JOURNAL OF PETROLOGY | VOLUME 55 | NUMBER 12 | PAGES 2403 2418 | 2014 | doi:10.1093/petrology/egu061

Plagioclase Fractionation in Troctolitic Magma

S. A. MORSE*

DEPARTMENT OF GEOSCIENCES, UNIVERSITY OF MASSACHUSETTS, 611 NORTH PLEASANT STREET, AMHERST, MA 01003-9297, USA

RECEIVED MARCH 29, 2014; ACCEPTED OCTOBER 14, 2014
ADVANCE ACCESS PUBLICATION NOVEMBER 13, 2014

Troctolitic intrusive rocks poor in augite are common in certain Proterozoic anorthosite complexes and related rocks. The Lower Zone of the Kiglapait intrusion, Labrador, consists of ~1570 km^3 troctolite today and possibly ~2900 km^3 before erosion. In this augite free Lower Zone, plagioclase fractionation is as low as 1·6% An km $^{-1}$ of cumulate thickness and averages 3% An km $^{-1}$. When augite crystal lizes after 84% of the magma has crystallized, the fractionation be comes as much as 17% An km $^{-1}$ of cumulate. Why such a difference? It is clear from first principles of phase equilibria that fractionation accelerates with saturation in augite, but not so clear that the difference should be so great. The answer is to be found in the silica poor nature of troctolitic magma that is critically undersaturated in silica. This low silica effect reduces the activity of the NaSi albite component rela tive to the CaAl anorthite component in the plagioclase, thereby favor ing the An component of the liquid and crystals and weakening the fractionation process. As the normative augite component in the magma rises from the base of the Lower Zone to the base of the Upper Zone, the activity of silica also rises slightly and its consequent effect on plagioclase composition tends to diminish. Liquid fraction ation paths derived from observed crystal paths, when plotted in the system Diopside Anorthite Albite, rise across the liquidus fraction ation lines toward diopside and reach augite saturation near the 1 atm cotectic. They produce plagioclase compositions 10 mol % higher in An than pure liquidus fractionation lines predict. The key criterion for the troctolitic fractionation of plagioclase composition is the absence of Ca poor pyroxene from the rocks. Noritic magmas, by contrast, have higher activities of silica and more effective fractionation of plagioclase. A parallel fractionation of olivine is also retarded in the Lower Zone by the accumulation of ferric iron in the liquid until augite and titanomagnetite crystallize in the Upper Zone.

KEY WORD: *plagioclase fractionation; troctolite melts; silica activity; layered intrusions; Kiglapait intrusion*

INTRODUCTION

Troctolite is not an uncommon rock, depending on where you look. Troctolite of age 4·3 Ga is one of the oldest rocks on the Moon (Nyquist *et al.*, 2012), and the freshest trocto lite sample in captivity. Troctolite of age 1·3 Ga is the major component of the Kiglapait intrusion in Labrador (Morse, 1969). Other occurrences of troctolite abound in the Nain Plutonic Suite (Ryan, 1990; Morse, 2006), in the Sept Iles intrusion (Namur *et al.*, 2010), in the Duluth Complex of Minnesota (Miller & Ripley, 1996) and at the base of the Skaergaard intrusion, East Greenland (Wager & Brown, 1967), among many others. Despite the moderate abundance of this simple rock composed mainly of plagio clase and olivine, the notion of troctolitic liquids has been occult in the imagination of many petrologists, for whom oceanic basalt is a reference point. However, there is much evidence in the field for the existence of troctolite melts, especially in the snowflake troctolite of the Hettasch intrusion (Berg, 1980) in which a very hot mela troctolite magma invaded a troctolite magma and was quenched to a remarkable variety of plagioclase textures derived from supercooling. Granitic magmas engulfing troctolite magma to form giant troctolite pillows in the Newark Island intrusion were vividly described by Wiebe (1988).

