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Silica precipitation triggered by clastic sedimentation in the Archean: New petrographic evidence from cherts of the Kromberg type section, South Africa

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ABSTRACT

The Kromberg Formation (ca. 3432 Ma) in the Barberton Greenstone Belt, South Africa, contains well-preserved chert beds at the tops of turbidite deposits. At the interface, siltstone, which consist of K-feldspar, K-mica, microquartz with minor lithic fragments and heavy minerals, grades into chert, which consists of microquartz and minor K-mica (<15%). K-feldspars show preserved twins typical of microcline, orthoclase and sanidine. Based on the heterogeneity of the clastic fraction (i.e. shape, size, nature), the lack of in situ metasomatic features (i.e. crystal overgrowths, silica replacement) and the continuity of the siliceous matrix through the siltstone-to-chert transition, we argue that (1) the clastic particles are detrital, (2) some were altered and metasomatized at their source, (3) in situ metasomatism was limited to minor seritization of K-feldspars, and (4) the silica is of primary origin and precipitated from ambient marine fluids. Our petrographic observations reinforce the model advocated by Rouchon and Orberger (2008) and Rouchon et al. (2009) for chert deposited in clastic-rich setting and we favor a formation of both the siltstones and cherts as chemico-clastic sediments. We argue for the contemporaneous deposition of clastic grains from turbiditity currents and precipitation of silica on phyllosilicate reactive surfaces, both in the water column and at the sediment–water interface. As the rate of clastic sedimentation declined, the accumulation of silica flocs on suspended phyllosilicates first accompanied, then replaced the deposition of detrital grains, to form a siliceous ooze at the seafloor. Contrary to current interpretations for detritus-rich cherts, which invoke a secondary origin via Si- and K-metasomatism, we propose that the present model prevailed in a variety of Archean settings where fine-grained sediments were deposited. The composition of both the siltstone and chert reflects mainly the environment in which they formed. They are interpreted as mixtures of two main components: (1) silica, which contains extremely low concentrations of trace elements and contributes only SiO_2 to the bulk composition, and (2) another phase that dominates the trace element composition. Here, K-mica and K-feldspar control the chemical signal and reflect a felsic source to the turbidites (i.e. Hooggenoeg dacites and volcaniclastics).

1. Introduction

On the modern Earth, ever since the Proterozoic, both the silica cycle and the formation of cherts are essentially controlled by biological activity; during the Archean, however, the absence of skeleton-forming organisms allowed only inorganic silica precipitation (e.g. Siever, 1992; Treguer et al., 1995; Perry and Lefticariu, 2003; Maliva et al., 2005). The voluminous chert deposits found in Archean greenstone belts are therefore interpreted to reflect the physico-chemical conditions of the eon, and particularly elevated concentrations of dissolved silica in the oceans (e.g. Siever, 1992; Maliva et al., 2005).

Cherts through geological time show a wide variety of depositional environments, chemical compositions, mineralogies and formation processes. There is, however, no consensus on the nomenclature, nor even on the definition, of chert. All authors agree that the silica content must exceed 75–80 wt% (e.g. Folk, 1980; Knauth, 1994), but differences emerge regarding the origin of cherts. Two models dominate the discussion: (1) silicification of preexisting rocks, or (2) direct precipitation of silica from seawater or hydrothermal fluids.

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In the first model, Archean cherts are considered to result from the pervasive replacement of a variety of rock precursors, including (i) volcaniclastic and terrigenous debris (e.g. Lowe and Knauth, 1977; Lowe, 1980; Paris et al., 1985; De Vries, 2004), (ii) chemical sediments such as carbonates and evaporites (Knauth, 1973; Lowe and Knauth, 1977; Knauth and Lowe, 1978; Weis and Wasserburg, 1987; Lowe and Fisher Worrell, 1999; Van Kranendonk et al., 2003) and (iii) massive lavas (Hofmann and Wilson, 2007; Hofmann and Harris, 2008). The silicification is thought to be triggered either by fluid circulation during hydrothermal activity (Knauth and Lowe, 1978; de Wit et al., 1982; Duchac and Hanor, 1987; Paris et al., 1985; de Wit and Hart, 1993; Knauth, 1994; Perry and Lefticariu, 2003; Hofmann, 2005; Hofmann and Wilson, 2007; Hofmann and Harris, 2008), or by low-temperature seawater–rock interaction at or below the surface during early diagenesis (Knauth and Lowe, 1978; de Wit et al., 1982; Sugitani, 1992; Lowe, 1999; Lowe and Fisher Worrell, 1999; Van Kranendonk and Pirajno, 2004; Tice and Lowe, 2006; Rouchon and Orberger, 2008).

The second model, which invokes direct precipitation of silica from oceanic water, was first proposed for jasper layers in banded iron formations, then extended to other siliceous deposits such as banded cherts. The silica can be precipitated from Si-oversaturated seawater (Knauth and Lowe, 1978; Hesse, 1989; Sugitani et al., 1998; Perry and Lefticariu, 2003; Hofmann, 2005; Maliva et al., 2005; Tice and Lowe, 2006), from hydrothermal vent fluids near active volcanic settings (e.g. mid-oceanic ridges) (e.g. Sugitani, 1992; De Vries, 2004; Hofmann and Bolhar, 2007), or from a mixture of both (e.g. Derry and Jacobsen, 1990; Frei and Polat, 2007; Van den Boorn et al., 2007, 2010; Marin-Carbonne et al., 2012). The composition of cherts considered to have precipitated from seawater is regarded as representative of early ocean chemistry, making them among the most powerful tools to investigate early Earth environments (e.g. Derry and Jacobsen, 1990; Sugitani et al., 1996, 1998; Knauth and Lowe, 2003; Perry and Lefticariu, 2003, 2006; Kato and Nakamura, 2003; Bolhar et al., 2005; Robert and Chaussidon, 2006; Jaffres et al., 2007).

