THE LATENT MAGMATIC STAGE OF THE MIDCONTINENT RIFT: A PERIOD OF MAGMATIC UNDERPLATING AND MELTING OF THE LOWER CRUST

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Field studies, seismic and gravity data, U-Pb zircon dating, and geochemical studies of volcanic and intrusive rock suites around the Lake Superior basin show that the Midcontinent rift (MCR) evolved in several distinct magmatic stages between 1109 and 1086 Ma (1-4). Most recently, a period of substantially reduced volcanism and a shift to more intermediate to felsic magma compositions has been identified between 1107 and 1100 Ma—an interval we refer to as the latent magmatic stage (Fig. 1). Overall, MCR magmatism resulted from an anomalously hot mantle plume emplaced at the base of the lithosphere at about 1109 Ma (5). The most obvious aspect of this magmatism is the large volume (over 2 million km$^3$) of mostly basaltic volcanic rock that accumulated in the central rift graben to thicknesses of up to 20 km (1). Less obvious, but equally significant is a comparable volume of mafic magma that intruded and underplated the crust beneath the Lake Superior region (6,7). We present evidence here that suggests a contemporaneous if not a causal relationship between the latent magmatic stage, magmatic underplating, and lower crustal melting.

The first hint of a latent magmatic stage was recognition of a hiatus in mafic intrusive activity in the Duluth Complex between 1107 Ma and 1099 Ma (8). More recent U-Pb dating of the North Shore Volcanic Group (9) and the Powder Mill Group (10) has revealed a decrease in volcanic activity over this same period. Volcanic rocks occurring within and adjacent to both these low production intervals are mixed rhyolite, andesite, and evolved basalt (4, 11). Insufficient dating has been conducted to determine if a similar decrease in basaltic volcanism is present in the Osler and Mamainse Point volcanics suites. However, it is noteworthy that the Agate Point rhyolite, which separates the upper and central suite of Osler Group (12), yields an age of 1105±2 Ma (9). At Mamainse Point, abundant felsic flows and intrusions have been mapped below the 420-m-thick, polymict Great Conglomerate (13), which presumably signifies a prolonged hiatus of volcanic activity. Further evidence that felsic volcanism predominated during an overall diminution of volcanic activity comes from the preponderance of rhyolite clasts in the Copper Harbor Conglomerate and their age of 1104±2 Ma (14).

We propose that the latent magmatic stage represents a period of reduced extension coupled with extensive magmatic underplating and melting of the lower crust. If the rate and intensity of extension in the MCR was largely controlled by external stresses imparted by contemporaneous Grenvillian tectonism (15), then ponding of mafic magmas at the crust-mantle interface was likely a passive response to decreased tensile (or perhaps compressive) stresses in the lithosphere. However, to the extent that lithospheric thinning and extension was driven by the buoyancy and thermal energy of the mantle plume (16), then perhaps magma underplating actually caused diminished extension of the crust by delaminating and structurally decoupling it from the lithospheric mantle. In either case, underplating was probably instigated by the heating and anatexis of the lower crust caused by the passage of the earliest mantle-derived magmas coupled with heating from the rising plume. The creation of felsic melts and an increasingly ductile lower crust would have created density and rheologic barriers to impede the passage of mafic melts and promote their ponding (17). Once initiated, mafic magma chambers would have continued to expand as additional rising mantle melts became trapped and triggered more widespread melting of the lower crust. At the peak of the latent stage, the lower crust may have been largely impermeable to mafic magmas. Although the resumption of volcanic activity at about 1102-1100 Ma (earlier near the axis of the rift) may have been externally triggered by increased extension of the crust, it seems also possible that density cleansing of the lower crust caused by the upward migration of low density felsic melts and perhaps thinning of the ductile lower crust concomitant with magma underplating may have played important roles in allowing basaltic magmas to emerge from deep crustal magma chambers.
The formation of large magma chambers in the lower crust helps explain many of the lithologic, and geochemical characteristics that are generally common to all volcanic suites formed during the latent magmatic stage as well as magmatism leading up to and following it (Fig. 1). Some of the more cogent features are:

• Felsic magmatism—The bulk and isotopic composition of rhyolite flows and their greater abundance relative to flows of intermediate composition indicates that many if not most were generated from partial melting of crustal sources rather than as differentiates of mafic magmas (18, 19). The greater concentration of felsic lavas in stratigraphic intervals straddling the latent stage (Fig. 1) is consistent with it being a period of lower crustal melting coupled with diminished basaltic volcanism. However, the moderately negative $\varepsilon_{Nd}(1100)$ (~-4) of felsic lavas in the lower part of the NSVG (Fig. 1) is difficult to explain by melting of Archean lower crust, which should have $\varepsilon_{Nd}(1100) = -12$ to -17 (18,19). Although this may indicate mixing of Keweenawan felsic differentiates with Archean crustal melts (19), an intriguing alternative explanation is that the lower crust is composed of Early Proterozoic rocks ($\varepsilon_{Nd}(1100) = -4$ to -12). The persistence of felsic volcanism with varied $\varepsilon_{Nd}(1100)$ well into the middle of main stage magmatism (~1096 Ma) may reflect melting of the base of the volcanic pile producing some of the high $\varepsilon_{Nd}(1100)$ (18) or melting of progressively higher (Archean) crustal levels with low $\varepsilon_{Nd}(1100)$.

