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PROCEEDINGS OF THE TWENTY-FIFTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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GEOCHEMICAL ANALYSIS OF TERTIARY DIKES NEAR HRAFNFJORDUR CENTRAL VOLCANO, NORTHWEST ICELAND: IMPLICATIONS FOR DIKE ORIGIN

NINA WHITNEY, Carleton College
Research Advisor: Cameron Davidson

INTRODUCTION

As is the case with all central volcanoes in Iceland, the approximately 14 Ma Hrafnfjordur central volcano in northwestern Iceland has a multitude of dikes emplaced within it. This paper uses geochemical analysis to investigate whether these dikes originated from the Hrafnfjordur central volcano or whether they instead originated from other fissures of the 15-7 Ma Skagi-Snaefellsnes paleo-rift, with which the Hrafnfjordur central volcano is associated.

There are two general hypotheses on where dikes emplaced in Icelandic central volcanoes originated. The first is that rift-parallel dikes originating from fissures of the active rift feed sills, which form under central volcanoes due to stress barriers. These sills eventually evolve into the magma chambers of the central volcanoes (Fridleifsson, 1977; Gudmundsson, 1986; Gudmundsson, 2000). Alternatively, it

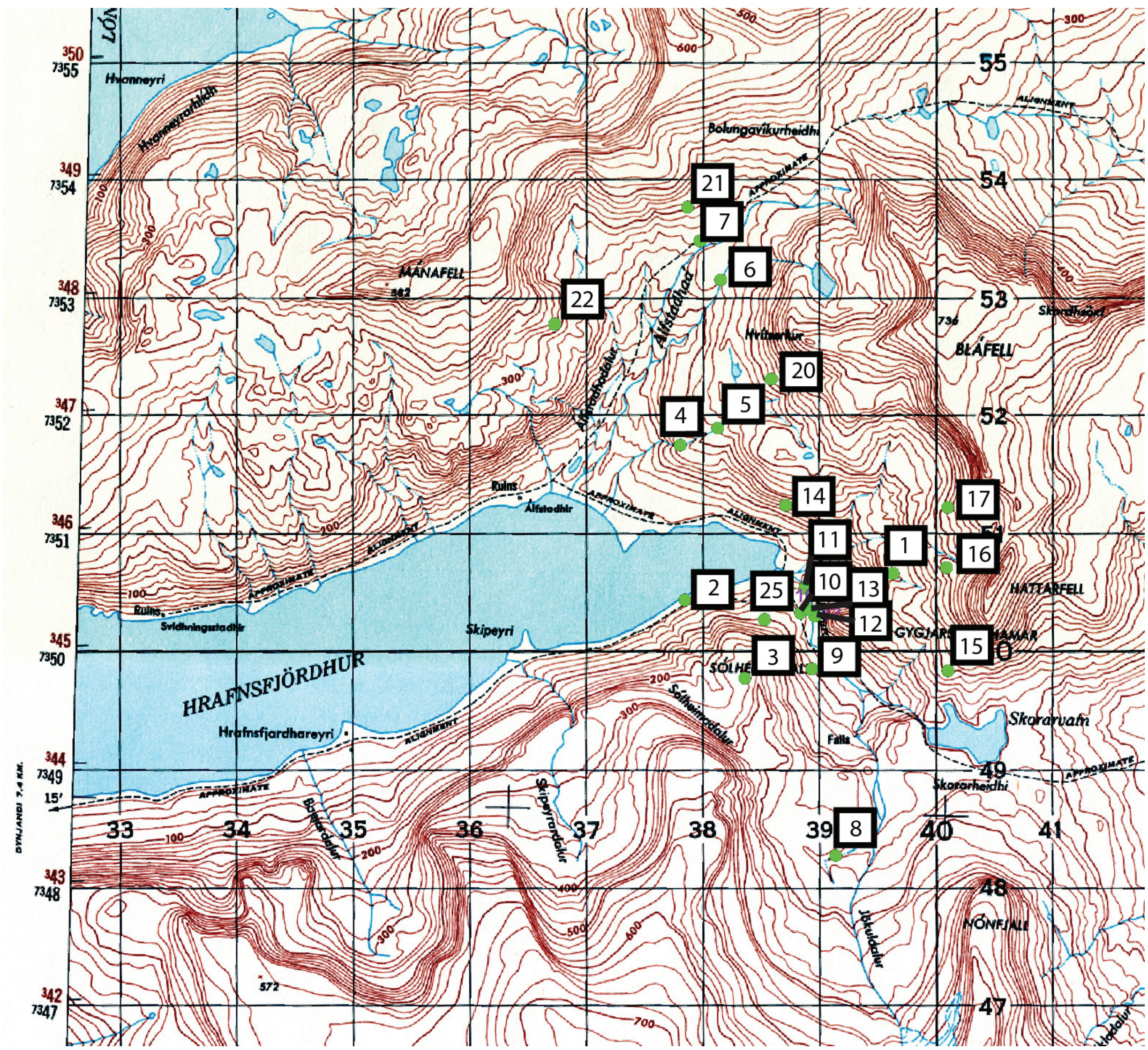

Figure 1. Topographic map of Hrafnfjordur showing dike outcrop locations (green dots).

has been argued that the magma chambers of central volcanoes are fed directly from the mantle and that it is this system that also feeds the dikes found in dike swarms near central volcanoes (Rubin and Pollard, 1987; Klausen, 2006 and references therein).

In order to help contribute to this discussion on the origin of dike swarms emplaced near central volcanoes, the major and trace element compositions of the Hrafnfjordur dikes are compared to the composition of both locally and regionally sourced (referred to hereafter as local and regional) Tertiary volcanic rocks. The local volcanic rocks are those that are thought to have erupted from the Hrafnfjordur central volcano and include all of the silicic rocks around the central volcano as well as the basalts that are intercalated with these silicic rocks. These basalts are likely the best representation of the composition of

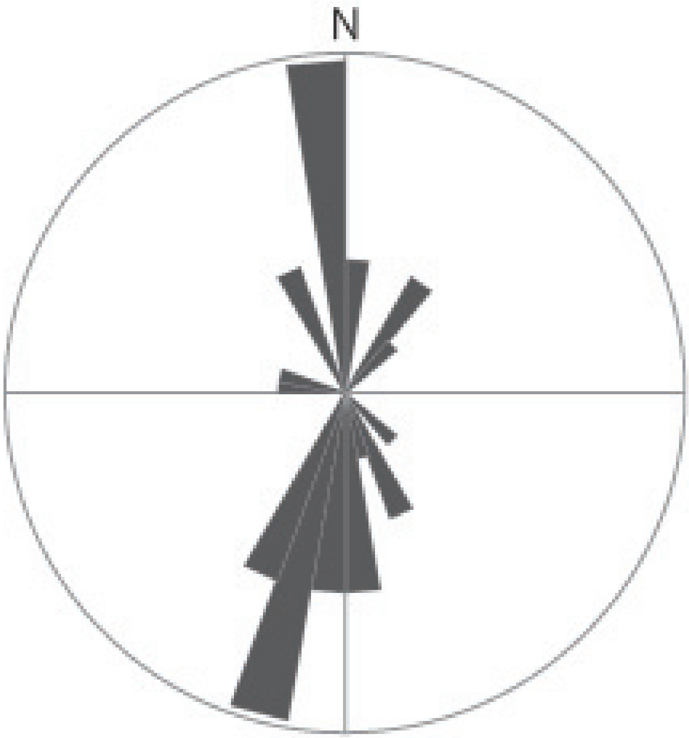

Figure 2. Rose diagram of the orientation of the Hrafnfjordur dikes. N=32.

