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The geochemistry, geochronology and paleomagnetism of dikes and sills associated with the Mesoproterozoic Midcontinent Rift near Thunder Bay, Ontario, Canada

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ABSTRACT

The Midcontinent Rift (MCR) of North America comprises a series of basaltic sheets, flows and intrusive rocks emplaced in the Lake Superior region during the Mesoproterozoic. The mafic rocks preserved on the northern flank of Lake Superior represent the older portions of the rift sequence and offer insights into the early development of the rift. New geochronological, geochemical and paleomagnetic data are presented for the dikes and sills located in and south of Thunder Bay, Ontario. Three sill suites are recognized within the study area; an earlier, spatially restricted ultramafic unit termed the Riverdale sill, the predominant Logan sills and Nipigon sills in the north of the study area. In addition three dike sets are recognized, the north-east trending Pigeon River swarm, the north-west trending Cloud River dikes and the Mt. Mollie dike. The geochemical data demonstrate that the majority of sills south of Thunder Bay are of Logan affinity and distinct from those of broadly similar age in the Nipigon Embayment to the north. The Pigeon River dikes that intrude the sills are geochemically coherent but distinct from the Logan sills and could not be feeders to the sills. The new age of 1109.2 ± 4.2 Ma for the Cloud River dike and its R polarity are consistent with published magnetostratigraphy. The Mt. Mollie dike age (1109.3 ± 6.3 Ma) indicates that it is not coeval with the spatially associated Crystal Lake gabbro as previously thought. The complexity of the dike and sill suites on the northern flank of suggests that the early phases of rifting occurred in distinct and changing stress fields prior to the main extensional rifting preserved in younger rocks to the south. The geochemistry and geochronology of the intrusions suggest a long-lived and complex magmatic history for the Midcontinent Rift.

1. Introduction

The Midcontinent Rift (MCR) of North America comprises ~1,500,000 km^3 of basaltic sheets, flows and intrusive rocks emplaced in the Lake Superior region during the Mesoproterozoic (Klewin and Shirey, 1992). Rocks of the 2500 km long MCR are predominantly covered by younger rocks in the midwestern United States, but are well-exposed around Lake Superior. The supracrustal and intrusive rocks of the MCR have been subdivided into the Keweenawan Supergroup and Midcontinent Rift Intrusive Supersuite, respectively, by Morey and Green (1982) and Miller et al. (2002). The majority of the igneous activity within the MCR is tholeiitic in composition (Green, 1983) and isotopic data have been used to infer contributions from lithospheric, asthenospheric and crustal sources (Lightfoot et al., 1991; Shirey et al., 1994; Nicholson et al., 1997; Hollings et al., 2007b).

The MCR has been the subject of considerable study, with much recent research focusing on the older portions of the rift sequence located to the north of Lake Superior (Easton et al., 2007; Heaman et al., 2007; Hollings et al., 2007a,b,c; Hart and MacDonald, 2007) and on the rhyolite/granophyre complexes of the North Shore Volcanic Group (NSVG) and associated intrusions (Vervoort et al., 2007). Many of these studies have portrayed a fully developed rift which was later subjected to compressive forces probably generated by the Grenvillian Orogeny (Van Schmus, 1992; Cannon and Hinze, 1992; Cannon, 1994; Manson and Halls, 1994), whereas Hollings et al. (2007c) showed that early phases of the rift involved significant changes in the orientation of the rift axis. It is now generally accepted that an upwelling mantle plume was responsible for the large volumes of mafic magmas associated with the rift (Hutchinson et al., 1990; Nicholson and Shirey, 1990; Hollings et al., 2007a,b,c). The oldest rift-related rocks on which U–Pb age

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Table 1
Geochronology of Midcontinent Rift igneous rocks, northern Lake Superior area. Intrusions located within the study area are denoted by an asterisk (*). *z* = Zircon, *b* = Baddeleyite, *p* = Perovskite.

Lithologic unit	Locality	Age (Ma)	Source
St. Ignace Island Complex Gabbro	St. Ignace Island	1089.2 ± 3.2 (*z*,*b*)	Smyk et al. (2006)
Pigeon River dikes*	Arrow River, Devon Township	1078 ± 3 (*b*)	Heaman et al. (2007)
Pigeon River dikes*	Crooks Township	1141 ± 20 (*z*,*b*)	Heaman et al. (2007)
Blake Gabbro*	Blake Township	1091.0 ± 4.5 (*b*)	Heaman et al. (2007)
Moss Lake Gabbro	Black Bay Peninsula	1094.7 ± 3.1 (*b*)	Heaman et al. (2007)
Crystal Lake Gabbro*	Great Lakes Nickel	1099.6 ± 1.2 (*b*)	Heaman et al. (2007)
Osler Group rhyolite (central suite)	Agate Point	1105.3 ± 2.1 (*z*)	Davis and Green (1997)
Osler Group rhyolite (lower suite)	Black Bay Peninsula	1107.5 + 4/−2 (*z*)	Davis and Sutcliffe (1985)
St. Ignace Island Complex Rhyolite	St. Ignace Island	1107.2 ± 2.4 (*b*)	Smyk et al. (2006)
Coldwell Complex	Coldwell Complex	1108 ± 1 (*z*,*b*)	Heaman and Machado (1987, 1992)
Logan Sills*	Mt. McKay	1114.7 ± 1.1 (*b*)	Heaman et al. (2007)
Nipigon Sills	Nipigon Embayment	1106.8 ± 1.9 (*z*)–1114.4 ± 8.3 (*b*)	Heaman et al. (2007)
Ultramafic Intrusions	Nipigon Embayment	1117.5 ± 3.7 (*b*)–1106.6 ± 1.5 (*b*)	Heaman et al. (2007)
Inspiration Sill	Lake Nipigon	1159 ± 33 (*z*,*b*)	Heaman et al. (2007)
Marathon lamprophyre dikes	McKellar Harbour	1145 + 15/−10 (*p*)	Queen et al. (1996)

