Proceedings of the Annual Joint Conference,
Mineralogical Society of Korea and Petrological Society of Korea
June 1, 2001, Pusan, Korea

Oxygen Isotopic Systematics of the Sonju Lake Intrusion, Northeastern Minnesota, Midcontinent Rift System, USA

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1. Introduction

1.1Ga, the Sonju Lake Intrusion (SLI) of northeastern Minnesota emplaced into the upper part of the Mesoproterozoic North Shore Volcanic Group(NSVG) developed along the Midcontinent Rift System. The SLI is composed of 1.2 km thick succession of layered mafic cumulates. The hanging wall of the SLI is composed of granitic rocks of the Finland Granophyre (FG). The granophyre is composed of two general lithologic units of quartz ferromonzodiorite and micrographic granite.

Five cumulate units that sandwitched between lower (fine melatroctolite) and upper (olivine ferromonzodiorite) marginal zones are distinguished in the SLI based on the successive cumulus arrivals of olivine, plagioclase, augite, ilmenite, and apatite. From the bottom to the top of the sequence, the SLI is composed of dunite, troctolite, gabbro, oxide gabbro, and apatite olivine diorite. The SLI shows a characteristic of a differentiated layered intrusion produced by fractional crystallization of mafic magma in the closed-system.

The cryptic variations of primocrystic olivine and augite calculated by applying the Chaos 2 fractional crystallization model, with the parameters to simulate closed-system fractional crystallization, immediately gives a good match to the observed phase paragenesis. The reasonable fit of the Chaos 2 model calculations to the observed cumulus phase layering and cryptic variation through the SLI provides supporting evidence that the intrusion formed via closed-system, moderately efficient fractional crystallization. Oxygen isotopic studies were initiated to evaluate fractional crystallization processes in a multiply-saturated tholeiitic system. We report the results of measurements from whole rocks and plagioclase from the SLI and overlying Finland Granophyre (FG), which suggest that both subsolidus isotopic exchange and assimilation have locally controlled oxygen isotopic systematics.

2. Analytical methods

Samples for this study were collected from the SLI and overlying FG. Most samples were taken from outcrops with some from drill cores. Sample for isotopic analyses included whole rocks and plagioclase. Plagioclase was extracted from flat slabs by diamond drilling. Samples for oxygen isotopic analyses were prepared using the BrF5 method of Clayton and Mayeda (1963). Isotopic ratios were measured on Finnigan MAT 252 stable isotope ratio mass spectrometer at Indiana University. Results are reported in delta notation relative to VSMOW for O.

3. Results

Variation in $\delta^{18}O$ values of whole rocks and plagioclase separate from the SLI and FG with stratigraphic height is shown in Figure 1. Stratigraphic height (in m) of samples are positioned relative to the hirizon marking the cumulus arrival of augite. $\delta^{18}O$ values of whole rocks and plagioclase from the SLI range from 5.41 to 8.32 , and 5.64 to 12.04, respectively. $\delta^{18}O$ values of whole rocks and plagioclase from the FG overlying the SLI range from 6.65 to 8.76, and 12 , respectively. While whole rocks from the lower and upper marginal zones of the SLI tend to have variable $\delta^{18}O$ values from 5.41 to 8.32, those from the center of the SLI are characterized by a more restricted range of $\delta^{18}O$ values between 5.3 and 6.5, but one sample with 7.70. Plagioclase from the dunite in the base of the SLI and the upper marginal zone below the granophyre tends to have high $\delta^{18}O$ values, up to 12. Both plagioclase and whole rocks tend to show a gradual decrease upward in $\delta^{18}O$ values from the dunite in the bottom of the stratigraphic seuence toward the center of the intrusion. Samples located in the vicinity of the hybrid dykes tend to have high $\delta^{18}O$ values in both whole rocks and plagioclase. $\delta^{34}S$ values of whole rocks from the SLI range from 2.19 to 2.21, and one sample from the FG has 0.09. Sulfur content of whole rocks range form 63 to 2419 ppm.

4. Discussion

Whole rocks from the lower and upper marginal zones, as well as locally from the interiors of the SLI are characterized by elevated and variable $\delta^{18}O$ values relative to 'normal' mafic igneous rocks (5.4-6.0). High and variable $\delta^{18}O$ values may result from: (i) fractional crystallization; (ii) crustal contamination; (iii) subsolidus hydrothermal alteration. In order to evaluate variation in $\delta^{18}O$ value of the SLI magma as a function of fractional crystallization, isotopic modeling has been conducted using mass balance equation and oxygen isotopic equilibrium fractionation factors between minerals and melt. The magma composition of the SLI determined by geochemical summation of a total 76 whole rock analyses was used

