Textural Maturity of Cumulates: a Record of Chamber Filling, Liquidus Assemblage, Cooling Rate and Large-scale Convection in Mafic Layered Intrusions

MARIAN B. HOLNESS1*, TROELS F. D. NIELSEN2 AND CHRISTIAN TEGNER3

1DEPARTMENT OF EARTH SCIENCES, UNIVERSITY OF CAMBRIDGE, DOWNING STREET, CAMBRIDGE CB2 3EQ, UK
2GEOLOGICAL SURVEY OF DENMARK AND GREENLAND, OSTER VOLDGADE 10, DK-1350 COPENHAGEN K, DENMARK
3DEPARTMENT OF EARTH SCIENCES, UNIVERSITY OF AARHUS, C. F. MOLLERS ALLÉ 110, DK-8000 AARHUS C, DENMARK

RECEIVED MARCH 14, 2006; ACCEPTED SEPTEMBER 4, 2006; ADVANCE ACCESS PUBLICATION NOVEMBER 14, 2006

Textural maturity describes the extent to which a rock has evolved from the initial reaction-controlled texture towards textural equilibrium controlled by the minimization of interfacial energy. Solidification in a magma chamber results in the formation of an impingement texture by the random juxtaposition of planar-sided grains. Orthocumulates, in which the initial melt-filled pores are pseudomorphed by later-crystallizing phases, have an ophitic or intersertal texture immediately after complete solidification, which then evolves towards solid-state equilibrium by rounding of initially planar grain boundaries and an increase in the median dihedral angle subtended at the junctions of two primocrystic grains with the interstitial phase. The bulk of the increase in angle occurs just below the solidus temperature in kilometre-scale mafic plutons. Quantification of textural maturity via measurement of dihedral angle populations in troctolitic and gabbroic cumulates from the Rum Eastern Layered Intrusion and the Skaergaard Intrusion demonstrates that the rocks preserve a record of thermal events related to magma chamber replenishment and the onset of chamber-wide convection. Textural maturity is also a function of the liquidus phase assemblage: for systems in which only olivine and plagioclase are liquidus (i.e. cumulus) phases in the main magma body above the crystal mush, the texture is significantly less mature than that in systems in which clinopyroxene is an additional liquidus phase. The difference in textural maturity reflects differences in the cooling and solidification rate, and demonstrates directly that the liquidus phase assemblage plays a role in determining the thermal history of plutons.

KEY WORDS: cumulates; dihedral angles; Rum; Skaergaard; textures

INTRODUCTION

The cooling of magmatic intrusions is a complex function of the temperatures of the magma and the environment in which it stalls, the thermal conductivity of the country rocks, the (evolving) convective regime of the magma, the action of hydrothermal convective systems (mainly for shallow-level plutons in fractured country rocks; e.g. Manning & Bird, 1991), crustal assimilation, and the release of latent heat of crystallization (Jaeger, 1964). During the crystallization of silicate magma the mineral assemblage on the liquidus varies with temperature and time and, in the early stages of solidification, commonly involves a series of increases in the number of crystallizing phases as the evolving liquid composition intersects new stability fields. In the classical model of magmatic intrusions these liquidus phases are distinguished by their cumulus status (e.g. Wager et al., 1960), and hence...
the changes in liquidus assemblage can be identified via petrographic observation (e.g. Wagner & Brown, 1968).

As a consequence of liquid compositional evolution, the latent heat released during crystallization will change in a stepwise fashion in tandem with the tracking of the liquid composition across a phase diagram in an appropriate system. A simple example of this is the burst of latent heat release accompanying crystallization at the eutectic in a simple binary system (such as sphene-anorthite; Prince, 1943), after a relatively slow release accompanying the crystallization of a single liquidus phase. Thus, in the case of a crystallizing magma, given that all the other variables such as convective regime and thermal conductivity remain constant, the cooling, or solidification, rate should change in response to changes in the liquidus assemblage in the main body of the magma.

In this contribution we show that such changes can be detected in fully solidified mafic plutons using the record of time-integrated cooling history preserved at grain junctions in orthocumulates (defined loosely as rocks in which originally melt-filled pore spaces in a framework of relatively early-formed primocrysts are pseudomorphed by interstitial phases). We provide not only direct evidence for a (partial) control of cooling rate by latent heat of crystallization, but also a method of identifying changes in the liquidus assemblage that is not reliant on the sometimes ambiguous textural distinction between cumulus and non-cumulus status (e.g. McBirney & Hunter, 1995; McBirney, 1998; Morse, 1998).

Precise textural identification of the stratigraphic level at which cumulus phases first appear is pivotal to constraining progressive changes of magma composition during solidification. For example, the debate over whether the Skaergaard magma evolved to iron- or silica-rich end-members is often thought to hinge on the role of cumulus magnetite (Hunter & Sparks, 1987; Brooks & Nielsen, 1990; McBirney & Nashlund, 1990; Topleis & Carroll, 1996; Tegner, 1997), although the level of the first cumulus clinopyroxene in the Lower Zone may be equally important. This is because the SiO$_2$ content of a cumulus assemblage with plagioclase, olivine and clinopyroxene exceeds that of a cumulus assemblage of only plagioclase and olivine, with potentially major consequences for the subsequent evolution of magma composition.

We also show that orthocumulate textures can preserve detailed thermal information that can be related to the history of chamber filling; this is used to demonstrate for the first time that the early history of the Skaergaard Intrusion of East Greenland involved chamber filling by a succession of magma pulses, rather than by a single pulse.

**TEXTURAL MATURITY**

In addition to constant mean curvature for all grain boundaries and interfaces (Thomson, 1887; Bulau et al., 1979), the relative orientations of grain boundaries and interfaces at three-grain contacts in a fully texturally equilibrated poly-crystal are also controlled by the relative magnitudes of the interfacial energies via the equation

\[ \sum_{i=1}^{3} \left( \gamma_i t_i + \frac{\partial \gamma_i}{\partial t_i} \right) = 0 \] (1)

where \( \gamma_i \) are the interfacial energies, \( t_i \) is the vector in the plane of the \( i \)th surface, normal to the line of intersection of the surfaces and pointing away from this line, and \( \frac{\partial \gamma_i}{\partial t_i} \) is a vector perpendicular to \( t_i \) and to the line of intersection (Herring, 1951). Equation (1) defines the orientation of the interfaces at a three-grain junction or a pore corner. For the specific case of a three-grain, two-phase, contact (such as that between two grains of plagioclase and one of pyroxene), or a two-phase contact between two grains of solid and a liquid, the angle defined by equation (1) is known as the dihedral angle.

