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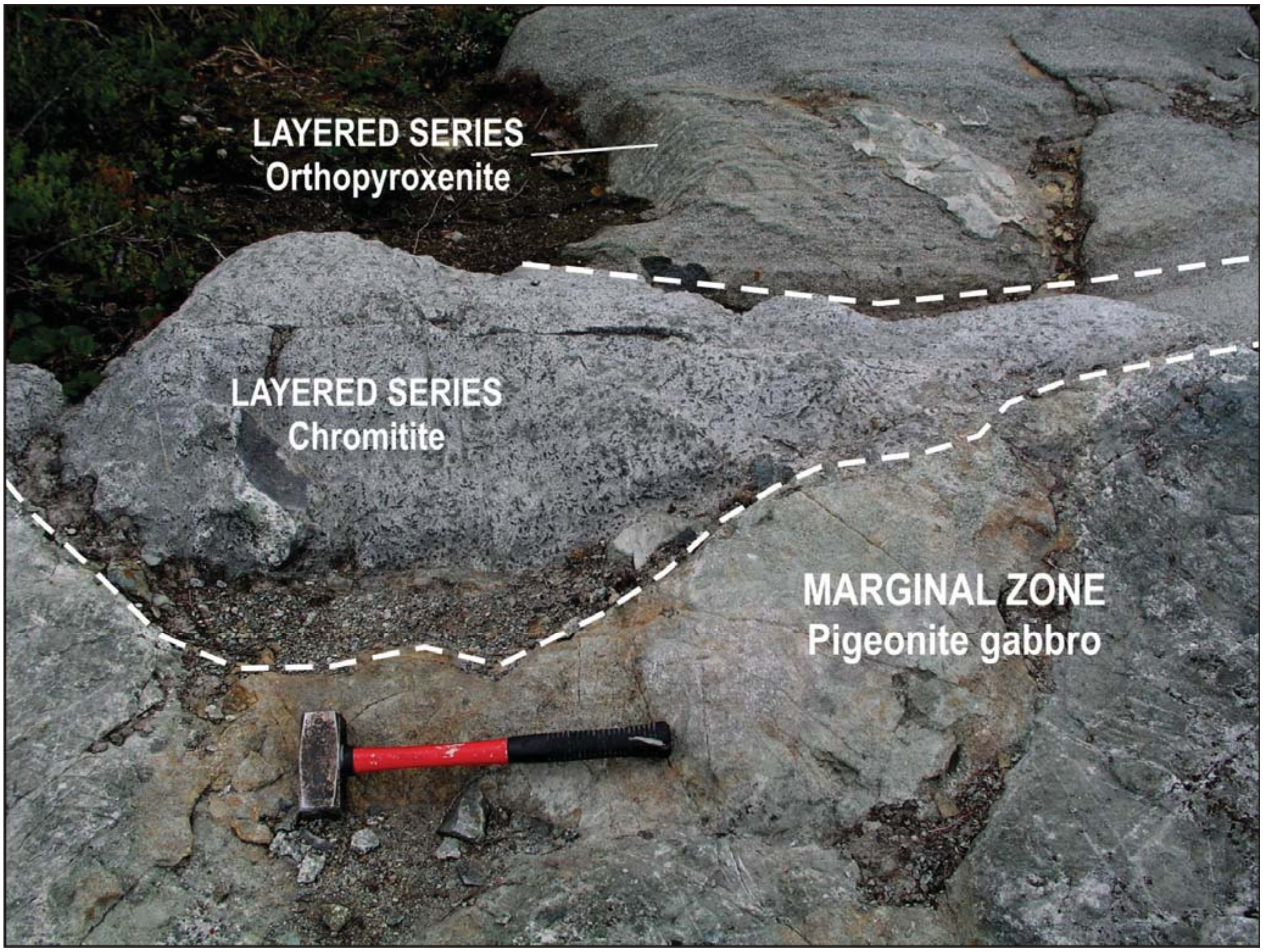
Mechanisms of differentiation operating at magma chamber margins: insights from marginal reversals in mafic layered intrusions and sills



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Cover Figure:

The contact between the chromitite layer of the Layered Series and the underlying pigeonite gabbro of the marginal zone of the Imandra Layered Intrusion

VERA EGOROVA

Mechanisms of differentiation operating at magma chamber margins: insights from marginal reversals in mafic layered intrusions and sills

Academic dissertation to be presented, with the assent of the Faculty of Science, University of Oulu, for public defense in Auditorium GO101, Linnanmaa, on May 23rd 2014, at 12 o´clock noon

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Mechanisms of differentiation operating at magma chamber margins: insights from marginal reversals in mafic layered intrusions and sills

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ABSTRACT

Marginal zones of igneous bodies are the early products of crystallization during the initial stage of magma emplacement into magma chambers. This stage is very important in the origin of intrusive rocks, but remains, however, insufficiently understood. Progress in its understanding is significantly hampered by the paucity of critical observations from the marginal zones of igneous bodies. To alleviate this deficiency, we have undertaken a detailed petrographic, geochemical and mineralogical study of the marginal zones of two mafic-ultramafic layered intrusions (the Imandra layered intrusion, Russia and the Fongen-Hyllingen layered intrusion, Norway) and three mafic sills (the Vavukansky, Vilyuysky and Kuz'movsky sills, Eastern Siberia, Russia). The study has resulted in observations that provide new constraints on and insights into the processes operating at magma chamber margins during the initial filling, subsequent crystallization and solidification of basaltic magma chambers.

Mineral crystallization sequences and compositional trends in the marginal zones of the studied layered intrusions and mafic sills are the opposite of that predicted by phase equilibria. The rocks in the marginal zones become more primitive from the base upwards as exemplified by significant increases in whole-rock MgO, Mg-number and normative An-content whereas all incompatible elements (e.g. TiO_2, K_2O, P_2O_5, Rb, Ba, Zr, Y, REE) decrease upwards. The reverse trends are also evident in upward increases in the An-content of plagioclase and Mg-number of olivine and pyroxenes. The marginal zones are therefore referred to as marginal reversals. Detailed mineralogical and geochemical studies support the distinction of two different types of marginal reversal in layered intrusions and mafic sills, i.e. fully-developed and aborted reversals. A fully-developed marginal reversal shows a crystallization sequence and mineral compositional trends that are essentially opposite to those in the overlying Layered Series into which it gradually passes via a maximum. This type exhibits a complete, but reversed, evolutionary path during its crystallization. Examples of such marginal reversals are abundant in the literature. An aborted marginal reversal develops when the evolution is

interrupted by a pulse of more primitive magma that is parental to the overlying Layered Series. As a result, such a reversal shows an incomplete crystallization sequence and mineral compositional trends, as well as a sharp compositional break with the overlying rocks of the Layered Series. Such marginal reversals are much less common in nature.

To explain the observed behavior of chemical components in both types of marginal reversal, a new petrological concept (Latypov et al., 2011) has been developed. The concept attributes the reversed compositional trends to three factors: (1) an increase in the extent of magma primitivity with time, (2) an increase in the extent of equilibrium crystallization of magma with distance from cold country rocks, (3) an increase in the proportion of cumulus minerals in progressively forming rocks (Latypov et al., 2011). According to this concept, a magma chamber initially develops as an open system and is slowly and then more rapidly inflated by magma that becomes gradually more primitive with time. Inflowing magmas are affected by previous differentiation in intermediate chambers or feeder conduits. Inflation is accompanied by *in situ* crystallization that records the preceding fractionation history of the injected magmas as marginal reversals in which minerals become more primitive inwards. The proportion of cumulus crystals in rocks will also increase away from intrusive contacts and hence give rise to whole-rock marginal reversals. The process culminates with inflation of the intrusions and sills to their final sizes owing to a major influx of primitive magma. Subsequently, flow of magma through the intrusions and sills ceases and the magma bodies evolve as closed systems by fractional crystallization. This results in Layered Series with minerals and rocks becoming more evolved inwards and upwards.

In summary, the principal result of this study is that the crystallization in magma chambers takes place in two distinct stages. The initial stage involves *in situ* crystallization under open-system conditions and the second stage is characterized by fractional crystallization in a closed system. Since similar reverse and normal compositional trends are observed in many mafic-ultramafic intrusions and sills, the model proposed may represent a common process in the origin of intrusive bodies.

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Oulu, January 2014

Vera Egorova

CONTENTS

ORIGINAL PUBLICATIONS

PAPER I

Vera Egorova & Rais Latypov (2012a) Processes operating during the initial stage of magma chamber evolution: insights from the marginal reversal of the Imandra layered intrusion, Russia. *Journal of Petrology* 53(1), 3–26. doi:10.1093/petrology/egr054

PAPER II

Vera Egorova & Rais Latypov (2012b) Prolonged magma emplacement as a mechanism for the origin of the marginal reversal of the Fongen-Hyllingen layered intrusion, Norway. *Geological Magazine* 149(5), 909–926. doi:10.1017/S001675681200009X

PAPER III

Rais Latypov & Vera Egorova (2012) Plagioclase compositions give evidence for in situ crystallization under horizontal flow conditions in mafic sills. *Geology* 40, 883–886, doi:10.1130/G33173.1

PAPER IV

Vera Egorova & Rais Latypov (2013) Mafic–ultramafic sills: New insights from M- and S-shaped mineral and whole-rock compositional profiles. *Journal of Petrology* 54(10), 2155–2191, doi:10.1093/petrology/egt045

INTRODUCTION

Marginal reversals are common features of mafic-ultramafic igneous bodies worldwide. They are generally characterized by an increasing in whole-rock MgO, Mg number and normative An with concomitant gradual changes to more primitive mineral compositions inwards from intrusive contacts. In terms of the compositional trends, basal reversals are mirror images of overlying Layered Series. Marginal reversals are found in dikes, sills and layered intrusions, as well as in basaltic pillows and komatiitic lava flows (e.g. Campbell, 1987; Irvine, 1980; Alapieti, 1982; Raedeke & McCallum, 1984; Bédard, 1987; Foland et al., 2000; Latypov, 2003a, b; Latypov et al., 2007; Aarnes et al., 2008; Galerne, 2010; Chistyakova & Latypov, 2009, 2010; Latypov et al., 2011). Marginal reversals are almost universally developed in magmatic bodies, irrespective of their age, geographical location, size, form, and even the composition of parental magmas, suggesting that some fundamental processes are involved in their genesis. An important question is: Which physico-chemical processes are responsible for this common, but apparently petrologically anomalous, behavior of magmatic systems? This work presents petrographic, mineralogical and geochemical evidence that help to resolve this issue.

EARLIER MODELS FOR THE ORIGIN OF MARGINAL REVERSALS

There are six characteristic features of marginal compositional reversals in mafic-ultramafic sills and layered intrusions that impose strict constraints on any model for their formation. These are: (1) an apparent lack of mass balance between the lower part of the marginal reversals, including the chilled margins, and the bulk composition of the intrusions; (2) crystallization sequences and (3) mineral compositional trends that are the inverse of those in the associated layered series; (4) the cotectic composition of the rocks constituting marginal reversals; (5) marginal reversals form from both phenocryst-rich and phenocryst-free parental magmas; (6) marginal reversals are found along the floors, subvertical walls and even the roofs of magma chambers (Latypov, 2003a,b). The models which purportedly account for the characteristic features of the marginal reversals fall into two major groups, interpreting them as a phenomenon of magma chambers that develop as either open or closed systems.

CLOSED SYSTEM MODELS

These models include the following (Fig. 1):

1) *Intra-chamber crystal settling* (Moore & Evans, 1967; Fujii, 1974; Bédard, 1987; Frenkel' et al., 1988, 1989; Marsh, 1989; Heltz et al., 1989; Gisselo, 2001). The crystal settling hypothesis regards marginal reversals as due to the gravitational accumulation of crystals (e.g. olivine), either already present in the magma as phenocrysts at the time of emplacement (Marsh, 1989; Ubide et al., 2012) or that grew in the magma after intrusion (Frenkel' et al., 1989; Worster et al., 1993; Ariskin & Yaroshevsky, 2006; Lopez-Moro et al., 2007). This hypothesis suggests that an upward increase in whole-rock MgO can be a consequence of a decreasing solidification rate that ensures a progressive increase in the number of crystals that are able to settle to the bottom of the magma body. In other words, basal reversals are regarded as mixtures of melt and accumulated crystals with the latter gradually increasing in abundance upward.