*Corresponding author. Fax: 413-545-1200 E-mail: tm@geo.umass.edu

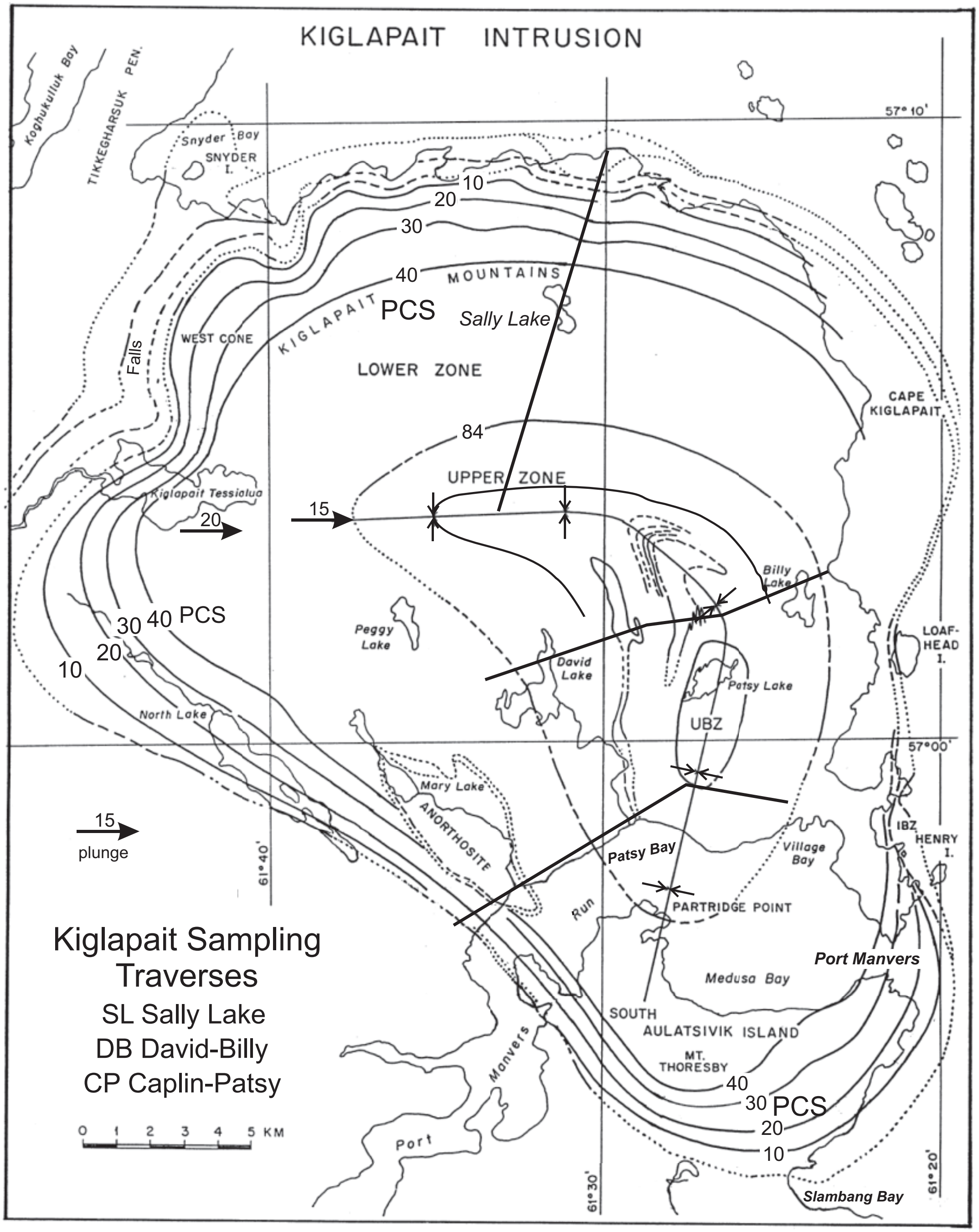

Fig. 1. Sketch map of the Kiglapait intrusion with sampling traverses. The traverse maps have been shown by Morse (1979*b*). The contours are those of volume per cent solidified (PCS) and are based on the strike of layering and the volumes of 13 cross-sections described in the original *GSA Memoir* (Morse, 1969). Plunge values of layering are shown in the western part of the synclinal axis; these show shallowing plunges that limit the probability that the steepness of layering has increased during subsidence: the layering seen must have been within 15° of the present dip. MOB, Main Ore Band at 93·5 PCS.