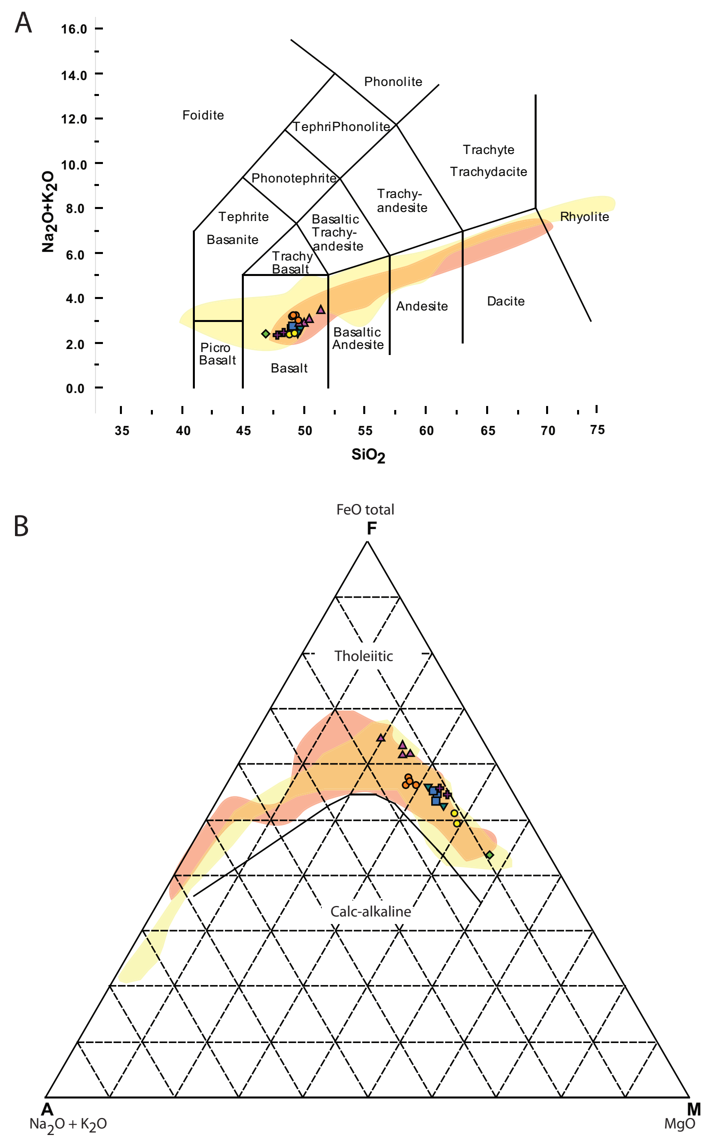

Figure 3. (right) (A) TAS diagram, wt.% (LeBas et al., 1986) and (B) AFM diagram (Irvine and Baragar, 1971) for the Hrafnfjordur dikes (individual symbols) and other volcanic rocks found throughout Iceland (filled outlines). Dike samples are differentiated by location: pink pentagon = dike 21F (sample 36-NW-11); violet triangles = dikes 8 (sample 26-,27,-28-NW-11) and 10 (sample 30-NW-11); orange circles = dikes 7B (sample 24-NW-11), 7C (sample 23-NW-11), 7D (sample 22-NW-11), 7E (sample 21-NW-11) and dike 21D (sample 35-NW-11); yellow circles = 7A (sample 25-NW-11) and 7F (sample 20-NW-11); blue squares = dike 2 (samples 3-, 4-, 7-NW-11); green inverted triangle = dike 3 (samples 9-, 11-NW-11); teal hexagon = 11 (samples 31-NW-11); purple crosses = dike 4 (samples 14-, 15-NW-11); green diamond = dike 19 (samples 34-KS-11). The yellow shading highlights the composition of Tertiary volcanic rocks collected from across Iceland (Wood, 1978; Hardarsson et al., 1997; Johnson, 2005). The vast majority of these rocks are assumed to be sourced from fissures of the Snaefellsnes paleo-rift due to their age. Some of the more silicic rocks were collected from central volcanoes in eastern Iceland. The red shading is from flows collected during the 2011 Keck project which are considered to have originated from the Hrafnfjordur central volcano.

