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Parental magma composition inferred from trace element in cumulus and intercumulus silicate minerals: An example from the Lower and Lower Critical Zones of the Bushveld Complex, South-Africa

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ABSTRACT

Major and trace element concentrations in whole-rock and cumulus and intercumulus minerals were determined in cumulate rocks from the Lower and the Lower Critical Zones of the Bushveld Complex, South-Africa. These new geochemical data are combined with microtextural observations to provide insights on the formation of the cumulates. The results are used to evaluate methods of calculation of parental liquid composition from which the cumulate rocks crystallized. Cumulus (orthopyroxene and olivine) and intercumulus (clinopyroxene and plagioclase) minerals have a relatively constant composition in terms of major and trace element throughout the Lower and the Lower Critical Zones suggesting that the minerals formed from a magma with a relatively constant composition and followed a similar crystallization history. The minerals are in most cases unzoned in terms of major and trace elements. However, Ti zonations are observed in pyroxene and are consistent with the steady increase in Ti concentrations in interstitial plagioclase with decreasing An. These features are interpreted to be the result of the crystallization of the trapped melt during closed system fractional crystallization without significant intercumulus melt migration as suggested by the absence of dihedral angle modification. Our calculations indicate that the rocks from the Lower and the Lower Critical Zones crystallized from a magma similar in composition to B1-type magma as suggested by previous authors. Our study illustrates that the combined analysis of whole-rock chemistry and cumulus and intercumulus minerals give useful results which allow the estimation of parental liquid composition from cumulate rocks for a wide range of elements. Moreover, our results indicate that the simple assumption of equilibrium between a melt and a mineral to calculate a parental magma can only be applied to pure adcumulate rocks. The methods of calculation presented in this study may be used to infer parental magma composition associated with Ni-Cu-PGE sulfide deposits and can potentially be used as an additional tool for mineral exploration to fingerprint prospective magma suites.

1. Introduction

Layered intrusions are studied to constrain and better understand the evolution of large magmatic systems including magma differentiation and magma chamber processes (e.g. Barnes et al., 2004; Bédard, 1994, 2001; Charlier et al., 2005; Cawthorn, 1983; Duchesne and Charlier, 2005; Maier et al., 2000; McBirney, 1995; Seat et al., in press; Tollari et al., 2008; Zingg, 1996). One of the key parameters in the modeling of the crystallization history of an intrusion is the estimation of the composition of its parental magma(s) (Wager and Brown, 1968). Traditionally, the composition of the parental liquid of a layered intrusion has been estimated by using two different approaches: (i) by analyzing the whole-rock composition of the fine-grained rocks found at the contact of the intrusion as chilled margins, or as dikes or sills spatially associated with the intrusion (Barnes et al., 2010; Cawthorn, 2006; Cawthorn et al., 1981; Curl, 2001; Davies and Tredoux, 1985; Godel et al., in press; Harmer and Sharpe, 1985; Seat et al., in press; Sharpe, 1981; Sharpe and Hulbert, 1985) or; (ii) by using the major and trace element compositions of cumulate minerals to back-calculate the parental magma with which they were in equilibrium (Bédard, 1994, 2001; Davies and Cawthorn, 1984; Duchesne and Charlier, 2005; Eales, 2000; Maier and Barnes, 1998).

Several issues arise in the estimation of the parental magma from the chilled margins or the fine-crystallized rocks spatially associated with an intrusion: (i) the rocks may represent melts that were contaminated by interaction with the country rocks; (ii) all the

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magmas from which a layered intrusion crystallized are not necessarily preserved as dikes or sills (Latypov et al., 2007; Marsh, 1995); (iii) complex mixing between several magma types may have occurred (Godel et al., in press) or; (iv) the magma may have undergone a complex fractional crystallization history between successive magma chamber replenishments. As a result, the fine-grained rocks may have formed from a melt which may not necessarily be representative of the parental magma of the intrusion with which they are associated.

The estimation of the parental magma from the analysis of cumulus minerals was, until recently, limited to major and few trace elements due to the lack of *in situ* methods to accurately determine the full range of trace elements at low level. Mineral separates are susceptible to containing inclusions of accessory phases often enriched in trace elements. Hence, although the separates may be analyzed to determine trace elements at low concentration level, the presence of inclusions may lead to the overestimation of the trace element abundances (Arndt et al., 2005) which in turn will impact on the estimation of the composition of the parental magma. In addition, the interpretation of the composition of cumulate minerals remains complicated as the composition of a given mineral depends on several factors including its degree of equilibration with the magma, the potential reaction between minerals and trapped liquid or fractionated melt which may have percolated during compaction, the exsolution of low-temperature phases during cooling, the potential homogenization of the mineral on cooling or metamorphism, and the alteration by late-stage magmatic or non-magmatic fluids.

