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Deciphering an Archean mantle plume: Abitibi greenstone belt, Canada

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ABSTRACT

The 2724–2722 Ma Stoughton-Roquemaure Group (SRG) of the Abitibi greenstone belt (the Archean Superior Province, Canada) is a $\leq$2 km thick komatiite–basalt succession intermittently exposed for about 50 km along strike. The ultramafic and mafic rocks occur mainly as pillowed, brecciated, and massive flows with well preserved spinifex textures in the komatiites. Volcanological, comparative stratigraphic and geochemical studies of the group along a volcanic marker horizon at the base of the succession allow the assessment of magma emplacement processes and mantle source rocks. Major feeder channels, secondary distributary tubes surrounded by pillowed flows with minor breccias and hyaloclastites display facies architecture of small volume flow fields (1–2 km^3). Within the SRG, Al-depleted (ADK; Barberton-type) and Al-undepleted (AUK; Munro-type) komatiitic lavas are intercalated with tholeiitic basalt flows at a m- to 10s of m scale. Basalts and komatiites are inferred to be mantle plume-related; both rock types form two groups with characteristics of ADK and AUK including $Al_2O_3/TiO_2 \sim 9–12$ for ADK versus 17–22 for AUK, as well as $(Gd/Yb)_n$ with >1.3 versus ~ 1, respectively. The interdigitation of compositionally different flow units, limited extent of SRG volcanic rocks and facies architecture with the prevalence of small volume flows argue for a relatively small, heterogeneous mantle plume during the incipient stage of the evolution of the Archean Abitibi belt. Assuming that the scale of heterogeneities is comparable to the field expression of compositional changes and stratigraphy, it can be suggested that geochemical plume 'layering' is on 10s to 100s of m-scale. The evolution of this Archean mantle plume from inception to demise compares favorably with the Yellowstone hotspot which is assumed to have developed over 17 m.y. and had a diameter of about 300 km.

1. Introduction

Mantle plumes are narrow upwellings of abnormally hot mantle material originating either from the stationary core–mantle boundary (Montelli et al., 2004) or the mobile upper–lower mantle boundary (Zhao, 2001). Plume heads melt when they reach shallow depths and may produce volcanic island chains with an age progression as the lithospheric plate overrides stationary "hot spots" (e.g., Hawaii-Emperor volcanic chain; Morgan, 1971). The width of the central stem varies from thick in diaper plumes to small in cavity plumes (Lenardic and Jellinek, 2009). Although a recent debate questioned the very existence of the mantle plumes (e.g., Anderson, 2005), the main arguments against the existence of plumes appear to have been resolved (Montelli et al., 2004, 2006; Farnetani and Samuel, 2005; Lenardic and Jellinek, 2009) and mantle plume models therefore remain a viable concept (Lenardic and Jellinek, 2009; White, 2010). However, the knowledge of ancient plumes, particularly from the Archean and early Proterozoic, is rather limited even though Archean plumes are a cornerstone of the models of the early Earth's thermal evolution. Some of the most prominent Archean and Proterozoic plumes were those associated with komatiites and related basalts (Polat et al., 1999; Polat and Kerrich, 2000; Condie, 2001, 2004; Arndt, 2008). Komatiites are Mg-rich ($>18\%$ MgO) low viscosity lava flows and subvolcanic rocks with distinct spinifex textures (Arndt, 2008). They typically occur in km-scale successions associated with tholeiitic basalts but they constitute only a small proportion of most greenstone belts (e.g., Abitibi belt $<5\%$; Sproule et al., 2002). Although Grove and Parman (2004) and Parman et al. (2003, 2004) among others suggested that some komatiites are related to a subduction-related process, the general consensus is that the komatiites of the Canadian Shield were anhydrous melts derived from mantle plumes (e.g., Polat and Kerrich, 2001; Sproule et al., 2002, 2005; Wyman et al., 2002; Arndt, 2008; Dostal, 2008).

