A year in the life of an aluminous metapelite xenolith—The role of heating rates, reaction overstep, \( \text{H}_2\text{O} \) retention and melt loss

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ABSTRACT

Xenoliths of aluminous metapelite within the Platreef magmatic rocks of the Bushveld Complex, South Africa, are mineralogically and texturally zoned, with coarse-grained margins rich in acicular corundum, spinel and feldspar and cores rich in finer-grained aluminosilicate and cordierite. Xenoliths exhibiting remarkably similar features occur within other intrusions, suggesting a common origin. Using a single 3 m wide xenolith as a case study, a model is proposed to explain their petrogenesis. Mineral equilibria calculations in the NCKFMASH system show that the thermal stability of the solid phases, in particular corundum, is highly sensitive to the quantity of \( \text{H}_2\text{O} \) retained in the protolith. Simple thermal considerations suggest the outermost 10 cm of the xenolith began to melt within a few hours following incorporation of the xenolith into the hot mafic/ultramafic magmas. Average heating rates of around 10^4 °C/year were sufficiently fast that the stability of low-grade hydrous phases within the protolith was overstepped by several hundred degrees, leading to retention of some or all of the structurally bound \( \text{H}_2\text{O} \) to suprasolidus conditions. As a result, marginal rocks developed peritectic corundum and spinel with \( \text{H}_2\text{O} \)-saturated melt, now preserved as hornfels with a (micro) diatexitic morphology. In the core of the xenolith, temperatures increased much more slowly, enabling progressive metamorphism by continual prograde reaction and loss to the margins of \( \text{H}_2\text{O} \) liberated by subsolidus dehydration reactions that consumed the low-grade hydrous phases before the rocks began to melt a week or more later. Thereafter, the preservation of fine-scale bedding in xenolith cores suggests that melt was lost efficiently as it was produced. Lower \( \text{H}_2\text{O} \) contents extend the upper thermal stability of aluminosilicate and cordierite to much higher temperatures, an effect exacerbated by the effects of melt loss. Whereas corundum growth occurred at the margins of the xenolith at temperatures below 800 °C, it is not predicted in the core until temperatures in excess of 1000 °C. The mineralogy and textures within the xenolith are consistent with a single-stage process involving equilibrium metamorphism and partial melting.

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1. Introduction

The quantity of \( \text{H}_2\text{O} \) in rocks plays a fundamental role in their metamorphic evolution (e.g. Guiraud et al., 2001). \( \text{H}_2\text{O} \) may occur both as an intragranular pore fluid and bound as OH-groups within the crystal structure of hydrous phases. During prograde regional metamorphism, in which heating rates are generally slow, \( \text{H}_2\text{O} \) produced by dehydration reactions is generally assumed to be lost, with assemblages equilibrating to become increasingly more \( \text{H}_2\text{O} \) depleted (i.e. progressive metamorphism). However, in contact metamorphism heating rates close to intrusive bodies are many orders of magnitude faster than in regional metamorphism. Metamorphic reactions may be overstepped (non-progressive metamorphism) and the thermal stability of low-grade hydrous phases exceeded by many tens or hundreds of degrees, enabling retention of much or all of the \( \text{H}_2\text{O} \) content of the rock to much higher temperatures (e.g. Buick et al., 2004). Under suprasolidus conditions, the quantity and retention of \( \text{H}_2\text{O} \) has important consequences for the amount, composition and viscosity of the melt produced.

Aluminous metapelitic xenoliths ranging from a few centimetres to several metres across are common in the Platreef magmatic rocks of the northern limb of the Bushveld Complex. The xenoliths are texturally and mineralogically zoned, with coarser-grained margins rich in spinel, corundum and feldspar and finer-grained cores rich in aluminosilicate and cordierite, and are strikingly similar to those within other mafic intrusions, most notably the Skaergaard Intrusion in Eastern Greenland (Markl, 2005), the Voisey’s Bay Intrusion in Labrador (Mariga et al., 2006a,b) and volcanic/subvolcanic rocks from the Isle of Mull, Scotland (Preston et al., 1999). While their petrogenesis has commonly been attributed in part to disequilibrium melting and, in the case of Markl (2005), to two stages of melting (pre- and post-incorporation as xenoliths) we offer an alternative and
We model the evolution of a single 3 m-thick xenolith of now highly residual Fe- and Al-rich metapelite within the southern Platreef magmatic rocks. We integrate field and petrographic data with mineral equilibria modelling within the framework of a simple 1-D thermal model to investigate the processes of metamorphism and partial melting occurring within the first year following incorporation of the xenolith into the Platreef magmas. Assuming an isochronal, hydrate rich (i.e. low grade) pre-intrusive bulk composition for the xenolith, we examine the effects of variable heating rates and consequent reaction overstep on the production and loss of melt and the microstructural and mineralogical evolution of the xenolith, and assess to what extent these can be explained by equilibrium processes.

2. Geological setting

Covering an area of some 65,000 km², the Bushveld Complex in northeastern South Africa is unique in its size and economic importance, hosting many important ores including much of the world’s PGE. It formed around 2.06 Ga (Buick et al., 2001) by the intrusion of up to 8 km of layered mafic/ultramafic rocks (the Rustenburg Layered Suite) and associated granite into rocks of the Transvaal basin, and an extensive contact metamorphic aureole is developed. The Bushveld Complex has four major sections, the eastern, western, southern (Bethal) and northern (Mokopane or Potgietersrus) limbs that are probably interconnected at depth (Hall, 1932; Cawthorn et al., 1998; Webb et al., 2004; Kruger, 2005; Clarke et al., 2009; Fig. 1 inset).