The tangential component of equation (1) acts to minimize the interfacial area, whereas the normal component acts to rotate the interface towards an orientation with a lower interfacial energy. Hence, in general, the dihedral angle varies with crystalline orientation (Herring, 1951; Laporte & Provost, 2000). For isotropic systems, in which the interfacial energy is constant regardless of the orientation of the interface, the normal term vanishes. The resultant simplified form of this equation, applicable only to isotropic systems, was first presented by Smith (1948):

\[ \gamma_{gb} = 2 \gamma_i \cos(\Theta/2) \] (2)

where \( \gamma_{gb} \) is the energy of the grain boundary, \( \gamma_i \) is that of the interface between the two phases, and \( \Theta \) is the dihedral angle.

Textural equilibrium is seldom attained in coarse-grained poly-mineralic silicate rocks (e.g. Hunter, 1987). Apart from examples such as granoblastic hornfelses in close proximity to the contact of large intrusions, and some mafic intrusions (e.g. Fig. 1b) the great majority of well-equilibrated, poly-mineralic, coarse-grained rocks are granulites (e.g. Vernon, 1968). Hence, for the most part, poly-mineralic cumulate rocks are far from textural equilibrium. However, it is possible to turn this general textural disequilibrium of cumulate rocks to our advantage by considering the extent to which they have approached textural equilibrium.

During solidification the solid grains assume growth-controlled shapes, commonly resulting in planar faces (Fig. 1a). Grain accumulation to form a crystal mush at the chamber floor, either by settling or by in situ growth, tends to result in random juxtaposition of the solid grains to form an impingement texture (Elliott et al., 1997; Holness et al., 2005). If there is no further solidification, the initial impingement texture will evolve, driven by
Fig. 1. (a) A schematic representation of the texture formed by the accumulation of planar-sided crystals (grey is liquid, white is solid), together with a photomicrograph of interstitial texture in a crystalline nodule in an Icelandic basaltic lava, in which the melt-filled pores in the framework formed by plagioclase laths are pseudomorphed and infilled by clinopyroxene. Plane-polarized light. (b) A schematic representation of a texturally equilibrated two-phase rock in which the minor phase forms isolated, rounded, grains (indicative of a high dihedral angle, shown as Θ in the inset) at three- and four-grain junctions, together with a photomicrograph of a layered olivine gabbro, Bretchow Complex, Sierra Leone. Harker collection (Cambridge) number 143462. The rounded shape of the minor phase (spinel) and a close approach to sub-solidus textural equilibrium should be noted. Partially crossed polars. (c) Schematic indication of the topology of melt in a texturally equilibrated silicate (for which the dihedral angle is 540°; Holness, 2006a), together with a photomicrograph of an olivine cumulate from Rum, Scotland (plane-polarized light). In this cumulate, the original, texturally equilibrated, melt-filled porosity has been pseudomorphed by clinopyroxene. Partial textural re-equilibration in the sub-solidus has resulted in the rotation of large areas of the grain boundary in the immediate vicinity of the three-grain junction towards higher angles.
the minimization of internal energies, towards the equilibrium texture in which the fluid-filled pores develop constant mean curvature and the equilibrium value of the melt–solid–solid dihedral angle (Fig. 1c).

However, this process is arrested in fully solidified cumulates by further crystallization, which infills the pore space, commonly pseudomorphing the melt-filled porosity (e.g. Platten, 1981; Harte et al., 1991; Holness & Clemens, 1999; Sawyer, 1999, 2001; Rosenberg & Riller, 2000; Holness, 2003; and Fig. 1a). These interstitial grains inherit the initial angle subtended at the pore corners, which is somewhere on the continuum between an impingement texture (median value ~60°) and a completely equilibrated melt–solid–solid angle (~10°), Holness, 2006a and references therein). These angles are much lower than the median solid–solid angles for poly-mineralic silicate rocks, which are 100–130° (from measurements in granulite-facies metamorphosed mafic rocks; Kretz, 1966; Vernon, 1968, 1970; Holness et al., 2005). The sub-solidus evolution of the orthocumulate texture (loosely defined as in the introduction) must therefore involve not only grain boundary migration to achieve constant mean curvature of all boundaries and interfaces, but also a general increase in the angle subtended at the corners of pseudomorphed pores (Fig. 1b and c). Here we introduce the concept of textural maturity to describe the extent to which a rock, either melt-bearing or fully solidified, has evolved from the initial texture formed by reaction (or, in the particular case of cumulates, solidification) towards textural equilibrium.

The quantification of progressive changes in grain boundary curvature presents a challenging problem, but it is straightforward to quantify the changing dihedral angle because the evolution of relative grain boundary orientation at two-phase contacts is achieved by the rotation of large areas of grain boundary in the manner of an opening or closing door (Fig. 1c; Holness et al., 2005). Because a range of possible angles is formed by the random juxtaposition of grains in the initial impingement texture and, similarly, a (smaller) range of angles is present in the equilibrated system (as a result of the finite amount of interfacial anisotropy in silicate minerals, e.g. Kretz, 1966; Laporte, 1994; Lupulescu & Watson, 1999), it is essential to measure a population of angles in three dimensions using a universal stage. Typically, the progression of the impingement texture towards textural equilibrium involves an increase of the median (and mean) of such a population from ~60° (with a standard deviation of ~25°) towards one of ~120° (and a standard deviation of ~15°) (Holness et al., 2005). Because the change in angle involves mass migration by diffusion, textural maturity of orthocumulates provides an indication of the time-integrated thermal history in the sub-solidus.

A detailed study of olivine–olivine–pyroxene dihedral angles in single clinopyroxene oikocrysts enclosing large numbers of olivine grains in a peridotite from the Isle of Rum demonstrated a significant difference in angle populations in the centre of the oikocrysts compared with the edges (Holness et al., 2005). The central regions have markedly higher angles compared with the edges, which have angle populations close to those plausibly inherited from the original melt-bearing olivine mush. This shows not only that the process of textural maturation occurs on a timescale commensurate with that of solidification and pyroxene growth, but importantly that the effective closure temperature for textural maturation and angle change is very close to the solidus for kilometre-scale mafic intrusions. Hence the extent of textural maturity, as measured by the angles subtended by interstitial phases, provides information about processes occurring at or near the magma–mush interface.

In this contribution we demonstrate that significant changes in textural maturity accompany changes in the liquidus assemblage, and thus show for the first time that cumulates record changes in their solidification rate associated with changing rates of latent heat release during crystallization, and with chamber filling and replenishment events.

