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Cover Figure:

Small dolerite dyke cutting across host granites (Bangalore, southern India).

SOFYA CHISTYAKOVA

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Academic Dissertation to be presented with the assent of the Faculty of Science, University of Oulu for public discussion in the Auditorium L10, Linnanmaa, on December 1st, 2011, at 12.00 noon.

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To the memory of my grandmother

Processes of magma differentiation and crystallization operating in basaltic conduits: insights from internal chemical zonation of mafic dykes

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Abstract

Basaltic magmas are delivered towards the Earth's surface to erupt as lavas or to stall as plutonic bodies via magma conduits that crystallize into a plexus of interconnected mafic dykes and sills. Mafic dykes thus essentially represent fossilized conduits that transported basaltic magmas through the crust towards the Earth's surface and provide therefore primary information on magma differentiation processes that operate in basaltic conduits. These processes still remain, however, poorly understood.

To shed light on this issue, we have undertaken an unprecedentedly detailed, cm-scale study of mafic dykes from many regions of the world (Finland, Russia, Spain, Antarctica, Mongolia, India, and Canada). The study has resulted in several important observations and conclusions that put strict constraints on our understanding of magma fractionation processes operating in mafic dykes. Contrary to common expectations, small (<50 cm thick) and superficially homogeneous dolerite dykes mostly consisting of plagioclase and clinopyroxene (±amphibole) have emerged to be remarkably zoned. The internal zonation has proved to be strongly anomalous in composition. It is not consistent with predictions of fractional crystallization of basaltic magma since compatible components are strikingly decoupled from incompatible ones. In particular, both compatible (e.g. MgO, Ni, Cr) and incompatible (e.g. P_2O_5, TiO_2, Zr) components commonly show a systematic decrease from margins inwards. Some dykes reveal prominent crossover points where one inward tendency in the distribution of compatible/incompatible components or parameters (e.g. MgO, Mg#, TiO_2) changes to the opposite one. Even more perplexing appears to be a decoupling between individual components belonging to the same geochemical group. This occurs, for instance, when incompatible components can either increase (P_2O_5) or decrease (Zr) inwards, or even initially increase at the margins and then decrease (TiO_2) in the centre. Of special interest is one case

of spatial chemical zonation in a large dolerite dyke and its narrow apophysis. Chemical zonation is found to systematically change with a decreasing thickness of studied sections. In particular, a tendency to become more primitive inwards in a large dyke (e.g. an increase in MgO, Mg-number, normative An content and a decrease in P_2O_5) gradually gives way to an opposite tendency to become more evolved inwards in a narrow apophysis (e.g. a decrease in MgO, Mg-number, normative An content and an increase in P_2O_5).

To explain the chemical zonation of small and large mafic dykes, a new concept has been developed that attributes compositional trends in mafic dykes to a competitive operation of two petrogenetic processes. These are (a) the filling of dykes with magmas that become increasingly more evolved with time as a result of magma fractionation in deeper parts of conduits and (b) *in situ* cumulate growth against dyke sidewalls accompanied by effective removal of an evolved liquid boundary layer from growing crystals by the continuously inflowing magmas. The processes have opposite effects on rock geochemistry, with the first making dykes more evolved and the second more primitive inwards. A key idea is that dykes that become more evolved inwards arise when quenching of inflowing magmas controls the distribution of all components, whereas dykes that become more primitive inwards emerge when *in situ* cumulate growth governs the distribution of all components. Various anomalous distributions of components may appear when these two processes control the behavior of separate groups of compatible/incompatible components. The spatial chemical zonation of a large dyke and its apophysis can be attributed to a gradual change from rocks mostly produced by quenching of progressively more evolved magmas (the apophysis) towards those predominantly formed by *in situ* cumulate growth of these magmas (the large dyke). This happens in response to the decreasing extent of magma cooling by country rocks in this direction. To validate the proposed concept, geochemical modelling of several scenarios involving compatible (MgO) and incompatible (P_2O_5) components were carried out. The geochemical modelling has confirmed that the concept is able to explain the puzzling compositional patterns of decoupling between compatible and incompatible elements in small mafic dykes by variations in the relative contribution of two competing petrogenetic processes. It can also be demonstrated that the remaining, more typical, compositional profiles of large mafic dykes can be interpreted using this concept, with possible minor contributions from other petrogenetic processes (e.g. flow differentiation). A major strength of the concept is that it is not only explains most known compositional profiles but also predicts new ones that may be found in the future. The proposed interpretation of chemical zonation of large and small dykes may represent a general feature of magma differentiation processes operating in basaltic magma conduits.