This model has been successful in reproducing the whole-rock compositional profiles but is not constrained by mineral compositions. However, the model predicts that minerals must either have constant composition (if they are intratelluric phenocrysts) or become more evolved in composition (if they crystallized from the magma after its emplacement) across the marginal reversal. In other words, no reverse trends in mineral composition are to be expected in the framework of this hypothesis.

2) *Flow differentiation* (Bhattacharji & Smith 1964; Bhattacharji, 1967; Simkin, 1967; Marsh, 1996; Gibb & Henderson, 2005). Bhattacharji & Smith (1964) and Bhattacharji (1967) have shown experimentally that magma flowing along a feeder can concentrate early-formed olivine phenocrysts at the center of the channel. On the basis of these results, they attributed the reverse fractionation at the base of the Muskox intrusion to successive pulses of magma precipitating high-temperature phases, which are pushed to the center during flow. Simkin (1967) extended this idea to sills and attributed reverse fractionation in the Skye alkaline basic sills to hydrodynamic migration of particles away from margins during magma flow. Campbell (1978), however, correctly reasoned that grain dispersive forces are small and could not produce the grain-to-grain contacts observed in cumulate textures. He also noted that although flow differentiation is a valid mechanism in relatively narrow, <100 m wide dikes (Barriere, 1976), it cannot be an important factor in the development of large intrusions such as Jimberlana and Muskox.

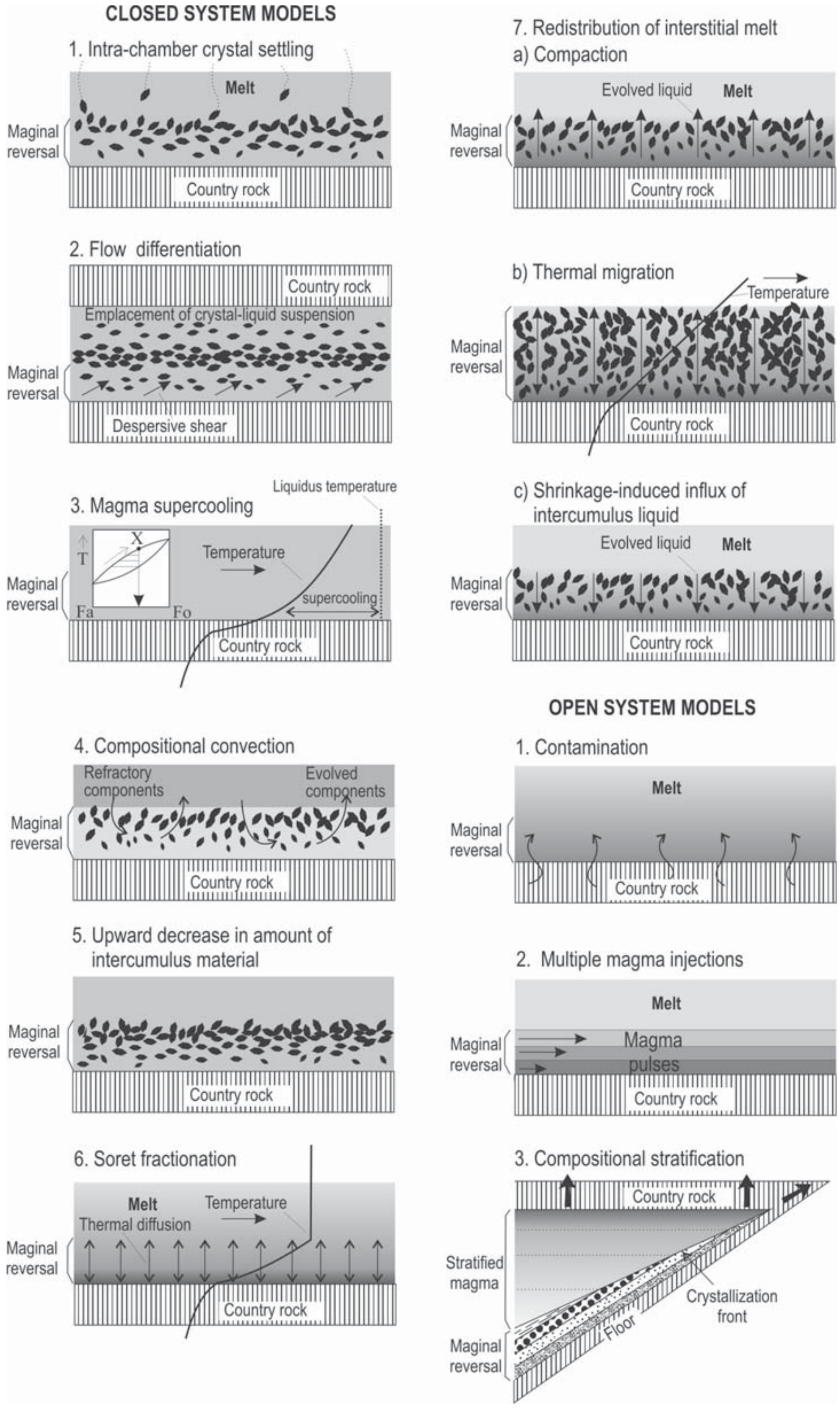

Fig.1. Current models for the formation of marginal reversals subdivided into two groups. The first group of hypotheses appeals to processes taking place under closed-system conditions: (1) intra-chamber crystal settling; (2) flow differentiation; (3) magma supercooling; (4) compositional convection; (5) upward decrease in the amount of intercumulus material; (6) Soret fractionation; (7) redistribution of interstitial melt by (a) compaction; (b) shrinkage-induced flux of intercumulus liquid; (c) thermal gradient-induced migration of interstitial liquid. The second group of hypotheses appeals to processes taking place under open system conditions: (1) contamination; (2) multiple magma injections; (3) compositional stratification in magma chamber.

A serious objection to flow differentiation was pointed out by Wager & Brown (1968, p. 517). They drew attention to the fact that the olivine grains in the Muskox feeder range in composition from Fo_{85} to Fo_{60}. This represents a correspondingly wide range in crystallization temperature and, if equilibrium was maintained between the magma and olivines of composition Fo_{60} in the feeder and the layered series, the feeder must have remained open while l.6 km of layered rocks were deposited. This objection also applies to the Jimberlana intrusion (McClay & Campbell, 1976). Flow differentiation has also been found to be an inadequate explanation of the reverse modal grading observed within komatiite lava flows (Bedard, 1987).

3) *Magma supercooling*. Wager & Brown (1968, p. 517) suggested that an inward increase in the Fo contents of olivine and the increase in the abundance of olivine relative to that of orthopyroxene in dikes and marginal zones could be due to a gradual reduction in the degree of supercooling during crystallization. This idea can be illustrated using a *T-X* phase diagram Fo-Fa (Fig. 1). A significant advantage of this model compared with others is that it provides an adequate explanation for reversed trends in mineral compositions. It predicts that the An- content in plagioclase and Mg-number in olivine should increase inwards from intrusive contacts. The main drawback of the model is that with a high degree of supercooling, the composition of the chilled margin would be identical to the parental magma composition. This is, however, not the case with many basic sills and layered intrusions, where chilled margins are compositionally different to the parental magmas (Latypov et al., 2011; Egorova & Latypov, 2012a). McClay & Campbell (1976) also noted that the idea of supercooling could not be applied to the Jimberlana marginal series because the high degree of supercooling required would make the marginal series a chilled margin. But it is not fine-grained. Only a very narrow zone of chilled gabbro at the edge of this series could have formed in this way, not the entire series. The variety of cumulate textures and layering displayed by the Jimberlana marginal series is also difficult to reconcile with extreme supercooling. The same is true with many other layered intrusions showing well-developed marginal reversals that consist of medium - to coarse-grained rocks.

4) *Compositional convection* (Jaupart & Tait, 1995; Tait & Jaupart, 1996; Latypov & Chistyakova, 2009). Reversed compositional profiles in mafic intrusions and sills have been attributed to a flux of chemical components into and out of a crystal mush within a thermal boundary layer during *in situ* crystallization. Compositional convection allows continuous exchange of components between the melt in the crystallizing boundary layer and the main

magma reservoir. During this process, dense refractory components are transported from the main magma body into the crystal mush while excluded low-temperature components move in the opposite direction. The hypothesis implies that an upward increase in whole-rock MgO in basal reversals is a result of a decreasing solidification rate that gives rise to a reduction in the amount of interstitial melt trapped in the rocks. A marginal reversal was successfully reproduced numerically in a hypothetical intrusive sheet on this basis by Kuritani (1999), but again without the constraint of mineral compositions. The hypothesis predicts, however, that minerals must become progressively more evolved from both margins inwards, with the most evolved compositions occurring in a Sandwich Horizon. This prediction is not consistent with the mineral compositional trends in the marginal zones that we have studied.

5) *Upward decrease in the amount of intercumulus material* (Raedeke & McCallum, 1984). Raedeke & McCallum (1984) attributed the upward increasing in Mg number in the 500-m-thick marginal zone of the Stillwater complex to reaction of cumulus orthopyroxene with a decreasing amount of trapped melt. They suggested that the amount of trapped liquid is highest in the lowermost rocks because heat loss through the floor caused strong cooling and rapid accumulation of orthopyroxene during the initial stage of crystallization. Reaction of intercumulus liquid and the orthopyroxene produces iron-rich pyroxenes. Higher up in the section, the amount of trapped liquid in the cumulates was lower because more of the intercumulus liquid can be squeezed back into the main magma chamber due to compaction and other processes. As a result, the high ratio of cumulus orthopyroxene to trapped liquid led to minor readjustment of the pyroxene composition, which therefore remains richer in magnesium. This model can explain one of the features of marginal reversals, namely, the mineral compositional trends that are inverse of those in the Layered Series. However, the model provides no explanation for another important feature of marginal reversals - reversed crystallization sequences.

6) *Soret effect* (e.g. Krivenko et al., 1980; Latypov, 2003a, b). This hypothesis contends that marginal reversals are due to the transfer of low-melting point components from the interior of a magma chamber towards its cooling margins down steep temperature gradients. The operation of Soret fractionation in nature requires a liquid boundary layer that is maintained in a non-equilibrium state. A stationary state can be attained when the compositions of the melts forming the boundary layer adjust to the imposed temperature gradient. The compositional adjustment is carried out by transfer of high-melting point components from the liquid boundary layer into the main magma body and low-melting point components in the opposite direction. The required mass transfer is provided by Soret-

induced diffusion, and may be aided by vigorous convection in the main magma body. The boundary layer that forms initially at the chamber margin can comprise liquid compositions spanning almost the entire liquid line of descent of the parental magma, but in reverse sequence. Nucleation and crystallization occur predominantly in the stagnant lowermost regions of the boundary layer that has the most evolved liquid composition. With a progressive decrease in the magnitude of the thermal gradient, related to the growing thickness of the cumulus pile and the reduction in the temperature of the magma body, the composition of the liquid boundary layer in the stationary state become more and more primitive. In this process, the stagnant crystallizing region within the boundary layer progressively moves backwards along the liquid line of descent of the parental magma. The formation of a marginal reversal can therefore be envisaged as a progressive inward movement of a liquid boundary layer a few centimeters thick, the lowest, stagnant part of which continuously crystallizes.

A major problem with the Soret effect is that it is unlikely to be petrologically significant due to serious physical and chemical limitations (e.g. Lesher & Walker 1991; Gibb & Henderson, 2006). One problem is that heat conduction (10^{-2} – 10^{-3} cm^2/s) is orders of magnitude faster than chemical diffusion (10^{-5} – 10^{-9} cm^2/s), so a magma would freeze long before diffusion could accomplish much fractionation (e.g. Bowen, 1928). Another problem is that the chemical fractionation produced by the Soret effect in silicate liquids does not resemble that seen in either mafic or felsic igneous rock suites (Lesher & Walker, 1986; Lesher, 1986). In particular, in mafic intrusive bodies the most abundant oxide, SiO_2, is enriched in the low temperature, lowermost part of basal reversals, while it is the principal constituent of the hot Soret fraction in laboratory experiments (Lesher & Walker, 1991).

