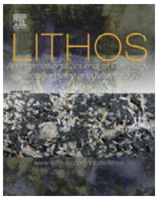
Lithos 172–173 (2013) 61–80

Contents lists available at SciVerse ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos



Melting of plagioclase + spinel lherzolite at low pressures (0.5 GPa): An experimental approach to the evolution of basaltic melt during mantle refertilisation at shallow depths

Françoise Chalot-Prat [a,*], Trevor J. Falloon [b], David H. Green [c], William O. Hibberson [d]

[a] CRPG-CNRS–Université de Lorraine, 15 rue Notre Dame des Pauvres, BP20, 54501 Vandoeuvre les Nancy, France
[b] School of Earth Sciences and Institute for Marine and Antarctic Studies (IMAS), Private Bag 79, Hobart, Tasmania 7001, Australia
[c] ARC Centre of Excellence in Ore Deposits and School of Earth Sciences, University of Tasmania, Private Bag 79, Hobart, Tasmania 7001, Australia
[d] Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia

ARTICLE INFO

Article history:
Received 12 June 2012
Accepted 30 March 2013
Available online 6 April 2013

Keywords:
Experimental petrology
Plagioclase + spinel lherzolite
Low pressure
MORB genesis
Mantle refertilisation

ABSTRACT

The presence of plagioclase + spinel lherzolites among ocean floor samples and in some ophiolite complexes invites speculation on their origin and relationships to processes of magmatism and lithosphere refertilisation beneath mid-ocean ridges. In an experimental approach to their petrogenesis, we have determined the compositions of liquids and co-existing minerals in the six phase assemblage [liquid + olivine + orthopyroxene + clinopyroxene + plagioclase + spinel] at 0.5 GPa and 1100 °C to 1200 °C. In our experimental approach we maintained the olivine Mg# [Mg / (Mg + Fe)] close to 90 (i.e., 88.8–95.5) but varied plagioclase from anorthite to albite. The major variations in liquid compositions are related to plagioclase composition. Liquids have much lower MgO and FeO and higher SiO_2 and Al_2O_3 than liquids in the 6-phase plagioclase + spinel lherzolite at 0.75 GPa and 1 GPa. Liquids are quartz-normative (silica-oversaturated) for plagioclase that are more calcic than An_{40} but nepheline-normative (critically silica-undersaturated) for plagioclase that are more sodic than An_{25}. Liquid compositions are quite unlike natural MORB glasses with similar Mg# (i.e., compatible with parental magmas from lherzolitic mantle with Mg# ≈ 90). Our study provides no support for models of MORB petrogenesis which suggest extraction of near-solidus melts from plagioclase lherzolite at low pressure. Similarly, referring to numerical models of melting volumes beneath mid-ocean ridges (Langmuir et al., 1992; McKenzie and Bickle, 1988) in which melt increments are calculated for different sites and these increments pooled to form MORB, our data argue that melts equilibrated with plagioclase ± spinel lherzolite at <1 GPa cannot be significant components of such 'pooled melt' focussed from within the melting volume. The compositions of minerals from plagioclase ± spinel lherzolite at Lanzo (northern Italy; Piccardo et al., 2007) are compared with our experimental assemblages at 0.5, 0.75 and 1 GPa, leading to the conclusion that the Lanzo plagioclase ± spinel lherzolites equilibrated at pressures between 0.75 and 1 GPa, at temperatures ~100–200 °C below the solidus. Field, petrological and geochemical studies argue that the Lanzo plagioclase ± spinel lherzolites are 'refertilised' by the reaction of residual harzburgite or lherzolite with percolating intergranular basaltic magma (Piccardo et al., 2007). The experimental study suggests that the process of refertilisation took place at depths of 25–30 km. Our experimental data also define the co-variance of Na_2O in coexisting plagioclase (An_{25} to An_{94}) and clinopyroxene at 0.5 and 0.75 GPa. From these data, the Na_2O content of clinopyroxene can be used as a predictor for the co-existing plagioclase composition in the very common occurrences of partially serpentinised peridotite in which plagioclase is completely saussuritised.