Komatiitic rocks can thus provide information about the composition of early Earth's mantle and ancient mantle plumes. In order to better understand the characteristics of such plumes, their size, internal structure and composition, we investigated (field studies and geochemistry) a komatiitic sequence from the Stoughton-Roquemaure Group (SRG) of the Abitibi greenstone belt (central Quebec, Canada). The sequence has an excellent exposure and underwent only low-grade metamorphism. It contains interstratified aluminum-depleted and aluminum-undepleted komatiitic (see e.g., Arndt, 2008; Dostal,

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2008) and related basaltic rocks. We infer that these rocks were derived from a heterogeneous mantle plume which was relatively small; smaller in size than those invoked for the recent volcanic activity such as the Hawaiian volcanic chain.

2. Geological setting

The 2.7 Ga Abitibi greenstone belt (Fig. 1), a part of the Superior Province of the Canadian Shield, is an E–W trending coherent Archean supracrustal sequence, which is about 700 km long and 300 km wide. The belt is characterized by protracted magmatism ranging from ca. 2735 to 2640 Ma (Mueller et al., 2009). The three main komatiitic events, which took place over a period of ca. 20 m.y., are closely associated with three volcanic cycles (Chown et al., 1992; Ayer et al., 2002; Mueller and Mortensen, 2002; Mueller et al., 2009). Volcanic cycle 1 (2735–2720 Ma) includes the Stoughton-Roquemaure Group containing komatiites, which conformably overlies the calc-alkaline Hunter Mine Group (HMG). The volcanic cycle 2 (2720–2705 Ma) comprises the 2718–2710 Ma Kidd-Munro assemblage which encompasses the well-known 1000 m thick Munro sequence of komatiite flows in Ontario (Arndt et al., 1977; Arndt, 2008) and the 2714 Ma Spinifex Ridge komatiites of the La Motte-Vassan Group (central Quebec; Champagne et al., 2002; Arndt, 2008; Fig. 1). Komatiites of the third cycle (2705–2698 Ma) include the Tisdale assemblage, Ontario (Sproule et al., 2002, 2005) and the 2703 Ma Jacola Formation (Louvicourt Group) in Quebec (Pilote et al., 1999).

In Quebec, the Abitibi belt has been interpreted to represent a collage of two oceanic arcs (Northern Volcanic [NVZ] and Southern Volcanic [SVZ)] zones; Chown et al., 1992) separated by a major tectonic lineament (Destor-Porcupine Manneville Fault Zone, Fig. 1). The NVZ, which is comprised of the first two volcanic cycles (i.e., dated at 2735–2720 Ma and 2720–2705 Ma respectively; Mortensen, 1993), includes the study area (SRG and underlying HMG). The SRG komatiitic volcanism occurred at the end of the volcanic cycle 1.

The 2732–2724 Ma HMG (Fig. 2), initially mapped by Eakins (1972), is a 4–6 km-thick subaqueous caldera sequence composed of relatively thick (10s to 100s of m) felsic dome–flow–hyaloclastite complexes, an extensive 5 km-wide, columnar-jointed, felsic dyke swarm, and 5–80 m-thick subaqueous felsic pyroclastic deposits (Mueller and Mortensen, 2002; Fig. 3). This volcanic complex can be traced along strike for 50 km. The felsic flows and dykes are calc-alkaline rhyolites whereas subaqueous mafic flows, sills and dykes are tholeiitic basalts (Dostal and Mueller, 1996, 1997). The top of the sequence is composed of felsic flows, massive to pillowed mafic flows, sills and dykes, and thick felsic volcaniclastic turbiditic and mudstone deposits. Hydrothermal seafloor alteration led to silicification and subsequent carbonatization which modified some of these volcaniclastic deposits to chert–iron carbonate and chert–magnetite iron-formation and pyrite-rich mudstone (Mueller et al., 2009). A deep-water caldera for the setting of HMG is suggested by the mudstones and thin-bedded turbidites. The HMG–SRG interface is a volcanic marker horizon which shows subaqueous felsic volcaniclastic deposits, mudstones (shales) and felsic flows in sharp depositional contact with the overlying SRG flows (Fig. 4a, b).

