Precambrian Research 229 (2013) 93–104

Contents lists available at SciVerse ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Archean gravity-driven tectonics on hot and flooded continents: Controls on long-lived mineralised hydrothermal systems away from continental margins

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ARTICLE INFO

Article history:
Received 1 February 2011
Received in revised form 17 February 2012
Accepted 1 March 2012
Available online 8 March 2012

Keywords:
Sagduction
Numerical simulation
Archean Tectonic
Thermal evolution
Gold mineralisation

ABSTRACT

We present the results of two-dimensional numerical modelling experiments on the thermal evolution of Archean greenstones as they sink into a less dense, hot and weak felsic crust. We compare this thermal evolution to that obtained via the analysis of isotopic data and fluid inclusion microthermometry data obtained in the Paleoarchean to Mesoarchean Warrawoona Synform (Eastern Pilbara Craton, Western Australia). Our numerical experiments reveal a two-stage evolution. In the first stage, cooling affects zones of downwelling as greenstone belts are advected downward, whereas adjacent domes become warmer as deep and hot material is advected upward. We show that this is consistent with stable isotopes data from the Warrawoona Synform, which reveal an early episode of seafloor-like alteration (90–160 °C) strongly focused along steeply dipping shear zones. In a second long-lived stage, lateral heat exchanges between domes and basins dominate the system as domes cool down while downwelling zones become increasingly warmer. In the Warrawoona greenstone belt, stable isotopes in gold-bearing quartz veins post-dating the sagduction-related vertical fabrics reveal that rock–fluid interaction occurred at much higher temperatures (234–372 °C) than seafloor-like alteration. We propose that emplacement of thick and dense continental flood basalts, on flooded hot and weak continental plates, led to conditions particularly favourable to hydrothermal processes and the formation of mineral deposits. We further argue that sagduction was able to drive crustal-scale deformation in the interior of continents, away from plate margins. On largely flooded continents, sagduction-related shear zones acted as fluid pathways promoting gold mineralisation far away from active plate boundaries, continental rift zones or collisional mountain belts.

1. Introduction

Several features made the Paleo- to Mesoarchean landscape (3.6–2.8 Gyr old) fundamentally different than it is today, and particularly favourable to the formation and preservation of gold deposits. First, most Archean cratons are buried under up to 15 km thick blanket of autochthonous Continental Flood Basalts (CFBs, e.g. Maurice et al., 2009), which include high-magnesium basalts and komatiites that have only few equivalents on modern Earth. Second, despite their thicknesses most of these thick volcanic piles were emplaced below, and remained below, sea level for most of their Archean history (Arndt, 1999; Flament et al., 2008, 2011; Kump and Barley, 2007). This characteristic is of great importance as it implies that an infinite fluid reservoir was available to feed hydrothermal circulations in the CBFs. Third, radiogenic heat production in the continental crust was much higher than it is today which, in combination to the thermal insulation effect of CFBs, provided the heat engine, in the form of a strong thermal gradient, to power hydrothermal cells in the CFBs. Fourth, Paleoarchean to Mesoarchean cratons throughout the world are characterised by ovoid granitic domes, 40–100 km in diameter, encircled by greenstone belts. Greenstone belts form strongly foliated vertical sheets connected through vertical triple junctions where constrictional fabrics dominate (Bouhallier et al., 1995; Chardon et al., 1996; McGregor, 1951). This dome and basin pattern, which characterises many Archean cratons, is commonly interpreted in terms of gravitational sinking (sagduction) of dense greenstone belts into hot, and therefore weak, felsic crust (Chardon et al., 1996, 1998; Collins et al., 1998; Dixon and Summers, 1983; Mareschal and West, 1980; McGregor, 1951). This process is often wrongly described as "vertical tectonics". Indeed, during sagduction horizontal and vertical displacements are perfectly coupled. Domes can rise and greenstone keels can sink because horizontal displacements provide the necessary space for vertical mass transfer (e.g. Mareschal and West, 1980). This process is also often wrongly opposed to plate boundary driven deformation. Indeed there is

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doi:10.1016/j.precamres.2012.03.001

no mechanical incompatibility between sagduction and plate tectonics processes as both can coexist spatially and temporarily (e.g. Bloem et al., 1997; Rey et al., 2003). While Archean lode gold deposits are interpreted traditionally as hydrothermal systems developed along convergent margins (Groves et al., 1998), sagduction provided a mechanism to deform the interior of continents, hence greatly enlarging the domain where mineral deposits could form. Fifth, considerations on the rheology of Archean continental lithospheres suggest that continents in the Archean were unable to sustain elevated mountain belts and high orogenic plateaux (Rey and Houseman, 2006; Rey and Coltice, 2008). Elevations > 3000 m would have been absent at the surface of the Earth, which would have strongly limited erosion, providing an explanation for the remarkable preservation of Archean supracrustal environments. We suggest that these Archean specificities provide some rationales to explain the exceptional endowment in mineral resources in general, and in gold in particular, of most Archean cratons when compared to younger terranes (Goldfarb et al., 2001).

In this paper, we present results of two-dimensional coupled thermo-mechanical numerical experiments on the sagduction of greenstones into a hot and weak felsic crust. We compare the modelled thermal evolution of greenstones to that obtained through stable isotopes analyses and fluid inclusions microthermometry on shear zones from the Warrawoona Synform, in the East Pilbara Granite-Greenstone Terrane (EPGGT, Fig. 1a). Results point to a protracted two-stage hydrothermal history involving: (1) low-temperature syn-deformation fluid–rock interactions during the early stage of sagduction, and (2) mid-temperature syn- to post-deformation fluid–rock interactions during thermal relaxation and warming of sagducted greenstone sheets. We argue that sagduction of thick greenstone piles, with a large and near-permanent seawater reservoir above and a hot and weak basement below, led to efficient, crustal-scale and long-lived plumbing systems that favoured fluid–rock interactions and the genesis of gold deposits in the interior of Paleoarchean to Mesoarchean cratons.