However, criteria for the recognition of the various chert types are ambiguous and none can reliably distinguish between primary oceanic precipitates, hydrothermal deposits and secondary cherts. Criteria commonly used include field relations and sedimentary structures (e.g. Knauth and Lowe, 2003; Maliva et al., 2005), petrological characteristics (e.g. Knauth, 1994; Knauth and Lowe, 2003), and trace element and/or isotopic compositions (e.g. Kato and Nakamura, 2003; Bolhar et al., 2005; Van den Boorn et al., 2007, 2010; Marin et al., 2010; Marin-Carbonne et al., 2011, 2012), the latter approach being perhaps the most popular. Identification of formation processes is especially challenging for cherts formed in clastic environments, which are made up of a detrital component and silica cement. Following accepted models, such a rock would be considered to have formed either by the precipitation of silica from marine fluids contemporaneously with clastic sedimentation, or by silica addition and replacement of primarily deposited sediments during diagenesis and secondary fluid circulation (i.e. Si-metasomatism).

For this study we chose the Kromberg type section (ca. 3432 Ma) in the Barberton Greenstone Belt, South Africa, because it contains well-preserved chert beds at the tops of turbidite deposits. We first report field and petrological criteria that allow us to infer the origin of the chert and to test both hypotheses of formation. We then use a geochemical approach to investigate the paleo-environment of chert deposition. Our results (1) offer new criteria for chert characterization, (2) provide a better understanding of the role of clastic sedimentation in silica precipitation, and (3) place constraints and open new possibilities on the use of cherts as paleo-environment proxies.

2. Nomenclature used for cherts

In addition to the long-standing debate on chert formation process, the absence of a clear distinction between different chert types hinders our understanding of their formation and their use as proxies of conditions at the Archean seafloor. The most commonly used nomenclatures are based on (1) chert color (e.g. light to dark gray, greenish gray to green, bluish to dark blue, etc.), (2) structure and outcrop organization (e.g. laminated, massive, vein, banded, etc.), and/or (3) minor components (e.g. carbonaceous, ferruginous, argillaceous, tuffaceous, etc.). Such terminologies, although useful for descriptive purposes, provide little information on the origin of chert, and they vary widely from one author to another.

Van den Boorn et al. (2007) were the first to propose a nomenclature based on the formation process and we adapt their scheme in this paper. (1) Primary cherts are defined as primary chemical precipitates. We conserve the term “C-chert” (i.e. chemical-chert) of Van den Boorn et al. (2007) for oceanic precipitates (Fig. 1a) on the ocean floor and for primary, early diagenetic cement in the uppermost sedimentary layers. (2) We introduce the term “F-chert” (i.e. fracture-filling chert) for discordant and concordant chert precipitated in veins/fractures (Fig. 1b) from fluids that circulated through the crust (e.g. hydrothermal fluids, diagenetic fluid escapement, shallow seawater circulation). (3) Secondary cherts, or “S-cherts”, differ from the other cherts in that they result from the replacement by Si-metasomatism of a sedimentary or volcanic protolith (Fig. 1c), either during percolation of low-temperature seawater or by circulation of low- to high-temperature silica-rich hydrothermal or diagenetic fluids. This nomenclature is illustrated in Fig. 1. As with most geological classifications, the differences between the three types of chert are not always well defined but the classification is useful to distinguish rocks forming by the three main chert-forming processes.

3. Geological background and scientific approach

Archean rocks of the Barberton Greenstone Belt (3.57–3.21 Ga), in South Africa and Swaziland, include a well-preserved volcano-sedimentary succession known as the Swaziland Supergroup (e.g. Viljoen and Viljoen, 1969b; Lowe and Byerly, 1999). The Sandspruit and Theespruit Formations are the oldest and most highly metamorphosed parts of the belt. They mark the base of the sequence and are overlain by three thicker and more extensive units: the mafic- to ultramafic-volcanic dominated Onverwacht Group (3570–3334 Ma), further divided into the Komati, Hooggenoeg, Kromberg and Mendon Formations, the argillaceous Fig Tree Group (∼3258–∼3226 Ma), and the arenaceous Moodies Group (∼3223–3240 Ma) (see the following papers for further stratigraphic details: Viljoen and Viljoen, 1969a; Armstrong et al., 1990; Kröner et al., 1991; Heubeck and Lowe, 1994; Kamo and Davis, 1994; Lowe and Byerly, 1999; Tice and Lowe, 2004; Hofmann, 2005; Brandl et al., 2006; de Wit et al., 2011; Furnes et al., 2011; Heubeck et al., 2013).

The studied site is located on the eastern limb of the Onverwacht anticline (Fig. 2a). Cherts and silicified sedimentary and volcanic strata are common in this well-exposed type section along the Komati River. They form part of the Kromberg Formation, in a unit referred to as the Noisy Formation by Biggin et al. (2011). Along the banks of the river, within the Songimvelo Nature Reserve, a 200 m-thick sequence of well-bedded clastic sedimentary rocks outcrops continuously and consists mainly of upward-fining conglomerates, diamictites and turbiditic sandstones (Fig. 2b). This section has been widely studied to constrain the depositional setting of some of the world’s oldest siliciclastic deposits and to better understand regional tectonic processes (e.g. Viljoen and Viljoen, 1969a; Lowe