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Geochemistry, Nd, Pb and Sr isotope systematics, and U–Pb zircon ages of the Neoarchean Bad Vermilion Lake greenstone belt and spatially associated granitic rocks, western Superior Province, Canada

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ABSTRACT

The ca. 2720 Ma Neoarchean Bad Vermilion Lake (BVL) greenstone belt, in the western Superior Province, Canada, is composed of a suite of tholeiitic to calc-alkaline basalts to rhyolites, volcaniclastic rocks, gabbros, and Timiskaming-type siliciclastic sedimentary rocks. The greenstone belt was intruded by Neoarchean granitic rocks, and underwent greenschist facies metamorphism and intense deformation, resulting in mobilization of many elements (e.g., Rb, Ba, Sr, K, U, Pb).

The high-field strength element and rare earth element systematics of the volcanic and volcaniclastic rocks, and gabbros are consistent with subduction zone geochemical signatures, suggesting that the BVL greenstone belt formed in a magmatic arc setting. On the basis of lithological associations and trace element systematics, the BVL greenstone belt is defined as a fragment of a Neoarchean subduction-related ophiolite. Three rhyolite samples from the belt have yielded 2722 ± 18 Ma, 2706 ± 13 Ma and 2710 ± 28 Ma U–Pb zircon ages, representing the approximate age of the arc volcanism in the study area and development of a subduction zone between the western Wabigoon terrane to the north and the Wawa-Abitibi terrane to the south. The intrusion of the ca. 2664 ± 15 Ma late- to post-tectonic, potassic Ottertail Lake granite marks the end of tectonic accretion in the study area.

Both the volcanic rocks and gabbros display large ranges of Nd ($^{143}Nd/^{144}Nd$ = 0.511600–0.512849; ε_{Nd} (2720 Ma) = + 0.8 to + 4.0), Pb ($^{206}Pb/^{204}Pb$ = 13.80–60.67) and Sr ($^{87}Sr/^{86}Sr$ = 0.701481–1.01154) isotopic compositions, suggesting that these isotope systems were variably affected by post-magmatic element mobility. Neither the Sm–Nd (2921 ± 200 Ma) nor Rb–Sr (2130 ± 610 Ma) system has yielded reliable regression (isochron) ages, reflecting the open-system behavior of these systems during metamorphism. Despite large uncertainties, Pb–Pb regression ages yielded by all rock types (2661 ± 60 Ma), and basalts and gabbros (2725 ± 83 Ma) agree with the zircon U–Pb ages of the rhyolites, suggesting that the U–Pb system was the most robust among all three systems.

1. Introduction

Archean greenstone belts are characterized by multiply deformed and variably metamorphosed supracrustal sequences (Condie, 1981, 1994; Hunter and Stowe, 1997; Kusky and Vearncombe, 1997; Polat et al., 2015). These belts are typically intruded by intermediate to felsic rocks displaying mainly a tona lite–trondhjemite–granodiorite (TTG) affinity; greenstone belts and TTG suites together form the composite granitoid-greenstone terranes in Archean cratons (de Wit and Ashwal, 1997; de Wit, 1998; Sylvester et al., 1997; Anhaeusser, 2014). Lithologically, greenstone belts consist of temporally and spatially related, ultramafic to felsic volcanic rocks, ultramafic to mafic intrusions, and subordinate sedimentary rocks (de Wit, 1998, 2004; Kusky and Polat, 1999; Furnes et al., 2013, 2015). Archean cratons are composed mainly of Mesoarchean to Neoarchean rocks (Szilas et al., 2012, 2013; Anhaeusser, 2014; Furnes et al., 2015). The Superior Province is the largest Archean craton in the world and consists of many well-preserved elongated granitoid–greenstone terrains

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(e.g., Thurston et al., 1991; Corfu and Davis, 1992; Henry et al., 1998, 2000; Tomlinson et al., 2002, 2003; Stott, 1997; Percival et al., 2006a, 2012). Given its well-preserved diverse rock types, the Superior Province provides an excellent opportunity for studying the petrogenetic and geodynamic origins of Archean crust (e.g., Kerrich et al., 1999; Sproule et al., 2002; Whalen et al., 2002; Lodge et al., 2013, 2014, 2015).

Greenstone belts in the Archean Superior Province are dominated by two principal volcanic sequences, which are represented by a tholeiitic to calc-alkaline basalt to rhyolite association and a komatiite–tholeiite association (Polat and Kerrich, 2002; Sproule et al., 2002; Dostal and Mueller, 2013). The tholeiitic to calc-alkaline volcanic association is characterized by LREE-enriched patterns and pronounced negative anomalies of Nb, Ta, P, and Ti, similar to those of typical Phanerozoic intra-oceanic arc magmatism; the komatiite–tholeiite association features high-Mg, Cr, and Ni contents, flat rare earth element (REE) patterns, as well as complex Th–U–Nb-LREE systematics, similar to that of modern mantle plumes (Condie, 1994; Polat et al., 1999; Polat and Kerrich, 2001a,b; Kerrich and Polat, 2006; Polat, 2009). Greenstone belts in the western Superior Province contain both types of volcanic associations (Ayer and Davis, 1997; Dostal et al., 2004; Ujike et al., 2007; Tomlinson et al., 1999; Hollings and Kerrich, 2004, 2006).

