distinct scales of bands recognized in BIFs, representing geological episodes with different time-scales and/or varying sedimentary rhythmites (Trendall and Blockley, 1970; Trendall, 2000). Mesobands contain microbands with a mean thickness of between 0.3 and 1.7 mm (e.g., Trendall, 2000); the thinnest microbands are ⩽0.05 mm thick (Morris, 1993; Williams, 2000), and were once thought to be the most informative bands (Morris, 1993). The thinnest microbands were envisaged as either diurnal precipitates (e.g., Cisne, 1984; Castro, 1994) or annual varves deposited as a result of seasonal oscillations in temperature and geochemistry (Trendall and Blockley, 1970; Trendall, 2000). Researchers have also suggested that these annual bandings

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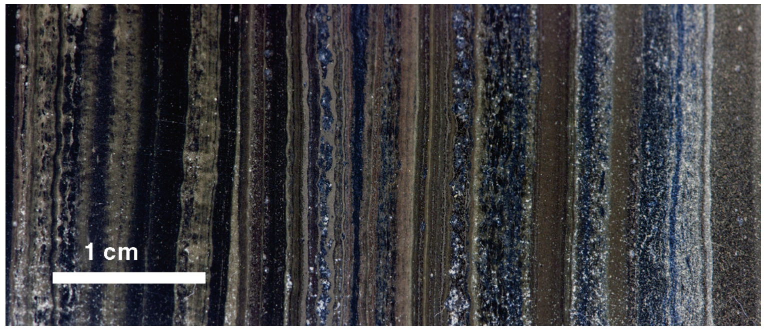

Fig. 1. Optical image of the segment of the Kuruman BIF sampled in this study.

reflect longer climatic cycles due to their cyclical appearance (see Walker and Zahnle, 1986 who proposed a 23.3-year cycle).

The deposition rates of BIFs can be determined by geochronologic methods only when they have been sandwiched by volcanic tuffaceous rocks containing minerals subject to radioactive dating. Using this method, the integrated depositional rates of BIFs have been calculated at time resolutions as high as ± 3 Myr (e.g., Trendall, 2000, 2002; Pickard, 2002, 2003; Trendall et al., 2004). However, no intrinsic speedometry with a time scale comparable to that of climatic and ecological cycles can be used to evaluate ocean-deposited banded iron. Although such bands, especially the famous "Trendall bands" of the Dales Gorge in Western Australia (e.g., Morris, 1993) and the Kuruman Iron Formation of South Africa, have well-developed rhythmites comparable to those of post-Cambrian deposits, the lack of accurate estimates of depositional rates makes it difficult to reconstruct the climatic, oceanographic and ecological cycles involved.

Baur et al. (1985) measured the carbon- and oxygen-isotopic compositions of a set of 32 adjacent microbands at millimeter scale, and found rough variations between adjacent bands. Recent geochemical studies of BIFs have revealed extensive interactions between the ocean, the atmosphere and their complementary biospheres, including a slowing down of the rise in atmospheric oxygen (e.g., Anbar and Knoll, 2002; Bjerrum and Canfield, 2002; Kump and Barley, 2007; Frei et al., 2009; Fru et al., 2013; Konhauser et al., 2009, 2011; Poulton et al., 2004). In particular, studies involving *in situ* measurements of unconventional isotopes in BIFs have great potential to illuminate the processes related to ocean chemistry, (bio)mineralization and diagenesis (e.g., Frost et al., 2007; Marin-Carbonne et al., 2011; Steinhoefel et al., 2009, 2010). The degree of accuracy of these analyses relies heavily on the microlandscapes of the BIFs under study. First, the geochemical behavior of trace elements or unconventional isotopes in BIFs is determined by their partitioning among submicrometer- or even nanometer-scale minerals; second, the size and distribution of magnetite crystals in BIFs may directly influence the distribution of electron beams and magnetic fields during *in situ* analysis. However, only a few high-resolution petrologic and mineralogical studies of BIFs have been carried out using electron microscopes (e.g., Ahn and Buseck, 1990; Kolo et al., 2009; Li et al., 2011, 2013a, 2013c; Huberty et al., 2012). In this study, electron microscopes are used to characterize BIF minerals from the early Palaeoproterozoic and late Archean eras, with initial attentions to micro- and nanobands in BIF hematite grains. Explanations of chert/jasper bands as the result of annual deposition and hematite nanobands as the result of diurnal precipitation are found to be consistent with the depositional rates of BIFs previously determined by geochronologic methods.

2. Samples and methods

Representative BIF samples from the late Archaen and early Palaeoproterozoic eras were examined. The BIFs sampled from the Kuruman Formation and Dales Gorge are of a similar age, and researchers have suggested that they formed on the same continent (Pickard 2002, 2003; Beukes and Gutzmer, 2008). The Kuruman Iron Formation is in the Transvaal Supergroup of the Northern Cape Province, South Africa; it has a SHRIMP U–Pb age of 2460 Myr (Pickard, 2003), and its peak metamorphic temperature has never exceeded 110–170 °C (Miyano and Beukes, 1984). The Dales Gorge Member BIF is in the Brockman Supersequence of the Hamersley Range Megasequence. It is 2480 Myr old (Pickard, 2002), and is known to have experienced low-grade metamorphism at 60–160 °C (Kaufman et al., 1990). The Dales Gorge Members are made of alternating layers of fine-grained iron oxides and chert, with occasional thin layers of carbonate (Ewers and Morris, 1981; Dukino et al., 2000). The Abitibi BIF is embedded in the uppermost section of the Hunter Mine Group, a bimodal volcanic complex in the Abitibi Greenstone Belt, and is 2728 Myr old (Mueller and Mortensen, 2002). The sample for this study was taken from the chert–jasper–magnetite facies preserved in a large, folded rip-up clast within volcanic breccias (Chown et al., 2000; Weiershäuser and Spooner, 2005). Fig. 1 shows part of the banding structures of a hand specimen from the Kuruman Iron Formation, in which more than 100 microbands can be identified easily using the naked eye. As emphasis is placed in this report on the general features of microbands in BIFs, the sources of the samples are not specified, unless otherwise noted.

A Hitachi S-4800 FEG scanning electron microscope (SEM) was used in the secondary-electron (SE) mode at a low voltage (3–5 kV) to characterize the surface structures. The same microscope was used in the backscatter-electron (BSE) mode at a high voltage (20 kV) to portray electron density, which results in textural differentiation. In terms of structural differentiation, a Tecnai G2 20 S-TWIN transmission electron microscope (STEM) was used to characterize the size and morphological behavior of single crystals of ultrafine hematite, and equipped energy-dispersive X-ray spectroscopy (EDS) was used to measure the chemical compositions.

3. Results

Consistent with previous petrologic observations (Trendall and Blockley, 1970; Morris, 1993; Trendall, 2002; Krapež et al., 2003), the SEM observations showed bands of various thicknesses, from macro scale (>cm, Fig. 1) to just a few µm. Hereafter, the term "microband" is used to describe bands with truly µm-scale thicknesses. Such microbands may be made of chert/jasper, magnetite, ferro-dolomite, hematite grains or stilpnomelane (Stp). Although