The northern limb of the Bushveld Complex has a maximum outcrop width of 15 km and extends northwards for over 100 km (Fig. 1). The rocks generally dip moderately-to-steeply towards the west or southwest. The mafic/ultramafic sequence in the northern limb is up to 5 km thick (e.g. Von Gruenewaldt et al., 1989; McDonald et al., 2005). The Platreef is a wide (up to ~400 m thick) irregularly-mineralised discordant facies at the base of the mafic/ultramafic sequence that extends from just north of Mokopane for approximately 50–60 km northwards (Fig. 1). It comprises mafic units enriched in Ni-Cu–PGE and contains numerous footwall xenoliths (e.g. Kinnaird et al., 2005).

In the northern limb, aluminous metapelitic rocks from the Timeball Hill Formation distal to the contact with the mafic/ultramafic rocks contain amphibolite–facies assemblages rich in andalusite, cordierite and biotite but without staurolite (Nell, 1984, 1985), consistent with pressures of around 2.5 kbar at this stratigraphic level in the area of the southern Platreef (Johnson et al., 2010). Stratigraphically-equivalent high-grade rocks traced to within a few metres of the contact generally lack quartz and contain assemblages rich in aluminosilicate, cordierite, spinel and corundum (Nell, 1984, 1985). The preservation of these minerals (e.g., White and Powell, 2002), their microstructural relations (e.g., Sawyer 1999, 2001) and the highly residual composition of the rocks relative to the lower-grade equivalents imply extreme degrees (>50%) of melting and subsequent melt loss (Nell, 1984, 1985). Peak temperatures at the contact are estimated at around 800 °C (Buick et al., 2004).

Xenoliths of all footwall rocks occur within the basal mafic/ultramafic rocks in the northern limb, including Archaean orthogneiss, Malmani Subgroup calc-silicate, Penge Formation meta-ironstones and various metaclastic rocks from stratigraphically higher...
units of the Pretoria Group (Fig. 1). In the southern Platreef, large rafts (metres to hundreds of metres across) of cordierite- and orthopyroxene-rich metapelite of the Duitschland Formation and much smaller (centimetres to metres across) xenoliths of Fe-rich aluminous metapelite of the Timeball Hill Formation are abundant. The latter commonly contain assemblages rich in corundum and/or aluminosilicate and are strongly depleted in K2O and H2O, consistent with significant degrees of melt loss and peak temperatures that probably exceeded 1000 °C (Johnson et al., 2010).

3. Sample description

Samples are from a 470 metre-long core (ITS017) drilled by Ivanhoe Nickel and Platinum Ltd. on the farm Turfspruit (Fig. 1). The top 110 m of core ITS017 comprises variably contaminated gabbro norite of the Main Zone. The underlying Platreef has an apparent thickness of over 300 m and consists mainly of variably serpenitised leuco- to melanorite. Hornfels xenoliths ranging from a few centimetres to several metres across are concentrated within the central 100 m of the Platreef, together with thin sheets of graphic granite. Toward its base, the core intersects hornfelsic metapelite at a depth of around 430 m.

The three metre thick xenolith that is the focus of this investigation is from the central portion of the Platreef, at a depth of 264–267 m below the surface (Fig. 2). At its base, the xenolith is in sharp contact with fine-grained orthopyroxenite, with the contact zone characterised by a layer of pure feldspar a few millimetres thick (Fig. 2). The bottom two centimetres of the xenolith (layer A in Fig. 2) are rich in dark coloured spinel and pale, coarse-grained feldspar. Spinel grains are both equant and acicular, the latter interpreted as the pseudomorphic replacement of corundum (Johnson et al., 2010). Above this to a distance of around 10 cm from the lower contact is a distinctive layer containing abundant, variably oriented, acicular glassy grey corundum porphyroblasts up to 30 millimetres in length and surrounded by coarse-grained feldspar (layer B in Fig. 2). This layer lacks any strong internal structures. Moving upwards towards the xenolith core, acicular porphyroblasts of corundum become scarce then absent. The main porphyroblast phase is equant spinel (up to 5 mm across) surrounded by feldspar patches (layer C in Fig. 2). Small stubby grains of corundum may occur within these spinel-dominated porphyroblast domains.

Compositional layering becomes increasingly well developed towards the centre of the xenolith. Fine-scale, laterally continuous horizons rich in purplish cordierite or pale green aluminosilicate have sharp contacts and show open folding and crenulations (layer D in Fig. 2). The layering is interpreted as the original fine-scale bedding, and is similar in scale to sedimentary layering in lower-grade (unmelted) samples of Timeball Hill metapelite. The orientation of the bedding, though folded, is broadly parallel to the long dimension of the drill core (layer D in Fig. 2). Towards the top of the xenolith, the layering becomes increasingly less well developed and the abundance of fine-grained hydrous phases increases dramatically (layer E in Fig. 2). The top few centimetres of the xenolith are rich in irregular fine-grained leucocratic patches, coarse plates of biotite and large grains of sulphide minerals several millimetres across (layer F in Fig. 2). The Platreef orthopyroxenite immediately overlying the xenolith is also rich in coarse biotite and sulphide minerals. The contact between the two is sharp and characterised by a thin layer of feldspar, similar to that developed at the base.