The matter of troctolitic magmas comes particularly into focus in the Kiglapait intrusion (KI), where an estimated 84% of the intrusion volume is troctolite of the Lower Zone (Fig. 1). This large body (initially $>3500\ km^3$; Morse, 1969) is notable for its very small variation in plagioclase composition in the Lower Zone (Fig. 2), raising the question of multiple injections of fresh magma or some other effect of slow compositional evolution.

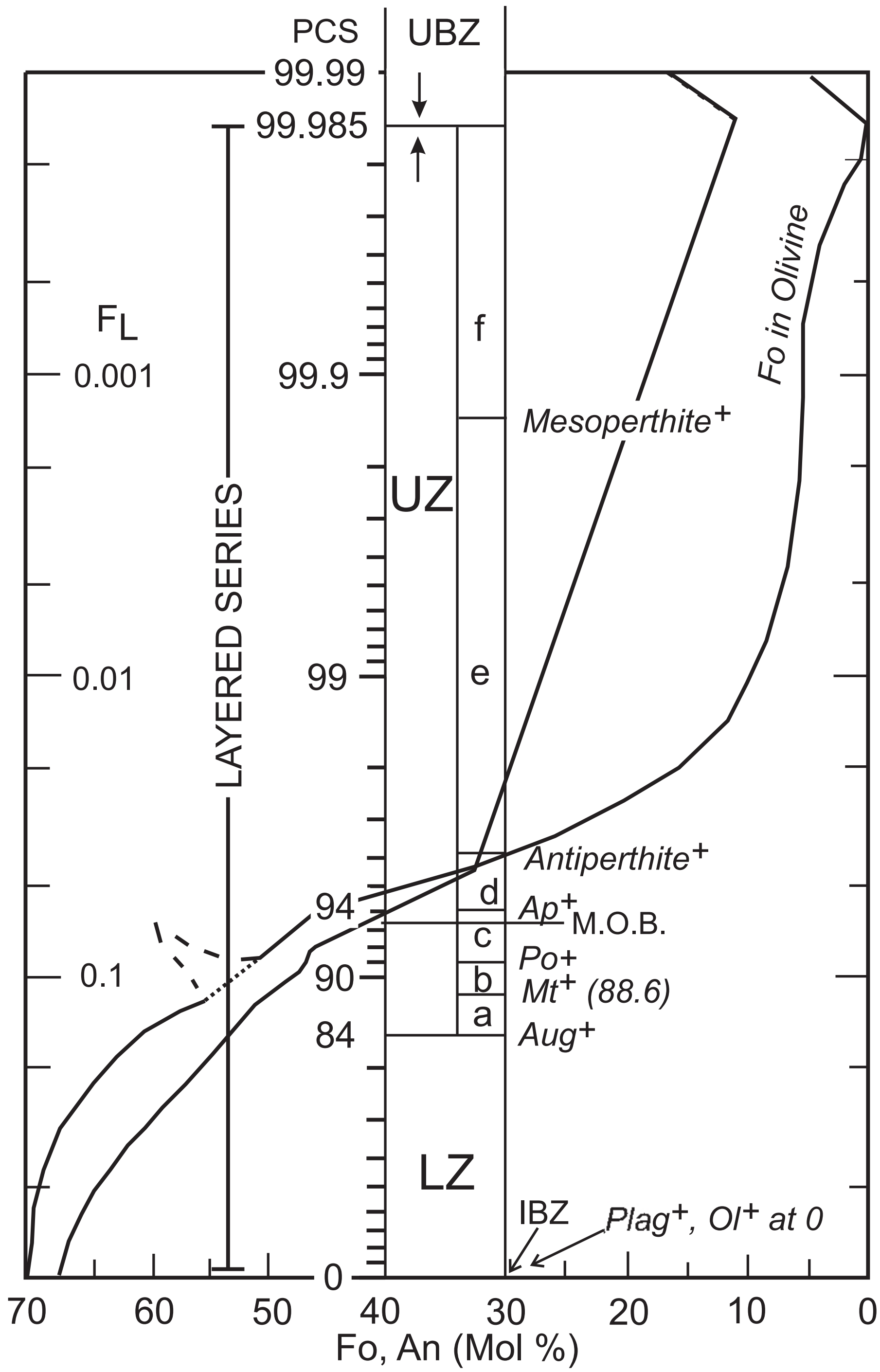

Fig. 2. Stratigraphic section of the Kiglapait intrusion, showing olivine and plagioclase composition trends superimposed; the crossover near 95·5 PCS should be noted. The vertical scale is logarithmic to show fine-scale changes in lithology over the last 300 m of stratigraphy (above 99·87 PCS). The subzones of the Upper Zone are indicated by letters a–f based on arrivals on the liquidus of augite (Aug^+), titanomagnetite (Mt^+), sulfide globules (Po^+), apatite (Ap^+), antiperthite, and mesoperthite. MOB, Main Ore Band at 93·5 PCS. F_L, fraction of liquid. The dashed excursion near 90 PCS represents the elevated Fo values interpreted as 'oxygen spikes' owing to the increasing components of Fe–Ti oxide minerals present in the system (Morse 1979*b*, 1980).

STATEMENT OF THE PROBLEM

A single, prolonged episode of magma chamber filling is assumed. Over the interval 0 40 PCS (volume per cent solidified) the model liquidus plagioclase composition in the basal Lower Zone of the Kiglapait intrusion varies only from An 67 to 64, a matter of 3 mol % over a