7) *Redistribution of interstitial melt.* Some explanations for the origin of marginal reversals appeal to the redistribution of interstitial melt during solidification due to the following processes: (a) compaction (Boudreau & Philpotts, 2002); (b) thermal gradient-induced migration of interstitial liquid (Lundstrom et al., 2007; Huang et al., 2009); (c) shrinkage-induced flux of intercumulus liquid towards the intrusive contacts (Cherepanov et al., 1982, 1983; Petersen, 1986); (d) post-emplacement redistribution of interstitial melt in a porous melt flow regime (Aarnes et al., 2008; Galerne et al., 2010). While all of these models may successfully reproduce reversed whole-rock compositional trends, they have not been tested against stratigraphic variations in the composition of rock-forming minerals, e.g. plagioclase. Some of the models predict that the compositions of minerals should be essentially constant throughout the intrusive bodies.

OPEN SYSTEM MODELS

These models include the following variants (Fig. 1):

1) *Crystallization of liquids of different composition due to wall-rock contamination* (e.g. Tyson & Chang, 1984). The first idea that comes to mind for producing more evolved liquids at magma chamber margins is wall-rock assimilation. This idea is supported by the common occurrence of partially melted fragments of country rock at the margins of many layered intrusions. However, Wilson & Engell-Sorensen (1986) rejected this idea, because it is difficult to envisage how such a mechanism could produce systematic compositional regressions. Additionally, there are a number of sills, such as the Noril'sk intrusions (Czamanske et al., 1995) and the Shiant Isles Main Sill (Foland et al., 2000), which show well-developed marginal reversals but lack evidence for crustal contamination, even in terms of isotopic composition. That wall-rock contamination is not responsible for the formation of marginal reversals is also clear from the fact that the mineral sequences within marginal reversals do not commonly change in response to differences in the composition of the adjacent country rock. For instance, at the base of Muskox intrusion and in its feeder dikes, the marginal reversal preserves the same crystallization sequence despite lateral variations in country rock composition from metasediment to granite. Another convincing argument against the contamination model is provided by the Penikat layered intrusion, Finland (Alapieti & Lahtinen, 2002), where there are five megacyclic units with each showing well-developed basal reversals despite the fact that only the lowest one is in contact with the country rocks.

2) *Compositional stratification in magma chambers* (e.g. Wilson & Engell-Sørensen, 1986). This model was developed by Wilson and Sørensen (1986) specifically for the marginal reversal of the Fongen-Hyllingen layered intrusion, Norway. The authors suggested that the origin of this marginal reversal is consistent with crystallization during gradual elevation of compositionally stratified magma up an inclined surface in response to the emplacement of dense, primitive magma at the base of the chamber. The chamber is envisaged as having a wedge shape which inflates and expands in response to the influx of new magma. Evolved, buoyant magma first comes into contact with the new floor at the leading edge of the expanding wedge where some crystallization occurs. During continued magma expansion, successively more primitive magma comes into contact with the previously formed marginal rocks leading to a crystallization sequence that was the reverse of that in the parental stratified magma (Wilson & Engell-Sorensen, 1986). The model adequately explains the marginal reversal in the Fongen-Hyllingen intrusion but fails, however, to account for the occurrence of compositional reversals at the base of thin sills, which lack evidence of either compositionally-

stratified magma or crystallization along inclined margins.

3) *Multiple magma injections* (e.g. Gorring & Naslund, 1995). Another common explanation for the origin of marginal reversals involves multiple injections of magmas with different composition during filling of a magma chamber. Reasons for changes in magma composition during filling include increasing degrees of partial melting of the mantle source, injections from a stratified crustal magma chamber, varying amounts of fractional crystallization during magma ascent in a conduit, etc. Therefore it seems reasonable to expect that if marginal reversals were formed by multiple and separate injections of magma, they would exhibit compositional breaks, disproportionate volumes of rocks composing the marginal reversals, crosscutting relations or chilled contacts between the different rock types. Such relationships are, however, not common within marginal reversals. Nevertheless, this does not exclude the possibility of continuous, uninterrupted filling of a chamber by magma that gradually changes its composition with time. This is consistent with the systematic compositional changes common in marginal reversals.

Latypov (2003a, b) and Latypov et al. (2007) have shown that most of the existing models do not adequately explain the characteristic features of marginal reversals and are therefore unlikely to represent realistic explanations for their origin. Recently, Latypov with co-authors (Latypov et al., 2011) suggests “three-increase model” that can be applied to explain the origin of the marginal reversal in mafic layered intrusions. This “three-increase model” implies that rocks of marginal reversals become more primitive inwards in response to (1) an inward increase in the extent of primitivity of successively intruding magmas, (2) an inward increase in the extent of chemical equilibrium between phases with distance from cold country rocks, (3) an inward increase in the proportion of cumulus minerals in progressively forming rocks. The emplacement of increasingly more primitive magmas is a factor having a major effect on the generation of reverse mineral and rock compositional trends (Fig. 2). A gradual inward decrease in the degree of magma supercooling is a factor that contributes to an inward increase in Mg-number of pyroxenes and An-content of plagioclase in the marginal zone. The last contributing factor is an increase in the proportion of cumulus minerals as a result of a removal of an evolved liquid boundary layer from *in situ* growing crystals by magma continuously flowing along the base of the intrusion.

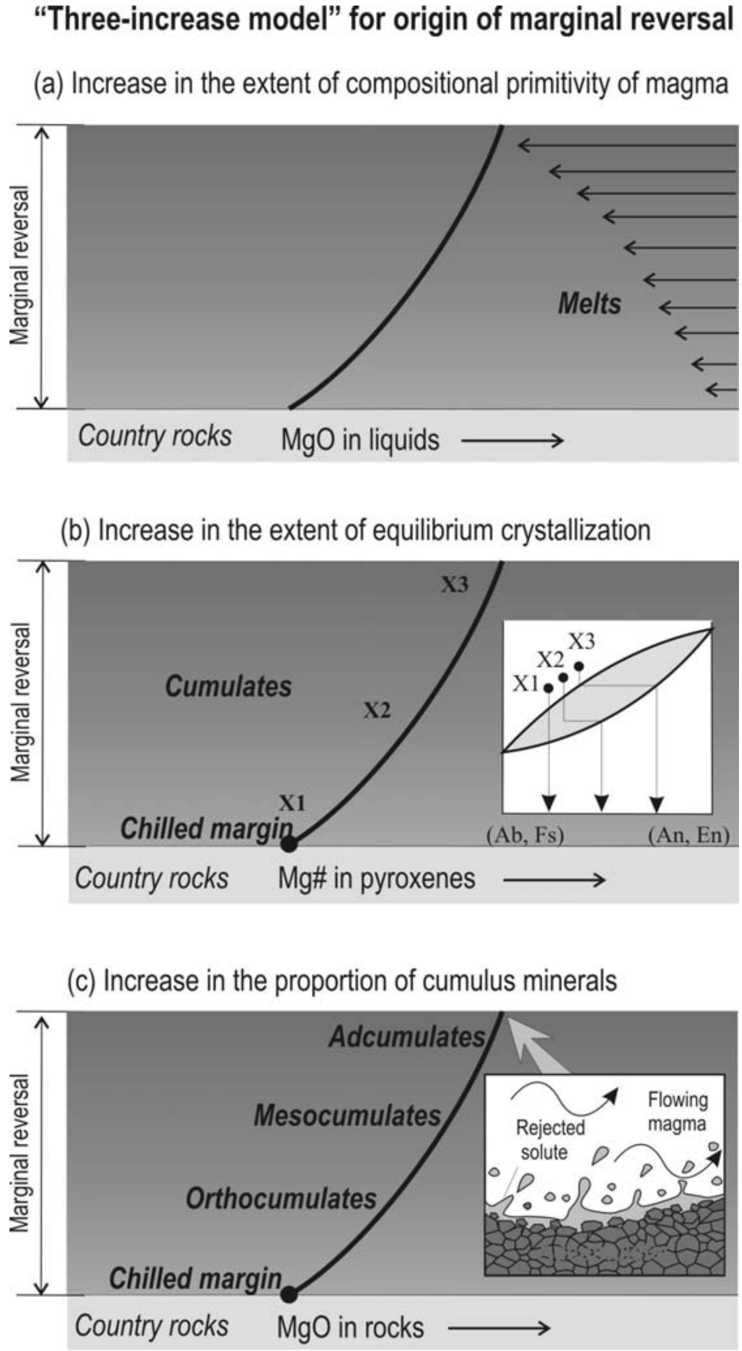

Fig. 2. Cartoon illustrating the "three-increase model" for marginal reversals (after Latypov et al., 2011). The model suggests that reverse compositional trends result from a combination of three major factors: (1) an increase in the extent of magma primitivity with time, (2) an increase in the extent of equilibrium crystallization of magma with distance from cold country rocks, (3) an increase in the proportion of cumulus minerals in progressively forming rocks. The simplified T-X phase diagram (Ab, Fs)-(An, En) illustrates how less supercooled magma crystallizes solid-solution minerals that are progressively enriched in high-temperature end members (e.g. An and En). The cartoon also shows the formation of adcumulates at the top of a cumulate pile owing to effective removal of evolved liquid (rejected solute) from crystals growing *in situ* by flowing magma.

To gain new insights into credible petrological processes for the formation of marginal reversals, we have undertaken extensive petrographic, mineralogical and geochemical studies of the marginal zones of two mafic-ultramafic layered intrusions (the Imandra layered intrusion, Russia and the Fongen-Hyllingen layered intrusion, Norway) and three mafic sills (Vavukansky, Vilyuysky and Kuz'movsky sills, Eastern Siberia, Russia). The results of these studies established the foundations for a rational model for the origin of marginal reversals that combines some the most convincing features of earlier concepts. The results of these studies are summarized in four original publications that are briefly discussed below.

REVIEW OF ORIGINAL PUBLICATIONS

BACKGROUND

This academic dissertation is based on four papers published in internationally-recognized scientific journals, which provide a detailed description of an important petrological phenomenon – marginal reversals in layered intrusions and mafic sills. In the first two papers (Egorova & Latypov, 2012a, b), the petrographic and geochemical characteristics of the marginal zones of two mafic-ultramafic layered intrusions, the Imandra intrusion in the Kola Peninsula, Russia, and the Fongen-Hyllingen layered intrusion, Norway, are documented. It is inferred that they are most compatible with an open-system initial evolution of the respective basaltic magma chambers. The rock sequences and mineral compositions are indicative of the prolonged emplacement of magmas that became more primitive with time. The last two papers (Latypov & Egorova, 2012; Egorova & Latypov, 2013) describe the marginal reversals and the overlying Layered Series in three dolerite sills from Eastern Siberia, Russia. The variations in mineral composition through these sills have allowed us to develop a new concept for the formation of mafic sills that involves two distinct stages in their development – crystallization first in an open and subsequently in a closed system.

PAPER I

Processes operating during the initial stage of magma chamber evolution: insights from the marginal reversal of the Imandra layered intrusion, Russia.

Vera Egorova and Rais Latypov

Journal of Petrology, 2012a, 53(1), 3-26.

This paper presents the results of detailed sampling and analysis of the ~13-m-thick marginal zone of the Imandra layered mafic intrusion in the Kola Peninsula, Russia. The marginal zone shows pronounced reversed compositional trends from the bottom to the top and can therefore be referred to as a marginal reversal. The Mg-number of pyroxenes and An-content of plagioclase, as well as whole-rock MgO, Mg-number and normative An-content show systematic upward increases whereas all incompatible components (e.g. TiO_2, K_2O, P_2O_5, Rb, Ba, Zr, Y, REE) exhibit upward decreases (Fig. 3). Similar reverse compositional trends are characteristic of intratelluric phenocrysts of plagioclase and inverted pigeonite that occur throughout the entire marginal zone. The marginal zone ends abruptly at the base of the Layered Series. The boundary between these two major units is a sharp break in terms of grain size, chemical composition and crystallization sequence. The marginal zone can thus be viewed as an example of an aborted reversal. It is noteworthy that the rocks of the marginal zone have much lower concentrations of all incompatible elements than the coarse-grained orthopyroxenite of the Layered Series. The data indicate that filling of the chamber started with evolved, phenocryst-bearing liquids that likely represent the leading fractionates of parental basaltic magma that crystallized against sidewalls of a deep conduit system. The formation of the marginal zone from these evolved liquids was interrupted by emplacement of a large portion of parental magma that reached the chamber without much fractionation *en route* to crystallize into the Layered Series.