3.1. Petrography

All samples from the xenolith contain fine-grained ilmenite and lack quartz and prograde biotite (although red-brown biotite is commonly present as a minor retrograde product). All samples also contain coarse-grained feldspar comprising plagioclase (twinned and colourless) and/or alkali feldspar (untwinned and pale brown) that are commonly intergrown. The abundance of feldspar varies greatly from sample to sample, from a few vol.% to >50 vol.%.
The margins of the xenolith (layers A and B) are rich in skeletal corundum and/or spinel, lack internal layering and contain the highest proportion of feldspar, which may be volumetrically dominant. Within the lowermost two centimetres of the xenolith (layer A), spinel most commonly occurs as stubby subhedral grains up to 2 mm across, but also as highly acicular grains that partially to completely replace corundum (Fig. 3a, b). A mosaic of large anhedral grains of plagioclase, many in excess of 5 mm across, enclose spinel and angular

Fig. 3. Photomicrographs showing the variety of assemblages and microstructures within the xenolith. (a) Plane polarised light (PPL) and (b) crossed polarised light (XPL) images showing assemblages and microstructures within layer A (width of field of view = 4 mm). Skeletal porphyroblasts of spinel sit within coarse-grained plagioclase. The thin acicular grains of spinel replace corundum. (c) PPL and (d) XPL images showing the transition from layer A to layer B (6 mm wide). Acicular corundum is common and shows partial to complete replacement by spinel, the latter which also occurs as stubby skeletal porphyroblasts. Fragments of aluminosilicate–cordierite matrix are resorbed at their margins. The feldspar is dominantly plagioclase. (e) PPL and (f) XPL images from the centre of layer B, which comprises skeletal acicular corundum porphyroblasts surrounded by brown alkali feldspar (6 mm wide). The matrix is more abundant and continuous. Spinel porphyroblasts are commonly surrounded by coarse-grained cordierite and may be associated with stubby corundum. (g) PPL image from layer D within the xenolith core (10 mm). The feldspar-deficient matrix comprises layers rich in aluminosilicate, cordierite or both interpreted as relict bedding. Porphroblast/pseudomorph domains contain altered spinel and feldspar and unaltered stubby corundum. (h) Porphroblast/pseudomorph domain within layer C (8 mm). Subhedral spinel is pseudomorphed by fine-grained hydrous phases and oxide minerals and is spatially associated with unaltered corundum. The feldspar patch comprises partially altered intergrown plagioclase and alkali feldspar. The matrix contains distinct compositional layering.
fragments of finer-grained (up to 0.5 mm) cordierite–aluminosilicate matrix, which are absent at the contact but become more abundant towards the centre of the xenolith and which are separated from spinel by plagioclase (Fig. 3a–d).

Further from the contact (layer B), the proportion of acicular corundum and cordierite–aluminosilicate matrix increases whereas the abundance of feldspar is reduced to 30 vol.% or less. Feldspar commonly occurs as patches surrounding acicular corundum porphyroblasts (Fig. 3e, f). Although variable, the feldspar patches in this layer are dominated by brownish alkali feldspar. Both corundum and spinel may be in direct contact with fragments of aluminosilicate–cordierite matrix, although spinel is more commonly surrounded by a coarse-grained mosaic of cordierite (Fig. 3e, f).

Further towards the core of the xenolith, acicular corundum becomes increasingly scarce. The xenolith here mainly consists of fine-grained matrix, in which horizons several millimetres thick comprising roughly equal proportions of cordierite and aluminosilicate alterate with thinner layers (commonly 1 mm thick) of near pure aluminosilicate (Fig. 3g, h). The matrix contains no spinel and less than 1 vol.% feldspar, which occurs as discontinuous cuspate grains against cordierite and aluminosilicate.

Rounded porphyroblast domains several millimetres across are common in the core of the xenolith. These contain porphyroblasts of euhedral spinel (up to 5 mm across) surrounded by feldspar, although both phases show partial to complete replacement by fine-grained hydrous phases and, in the case of spinel, oxide minerals (Fig. 3g, h). Identical domains with unaltered spinel and feldspar are common within cores of other xenoliths (Johnson et al., 2010, Fig. 3d). Stubby corundum grains up to 1 mm across are common in these porphyroblast domains, although corundum shows no signs of retrograde breakdown or hydration (Fig. 3g, h; see also Johnson et al., 2010 Fig. 3 h).

Towards the top of the xenolith, the compositional layering becomes increasingly less distinct and the degree of alteration (hydration) of all minerals inferred to have grown at the metamorphic peak increases. The top several centimetres of the xenolith resemble the bottom few centimetres, principally comprising feldspar and spinel, although here both are extensively or completely altered to aggregates of fine-grained hydrous phases and opaque minerals.

3.2. Petrographic interpretations

Coarse-grained feldspar, abundant at the xenolith margin but also present in minor quantities within the xenolith core, is interpreted to record the former presence of melt. However, the feldspar at the margins of the xenolith (e.g. Fig. 3a), including the thin continuous layers that characterise both contacts, is exclusively plagioclase, suggesting it does not simply represent crystallised in situ melt. Although alkali feldspar-rich patches surrounding corundum porphyroblasts in layer B and within the matrix and porphyroblast domains in the xenolith core are closer to melt compositions (e.g. Tuttle and Bowen, 1958), these are also unlikely to represent liquid compositions (e.g. White and Powell, 2010).

At the base of the xenolith, features within layers A and B are consistent with rapid production of significant melt volumes resulting in the loss of internal structures. Since these domains represent partial-melt residues in which primary features such as compositional layering have been destroyed, we refer to the rock as (micro) diatexite (Sawyer, 2008; Johnson et al., 2010). The microstructures in layer A suggest growth of corundum and spinel as peritectic products of melting reactions, followed by replacement of corundum by spinel (e.g. Fig. 3a,b). The assemblages and microstructures within layer B similarly suggest rapid reaction that initially produced a fine-grained cordierite–aluminosilicate matrix with spinel and corundum porphyroblasts, the latter as peritectic products around which melt production was focussed (e.g. White et al., 2004). The resorbed nature of the fragments of aluminosilicate–cordierite matrix suggest its prograde replacement by corundum and melt ± spinel (Fig. 3c,d). The association of coarse-grained cordierite surrounding spinel (Fig. 3e,f) suggests replacement of the latter by the former, probably along the retrograde path.

