

Evolution of low-Ti and high-Ti rocks of the Jurassic Ferrar Large Igneous Province, Antarctica: Constraints from crystallisation experiments

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Summary The Jurassic Ferrar Large Igneous Province comprises two compositionally distinct magma series. In order to describe the differentiation history of these low-Ti and high-Ti series, equilibrium crystallisation experiments have been performed at 1100 °C and 2 kbar in internally heated pressure vessels. The experiments were conducted under variable redox conditions and water activities using a chilled margin sample from a low-Ti sill in northern Victoria Land as starting material. The phase relations and phase compositions of the experimental products exhibit systematic variations with changing run conditions. Based on the comparison of the experimental results with the compositional differences analysed in the natural low-Ti and high-Ti rocks, a model is proposed after which the high-Ti magmas differentiated under lower oxygen fugacity and water activity at lower pressures compared to the low-Ti magmas.

Citation: Hanemann, R. and L. Viereck-Goette (2007), Evolution of low-Ti and high-Ti rocks of the Jurassic Ferrar Large Igneous Province, Antarctica: Constraints from crystallisation experiments, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, edited by A. K. Cooper and C. R. Raymond et al., USGS Open-File Report 2007-1047, Extended Abstract 070, 4 p.

Introduction

The Jurassic Ferrar Large Igneous Province (FLIP) comprises numerous sills, dikes and lava flow sequences of basaltic andesites and andesites, which are exposed in a linear belt along the Transantarctic Mountains. Uniform crust-like trace element and isotope signatures indicate an identical magma source for the > 3000 km long Ferrar LIP. A subcontinental lithospheric mantle (SCLM) source has been proposed, which is characterised by enrichment in some crustal component due to Palaeozoic subduction along the Palaeo-Pacific margin of Gondwana (e.g., Hergt et al., 1989). The FLIP includes two compositionally distinct rock types of a tholeiitic magma series, the Mt. Fazio and Scarab Peak chemical type, which are referred to as low-Ti (LTS) and high-Ti series (HTS), respectively.

Our ongoing petrogenetic studies intend to further describe the genesis of the Ferrar magmas, especially the evolution of the two magma series. Based on mineral and bulk-rock chemical data for tholeiitic Ferrar rocks from northern Victoria Land (NVL), a differentiation model is proposed suggesting that the two magma series experienced pre-emplacment differentiation under different conditions. This differentiation model, which is developed considering the results of recent experimental studies, has been tested by crystallisation experiments with systematically varying run conditions. Some of the most important findings will be discussed with respect to the compositional data obtained for the studied Ferrar low-Ti and high-Ti rocks from NVL.

Prerequisites

The analysed basaltic andesites and andesites exhibit the common phase assemblage of tholeiitic differentiation sequences composed of varying amounts of pyroxenes, plagioclase, oxides and mesostasis. All samples have been classified into low-Ti ($\text{TiO}_2 \sim 0.4\text{-}1.2 \text{ wt}\%$) and high-Ti series ($\text{TiO}_2 \sim 1.7\text{-}2.1 \text{ wt}\%$). In contrast to the LTS, rocks of the HTS contain clinopyroxenes and plagioclase that are richer in Fe and Na, respectively. They generally lack orthopyroxene and exhibit higher concentrations of incompatible elements (e.g., FeO, TiO_2 , Y, Zr, REE) at only slightly enriched SiO_2 contents relative to the LTS.