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Finally I express my gratitude to my family for patience and understanding that help me greatly to manage this work.

Oulu, July 2011

Sofya Chistyakova

CONTENTS

ORIGINAL PUBLICATIONS

PAPER I

Chistyakova S. Yu. & Latypov R. M. (2009a). Fine-scale chemical zonation of small dolerite dykes, Kestiö Island, SW Finland. *Geological Magazine* 146, 485-496.

PAPER II

Chistyakova S. Yu. & Latypov R. M. (2009b). Two independent processes responsible for compositional zonation in mafic dykes of the Åland-Åboland Dyke Swarm, Kestiö Island, SW Finland. *Lithos* 112, 382-396.

PAPER III

Chistyakova S. Yu. & Latypov R. M. (2010). On the development of internal chemical zonation in small mafic dykes. *Geological Magazine* 147, 1-12.

PAPER IV

Chistyakova S. Yu. & Latypov R. M. (2011a). Primary and secondary chemical zonation in mafic dykes: a case study of the Vochelambina dolerite dyke, Kola Peninsula, Russią. (Ed.) R.K. Srivastava, *Dyke Swarms: Keys for Geodynamic Interpretation*, DOI 10.1007/978-3-642-12496-9_29, Springer-Verlag Berlin Heidelberg 2011, p. 569-581.

PAPER V

Chistyakova S. Yu. & Latypov R. M. (2011b). Small dacite dyke, Southern Urals, Russia: rapidly quenched liquid or fine-grained cumulate? (Ed.) R.K. Srivastava, *Dyke Swarms: Keys for Geodynamic Interpretation*, DOI 10.1007/978-3-642-12496-9_29, Springer-Verlag Berlin Heidelberg 2011, p. 583-601.

PAPER VI

Latypov R. M. & Chistyakova S. Yu. (2011a). A novel concept of two competing processes in petrogenesis of basaltic magma conduits. *Contributions to Mineralogy and Petrology (under review).*

PAPER VII

Latypov R. M. & Chistyakova S. Yu. (2011b). A magma differentiation history recorded in a single dyke apophysis. *The American Mineralogist (under review).*

PAPER VIII

Chistyakova S. Yu. & Latypov R. M. (2011c). Magma differentiation processes in basaltic conduits: insight from spatial chemical zonation of a large dolerite dyke and its apophysis. *Lithos (manuscript to be submitted).*

INTRODUCTION

Mafic dykes are among the simplest and most spectacular geological objects that form discordant tabular or sheet-like bodies of magma that cut vertically through and across strata and have great lateral extent relative to their thickness. They range from mm-thick films to massive sheets, hundreds of meters thick and tens of km long. Mafic dykes form when hot ascending basaltic magmas cool and crystallize against cold sidewalls of magma conduits and therefore their textural and chemical features provide primary information on petrogenetic processes that operate during a transport of magmas through basaltic conduits.

Significant progress has recently been made in our understanding of magma conduit behaviour owing to studies involving various physical aspects of dykes, such as the mechanics of their emplacement, propagation and arrest (e.g. Gudmundsson, 1995, 2006, 2011), magma flow dynamics (e.g. Melnik and Sparks, 1999, 2005; Costa et al., 2007), thermal history of magma eruptions through dykes (e.g. Bruce & Huppert, 1989; Hersum et al., 2007) and a mechanism of dyke growth (e.g. Annen & Zelmer, 2008; Platten & Watterson, 1987; Platten, 2000). Little, however, has been obtained from studies involving chemical aspects of dykes (e.g. Cadman & Tarney, 1990; Summers et al., 1995; Hoek, 1995; Del Gaudio et al., 2010). In particular, there is still no clear understanding of many aspects of magma crystallization, differentiation and solidification in basaltic conduits.