Laterally-continuous compositional layering preserved within the xenolith core comprises alternating feldspar-deficient aluminosilicate and/or cordierite-rich horizons (Fig. 3g–h). Individual layers are commonly less than 1 mm thick and boundaries between layers are commonly sharp, consistent with the interpretation that they represent relict bedding and mimic fine-scale bedding laminations in lower grade protoliths (see Johnson et al., 2010 Fig. 2a). The scarcity of feldspar in the matrix within the xenolith core implies either low melt production or efficient loss of melt. The K2O and H2O-deficient composition of the matrix layers is consistent with significant melt loss. Such exceptional preservation of the pre-existing layering implies that melt extraction from these samples must have been efficient and kept pace with melt production.

The clear spatial association of feldspar surrounding stubby euhedral porphyroblasts of corundum in the margins of the xenolith (Fig. 3e,f) and spinel in the core (Fig. 3g,h) are interpreted to record spatially focussed melting reactions that grew these phases as peritectic products (e.g., Powell and Downes, 1990; White et al., 2004). The formation of stubby porphyroblasts of corundum within porphyroblast/pseudomorph domains within the xenolith core (Fig. 3g,h) is consistent with late-stage growth of this phase.

The abundance of hydrous phases in the feldspar-rich uppermost parts of the xenolith may have been the result of retrograde reaction with crystallising hydrous melt that pooled in the roof of the xenolith. However, this interpretation is equivocal and hydration may have occurred much later. The conspicuous lack of retrograde reaction in the basal corundum–spinel- and feldspar-rich layers implies significant loss of melt, as implied within the core of the xenolith (e.g. White and Powell, 2002).

4. Mineral equilibria modelling

4.1. Methodology

Mineral equilibria calculations in the NCKFMASHTO (Na2O–CaO–K2O–FeO–MgO–Al2O3–SiO2–H2O–TiO2–O) system use THERMOCALC 3.3.3i (Powell and Holland, 1988) and the thermodynamic data set of Holland and Powell (1998; ds55, November 2003 update). The calculations use the following a–x models: biotite and melt (White et al., 2007), garnet (Diener et al., 2008, modification after White et al., 2007), spinel and magnetite (White et al., 2002), cordierite (Holland and Powell, 1998), K-feldspar and plagioclase (Holland and Powell, 2003), muscovite (Coggon and Holland, 2002) and ilmenite/hematite (White et al., 2000). Mn is not considered for the reasons given in White et al. (2007). Although the aluminosilicate phase is a solid solution between sillimanite and mullite (Johnson et al., 2010), the modelling uses the thermodynamic data of end-member sillimanite as data for mullite are not included within the Holland and Powell (1998) dataset. Although this has implications for the highest-T thermal stability of the aluminosilicate phase, this effect is probably small. Similar caveats exist for other modelled phases, particularly with respect to minor elements that may occur in significant concentrations at the high temperatures experienced by the xenoliths (e.g. Fe3+ and Ti in corundum, aluminosilicate and quartz).

Where given, proportions of phases are on a molar basis normalised to one oxide such that they approximate volume proportions. Concentrations of ferric iron in the protoliths are unknown and fixed to 5% of total Fe. Mineral abbreviations are as follows: cd = cordierite; sp = (hycrystitic) spinel; bi = biotite; mu = muscovite; and andalusite; sill = sillimanite;
ksp = alkali feldspar; pl = plagioclase feldspar; ilm = ilmenite; mt = magnetite; q = quartz; cor = corundum; and liq = silicate melt.

4.2. Bulk compositional constraints

Metapelitic rocks of the Timeball Hill Formation are Al- and Fe-rich. Although there are significant variations in the FeO/(FeO + MgO) and Al2O3/(Al2O3 + FeO + MgO) ratio of these rocks, large variations in SiO2 content also represent a first-order variation in the bulk composition of the protoliths, presumably due to a variable supply of fine sand or silt. The molar FeO/(FeO+MgO) proportion close to the average of protolith bulk compositions (Johnson et al., 2010).

Given these constraints, the evolution of the xenolith was modelled using a bulk composition based on sample ET-194, an unmetamorphosed sample from Reczko (1994). Sample ET-194 is silica-poor with high molar Al2O3/(Al2O3 + SiO2) = 0.34 and, based on around 8 wt.% loss on ignition, contains a high volatile content and Al2O3/(Al2O3 + FeO + MgO) ratio of these rocks, large variations in SiO2 content also represent a first-order variation in the bulk composition of the protoliths, presumably due to a variable supply of fine sand or silt. The molar FeO/(FeO+MgO) proportion close to the average of protolith bulk compositions (Johnson et al., 2010).

4.3. Results

4.3.1. P–T pseudosection

Assemblages in amphibolite facies metapelitic rocks of the Timeball Hill Formation in the area of the southern Platreef, which everywhere lack staurolite, are consistent with pressures of around 2.5 kbar (Johnson et al., 2010). At distances of many kilometres from the contact, these pressures must record conditions after the emplacement of the entire thickness of the layered mafic/ultramafic rocks present in this part of the northern limb (Cawthorn and Walraven, 1998). However, if the Platreef magmas intruded significantly earlier than the main volume of overlying Main and Upper Zone magmas (e.g. Holwell et al., 2005; McDonald et al., 2005), the xenoliths should record near peak-T assemblages that initially developed at lower pressures (1.0–1.5 kbar).

Fig. 4 shows a P–T pseudosection from 1 to 4 kbar and ranging from subsolidus amphibolite facies conditions to ultra-high temperature granulite facies conditions. The subsolidus part of Fig. 4 is calculated with H2O in excess. The suprasolidus region is calculated with an H2O content just sufficient to saturate the solidus at 2.5 kbar, and thus only shows phase relations appropriate to low H2O compositions.