**GEOLOGICAL EXAMPLES**

**Skaergaard, East Greenland**

The Skaergaard Intrusion forms part of a group of gabbroic and syenitic bodies found in East Greenland and formed during the opening of the Atlantic at about 55 Ma (Deer, 1976; Brooks & Nielsen, 1982; Tegner et al., 1998). It formed by the shallow-level intrusion of a large (9 km × 11 km × 4 km, Nielsen, 2004) body of relatively evolved tholeiitic basaltic magma at the contact between underlying Precambrian gneisses and an overlying ~2 km thick sequence of Tertiary plateau lavas (Fig. 2a). Once the chamber was filled, it fractionated as a closed system to form the prime example of shallow magmatic differentiation.

Tilting of the eastern coast of Greenland by about 20° (Wager & Brown, 1968; McBirney, 1996), associated with regional stretching, has resulted in the almost continuous exposure of >3.5 km of stratigraphy, which dips gently to the SE. The intrusion has been divided into three major units: the Layered Series, formed on the floor of the intrusion; the Marginal Border Series, crystallized inwards from the walls; and the Upper Border Series, which grew downwards from the roof (Fig. 2a). The Layered Series is subdivided into Lower, Middle and Upper Zones by the disappearance of abundant primary olivine at the base of Middle Zone and its reappearance at the base of the Upper Zone. The Lower Zone is further divided into three sub-zones: LZA in which
The cumulus phases are olivine and plagioclase; LZb, the base of which is marked by the appearance of cumulus clinopyroxene; LZc which is marked by the appearance of cumulus Fe–Ti oxide minerals. For further details of the intrusion see the study by McBirney (1996), from which this account was drawn.

The division between LZa and LZb was originally defined as the change from poikilitic to granular habit of the clinopyroxene, which is clearly visible in outcrop and was assumed by Wager & Brown (1968) to indicate the onset of clinopyroxene crystallization as a liquidus phase. This division was placed at the 200 m level by Wager & Brown (1968), and at 180 m by McBirney (1989). These stratigraphic heights are relative to a zero point defined by Wager & Deer (1939) as the lowest exposed level in the Layered Series. However, there is dissent over whether this textural change actually reflects the arrival of clinopyroxene on the liquidus. For example, at the location of the 1966 Cambridge drill core (Fig. 2b), Nwe (1976) placed the onset of clinopyroxene crystallization in the main body of magma (i.e. as a cumulus phase, rather than as a phase grown in the more evolved interstitial liquids in the mush) at a stratigraphic height of 110 m, 70–90 m lower than the field-based textural change, on the basis of clinopyroxene grain shape.

The results reported here pertain to the lower part of the Layered Series: LZa, LZb and the Hidden Zone, which is the lowermost unexposed region. Samples comprise three separate suites. The first is a set of samples collected in 2000 along a traverse of the exposed stratigraphy (Fig. 2b) and accurately located using the global positioning system (GPS). The second is the 1966 Cambridge drill core (drilled by W. A. Deer and G. A. Chinner; Fig. 2b). This 349 m long core, which begins in LZb [defined according to McBirney (1989)], penetrates the Hidden Zone and represents the only currently available material.
from the unexposed region of the intrusion. The zero point of the stratigraphy in the drill core was placed by Maaloe (1976), on the basis of plagioclase compositions, at a depth of 199 m. Maaloe (1976) also suggested, again on the basis of plagioclase composition, that the deepest part of the core is close to the floor of the intrusion.

The third set of samples was collected by L. R. Wager and W. A. Deer during the original 1936 expedition. These samples are housed in the Oxford Museum of Natural History and in the Harker Collection of the University of Cambridge, and were reported by Wager & Deer (1939). As a result of cartographic inaccuracies these samples are not located sufficiently well to permit direct comparison with the other two sample suites, but were used to assess the extent of the features discussed here.

**Rum, Inner Hebrides, Scotland**

The Tertiary intrusion of Rum intruded at 60.53 ± 0.08 Ma (Hamilton et al., 1998) and at <0.5 kbar (Holness, 1999) into Precambrian arkose of the Torridonian Group in the east, and into an earlier granite in the west. Early activity on Rum was dominated by acid magmatism, with a granitic body intruded during doming and uplift within a ring fault. Subsequent caldera-forming collapse was followed by further central uplift and emplacement of a layered series of ultramafic and mafic rocks. The current outcrop of the Rum Layered Suite extends over an ellipsoidal area 10 km × 5 km (Fig. 3a), and the periodically replenished magma chamber is believed to have been sill-like, with a magma depth of perhaps 200 m overlaying a considerable crystal pile (Emeleus et al., 1996). For greater detail of the geological history, and for the primary published sources of this information, the reader is referred to Emeleus et al. (1996) and Emeleus (1997).

The Rum Layered Suite, which is a focus of the present study, comprises olivine cumulates (feldspathic peridotites), troctolites and gabbros (known collectively by the local term allivalite), and is divided into a Western, Central, and Eastern Layered Intrusion. The Eastern Layered Intrusion comprises 16 macro-units [defined originally as a set of 15 by Brown (1956) with an additional unit added by Volker & Upton (1990)], each comprising a lower peridotite and an overlying allivalite (Fig. 3b), although in detail the upper, allivalitic, parts of the macro-units contain many minor peridotite layers (Emeleus et al., 1996). The alternating rock types resulted from crystal accumulation on the chamber floor from a sequence of magma injections into the Rum chamber. The majority of these periodic replenishments were by picritic liquids (Upton et al., 2002), although some were basaltic (Renner & Palacz, 1987).

For the present study we concentrate on samples that are petrologically closest to the LZa and LZb of Skaergaard—such rocks on Rum are the allivalites. The allivalites of the Eastern Layered Intrusion can be divided into two groups: those from Units 10 and below have clinopyroxene as a cumulus phase, in addition to olivine and plagioclase (and are hence approximately equivalent to LZh on Skaergaard); those from Units 11 and above have only olivine and plagioclase as liquidus phases (and are approximately equivalent to LZa and the Hidden Zone of Skaergaard).

In contrast to many of the other major peridotite layers in the Eastern Layered Intrusion, that of Unit 9 is an intrusive body (Butcher et al., 1985; Bédard et al., 1988; Holness, 2005), forming a series of discontinuous lenses (Fig. 3b) within a single, thick (~45 m), original allivalite body that was divided into two by Brown (1956). A true picture of the thermal history of this unit, called Unit 8/9 by Holness (2005), is gained from regions distant from the intrusive peridotite. In this study we refer to the results of Holness (2005), Traverse f (Fig. 3b).

Unit 10 was given the status of type unit by Brown (1956), by virtue of its excellent exposure. His sample set from the (20 m thick) allivalite is labelled b in Fig. 3b, and we refer to the results of Holness (2005) for these samples. We have made an additional, incomplete, traverse across the Unit 10 allivalite, labelled c in Fig. 3b.