in this modeling. Mineral proportions were determined by applying the Chaos 2 fractional crystallization model to the calculated SLI bulk composition. Initial oxygen isotopic composition of melt is estimated to be 5.8. Temperature range for crystallization of melt is set from 1160 to 1030 °C. Isotopic modeling results show that the crystallization of ^{18}O-enriched plagioclase and ^{18}-O depleted olivine, pyroxene, and oxide keeps δ^{18}O value of melt uniform during 95 mole % crystallization. Whole rocks crystallized from the melt show a variation of ~0.75 in δ^{18}O value during 95 mol crystallization, which occurred at the beginning of the fractional crystallization during formation of dunite as a result of olivine crystallization. Modeling result indicates, therefore, that fractional crystallization alone cannot produce high and elevated δ^{18}O values observed in the SLI. Therefore, other processes such as assimilation of crustal rocks by mafic magma, and subsoliduc isotopic exchange should be considered. However, although assimilation of granitic country rocks by the SLI magma during emplacement may have played a role to produce high oxygen isotopic composition in the upper marginal zone of the SLI where it is underlain by granophyres, it is not likely that contamination of the SLI magma by granitic rocks occurred throughout the whole sequences of the cumulates. Furthermore, sulfur isotopic values of the SLI ranging from 2.2 to 2.2 which are indicative of mantle-derived sulfur origin (0±3‰) also suggest that the SLI magma experienced neither bulk nor selective assimilation of Proterozoic metasedimentary country rocks of Virginia Formation during assent. Virginia Formation has variable δ^{34}S value ranging from 0 to 30 (Ripley, 1981). If the SLI magma experienced contamination by Virginia Formation during assent, higher δ^{34}S values will be observed from the SLI samples.

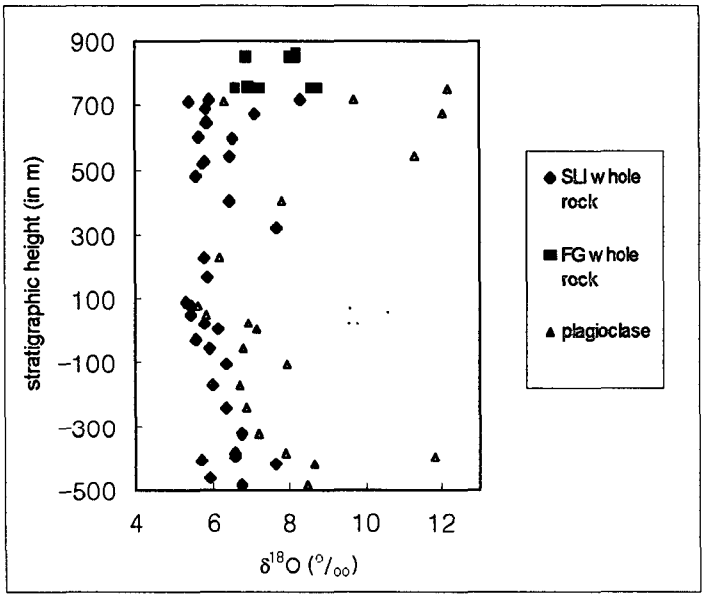

Fig. 1. Variation in δ^{18}O values of whole rocks and plagioclase from the Sonju Lake Intrusion and Finland Granophyre with stratigraphic height.

From petrographic evidence of hydrothermal alteration of plagioclase and a wide range in plagioclase δ^{18}O values from 5.5 to 12, as well as lack of close association of the SLI with crustal country rocks in the lower marginal zones where high and variable δ^{18}O value are

observed, we believe that subsolidus isotopic exchange with a high-^{18}O fluid was a primary process to produce high and variable oxygen isotopic compositions of the SLI. The positive correlation in $\delta^{18}O$ values between whole rocks and plagioclase indicates that elevation of $\delta^{18}O$ value of whole rocks from the SLI is primarily caused by the enrichment of ^{18}O in plagioclase during post-crystallization isotopic exchange.

A gradually decreasing trend in ^{18}O values upward from the dunite unit in the bottom of the stratigraphic sequence toward the center of the SLI in both plagioclase and whole rocks indicates that the dunite unit provided a conduit for fluid infiltration in the lower marginal zone and isotopic exchange front encroached toward the center of the intrusion. The well-developed fractures in serpentinized olivines in dunite zone may have served as a pathway for the movement of fluid flow. In the upper marginal zone of the SLI, isotopic exchange with a high-^{18}O fluid, as well as assimilation of granitic country rocks during emplacement are thought to produce high oxygen isotopic composition of the SLI. In contrast to high and variable ^{18}O values from 5.3 to 6.5 in the interiors of the SLI indicates that fluid infiltration was not pervasive through the whole sequence of the intrusion. However, the non-magmatic oxygen isotopic composition of some plagioclase from the interiors suggests that interiors of the SLI locally experienced isotopic exchange with high-^{18}O external fluid. High $\delta^{18}O$ values of the SLI located in the vicinity of the hybrid dykes indicate that the SLI also locally experienced isotopic exchange with these dykes after solidification.

Park and Ripley (2000) suggested that the NSVG and related hypabyssal sills experienced hydrothermal alteration by fluids of $\delta^{18}O$ of ~3. On the basis of O and H isotopic data of vesicle-filling amygdules and whole rocks, Park and Ripley (2000) suggested that both sea water and meteoric water that experienced isotopic exchange with volcanic rocks were responsible for hydrothermal alteration and accompanying isotopic exchange in the NSVG and related hypabyssal sills. Hydrothermal flow systems developed in the NSVG and interflow hypabyssal sills may also have influenced the SLI which is located to the NSVG closely.

5. References

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