2. The East Pilbara Craton: an example of sagduction-related “simple structural complexity”

The East Pilbara Granite Greenstone Terrane (Fig. 1a) is one of the best documented examples of dome-and-basin pattern interpreted in terms of gravitational instability (Collins, 1989; Delor et al., 1991; Hickman, 1983; Teyssier et al., 1990; Thébaud, 2006; Van Kranendonk et al., 2004a), although alternative views exists (Blewett, 2002; Kloppenburg et al., 2001). The East Pilbara Granite Greenstone Terrane provides a Paleoarchean to Mesoarchean geologic backdrop to study tectono-thermal processes and fluid–rock interactions in a sagduction setting. It preserves a geologic history often largely overprinted in many Neoarchean cratons. The bulk of the domes consist of 3324–3300 Ma old syn- to post-kinematic suites of high-K granitic suites that are derived from, and intrusive in, older 3460–3430 Ma Tonalite–Trondjhemite–Granodiorite (TTG) gneisses and greenstones of the Warrawoona Group (Hickman, 1983; Hickman and Van Kranendonk, 2004; Smithies et al., 2003; Van Kranendonk et al., 2002, 2007). The domes are themselves intruded by younger, mainly 3300–3240 Ma old, granites. The older TTG gneisses formed the basement of greenstones, the emplacement of which is associated with two major volcanic cycles starting with the deposition of Warrawoona Group at ca. 3490 Ma and followed by the deposition of the Kelly Group at ca. 3335 Ma (Fig. 2) (Van Kranendonk et al., 2007). The thicknesses of the greenstone covers show significant lateral variation from 8 to 12 km for the Warrawoona Group, and 4–9 km for the Kelly Group (e.g. Hickman, 1983; Van Kranendonk et al., 2007). Considerations on both the present crustal thickness of the Pilbara (35–37 km) and the average erosion level (ca. 7 km) suggest that the greenstones accumulated on top of a 30–35 km thick continental crust. Ubiquitous pillow-lava, hydrothermal cherts, VMS mineralisation, epidote-chlorite-Ca–Na-plagioclase-Ca-amphibole secondary mineral assemblages and intense silicification throughout the greenstone pile imply subaqueous emplacement (Barley, 1984; Barley and Pickard, 1999; Buick and Barnes, 1984; DiMarco and Lowe, 1989; Van Kranendonk, 2006).

The structural complexity of greenstone covers is a function of their position with respect to the domes. On the NE flank of the Mount Edgar dome, the Marble Bar greenstone belt lies directly on top of the Mount Edgar granitic complex and is structurally part of the dome (Fig. 1b). In the Marble Bar greenstone belt, the stratigraphy of the Warrawoona and Kelly Groups is relatively well preserved and structurally simple with a monotonous dip of 20–60° to the NE. In contrast, in the Warrawoona synform (white star in Fig. 1b1), greenstones are steeply dipping and strongly deformed against the near-vertical southwest margin of the Mount Edgar dome (Fig. 3). At this location, the greenstone cover belongs to a basin pinched between the Mount Edgar dome to the north and the Corunna Down dome to the south. Compared to that of the Marble Bar greenstone belt, the structure in the Warrawoona synform is more complex showing multiple phases of folding, a prominent horizontal to vertical stretching lineation, and numerous shear zones and quartz vein arrays (e.g. Thébaud et al., 2008). Contrasting, yet predictable structural complexity, with complex structures above downwelling regions (e.g. Warrawoona syncline) and simpler structures above rising domes (e.g. Marble Bar belt) is a key attribute of sagduction settings (e.g. Bouhallier et al., 1995; Thébaud, 2006).

3. Numerical experiment setup

In order to interpret the thermal history derived from isotopic studies, and to understand fluid flow in a sagduction setting, we have performed a series of numerical experiments to document the thermal and mechanical history of sagducted greenstones. The process of sagduction has been tested through numerical and physical experiments (de Bremond d'Ars et al., 1999; Dixon and Summers, 1983; Mareschal and West, 1980; Robin and Bailey, 2009; West and Mareschal, 1979). This process is driven by the need for minimisation of internal gravitational potential energy of a system involving a density inversion (denser layer above a layer of lower density). It is resisted by the viscosity of the system, in particular by that of the stronger layer involved in the sagduction. Hence, the timing of sagduction is inversely proportional to the density contrast and proportional to the viscosity of the stronger layer. The emplacement of greenstones increases the geothermal gradient (e.g. Rey et al., 2003; Sandiford et al., 2004; West and Mareschal, 1979), which in turn reduces the viscosity and accelerates sagduction. To model this process, we use Ellipsis, a Lagrangian integration point finite element code capable of tracking time dependent variables in combination with an Eulerian mesh. This coupled Lagrangian/Eulerian approach allows for the accurate tracking of density interfaces during large deformation (Moresi et al., 2001, 2002). We use viscoplastic rheologies mimicking standard rheological profiles for the continental lithosphere (e.g. Brace and Kohlstedt, 1980). Our experiments include realistic geotherms with self-radiogenic heating and partial melting with feedback on viscosities and densities.

In our numerical experiments, the greenstone cover is 15 km thick in average, consistent with the thickness of many Archean greenstone covers, and in particular the average cumulative thickness of the Warrawoona and Kelly Groups in the EPGG (e.g. Van Kranendonk et al., 2007) to which we will confront our results.