As illustrated on the diagrams of figure 1, the single element concentrations of low-Ti rocks exhibit good correlations with the degree of differentiation of the distinctly evolved samples. These variations are interpreted to result from

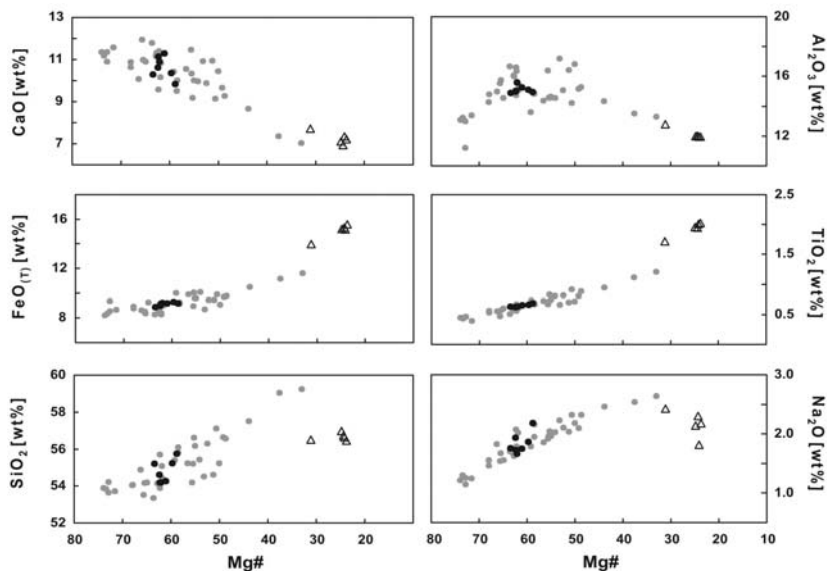


Figure 1. Variations of selected major elements with Mg# [$\text{Mg}\# = \text{Mg}/(\text{Mg}+\text{Fe}) \cdot 100$] as a differentiation index of the Ferrar low-Ti (●) and high-Ti (Δ) rocks from NVL. Black circles – “near”-chilled margins.

low-pressure in-situ differentiation. From the chilled margins of low-Ti sills (Mg# ~ 62), which are suggested to represent the pre-intrusive composition of the low-Ti magmas, cumulates and differentiates (Mg# ~ 74-33) developed after magma emplacement in the upper crust. However, based on our mineral and bulk-rock chemical data, the magmas of the chemically more evolved but uniform HTS (Mg# ~ 31-24) can not be generated by subsequent fractionation of the LTS magmas under low-pressure conditions. Furthermore, the uniform isotope and trace element signatures of the two Ferrar magma series indicate that commonly proposed models for the generation of distinct magma series in other LIPs, such as derivation from different magma sources or differences during melt generation, can be excluded. Thus, assuming an identical primary magma for both Ferrar magma series, differences during their pre-emplacement differentiation are proposed to explain their distinct compositions.

Preliminary Differentiation Model

Starting from a uniform primary magma composition (modelled for the LTS by Hergt et al., 1989), we observe stronger enrichment in FeO and TiO₂ but comparably less significant enrichment in SiO₂ and Na₂O for the high-Ti than for the low-Ti magmas, if unchanged conditions during pre-emplacement differentiation were assumed. Since it is widely accepted that the differentiation trend of a basaltic magma depends on its primary composition, its volatile content and composition, pressure and temperature as well as the prevailing oxygen fugacity, the distinct differentiation trends inferred for the Ferrar magma series are attributed to fractionation of compositionally distinct mineral phases caused by different conditions.

Several recent experimental studies investigated the influence of different crystallisation parameters on the phase relations and compositions during the evolution of tholeiitic basaltic magma. Villiger et al. (2007), for example, investigated the liquid lines of descent of tholeiitic magmas and obtained more significantly enriched FeO and TiO₂ concentrations for experiments at 7 kbar than at 10 kbar. Concomitantly, they demonstrate that SiO₂ and Na₂O reach higher concentrations at higher pressure. Furthermore, Muentener et al. (2001) and Feig et al. (2006) obtained phase relations in tholeiitic basaltic systems indicating that the plagioclase saturation curve is markedly shifted to lower temperatures with increasing water contents. Hence, magmas containing higher amounts of water evolve towards higher SiO₂ and Na₂O concentrations since plagioclase fractionation is suppressed and ferro-magnesian phases are preferentially fractionated (Sisson and Grove, 1993). In another study, Feig et al. (2004) observed an increased stability of orthopyroxene at higher pressure and at oxidising compared to reducing conditions. Moreover, Freise (2004) and Berndt et al. (2005) denoted higher Mg/Fe ratios in pyroxenes synthesised under oxidising *f*O₂.