A new traverse across the ~40 m thick Unit 14 allivalite at the summit of Hallival (labelled c in Fig. 3b) has been collected at the same place as that of Renner & Palacz (1987). These workers have shown that Unit 14 can be divided into six sub-units on the basis of modal mineralogy, olivine Ni content and Sr isotope ratios, and suggested that the Unit 14 allivalite records two separate injections of basaltic magma into the chamber, together with physical disturbances and slumping related to the intrusion of picrite within an unconsolidated troctolitic mush forming the top 5 m or so of the Unit.

The final traverses considered here are the two traverses of Unit 12 described by Holness (2005), although she erroneously ascribed them to Unit 11. These are shown as b' and c' in Fig. 3b, cover about 17 m of stratigraphy, and are separated along strike by 120 m.

**ANALYTICAL METHODS**

Following the metallurgists, who pioneered work in this field using opaque materials, geologists have generally measured dihedral angles using a conventional, flat-stage, optical microscope or by analysis of images generated by scanning electron microscopy. This method relies on measuring a population of angles on a randomly oriented two-dimensional section through the material. For samples with a single-valued dihedral angle the median of a population of these angles is within 1° of the true three-dimensional angle (Harker & Parker, 1945; Riegger & Van Vlack, 1960). For other samples, including those with any anisotropy of interfacial energy and incompletely
equilibrated samples, sophisticated statistical techniques are required to constrain the true range of angles (e.g. Jurewicz & Jurewicz, 1986). This problem can be neatly circumvented by the use of the universal stage on an optical microscope (Kretz, 1966; Vernon, 1968, 1970, 1997; Holness, 2005, 2006a; Holness et al., 2005) which permits the direct measurement of almost every angle in a thin section.

We used a four-axis Leitz universal stage, mounted on a James Swift microscope. We measured between 30 and 100 angles in each sample (30 for the most part), with a magnification of ×320, of the junction of interstitial clinopyroxene and framework-forming primocrystic plagioclase (the clinopyroxene–plagioclase–plagioclase dihedral angle, or \( \Theta_{cpp} \)). The error on each measurement is of the order of a few degrees.

Following Holness (2005) and Holness et al. (2005) we report the medians of the population for each sample. In contrast to the median of a population of dihedral angles measured in a randomly oriented, two-dimensional section through a polycrystal of an isotropic material, which has a clear significance, the median of a nonequilibrated polycrystal has no special meaning relative to that of other statistical measures, such as the mean for example. However, it is a useful measure of the extent of textural equilibrium when compared with the median of a fully equilibrated sample. The error on the median of the population of measurements from each sample is hard to constrain, but because the median remains within a few degrees for an increasing population once the number of measurements exceeds about 20, we consider that the error on the median value is of the order of ±2°.

PETROGRAPHY

Skaergaard

The lower parts of the Skaergaard Intrusion sampled by the 1966 Cambridge drill core are gabbroic troctolites and gabbros. Rounded grains of cumulus olivine are present throughout the core in variable amounts. The main framework-forming phase is plagioclase, which comprises subequant to elongate grains with random orientations or a weak foliation. In the lowermost 180 m of the core, many grains have oscillatory-zoned cores, or complex cores with evidence of corrosion and further growth (Fig. 4a; for details, see Maaløe, 1976). These are absent in the higher parts of the core (Maaløe, 1976). Plagioclase grains with high aspect ratio may be bent, with deformation twins, suggestive of compaction (Fig. 4b; Hunter, 1996): these are uncommon in the lowest parts of the core but become common above about 50 m stratigraphic height.

Pyroxene (augite ± inverted pigeonite) forms interstitial wedges and oikocrysts, the edges of which may have local, late-stage, replacement and overgrowth by brown amphibole (Fig. 4c). Pyroxene commonly forms irregular, monomineralic, rims surrounding cumulus olivine, and sometimes also around adjacent grains of Fe–Ti oxides (Fig. 4d). These rims [the ‘fungus texture’ of Hunter (1967)] have been ascribed to some kind of reaction with the olivine (e.g. olivine + melt = orthopyroxene; Nwe, 1976), but the clinopyroxene rims are more likely to be primary pseudomorphs of a melt phase (Holness, 2005). In the higher parts of the core, pyroxene grains...
Fig. 4. (a) Sample 118737, Skaergaard LZA, drill core, stratigraphic height ~1241 m. Crossed polars. Framework-forming plagioclase grains have low aspect ratio and only a very weak preferred orientation. Clinopyroxene is interstitial. The grain labelled A has a complex core, with a central oscillatory zoned region with irregular margins, a further zone of oscillatory zoning but this time with planar growth faces, and a final, non-zoned, adcumulus growth phase. The two grains labelled B have complex, non-oscillatory zoned cores. Scale bar represents 0.5 mm. (b) Sample 118599, Skaergaard LZb, drill core, stratigraphic height 864 m. Crossed polars. The elongate plagioclase grain crossing the centre of the image shows kinking and deformation twins consistent with compaction. The plagioclase grain immediately overlying it has an adcumulate outer growth zone. The large, compact, cumulus, clinopyroxene grains should be noted. Scale bar represents 0.5 mm. (c) Sample 118726, Skaergaard LZA, drill core, stratigraphic height ~99.7 m. Interstitial clinopyroxene infilling an impingement texture formed by a framework of planar-sided plagioclase grains. The localized replacement (arrowed) and overgrowth of the pyroxene by brown amphibole should be noted. The arrowed dihedral angle is showing outwards grain boundary rotation in response to textural maturation (see Fig. 1c). Scale bar represents 100 µm. (d) Sample 118726, Skaergaard LZA, drill core, stratigraphic height ~99.7 m. Two cumulus olivine grains partially replaced by a symplectite of Fe–Ti oxide and orthopyroxene. The more compact, interstitial, grains of Fe–Ti oxides, as well as the olivine, are partially rimmed by brown amphibole, which directly replaces an original clinopyroxene rim. The small patches of brown mica adjacent to the Fe–Ti oxide grains should also be noted. Scale bar represents 100 µm. (e) Troctolitic allivalite from Unit 12, Rum Eastern Layered Intrusion. The clinopyroxene infilling an impingement porosity defined by the framework-forming plagioclase grains, and forming monocryssalline continuous rims around cumulus olivine grains, should be noted. Scale bar represents 100 µm. (f) Gabbroic allivalite from Unit 10, Rum Eastern Layered Intrusion, Harker collection number 79257. A weak magmatic foliation is defined by preferred alignment of low aspect ratio cumulus clinopyroxene and rarer olivine grains (labelled o). Scale bar represents 0.5 mm.
(again both augite±inverted pigeonite) are still strongly interstitial or poikilitic in character, but have a large, equant, compact core. The transition from a dispersed to a more compact form occurs at about 100 m stratigraphic height in the 1966 drill core (Nwe, 1976), although it is not well defined.