At temperatures below those shown in Fig. 4, greenschist facies assemblages (~500 °C) are rich in the hydrous phases muscovite and chlorite. Heating paths to high-T subsolidus conditions pass from assemblages rich in muscovite, andalusite and biotite to assemblages rich in andalusite, K-feldspar and biotite (Fig. 4), resulting in significant dehydration and loss of most of the H2O.

In P–T space, the near-solidus phase relations are controlled by the equilibria extending from the divariant NCKFMASHTO field equivalent to the KFMASHO univariant reaction (Fig. 4):

\[ \text{bi} + \text{sill} + q = \text{cd} + \text{sp} + \text{ksp} + \text{liq}. \]
At pressures above 2 kbar, the solidus is crossed at lower-\( T \) than the low-variance field extending from Reaction 1 that first forms cordierite. Crossing this region consumes all quartz and is the principal cordierite-producing reaction, with 20 mol% forming over just 15 °C by the NCKFMASHTO equivalent of the KFMASH divariant reaction:

\[
\text{bi + sill + q = cd + ksp + liq.} \tag{2}
\]

Reaction 2 produces around 5 mol% melt.

At around 700 °C and pressures of 2–3 kbar, the heating path crosses another low-variance region, across which biotite and sillimanite (and all plagioclase and magnetite) are consumed to produce spinel and liquid (with K-feldspar, minor cordierite and ilmenite) by the NCKFMASHTO equivalent of the KFMASH divariant reaction:

\[
\text{bi + sill = cd + sp + ksp + liq.} \tag{3}
\]

Reaction 3 is the major spinel-forming reaction and represents a pronounced melting step, producing around 15 mol% melt and almost 20 mol% spinel over around 40 °C until biotite is exhausted.

At temperatures of around 750 °C, the phase assemblage comprises roughly equal proportions of cordierite, K-feldspar, spinel, sillimanite and melt. To higher temperatures K-feldspar contents markedly decrease and this phase disappears at 850–900 °C. At temperatures around 950 °C and pressures of 2–3 kbar, cordierite is totally consumed a few degrees or tens of degrees below or above, the first appearance of corundum, with sillimanite exhausted a few tens of degrees above this. At pressures above 1.6 kbar, assemblages composed of corundum, spinel and liquid are predicted at temperatures above 975 °C, with corundum being consumed at the highest temperatures (Fig. 4). The total amount of melt produced at 1000 °C exceed 70 mol% with spinel the only solid phase remaining.

A prograde evolution at lower pressures (<2.0 kbar) for this composition differs significantly. The principal cordierite-producing and spinel-producing reactions that exhaust quartz and biotite, respectively, both occur subsolidus (i.e. via reactions 2 and 3 but with \( H_2O \) rather than melt as a product phase). The pronounced up-\( T \) step in the solidus is due to the subsolidus exhaustion of quartz as a reactant at low-\( P \) (White et al., 2003; Johnson et al., 2004). The solidus is crossed at \( T > 750 \) °C and corundum growth occurs before the exhaustion of first K-feldspar, then sillimanite, then cordierite, although the prograde appearance of corundum in Fig. 4 is greatly exaggerated (stabilised to lower-\( T \)) due to the higher \( H_2O \) contents required to saturate the solidus at higher pressure (2.5 kbar). At pressures less than 1.6 kbar, corundum is consumed at lower-\( T \) than cordierite and there is no field containing only corundum, spinel and liquid (Fig. 4).

The stability of corundum exhibits a strong bulk compositional dependence, particularly with respect to the \( Al/(Al+Si) \) ratio of the

![Fig. 5. Isobaric (\( P = 2.5 \) kbar) NCKFMASHTO \( T-X(H_2O) \) pseudosection for the aluminous metapelitic bulk composition. The variation in \( H_2O \) reflects the quantity of hydrates retained in the protolith, from a quantity based on LOI from the unmetamorphosed sample ET-194 (right hand edge) through that calculated for muscovite–chlorite rich greenschist facies assemblages (black rectangle), to a quantity appropriate to upper amphibolite facies (or progressive metamorphism) on the left hand side. Reactions 1 and 2 in the text are highlighted and the calculated proportions of corundum (bold dashed) and melt (thin dashed) are shown (as mol%). The arrows show the interpreted prograde evolution for xenolith margins (black dotted paths) and cores (white dotted path) as discussed in the text. The black dotted paths passing from subsolidus to supersolidus conditions are meant to imply non-progressive metamorphism in which the evolution passes directly from low-grade (450 °C) to high grade (800 °C), without equilibrating within the intervening fields. The prograde evolutions from the black and white stars to higher-\( T \) are only appropriate if no loss of melt occurred.](image-url)
protolith (Johnson et al., 2010). However, the $P$–$T$ location of the solidus and of the low-variance field recording reaction 1, which in turn controls the position of the main cordierite and spinel forming equilibria (Reactions 2 and 3 respectively), are insensitive to moderate bulk compositional variations.

Large euhedral porphyroblasts of spinel surrounded by feldspar within the cordierite- and sillimanite-rich, spinel-absent matrix (Fig. 3g, h) are most consistent with their formation via a melting reaction that was spatially focussed on peritectic spinel grains. The narrow low-variance suprasolidus field representing Reaction 3 is consistent with the formation of these microstructures (Fig. 4), implying a heating path in excess of 2 kbar. Given this constraint, we model the evolution of the xenolith in $T$–$X$ space at a pressure of 2.5 kbar, representing the simplest case in which the entire thickness of the mafic rocks was intruded instantly. Whereas this is undoubtedly simplistic, the difference in the mineralogical and melting history between 2.0 and 2.5 kbar is trivial.