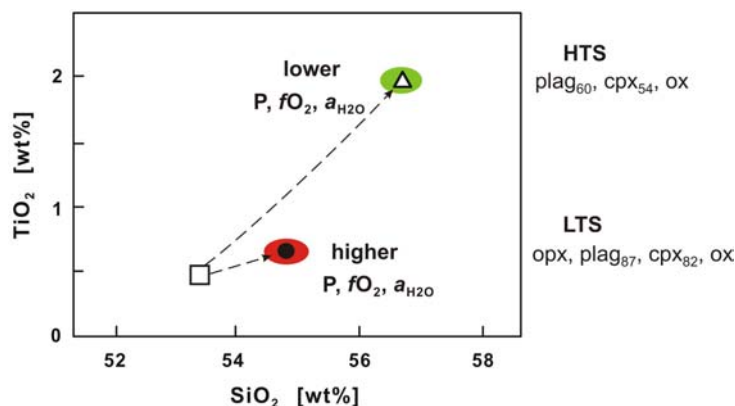


Figure 2. Differentiation model based on variations of TiO₂ with SiO₂ for Ferrar low-Ti (●) and high-Ti (Δ) rocks that are not influenced by in-situ differentiation. Primary magma composition (□) from Hergt et al. (1989). Conditions during pre-emplacement differentiation: P – pressure, *f*O₂ – oxygen fugacity, *a*_{H₂O} – water activity. Mineralogical differences of the natural rocks are indicated by the phases on the right: opx – orthopyroxene, plag – plagioclase with maximum An content, cpx – clinopyroxene with maximum Mg# [Mg# = Mg/(Mg+Fe)*100], ox – oxides.

Equilibrium Crystallisation Experiments

Experimental Techniques

Equilibrium crystallisation experiments were carried out using internally heated pressure vessels (IHPV) in the experimental petrology laboratory at the Institute of Mineralogy at the University of Hannover. The IHPV are pressurised with pure Ar or defined Ar-H₂ mixtures adjusted by an implemented hydrogen sensor membrane, which allows exact control of the *f*O₂. The vessel is furthermore equipped with a rapid-quench device to avoid quench-crystallisation. A detailed description of the vertically mounted furnace apparatus is given by Berndt et al. (2002).

The temperature and oxygen fugacity conditions applied during the experiments were selected according to the intensive crystallisation parameters, which were estimated from the mineral chemical data of the studied Ferrar samples. Hence, two experimental runs were conducted at 1100 °C under crustal pressure (2 kbar) at two different *f*O₂ in the range of the fayalite-magnetite-quartz (FMQ) oxygen buffer. For each of the two experimental runs, four Au₈₀Pd₂₀

capsules were prepared containing ~ 30 mg of a fused glass of a chilled margin of a low-Ti sill in NVL as starting material. The water activity in the particular capsules was varied by adding a well-defined mixture of H₂O and CO₂. The sample charges were fixed to a Pt-wire inside the rapid-quench device of the IHPV and heated directly to the desired run temperature of 1100 °C. The experiment under oxidising conditions ($\log fO_2 \sim \Delta FMQ+3$) was performed for 22 hours, while the run duration at reducing conditions ($\log fO_2 \sim \Delta FMQ-1$) was limited to 4 hours in order to minimise Fe-loss to the capsule material. At the end of the experiments, the Pt-wire holding the sample capsules in the hot spot of the furnace was fused electrically, and the charges were quenched isobarically as the capsules dropped down to the cold-quench area (20 – 25 °C) of the vessel chamber. Finally, polished sections were prepared from the synthesised solid material for electron microprobe analysis.