Other interstitial phases (present throughout the core) include magnetite, ilmenite and apatite. Apatite commonly fills the actual corners of pores otherwise pseudomorphed by pyroxene, consistent with its position as a late phase and indicating trapping of melt in the cumulus pile. Iron–titanium oxide grains commonly are rimmed by brown mica and, where in contact with cumulus olivine, the olivine may be replaced by a symplectite of oxide and orthopyroxene (Fig. 4d).

**Rum**

Allivalites from the upper parts of the Eastern Layered Intrusion contain slightly elongate, rounded to sub-equant, cumulus olivine grains, scattered and rare, euhedral to equant, Fe–Ti oxide grains, and elongate grains of plagioclase. The olivine and plagioclase display a preferred orientation, forming an igneous lamination. This lamination is best developed in regions poor in olivine, and tends to wrap around large isolated olivine grains. Diopsidic clinopyroxene forms small interstitial wedges between the plagioclase grains (Fig. 4c). These wedges form groups in optical continuity extending over many (up to 10) plagioclase grain lengths, and pseudomorph an original impingement porosity (Holness et al., 2005). Clinopyroxene also forms thin, monomineralic, rims surrounding olivine grains (Fig. 4c). These rims are both more extensive and of a more uniform thickness in comparison with the Skaergaard rims. Orthopyroxene is absent.

Although parts of the allivalites from the lower parts of the Eastern Layered Intrusion may closely resemble those from the upper parts, they also contain layers with variable quantities of cumulus, equant, primocrystic clinopyroxene (Fig. 4f). Cumulus pyroxene may form >50 vol.% of some (gabbroic) allivalites, and (cumulus) olivine is generally rare in such pyroxene-rich gabbros. Large (up to 1 cm diameter), pyroxene oikocrysts are present locally, and these contain randomly oriented plagioclase grains, which are smaller than those outside the oikocryst.

Many of the Rum allivalites also contain minor layers of feldspathic peridotite (Renner & Palacz, 1987; Emelius et al., 1996). These are dominated by rounded olivine grains, which form a well-equilibrated ‘bubble-like’ texture in monomineralic regions, but are generally set in a coarse-grained plagioclase matrix. Clinopyroxene forms rare oikocrysts, up to 5 mm in diameter, and even rarer rims around olivine grains. It is not possible to measure clinopyroxene–plagioclase–plagioclase dihedral angles in the most olivine-rich of these layers.

**DIHEDRAL ANGLE POPULATIONS**

**Skaergaard**

The median values of $\theta_{cpp}$, measured every 3–5 m in the 1966 Cambridge drill core, are shown in Fig. 5 as a function of stratigraphic height. The drill core can be divided, on the basis of $\theta_{cpp}$ into several different zones. The lowest region has low $\theta_{cpp}$ whereas the rest of the Hidden Zone has a series of irregular peaks in $\theta_{cpp}$ relative to a baseline value of 80–85°. This irregularity disappears after a prominent dip in $\theta_{cpp}$ at a stratigraphic level of ~30 m, and $\theta_{cpp}$ remains at a constant and well-defined range of 80–85° until 100 m. Here the median $\theta_{cpp}$ increases rapidly over <1 m to a new range of 100–105°.

Also shown in Fig. 5 are the median values of $\theta_{cpp}$ from the sample traverse across the exposed region of the Lower Zone. These samples show exactly the same pattern as the drill core, with not only the large step in $\theta_{cpp}$ but also the second-order variations. The direct correspondence between the two sample sets is reinforced in Fig. 2b. The large step in the surface sample traverse occurs where one would predict it to occur, using the orientations of the igneous layering measured at the surface (McBurney, 1989) and dips of 25–30°. This large step in $\theta_{cpp}$ (textural maturity), and thus change in the time-integrated thermal history, is therefore likely to be an intrusion-wide event. A corollary of this is that the second-order variations in $\theta_{cpp}$ may also be intrusion-wide.

The samples collected by Wager and Deer follow the same patterns, with low angles in the lowermost samples adjacent to the Marginal Border Series, and high angles in samples collected further away. Because of sparse sample coverage and difficulties in accurate location it is not possible to make a more direct comparison, although this sample suite reinforces the interpretation that there are chamber-wide variations in $\theta_{cpp}$.

**Rum**

The median values of $\theta_{cpp}$ have already been presented for the allivalites of Units 8/9, 10 and 12 by Holness (2005) and the results, normalized with respect to the thickness of each allivalite horizon (the data for each are spaced every metre or so) are shown in Fig. 6. They show that the median $\theta_{cpp}$ remains constant (within a range of $\pm 3^\circ$) where the allivalite is unaffected by either infiltration of late-stage liquids or heating by incoming replenishing magma (Holness, 2005). The baseline level is ~90° for Units 8/9 and 10, but ~82° for Unit 12. Within each traverse in Units 8/9 and 10 the baseline level does not change with small length-scale changes in lithology: interlayered gabbroic and troctolitic allivalites show the same baseline level of textural maturity. Holness (2005) interpreted
this to mean that the outer parts of cumulus grains represent post-cumulus, \textit{in situ}, overgrowth, and pseudo-morphed the vestigial porosity.

The median $\Theta_{\text{cpp}}$ of the new traverse of Unit 14 is shown in Fig. 7a. This has a baseline level of 80–85$^\circ$, with excursions to higher values at stratigraphic heights of 2, 18, 29 and 36 m [the base of the allivalite is placed at the first arrival of cumulus plagioclase, and lies 1 m above that of Renner & Palacz (1987)], and an excursion to lower angles at the base of Traverse f.

Holness’s (2005) results from Unit 10 pertain to a traverse collected by Brown (1956), and they differ significantly from a new, incomplete, traverse of the same unit from slightly further east (Figs 3b and 8a).
Median $\Theta_{cpp}$ varies between 77° and 88° for the new samples, with a positive correlation with the modal clinopyroxene content (Fig. 8b). A further correlation is between median $\Theta_{cpp}$ and the form of the clinopyroxene. Median $\Theta_{cpp}$ in samples in which clinopyroxene forms oikocrysts is in the range 86–89° [measured only on the edges of oikocrysts; see Holness et al. (2005)], whereas that in samples in which clinopyroxene forms much less extensive interstitial grains is 77–86°. With only two exceptions, samples with cumulus clinopyroxene have median $\Theta_{cpp}$ of 86–89°. Of these exceptions one has very rare cumulus grains of clinopyroxene, whereas the other has abundant cumulus clinopyroxene confined to a thin layer on one side of the section (the other part of the section, in which pyroxene is interstitial, contains only 1 vol.% clinopyroxene, and it is this value that is plotted in Fig. 8b).