A key to all these processes is the nature of chemical zonation of mafic dykes (Ragland et al., 1968; Steel & Ragland, 1979; Ross & Heimlich, 1972; Ross, 1983, 1986; Kretz, et al., 1985; Cadman & Tarney, 1990; Brouxel, 1991; Ernst & Bell, 1992; Hoek, 1995). The puzzling feature of this phenomenon is that dykes from the same swarm (Kalsbeek & Taylor, 1986) and even different parts of the same dyke (Ervamaa, 1962; Sipilä et al., 1985) may display distinctly different patterns of compositional zonation, ranging from normal (e.g. with inward *decrease* in whole-rock MgO and Mg#) to reverse (e.g. with inward *increase* in whole-rock MgO and Mg#) patterns, with some combining simultaneously features of both normal and reverse fractionation. This feature appears to be almost universally developed in dykes, irrespective of their age, geographical location, and even the composition of parental magmas, strongly indicating that some fundamental process or processes are involved in the origin of dyke zonation.

In earlier attempts to explain this phenomenon, igneous petrologists have suggested about ten different hypotheses over the last century (contamination, flow differentiation, multiple emplacement, Soret effect, viscosity segregation, secondary alteration, etc.). Most of these have recently been reviewed in detail (Chistyakova & Latypov, 2009a, b; 2010a). Based on the compiled literature and our original data, we found that most of the above-mentioned mechanisms are inadequate to explain some characteristic features of dyke zonation and are therefore unlikely to represent fundamental explanations for its origin, although they may certainly contribute in some way. To get a key to understanding this phenomenon, we have undertaken an extensive petrographic, mineralogical and geochemical study of about 50 mafic dykes (including ~650 whole-rock and ~600 mineral chemical analyses) from different geological regions of the world (Finland, Russia, Spain, Antarctica, Mongolia, India, and Canada). This unprecedentedly detailed, cm-scale study has resulted in several important observations that put strict constraints on our understanding of magma fractionation processes operating in mafic dykes. These new findings gave us grounds to introduce a new concept of two competing petrogenetic processes (prolonged magma emplacement and *in situ* cumulate growth) as generating a wide spectrum of compositional profiles observed in basaltic magma conduits. The major results of this study together with a new concept are presented in 8 original publications that are briefly discussed below.

REVIEW OF ORIGINAL PUBLICATIONS

BACKGROUND

My thesis consists of eight papers with five of which being already published (Chistyakova and Latypov 2009a, b; 2010; 2011a, b – Papers I-V) and last three being under review (Chistyakova and Latypov 2011c; Latypov and Chistyakova 2011a, b – Papers VI-VIII). In these papers I described in detail a new natural phenomenon – a chemical zonation of small mafic dykes. The documented zonation patterns in the studied dykes are so compositionally complicated that in my earlier interpretations I had to appeal to some not yet specified process of magma differentiation in deep staging chambers from which magmas were supplied upwards to fill dykes (Chistyakova and Latypov 2009a, b; 2010; 2011a, b). In the last three papers (Chistyakova and Latypov 2011c; Latypov and Chistyakova 2011a, b) I came up with a new concept that allows explaining the internal zonation of dykes without appealing to the unknown process. This concept involves a combined operation of two competing processes of magma differentiation operating entirely within basaltic magma conduits. To help a reader to "unravel" our ideas that pass through the presented papers, a Table 1 summarizes the progressive development of our understanding of chemical zonation of the studied dykes.

PAPER I

This paper presents results of detailed cm-scale sampling across two small dolerite dykes (7 and 21 cm wide) of Kestiö Island, SW Finland that have revealed a well-developed internal zonation, with surprisingly systematic compositional variations. From the margins inwards the dykes exhibit a steady decrease in whole-rock MgO, Mg number (100Mg/(Mg+Fe_{total})), and normative Opx (indicating a normal fractionation trend) with simultaneous increase in normative An (100An/(An+Ab)) and decrease in incompatible Zr, Y, TiO_2, and P_2O_5 (indicating a reverse fractionation trend). In addition, marginal rocks of dykes contain normative corundum that is apparently associated with their significant depletion in whole-rock CaO. The extent of margin-to-centre differentiation of dykes in terms of most components is slight to modest, although in some petrochemical parameters is quite high

Table 1. Short summary of papers and an overview of the progressive development of our understanding of chemical zonation of the studied dykes

