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A year in the life of an aluminous metapelite xenolith—The role of heating rates, reaction overstep, H_2O 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 NCKFMASHTO system show that the thermal stability of the solid phases, in particular corundum, is highly sensitive to the quantity of H_2O 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 H_2O to suprasolidus conditions. As a result, marginal rocks developed peritectic corundum and spinel with H_2O-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 H_2O 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 H_2O 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.

1. Introduction

The quantity of H_2O in rocks plays a fundamental role in their metamorphic evolution (e.g. Guiraud et al., 2001). H_2O 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, H_2O produced by dehydration reactions is generally assumed to be lost, with assemblages equilibrating to become increasingly more H_2O 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 H_2O content of the rock to much higher temperatures (e.g. Buick et al., 2004). Under suprasolidus conditions, the quantity and retention of H_2O 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

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simpler interpretation, consistent with a single stage equilibrium evolution.

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 isochemical, 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 km^2, 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

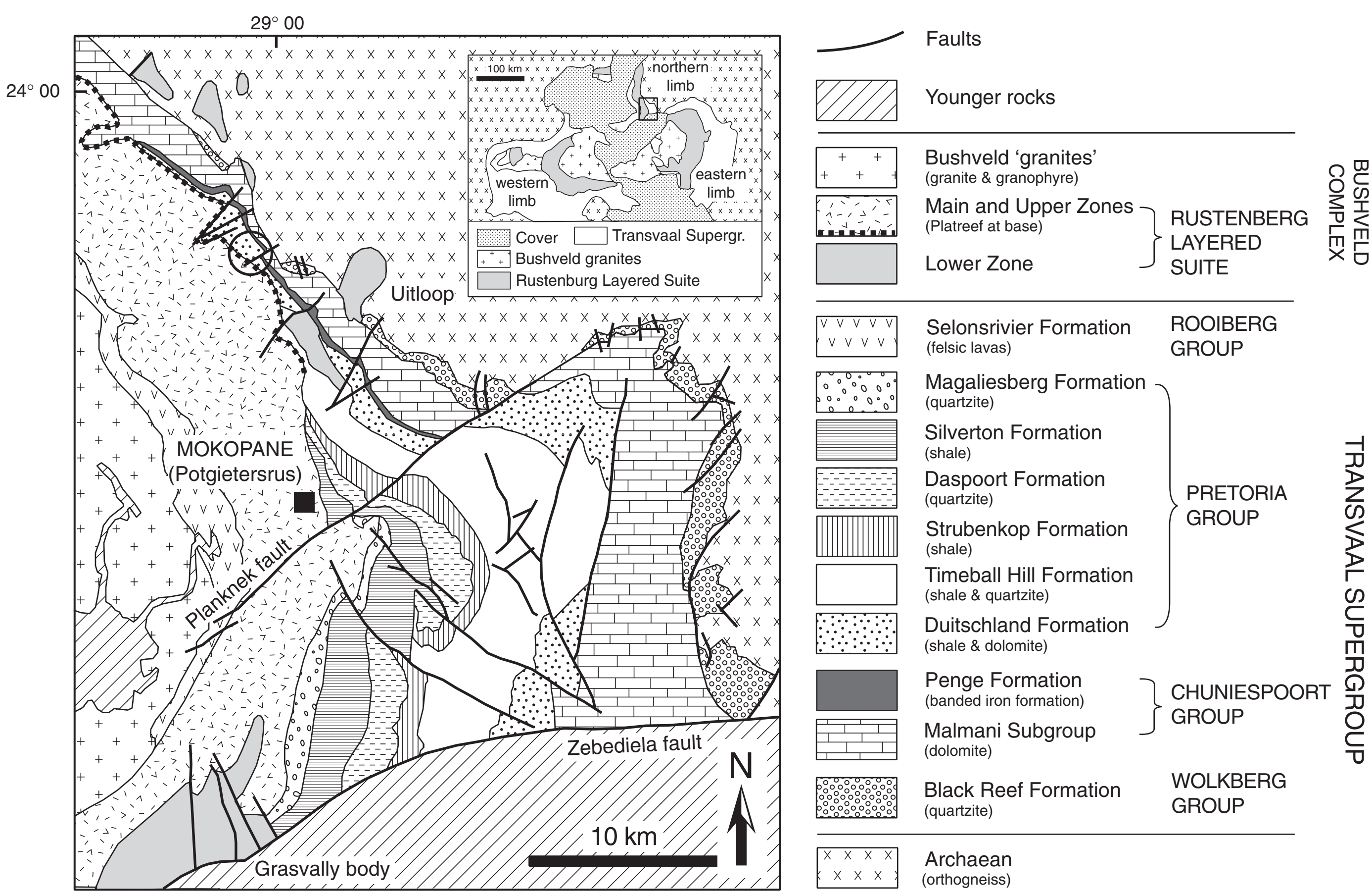

Fig. 1. Simplified geological map of the southern and central sectors of the northern limb of the Bushveld Complex (after Nell, 1985). Core samples are from the farm Turfspruit, located within the circle. The inset shows a simplified regional map of the Bushveld Complex.