1. Introduction

We report an experimental study to determine the compositions of liquids and co-existing phases near the solidus of plagioclase + spinel lherzolite at a pressure of 0.5 GPa, i.e., equivalent to a depth of ~17 km. The motivation for the studies was to provide data to evaluate models of petrogenesis of Mid-ocean Ridge Basalts (MORB) in which adiabatic melting in upwelling lherzolite continues to shallow depths in mid-ocean settings (Asimow et al., 2001; Langmuir et al., 1992; McKenzie and Bickle, 1988; Presnall and Gudfinnsson, 2005; Presnall et al., 2002). It follows an equivalent study at 0.75 GPa (Chalot-Prat et al., 2010) in which the composition of liquids (Liq) saturated with five phases (olivine, orthopyroxene, clinopyroxene, plagioclase, spinel — Ol, Opx, Cpx, Plag, Sp) were determined as a function of plagioclase composition [An content or 100Ca / (Ca + Na)]. The

---

* Corresponding author. Tel.: +33 3 83 59 42 48 (Mobile), +33 6 70 74 17 36; fax: +33 3 83 51 17 98.
E-mail addresses: chalot@crpg.cnrs-nancy.fr (F. Chalot-Prat), Trevor.Falloon@utas.edu.au (T.J. Falloon), David.H.Green@utas.edu.au (D.H. Green).

0024-4937/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.lithos.2013.03.012

compositions of melts at the solidus are determined by the phase assemblages stable at the solidus. These phase assemblages are controlled by bulk composition, pressure and temperature. Fertile lherzolite compositions occurring naturally, or suggested as model compositions for the Upper Mantle, crystallise as plagioclase + spinel lherzolite at a pressure of <0.8 GPa (Borghini et al., 2010; Green and Ringwood, 1967). The upwelling mantle of lower potential temperature, or upwelling diapirs/plumes which lose heat to surrounding mantle and depart from the adiabatic ideal, may intersect the mantle solidus at shallow depths, i.e., in the plagioclase ± spinel lherzolite stability field (Jaques and Green, 1980; Presnall and Hoover, 1987; Walter and Presnall, 1994). The experimental study was designed to determine the compositions of such melts and of their residual phases.

In addition to melt extraction during upwelling, melt refertilisation by porous flow may occur particularly in the late or waning stage of diapirism and upwelling. This process has been invoked for many natural occurrences of plagioclase ± spinel lherzolite (Dijkstra et al., 2001; Kaczmarek and Müntener, 2008, 2010; Müntener et al., 2004, 2010; Piccardo and Vissers, 2007; Piccardo et al., 2004, 2007; Rampone and Borghini, 2008; Rampone et al., 1997, 2005, 2008; Seyler and Bonatti, 1997; Takahashi, 2001; Tartarotti et al., 2002; Warren and Shimizu, 2010). The upwelling peridotite may become quite refractory and residual in character as it reaches shallow levels. However, if residual, refractory peridotite continues to act as a channel or pathway for basaltic magma, then any unextracted magma may back-react to plagioclase ± spinel lherzolite mineralogy. Similarly, basaltic magma in dykes or in dunite channels may percolate into surrounding harzburgite or lherzolite. Such invasive percolation leads to a refertilised lherzolite, sometimes called 'secondary lherzolite'. Our experimental study may be applied to predict the evolutionary paths of both liquids and residues during mantle refertilisation at shallow depths. The pressure at which such a process occurs may be estimated from mineral compositions if we have an adequate experimental database (Borghini et al., 2011).

We conducted experiments which determine the compositions of all six phases *at the solidus* of plagioclase + spinel lherzolite. However we note that some plagioclase lherzolites form by *subsolidus* recrystallisation during upwelling (adiabatic or near-adiabatic decompression) at temperatures which are too low to intersect the anhydrous lherzolite solidus (e.g., Fig. 5 in Borghini et al., 2011) In other examples, higher temperatures and/or the presence of small water contents (indicated by trace pargasite) may cause upwelling lherzolite to intersect the anhydrous solidus, or the dehydration solidus or the fluid-saturated solidus (Cook et al., 2000; Green et al., 2010; Niida and Green, 1999) in the plagioclase + spinel lherzolite stability field. Borghini et al. (2010, 2011) demonstrated that for a particular bulk composition at constant temperature, the Ca/(Ca + Na) ratio of both plagioclase and clinopyroxene decreased with increasing pressure. For these conditions, plagioclase composition and modal abundance could be used for the estimation of pressure of crystallisation. However, the relevant reactions for the decrease of plagioclase with an increase of pressure include coupled substitutions of $^{+}Na^{+}Al^{-}Ca^{-}Mg$, $^{+}Na^{+}Cr^{-}Ca^{-}Mg$, $^{+}Al^{+}Al^{-}Mg^{-}Si$ and $^{+}Cr^{+}Al^{-}Mg^{-}Si$ in both ortho- and clinopyroxenes, and reaction of anorthite + olivine to yield pyroxenes + spinel. Therefore the bulk composition, particularly normative diopside, enstatite and chromite contents, will affect plagioclase compositions, in addition to the effect of pressure. In reducing the variance of the spinel lherzolite to plagioclase lherzolite experiments by the constraint of an additional phase (melt) and by systematically varying the plagioclase composition from albite to anorthite, our data should clarify the role of bulk composition in controlling plagioclase composition in the spinel lherzolite to plagioclase lherzolite transition. Finally, by studying the effects (on melt and residual phase compositions) of varying one key chemical exchange (Ca vs Na) at a fixed pressure, our data are useful for deriving predictive numerical models of melting of mantle lherzolite and particularly for relating empirical melt variations to particular mineral solid solutions and reactions.