Papers	Dyke types; location	Dyke widths	Chemical zonation (outside inwards)	Nature of zonation
Paper I	2 small doleritic dykes; Kestiö Island, Åland-Åboland swarm, Finland	7 cm and 21 cm	Decreasing MgO, Mg $_{number}$, Opx(norm), = normal zonation Increasing An(norm), decreasing Zr, Y, TiO_2, P_2O_5 = reverse zonation	1 process proposed: changes in incoming magma composition, by unknown mechanism
Paper II	3 doleritic dykes of variable width; Kestiö Island, Åland-Åboland swarm, Finland	7 cm (small) 75 cm (middle) 675 cm (thick)	Small dyke: decreasing in MgO, Mg $_{number}$ = normal zoning; increasing in An(norm), decreasing in Zr, Y, Ca, TiO_2 = reverse zonation Middle dyke: same overall + increasing in Mg $_{number}$, MgO = reverse zonation in dyke core Thick dyke: same as Middle dyke	2 processes proposed: Small dyke = changes in magma composition by unknown mechanism (to explain decoupled trends); Middle and Thick dykes = as above + *in situ* cumulate growth on sidewalls of dyke (to explain reverse zoned interiors)
Paper III	3 doleritic dykes of variable width; Torsholma Island, Åland-Åboland swarm, Finland	3.2 cm (small) 13.5 cm (middle) 50 cm (thick)	Small dyke: increasing in Pl, decreasing in An(norm), MgO, Mg $_{number}$, TiO_2, K_2O, Zr Middle dyke: same as Small dyke at margins + central increasing in Pl, An(norm), Sr and Mg $_{number}$ Thick dyke: same as Small dyke at margins, then increasing in MgO, Mg $_{number}$, An(norm), then centre like Middle dyke	3 processes proposed: Small dyke = changing magma composition; Middle dyke = changing magma composition+ flow differentiation (concentration of Plag, Ol crystals in centre); Thick dyke = as above + *in situ* growth against dyke sidewalls
Paper IV	1 doleritic dyke; Vochelambina area, Kola Peninsula, Russia	140 cm thick	Increasing in An(norm), Mg $_{number}$, MgO, Cr; decreasing in TiO_2 = reverse zoning Increasing in K_2O, Rb, Ba, Sr = normal zoning	2 processes proposed: changes in magma composition+ fluxing of dyke centre by post-magmatic fluids (alteration and hydrous element enrichment)
Paper V	1 dacitic dyke; Southern Urals, Russia	16 cm thick	Increasing in An(norm), Opx(norm), MgO, FeO, decreasing in Pl, SiO_2, Na_2O, Ba, Sr = reverse zoning	1 process proposed: *in situ* cumulate growth on sidewalls by flowing magma
Paper VII	1 doleritic dyke apophysis, narrowing out; Karelia, Russia	17 cm 29 cm 69 cm	Change in zonation along strike: MgO = decreasing→decreasing at margins+central increasing P_2O_5 = increasing→increasing at margins+central decreasing TiO_2 = increasing at margins+central decreasing→decreasing Zr = decreasing	2 competing processes change emphasis with dyke width: emplacement of magma becoming more evolved with time and *in situ* cumulate growth against dyke sidewalls
Paper VIII	1 large dyke + 3 transects across an apophysis; Karelia, Russia	21 m master dyke; apophysis as above	Master dyke: MgO = decreasing at margins+central increasing P_2O_5 = increasing at margins+central decreasing TiO_2, Zr = decreasing	Larger/wider dykes = more control by *in situ* wall cumulate crystallization; smaller dykes = more influence by quenched inflowing magmas whose composition have been fractionated at depth

(e.g. 15 mol.% of normative An). The dykes are almost glassy and uncontaminated by host rocks, suggesting that their compositional profiles are primary and most likely reflect temporal changes in composition of magma filling the dykes. A mechanism responsible for the systematic changes in composition of inflowing magma remains, however, elusive since no known processes are able to force magma to evolve simultaneously along both normal and reverse fractionation trends. The study appears thus to indicate some not yet specified process of magma differentiation.