strati graphic thickness of ~1900 m and 40% by volume of the entire magmatic history (bold line in Fig. 3). Over the entire Lower Zone, a cumulate thickness of ~5 km, the variation is 2·9% An per km of cumulate deposited. In contrast, the (pre augite) Skaergaard Lower Zone frac tionates plagioclase at a rate of ~13·6 mol % An km ^{1} (McBirney, 1996). The rational mind queries, what is going on here? The evolution of the Kiglapait liquid is evidently retarded. Is the cause exotic or intrinsic?

Among exotic causes might be the injection of new magma, or even better, a leading edge fractionated magma that could cause the scatter to low An values. Such periodic reversals are well known and distinct on a small scale in many other troctolitic intrusions, particu larly at Rum (Emeleus *et al.*, 1996). The only small scale study at Kiglapait so far found four paired reversals and returns in a 65 cm section, but the variations are not large (<1 % An; Morse, 1969, p. 127). Because the lens like layer ing in the intrusion generally extends for only a few hun dreds of meters (Young, 1983), it is inferred that the section described is a local phenomenon, and intrinsic. In the absence of more small to medium scale traverses, the case for significant new refreshments of magma above 10 or 20 PCS cannot be made. Given this stand off, it is worthwhile to consider all possible intrinsic effects that could cause retardation of the mineral compositional evo lution. If these can be shown to suffice, then the exotic scenario becomes moot, and unnecessary.

