Lithos 119 (2010) 181–192

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Melt-rich segregations in the Skaergaard Marginal Border Series: Tearing of a vertical silicate mush

M.C.S. Humphreys *, M.B. Holness

Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK

ARTICLE INFO

Article history:
Received 31 March 2010
Accepted 29 June 2010
Available online 8 July 2010

Keywords:
Skaergaard Intrusion
Wavy pyroxene rock
Segregations
Hot tearing
Cumulate
Marginal Border Series
Crystal mush

ABSTRACT

The Marginal Border Series (MBS) of the Skaergaard Intrusion crystallised on the steeply dipping sidewalls of the magma chamber. Melt-rich segregations, previously described as the 'wavy pyroxene rock' are a key feature of the otherwise homogeneous outermost parts of the MBS. The lens-shaped segregations consistently strike parallel to the chamber wall and have a moderate dip towards it. The shape, size, grain size and mineralogy of the segregations evolve systematically away from the chamber wall. The segregations become bigger, more widely spaced, chemically more evolved and more irregular in shape with increasing distance from the margin.

The segregations were previously interpreted as a nucleation effect parallel to the thermal gradient. However, they dip toward the margin, not parallel to it. We offer a new interpretation: that the segregations represent tearing of poorly consolidated crystal mush during localised sagging of the vertical solidification front. The tears form during a process analogous to 'hot tearing' of metal alloys, although the driving force for tearing is probably gravitational collapse of the vertical solidification front, or perhaps contemporaneous faulting during chamber filling. Small, regular tears formed in the thinner, more rapidly cooled outer parts of the MBS, while the larger, irregular tears formed in the coarser grained, inner parts. Movement of interstitial liquid fed the cracks after tearing, and the liquid crystallised as relatively evolved, coarse-grained segregations. The mineral chemistry and texture of the segregations suggest that the tearing occurs relatively early in the crystallisation history.

1. Introduction

Understanding the rheology of semi-solid rocks is important because it affects mechanisms of melt segregation during partial melting, controls the efficiency of compaction of melt-bearing rocks, and determines the response of partially crystalline magma to stress. In high-level magmatic systems, the mechanical behaviour of a developing crystal mush can influence differentiation processes, the nature of the resultant layering, and the ease with which partially solidified remnants of earlier magma batches are recycled by entrainment or mixing with younger magma, either as nodules or isolated crystals (e.g. Dungan and Davidson, 2004; Maclennan, 2008).

Layered intrusions represent the fully crystalline products of magmas that may have experienced many different physical and mechanical processes. The evolution of the melt-bearing mush can be difficult to discern in the fully solidified cumulates. However, melt-rich segregations provide a window into the mechanisms of late-stage melt migration in cumulates. Melt-rich segregations have been observed in a variety of settings, including thick basaltic lava flows (Puffer and Horter, 1993; Philpotts et al., 1996), alkaline intrusions (Carman, 1994), basaltic andesite intrusive complexes (Geshi, 2001), thick sills (Gunn, 1966; Marsh, 2002) and basaltic lava lakes (Helz, 1980; Marsh et al., 2008). Marsh (2002) discriminated between silicic segregations, which typically have sharp, coarsely crystalline upper contacts and gradational lower contacts, and non-silicic segregations, which tend to be coarsest in the centre and have gradational upper and lower contacts. However, these structures, interpreted as the residue of 25–75% *in situ* fractionation, are reported to have a range of textural characteristics, from sharp contacts on vertical veins (Geshi, 2001) or sub-horizontal sheets (Philpotts et al., 1996), to sub-horizontal sheets with sharp upper contacts and gradational lower contacts (Gunn, 1966; Carman, 1994; Marsh, 2002) or gradational upper and lower contacts (Puffer and Horter, 1993). The segregations may be vesicular or non-vesicular. Formation mechanisms typically involve either diapiric rise of interstitial melt from an advancing lower solidification front, or passive filtering of late-stage residual melt into macro-scale tears in the solidification front (see Fig. 1), but crystal mush compaction and shear deformation have also been proposed as viable mechanisms (Philpotts et al., 1996; Geshi, 2001). However, the behaviour of residual liquids in *vertical* crystallisation fronts has been almost completely neglected, and one might reasonably anticipate it to be different from that in horizontal fronts.