**INTERPRETATION**

The dihedral angle populations measured in the cumulates of both Rum and Skaergaard are not in textural equilibrium. A fully equilibrated population of clinopyroxene-plagioclase-plagioclase grain junctions should have a median value of $\approx 115^\circ$ (reported median values range from 109 to 120°; Vernon, 1968, 1970; Holness, 2005). All the medians reported here are lower than this. Hence the departure of the median from the equilibrium value provides information about textural maturity and thus about the time-integrated thermal history.

The concept of textural maturity and the observation of incomplete establishment of the equilibrium dihedral angle at the junctions of interstitial phases in cumulates are both very recent and, in the absence of firm experimental information on the rates of textural equilibration in silicates, interpretation of the extent of textural maturity must be qualitative. However, previously published studies of the Rum allivalites can be used for comparative purposes, and permit interpretation of both the new Rum data and those from Skaergaard. We will show that the extent of textural maturity can reveal information about chamber filling processes,
the initiation of chamber-wide convection, and the phase layering in progressively fractionating cumulate piles.

**Chamber filling**

Holness (2005) suggested that for cumulates forming under steady-state conditions on the chamber floor, with a constant rate of upwards movement of the solidification front, the time-integrated thermal history will be constant for any individual horizon within the cumulate pile, leading to a constant median $\Theta_{cpp}$ throughout. With reference to the previously published results of Holness (2005) for Units 8/9, 10 and 12 of Rum, a normal variation of $\Theta_{cpp}$ within such a constantly accumulating mush is $\pm 3^\circ$ (perhaps as a result of errors in accurate determination of the median, together with minor fluctuations of time-integrated thermal history). The signature of a replenishing, hot, primitive magma above the cumulate pile on the chamber floor is a steep increase in median $\Theta_{cpp}$ within a few centimetres of the contact (Holness, 2005).

The median $\Theta_{cpp}$ in the Unit 14 allivalite shows four peaks, demonstrating a significant input of heat and a slowing of the solidification rate at stratigraphic heights of 2, 18, 29 and 36 m. The lower two of these events correspond to major excursions of Sr isotope ratios, which were interpreted by Renner & Palacz (1987) as the result of influx into the chamber of relatively uncontaminated, mantle-derived, basalt (Fig. 7b). We therefore interpret the lower two peaks as the thermal record of magma chamber replenishment.

The third peak lies just above the base of Renner & Palacz's third subdivision of the Unit 14 allivalite, the disturbed troctolite, which contains a minor, intrusive peridotite horizon believed to be an extension of the overlying Unit 15 peridotite (Renner & Palacz, 1987). The allivalite immediately overlying this subsidiary peridotite also has elevated median $\Theta_{cpp}$ (Fig. 7a). Although the increase in Sr isotope ratios towards the top of the Unit 14 allivalite is enigmatic, with no obvious explanation, the abundance of layers rich in olivine, together with an increase of both Fo and Ni values in olivine with increasing height led Renner & Palacz (1987) to suggest that the disrupted troctolite was strongly affected by mixing with the subsidiary peridotite. The thermal history information preserved in the highly variable textural maturity in the disrupted troctolite is consistent with localized effects of mixing with hot invading liquids.

Although the contact between the overlying Unit 15 peridotite and the top of the Unit 14 allivalite is exposed and was sampled, there is no increase in median $\Theta_{cpp}$ in the uppermost allivalite. This is in contrast to the top of Unit 8/9 and Unit 10 (Holness, 2005) where the thermal signature of the hot replenishing picritic liquid is preserved. Given the probable intrusion of this replenishing liquid into the underlying mush (to account for the disruption in the troctolites) it is unlikely that the absence of a positive $\Theta_{cpp}$ excursion relates to a turbulent mixing of the incoming magma with the resident magma, rather than the formation of a ponded layer. We currently have no explanation for this apparent anomaly.

By comparison with the interpretation of Holness (2005) and the evidence from Unit 14 we can now interpret the Skaergaard 1966 Cambridge drill core. The regions of almost constant median $\Theta_{cpp}$ in the drill core signify times of relative stasis and steady-state conditions in the Skaergaard chamber. The varying textural maturity below +30 m stratigraphic height, as measured by median $\Theta_{cpp}$ demonstrates that there were significant changes in the time-integrated thermal history during the early history of this intrusion.

The low median values of $\Theta_{cpp}$ at the base of the drill core indicate a relatively rapid cooling rate in the sub-solidus, consistent with the end of hole being close to the floor of the intrusion (e.g. Maaloe, 1976). We interpret this region as the basal chill zone.

The series of irregular peaks of $\Theta_{cpp}$ in the Hidden Zone, ending at +30 m stratigraphic height, indicates a number of thermal events in the mush developing on the chamber floor. This part of the stratigraphy contains plagioclase grains with complex, corroded and recrystallized cores, which disappear above a stratigraphic height of +30 m (Maaloe, 1976). In other magmatic systems, such corroded and complex cores are generally attributed to chamber recharge and magma mixing. With reference to the peaks of similar magnitude in median $\Theta_{cpp}$ in Unit 14 of the Rum Eastern Layered Intrusion, which correlate directly with magma replenishment, we suggest that the variations in $\Theta_{cpp}$ in the Hidden Zone are recording a prolonged history of successive episodes of magma influx and chamber filling. The Skaergaard chamber thus did not become closed to major inputs of magma until the lower part of the exposed stratigraphy.

**The onset of chamber-wide convection**

The Skaergaard drill core records a further exception to steady-state conditions (indicated by median values varying by only $\pm 3^\circ$), with a pronounced region of low median $\Theta_{cpp}$ between 25 and 45 m stratigraphic height. This low median value suggests a period of relatively rapid sub-solidus cooling, for which there is no direct analogue in the Rum allivalites. The 25–45 m region of the Skaergaard stratigraphy is characterized by: (1) a series of discontinuities in the layering [N. Irvine, personal communication reported by Maaloe (1987)]; (2) a discontinuity in the trend of the average plagioclase composition (with a stepwise decrease from An_{66} to An_{63}); (3) an average plagioclase composition ($\sim$An_{64})
corresponding to that of the edge of the Tranquil Zone of the Marginal Border Series (Maaloe, 1976).

Developing the original suggestion of Wager & Brown (1968) that convection began in the lower parts of Lower Zone, Maaloe (1987) suggested that these features were the result of the onset of chamber-scale convective currents at this level. A sudden increase in cooling rate as evidenced by the decreased $\Theta_{cpp}$ is consistent with the arrival of a large crystal-laden body of cool material derived from an unstable thermal boundary layer at the chamber roof. It is tempting to interpret the features at 25–45 m stratigraphic height as a record of the onset of large-scale convection shortly after the last batch of incoming magma had arrived.

