The Origin of Basic-Ultrabasic Sills with S-, D-, and I-Shaped Compositional Profiles by In Situ Crystallization of a Single Input of Phenocryst-Poor Parental Magma

Rais Latypov
Geological Institute, Kola Science Centre, Apatity, 184200, Russia (Present address: Institute of Geosciences, P.O. Box 3000, FIN – 90014, University of Oulu, Finland)
e-mail: Rais.Latypov@oulu.fi

Basic-ultrabasic sills are likely to provide the best insight into the processes leading to differentiation of natural magmas. They usually show complete rock sequences including roof and basal chilled zones, that provide information about phase, modal and cryptic layering of magmatic bodies. Apart from the cases where multiple intrusions are involved, the bulk composition of sills can safely be taken as providing a reliable estimate of parental magma compositions, which are of paramount importance for any model of magma differentiation. The course of emplacement and solidification is also commonly clear in sills, allowing resolution of the conflict over whether the final rock sequence was produced by a single injection or by multiple injections.

Three main types of basic-ultrabasic sills have been identified on the basis of the shape of modal or MgO compositional profiles along their stratigraphic sections (Gibb & Henderson, 1992; Marsh, 1996). These are sills with S-, D- and I-shaped compositional profiles (Fig. 1). The well-known S-type sills are the most differentiated bodies, which are characterized by high concentrations of olivine near the base (Gray and Crain, 1969; Fujii, 1974; Frenkel' et al., 1988, 1989; Marsh, 1989). The term D-type sills was introduced to distinguish bodies in which modal olivine contents tend to decrease towards the upper and lower margins in a roughly symmetrical manner (Gibb and Henderson, 1992). The name I-type sill (Marsh, 1996) is used for bodies showing little field, petrographic or geochemical evidence of differentiation and displaying neither well-developed cumulate zones or late-stage differentiates (Gunn, 1966; Froelich and Gottfried, 1988; Mangan and Marsh, 1992).

For the last few decades there have been several attempts to resolve the problem of the existence of sills with S-, D- and I-shaped compositional profiles (see discussion in Simkin, 1967; Gibb and Henderson, 1992; Marsh, 1996). Different mechanisms have been suggested to explain this phenomenon. Among them are a gravity-induced settling of crystals either carried at the time of emplacement (Gray and Crain, 1969; Fujii, 1974; Marsh, 1989) or newly-grown in the chamber (Frenkel' et al., 1988, 1989; Woster et al., 1990; 1993), flow differentiation (Komar, 1972; Marsh, 1996), the multiple injection of several magmas with different compositions (Gibb and Henderson, 1992; Czamanske et al., 1994; 1995), and the convective flux of refractory components into a crystal-liquid mush of the boundary layer during in situ differentiation (Tait and Jaupart, 1996). All of the aforementioned processes certainly work and, in some circumstances, can contribute to the final shape of compositional profiles. These processes can hardly, however, represent the major reasons for the appearance of sills with different compositional profiles because they are unable to provide the formation of basal and top reversals that represent remarkable compositional features of sills.

Adequate explanation for the nature of different compositional profiles in sills can be provided by the current model of in situ crystallization (Jaupart and Tait, 1995; Tait and Jaupart, 1996) provided it is combined with the thermogravitational model for the origin of basal and top reversals (Latypov, 2002). The in situ crystallization model can explain the origin of commonly observed S-, D-, and I-shaped compositional profiles in sills from a single pulse of phenocryst-poor parental magma. The model envisages that the complete section of a sill is composed of floor and roof sequences; the former comprises the Basal Zone and Layered Series, while the latter encompasses the Top Zone and Upper Border Series (Fig. 2). The lines of demarcation between the coupled units of the floor and roof sequences run through the crossover maxima. Basal and Top Zones represent the mirror images of Layered and Upper Border Series, respectively, and therefore are referred to as basal and top reversals. It is proposed that the formation of basal and top reversals takes place through the evolution of liquid boundary layers maintained out of equilibrium due to a temperature gradient imposed by cold country rock. The boundary layers tend toward a stationary non-equilibrium state that is attained when compositions and consequently the liquidus temperatures of melts composing boundary layers are adjusted to an imposed temperature gradient. Compositional adjustment is accomplished by transfer of high melting point components from the boundary liquid layer into the main magma body and low melting point components in the opposite direction. Mass transfer is provided by thermogravitational fractionation that combines Soret-induced diffusion across thin liquid boundary layers aided by vigorous thermal convection in the main magma body. Upon reaching the crossover maxima, Soret fractionation is no longer able to cause magma differentiation because of waning of the thermal gradient in the boundary layers. Therefore non-equilibrium conditions of formation of basal and top reversals give way to equilibrium conditions of crystallization of the Layered and Upper Border Series. During this period the liquid differentiation predominantly takes place through compositional convection in a mushy region of a floor crystal-liquid boundary layer.