4.3.2. $T$–$X$(H$_2$O) pseudosection

Fig. 5 shows an isobaric ($P = 2.5$ kbar) $T$–$X$ pseudosection for the modelled protolith composition against varying H$_2$O. The H$_2$O contents shown range from a quantity just sufficient to saturate the wet solidus on the left-hand side (4.7 mol%), increasing to a quantity based on the loss on ignition from the unmetamorphosed sample ET-194 on the right-hand side (27.1 mol%). At greenschist facies conditions, the modelled composition is rich in muscovite, chlorite, andalusite and quartz and contains 14.3 mol% H$_2$O at 450 °C and 14.0 mol% at 500 °C (Fig. 5). Upper amphibolite facies subsolidus...
assemblages rich in biotite, andalusite and K-feldspar contain H₂O contents close to those required to saturate the solidus.

The composition and abundance of solid phases in the subsolidus assemblage and the temperature of the solidus (660 °C) are independent of H₂O contents for the range shown. The suprasolidus region of Fig. 5 broadly comprises two regions separated by the H₂O-out line (emboldened on Fig. 5). At high H₂O contents, assemblages contain a free H₂O volatile phase and the boundaries between fields that record the incoming or outgoing of particular phases are isothermal. At low H₂O contents, assemblages lack a free H₂O volatile phase and field boundaries have a variable slope in T–X(H₂O) space (Fig. 5).

The temperature of the prograde appearance of cordierite (665–670 °C) and spinel (700–710 °C) and the disappearance of biotite (740–760 °C), quartz (660–670 °C), plagioclase (710–715 °C) and magnetite (710–725 °C) are only very weakly dependent on H₂O contents (Fig. 5). In contrast, the prograde disappearance of K-feldspar, aluminosilicate and cordierite occur at much higher T in the lowest H₂O compositions (890 °C, 990 °C and 960 °C, respectively) than in high H₂O compositions (770 °C, 840 °C and 905 °C, respectively) (Fig. 5). The stability of corundum shows the most extreme dependence on H₂O contents. In high H₂O compositions, prograde corundum first grows at 760 °C and is consumed further up temperature at 950 °C. In compositions with the lowest H₂O contents, corundum first appears at around 970 °C and is consumed further upgrade at temperatures in excess of 1000 °C (Fig. 5). The proportion of melt is strongly dependent on the quantity of H₂O, although once the melt is H₂O saturated at any particular T, increasing the quantity of H₂O further has no further effect on melt volumes (Fig. 5).

5. Thermal model

5.1. Parameters

The simple thermal model used here considers only conductive heat transfer and a simple one-dimensional geometry (e.g. Jaeger, 1964) in which a sheet of country rock of thickness 3 m and at an initial temperature (T₀) of 450 °C is enclosed within an effectively infinite body of magma that intruded instantaneously (t = 0) at a temperature (Tm) of 1250 °C. Distance (x) is measured from the centre of the xenolith (Fig. 6a). Thermal diffusivity (κ) is taken as 0.6 mm² s⁻¹, reflecting the weak temperature dependence of κ above 850 °K (Whittington et al., 2009). The initial temperature of the magma is constrained by the composition of cumulate orthopyroxene that implies magnatic temperatures of 1200–1300 °C (Cawthorn and Biggar, 1993; Cawthorn and Walraven, 1998). The pre-intrusive temperature of the country rocks (xenolith) is less well constrained, although the significant volume of pre-Bushveld sills will have raised the ambient temperature in the footwall rocks prior to intrusion of the main magma body (Buchanan et al., 1981; Cawthorn et al., 1981; Sharpe and Hulbert, 1985; Engelbrecht, 1990). Although the model does not consider latent heat, during the prograde evolution of the xenolith the exothermic contribution of latent heat from crystallisation of the mafic magma around the xenolith is likely of the same order as the endothermic contribution from melting reactions within the xenolith. In any case, the influence of these effects on the model results is likely to be small relative to those resulting from an oversimplification of the xenolith geometry and the intrusive history of the host magmas.

5.2. Results

The results of the simple thermal model are shown in Fig. 6. From the thermal model, immediately following emplacement of the Platreef magmas, temperatures at the contact (z = 1.5) would be intermediate between the initial T of the xenolith and the intrusive T of the magma (850 °C). The bottom 2 cm of the xenolith (layer A) would attain suprasolidus temperatures (>660 °C) some 15 min after intrusion, reached 750 °C within an hour and 830 °C within a day, rising more slowly thereafter to 850 °C within a week. Corundum growth is predicted in H₂O-rich compositions within around 2 h. Heating rates for this layer would reach a maximum within 2 min following intrusion.

The entire lowermost 10 cm layer of the xenolith, in which acicular corundum is abundant, is predicted to have attained suprasolidus conditions within 6 h, 750 °C within a day and 810 °C within a week. Corundum growth is predicted in H₂O-rich compositions after around 2 days. Heating rates for this layer peaked within an hour of intrusion.

Temperatures in the xenolith 50 cm from the contact would reach around 500 °C within the first day and would just exceed that of the solidus after a week, by which time heating rates had peaked. Modelled temperatures within the geographic centre of the xenolith (z = 0) would be 510 °C after a week, around which time heating rates peaked. Temperature did not exceed that of the solidus in the core of the xenolith until 2–3 weeks after intrusion. After a month or so, heating rates at all points in the xenolith converge to a value of around 1000 °C/year. Modelled temperatures in all parts of the xenolith were >1000 °C after around 6 months.

6. Discussion

6.1. The role of reaction overstep and H₂O retention

The features developed within the xenolith are consistent with the modelled equilibrium phase diagrams. The distinct mineralogical and textural differences between xenolith margins and cores can be explained by variable retention (or loss) of H₂O contained within hydrous phases that would have been abundant in the protoliths prior to their incorporation with the Platreef magmatic rocks.

