
Thermogravitational Fractionation as a Mechanism for the Formation of Basal Compositional Reversals in Basic-Ultrabasic Lavas, Sills and Layered Intrusions

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Much of our present understanding of the fractionation of basic magma is derived from the record of crystallization preserved in peculiar natural laboratories - basic-ultrabasic sills and layered intrusions. Despite a long period dedicated to their study they still contain a lot of enigmas one of which is the origin of so-called basal compositional reversals. These are a remarkable and common feature of many basic-ultrabasic sills (e.g., Gunn, 1966; Simkin, 1967; Froelich and Gottfried, 1988) and layered intrusions (e.g., Irvine, 1980; Campbell, 1978; Alapieti, 1982; Wilson and Engell-Sørensen, 1986). They also occur in some lavas and lava lakes (e.g., Moore and Evans, 1967; Bédard, 1987; Helz et al., 1989). The mystery of basal compositional reversals is that in terms of modal, phase and cryptic layering they represent a kind of mirror image of the overlying Layered Series. There are six distinctive features of basal compositional reversals in basic-ultrabasic sills and layered intrusions that impose strong constraints on any model for their formation. These are: (1) an apparent lack of mass balance between the lower part of basal reversals, including chilled margins, and the bulk composition of the intrusions, (2) phase crystallization sequences and (3) mineral compositional trends that are inverse to those in the overlying Layered Series, (4) cotectic composition of rocks composing basal reversals, (5) the capacity to form both from phenocryst-rich and phenocryst-free parental magmas, (6) the capability to develop along floor, subvertical walls and even on the roof of a magma chamber.

Critical review of the current models for magma differentiation (crystal settling, multiple magma injection, flow differentiation, compositionally zoned magma, in situ crystallization) reveals that none of them provide a universally adequate explanation for the mirror image of the basal compositional reversals. Their origin still remains uncertain. It is instructive therefore to summarize the most important constraints on the required mechanism for basal reversal formation (Fig.).

1. It is clear that the evolved composition of chilled margins, mineral crystallization sequen-

ces and trends of mineral composition, which are essentially the opposite of those in the overlying Layered Series, represent very common features of sills and layered intrusions and not just anomalous features. Such basal reversals are developed in igneous bodies regardless of their size and bulk composition. This strongly suggests that the Layered Series and their mirrors – basal reversals – in each specific intrusion are produced from the same parental magma (Wilson and Engell-Sørensen, 1986). Therefore any attempt to explain the universal features of basal reversals by appealing to some external and hardly predictable processes such as multiple magma emplacements will be ineffectual. This conclusion is also strongly supported by the occurrence of clearly defined basal reversals in many lava flows, which have crystallized as closed systems. Obviously the answer to the problem of the basal reversals must be found in the context of a model of a single magma pulse.

2. It is important that basal reversals are composed of rocks with a roughly cotectic composition. This suggests that they formed without any significant contribution from settling phenocrysts. This means that the magmas parental to mafic-ultramafic plutonic bodies generally contained only small amount of phenocrysts, which could not therefore have any significant impact on the formation of basal reversals. This is strongly supported by the occurrence of clearly defined basal reversals in several igneous bodies thought to have formed from phenocryst-free parental magmas. Thus the desired mechanism must be capable of producing basal reversals from phenocryst-free or phenocryst-poor parental magmas.

3. The reverse mineral crystallization sequences and cotectic composition of rocks in basal reversals strongly indicate their successive formation from magma compositions spanning, in reverse sequence, the liquid line of descent of the parental magmas. Whatever process is responsible for the formation of basal reversals, it must be able to produce such a column of liquid compositions from an initially homogeneous parental magma.

