Garnet Stability in Metabasites Inferred from Dehydration Melting Experiments and Implications for Lower Crustal Delamination

R. Nair*
Department of Geoscience, University of Calgary, Calgary, Canada T2N 1N4
rnair@ucalgary.ca

and

T. Chacko
Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada T6G 2E3

Summary

We present garnet stability relations during dehydration melting of two MORB-type mafic bulk compositions in the temperature range 775-1050 ^{o}C and from 7-22.5 kbar. Garnet was found to be stable at pressures above 10 kbar and at temperatures >800 ^{o}C. Calculated density of the restite during the experiments is directly correlated with the modal abundance of garnet and plagioclase. Based on the variation of the restite density during melting we argue that crustal thickness in excess of 55 km is required to effect delamination of lower crust.

Introduction

Phase relations in metabasaltic rocks are considered to play an important role in geodynamic processes (Cloos, 1993; Peacock 1993). The density increase accompanying the transformation of basalt to eclogite is thought to provide the driving force for lower crustal delamination (Zegers and van Keken, 2001). Stability and growth of garnet during the metamorphic evolution of metabasaltic rocks plays a fundamental role in the density transformations that occurs in these rocks. Here, we report the garnet stability and growth relations in MORB-type bulk composition during dehydration melting and discuss its implications on lower crustal delamination.

Methodology, Summary of Results and Conclusions

We investigated the dehydration melting behavior of two natural high grade amphibolites in the temperature range 775-1050 ^{o}C and from 7-22.5 kbar using a piston cylinder apparatus. The whole-rock and mineralogical composition of the starting materials (KAP and 3VG) are shown in Table 1. The powdered starting materials were held in sealed Au-capsules during the experiments and the details of the experimental procedures are as in Nair and Chacko (2002). The starting materials contained minor amounts of garnet, which would have acted as nuclei for the growth of garnet during the experiments. The experimental duration varied from 720 hours at 775 ^{o}C to 48 hours at 1050 ^{o}C. After the experiments, the phases were analyzed using an electron microprobe. Modal proportions of phases in the experimental products were determined using a combination of mass balance mineral compositional data from microprobe analyses and grayscale thresholding of backscattered electron (BSE) images using the software ImageJ (Rasband, 1999). Restite densities were calculated using measured mineral compositions and abundances and mineral molar volume, compressibilities and expansivities given by Berman and Aranovich (1996).

Table 1: Whole-rock and mineralogical composition of starting materials used in the experiments.

Wt.%	SiO$_2$	TiO$_2$	Al$_2$O$_3$	FeO^T	MnO	MgO	CaO	Na$_2$O	K$_2$O	Total	Mode*	Mg#
Kapuskasing (KAP)												
Hornblende	42.28	1.81	12.53	17.82	0.28	9.23	10.95	1.12	1.12	97.14	55	0.48
Plagioclase	58.19	0.00	26.19	0.03	0.01	0.00	7.98	7.00	0.25	99.65	35	
Garnet	37.56	0.04	20.72	26.02	2.86	2.99	9.69	0.02	n.a.	99.90	1	0.17
Clinopyroxene	50.87	0.27	2.68	11.89	0.38	10.94	21.97	0.68	0.03	99.71	4	0.62
Quartz											6	
Three Valley Gap (3VG)												
Hornblende	43.14	2.17	12.28	14.76	0.12	11.01	11.11	1.50	1.48	97.57	53	0.57
Plagioclase	56.60	0.00	27.25	0.09	0.01	0.00	9.42	6.21	0.40	99.98	35	
Garnet	37.97	0.05	21.46	26.21	1.17	5.77	7.24	0.02	n.a.	99.89	<1	0.28
Clinopyroxene	52.08	0.15	2.10	11.05	0.24	12.80	21.12	0.50	0.03	100.07	5	0.67
Quartz											7	
whole-rock composition (wt.%)												
KAP$^+$	51.44	1.09	15.01	11.44	0.24	5.79	11.22	3.00	0.77	100.00		0.47
3VG$^+$	51.95	0.80	14.14	11.18	0.18	7.29	11.06	2.52	0.88	100.00		0.54
MORB	50.58	1.45	15.45	9.98	n.a	7.95	11.56	2.71	0.18	99.86		0.59
	(0.62)	(0.30)	(0.75)	(1.02)	-	(0.71)	(0.60)	(0.38)	(0.15)			

*- mode estimated from thin sections of the rocks from the starting materials was taken; Mg# = Mg/(Mg+Fe) molar; n.a.- not available
+- XRF anyalses recalculated to 100; MORB data from PETDB database; numbers in brackets are 1 sigma std. deviation of oxide (wt.%) for MORB.

Garnet is stable in these bulk composition at pressure >10 kbar and temperatures >800 ^{o}C. We argue this to be the minimum P-T conditions required for garnet formation during dehydration melting. The proportion of garnet coexisting with melt increases from 10-22.5 kbar and is correlated with a near-linear increase in restite (from ~2.95-3 g/cm^3 to 3.45-3.47 g/cm^3) in both bulk compositions (Figure 1). The increase in density with increasing pressures is also correlated with decrease in the abundance of plagioclase.