Characterisation and Analyses of the Experimental Products

The major element compositions of the experimental phases (as well as of the starting glass) were analysed by wavelength-dispersive technique using a Cameca SX-100 electron microprobe. The modal phase proportions of each experimental product were determined by mass balance calculations following the principle of least-squares linear regression, which balance the major elemental composition of the starting material against the averages of all synthesised phases in each charge. For calculating the exact fO_2 in each capsule, which is influenced by the water activity, the water contents in the residual melts were estimated following the “by-difference” method (Devine et al., 1995).

Experimental Results

There are several observations that indicate attainment of near-equilibrium conditions within the sample charges. In all experimental runs, the produced phase assemblage is composed of residual melt and homogeneously distributed mineral phases (pyroxenes and plagioclase). These \pm idiomorphic phases do not show disequilibrium features such as complex mineral zonations, they are chemically homogeneous within analytical error. Spatial variations in phase compositions within the single charges as well as quench crystallisation in the residual glasses could not be observed. Further evidence of equilibrium conditions is given by the phase relations and compositions, which change systematically with varying experimental conditions within the two run series. Moreover, the correlations of compositional parameters such as Mg# of pyroxenes and anorthite contents of plagioclase with the Mg# of the residual melts are in agreement with expected compositional trends.

One of the most obvious evidence of systematic compositional variations of the synthesised products is the inverse

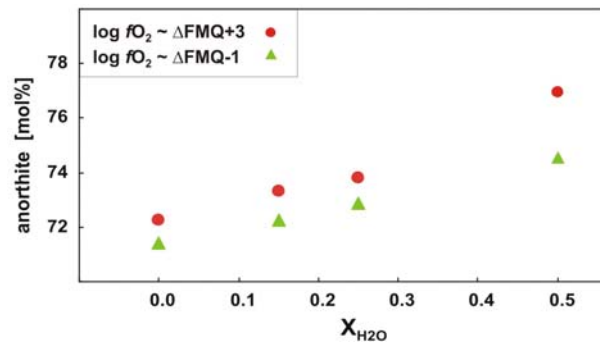


Figure 3. Variation of anorthite contents of experimental plagioclase with changing water contents X_{H_2O} preset in the experimental charges under oxidising ($\sim \Delta FMQ+3$) and reducing ($\sim \Delta FMQ-1$) conditions.

correlation of the crystallinity of the charges with the prevailing water activity. This observation is attributed to the fact that water added to a dry system shifts the solidus drastically to lower temperatures. Consequently, the modal abundances of mineral phases crystallised within the same run time increase with decreasing a_{H_2O} . However, plagioclase is the most affected phase; its amount increases more significantly with decreasing water content than those of low-Ca and high-Ca clinopyroxenes. Additionally, plagioclase exhibits strong compositional dependence on the presence of water; its anorthite content continuously decreases with decreasing water content. As displayed in figure 3, this relation is more pronounced at oxidising than at reducing conditions. A further important feature is the appearance of orthopyroxene; it is synthesised only under the most oxidising conditions at high a_{H_2O} . At the same conditions, plagioclase with the highest anorthite content has been produced.

Discussion

The described phase relations and compositions of the experimental products are compared with the compositional differences of the natural Ferrar low-Ti and high-Ti rocks. Since only low-Ti chilled margin samples and some low-Ti cumulates contain orthopyroxene, its appearance in experiments at higher fO_2 and a_{H_2O} defines the conditions during differentiation of the low-Ti magmas prior to their ascent into the upper-most crust. Furthermore, the stability of orthopyroxene correlates positively with pressure (Feig et al., 2004). In contrast, the high-Ti rocks do not contain orthopyroxene indicating that they experienced differentiation at lower fO_2 , lower a_{H_2O} and lower pressure as suggested in figure 2. This conclusion is supported by the comparably low anorthite content of plagioclase analysed in high-Ti rocks, since synthesised plagioclase is shown to become more albitic with decreasing a_{H_2O} and fO_2 (Figure 3). In addition, at lower water contents increasing amounts of plagioclase crystallised in the experimental charges. In conclusion, the increased fractionation of more albitic plagioclase may explain the less pronounced enrichment of SiO₂