The resulting shape of the compositional profile of the sill is dependent on two principle factors: (1) the magnitude of the initial temperature gradient (ΔT), which is established in liquid boundary layers after remelting of original chilled margins or/and heating of cold country rock and (2) the initial parental magma composition. Depending on the magnitude of ΔT in situ crystallization of phenocryst-poor parental magmas of the same composition can result in the appearance of the various modal and cryptic profiles. At an intermediate ΔT, the effective development of both compositional reversals provides the formation of D-shaped modal profiles characterized by a decrease in olivine content in a roughly symmetrical manner towards the upper and lower margins. At a relatively low ΔT, the less successful development of basal and top compositional reversals leads to production of the most common S-shaped modal profiles that are distinctive by having high concentrations of olivine near the base of the sills. A variety of S-shaped profiles with additional upper olivine-rich units, referred to as double-humped profiles, can also be produced under these conditions. The rather high ΔT prevents the growth of both compositional reversals and any liquid evolution in the chamber due to the very fast crystallization of the parental magma. This gives rise to the origin of the I-shaped modal and cryptic profiles, showing little evidence of chemical differentiation. The initial parental magma composition has a major impact on the shape of the modal profiles. The most favourable parental magmas for the formation of sills with S- and D-shaped modal profiles are of above-cotectic or, to a lesser degree, of cotectic composition. The sills forming from a near-eutectic composition parental magma are always roughly I-shaped in modal mineralogy, but can display S-, D-, and I-shaped cryptic profiles depending on the magnitude of ΔT. The advantage of the proposed mechanism is that it does not appeal to any external or accidental processes such as multiple magma emplacement, the initial amount of phenocrysts and their mode of distribution in the injected magma, or the ability of newly-formed crystals to settle, etc. All that is necessary to produce a specific shape of compositional profile is an appropriate temperature gradient imposed by cold country rock on liquid boundary layers of a phenocryst-poor parental magma of a certain composition.

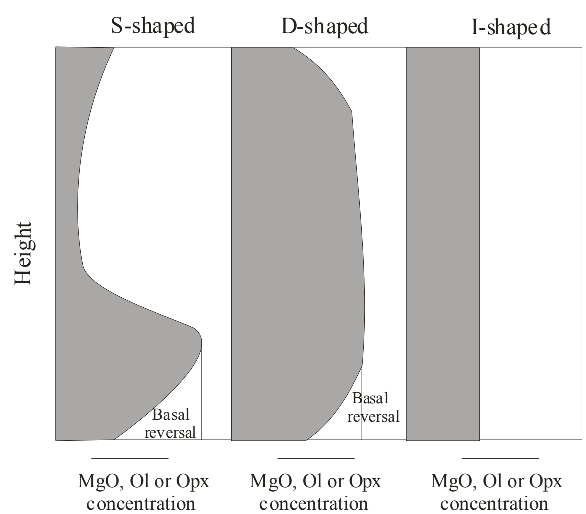

Figure 1. *Vertical compositional profiles of refractory component (MgO) and modal abundance of olivine or orthopyroxene in S-, D-, and I-shaped sills. Note well-developed basal reversals in the S and D-shaped sills.*