* Corresponding author. Tel.: +44 1223 333400; fax: +44 1223 333450.
E-mail address: mcsh2@cam.ac.uk (M.C.S. Humphreys).

0024-4937/$ – see front matter
doi:10.1016/j.lithos.2010.06.006

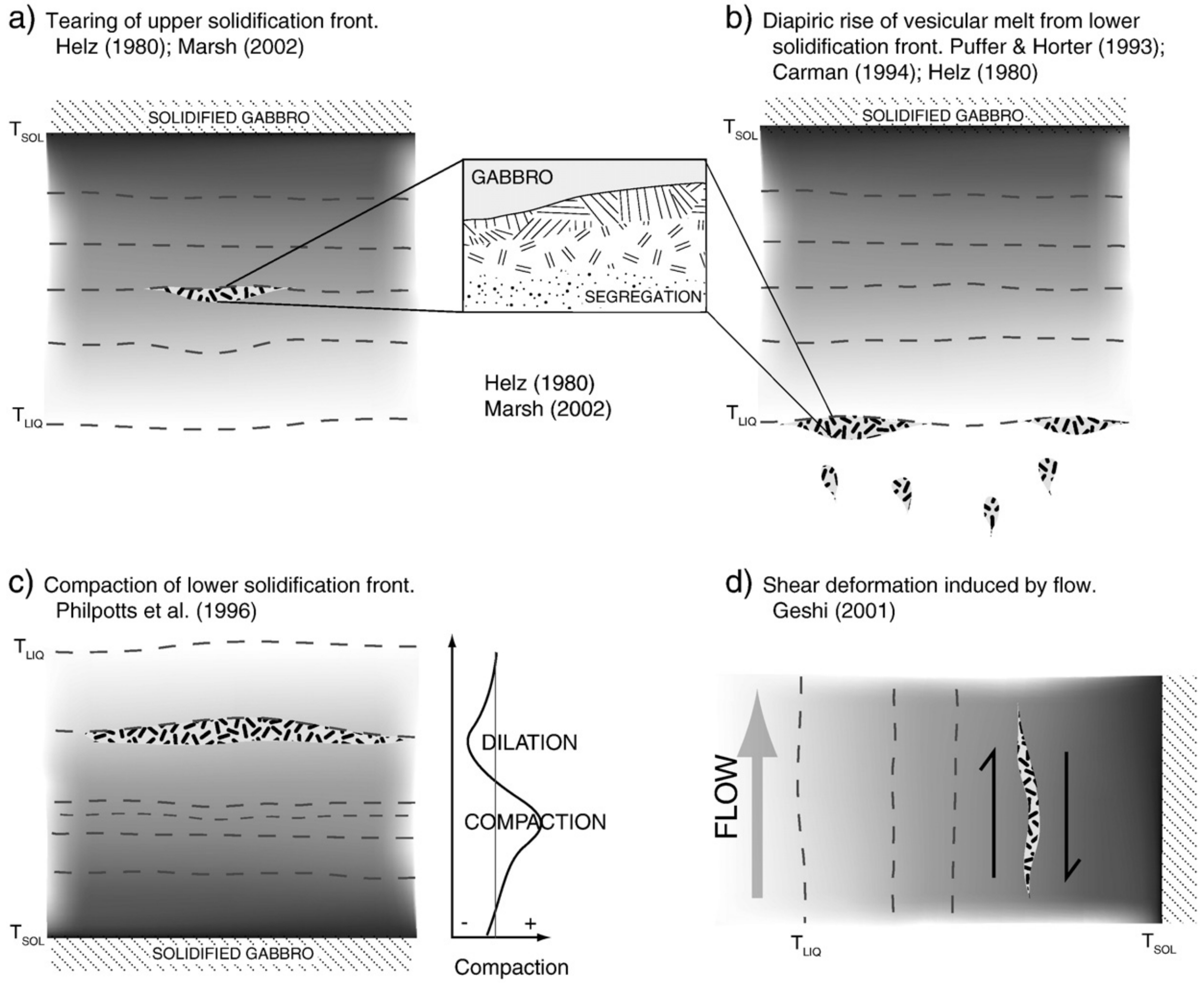

Fig. 1. Schematic figure showing mechanisms of formation of melt-filled segregations as described by previous authors.

In this contribution, we describe the structure, modal mineralogy and mineral compositions of the so-called wavy pyroxene rock (Wager and Brown, 1968) from the sub-vertical Marginal Border Series of the Skaergaard Intrusion, East Greenland. The Marginal Border Series is unusual in that it offers the opportunity to study progressive solidification in a km-scale intrusion in a system without the complication of compaction. The crystallisation environment is therefore significantly different compared with the compacting Layered Series cumulates on the chamber floor. Here we argue that the wavy pyroxene rock represents melt-filled segregations that formed by small-scale ductile tearing of the vertical crystal mush during partial and localised collapse, and are analogous to healed 'hot tears' in solidifying metal alloys.

2. Geological background

2.1. The Skaergaard Intrusion

The Skaergaard Intrusion, East Greenland, formed when essentially a single pulse of ~280 km^3 of tholeiitic magma intruded the upper crust at the contact between PreCambrian gneiss basement and the overlying Eocene plateau basalts (Tegner et al., 1998; Nielsen, 2004). The intrusion measures approximately 8 km × 11 km in plan view, and was tilted at a shallow angle towards the southeast by coastal flexure during the Lower Tertiary (Nielsen, 2004) such that approximately 3000 m of stratigraphy are now exposed. The intrusion underwent essentially closed-system fractional crystallisation, resulting in the accretion of a continuously evolving series of