The 0.2–2 km-thick 2724–2722 Ma SRG represents a submarine lava plain that inundated the HMG caldera (Mueller and Mortensen, 2002; Mueller et al., 2006,2008). The SRG (Eakins, 1972; Dostal and Mueller, 1997) is characterized by the occurrence of basaltic komatiites (12–18 wt.% MgO; Arndt and Nisbet, 1982) and komatiites. Basaltic komatiites and komatiites have similar flow attributes and textures although the basaltic komatiites typically show a pyroxene–spinifex texture in contrast to the olivine–spinifex of typical komatiites.

Goutier (1993) and Dostal and Mueller (1997) identified the two thick (100s of m), lower and upper komatiitic units alternating with voluminous (100–1000 m thick) tholeiitic basalts (Fig. 2). The HMG and SRG are steeply dipping sequences (70–90°) with locally overturned strata that young to the south. Both units trace a large anticline that closes to the west (Fig. 2). The SRG extends for 50 km around the Abitibi Lake anticline and is truncated by the Lyndhurst Fault in the

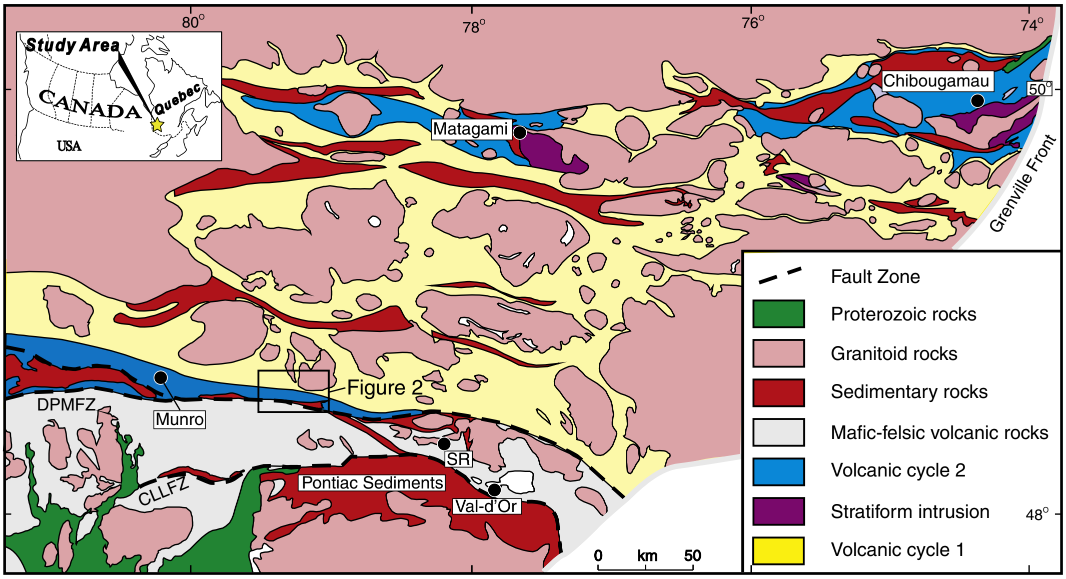

Fig. 1. Simplified geological map of the Abitibi greenstone belt showing the Northern and Southern volcanic zones separated by the W–E trending crustal-scale fault (Destor-Porcupine Manneville Fault Zone — DPMFZ) running through the study area. The supracrustal sequence includes several volcanic cycles. Two volcanic cycles are shown in the Northern zone (Volcanic cycles 1 and 2) but are not separated in the Southern zone where the volcanic rocks are grouped together (Mafic and felsic rock unit) (modified after Mueller et al., 2006). The study area (Fig. 2) is located at southern margin of the Northern volcanic zone. Locations of the Munro komatiites (Munro) as well as the La Motte-Vassan Formation with komatiites of Spinifex Ridge (SR) and the Cadillac-Larder Lake Fault Zone (CLLFZ) which separates the Southern volcanic zone from the Pontiac flysh deposits are indicated. Inset map of Canada shows the location of Fig. 1.