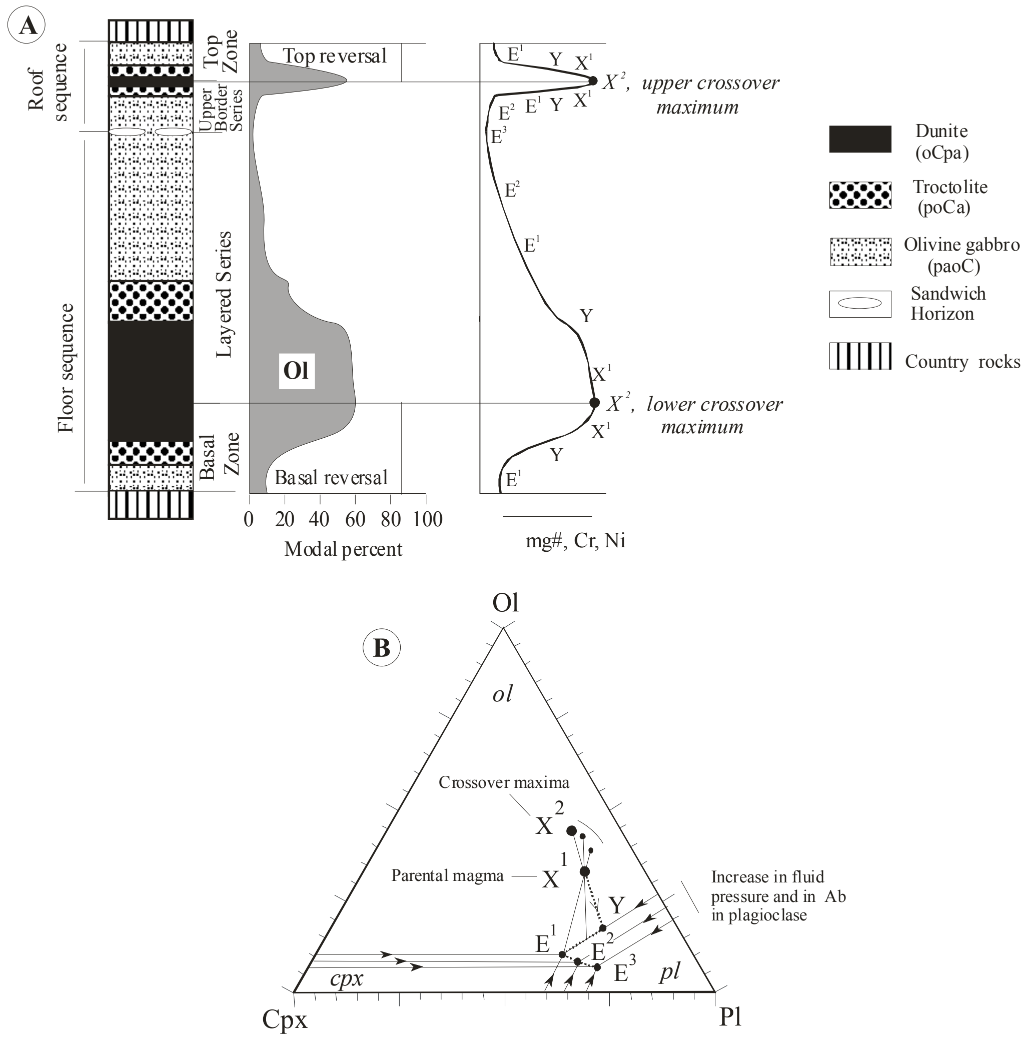

Figure 2. *A hypothetical basic-ultrabasic sill with a double-humped compositional profile (A). The sill is composed of floor and roof sequences that converge at the Sandwich Horizon. The floor sequence comprises the Basal Zone and Layered Series, while the roof sequence contains the Top Zone and Upper Border Series. The Basal and Top Zones represent the condensed compositional mirror images of the Layered and Upper Border Series, respectively, and are therefore referred to as basal and top reversals. The trend of crystallization of the parental magma X1 (B) can be traced using a silica-undersaturated system Ol-Pl-Cpx and letter abbreviations along the compositional profile of mg#, Cr and Ni in (A). The rock succession dunite, troctolite and olivine gabbro in the Layered and Upper Border Series is consistent with the expected trend of crystallization of the parental magma X1: Ol, Ol+Pl, Ol+Pl+Cpx. The trends of crystallization in the basal and top reversals are quite the opposite. The lower and upper crossover maxima (X2) marking the interior boundaries of the basal and top reversals exhibit the most primitive composition of minerals and rocks observed in the entire section of the sill. These arise due to progressive removal of low melting fractions from the initial composition X1 while it crystallizes the basal and top reversals along the path E1, Y, X1 (B). Progressive contraction (E1 , E2, E3) of the plagioclase field due to an increase in fluid pressure and sodic content of plagioclase during liquid fractionation is also shown.*