determinations have been performed lie along the northwestern portion of the MCR in northwestern Ontario. Mafic–ultramafic intrusions in the vicinity of Lake Nipigon yielded ages ranging from 1117 Ma (Kitto intrusion) to 1109–1113 Ma for extensive diabase sills (Heaman et al., 2007; Table 1). The discovery of these older ages has suggested that the initial stages of MCR magmatism occurred earlier than previously thought, significantly pre-dating main rift-stage volcanism (1108–1094 Ma). Heaman et al. (2007) have suggested that MCR magmatism can be divided into four stages extending from 1150 to 1087 Ma with a marked gap between 1130 and 1115 Ma. This ~60 m.y. time span is considerably longer than is recognized for most recent plume-related Large Igneous Provinces (LIPs) that are emplaced within ~10 m.y. with the bulk of magmatism within ~1 m.y. (Ernst et al., 2005) but is similar to that proposed for the Marathon plume (Halls et al., 2008). However, Ernst and Buchan (2002) believe that the longer lived Matachewan and Mistassini dike swarm events which span 2490–2408 Ma may represent plume cluster events, where a number of plumes erupt in a spatially restricted area.

Around most of Lake Superior a single magnetic field reversal is found in Keweenawan volcanic sequences, with the normal (N) polarity event younger than the reversed (R) (Halls and Pesonen, 1982). The asymmetry of the reversal (with the R direction having a steeper inclination than the N) is probably the result of apparent polar wander because major erosional breaks, typically marked by conglomerates, occur between the N and R polarized volcanic sequences of the Keweenawan (e.g., Halls, 1974). At Mamainse Point in eastern Lake Superior, the volcanic sequence shows a polarity sequence of R–N–R–N, suggesting three asymmetric polarity reversals (Palmer, 1970). However, more recent work reports a progressive shallowing of inclination in the lowest R unit with stratigraphic height, leading to the subsequent reversal being almost 180° (Swanson-Hysell et al., 2006). This suggests that apparent polar wander is the simplest explanation for the asymmetry. A synopsis of Midcontinent Rift geochronology and paleomagnetism (Davis and Green, 1997) shows that 1115–1105 Ma intrusions and volcanic rocks have R polarity. A magnetic polarity reversal occurred circa 1105–1102 Ma, after which most of the MCR igneous rocks, with the exception of the Mamainse Point succession, have N polarity.

This study focuses on the mafic intrusive rocks in and south of Thunder Bay, Ontario in order to subdivide them on the basis of geochemistry, petrology, paleomagnetism and age, and to provide new insights into the timing, nature and tectonic setting of MCR magmatism, particularly whether or not the extended time span of the rift event represents a single plume or possibly a plume cluster event. Specifically, we investigate the relative timing and source regions of the previously recognized dike suites and relate these to models for rift evolution that have been proposed to account for the older intrusive sequences in Northern Ontario.

2. Regional geology

2.1. General stratigraphy

The study area, situated in the Southern Province of the Canadian Shield, consists of Proterozoic rocks that overlie Archean basement rocks of the southern Superior Province (Fig. 1). Largely unexposed in this area, Archean basement rocks of the Wawa Subprovince are predominantly granitoid plutons and slivers of greenschist- to amphibolite-facies supracrustal (i.e. greenstone belt) rocks (Williams et al., 1991; Fig. 1). The Paleoproterozoic Animikie Group is represented by the Gunflint Formation and overlying Rove Formation (Fig. 1). These dominantly sedimentary formations constitute a largely unmetamorphosed, undeformed, homoclinal succession with dips of 10° or less towards the centre of the MCR to the southeast. The Gunflint Formation is a chemical iron formation-clastic assemblage which has yielded a U–Pb age from reworked volcanic ash of 1878.3 ± 1.3 Ma (Fralick et al., 2002). These rocks grade upward into turbiditic sandstone and shales of the Rove Formation south of Thunder Bay. Zircons from ash beds in the basal Rove Formation yielded U–Pb ages of 1836 ± 5 and 1832 ± 3 Ma (Addison et al., 2005). A sandstone sample from the submarine fan portion of this succession yielded a youngest detrital zircon U–Pb age of approximately 1780 Ma (Heaman and Easton, 2006).

The Mesoproterozoic Sibley Group (ca. 1.35 Ga) is a relatively flat-lying assemblage of siliciclastic and chemical sedimentary rocks, preserved predominantly in the Nipigon Embayment (Rogala et al., 2007) where it overlies Archean basement. Further south, it disconformably overlies Animikie Group rocks, but does not extend into the study area (Fig. 1). Above the Sibley, and occurring at many localities around Lake Superior, are subaerial basaltic volcanic sequences, including the Osler Volcanic Group, with minor felsic lava flows and interflow sediments (Wallace, 1981; Nicholson and Shirey, 1990; Lightfoot et al., 1991; Hollings et al., 2007c; Fig. 1). The Osler volcanics, part of the Keweenawan Supergroup, dated at between 1108 and 1105 Ma (Table 1) which may locally be up to 15 km thick, are overlain by about 10 km of clastic sedimentary rocks, and the entire package accumulated in a subsiding, locally fault-bounded rift basin (Green, 1983; Cannon and Hinze, 1992).