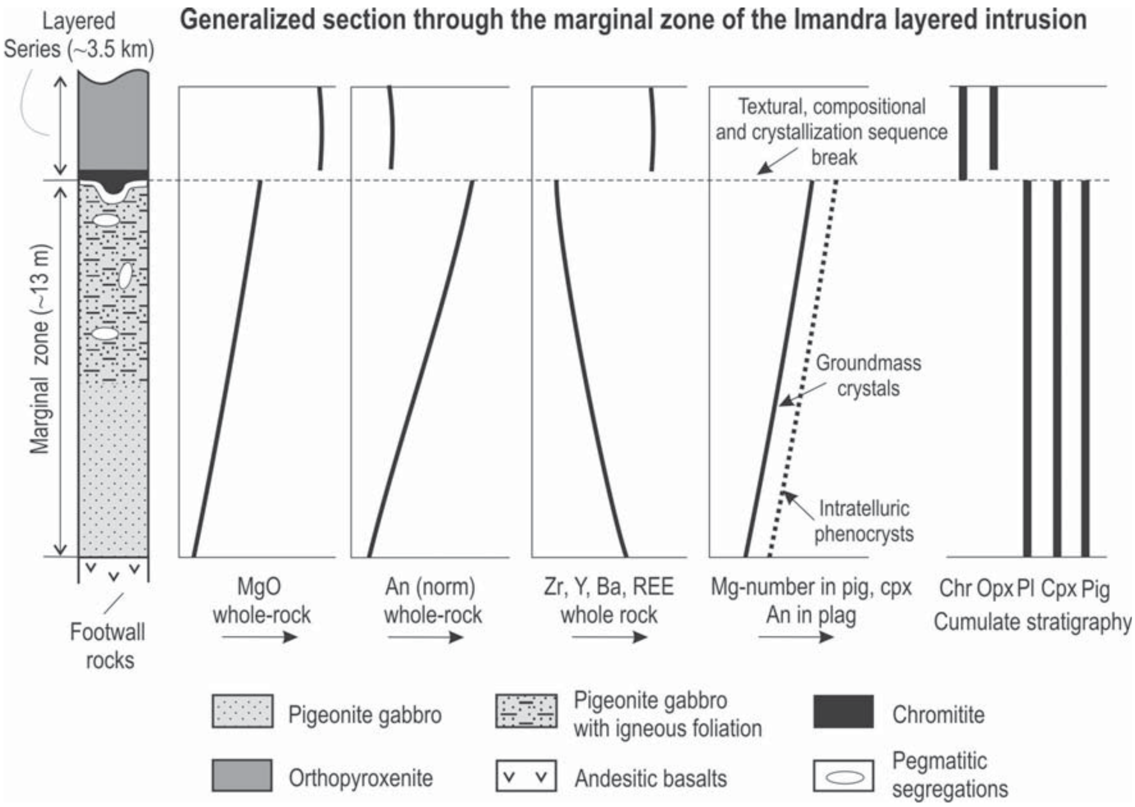

Fig. 3. A generalized stratigraphic section through the basal part of the Imandra Layered Intrusion, showing the lithological sequence and the whole-rock and mineral compositional variations (after Egorova & Latypov, 2012a). There is a sharp break in texture, chemical composition and mineral assemblage at the contact between the pigeonite gabbro of the marginal zone and the orthopyroxenites of the overlying Layered Series. Note that the marginal zone exhibits pronounced reversed fractionation trends in terms of An (norm), Mg-number, MgO, An-content of plagioclase and Mg-number of pyroxenes that abruptly end at the contact with the overlying Layered Series. Note that reversed trends in the rock-forming minerals are characteristic of both groundmass crystals and intratelluric phenocrysts. An (normative)=100*An/(An+Ab); Mg number=100*Mg/(Mg+Fe).

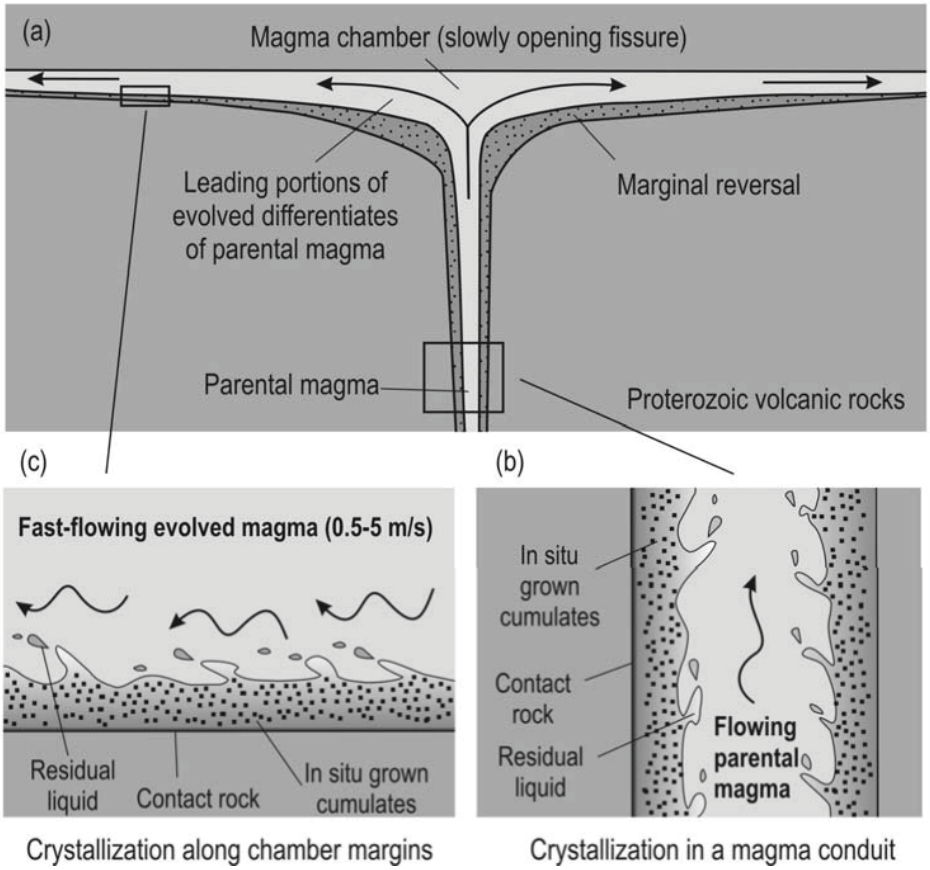

Fig. 4. Schematic illustration of the idea that filling of a magma chamber starts with the leading portions of evolved differentiates of the parental magma (a) that undergoes fractional crystallization in the deeper parts of a conduit (b). With time the inflowing magma becomes more primitive in composition as a result of the decreasing extent of crystallization in the conduit due to heating and insulation of the country rocks. The marginal zone crystallizing from inflowing magma acquires the features of a typical marginal reversal, with rocks and minerals becoming more primitive in composition inwards. The pigeonite gabbros of the marginal zone have meso- to adcumulate compositions because inflowing magmas travelling fast along the base of the intrusion removed the evolved liquids from crystals growing *in situ* very effectively (c). Figure is from Egorova & Latypov (2012a).

The characteristics of the marginal reversal are consistent with the “three-increase model” (Latypov et. al., 2011) that implies that the rocks become more primitive inwards due to: (1) an increase of primitivity of successively intruding magmas, (2) an inward increase in the extent of chemical equilibrium between phases with distance from cold country rocks, (3) an increase in the proportion of cumulus minerals in progressively forming rocks. The difference in incompatible element abundances between the marginal zone and Layered Series is attributed to fundamentally different regimes of magma flow during their formation. The crystallization of the marginal zone was dominated by fast-flowing (0.5-5 m/s) magmas that favored an effective removal of evolved liquids from the crystals growing *in situ* and hence the generation of incompatible element-depleted meso- to adcumulates (fine-grained pigeonite gabbro). In contrast, the Layered Series crystallized from slower moving (0.5-5 km/year), thermally convecting magma that was much less effective in stripping evolved liquid from crystallizing minerals and therefore gave rise to incompatible element-enriched orthocumulates (coarse-grained orthopyroxenites) (Fig. 4). It is suggested that the inferred petrological processes may commonly take place during the initial stages in the development of basaltic magma chambers.

PAPER II

Prolonged magma emplacement as a mechanism for the origin of marginal reversal of the Fongen-Hyllingen layered intrusion, Norway.

Vera Egorova and Rais Latypov

Geological Magazine, 2012b, 149, 5, 909-926.

This paper focuses on the results of detailed sampling along a section through the ~100-m-thick marginal zone of the Hyllingen Series in the Fongen- Hyllingen intrusion (FHI), which is the largest mafic intrusion in the Scandinavian Caledonides of Central Norway (Wilson et al., 1981, 1983, 1987; Wilson & Engell-Sørensen, 1986, 1996; Wilson & Larsen, 1982, 1985; Thy & Wilson, 1980; Thy et al., 1988; Wilson, 2010). The marginal zone of the FHI is composed of ferrodiorites. The most important feature of the marginal zone is the remarkable reversed compositional trends in terms of whole-rock major and trace elements from near the base to the top (Fig. 5). The reversed trends are particularly well exemplified by an upward increase in whole-rock MgO from ~1 to 2.66 wt.%, Mg/Mg+Fe ratio from 10 to 19 at.%, normative An from 34 to 43 mol.% and by decreases in SiO_2 from 52 to 43 wt.% and Na_2O from 5.6 to 3.8 wt.%. Especially noteworthy is the systematic 2- to 3-fold upward decrease in the concentrations of all incompatible components (Fig. 5). The reverse trends are also evident from an upward increase in the An-content of plagioclase (from ~30 to ~43 at.%), and the Mg-numbers of amphibole (from ~9 to ~23 at.%) and clinopyroxene (from ~23 to ~37 at.%) (Fig. 6). The marginal zone has a sharp contact with the overlying Layered Series as is evident from a step-like increase in the Mg- number of mafic minerals and the An-content of plagioclase, as well as a sharp increase in whole-rock MgO and Mg-number in the olivine gabbronorites of the Layered Series. Based on these observations, the marginal zone of the FHI can be interpreted as an aborted marginal reversal.