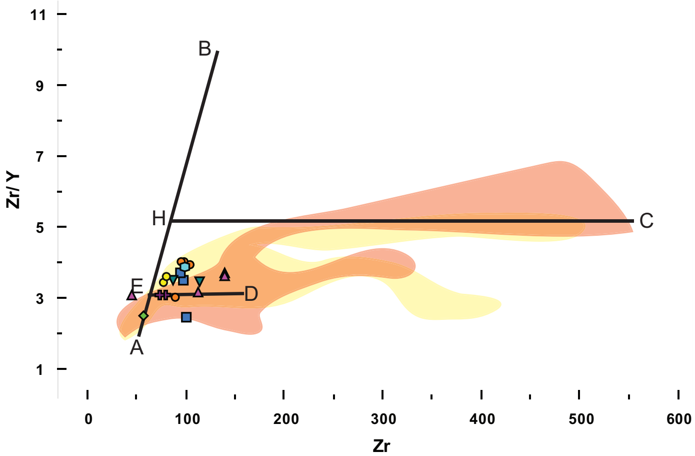

Figure 4. Zr/Y versus Zr (ppm) (modified from Gautneb et al., 1989). Color and symbol assignments are the same as in Figure 3. Compositions that fall along the line AB probably indicate mixing between magmas with different initial Zr/Y ratios, whereas compositions that fall along lines parall to HC, including line ED, can be explained by fractional crystallization (Gautneb et al., 1989).

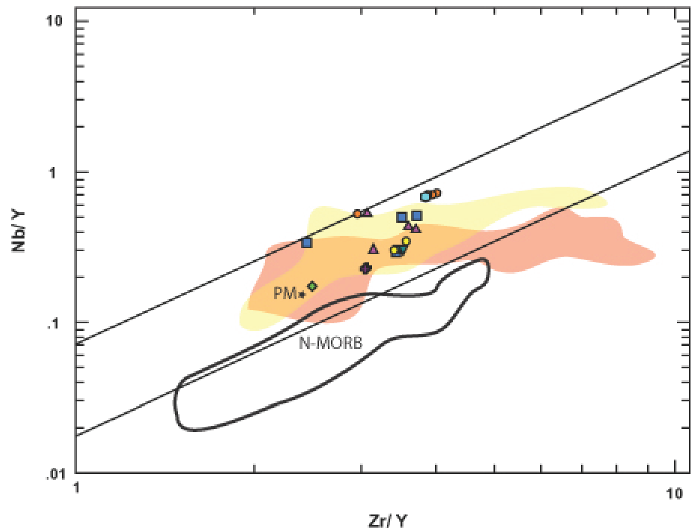

Figure 5. Plot of log (Nb/Y) versus log (Zr/Y). Parallel lines indicate the compositional limits for Iceland volcanic rocks, termed the Icelandic array (Fitton et al., 1997). PM is the abbreviation for primitive mantle and is plotted as a star (Fitton et al., 1997 and references therein). The limits of N-MORB are included for reference (Hardarson et al., 1997). Color and symbol assignments are the same as Figure 3.

the magma within the magma chamber of the central volcano (Gautneb et al., 1989), so dike compositions similar to these basalts would indicate dike origin from the central volcano. The regional volcanic rocks are rocks thought to have formed by melts that were erupted from fissures of the Skagi-Snaefellsnes paleo-rift. Note that the term regional, as it is used in this paper, could therefore refer to rocks sourced from fairly close to Hrafnfjordur. These regional volcanic rocks include samples collected by other authors from various locations around Iceland as well as samples collected during the field research for this project from basalt flows stratigraphically overlying those volcanic rocks believed to have erupted from the Hrafnfjordur central volcano.

METHODS

Twenty-five dikes or dike complexes located in Hrafnfjordur were mapped and sampled in the field (Fig. 1). Along with general observations, the orientations of the dikes were recorded where possible (Fig. 2). Twenty representative dike samples were analyzed using x-ray fluorescent spectrometry at The College of Wooster.

FIELD OBSERVATIONS

Most of the dikes observed in the field appeared to be basaltic in composition. The groundmass varied from aphanitic to fine-grained phaneritic. Phenocrysts generally made up less than 10% of the dikes, although phenocryst concentration was observed to reach as much as ~30% (dike 14). Phenocrysts are predominantly plagioclase feldspar, with some pyroxene and olivine phenocrysts present. All dikes were subvertical and tended to strike in a north-south direction (Fig. 2), parallel to the Skagi-Snaefellsnes paleo-rift. However, two dikes were found to strike east-west (dikes 19 and 20) and were therefore likely influenced by the local stress fields created by the magma chamber of the central volcano, indicating their formation occurred around the time that the central volcano was active.