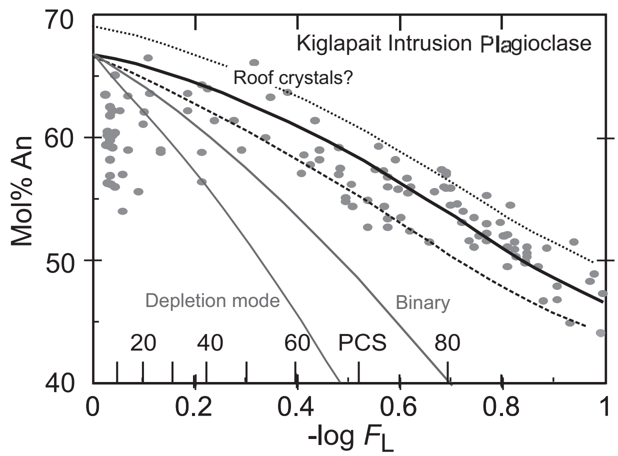

Fig. 3. Kiglapait plagioclase compositions for 0–90 PCS. Each data point represents a bulk analysis for the sample. Causes of scatter are discussed in the text. Various paths can be modelled through or away from the data, according to varying multiphase Rayleigh fractionation processes (Morse, 2008). The main path (bold continuous line) is a model for the liquidus at variable depth and pressures, 5·1–3·3 kbar, and hence a variable K_D The uppermost, dotted curve would satisfy limiting cumulus compositions starting from An_{69}. The dashed line near the lower bound of the data represents another Rayleigh fractionation path without the pressure effects; it is of no concern in this study. Paths for the binary and depletion mode represent special fractionation effects not of interest here except to note that they may satisfy many of the low values at stratigraphic levels above 20 PCS (volume per cent solidified). Figure modified from fig. 13 of Morse (2008). The horizontal axis is the negative log of the fraction of liquid remaining; the PCS scale denotes the per cent of liquid solidified.

INTRINSIC EFFECTS

The effect of pressure

The inferred central magma depth of the intrusion is 8400 m (Morse, 1979*b*) at PCS 0. This depth decreases outward toward the limbs of the basin shaped structure (Morse, 1969, 1979*b*) so that the ambient pressure at the cu mulate interface also decreases. The following discussion refers only to the central maximum pressure range from 5·1 to 2·8 kbar, giving only the maximum effects of pressure on plagioclase composition. Crystals of plagioclase at high pressure are closer in composition to their parent li quids than at lower pressures. This relationship is quanti fied in the direct variation of the exchange coefficient K_D with pressure, as

$$K_D \quad 0.0516P + 0.2622 \qquad (1)$$

where P is in kbar (Morse, 2013, fig. 7). The systematics of linear partitioning bearing on equation (1) are reviewed in Supplementary Material Appendix 1 (supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). As K_D increases, the binary loop narrows to a limit of zero width at K_D 1·0. Lower values of K_D describe fatter loops. The effects of compres sion in a deep magma chamber can be highly variable and significant (Table 1). To first order a magma crystalliz ing plagioclase of composition An 67 at the roof, if trans ferred instantly and adiabatically to the floor, could be in equilibrium with plagioclase An 61, a drop of ~6·5 mol % (Fig. 4). Because the crystal liquid tielines are shorter at depth, the magma fractionates more slowly at depth than at higher levels and lower pressures. This is the intrinsic pressure effect on fractionation; pressure damps the ten dency for the liquid to evolve.

There are other features of interest in this context. Crystals may grow over time within the magma and encounter liquid motions leading to reverse, normal, and oscillatory zoning (Maaløe, 1976) to cause pre cumulus zoning. This effect has been estimated to cause up to 4% An variation in the An range in the Kiglapait intrusion (Morse, 2012). If a low pressure plagioclase crystal sud denly becomes taken down to the floor and survives, it

*Table 1: Pressure effect on plagioclase and liquid compositions**

Line	PCS	P (kbar)	K_D	log F(L)	X An Xl	X An Liq	Difference
1	Roof	2·8	0·409	n.a.	0·7	0·484	0·216
2	Roof	2·8	0·409	n.a.	0·67	0·451	0·219
3	Roof	2·8	0·409	n.a.	0·502	0·298	0·204
4	86	3·6	0·445	0·854	0·502	0·310	0·192
5	70	4·0	0·468	0·523	0·579	0·392	0·187
6	35	4·6	0·4996	0·187	0·642	0·474	0·169
7	0	5·1	0·5254	0	0·671	0·519	0·152

*Morse (2008, fig. 10).
n.a., not applicable.