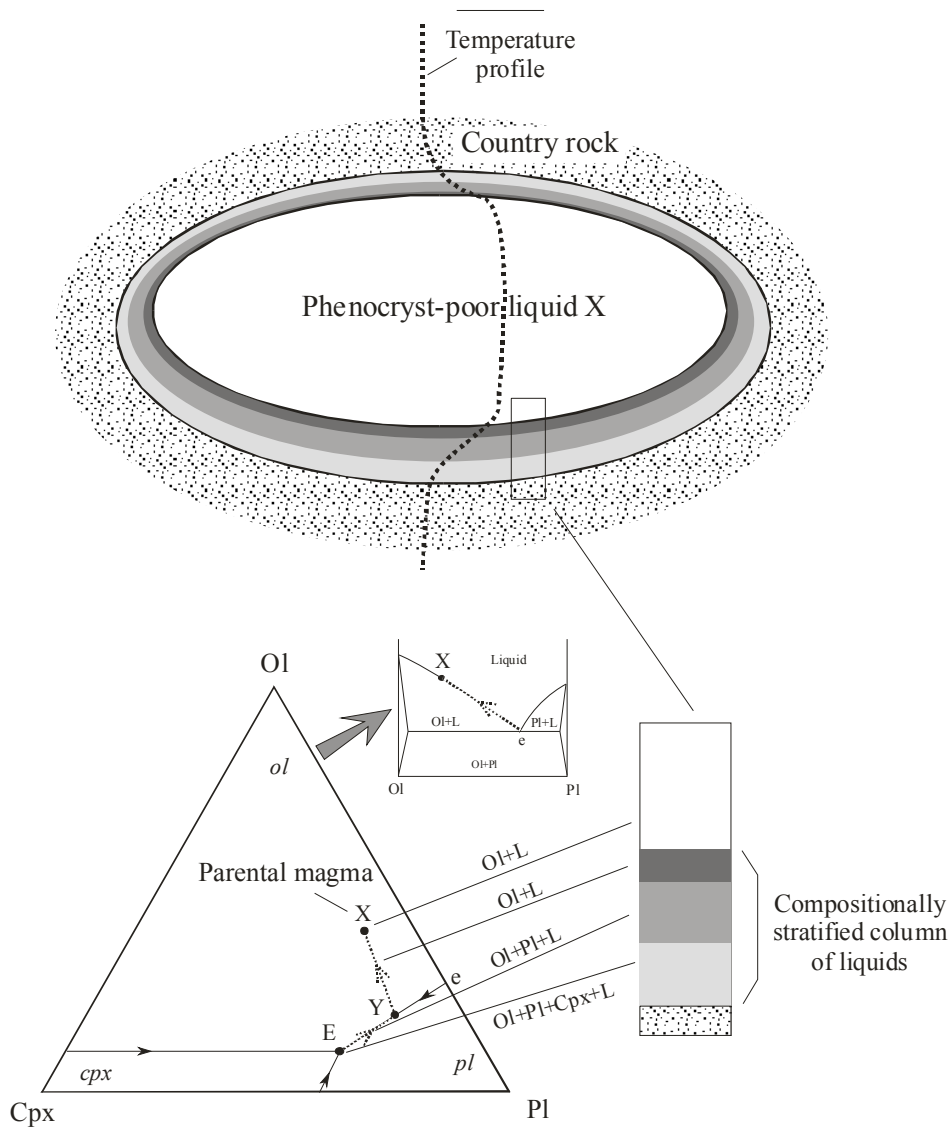


Figure 1. Schematic illustration of an idea that the physicochemical process required to explain the origin of compositional reversals must be capable of producing a column of liquids spanning in reverse sequence the liquid line of descent of the parental phenocryst-poor olivine-saturated magma X at the floor, walls and roof of magma chambers. This does not imply that the entire compositionally stratified liquid column is produced shortly after emplacement and exists until it crystallizes to a solid. Rather the column forms and crystallizes progressively during the juvenile stage of magma differentiation in the chamber.

4. The ability of compositional reversals to develop equally well along both subhorizontal and subvertical margins and even roofs of magma chambers significantly shortens the list of mechanisms that can be potentially responsible for their origin. In particular, such a popular mechanism as gravitational crystal-liquid differentiation can be safely excluded from this list. The required mechanism must be practically independent of gravitational forces.

5. The thermodynamic conditions of marginal rock crystallization are characterized by the occurrence of a significant temperature gradient that is imposed by cold country rock on hot magma at the chamber margins during its juvenile stage of evolution. It is therefore quite reasonable to suggest that it is the temperature gradient that is a driving force of the process responsible for the formation of compositional reversals.

To sum up, the process required to explain the origin of compositional reversals must be capable of producing a column of liquid spanning in reverse sequence the liquid line of descent of parental phenocryst-poor magma at the floor, walls and roof of magma chambers. For instance, for the parental magma X lying in a primary field of olivine in the system Ol-Cpx-Pl (Fig.), such a column must be composed of liquids following along the liquidus path Ol+Cpx+Pl+L (E), Ol+Pl+L (E-Y), Ol+L (Y-X), Ol+L (X). This does not imply, of course, that the entire compositionally stratified liquid column is produced shortly after emplacement and exists until it finally crystallizes to solid. Rather, the column forms and crystallizes progressively during the juvenile stage of magma differentiation in the chamber. The question which remains to be answered is what is the nature of this universal physicochemical process that causes liquid state separation ranging from the lowest temperature eutectic points through all intermediate lines and surfaces to an initial composition in the volume of one phase? One can safely reason that the only known process that is not dependent on gravity forces is diffusion. The only type of diffusion that can provide substantial chemical separation of initially homogeneous silicate liquids in a temperature gradient at chamber margins is Soret diffusion provided it is combined with vigorous thermal convection in the main magma body. The mechanism of magma differentiation combining the operation of Soret diffusion in thin liquid boundary layers at chamber margins and thermal convection in the main magma body is known under the name of thermogravitational fractionation (Hildreth, 1977, 1979, 1981). The hypothesis of thermogravitational fractionation was previously dismissed as an important agent for igneous petrogenesis due to a lack of convergence between the character of chemical fractionation in nature and laboratory Soret diffusion (Leshner and Walker, 1991). The analysis of the problem has shown, however, that this discrepancy is a quite reasonable consequence of constraints imposed on Soret fractionation in near-liquidus natural magmas by liquidus phase equilibria. Thermogravitational fractionation renewed by a new interpretation of the character of Soret fractionation in natural near-liquidus magmas was found to provide an adequate explanation for the origin of most basal compositional reversals.

The key proposal is that the formation of a basal reversal 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. The compositional adjustment is accomplished by the 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. The first liquid boundary layer formed at the chamber margins comprises liquid compositions spanning a nearly entire liquid line of descent of parental magma in reverse sequence. The nucleation and crystallization occurs predominantly in the stagnant lowermost regions of the boundary layers composed by the most evolved liquid compositions. Upon progressive decrease in magnitude of a thermal gradient related to the growing cumulus pile and an overall decrease in the temperature of the whole magma body, the compositional patterns of liquid boundary layers in a stationary state become more and more primitive. In this process the stagnant crystallizing region of liquid boundary layers progressively travels all the way along the liquid line of descent of the parental magma providing the formation of a basal compositional reversal. When a thermal gradient in the liquid boundary layer wanes the Soret fractionation becomes ineffective and is overwhelmed by compositional convection in the mushy region of the crystal-liquid boundary layer. At this point, referred to as a crossover maximum, the formation of the Basal Zone in non-equilibrium conditions is supposed to give way to the formation of the Layered Series in equilibrium conditions. Thus the fundamental explanation for the mirror image of a basal reversal is that the non-equilibrium Soret fractionation works in a manner distinctly opposite to that of the equilibrium crystal-liquid fractionation that produces the Layered Series.

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