• Evolved basalt and intermediate lavas—Basalt in all stratigraphic intervals straddling the latent stage displays a broad, but overall low range of $\text{mg}^\#$ - a general indicator of the differentiated composition of mafic magmas (Fig. 1). Moreover, intermediate lava compositions that were probably generated by differentiation of mafic magmas (e.g., basaltic andesite, andesite and icelandite) are highly concentrated within these same intervals in the Powder Mill Group (4) and North Shore Volcanic Group (11). This concentration of evolved lava compositions is consistent with prolonged crustal staging of mantle-derived magmas leading to greater degrees of differentiation during this period. The broad and commonly erratic range of compositions erupted prior to and following the latent stage (e.g., 21) suggests that multiple, open-system staging chambers existed throughout the lower crust.

• Contaminated basalt—Trace element (e.g. Th/Yb) and Nd isotope geochemistry of basalts (Fig. 1) suggest that crustal contamination was most prevalent in the period leading up to the latent magmatic stage. The greatest potential for interaction between mantle melts and continental crust would be expected to occur during the initial development of lower crustal magma chambers. Once established, crystallization and continued inflation of such chambers would have insulated them from further contamination and diluted the initial contamination.

• Plagioclase crystal mush—Leucocratic intrusions of the Mellen Complex formed at 1102 Ma (10), the anorhotitic series of the Duluth Complex at 1099 Ma (9), and the widespread occurrence of plagioclase-phyric lava flows (p, Fig. 1) indicate that plagioclase-enriched basaltic magmas were commonly emplaced into the upper crust between 1108 and 1096 Ma. Such plagioclase crystal mushes were likely generated in lower crustal magma chambers where high pressures would have promoted the flotation of plagioclase (20). An implied consequence of this flotation is the formation of anorhotitic roof zones in these deep chambers. Such roof-zone material was the likely source of anorhotite inclusions found in the Beaver Bay Complex.

The interpretation of the latent magmatic stage as a period of extensive magmatic underplating and crustal melting carries significant implications for the geodynamic and magmatic evolution of the MCR which need to be more fully explored. Whether underplating was the cause or effect of reduced crustal extension and the development of the latent magmatic stage hinges on the larger question of what drives continental rifting. Future petrologic studies should be directed at evaluating the extent to which open-system crystallization differentiation of mantle-derived magmas under high pressures (7-10 Kb) can account for the compositional range of MCR lavas and at more precisely determining the sources of felsic magmas. In addition, more high precision U-Pb ages are necessary to verify the existence and duration of the latent magmatic stage in all sequences and to better establish correlation between Mamainse Point lavas and volcanic sequences in the western Lake Superior region.
## References


### Figure 1. Correlation of units, summary of lithologic and chemical characteristics, and interpretations of the tectonomagmatic evolution during magmatic stages of the Midcontinent rift. Intervals of Normal and Reversed magnetic polarity indicated (P). Relative abundances of basaltic and felsic volcanics schematically portrayed and general locations of plagioclase porphyritic flows (p) noted for the major volcanic suites—NSVG-North Shore Volcanic Group(1); PL/PMM- Portage Lake Volcanics and Powder Mill Group (4); OG/IR- Osler Volcanic Group and PL on Isle Royale (12); MPP- Mamainse Point Formation(2,13). Subdivisions of volcanic suites are NSVG: IGP46P, HL, NSV-o, SLB- lower/upper Grand Portage lavas, Hovland lavas, NSVG-normal polarity, and Schroeder-Lutsen basalt of (11); PMP: ISC/GrSC, KIC/KC- lower/upper Seimens Creek lavas and lower/upper Kallander Creek volcanics of (4); OG: lower, central, and upper suites of (12); MPP: Groups 1-7 of (2); CHC-Copper Harbor Conglomerate; GC- Great Conglomerate. Intrusive rock units are LS- Logan Sills, CC- Coldwell Complex, NLS-Nathan's Layered Series, MC- Mellen Complex, DC- Duluth Complex, BBC- Beaver Bay Complex. Average U-Pb ages for various volcanic and intrusive rocks indicated by filled (felsic) and open (mafic) circles; data from (8), (9), (10), and sources listed therein. $E_{U/Pb}$ data from MPP (2), PL/PMM (4), NSVG rhyolite (19), NSVG basalt (21). $mg^{#} = (MgO/[(MgO+FeO)\times 100])$ of common range displayed by basalt in all volcanic suites (2,4,11,12,21, 22, 23). T/Hb data from MPP (2), PM (4), OG (12), NSV-n (21), PL (22, 23). Relative eruption and extension rates (Low, Medium, High) interpreted from thicknesses of volcanic suite relative to period of eruption. Magma sources for basaltic composition: EP- enriched plume, Lm- lithospheric mantle, DM- depleted asthenospheric mantle (modified from (2) and (3)). Magma sources for felsic compositions in parentheses: LC- lower crust, UC - upper crust, KL - Kawecanawan lavas. Interpretations of relative volumes of magma staging in the lower crust (LC) and upper crust (UC) denoted by relative widths of curves.