6.1.1. Xenolith margin

The formation of acicular skeletal corundum with skeletal spinel and a large volume of melt, consistent with the mineralogy and microstructures developed in the bottom 10 cm of the xenolith (layers A and B in Fig. 2), is consistent with rapid heating and high H₂O contents (Fig. 5). In such compositions, corundum growth is predicted throughout this layer within two days, a time period over which average heating rates are around 10⁴ °C/year. At the modelled instantaneous (t = 0) temperatures of 850 °C at the xenolith-Platreef contact, the phase constraints on Fig. 5 are consistent with minimum X(H₂O) values of 0.35 (around 12.5 mol%), a quantity appropriate to that contained within a muscovite–chlorite dominated green schists facies assemblage (Fig. 5). Therefore, the thermal stability of the low-grade hydrous phases in the protolith was overstepped by several hundred degrees due to the extreme heating rates.

The modelled evolution is illustrated on Fig. 5 (white and black dotted paths) using an example of a point 5 cm from the base of the xenolith, within layer B. After one day the temperature rises to 800 °C. If, within this timescale, all H₂O within lower-grade hydrates is lost by progressive metamorphism and dehydration, or the protolith had been metamorphosed to high-T prior to its incorporation as a xenolith, the evolution follows the dotted white path on Fig. 5. In this case, the solid assemblage sp–cd–sill–ksp should develop along with the formation of around 30 mol% H₂O undersaturated melt. However, if some or all of the H₂O locked within the lower-grade hydrates is retained (black dotted paths on Fig. 5), the evolution passes directly from a hydrate-rich low-T subsolidus assemblage to develop a solid assemblage of cor-sp–cd–sill coexisting with an H₂O volatile phase and 45–60 mol% H₂O saturated melt (Fig. 5), consistent with the mineralogy and microstructures. The near instantaneous development of such high melt volumes that result from this overstepping is consistent with the destruction of any pre-existing structures and the formation of a marginal diatexite.

Assuming loss of any free H₂O volatile phase, the bulk composition is displaced to the H₂O-out line (i.e. along the solid black path to the
black star in Fig. 5). With a continued but slower increase in temperature, and assuming no loss of melt, complete consumption of sillimanite is predicted at around 850 °C, cordierite is exhausted at 900 °C and corundum disappears at temperatures in excess of 950 °C (Fig. 5).

6.1.2. Xenolith core

The preservation of fine-scale bedding lamination and the scarcity of feldspar in xenolith cores suggest these layers contained much lower H$_2$O contents when they attained solidus temperatures, and that they lost melt efficiently as it was produced thereafter. If H$_2$O-content were high, 10–20 mol% melt would have been produced at and within a few degrees of the wet solidus (Fig. 5), which would likely have destroyed the pre-existing bedding laminae. Modelled heating rates in the core were up to three to four orders of magnitude slower than at the rim. Predicted temperatures within the central portion of the xenolith (z = 0–0.5) remained at subsolidus conditions for a week or more, a time scale that would appear sufficient to allow progressive metamorphism from low- to high-grade and the loss of the volatile H$_2$O produced by dehydration reactions consuming the low-grade hydrate phases within the protolith.

On crossing the solidus (white star in Fig. 5), trivial amounts of melt are produced by H$_2$O-present melting. Cordierite appears first with small quantities of melt by Reaction 2. As temperatures exceeded 700 °C, a significant melting step occurred by Reaction 3, which we interpret resulted in the formation of spinel poikiloblasts surrounded by melt. With no loss of melt, an evolution to higher temperatures (i.e. along the left hand edge of Fig. 5) predicts the disappearance of biotite around 740 °C, K-feldspar around 890 °C, sillimanite around 970 °C and cordierite around 990 °C. Corundum should first appear at around 970 °C but disappear again around 1020 °C.

6.2. The role of melt loss

Several mineralogical, textural and bulk-compositional considerations suggest the xenoliths have lost a significant amount of melt (Nell, 1984, 1985; Johnson et al., 2010). Assuming no loss of melt, at the temperatures expected throughout the xenolith after six months to a year (1050–1100 °C; Fig. 6) all parts of the xenolith should comprise spinel with liquid (Figs. 4, 5). Although this extreme high-temperature assemblage is developed at the xenolith margin (e.g. Figs. 3a, b), assemblages throughout most of the xenolith are inconsistent with this prediction, suggesting either that temperatures were significantly lower than those modelled, or that loss of melt resulted in the preservation of the other solid phases to much higher T.

Although melting of metapelitic protoliths is inevitable at such high temperatures, and loss of most of this melt is implied by the geochemistry and microstructures, constraining exactly how, and to where, the melt escaped is problematic as the cores do not permit a detailed examination of field relations. However, we suggest that the melt was lost to the margins of xenoliths and collected into larger granite sheets that are common within cores transecting the Platte reef.

6.2.1. Xenolith margin

Again taking the example of a point in the central portion of layer B, Fig. 7 shows the effect of melt loss from a composition plotting at the black star on Fig. 5 (i.e. an initially H$_2$O-rich composition instantly metamorphosed at 800 °C and the subsequent loss of all volatile H$_2$O). The assemblage at 800 °C comprises 10 mol% cordierite, 18 mol% spinel, 8 mol% sillimanite, 4 mol% corundum, 2 mol% ilmenite and 58 mol% melt. With increasing melt loss (towards the right on Fig. 7), the temperature at which the solid phases are exhausted from the assemblage increases. If 60–65% of the melt is lost (i.e. 20–23 mol% remains), both cordierite and sillimanite remain stable to temperatures approaching 1000 °C, and corundum remains stable, with spinel, to temperatures of around 1100 °C. These features are consistent with the assemblages developed in layer B at the modelled temperatures.