PAPER II

This paper focuses on detailed sampling across three dolerite dykes of different size (small, 7 cm; middle, 75 cm; and thick, 675 cm) of the Åland-Åboland dyke swarm. These dykes have revealed an internal zonation of an anomalous nature. The small, almost glassy dyke exhibits a systematic inward decrease in whole-rock MgO and Mg# (indicating a normal fractionation trend) together with a simultaneous increase in normative An and Cpx and decrease in whole-rock Zr, Y, CaO, TiO_2 (indicating a reverse fractionation trend). The middle dyke shows similar compositional trends across its narrow margins, but in the more crystalline interior whole-rock MgO and Mg# gradually but steadily increase inwards. As a result normal and reverse fractionation trends of the margins grade to exclusively reverse fractionation trends of the interior. The thick, almost totally crystalline dyke exhibits an internal zonation similar to that of the middle dyke, with fractionation trends becoming much more pronounced in the centre of the dyke. The almost glassy nature of small dyke suggests that its anomalous compositional zonation most likely resulted from temporal changes in the composition of magma as it formed the dyke. The mechanism(s) responsible for such systematic changes in composition of inflowing magma remains, however, unknown. The margins of middle and thick dyke form in a similar way whereas their interiors formed by *in situ* cumulate growth against dyke sidewalls. This process resulted in a gradual inward increase in the proportion of *in situ* grown cumulus phases owing to magma crystallization in progressively less supercooled conditions with increasing distance from cold country rocks. The compositional zonation of these dolerite dykes is thus produced by two independently operating mechanisms: successive changes in composition of inflowing magma (*an external liquid-state process*) and an *in situ* cumulate growth on dyke sidewalls (*an internal crystal-liquid process*). Based on the relatively minor development of internal zonation in interiors of middle and thick dykes, the former mechanism appears to be several times more effective in causing magma differentiation than the latter. It remains to be determined whether these two processes are a general reason for the formation of marginal reversals in mafic-ultramafic dykes, sills and large layered intrusions.

PAPER III

This paper describes three dolerite dykes (Small, 3.2 cm; Middle, 13.5 cm; and Thick, 50 cm) from Torsholma Island, SW Finland. These dykes reveal distinctly different internal zonation that becomes more complicated with increasing thickness of dykes. The Small Dyke shows a systematic inward increase in normative Pl (An+Ab+Or) and a decrease in normative An (100*An/(An+Ab)), whole-rock MgO, Mg number (100*Mg/(Mg+Fe_{total})), TiO_2, K_2O and Zr. The Middle Dyke exhibits the same compositional pattern at the margins, while the centre is distinguished by an abrupt increase in normative Pl and An, whole-rock Sr and Mg number. From the margins inwards, the Thick Dyke displays first a compositional pattern identical to that observed in the Small Dyke and the margins of the Middle Dyke. This is followed by a region where whole-rock MgO, Mg number and normative An start increasing inwards, while the transition to the centre of the dyke is characterized by a compositional pattern similar to that in the centre of Middle Dyke. The origin of chemical zonation in these dykes is attributed to the operation of three independent physico-chemical processes, namely: the Small Dyke formed exclusively by progressive changes in the composition of inflowing magma; the Middle Dyke by changes in composition of inflowing magma (margins) and concentration of plagioclase and olivine phenocrysts by flow differentiation (centre); the Thick Dyke by changes in composition of inflowing magma (margins), *in situ* cumulate growth against dyke sidewalls (middle) and flow differentiation (centre). Systematic changes in these processes and, as a result, in internal chemical zonation, likely take place in response to crystallization of magma under less supercooled conditions with increasing dyke thickness. A comprehensive geochemical study of the internal zonation of small mafic dykes worldwide is required to develop a complete understanding of the processes operating in mafic dykes.

PAPER IV

This paper draws attention to a 140 cm thick dolerite dyke in the Vochelambina area of the Kola Peninsula, Russia, which shows an unexpected internal zonation combining the features of both reverse and normal differentiation trends. From the margins inwards, the dyke exhibits a steady increase in normative An (100An/(An+Ab)), whole-rock Mg# (100Mg/(Mg+Fe_{total})), MgO and Cr and decrease in TiO_2 (indicating a reverse differentiation trend) with simultaneous increase in K_2O, Rb, Ba and Sr (indicating a normal differentiation trend). As indicated by the composition of chilled margins, the reverse trends were probably produced by progressive changes in the composition of inflowing magma (primary zonation). The normal compositional trends correlate with loss on ignition and are apparently related to fine-grained aggregates of sericite that replaced plagioclase crystals. These trends likely reflect increasing alteration caused by the concentration of post-magmatic fluids in the centre of the dyke (secondary zonation). The anomalous compositional trends in the dyke result from the combination of primary and secondary internal zonation.