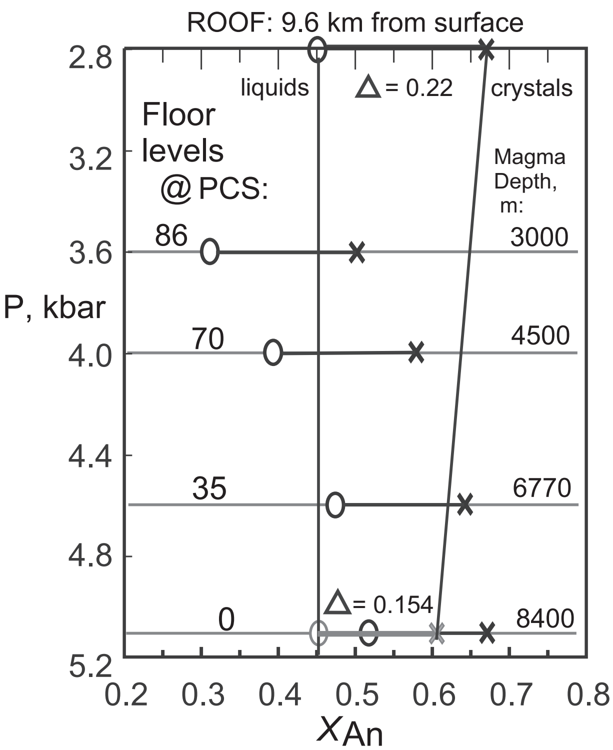

Fig. 4. Pressure effect on plagioclase–liquid tielines. The diagram shows crystal–liquid tielines at the roof and at four selected pressures corresponding to several PCS levels in the Lower Zone. The upward trend in decreasing X_{An} of the crystal compositions (× symbol) is taken from the plagioclase model, Fig. 1. The liquid compositions (ellipses) are calculated from the crystal compositions using the linear partitioning equation and the pressure variation of K_D taken as $K_D = 0{\cdot}0525\,P + 0{\cdot}2622$ (Morse, 2013); P is in kbar. The point of the diagram is to illustrate quantitatively the narrowing of the plagioclase loop with increasing pressure. Liquids descending directly from the roof would be in equilibrium with crystals 0·22 − 0·154 = 0·065 X_{An} units closer than at the roof. Pressure–depth relations are developed from the modified PREM table of Stacey & Davis (2009). The emplacement pressure at the top of the UBZ is taken as 2·5 kbar based on the phase relations of the contact aureole (Berg & Docka, 1983).

will be richer in An than the local high pressure crystals, and this might be the cause of local high An crystals as suggested in Fig. 3, none of which exceeds the main trend by more than 4% An.

The pressure difference decreases with stratigraphic height as the cumulate surface rises to lower pressure. It also decreases from the center of the chamber to the margins, which is where we see and sample all the rocks at the present erosion level. However, any pre cumulus or complexly zoned crystals may contribute to local variety anywhere. Perhaps this is the effect of wandering crystals.

Effect of trapped liquid

The resident melt trapped in a cumulate presumably has partition coefficients equal to 1 0 for all components, hence it has no capacity to cause the parent magma to evolve. The residual porosity has been calculated for single rocks in the KI from the range of An content in plagioclase (Morse, 2012). It ranges erratically from 35% to zero in the range from zero to 40 PCS and can therefore cause the local orthocumulates and mesocumulates to re duce their bulk plagioclase composition by ~6 to ~2 mol % An in that range. This effect tends to damp the fraction ation process by sequestration. Trapped liquid solidification has been discussed by Morse (2013).

Modal effect of olivine

The systematics of multiphase Rayleigh fractionation re veals that a fractionation curve can become steepened when a given phase component is scarce, having nothing to do with chemistry (Morse, 2008). This effect causes the 'depletion mode' curve shown in Fig. 3. That effect is brought into play to some extent when the local cumulate is richer in olivine than the Ol:Pl cotectic ratio of about 25:75 in oxygen units (Morse *et al.*, 2004). This effect may account for some rocks with low An in plagioclase over the range 10 40 PCS, or even in the olivine rich basal Lower Zone at <10 PCS. Here the olivine compositions and abundance tend to be high even where the plagioclase compositions are low in An, a condition fostering depletion in An owing to modal scarcity of plagioclase. Where both Fo and An are low together, recharge with fractionated magma may be inferred (there are five examples in the range 0 20 PCS).

Magmatic characteristics

Experimental studies of the inferred parent magma com position, designed to mimic the evolution of the Lower Zone to its eventual saturation with augite (Morse *et al.*, 2004), show that the path from very little augite compo nent to saturation can indeed be very long, with about 83% of the primary melt crystallizing as troctolite. That result is to some extent embedded in the experimental design. Nevertheless, the estimated bulk composition of the intrusion is very similar to that of the chilled margin