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Mantle plumes, supercontinents, intracontinental rifting and mineral systems

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ABSTRACT

The formation and disruption of supercontinents exert major influence on mantle dynamics and have important bearing on continental dynamics and mineral systems. Here we evaluate the role of mantle plumes in the rifting and breakup of supercontinents with specific examples involving Columbia, Rodinia and Gondwana. We attempt to trace the formation of associated rift systems and the making of mineral deposits in the processes from failed rifts (aulacogens) to successful rifts. Models on the rifting and breakup of supercontinents through mantle upwellings range from 'thermal blanket' effect and supercontinent self-destruction through plumes rising from the mantle transition zone at the 410–660 km boundary layer to superplumes generated at the core–mantle boundary with subducted slabs acting as the fuel. Intracontinental rifts are potential sites of giant ore systems, such as sedimentary exhalative (SEDEX), stratiform, stratabound and Fe oxide-Cu-Au-U (IOCG) deposits. The age span of these ore systems (~1.6–0.8 Ga) broadly corresponds with the assembly and dispersal of the Palaeoproterozoic supercontinent Columbia, followed by the amalgamation of the Neoproterozoic Rodinia and its subsequent breakup. The Phanerozoic Pangea supercontinent at 260 Ma had two main components, Laurasia in the north and Gondwana in the south, separated by the Palaeotethys Ocean. We focus on the rifting of Gondwana, which led to the formation of present day Atlantic and Indian oceans. Thus, rift systems effectively act as major conduits for both magmas and hydrothermal fluids. Intracontinental rifts host magmatic and hydrothermal mineral deposits including Ni-Cu and Ti-Fe±V and Cu-Ni±PGE deposits in mantle-sourced mafic–ultramafic rocks, U-REE-Nb-Cu sourced from metasomatised subcontinental lithospheric mantle, and hydrothermal Sn-W, among other types. Upwelling plumes and their migration beneath trans-crustal faults or lithospheric discontinuities drive hydrothermal factories channelling heat and fluids and generating economic ore deposits.

1. Introduction

Mantle plumes theory purports a major role in the breakup of supercontinents due to the effects that plume impingement at the base of the sub-continental lithospheric mantle have in forming major rift systems. These rift systems, whether failed or successful, contribute to the breakup of a supercontinent and in the process the rifts truly become major "ore-making factories" (e.g. Condie, 2001; Yuen et al., 2007; Santosh et al., 2009; Begg et al., 2010; Ernst and Jowitt, 2013; Pirajno and Santosh, 2014). Over the years, before and when palaeomagnetism became an important tool for supercontinent reconstructions, several different supercontinent configurations, often contradictory, have been reported in the literature (e.g. Meert, 2014). In this contribution, we attempt to evaluate the role of mantle plumes in the breaking up of supercontinental masses, the formation of associated rift systems and the making of mineral deposits from failed rifts (aulacogens) to successful rifts and eventually the creation of new oceanic crust. To illustrate these processes, we specifically focus our discussion on the Columbia, Rodinia and Gondwana supercontinents.

The superplume concept suggests some form of plate tectonic cyclicity. Barley et al. (1997) considered that cycles of mantle plume breakouts have occurred since the Archaean, through to and including the Phanerozoic. Thus, plume "breakouts" can be linked to assembly and rifting of continents, and expansions or contractions of oceans (Gurnis, 1988; Barley and Groves, 1992; Barley et al., 1997, 1998; Santosh et al., 2009, 2010, 2014; Nance et al., 2014). A wider implication is that tectonic cyclicity has a direct relationship to metallogeny, because of the interaction between continents, orogenic and anorogenic tectono-thermal processes, biotic evolution and

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eustasy (Barley and Groves, 1992; Barley et al., 1997, 1998; Pirajno, 2009; Cawood and Hawkesworth, in press). The idea that supercontinents have been cyclically forming and fragmenting throughout most of Earth's geological history is not new. One theory (Nance et al., 1988; Gurnis, 1988; Coltice et al., 2007, 2009) proposed that the aggregation of a supercontinental mass results in the accumulation of heat in the mantle beneath it. This eventually leads to heat dissipation by means of rifts that break the supercontinent into fragments. The fragments then drift and coalesce through collision processes and a new supercontinent is then assembled.

In the context of mantle plumes, fragments of continental crust tend to aggregate above plume downwellings to form supercontinents (e.g. Gurnis, 1988; Bierlein et al., 2009; Santosh et al., 2010). In this way, convective upwellings form, resulting in the uplift of the lithosphere, injection of melts into the crust and partial melting of the crust. This is accompanied by continental ruptures and dispersal of continental fragments, which then reaggregate over mantle downwellings to start another cycle. This is followed by collision, suturing and the re-assembly of a new supercontinent, until new hot upwelling forms beneath the supercontinent, and the cycle begins again (Gurnis, 1988; Fig. 1). The duration of the full cycle is envisaged to take approximately 360 Ma (Barley et al., 1997). Barley and Groves (1992) and Barley et al. (1997, 1998) proposed a relationship between mantle plumes to supercontinent aggregation and dispersal, and the distribution of metalliferous ore deposits through geological time. The relationship between Earth's geological evolution and its mineral resources has been reviewed by a number of authors (e.g. Sawkins, 1990; Solomon and Sun, 1997; Kerrich et al., 2005) who among other things considered ore deposits either as orogenic or anorogenic, linked to mantle plume activity, extension, rifting and convergent tectonic regimes.