**Effects of phase layering on textural maturity**

Returning now to the part of the Skaergaard drill core in which steady-state conditions are likely to have pertained, i.e. that part lying above a stratigraphic height of +45 m, we must now address the step-change in $\Theta_{cpp}$ and textural maturity that occurs at +40 m. We think that the key to understanding this again lies in a comparison with the data from Rum.

The time-integrated thermal history of a cumulate pile, and hence the baseline, steady-state, value of median $\Theta_{cpp}$ depends on the solidus temperature of the system and the rate of heat loss to the surroundings. The liquid compositions from which the Rum allivalites crystallized were plausibly basaltic, and similar to that from which the lower parts of the Skaergaard Intrusion formed. The temperatures of formation, and thus the solidus temperature, are therefore likely to be very similar. The depth of intrusion of the Skaergaard and Rum chambers was very similar (Lindsley et al., 1969; Holness, 1999), and the horizontal dimensions of the two chambers are also similar. However, the Skaergaard chamber is an order of magnitude larger in the vertical dimension than the sill-like Rum chamber (Emeles et al., 1996), suggestive of a significantly slower cooling rate in the former compared with the latter. However, the highly fractured basaltic roof of the Skaergaard chamber resulted in the development of an extensive hydrothermal system (Norton & Taylor, 1979; Bird et al., 1988; Manning & Bird, 1991), whereas that of Rum was probably not so well developed (e.g. Greenwood et al., 1992). Additionally, the Rum system was kept hot by repeated replenishment of the chamber whereas the Skaergaard chamber was probably closed to major inputs of fresh magma after LZA times. We therefore suggest that although the liquid-filled part of the Rum chamber was probably less than 1/20 of the depth of Skaergaard it may have cooled on a comparable timescale. First-order comparisons of the extent of textural maturity of the Rum allivalites and the Skaergaard Lower Zone are, therefore, probably valid.

The baseline median of Rum allivalites, reported by Holness (2005), is ~90° in Units 8,9 and 10 whereas that in the allivalites of Units 12 (Holness, 2005) and 14 (this study) is ~82°. Although the units higher in the cumulate pile are certainly closer to the roof of the intrusion at the present time, we do not believe that their relative textural immaturity reflects a greater cooling influence of the Earth’s surface. This is both because it is likely that subsidence of the crystal pile resulted in a fairly constant depth of crystallization throughout the growth of the Eastern Layered Intrusion, and also because the change in median $\Theta_{cpp}$ is abrupt and not gradual. Instead, we suggest that the difference in textural maturity is linked to the liquidus assemblage.

Allivalites from Unit 10 and below, associated with a relatively high median $\Theta_{cpp}$, contain cumulus clinopyroxene, whereas those from Units 11 and above have only olivine and plagioclase as cumulus phases, and are associated with a relatively low median $\Theta_{cpp}$. A correlation between $\Theta_{cpp}$ and the textural status of clinopyroxene is also evident in the new sample suite from Unit 10 (Fig. 8c). Low angles tend to be associated with interstitial clinopyroxene, whereas cumulus grains (with two exceptions, which will be discussed below) and oikocrysts tend to be associated with higher angles. A plausible interpretation of this correlation is that the liquidus assemblage affects the sub-solidus thermal history of an accumulating crystal pile by a control on the rate of cooling. The mechanism by which it achieves this is by changing the relative contribution of cooling and the latent heat of crystallization to the intrusion’s total heat loss budget. In our model we assume that the intrusion has a constant rate of heat loss to the surroundings. In practice, the rate of heat loss is controlled by the temperature gradient, which decreases with time. However, an assumption of constant heat loss over short time intervals is permissible.

Such an assumption, based on a steady state in which hydrothermal convection is well established (although we neglect the effects of latent heat of reaction in the metamorphic aureole), requires a constant cooling rate. When the rate of crystallization (in terms of vol.% or mass% crystallized per °C of cooling) is increased by the addition of phases to the liquidus assemblage, the amount of latent heat released increases. In a system in which the total heat loss budget remains constant, this must be accompanied by a decrease in the cooling rate. Hence, the change from a two-phase liquidus assemblage to a three-phase liquidus assemblage results in an increase in the rate of accumulation of crystals on the chamber floor as a function of time and a slower rate of cooling, i.e. a greater time-integrated temperature in the sub-solidus for each subsequent layer in the accumulating mush, and a stepwise increase in
the textural maturity. The 10° increase in baseline median $\Theta_{cpp}$ between Units 8/9 and 10 compared with Units 12 and 14, and the 20° increase in Skaergaard Lower Zone at a stratigraphic height of 101 m thus reflect the presence of clinopyroxene as a liquidus (i.e. cumulus) phase in the main magma body in addition to olivine and plagioclase.

An illustration of the changing rates of crystallization can be provided using simple calculations and the results of experimental determinations of the liquid line of descent of the Skaergaard magma.

Using the composition of sample M9, a picritic dyke believed to be a plausible parental magma composition for Rum (McClurg, 1982; Upton et al., 2002), calculation of the increase in solid fraction during cooling was performed using the program MELTS (Ghiorso & Sack, 1995; Asimow & Ghiorso, 1998) assuming a pressure of 200 bars, $fO_2$ at QFM (quartz-fayalite-magnetite; Upton et al., 2002) and bulk equilibrium crystallization. Albeit with this very simple calculation, and a hugely oversimplified model, Fig. 9 demonstrates that the arrival of plagioclase and then clinopyroxene on the liquidus of the Rum crystallizing system both result in a significant increase in the rate of crystallization for each increment of cooling. For a cooling magma chamber, additional phases joining the liquidus assemblage result in a reduction in the cooling rate and a stepwise increase in textural maturity.

Interestingly, this calculation also shows that clinopyroxene arrives as a liquidus phase only a few degrees below the arrival of plagioclase, perhaps explaining the prevalence of gabbros in the lower units of the Eastern Layered Intrusion, and suggestive that M9 is not a plausible composition for the replenishing magma for higher units. This is corroborated by a significant difference in the Mn content of olivine between the upper and lower parts of the Eastern Layered Series (M. B. Holness, unpublished data). However, the modal mineralogy and bulk compositions of the upper units are sufficiently similar to those of the lower units that we consider the latent heat argument sufficient to explain the changes in baseline median $\Theta_{cpp}$.