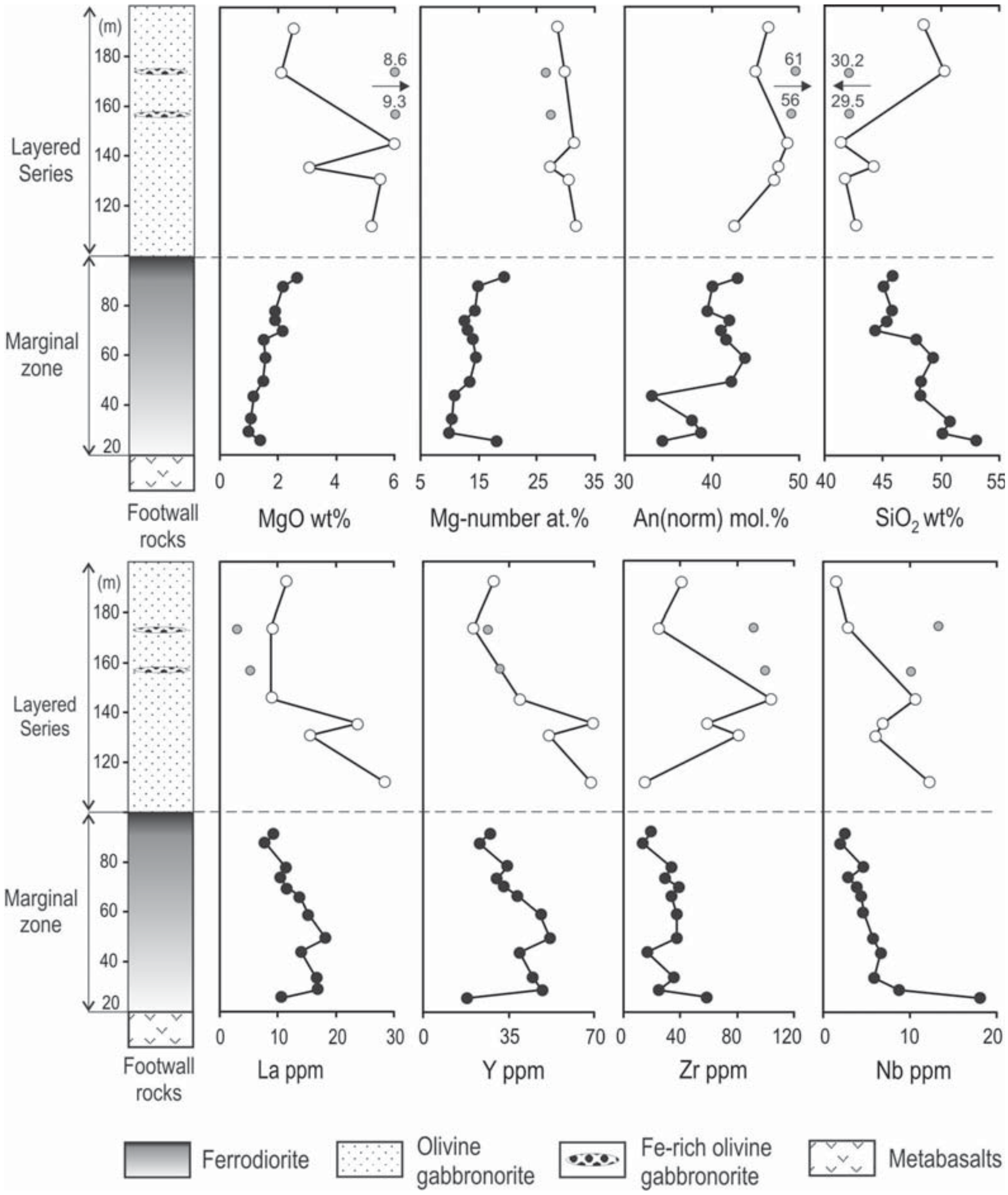

Fig. 5. Lithological sequence and whole-rock chemical compositions through the marginal zone (filled circles) and the lower part of the Hyllingen Series (open circles) of the Fongen-Hyllingen intrusion in the studied section (after Egorova & Latypov, 2012b). Note that the Marginal Zone exhibits reversed fractionation trends in terms of An (norm), Mg-number, MgO, SiO_2 and Na_2O that end abruptly at the contact with the overlying layered series. The compositions of Fe-rich olivine gabbronorite shlieren (grey circles) are shown out of scale.

The origin of the studied marginal reversal is much more compatible with the hypotheses invoking open-system development of a basaltic magma chamber. The upward increase in An-content of plagioclase and an upward increase in Mg-number of mafic minerals (Fig. 6) are indicative of the formation of the marginal reversal by the prolonged emplacement of magmas that became more primitive with time. The emplacement of increasingly more primitive magmas is also strongly supported by the composition of interstitial calcic amphibole that reveals a reverse trend in Mg-number, indicating that intercumulus liquid also becomes more primitive up the section of the marginal zone. This process was followed by emplacement of a much larger portion of more primitive magma that crystallized into the overlying Layered Series with a sharp compositional break with the underlying marginal zone.

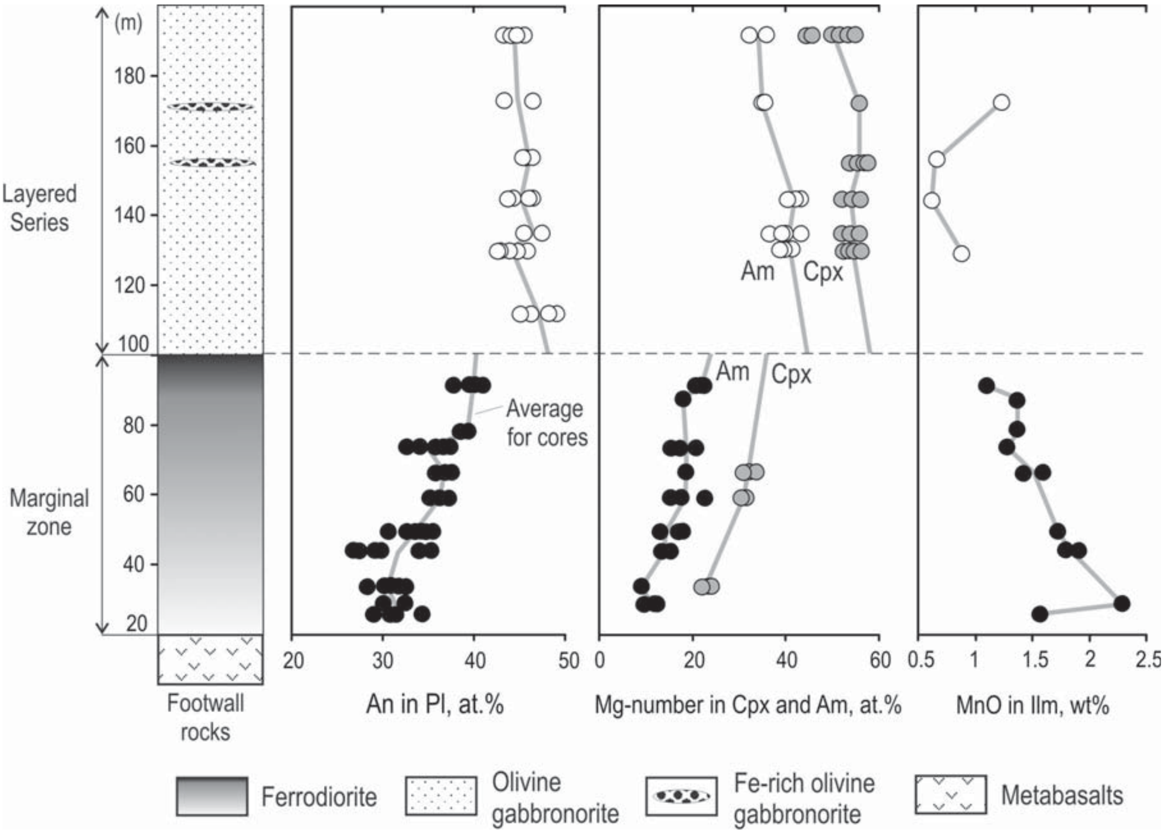

Fig. 6. Stratigraphic section with mineral compositional variations through the Marginal Zone and the lowest part of the Layered Series of the Fongen-Hyllingen Intrusion at the studied area (after Egorova & Latypov, 2012b). Note that the Marginal Zone exhibits reverse fractionation trends in terms of An-content of plagioclase, Mg-numbers of clinopyroxene and amphibole and the Mn-content of ilmenite. An=100*An/(An+Ab); Mg-number=100*Mg/(Mg+Fe).

This sequence of events during the formation of the studied marginal reversal can be reconciled with two principle models. These are the model by Wilson and Sørensen (1986) involving a compositionally stratified magma and the so-called "three-increase" model by Latypov et al. (2011). A first model was developed by Wilson and Sørensen (1986) specifically for the marginal reversal of the FHI. The authors suggested that the origin of this marginal reversal is consistent with crystallization during gradual elevation of compositionally stratified magma up an inclined surface in response to the influx of dense, primitive magma at the base of the chamber. The chamber is envisaged as having a wedge shape, which inflates in response to the influx of dense increasingly primitive magma at the base. Evolved buoyant magma first comes into contact with the floor at the leading edge of the expanding wedge where some crystallization occurs. During continued magma expansion, successively more primitive magma comes into contact with the previously formed marginal rocks where the crystallization sequence would be the reverse of that in the parental stratified magma (Wilson & Engell-Sorensen, 1986). The compositional range of the reversal depends on that of the parental stratified magma. A stratified magma chamber (Fongen) was already present to the north before development of the Hyllingen part, and this is envisaged as having expanded southward by the process outlined above (Wilson & Engell-Sorensen, 1986).

In the frame a second "three-increase model" one can propose that the marginal zone of the FHI starts developing during the filling of magma chamber by evolved magmas, which arrive from the fractionating feeder channel and become more primitive with time. The emplacement of increasingly more primitive magmas is a factor having a major effect on the generation of reverse mineral and rock compositional trends (Fig. 7). A gradual inward decrease in the degree of magma supercooling is a factor that contributes to an inward increase in Mg-number of pyroxenes and An-content of plagioclase in the marginal zone. The last contributing factor is an increase in the proportion of cumulus minerals as a result of a removal of an evolved liquid boundary layer from *in situ* growing crystals by magma continuously flowing along the base of the intrusion. This process has the strongest effect on an inward depletion of marginal rocks in highly incompatible elements such as Ba, REE, Y, Zr and Nb (Fig. 6).

In principle, the above two models suggest an equally good explanations for the origin of the marginal reversal of the FHI, since they both invoke filling of the opening chamber with magmas that become more primitive with time. The only difference between these models is in the source which these inflowing magmas are derived from: a fractionating feeder channel (Latypov et al., 2011) versus a compositionally stratified magma chamber (Wilson & Engell-Sorensen, 1986). Since compositional features of marginal reversals produced by these two models are almost indistinguishable, no attempt is made here to make a choice between these models. One should note, however, that the model of Wilson and Sørensen (1986) appears to be more preferable for this particular case since it explains not only the reverse trends of the marginal zone but also a discordant relationship between modal and cryptic layering in the intrusion as a whole. In fact, we agree with Wilson and Sørensen (1986) that the Layered Series has most likely been produced from the subsequent major influx of a compositionally stratified magma. This is, however, beyond the scope of this study. At the same time, the model of Latypov et al. (2011) appears to be more universal since it can be applied to a larger number of magmatic bodies of various sizes and shapes. In particular, it is able to explain marginal reversals at the margins of dikes (e.g. Chistyakova & Latypov, 2009, 2010) and bases of mafic sills (e.g. Latypov, 2003a, b) and sheet-like layered intrusions (Latypov et al., 2011; Egorova & Latypov, 2012a) where compositionally stratified magma or crystallization along an inclined floor are not evident.