The basic idea is that groups of ore deposits appear to be associated with cycles of aggregation and dispersal of continental masses (Barley and Groves, 1992; Cawood and Hawkesworth, in press), which in turn may be linked to mantle upwellings (or plumes) and downwellings. Ore deposits that form during continental rifting can be considered as anorogenic. Collisional tectonics can be related to mantle downwellings, in which case the associated ore deposits can be considered as orogenic.

One of the unresolved issues of our planet's geological history is whether increased cratonisation at the end of the Archaean, coupled with a changed mantle convection system of more regular cells, led to the onset of Wilson tectonic cycles and the assembly of supercontinents (Nance et al., 1988, 2014; Dalziel et al., 2000; Nance and Murphy, 2013; Van Kranendonk et al., 2014). It is well-established, however, that during the Proterozoic there was development of large sedimentary basins or platforms, supporting the idea of widespread cratonisation and the presence of large continental masses. Evidence, although not too well constrained, and with different configurations by different authors, suggests that supercontinents have been cyclically assembling and fragmenting (Rogers and Santosh, 2004).

2. Mantle plumes, rifting and supercontinent breakup

2.1. Supercontinents

The assembly, evolution and breakup of supercontinents have been the focus of many research topics and projects (e.g. Bleeker, 2003; Rogers and Santosh, 2004; Santosh et al., 2009; Meert, 2012, 2014; Ernst et al., 2013a,b; Condie and Aster, 2013; Nance and Murphy, 2013; Young, 2013; Roberts, 2013; Cawood et al., 2013a; Pisarevsky et al., 2014). Nance et al. (2014) reviewed the supercontinent cycle considering assemblies and breakups of Superia-Sclavia at ∼2.6 Ga, Columbia at ∼1.6–1.2 Ga, Rodinia at ∼1.1–0.8 Ga and Pangea-Gondwana at 0.6–0.26 Ga. These authors pointed out that whereas the assembly of supercontinents requires collision, accretion and the activity of subduction systems along their margins, their breakup will require rifting.

The ancient globe (Precambrian) is considered to be somewhat analogous to the modern western Pacific region, dominantly composed of island arcs in the absence of large continental masses (Santosh, 2013). Parallel collision of arcs and arc-continent collision led to the formation of primitive continents (Santosh et al., 2009), although it has also been argued that arc collision would not be the best way to produce and preserve continental crust (Condie and Kröner, 2013). Further growth was aided by both vertical addition through arc magmatism and lateral growth through accretionary orogenesis, analogous to the tectonic history of the Central Asian Orogenic Belt, which together with Terra Australis are considered the world's largest Phanerozoic orogens (Cawood, 2005; Xiao and Santosh, 2014, and references therein). Earth's oldest coherent supercontinent assembly referred to as Nuna (Hofmann, 1997) or Columbia (Rogers and Santosh, 2002; Zhao et al., 2002; Meert, 2012) witnessed the 'close packing' of continental fragments during the Palaeoproterozoic at around ca. 2.0–1.9 Ga. Columbia started rifting in the Mesoproterozoic, the final phase of which at 1.3–1.2 Ga is assumed to be marked by extensive mafic dyke swarms, flood basalts and layered intrusions tracing a hot spot track (Ernst and Buchan, 2001, 2003; Hou et al., 2008a,b; Wang et al., 2014a,b).

The Neoproterozoic and Phanerozoic aeons are characterised by the initiation and eventually final breakup of the supercontinent known as Rodinia at about 900–800 Ma, a re-assembly to form Pangea between 400 and 200 Ma and its subsequent breakup. The breakup of Pangea was heralded by the emplacement of continental flood basalts, layered intrusions and related magmatic Ni and PGE mineralisation (Storey, 1995; Pirajno, 2000 and references therein; Ernst, 2014). Continuing breakup and dispersal of continental fragments led to the inception of peripheral subduction systems, magmatic arcs, and metal deposits that are typically formed at convergent margins, such as porphyry and epithermal systems. Barley and Groves (1992) pointed out that the preservation in the geological record of ore deposits is dependent on whether these are part of interior or peripheral orogens, as defined by Murphy and Nance (1991). Peripheral orogens (Cawood et al., 2009) are those that form at continental margins, adjacent to an ocean, as for example along the Cordilleran and Andean side of the Americas. Interior or collisional orogens, develop during closure of oceanic basins and continental collision, resulting in crustal thickening and uplift, of which the Alpine-Himalayan and Central Asian orogenic systems are examples. The "Terra Australis" giant orogen had a length of about 18,000 km along the Gondwana margin, following the breakup of Rodinia (Cawood, 2005; Fig. 2). It follows that the preservation potential for ore deposits in the upper portions of interior orogens is limited, due to erosion that inevitably accompanies strong uplift associated with collisional and accretionary tectonics (Cawood and Hawkesworth, in press).

Barley et al. (1997) reasoned that what is true for Pangea and the Phanerozoic, probably happened also in the preceding eras. They recognised global tectonic cycles that appear to last about 360 Ma, and which can be seen as 180 Ma cycles of ocean opening and closure. The 180 Ma cycles may be related to what the authors called "mantle plume breakouts". Barley et al. (1997, 1998) suggested that plume breakouts and similar full cycles are apparent for the Neoarchaean and Palaeoproterozoic, between 2.8 and 1.6 Ga. The breakup of the late Archaean Pilbara-Kaapvaal continent and the aggregation of a large continental mass at approximately 2.6 Ga, are associated with global production of komatiites between 2.72 and 2.69 Ga, relating to plume activity. Linked with the emplacement of komatiitic magmas are major Ni ore deposits (plume-related