layered cumulates. The cumulates forming the intrusion are split into three series (Fig. 2): the Layered Series (LS) represents the biggest volume component, shows the most spectacular mineralogical layering and crystallised upwards from the floor; the Marginal Border Series (MBS) crystallised inwards on the steeply sloping sidewalls of the intrusion; and the Upper Border Series (UBS) crystallised downwards from the roof, meeting the LS at the poorly defined Sandwich Horizon (Wager and Brown, 1968). Each Series is divided into zones and sub-units on the basis of cumulate mineralogy: cumulus olivine is present in the Lower Zone (together with cumulus plagioclase in Lower Zone A (LZa), cumulus augite in LZb and cumulus Fe-Ti oxides in LZc), is absent in Middle Zone (MZ) and reappears again (but more fayalitic) in Upper Zone (with cumulus apatite in Upper Zone b (UZb) and cumulus ferro-bustamite in UZc). Cumulus pigeonite occurs locally in MZ, replacing olivine (Irvine et al., 1998). The LS also includes the Hidden Zone (HZ, cumulus olivine and plagioclase, essentially part of LZa), which comprises the unexposed parts of the stratigraphy. The MBS, which is the focus of this study, may be similarly subdivided according to cumulate mineralogy, with subdivisions labelled LZa*, LZb* etc. by Hoover (1989).

The continuous fractional crystallisation is also recorded in the cumulates as the gradual compositional change of the constituent minerals. For example, plagioclase composition varies from ~An_{70} in the Hidden Zone to ~An_{25} at the Sandwich Horizon, olivine varies from Fo_{74} to Fa_{100}, while clinopyroxene changes from $En_{80}Fs_{17}Wo_3$ in LZa to $En_{28}Fs_{57}Wo_{15}$ at the Sandwich Horizon (Brown and Vincent, 1963). The cumulates of the MBS are slightly different to those of equivalent stratigraphic levels in the LS, in that plagioclase is typically