RESULTS AND DISCUSSION

Chemical variations along strike

It was thought in the field that dike 8A and dike 10, which outcrops approximately 2.1 kilometers north of dike 8A (Fig. 1), were two outcrops of the same dike along strike. Major element plots confirm that the two outcrops have very similar compositions and therefore likely represent two outcrops of the same dike along strike (Fig. 3). The increase in concentration of the incompatible elements Rb, Ba and Zr from dike 10 (3, 47 and 113 ppm respectively) to dike 8A (8, 72 and 140 ppm respectively) (Fig. 4) suggests that dike 8A was formed from a magma that had undergone a greater amount of fractional crystallization than dike 10, which suggests that the dike was laterally emplaced (Schmitz et al., 1995). If the compositional difference between the two dike outcrops is a result of temporal fractional crystallization of the magma as the dike was emplaced, the dike would be expected to be more evolved farther from the source as the magma would have had more time to undergo fractional crystallization. As dike 8A outcrops to the south of dike 10, the above hypothesis suggests that the dike originated from the Hrafnfjordur central volcano, the center of which is believed to have been situated directly to the north of the present locations of the outcrops of dikes 8A and 10. Another interpretation of the more evolved geochemical signature found in dike 8A as compared to dike 10 is that these two dikes were sourced from a heterogeneous magma chamber (either zoned by fractionation or due to a recharge event), with a more primitive magma feeding the latter half of the eruption in which the dike was emplaced. Support for the model of a heterogeneous magma chamber feeding Hrafnfjordur dikes is derived from the geochemical analysis of samples taken from both the margin and core of dikes 3 and 4. Both dikes were found to have more primitive cores than margins, suggesting the dikes were fed by a more primitive melt later on in their formation. If the dike comprised of dikes 8A and 10 was also fed by a more primitive magma towards the later end of its formation, the difference in incompatible element concentrations between dikes 8A and 10 would suggest a source originating not from the central volcano but from south of where the dike outcrops at dikes 8A and 10, such as a fissure of the Skagi-Snaefellsnes paleo-rift.

Chemical variation within dike complexes

Dike 2, dike 7 and dike 8 were all considered to be dike complexes in the field and were sampled to evaluate how these dike complexes formed. Dike 2, which is a swarm of thin dikes, has a total width of approximately 10 meters and is comprised of at least 52 individual dikes. The geochemical results from samples taken from this dike swarm indicate that while the three samples show that the major element composition is almost identical for all three dikes, there is some variability in the Zr/Y ratio for the three samples. Specifically, sample 03-NW-11, which was taken from the eastern most margin of the dike zone, has a significantly lower Zr/Y ratio (2.4) than the two samples taken from the middle of the dike swarm (3.5) (Fig. 4 and 5). This may indicate that the interior dikes of the dike swarm represent a later injection of melt from a magma chamber that had been replenished with a magma that contained a higher Zr/Y ratio since the margin dikes were intruded (Gautneb et al., 1989). The variability in Zr/Y ratios could also suggest that the melts that formed the individual dikes simply came from two different sources that had different Zr/Y ratios, although this seems less likely given the similarity in physical characteristics between the dikes within the dike complex.

The dike 7 complex has a total width of approximately 8 meters. Based on weathering patterns, structure and petrology of the dikes within this dike complex, it was thought in the field that there might be as many as 5 different dikes within this complex, although dikes 7A and 7F, which are the most westerly and most easterly dikes of the complex respectively, were likely outcrops of the same dike. Dikes 7B and 7D were likely just the margins between the other dikes. Geochemical results revealed that while the dikes might appear in the field to be distinct, dikes 7C, 7D and 7E appeared to be geochemically very similar (Fig. 3-5). Dikes 7A and 7F are also geochemically similar but are less evolved than the interior dikes, with MgO concentrations of 8.1 - 8.2 wt. % as compared to dikes 7C-7E, which have MgO concentrations between 5.5 - 5.9 wt.%. Dike 7C was comprised of a thin dike swarm, much like dike 2, so it is unlikely that dike 7C and dikes 7D and 7E are in fact the same dike. However, geochemical evidence suggests that they formed from the same source at roughly the same time in the evolution of the melt.