PAPER V

This paper investigates the premise that small dykes are traditionally considered as rapidly quenched bodies that preserve information on the parental liquid composition. This is because a fast cooling regime in small dykes promotes magma quenching that impedes any cumulate growth processes. However, the assumption appears to be not universally valid. A 16 cm thick, fine-grained, dacitic dyke from the southern Urals has revealed a remarkable internal zonation showing a systematic inward increase in normative An (100An/(An+Ab)), normative Opx, and whole-rock MgO and FeO, and a decrease in normative Pl content, whole-rock SiO_2, Na_2O, Ba and Sr. All these compositional trends indicate that the dyke becomes more primitive in composition inwards from its margin the opposite to normal fractionation. This chemical zonation is best explained by *in situ* cumulate growth against dyke sidewalls from flowing magma, a process resulting in a progressive inward increase in the proportion of *in situ* grown cumulus plagioclase and pyroxenes. This suggests that, despite being fine-grained, the dacitic dyke should be interpreted as a cumulate that provides only indirect information on the parental magma composition.

PAPER VI

This paper combines results of our geochemical studies of dolerite dykes from many regions of the world. The study has revealed that small dolerite dykes (<50 cm wide) representing shallow parts of basaltic magma conduits are remarkably zoned. The zonation is compositionally anomalous since compatible and incompatible components behave in dykes in a manner inconsistent with predictions of fractional crystallization of basaltic magma. Here we put forward a novel concept interpreting the anomalous compositional trends in dolerite dykes as a result of competition between two petrogenetic processes with opposite effects on dyke composition. These are (a) the filling of dykes with magmas that become increasing more evolved with time and (b) *in situ* cumulate growth of these inflowing magmas against dyke sidewalls. The first process makes inward-solidifying rocks geochemically more evolved whereas the second process more primitive. A key idea is that the nature of compositional profiles of dykes (normal, reverse or anomalous) is primarily controlled by the "winner" in this competition between the processes. Normal compositional trends will arise when quenching of inflowing magmas (glassy dykes) controls the distribution of all components, whereas reverse compositional trends will emerge when *in situ* cumulate growth (fully crystalline dykes) governs the distribution of all components. Finally, anomalous compositional trends can develop when one of these processes controls the distribution of one group of components (e.g. compatible), whereas another process governs the distribution of another group (e.g. incompatible). It should be noted that both petrogenetic processes are well-known and widely applied in igneous petrology, but so far it has not been realized that their combined operation in dykes may give rise to quite unexpected petrological results. Geochemical modelling indicates that all the observed patterns in distribution of compatible and incompatible elements in small dolerite dykes can be reproduced by variations in the relative contribution of these two petrogenetic processes.

PAPER VII

This paper focuses on a single apophysis of dolerite dyke that provides a novel insight into differentiation processes operating in basaltic magma conduits. The apophysis emanates from a large master dyke and gradually pinches out along a distance of about 11 m. Three continuous profiles across an apophysis (17 cm, 29 cm and 69 cm thick) were geochemically studied. Contrary to common thinking, an apophysis has revealed remarkable internal zonation that systematically changes along its strike. As it becomes thicker, a zonation pattern with an inward decrease in compatible components and an increase in incompatible components progressively give way to one with opposite compositional tendencies. Here we argue that such spatial zonation is consistent with predictions of our new concept that attributes compositional trends in mafic dykes to a competitive operation of two petrogenetic processes. These are (a) the filling of dykes with magmas that become increasingly more evolved with time and (b) in situ cumulate growth of these magmas against dyke sidewalls. The two processes have opposite effects on rock geochemistry, with the first making dykes more evolved and the second more primitive inwards. The spatial zonation of a dyke apophysis likely reflects a gradual change from rocks mostly produced by quenching of progressively more evolved magmas (the thinnest profile) towards those formed by in situ cumulate growth of these magmas (the thickest profile). This change results from the decreasing extent of magma cooling as a dyke apophysis becomes thicker with approaching a master dyke. It is quite exciting to speculate as to whether this phenomenon is common for small mafic dykes worldwide.

