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ScienceDirect

Precambrian Research 157 (2007) 235–268

Precambrian Research

www.elsevier.com/locate/precamres

The magmatic evolution of the Midcontinent rift: New geochronologic and geochemical evidence from felsic magmatism

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Received 18 May 2006; received in revised form 26 November 2006; accepted 5 February 2007

Abstract

The Midcontinent Rift System (MRS) is an example of a mafic-dominated continental rift where silicic magmatism is locally significant. The best-preserved example of this is on the NE limb of the rift along the North Shore of Lake Superior where rhyolites comprise a large percentage (up to 25%; Green, J.C., Fitz, T.J., III, 1993. Extensive felsic lavas and rheoignimbrites in the Keweenawan Midcontinent rift plateau volcanics, Minnesota: petrographic and field recognition. J. Volcanol. Geotherm. Res. 54, 177–196) of lava flows and where hypabyssal granophyric intrusive complexes are common. In this paper, we report U–Pb zircon ages, Nd isotopic compositions, and major and trace-element data for seven granophyric complexes of the MRS exposed in NE Minnesota.

U–Pb zircon ages for the granophyres define two different age groups: an older group with ages from 1109 to 1106 Ma; and a younger group with ages from 1099 to 1095 Ma. These ages coincide with the "early" and "main" magmatic stages of Midcontinent rift evolution suggested by Miller and Vervoort [Miller, J.D., Jr., Vervoort, J.D., 1996. The latent magmatic stage of the Midcontinent rift: a period of magmatic underplating and melting of the lower crust. Inst. Lake Superior Geol., 42nd Ann. Mtg., Proceedings, vol. 42, pp. 33–35] and Miller and Severson [Miller, J.D., Jr., Severson, M.J., 2002. Geology of the Duluth Complex. In: Miller, J.D., Jr., Green, J.C., Severson, M.J., Chandler, V.W., Hauck, S.A., Peterson, D.M., and Wahl, T.E. (Eds.), Geology and Mineral Potential of the Duluth Complex and Related Rocks of Northeastern Minnesota. Minnesota Geological Survey Report of Investigations, vol. 58, pp. 106–143]. Although the two groups of granophyres have similar major and trace-element compositions, they have different Nd isotopic compositions. The older, or "early stage", granophyres have more radiogenic Nd isotopic compositions ($\varepsilon_{Nd(i)} = -3.7$ to -0.5) whereas the younger, or "main stage", granophyres have more crustal, unradiogenic Nd isotopic compositions ($\varepsilon_{Nd(i)} = -7.6$ to -3.1). The age correlative Nd isotopic signatures of the granophyres are broadly consistent with the ages and isotopic compositions of the rhyolites within the North Shore Volcanic Group (NSVG) and illustrate the episodic nature of the Midcontinent rift evolution.

The early stage (1109–1106 Ma) of MRS magmatism is characterized by mafic mantle-derived magmas with minor amounts of silicic magmas. The evolved magmas were likely derived by partial melting of either earlier formed rift related rocks or older crust with near chondritic Nd isotopic composition. This was followed by a period of relative quiescence lasting about 5 million years from which no significant MRS magmatism has been preserved. The main stage of MRS magmatism resumes at ca. 1100 Ma

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0301-9268/$ – see front matter
doi:10.1016/j.precamres.2007.02.019

with voluminous basaltic volcanism and mafic intrusions. The silicic magmas produced during this stage are more abundant and distinctly more crustal in character than during the early magmatic stage magmas. We suggest that these silicic magmas have been derived from partial melts of more evolved crustal sources, perhaps at higher levels in the crust.

Keywords: Granophyre; Midcontinent rift; Keweenawan; Granite; Mesoproterozoic; Crustal evolution; Lake superior region; Precambrian; U–Pb geochronology; Sm–Nd isotopes

1. Introduction

The magmatism associated with continental rifts and continental flood basalt provinces throughout Earth's history is dominantly basaltic. In many of these geological settings, silicic magmatism is largely absent (e.g., Columbia River Basalts; Hooper, 1997) or greatly subordinate, while in others (e.g., Snake River Plain; Bonnichsen and Kauffman, 1987) it can be volumetrically significant. Silicic magmatism may be manifest in different geological settings through both high-temperature extrusive (flow, pyroclastic, rheoignimbrite) and intrusive (dike, sill, pluton) activity and can occur coincident with all stages of mafic magmatism, from early to late (Bryan et al., 2002). The origin of silicic magmas in these settings is enigmatic and despite research spanning several decades, we still do not have a complete understanding of how these magmas form (e.g., crustal melting, assimilation, fractionation), where the primary sites of magma generation are (upper crust, middle crust, at the base of the crust, or mantle), or how extensively the magmas have been modified during transport. The reason for this complexity is that many different processes are likely to be involved and these are manifest in different ways in different geological settings. Nevertheless, constraining the genetic relationships between the felsic and mafic magmas is crucial for understanding the origin and evolution of silicic magmatism.

The Midcontinent Rift System (MRS) is an example of a mafic-dominated system where coeval silicic magmatism is locally significant. Throughout much of the MRS, magmatism was dominantly mafic with only minor amounts of evolved compositions (e.g., Morey and Mudrey, 1972; Basaltic Volcanism Study Project, 1981; Green, 1982a; Brannon, 1984; Dosso, 1984; Paces, 1988; Nicholson and Shirey, 1990; Lightfoot et al., 1991; Klewin and Berg, 1991; Shirey et al., 1994; Wirth et al., 1997; Vervoort and Green, 1997). An exception to this is along the northeast limb of the MRS in northeastern Minnesota where rhyolites comprise a significant percentage (10–25%; Green and Fitz, 1993) of the total volume of erupted material. The Lake Superior region also has excellent exposures of MRS intrusive rocks. The Duluth and Beaver Bay complexes were intruded beneath and into the extrusive rocks of the rift in a series of complex subvolcanic units (Miller et al., 2002). These are dominantly gabbroic in composition but range from troctolite to anorthosite to granite (granophyres). The large percentage of silicic compositions, in conjunction with the occurrence of intrusive and extrusive MRS rocks exposed at different crustal levels, provides an excellent opportunity for a detailed examination of the relationships between felsic and mafic magmatism. The mafic and felsic intrusive and extrusive rocks within the Midcontinent Rift System may be the best exposed of all continental rifts. In this paper we report major and trace-element, Nd isotopic, and U–Pb zircon data from a series of granophyre intrusions and related rocks from the Midcontinent Rift System in northeast Minnesota. Specifically, we analyzed 81 samples from seven granophyre intrusions as well as nine samples from closely related volcanic and hypabyssal plutonic rocks. The first order goal of this investigation is to constrain the genesis of rhyolitic magmas in mafic-dominated continental rift systems. This will also allow us to address other second-order questions related to the Midcontinent Rift System and rhyolite–granite genesis in continental rifts: (1) what is the mechanism by which felsic magmas are produced in the MRS? (2) What is the age relationship between mafic and felsic magmatism in the MRS? And finally (3) what do these temporal and compositional relationships tell us about the overall magmatic and chemical evolution of the MRS? This study follows a similar Nd isotope and trace-element study of the rhyolites of the North Shore Volcanic Group (NSVG) exposed along the north shore of Lake Superior in Minnesota (Vervoort and Green, 1997). We will show that the granophyre Nd data are consistent with results from the rhyolite study and together demonstrate an increasing role of evolved crustal sources in the generation of silicic magmas with time.