6.2.2. Xenolith core

Modelling the effects of melt loss from the xenolith core is more complex. As discussed above, the microstructures are consistent with gradual loss of H$_2$O and melt as it was produced by progressive metamorphism. Fig. 8 shows the modelled evolution of xenolith cores in which continuous prograde equilibration beyond the solidus (from the white star in Fig. 5) gives rise to steadily increasing melt fractions. Fig. 8 was calculated by considering successive melt loss steps (at the temperatures indicated by the vertical dashed lines). Starting with the bulk composition plotting at the white star in Fig. 5, the proportion of minerals in the residue was calculated up temperature until melt fractions reached 10 mol%, at which point 5 mol% was removed. The new residual bulk composition was recalculated and the prograde evolution calculated until melt fractions again reached 10 mol%, at which point 5 mol% was removed, and so on. At each step, the composition of the melt removed is that calculated using THERMOCALC for the appropriate temperature and (residual) bulk composition.

Fig. 8 shows that sequential melt loss results in the retention of sillimanite and cordierite to much higher temperatures (>1000 °C), consistent with the assemblages developed within the xenolith core. However, cordierite is completely consumed at around 1030 °C and small quantities of corundum are predicted to grow in xenolith cores only at >1050 °C. Rates of melt production within the core were 1–2 mol% per day on average.

6.3. Alternative models

Xenoliths of aluminous metapelite exhibiting almost identical textural and mineralogical features occur within other intrusions, most notably the Voisey’s Bay Intrusion (Mariga et al., 2006a,b), the Skærgaard Intrusion (Markl, 2005) and from sub-volcanic sheets from the Isle of Mull (Preston et al., 1999). Markl (2005) proposes a complex multi-stage petrogenetic process, involving two separate stages of melting and melt loss. Prior to incorporation as xenoliths, it is suggested the rocks had undergone contact metamorphism that resulted in partial melting and melt loss. The aluminous residual rocks were subsequently incorporated into their host magmas as xenoliths, where they underwent a second stage of melting. Both authors consider that the phases developed at the margins of the xenoliths (principally plagioclase, corundum, aluminosilicate and spinel) crystallised directly from Al-rich melt as it reacted with the host magmas (Preston et al., 1999; Markl, 2005).

Based largely on the experimental results of Brearley and Rubie (1990), Preston et al. (1999) and Markl (2005) attributed the petrogenesis of the xenoliths in part to disequilibrium melting involving the breakdown of muscovite. The highest temperature experiments of Brearley and Rubie (1990), performed at 1 kbar, showed distinct mineralogical differences under H$_2$O-saturated and H$_2$O-undersaturated conditions. The solid products of the H$_2$O-undersaturated experiments, K-feldspar and aluminosilicate, were considered to be the equilibrium assemblage. The growth of corundum and mullite-rich aluminosilicate (without K-feldspar), which occurred only under H$_2$O-saturated conditions, was considered to represent disequilibrium, in which the metastable nucleation of these phases inhibited growth of the stable assemblage.

Although modelled at higher P, our calculations suggest that, in H$_2$O-saturated conditions, sillimanite-, K-feldspar- and cordierite rich assemblages are metastable with respect to corundum- and spinel-rich assemblages (Fig. 5), and that the mineralogical features are consistent with equilibrium processes, at least for the major elements. Although a significant degree of reaction overlap is required to preserve the H$_2$O in the protolith, Fig. 5 suggests that
the rocks reacted to form the equilibrium assemblage predicted for these H2O-rich compositions at the appropriate temperature. Other than plagioclase, we suggest that all solid phases present within the xenolith margin grew as solid peritectic products of the overstepped equilibrium melting reaction, as opposed to growing from the melt as it crystallised. Moreover, the model presented herein requires that the protoliths retained some or all of their lower-grade hydrous phases (and H2O) when they were incorporated as xenoliths. This argues against an earlier (pre-entrainment) stage of metamorphism, partial melting and melt loss, and favours a simpler, single stage process.

6.4. Reaction with the Platreef

Although the mineralogical and textural evolution of the xenoliths is broadly consistent with an equilibrium approach, chemical and/or physical interaction with the Platreef magmatic rocks must have played a significant role. Although sheets of graphic granite are common within the Platreef (see Johnson et al., 2010, Fig. 2b), there is commonly little evidence for physical interaction between the xenoliths and their host magmas, and the contact between the two is extremely sharp (Fig. 2). The distinct margin of the melt-depleted xenolith is consistent with simple contraction by compaction during melt loss without destruction of the interface. However, plagioclase-rich (K-poor) feldspar compositions (Fig. 3a,b,) in the xenolith margin and the ubiquitous development of coarse biotite within the Platreef magmatic rocks (Fig. 2) is consistent with diffusion of Fe, Mg and Ca from the Platreef to the xenolith, and diffusion of K and H2O in the opposite direction.

7. Conclusions

Xenoliths of aluminous metapelite are common within mafic intrusions. The cores and margins of xenoliths commonly preserve distinct mineralogical and microstructural features, which, while in part due to physicochemical interaction with the host magmas, are largely the result of the ability of the xenolith to retain H2O. Heating rates at xenolith margins are sufficiently rapid that low-grade hydrates are unable to break down and dehydrate the rock before melting begins. Subsolidus reactions are overstepped as assemblages equilibrate to the extreme suprasolidus conditions. Much or all of the H2O previously locked within the low-grade hydrous phases is incorporated into the large volumes of melt that form within hours or days following incorporation of the xenolith. The equilibrium
assemblage is strongly dependent on the H$_2$O-contents of the protolith, with the lower temperature stability of corundum varying by up to 200 °C in H$_2$O-saturated versus -undersaturated compositions. Cores of larger xenoliths heat up much more slowly, and dehydrate by progressive metamorphism prior to melting. Rates of melt production thereafter are orders of magnitude slower in the core than the margins, and commonly slow enough that the melt is lost as it is produced, preserving primary sedimentological features. The evolution of the xenoliths is consistent with equilibrium metamorphism and anatexis, at least for the major elements.

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References