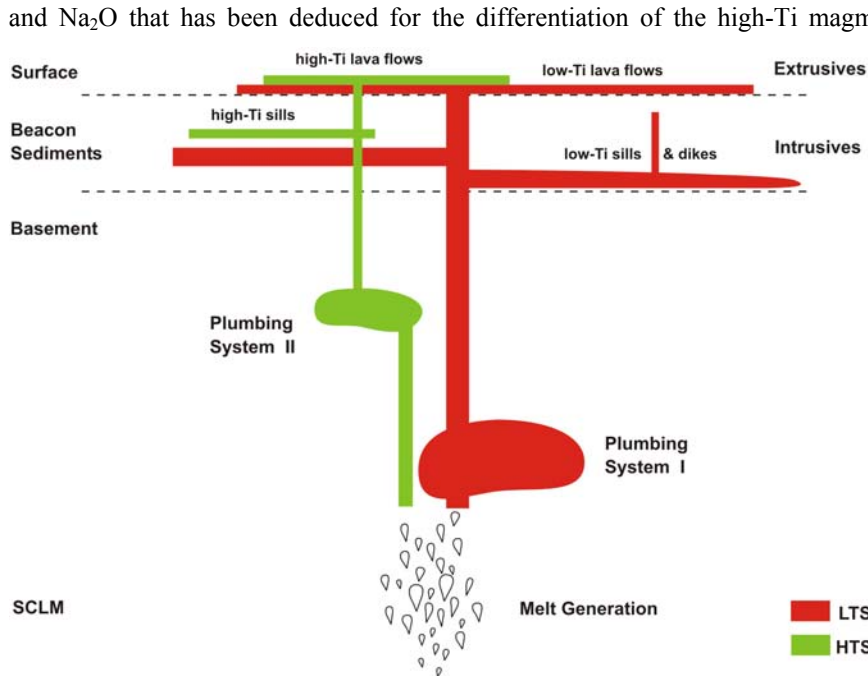


Figure 4. Petrogenetic model developed for the distinct evolution of the Ferrar low-Ti and high-Ti magma series.

Summary

The evolved bulk-rock compositions of the Ferrar low-Ti and high-Ti magma series are ascribed to an extensive pre- and post-emplacement differentiation history. However, the compositional differences between both magma series are attributed to pre-emplacement differentiation under different conditions. The influence of distinct parameters on the evolution of both magma series has been examined by crystallisation experiments in internally heated pressure vessels. Based on systematic variations of phase relations and compositions with the applied run conditions, a petrogenetic model is developed. We propose magma derivation by melt generation from a uniform source within the subcontinental lithospheric mantle that was followed by differentiation in temporary magma reservoirs at different crustal depths and hence different prevailing conditions for both magma series. The experimental results indicate lower water activity and oxygen fugacity at lower pressure during differentiation of the high-Ti magmas compared to the low-Ti magmas.

Acknowledgements. The authors would like to thank the co-editor Philip Kyle. The excellent support during the experiments by the working group of François Holtz and Juergen Koepke is gratefully appreciated. This study was financially supported by a grant from the German Science Foundation.

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and Na₂O that has been deduced for the differentiation of the high-Ti magmas. This finding can be related to the experimental results of Villiger et al. (2007), who obtained such a differentiation trend rather at lower pressure (7 kbar) than at higher pressure (10 kbar) conditions.

From these considerations, a model explaining the differences between both Ferrar magma series is deduced as displayed in figure 4. After melt generation from an identical magma source within the SCLM, the LTS magmas differentiated at lower-crustal conditions, whereas the HTS magmas possibly stagnated at mid-crustal depths and differentiated at lower fO_2 and a_{H_2O} than the LTS magmas.

The higher density contrast to the surrounding rocks at shallow crustal depth (compared to deeper levels) depressed the buoyancy of the high-Ti magmas and hence increased their residence time, which may explain the higher degree of differentiation of the high-Ti compared to the low-Ti magmas.