PAPER VIII

This paper discusses whole-rock geochemistry of one section across a large dolerite dyke (21 m thick) and three sections across its narrow apophysis (17 cm, 29 cm and 69 cm thick) from Fennoscandian Shield, Russia. The dyke is remarkably fresh, phenocryst-free and not in situ contaminated by crustal rocks. Chemical zonation is found to systematically change with a decreasing thickness of studied sections. In particular, a tendency to become more primitive inwards in a large dyke (e.g. an increase in MgO, Mg-number, normative An content and a decrease in P_2O_5) gradually gives way to an opposite tendency to become more evolved inwards in a narrow apophysis (e.g. a decrease in MgO, Mg-number, normative An content and an increase in P_2O_5). In this process some components (e.g. Zr) behave anomalously and tend to decrease inwards in all studied sections. To explain the spatial chemical zonation, we apply a new concept that attributes compositional trends in mafic dykes to a competitive operation of two petrogenetic processes. These are (a) the filling of dykes with magmas that become increasingly more evolved with time as a result of magma fractionation in deeper parts of conduits and (b) in situ cumulate growth against dyke sidewalls accompanied by effective removal of an evolved liquid boundary layer from growing crystals by the continuously inflowing magmas. The processes have opposite effects on rock geochemistry, with the first making dykes more evolved and the second more primitive inwards. A key idea is that dykes that become more evolved inwards arise when quenching of inflowing magmas controls the distribution of all components, whereas dykes that become more primitive inwards emerge when in situ cumulate growth governs the distribution of all components. A various anomalous distribution of components may appear when these two processes will control the behavior of separate groups of compatible/incompatible components. The studied spatial chemical zonation can thus be attributed to a gradual change from rocks mostly produced by quenching of progressively more evolved magmas (an apophysis) towards those predominantly formed by in situ cumulate growth of these magmas (a large dyke). This happens in response to the decreasing extent of magma cooling by country rocks in this direction. We believe that the proposed interpretation of spatial chemical zonation of a large dyke and its apophysis may represent a general feature of magma differentiation processes operating in basaltic magma conduits.

CONCLUSIONS

1. An unprecedentedly detailed, cm-scale study of mafic dykes from different geological regions of the world has revealed that small dolerite dykes (<50 cm thick) that appear to be macro- and microscopically homogeneous possess a conspicuous compositional zonation that is not expected for superficially homogeneous dykes of such small thicknesses. It appears that such compositional zonation is a common feature for small mafic dykes worldwide. The compositional zonation of most small dykes is anomalous since it shows normal fractionation trends for some geochemical indices (e.g. whole-rock MgO and Mg#) but reverse fractionation trends in terms of others (e.g. An(norm), Cpx, CaO, Y, Zr and TiO_2). Such an anomalous compositional zonation is also characteristic of the narrow marginal parts of large dykes (>5-10 m thick). The interiors of the larger dykes display, however, a different pattern of an internal zonation in which whole-rock MgO and Mg# tend to increase, rather than to decrease, inwards. The interiors thus exhibit reverse fractionation trends in terms of all the above geochemical parameters. Anomalous compositional zonation observed in most small dykes and marginal parts of large dykes does not appear to have been previously reported from dykes.

2. The internal distribution of major and trace elements in the dykes reveals that *in situ* contamination of dykes by host gneisses is either absent (small dykes) or spatially limited to 2-5 cm thick marginal portions (large dykes) that are selectively enriched in components of host granitic gneisses. This implies that *in situ* contamination plays no role in the derivation of the internal zonation of the dykes. In a similar manner, the uniform distribution of minor amounts of plagioclase microphenocrysts as well as amygdales across the dykes indicates that flow differentiation is not a factor in the origin of their internal chemical zonation. These observations imply that the compositional trends of the dolerite dykes must owe their origin to some primary magmatic processes. The almost glassy nature of some small dykes strongly suggests that a liquid-state process must be responsible for the origin of its compositional zonation. The most likely mechanism appears to be the filling of the dyke with magma that was continuously changing its composition with time. A fundamental change in the character of compositional zonation in large dykes is likely due to another process – an *in situ* cumulate growth on dyke sidewalls that provides a progressive inward increase in the proportion of *in*

situ grown cumulus plagioclase and mafic phases (amphibole, pyroxene and olivine) in response to magma crystallization in less- supercooled conditions.

3. There are thus two major petrogenetic processes that appear to operate in basaltic magma conduits and produce internal chemical zonation of mafic dykes. These are (a) the filling of dykes with magmas that become increasingly more evolved with time as a result of magma fractionation in deeper parts of conduits and (b) *in situ* cumulate growth against dyke sidewalls accompanied by effective removal of an evolved liquid boundary layer from growing crystals by the continuously flowing magmas. It is intriguing that these two processes have opposite effects on rock geochemistry, with the first making dykes more evolved and the second making them more primitive inwards. As a result, each mafic dyke can be considered as a “battlefield” of these two competing petrogenetic processes, with its compositional profile being dependent on the process that will finally prevail in this competition.