The tectonic setting of greenstone belts in the Wabigoon subprovince is still hotly debated (e.g., Hollings and Wyman, 1999; Tomlinson et al., 1999; Wyman et al., 2000; Backeberg et al., 2014). In order to understand the petrogenesis and geodynamic evolution of the Wabigoon subprovince and especially for its western part, we focus on the BVL greenstone belt and its spatially related Ottertail Lake granitic stock on the northern shore of Rainy Lake (Fig. 1). Given that all rocks in the BVL greenstone belt have been metamorphosed under greenschist facies conditions, the prefix "meta" will be taken as implicit throughout the paper. In this study, we report new major and trace element data for forty-seven samples from the BVL greenstone belt, including volcanic and volcaniclastic rocks, gabbros and the spatially associated Seine siliciclastic sedimentary rocks, and the Ottertail Lake granitic stock. Seventeen samples from the volcanic rocks and gabbros were analyzed for Nd, Pb and Sr isotope systematics. In addition, three rhyolite samples and one granite sample were dated using the zircon U–Pb dating technique to constrain the ages of the greenstone belt and the Ottertail Lake stock. Integrated field and petrographic observations, and geochemical, isotopic and geochronological data are used to constrain the petrogenesis and geodynamic evolution of the BVL greenstone belt, and to assess the effects of post-magmatic processes on element mobility.

2. Regional geology and field characteristics

The Superior Province is divided into four major regions on the basis of general structural and lithological characteristics, including the western, central, Moyen-Nord and northeastern regions (Percival et al., 2006a,b, 2012). The western Superior region from north to south consists of the following terranes and belts (tectonic blocks): the Hudson Bay terrane, North Caribou terrane, English River belt, Winnipeg River terrane, Western Wabigoon terrane, Marmion terrane, Quetico belt, Wawa-Abitibi terrane and Minnesota River Valley terrane (Fig. 1a; Percival et al., 2006a,b, 2012). The Superior Province, nucleus of the North American continent, was developed by the amalgamation of many distinct protocontinental and oceanic terranes ranging in age from 3.7 to 2.65 Ga, during discrete orogenic events between 2720 and 2680 Ma (Card and Ciesielski, 1986; Percival et al., 2006a, 2012 and references therein).

The assembly of these accretionary terranes with the rest of the Superior craton was initiated by the collision between the 3.0 Ga North Caribou terrane and the 3.70–2.75 Ga North Hudson Bay terrane at 2720 Ma, and ended by welding of the Minnesota River Valley and Pontiac terranes to the Abitibi-Wawa terrane at 2680 Ma, showing an overall orderly north to south progression (Percival et al., 1994, 2006a,b, 2012; Stott, 1997). Seismic reflection and refraction images display common north-dipping structures and variable thickness of 10–15 km among these disparate tectonic fragments (Musacchio et al., 2004; White et al., 2003), supporting the importance of a diachronous northward directed accretionary-collisional process in the formation of the Superior Province. However, komatiite and tholeiitic basalt flows are exposed in many locations (Xie et al., 1993; Hollings et al., 1999; Polat et al., 1999; Kerrich et al., 1999; Tomlinson et al., 1999; Sproule et al., 2002; Dostal and Mueller, 2013) in the Superior Province, reflecting the important role of mantle plume magmatism in the evolution of the province. A comparison of the eastern and central sections of the Western Superior Province indicates relatively well-preserved east–west trending subprovinces of alternating plutonic, volcanic–plutonic (granitoid–greenstone), high-grade gneissic, and sedimentary rocks. The majority of these linear subprovinces extend along bounding faults for over 1000 km (Fig. 1a; Percival, 1989; Percival and Williams, 1989; Williams, 1990; Stott, 1997; Percival et al., 2006a,b, 2012).

The Wabigoon subprovince is a typical granitoid–greenstone composite terrain in the western Superior Province (Fig. 1a; Percival et al., 2006a, 2012). It is characterized by ca. 900 km long, and ca. 150 km wide east–west trending greenstone belts and platformal carbonate sequences that are intruded by granitoid batholiths, gabbroic sills and stocks of various compositions (Blackburn et al., 1991; Thurston et al., 1991; Stott, 1997; Kusky and Hudleston, 1999). The lithologies of the greenstone belts in the Wabigoon subprovince are dominated by mafic to felsic volcanic rocks and lesser amounts of komatiites and sedimentary rocks, ranging in age from ca. 3.0 to 2.7 Ga (Blackburn et al., 1991). On the basis of different lithological, structural, and tectonic evolutionary characteristics, the subprovince is divided into three distinct terranes: (1) the eastern Wabigoon terrane, which is composed predominantly of Mesoarchean to Neoarchean (ca. 3056–2720 Ma) supracrustal successions (Stott and Davis, 1999) intruded by ca. 2770–2680 Ma syn- to post-tectonic plutons, in conjunction with Neoarchean (ca. 2740–2720 Ma) mafic to felsic volcanic rocks (Davis, 1999; Kwok et al., 2000); (2) the central Wabigoon terrane, which is characterized by a number of Mesoarchean greenstone belt remnants intruded by several generations of TTG batholiths (Blackburn et al., 1991), such as the ca. 3075 Ma tonalite at Caribou Lake near its northern margin (Davis et al., 1988) and a ca. 3003 Ma tonalite in the Lumby Lake area in the southern part of the region (Davis and Jackson, 1988); and (3) the western Wabigoon terrane, which is dominated by large, ca. 2735–2720 Ma tonalitic to granodioritic batholiths (Davis and Edwards, 1982, 1986), surrounded by numerous Neoarchean (ca. 2775–2685 Ma) greenstone belts (Blackburn et al., 1991). The western Wabigoon terrane is also distinct from the other two regions in that it shows depleted mantle Nd isotopic compositions (Ayer and Dostal, 2000; Ujike et al., 2007). It is noted that the exact location and nature of the boundaries among the three terranes remain ambiguous, and correlations of greenstone belts in the different terranes are not well-defined.

2.1. The Bad Vermillion Lake (BVL) greenstone belt

The BVL greenstone belt is bounded to the north by the dextral Quetico fault and the Rainy Lake batholithic complex; its southern boundary is marked by the dextral Seine River fault, which