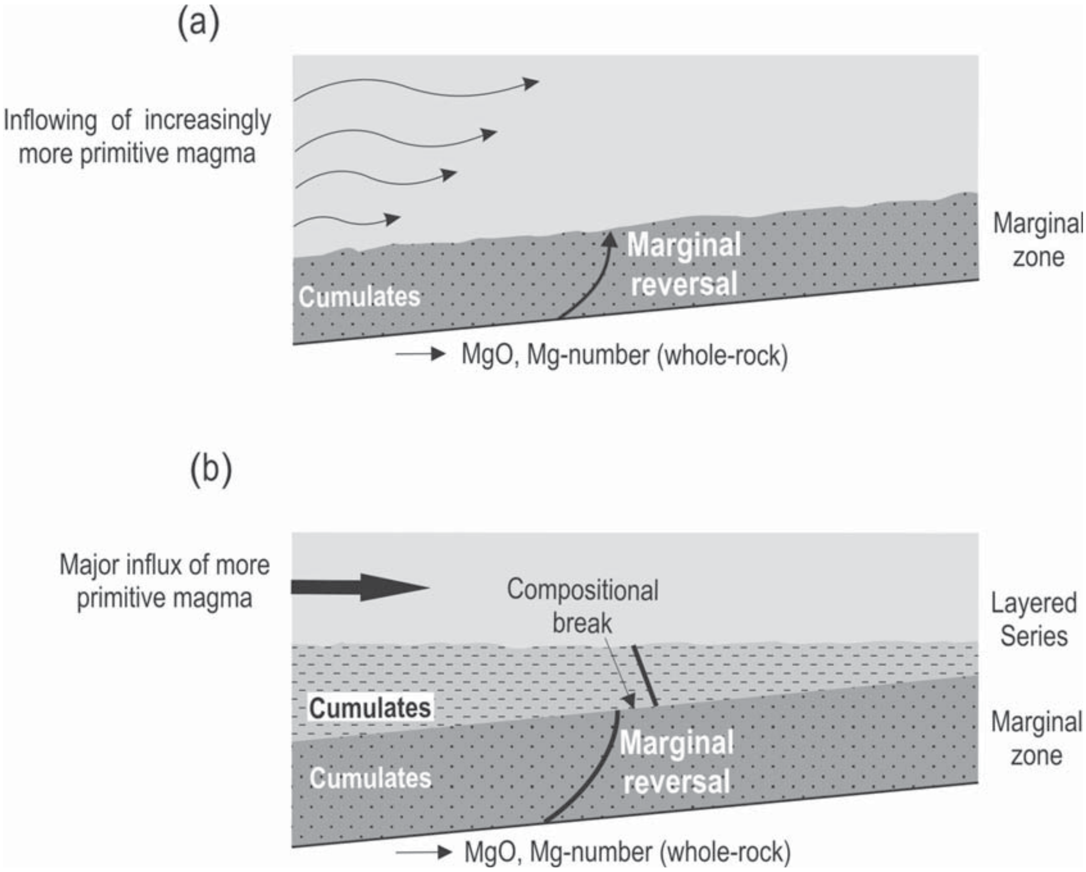

Fig. 7. Schematic illustration of the formation of the marginal reversal below the Hyllingen Series of the Fongen-Hyllingen intrusion from inflowing magmas which become more primitive in composition with time (after Egorova & Latypov, 2012b). A marginal zone crystallizing from such inflowing magmas acquires features of a typical marginal reversal, with rocks and minerals becoming more primitive in composition upwards (a). This is followed by a rapid influx of a new magma that terminates the development of a marginal reversal and starts crystallization of the layered series with more primitive mineral and rock compositions. This results in the formation of a sharp compositional break of the Layered Series with the underlying rocks of marginal reversal (b).

PAPER III

Plagioclase compositions give evidence in situ crystallization under horizontal flow conditions in mafic sills

Rais Latypov and Vera Egorova

Geology, 2012, 40, 883-886

This paper focuses on the thorny problem of the relative roles of crystal settling and *in situ* crystallization in the formation of igneous bodies, which is still the subject of active debate in igneous petrology. Despite the fundamental differences in these two processes, they can both result in minerals that become more evolved in composition during the crystallization of an igneous body. Variations in mineral composition across the Vavukansky dolerite sills studied in SE Siberia, Russia indicate, however, that this is not always the case. In terms of petrography, CIPW norms, whole-rock compositions (MgO, Mg-number, Ni, TiO_2, An (norm)) and An-content of plagioclase, the sill can be subdivided into floor and roof sequences that meet at a Sandwich Horizon. The floor sequence of the sill comprises a basal reversal and a Layered Series, while the roof sequence includes a top reversal and an Upper Border Series. The boundaries between the subdivisions of the floor and roof sequences are marked by the lower and upper crossover points exhibiting the most primitive mineral and rock compositions in the sill. The compositional profile of the Vavukansky sill is M-shaped, a variety of an S-shaped profile (Latypov & Chistyakova, 2009). The most significant observation is that the compositions of plagioclase cores in the Vavukansky sill also define an M-shaped profile. This mineral reveals two contrasting compositional trends. The basal and top reversals are accompanied by inward increases in the An-content of plagioclase cores (from ~An 63 to ~An 82 at the base and from ~An 63 to ~An 70 at the top) (Fig. 8). In contrast, plagioclase cores in the Layered and Upper Border Series show an inward decrease in An, with the most evolved plagioclase (An 55-58) occurring in the Sandwich Horizon (Fig. 8).

Such trends in plagioclase composition are clearly not compatible with any closed-system model (crystal settling or *in situ* crystallization) since minerals cannot become more primitive during fractional crystallization of basaltic magmas. We propose a modified version of *in situ* crystallization that involves two distinct stages for the formation of M-shaped profiles in mafic sills.

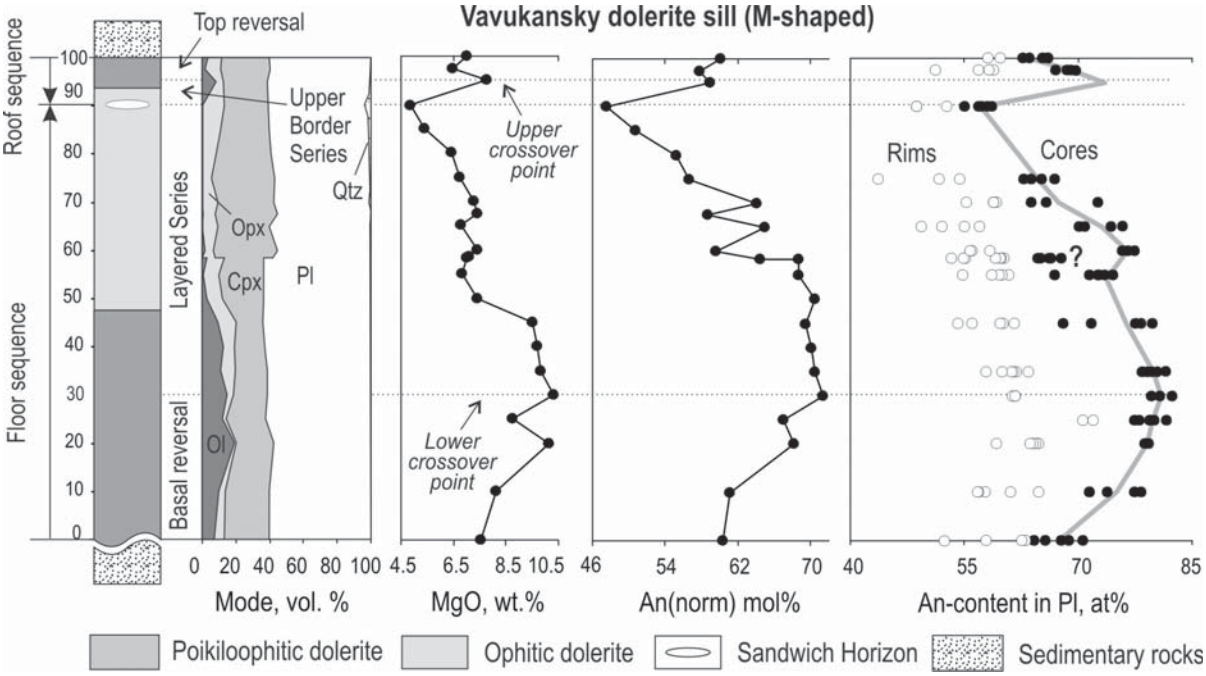

Fig. 8. Simplified stratigraphic section through the Vavukansky mafic sill, SE Siberia, showing an M-shaped variation in modal composition and whole-rock geochemistry (after Latypov & Egorova, 2012). The sill is subdivided into floor and roof sequences that meet at a sandwich horizon. The floor sequence of the sill comprises a basal reversal and a layered series, while the roof sequence contains an upper reversal and an upper border series. Subdivisions of the floor and roof sequences are marked by upper and lower crossover points with the most primitive mineral and rock compositions in the sill. The shaded line gives the mean composition of plagioclase cores. An content = 100*An/(An + Ab).

In contrast to general opinion, we suggest that such mafic sills do not form instantaneously from a single pulse of parental magma. Rather, they develop initially as an open system with inflowing magmas becoming increasingly more primitive with time. In the literature this has previously been termed "leading-edge fractionated magma". The concept is quite old in petrology and is thought to result from progressive mantle melting, magma differentiation at some intermediate level (Morse, 1979, 1981) or partial crystallization in feeder conduits (Latypov et al., 2011; Egorova & Latypov, 2011a). As a result, minerals growing at crystal-liquid interfaces from such magmas will become more primitive inwards. In particular, plagioclase and olivine will show inward increases in An-content and Mg-number, respectively (Fig. 8). An additional factor that may have contributed to the formation of reverse compositional trends in minerals is a gradual decrease in the degree of magma supercooling, an idea that was first launched by Wager and Brown (1968, p. 517). The proportion of cumulus minerals in rocks will increase away from intrusive contacts to give rise to the whole-rock marginal reversals. When the filling of a sill with magma ends, it starts evolving as a closed system. The onset of this stage is marked by crossover points displaying the most primitive mineral and rock composition in the sill. Subsequently the magma evolves both upwards and downwards by uninterrupted fractional crystallization that results in olivine and plagioclase becoming more evolved in composition inwards, as observed in the Layered and Upper Border Series (Fig. 8).

We believe that the proposed *in situ* crystallization model involving two distinct stages may represent a general mechanism for the origin of intrusive bodies since similar reverse trends in plagioclase composition are observed in many other mafic sills and layered intrusions. In particular, such trends are documented in marginal zones of the Duluth (Chalokwu & Grant, 1990), Koitelainen (Latypov et al., 2011), Imandra (Egorova & Latypov, 2012a), Hasvik (Tegner et al., 1999) and Fongen-Hyllingen (Wilson & Engell-Sørensen, 1986; Egorova & Latypov, 2012b) layered intrusions. Such trends are also evident in the basal parts of some Antarctic dolerite sills (Gunn, 1962; 1966), Greenland dolerite sills (Gisselø, 2001), and Golden Valley Sill, South Africa (Aarnes et al., 2008; Galerne et al., 2010).

PAPER IV

Mafic–ultramafic sills: New insights from M- and S-shaped mineral and whole-rock compositional profiles.

Vera Egorova and Rais Latypov

Journal of Petrology, 2013, 54(10), 2155-2191

This paper discusses the origin of mafic and ultramafic sills with M- and S-shaped compositional profiles, the origin of which remains controversial. This issue is addressed by comparison of three ~100-m-thick Siberian dolerite sills (the Vavukansky, Kuz’movsky and Vilyuysky sills) that all display remarkable internal differentiation. The Vavukansky sill has an M-shaped profile with prominent basal and roof reversals showing inward increases in whole-rock MgO, Mg-number and normative An-content, followed by the Layered and Upper Border Series with inward decreases in these indices (Fig. 9). The Kuz’movsky and Vilyuysky sills both show S-shaped profiles, similar to that of the Vavukansky sill, but lacking an upper reversal (Fig. 9). These whole-rock M- and S-shaped profiles are accompanied by similar variations in mineral compositions (Fig. 9). Plagioclase and, to a lesser extent, olivine show systematic inward increases in An-content and Mg-number, respectively, across the basal and upper reversals. These compositional trends are followed by inward decreases in these ratios into the interiors of the Vavukansky and Kuz'movsky sills.

Currently accepted models attribute whole-rock M- and S-shaped compositional profiles to crystal settling, compositional convection or compaction operating in closed bodies of magma. Our observations challenge these traditional interpretations because variations in mineral compositions in the marginal reversals cannot result from closed-system fractionation. We suggest instead that initially the sills were slowly inflated by magmas that became gradually more primitive with time (Fig. 10) in response to partial crystallization of the parental magma along the walls of the feeder conduits (Latypov et al., 2011; Egorova & Latypov, 2012a, 2012b). As a result, minerals crystallizing from the inflowing magma on the floor and roofs of sills will become more primitive inwards. In other words, the reversals essentially fossilize a systematic change in the composition of the influxed magma. This happens because inflation occurs slowly enough for the crystallization front to advance fast enough to freeze in the variable influx. The filling of a sill culminates with a major influx of the most primitive magma that leads to its rapid inflation to its final size (Fig. 10).When the filling of a sill with this last magma pulse ends, closed-system fractional crystallization becomes the predominant mechanism of differentiation (Fig. 10). This resulted in the Layered and Upper Border Series with minerals becoming more evolved inwards.