Delamination of lower crust through the development of Rayleigh-Taylor instabilities requires that the basaltic crust attain a density greater than that of the underlying mantle. Our experimental phase relations and calculations show that density increase above 3.3 g/cm^3, a value appropriate for the density of mantle, is only achieved at pressures >17.5 kbar. This corresponds to garnet abundance in the restite >20 vol. % and plagioclase abundance <5-10%. These results places constraints on the thickness a basaltic crust should have to affect delamination. Our calculations indicate that a minimum crustal thickness of ~55 km is required for lower crustal delamination for crust of MORB-type bulk compositions.

Delamination of crust has been proposed as an alternative geodynamic process to subduction and recycling of ocean crust/oceanic plateaus in early Earth (van Thienen et al., 2004; Bedard, 2006). Zegers and van Keken (2001) and Bedard (2006) proposed delamination events in lower crust to explain the formation of Tonalite-Trondhjemite-Granodiorite (TTG) suite of igneous rocks in the Archean. Implicit in these models is the assumption that crustal thickness in the Archean exceeded the thickness required to affect delamination. The maximum crustal thickness predicted by parameterized mantle melting models (e.g. Vlaar and van den Berg, 1991) for an Archean mantle potential temperature of 1750 ^{o}C (the highest mantle potential

temperature inferred from eruption temperatures of Archean komatiite lavas) is significantly less than 55 km, our estimated threshold oceanic crust thickness to affect delamination. Density of lower crust would not have exceeded that of underlying mantle at the base of normal Archean crust derived from decompression melting of mantle. We argue that delamination processes could not have operated in the Archean without tectonic or magmatic thickening of the crust after it formed.
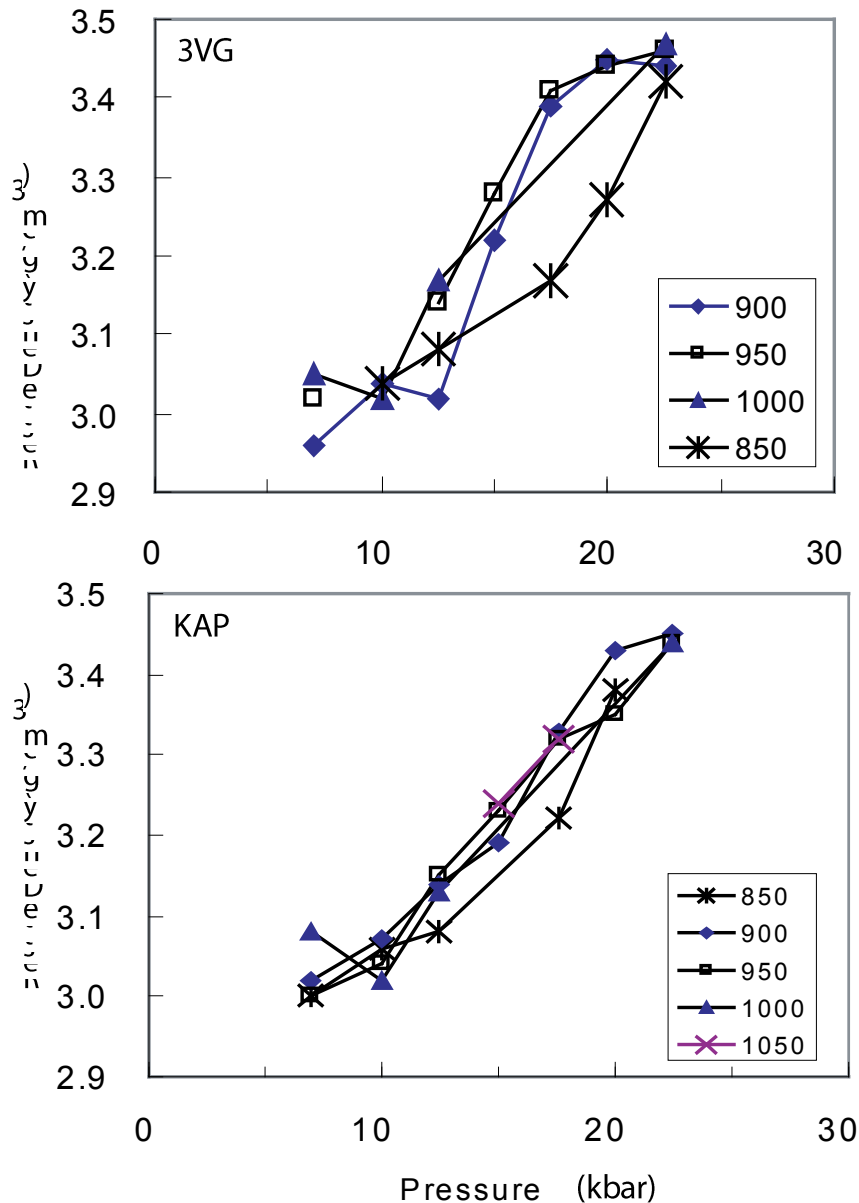

Figure 1. Calculated restite density (g/cm^3) as a function of pressure (kbar) for the two starting compositions (top- 3VG; bottom-KAP). Variations in density shown for different temperatures (^{o}C).

Acknowledgements

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