4. There is a fundamental difference in the nature of chemical zonation between small and large mafic dykes. To a first approximation, small dykes (usually much less than 50 cm thick) are mostly produced by prevailing quenching of inflowing magmas that become progressively more evolved and therefore commonly should reveal normal compositional trends. In contrast, large dykes (usually more than 1-5 m thick) are mostly formed by prevailing *in situ* cumulate growth of these inflowing magmas against dyke sidewalls and therefore commonly should exhibit reverse compositional trends. This fundamental distinction is primarily due to a difference in cooling regime imposed by cold country rocks that favors magma quenching in small dykes but *in situ* cumulate growth in large dykes.

5. In detail, a simultaneous operation of these two competing processes leads to much more intricate compositional patterns of dykes. This is exemplified by dykes in which distribution of compatible and especially incompatible components is not consistent with fractional crystallization of basaltic magmas (e.g. when components belonging to the same geochemical group behave differently). In this case internal zonation of dykes combines features of both normal and reverse compositional trends. This happens because the competition between the

two petrogenetic processes takes place for each individual compatible/incompatible component so that one process may be a "winner" for some components but a "loser" for others. The results of this competition are primarily dependent of two major parameters that are specific for each individual component: (a) an inward increase in the proportion of *in situ* grown cumulus phases concentring this particular component and (b) an inward decrease/increase in concentration of compatible/incompatible components in successively inflowing magmas.

6. As a rule, both small and large mafic dykes consist of two individual subunits with contrasting compositional tendencies that are indicative of two principally different regimes in dyke crystallization/solidification. These are (a) thin marginal zones whose chemical variations are controlled by quenching of inflowing magmas that become progressively more evolved and (b) thick central zones whose chemical variations are controlled by *in situ* cumulate growth of these inflowing magmas against dyke sidewalls. A level at which one compositional tendency gives way to another one is referred to as a crossover point. Since a competition between two petrogenetic processes occurs for every individual compatible/incompatible component, each of them will have its own crossover point located at some specific distance from an intrusive contact of dyke. For this reason a transition from marginal zones towards central zones of dykes is often difficult to define.

7. Internal compositional zonation is best-developed in small mafic dykes and it becomes much less pronounced in larger dykes. This likely reflects a fact that upon fractional crystallization of the same gabbroic assemblage a parental liquid changes its composition much more strongly than the corresponding cumulates. Small dolerite dykes are thus remarkably zoned because they mostly record a rapid change in composition of inflowing residual liquids, whereas large dykes are weakly zoned because they mostly reflect a slow change in composition of *in situ* crystallizing cumulates. A transition from these two contrasting regimes in dyke crystallization/solidification is best observed in marginal parts of dykes. These parts commonly show the largest compositional range because of an inward progression from essentially chilled liquids towards largely cumulate gabbroic rocks of central zones.

8. There are several implications of this study. Firstly, chemical zonation patterns of mafic dykes, both small and large ones, indicate their formation by an incremental growth from continuously inflowing magmas that change their composition with time. Even the smallest dykes, down to several cm thick, appear to form incrementally, not instantaneously. Secondly, mafic dykes should be employed for estimation of parental magma compositions with a great caution. This is because each mafic dyke forms from liquids with a wide range in chemical composition, not from a single parental magma. In addition, even small dykes and fine-grained margins of large dykes experience to some extent *in situ* cumulate growth and therefore provide distorted information on compositions of parental magmas. Thirdly, care should be taken when interpreting the nature of internal compositional zonation in some mafic dykes since the inwardly-increasing extent of alteration may also produce systematic variations in chemical composition of rocks. Fourthly, there is one application of practical significance. In all studied mafic dykes the highest concentrations of Zr were observed at their margins. This implies that marginal rocks are the best candidates for finding baddeleyite or zircon crystals for geochronological studies.

In conclusion, I would like to reinforce an idea that chemical zonation of small dolerite dykes is a result of quenching of residual liquids coming from below. These dykes thus essentially represent "snapshots" of fractional crystallization of parental magma at deeper parts of basaltic magma conduits that takes place by *in situ* cumulate growth on conduit sidewalls. This process appears to represent a major mechanism that causes differentiation of basaltic magmas ascending through conduits towards the Earth's surface. In this context, the chemically-zoned dykes can probably be considered as a direct evidence for fractional crystallization of magmas in conduits by *in situ* cumulate growth against dyke sidewalls. If there were no magma crystallization and differentiation below, then these dykes would mostly likely be entirely homogeneous. The significance of small dolerite dykes, as representing a "window" into petrogenetic processes in magma conduits, is yet to be appreciated by igneous petrologists.

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