Although the magma crystallizes at both margins, the crystallization front at the roof will advance more slowly than that at the base owing to either convection keeping the thermal boundary layer thin (e.g. Jaupart & Tait, 1995; Tait & Jaupart, 1996) or crystals settling out of the upper boundary layer (e.g. Morse, 1986, 1988; Frenkel' et al., 1988, 1989). In the resulting sill, the floor sequence is characteristically about 6-7 times thicker than the roof sequence (Jaupart & Tait, 1995). The ultimate result emerging from this model is the generation of a sill with M-shaped profiles in terms of both mineral and whole-rock compositions, as observed in the stratigraphic section of the Vavukansky sill. If the top reversal for some reason does not develop or is destroyed by inflowing magmas by melting or stoping, then the resulting compositional profile will be S-shaped, as observed in the stratigraphic section of the Kuz'movsky sill (Fig. 9). The S-shaped profile can be regarded as a variant of an M-shaped profile lacking a top reversal.

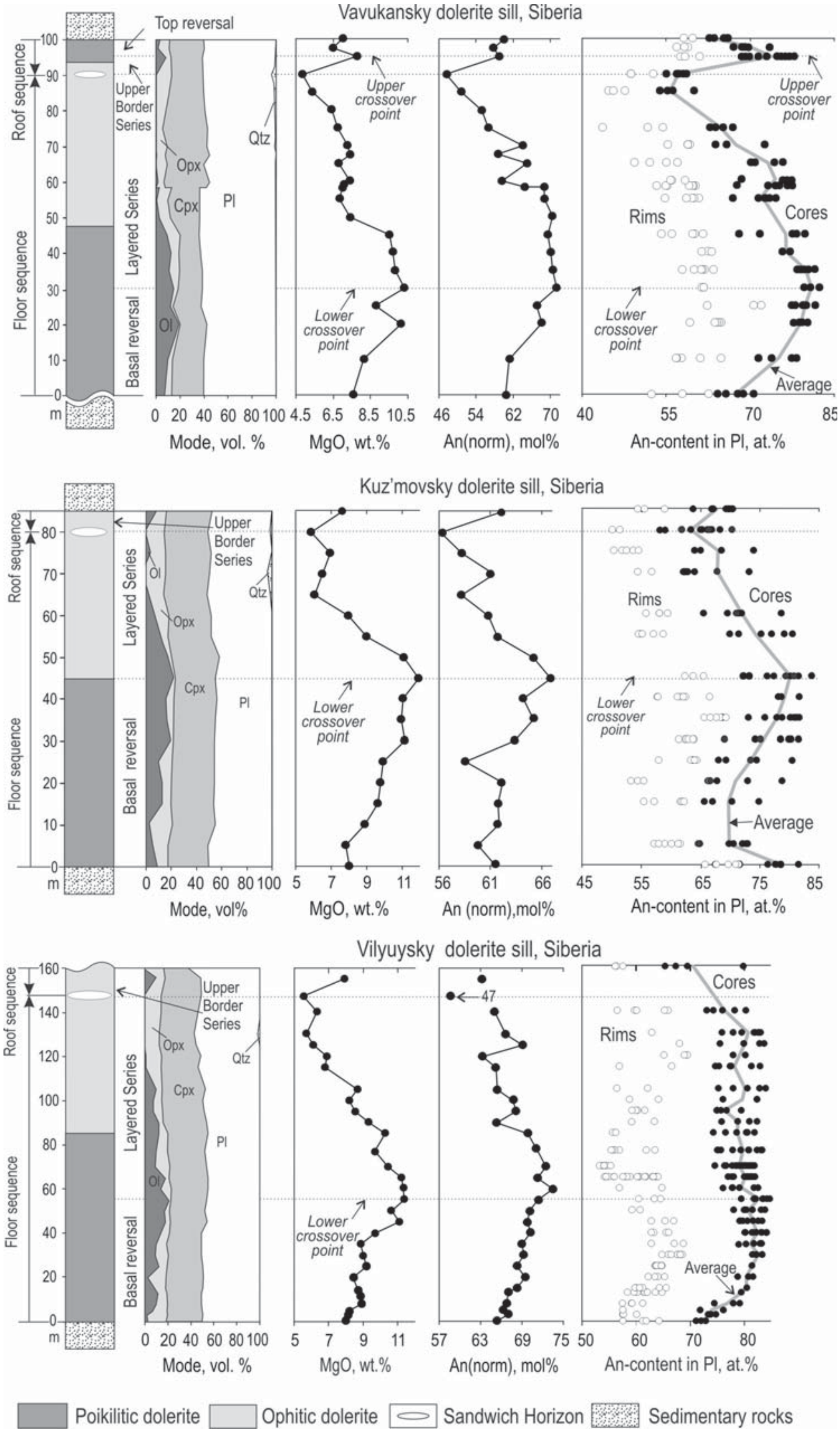

Fig. 9. Simplified sections through the Vavukansky, Kuz'movsky and Vilyuysky dolerite sills showing their stratigraphic subdivisions and S- and M-shaped variations in mineral composition and whole-rock geochemistry (after Egorova & Latypov, 2013). The sills are subdivided into floor and roof sequences that meet at sandwich horizons. In the Vavukansky sill, the floor sequence comprises a basal reversal and a Layered Series, while the roof sequence contains an upper reversal and an Upper Border Series.

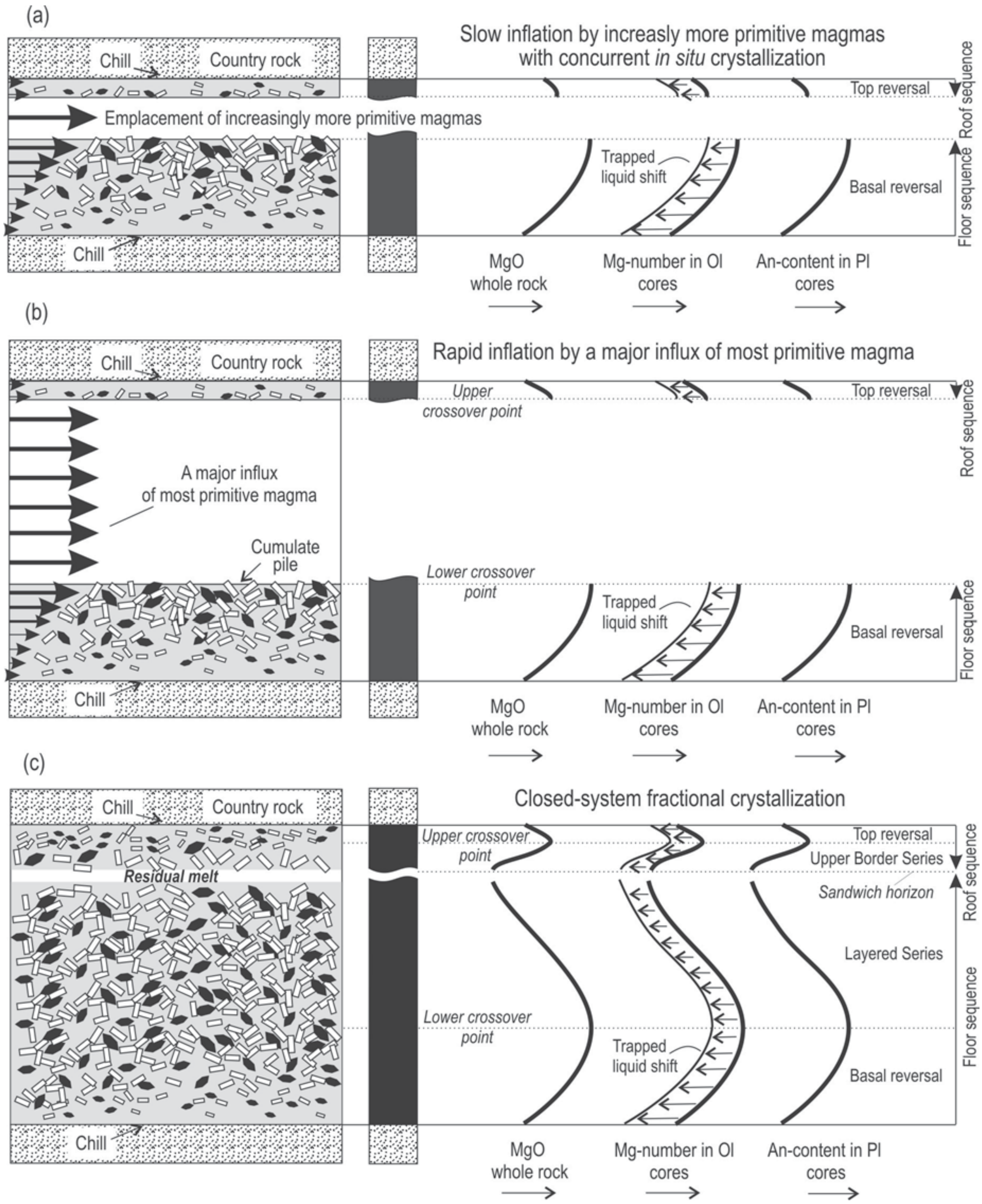

Fig. 10. A model for the formation of mineral and whole-rock M-shaped compositional profiles in mafic sills during *in situ* crystallization (after Egorova & Latypov, 2013). (a) During the initial stage, the sill is slowly inflated by magma that becomes more primitive with time. This gives rise to zones with minerals showing reverse compositional trends (e.g. an inward increase in the An-content of plagioclase and Mg-number of olivine. (b) Rapid inflation of the sill up to its final size takes place in response to emplacement of a large pulse of primitive magma. (c) During an advanced stage, the sill evolves by fractional crystallization in a closed system. This results in crossover points that mark the time when magma inflow ended. Subsequent reaction of olivine with interstitial melt (trapped liquid shift) gives it a more evolved composition but does not change the original shape of the profile. The final sill consists of floor and roof sequences that meet at a sandwich horizon and has an M-shaped profile in both mineral and whole-rock compositions.

CONCLUSIONS

1. A puzzling feature of some mafic-ultramafic intrusions and sills is the occurrence of marginal zones in which both mineral crystallization sequences and compositional trends are distinctly opposite to that predicted by phase equilibria diagrams. The marginal zones show pronounced reversed compositional trends and can therefore be referred to as marginal reversals. In particular, the Mg-number of pyroxenes and An-content of plagioclase as well as whole-rock MgO, Mg-number and normative An-content show systematic inward increases whereas all incompatible components (e.g. TiO_2, K_2O, P_2O_5, Rb, Ba, Zr, Y, REE) decrease. Two different types of marginal reversals can be identified in layered intrusions - fully-developed and aborted reversals (Fig. 11). The fully-developed marginal reversals are the most common type in layered intrusions (see summary in Latypov, 2003a,b; and Latypov et al., 2007) and present rock sequences that become progressively more primitive away from the intrusive contact. This continues until a horizon is reached that is characterized by the most primitive rocks in the entire intrusion (e.g. highest MgO, Mg-number or normative An). At this point the marginal reversal gives way to the Layered Series containing rock sequences that become progressively more evolved. Thus, in terms of compositional trends, a typical marginal reversal represents a condensed mirror image of the overlying Layered Series, with the boundary between these two units running through the crossover maximum.

An aborted marginal reversal occurs if the development of the marginal zone is terminated by a new large pulse of primitive magma that interrupts the crystallization history. As a result, such a reversal shows an incomplete crystallization sequence and mineral compositional trends, as well as a sharp compositional break with overlying rocks of the Layered Series. Such specific marginal reversal seems to be quite rare in nature. It was discovered at the base of the Koitelainen intrusion, Finland (Latypov et al., 2011). Owing to our investigations, an aborted marginal reversal has discovered at the base Imandra intrusion, Russia (Egorova & Latypov, 2012a) and in the Fongen-Hyllingen intrusion, Norway (Egorova & Latypov, 2012b).