Experimental determination of the liquid line of descent for a range of plausible Skaergaard liquids (Thy et al., 2006) demonstrates that the rate of crystallization (measured in weight% per °C temperature decrease) of each phase remains relatively constant after its appearance on the liquidus within the range of temperatures applicable to the Lower Zone. This means that the arrival of clinopyroxene as a liquidus phase results in a 30% increase in the rate of crystallization. Although the difference is not as marked as that shown in Fig. 9 it is still a significant change in the rate of crystallization and we believe that it was sufficient to change the baseline median $\Theta_{cpp}$ from ~0° to ~102°.

**DISCUSSION AND CONCLUSIONS**

Key to our proposed direct correlation between solidification rate and baseline value of median $\Theta_{cpp}$ are the new data from Unit 10 in Rum. These data demonstrate the change in sub-solidus thermal history resulting from clinopyroxene joining the liquidus paragenesis in the main body of the magma. Importantly, however, this sample set contains two samples that are apparently anomalous—they have cumulus clinopyroxene, but with a low median $\Theta_{cpp}$ rather than the high median that should result from a three-phase liquidus paragenesis. If we are correct in our interpretation, then the cumulus clinopyroxene in these two samples was out of equilibrium in the parent liquid. It is possible that these grains (and there are only a few grains in each sample on the thin-section scale) were derived from elsewhere (see Tepley & Davidson, 2003). Their uncorroded margins may reflect the fact that the magma in this region of the chamber was very close to saturation with all three phases and so the interstitial liquid in the mush rapidly evolved onto the three-phase cotectic. We suggest that the new Unit 10 samples are from a region of the chamber in which the magma composition hovered around the three-phase cotectic, sometimes on the olivine-plagioclase cotectic, and sometimes with clinopyroxene as an additional liquidus phase, changing in response to small-scale convective processes.

A corollary of our interpretation of the new Unit 10 samples is that the Unit 10 allivilite, and hence the magma chamber within which it formed, was highly heterogeneous along strike. Significant along-strike variations in major element compositions in Units 8/9 and 10 have already been pointed out by Holness (2006b).
However, the new results suggest that the magma composition during the formation of Unit 10 may have varied significantly enough to have a different liquidus assemblage in different parts of the sill-like chamber, and over metre-scale stratigraphic distances. The Unit 10 allivinite is thus a truly transitional unit (at least in places), between the lower units with clinopyroxene on the liquidus, and the upper units with only olivine and plagioclase as liquidus phases.

A further corollary of our interpretation is that median $\Theta_{cpp}$ can be used to constrain whether clinopyroxene oikocrysts are interstitial (forming within the crystal mush once the interstitial liquid is sufficiently evolved) or cumulus (in the sense of forming either in the main magma body and accumulating on the chamber floor, or nucleating in the early stages of mush development while the mush was still highly porous). Such distinctions can have important implications for our understanding of nucleation and crystal growth rates and their control by undercooling (e.g. Mathison, 1987; Tegner & Wilson, 1995). Figure 8c suggests that the poikilitic clinopyroxene of the Rum Unit 10 samples grew early as a cumulus phase. In contrast, poikilitic grains in the lower part of the 1966 Skaergaard drill core were later and interstitial, although they became cumulus at higher levels in the stratigraphy once clinopyroxene had joined the liquidus in the main body of magma.

A recent debate on the usefulness of the cumulate paradigm centred on the interpretations of textures in a Skaergaard rock purportedly from LZa (McBirney & Noyes, 1979; McBirney & Hunter, 1995; Morse, 1998). It was these rocks, formed by plagioclase grains enclosed by oikocrystic clinopyroxene, that Wager et al. (1960) considered the best examples of orthocumulates. Morse (1998) pointed out that these so-called LZa rocks must include significant quantities of cumulus pyroxene, as the rocks are so pyroxene-rich, and thus actually belong to LZb [as defined according to Wager & Brown (1968)]. This was also the view of McBirney (1998). Determination of the median value of $\Theta_{cpp}$ would confirm whether clinopyroxene was a liquidus phase, in the absence of chemical data, with no ambiguity related to the grain-scale shape of the crystals.

The currently accepted, easily mappable, position of the LZa-b boundary, as originally defined by Wager & Brown (1968), is marked by the cessation of poikilitic clinopyroxene growth. Wager & Brown (1968) assumed that this change to a granular habit marked the onset of clinopyroxene growth as a cumulus phase. However, the new results show that the onset of clinopyroxene nucleation and growth in the main magma body is extremely well-defined and unambiguous (although not detectable using either conventional petrography or field-based observations), occurring over a distance <1 m, some 80 m lower in the stratigraphy than the change in habit [in agreement with the suggestion of Nwe (1976)]. Future models of the liquid line of descent in Skaergaard should assume that clinopyroxene is a cumulus phase in much of LZa, despite its poikilitic habit.

Variations in textural maturity can be used as a sensitive thermal probe. The stepwise change in $\Theta_{cpp}$ related to the incoming of clinopyroxene as a liquidus phase in the 1966 drill core not only demonstrates that plutons exert some control on their cooling rate via the rate of crystallization, but also has the potential to reveal further information about the accumulating crystal pile on the chamber floor. Although the closure temperature for textural maturation in this system is not yet well constrained, it is clear that the temperature gradient in the solidifying pile was steep, given the abrupt change in $\Theta_{cpp}$ with stratigraphic height.

Because $\Theta_{cpp}$ changes in response to changes in cooling history, variations in textural maturity can be used to detect magma recharge events, even if the replenishment is by hotter magma of similar major element composition (but a different H$_2$O content) to that already present in the chamber (leading to an indistinct chemical signature in the resultant cumulates; e.g. Renner & Palacz, 1987). The new data show that the Skaergaard chamber filled over a period of time, with a series of pulses of magma. That this has not previously been seen can be attributed to the chamber being essentially closed in the exposed part of the stratigraphy. Although there are a series of small peaks in the upper reaches of the 1966 drill core (Fig. 5) it is likely that these represent only small inputs of magma or variations in the convective regime within a closed chamber.

ACKNOWLEDGEMENTS

We are grateful to Monica Price for facilitating access to material held by the Oxford Museum of Natural History, and to Hans Jepsen (of the Geological Survey of Denmark and Greenland) for re-calibrating the topographic map of the Skaergaard area to permit accurate sample location. The Danish Lithosphere Centre is thanked for supporting fieldwork at Skaergaard in 2000. C.T. acknowledges support from the Danish Natural Science Research Council. Annett Moenicke helped with the Unit 14 sampling. M.B.H. acknowledges support from the Isaac Newton Trust and helpful discussions with Michael Carpenter, Dan McKenzie and Mike Bickle. Helpful and constructive reviews by Jens Andersen, Richard Naslund and Ron Vernon helped clarify aspects of the original manuscript.
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