2. Experimental methods

All experiments were carried out at the Research School of Earth Sciences, The Australian National University (Canberra, Australia) using 1.6 cm diameter end-loaded piston-cylinder apparatuses. The experimental assembly used an inner pyrex glass sleeve surrounding the graphite heater, and enclosed in a salt (NaCl) outer sleeve, (Chalot-Prat et al., 2010). Because of the large diameter of the pressure vessel, the salt and pyrex glass pressure media, and the long run times, the pressure for the sample was equated with the applied load pressure and is estimated as 0.5 +/− 0.05 GPa. Several experiments were carried out at nominal 0.25 GPa and 0.375 GPa to explore a particular feature of melt compositions in the Ca-free, sodic system. The same experimental set-up, i.e., 1.6 cm pressure vessel and salt + pyrex glass pressure media, was employed, and pressure was estimated from the load pressure. At these low pressures the pressure calibration of the piston–cylinder apparatus is imprecise but our observations over the 0.25 GPa to 1 GPa are internally consistent with equating load pressure and sample pressure.

As noted for the 0.75 GPa experiments reported in Chalot-Prat et al. (2010), several sample capsule types were trialled, in which the most successful technique was the '3-in-1' method in which three small diameter $Au_{25}Pd_{75}$ capsules were placed within a large $Au_{25}Pd_{75}$ capsule containing a Fe-enriched hydrous basanite melt. The three inner capsules contained mixes of slightly different compositions with the intent to obtain at least one, and preferably 2 or 3, experiments which had a large melt fraction in contact with four or five mineral phases. A temperature correction of +20 °C was applied because of the capsule length and thermocouple position. Temperatures are considered accurate to ±20 °C. Note that in the '3-in-1' experiments, all charges experience the same P,T such that differences in phase assemblages and compositions between the three inner capsules of the 3-in-1 assembly are a consequence of compositional differences alone, and cannot be attributed to temperature or pressure uncertainties.

Classical experimental petrology in simple systems, construction of phase diagrams in ceramics, metallurgy, etc… involves varying bulk compositions with different proportions of phases 'A', 'B', 'C' ('3-component system') and for each bulk composition observing the phases present as a function of temperature. If we are seeking the solidus temperature and melt composition at the solidus then in a simple eutectic melting with each phase melting congruently, then we will map compositional fields in which each of A, B, C is a liquidus phase, together with field boundaries along which 2 phases + Liq are present and a point at which these boundaries meet and we have eutectic melting i.e., *the solidus temperature for any mixture of different proportions of A, B and C*. From its position in the 3-component triangle we can calculate the melt composition at the solidus. Different bulk compositions in the system have *the same composition* L for the melt at the solidus but will have different proportions of residual mineral(s) and different melt fractions.

This is the strategy that we have followed in the chemically complex 'basalt–peridotite' system — we have varied bulk compositions which can be presented as mixes of normative minerals Ol, Qz, Di, Plag, Sp rather than as oxides This compositional space can be explored experimentally for liquids which are saturated in 5 mineral phases. We have deliberately varied Plag composition but attempted to keep Mg–Fe solid solution near Mg# = 90 for olivine. In this approach the bulk or starting compositions are a convenience to achieve the desired equilibrium 6-phase assemblage of minimum variance. The bulk compositions do not relate to a particular model mantle composition and the equilibrium relationships remain correct for any modal proportions of the six phases analysed at a given P,T.

Our results can be applied to any model mantle composition such as MOR pyrolite, or HZ1, or Tinaquillo Lhz, or Hawaiian pyrolite by choosing an An content of Plag (say An85) and thus the liquid