Evidence for the presence of fractional crystallization between dikes 7A and 7F and the interior dikes can be seen when looking at Zr concentrations (Fig. 4), as dikes 7C-7E had Zr concentrations of 97-106 ppm, which are higher than those of dikes 7A and 7F, which had Zr concentrations of 79-82 ppm. Therefore, the dike 7 complex formed through two injections of magma that, given the close proximity of the dikes within the complex to each other, originated from the same magma chamber, using the same dike conduit (Schmitz et al., 1995). Geochemical results therefore suggest that the interior dikes (7B, 7C, 7D and 7E) formed some time after dikes 7A and 7F did, when the magma chamber had undergone a certain amount of fractional crystallization. This analysis suggests that dikes 7B-7E were intruded into the previously formed dike (7A and 7F), splitting it apart. Given the fact that the Nb/Y ratios of the interior dikes are more enriched than any local volcanic rocks (Fig. 5), it is likely that the magma source that fed the dike 7 complex was not from the Hrafnfjordur central volcano.

The dike 8 complex consists of three dikes, with dike 8A being the largest with an outcropping width of 5 meters. Dikes 8B and 8C both had widths of less than 1 meter. Unlike within the dike 7 complex, the margins of the dikes within the dike 8 complex do not touch, suggesting that the three dikes were not directly intruded into each other and may not have come from the same dike conduit. When looking at the geochemical results for this dike complex, it is clear that the three dikes are geochemically very similar (Fig. 3). However, Figure 4 reveals that dike 8C has a much lower Zr concentration than dikes 8A and 8B, suggesting that it formed from a melt that underwent very little fractional crystallization, and contained a lower Zr/Y ratio than the other dikes within the complex. As major element geochemistry suggests that 8C is in fact more evolved than dike 8A and 8B, it is unlikely that dike 8C was simply intruded first and that dikes 8A and 8B are the result of the fractional crystallization of the same magma chamber. Therefore, while dikes 8A and 8B are likely from the same magma source and were likely intruded at roughly the same time if not at the same time, given their major element similarity, dike 8C did not originate from the same melt source as dikes 8A and 8B. Its location so close to dikes 8A and 8B suggests that the intrusion placement and orientation of these dikes might have been governed by a fault plane or other weak feature in the country rock (Schmitz et al., 1995).

Further analysis of dike origin

In addition to looking at the geochemical characteristics of individual dikes, it is also important to look at how these dikes compare to the overall trends of local and regional volcanic rocks with the hope that similarity to these trends might help to explain the origin of the Hrafnfjordur dikes.

The regional and local volcanic rocks tend to show very similar trends in most of the geochemical diagrams plotted and therefore comparison of the Hrafnfjordur dikes sampled with these local and regional trends gives little insight as to the origin of the Hrafnfjordur dikes. The exception to this can be found in Figure 5, where there is a clear difference in enrichment of the Nb/Y ratio between the local and regional rocks, despite significant overlap as the regional rocks include higher Nb/Y ratios than the local volcanic rocks. Several dikes have higher Nb/Y ratios than the local volcanic rocks and a few have higher Nb/Y ratios than the regional volcanic rock, although they are still within the Icelandic array, and therefore suggests a lack of scope in the regional rock data that was used in this paper. It can therefore be concluded that those dikes with high Nb/Y ratios, including the dike 2 complex, as well as the dike 7 complex, dike 8C and dike 11, all originated from a regional source.

CONCLUSION

Geochemical analysis of the dikes intruded in the Hrafnfjordur central volcano reveals that there are likely both locally and regionally sourced dikes emplaced in this area. Dikes 2, 7, 11, 19, and 21 were likely regional in origin, with melts originating from the fissures of the Skagi-Snaefellsnes paleo-rift. Dike 8A and 10 likely originated from the central volcano, as did 8B since it was determined to have a similar origin to dike 8A, although there is a possibility that these dikes in fact also originated from a fissure of the Skagi-Snaefellsnes paleo-rift. The other dikes analyzed could have originated from either source. It is clear that regional stresses played the greatest role on the emplacement of the Hrafnfjordur dikes as almost all were oriented parallel to the Skagi-Snaefellsnes paleo-rift. Therefore, geochemical analysis of the Hrafnfjordur dikes does not fully support one side or the other in the debate over the origin of dikes emplaced in Icelandic central volcanoes. Instead, the geochemical analysis done in this paper suggests that the source for the melts that form the dikes in Icelandic central volcanoes varies from dike to dike and it is possible to have dikes that originate from the central volcano as well as dikes that originate from fissures of the active rift in close proximity to each other.

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