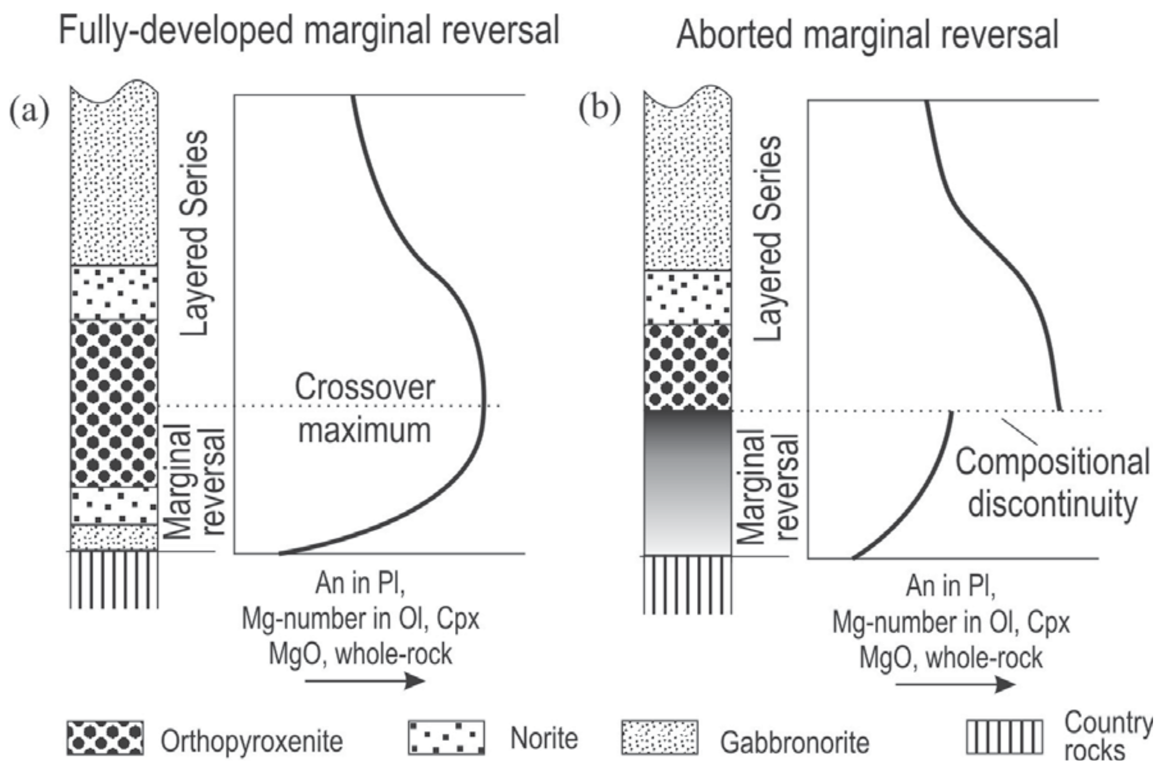

Fig. 11. Cartoon illustrating two different types of marginal reversal in layered intrusions (after Latypov et al., 2011). A fully-developed marginal reversal shows a crystallization sequence and mineral compositional trends essentially opposite to those in the overlying Layered Series into which it passes through the crossover maximum. This type is supposed to follow a complete evolutionary path during the formation of the reversal. An aborted marginal reversal results when the evolution is interrupted by major pulse of primitive magma parental to the overlying Layered Series. Consequently, it shows an incomplete crystallization sequence and a sharp compositional break with the overlying Layered Series.

2. The origin of the both types of marginal reversal can be satisfactorily explained by the “three-increase model” (Latypov et al., 2011) that involves three reinforcing processes: (1) an increase in the extent of magma primitivity with time, (2) an increase in the extent of equilibrium crystallization of magma with distance from cold country rocks, (3) an increase in the proportion of cumulus minerals in progressively forming rocks, which is related to the effective removal of evolved melt from the surfaces of growing crystals by flowing magma. These are the processes that appear to have been most effective at cooling margins during the initial stages of magma chamber evolution. We suggest that magma chambers develop initially as open systems with inflowing magmas becoming increasingly more primitive. In the literature, this has previously been termed “leading-edge fractionated magma” (Morse, 1981). The concept is quite old in petrology, and is thought to result from progressive mantle melting, magma differentiation at some intermediate level or partial crystallization in feeder conduits. As a result, minerals growing at crystal-liquid interfaces from such magmas will become more primitive inward. One most compelling piece of evidence for the filling of chambers by magma that became more primitive with time is the occurrence of plagioclase and/or pyroxene

phenocrysts in marginal zones of layered intrusions and sills that show systematic upward increases in An-content and Mg-number, respectively.

3. In Latypov et al.'s model, the emplacement of increasingly more primitive magma is the major factor in the generation of reverse mineral and rock compositional trends. A gradual decrease in the degree of magma supercooling may have contributed to the inward increase in the Mg-number of pyroxenes and amphiboles and the An-content of plagioclase in marginal zones. Another contributing factor is an increase in the proportion of cumulus minerals as a result of removal of an evolved liquid boundary layer from growing crystals by magma continuously flowing along the base of the intrusion. This process results in an increasing depletion in highly incompatible elements such as Ba, REE, Y, Zr and Nb such as is observed in Imandra and Fongen-Hyllingen intrusions (Egorova & Latypov, 2012a,b). The systematic nature of the reversed trends indicates that magma emplacement took place during an extended period and that there were no abrupt compositional changes.

4. Marginal reversals are commonly developed at the bases of mafic sills but in some cases also beneath their roofs. The development of a basal reversal at the floor of the sill results in an S-shaped compositional profile, as in the Kuz'movsky and Vilyuysky sills. S-shaped compositional profiles are generally characterized by an upward increase in the concentrations of cumulus crystals (e.g. olivine), whole-rock MgO, Mg-number and normative An-content, followed by a systematic decrease in these variables in the overlying Layered Series. The boundary between the basal reversal and the Layered Series runs through a horizon exhibiting the most primitive rock compositions in the sill. This horizon does not coincide with any lithological boundary. It is located within modally uniform rocks and can only be identified by compositional data. The development of reversals both at the floor and roof of a sill results in an M-shaped compositional profile, such as seen in the Vavukansky sill. Sills with M-shaped profiles are the most complicated and include a reversal at the roof, referred to as a top reversal. Like basal reversals, these are mirror images of the underlying Layered Series with regard to crystallization sequences and compositional trends. The sills with prominent basal and top reversals show inward increases in whole-rock MgO, Mg-number and normative An content, followed in the interiors by decreases in these indices. The whole-rock M- and S-shaped profiles are accompanied by similar changes in mineral compositions. Plagioclase and, to a lesser extent, olivine show systematic inward increases in An-content and Mg-number, respectively, across basal and top reversals. These compositional trends are followed by

inward decreases in these ratios in the interiors of sills.

5. The study of three Siberian dolerite sills indicates that their M- and S-shaped mineral and whole-rock compositional profiles were the result of *in situ* crystallization in two consecutive stages (Fig. 12). During the initial stage, the sills were slowly and then rapidly inflated, with the inflowing magmas becoming increasingly more primitive with time. Basal reversals, and in some cases top reversals, crystallized during this stage on both margins.

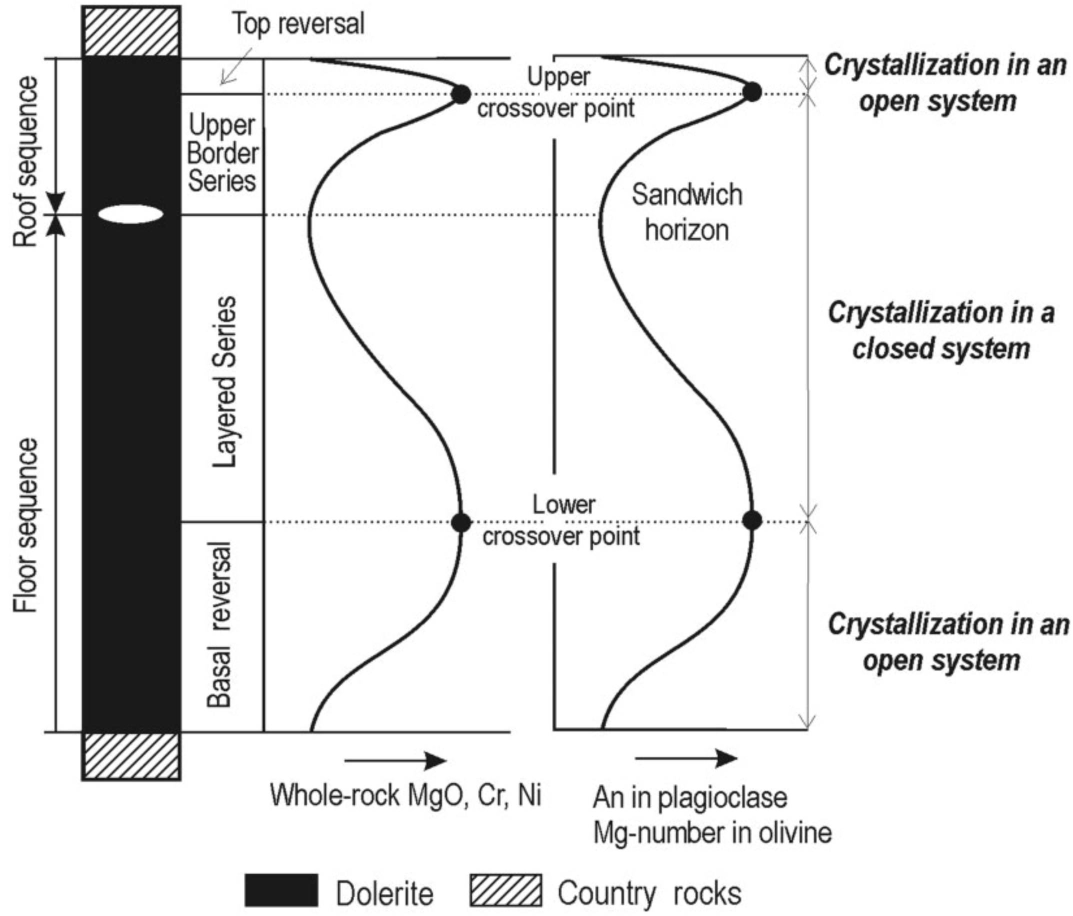

Fig. 12. Generalized section through a mafic-ultramafic sill with M-shaped compositional profiles. The sill is subdivided into floor and roof sequences that meet at a Sandwich Horizon. The floor sequence of the sill comprises a basal reversal and a Layered Series, whereas the roof sequence contains a top reversal and an Upper Border Series. The floor and roof sequences are subdivided by the lower and upper crossovers exhibiting the most primitive mineral and rock compositions in the sill. Our interpretation implies that roof and basal reversals were the result of *in situ* crystallization that took place as inflowing magmas became progressively more primitive. In contrast, the Layered and Upper Border Series were the result of closed-system fractional crystallization. S-shaped compositional profiles can be regarded as a variety of M-shaped ones in which an upper reversal was either never developed or was destroyed by inflowing magmas or by melting or by assimilation of hot magma.

The crossover horizons, distinguished by the most primitive rock and mineral compositions, mark the end of magma emplacement. Subsequently, they evolved as a closed system. During this stage, the sills crystallized increasingly more evolved rocks of the Layered Series. *In situ* fractional crystallization was the principal mechanism of differentiation during this period. The ultimate result was the generation of sills with S- and M-shaped profiles defined by both mineral and whole-rock compositions. The initial emplacement of increasingly more primitive magmas implies that the chilled margins of the sills are not representative of the parental magma composition and that the concentrations of incompatible elements in basal and top reversals cannot be used for the estimation of the amount of interstitial melt trapped in cumulates.

Many studies of marginal reversals in mafic sills and layered intrusions have exclusively utilized whole-rock compositional data, e.g. Jimberlana intrusion (Campbell, 1987), Muskox intrusion (Irvine & Smith, 1967), Monchegorsk intrusion (Dokuchaeva & Yakovlev, 1994), Noril'sk intrusion (Czamanske et al., 1994, 1995; Krivolutskaya et al., 2001), Koillismaa intrusion (Alapieti, 1982), Kharayelakh sill (Czamanske et al., 1994), Antarctic dolerite sills (Gunn, 1962; 1966), Greenland dolerite sills (Gisselø, 2001). Mineral compositions have rarely been used to constrain this phenomenon. However, the compositions of rock-forming minerals (e.g. plagioclase and pyroxenes) record crucial information about magma composition, temperature and crystallization processes. This study indicates the need for more detailed investigations on mineral compositions in layered intrusions and mafic sills to make further progress in our understanding of the processes involved in their formation.

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