The Rustenburg Layered Suite of the Bushveld Complex forms the largest layered intrusion on Earth which has been extensively studied over the past 100 years. Hence, the Rustenburg Layered Suite is an ideal natural laboratory to assess and constrain the effects of trapped liquid migration and other postcumulus modifications in the formation of cumulate rocks. We determined for the first time the trace element concentrations (by laser ablation ICP-MS) in cumulus (orthopyroxene and olivine) and intercumulus (clinopyroxene and plagioclase) minerals from the Lower and Lower Critical Zones of the Rustenburg Layered Suite. Together with whole-rock chemistry and micro-textural observations, these new chemical data are used to provide additional insights on the formation of these cumulates and to evaluate and test methods of calculation of parental magma composition from which the cumulates crystallized.

2. Geology

2.1. Geological settings

The 2054.4 ± 1.3 Ma old Rustenburg Layered Suite of the Bushveld Complex (Harmer and Armstrong, 2000; Scoates and Friedman, 2008) (Fig. 1) is the world's largest layered intrusion (Eales and Cawthorn, 1996) and has undergone little deformation or metamorphism after its solidification (Eales et al., 1993b). The 6.5 to 8.7 km thick ultramafic and mafic rocks of the Rustenburg Layered Suite are subdivided into five major zones (South African Committee for Stratigraphy, 1980): the Marginal, Lower, Critical, Main and Upper Zones (Fig. 1B).

2.2. Lower and Lower Critical Zones

The present study focuses on the Lower Zone and the Lower Critical Zone of the Union Section in the northern part of the Western Limb of the Bushveld Complex (Fig. 1). The studied samples were taken from boreholes NG-1 to NG-3 drilled by the Geological Survey of South-Africa in 1987 (Fig. 1A). At this locality, the Marginal Zone is absent and the Lower Zone directly overlies the sedimentary floor rocks. The Lower Zone at the Union Section (Fig. 2) has a thickness of approximately 800 m and consists principally of cyclic units of dunite, harzburgite, and orthopyroxenite (Teigler and Eales, 1996). The Lower Critical Zone consists of cyclic units of orthopyroxenite, minor

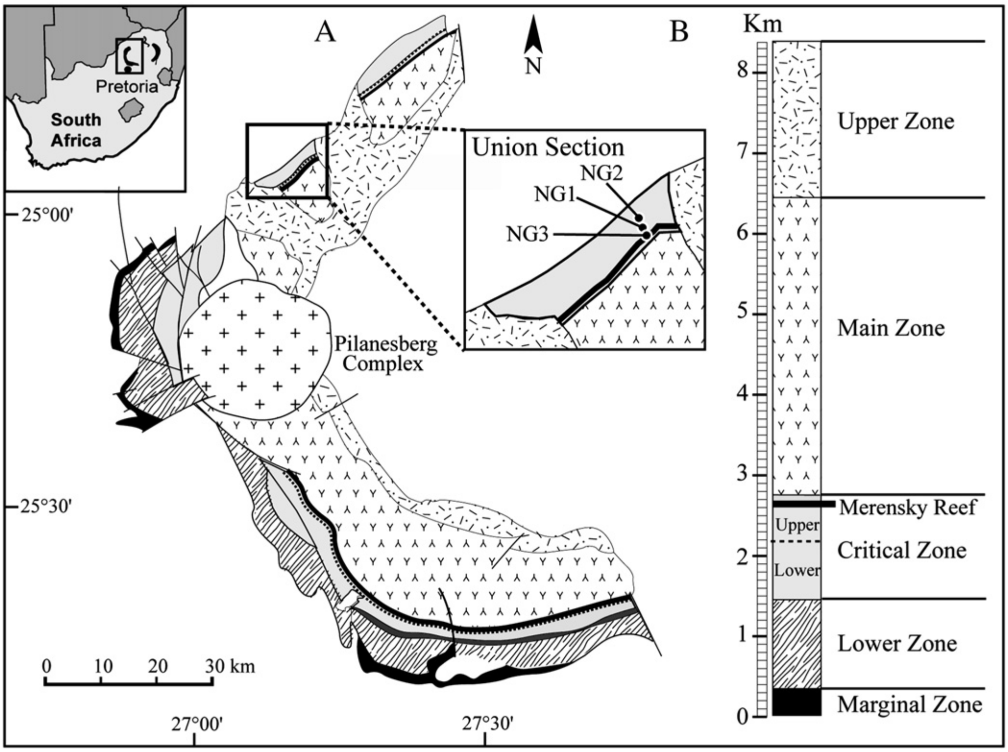

Fig. 1. Simplified geology of the Western Limb of the Bushveld Complex (modified after Godel et al., 2006) showing the locations of the drillholes NG1, NG2 and NG3. The locations of the drillholes are from Maier et al. (2000).