

**Kinetics of Partial Melting and Melt-Rock Reaction
in the Earth's Mantle**

by

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of Philosophy in the Department of Geological Sciences at Brown University

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Scoates JS, **Lo Cascio M**, Weis D, Lindsley DH. Experimental constraints on the origin and evolution of mildly alkalic basalts from the Kerguelen Archipelago, South East Indian Ocean. *Contributions to Mineralogy and Petrology*, 151, 582-5991 doi: 10.1007/s00410-006-0070-y, 2006

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MANUSCRIPTS IN PREPARATION

Lo Cascio M and Liang Y. Kinetics of peridotite and pyroxenite-derived melts interaction: Implications for the style and extent of melt-rock reaction in the Earth's mantle

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Lo Cascio M. Etude expérimentale du fractionnement polybarique dans les laves basaltiques à tendance alcaline de l'Archipel de Kerguelen et implications pour le volcanisme des îles océaniques. Mémoire de fins d'études (Senior Thesis), Département des Sciences de la Terre et de l'Environnement, Faculté des Sciences, Université Libre de Bruxelles, June 2001

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1. **Lo Cascio M**, Liang Y. Reaction between lherzolite and eclogite-derived melts in the upper mantle. *Eos Trans. AGU*, 88, Fall Meet. Suppl., Abstract, 2007
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- in the Lunar volcanic glasses: Evidence for the presence of indigenous water in the Moon's interior. *Eos Trans. AGU*, 88, Fall Meet. Suppl., Abstract, 2007
3. Liang Y, **Lo Cascio M**, Morgan Z, Peng Q, Kelemen P. Melt-peridotite reaction in the mantle: Grain-scale processes and geological applications. *Journal of China University of Geosciences*, 18: 194-197, 2007
 4. Liang Y, **Lo Cascio M**, Hess PC. Preferential assimilation of armalcolite and ilmenite during melt migration and melt-rock reaction in the lunar mantle: An experimental study. *Lunar and Planetary Science Conference, XXXVIII*, 2007
 5. **Lo Cascio M**, Liang Y. Kinetics of peridotite and pyroxenite-derived melts interaction: Implications for the style and extent of melt-rock reaction in the mantle. *Eos Trans. AGU*, 87 (52), Fall Meet. Suppl., Abstract V23D-0651, 2006
 6. **Lo Cascio M**, Liang Y, Shimizu N. A new experimental method for determining cpx/melt trace element partitioning during peridotite melting. *Goldschmidt Conference Abstracts 2005. Geochimica Cosmochimica Acta*, 69-10, sup.1, A823, 2005
 7. **Lo Cascio M**, Liang Y. The behavior of pyroxenes during partial melting of pyroxenite and lherzolite in the mantle: An experimental and numerical study. *Eos Trans. AGU*, 85 (47), Fall Meet. Suppl., Abstract V41C-1406, 2004
 8. **Lo Cascio M**, Liang Y, Hess PC. Grain-scale processes during isobaric and isothermal melting of lherzolite. *Eos Trans. AGU*, 84 (46), Fall Meet. Suppl., Abstract V12C-0605, 2003
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 10. **Lo Cascio M**, Scoates J, Damasceno D, Weis D. Experimental constraints on the evolution of mildly alkaline basalts from the Kerguelen Archipelago. *EUG XI Meeting in Strasbourg, France*, 2000
 11. Scoates J, **Lo Cascio M**, Weis D, Doucet S, Damasceno D, Giré A. The significance of thick, aphyric basaltic lava flows on the Kerguelen Archipelago. *EUG XI Meeting in Strasbourg, France*, 2000

DOCTORAL EXPERIENCE

Graduate Research, Brown University

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- Devised new high-pressure experimental techniques to understand the grain-scale processes associated with partial melting of pyroxene-rich lithologies in the Earth's upper mantle
- Investigated numerically the implications of melt-rock reaction during partial melting and melt-transport in the Earth's upper mantle
- Determined the interfacial energy between quartz and $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$ melt at 1.0 GPa and 1500°C through Ostwald ripening experiments
- Presented discoveries at 8 international conferences, 4 invited talks, and 7 departmental lectures
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- Summarized students' views to the 2006 geology faculty search committee for the top 6 candidates

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Abstract

Partial melting of the mantle occurs predominantly in the spinel lherzolite stability field, where pyroxenes are consumed to produce olivine and basaltic melt. The phase equilibria of this reaction are relatively well understood but the grain-scale processes through which pyroxenes undergo partial melting are not. With a combination of kinetic experiments and numerical modeling, I demonstrated that during partial melting of lherzolites of varying bulk compositions, lherzolites do not simply melt at equilibrium but go through a series of kinetic process that involve primarily dissolution and reprecipitation. The most important feature of these grain-scale processes is the reduction in equilibration times between melt and minerals by several orders of magnitude, suggesting that melting in the mantle might take place closer to equilibrium conditions than currently believed. These results are presented in Chapters 1, 2, and 4.

In Chapter 3, I explored the nature of the interface between peridotites and pyroxenites in the mantle to understand the mechanisms controlling the style and extent of chemical interaction between these two lithologies. The motivation behind this study is to determine the scale and evolution of heterogeneities in the Earth's mantle and to determine their role in basalt petrogenesis. My dissolution experiments demonstrated the existence of two melt-rock reaction regimes depending on whether the lherzolite is subsolidus or partially molten. At subsolidus conditions, dissolution is extremely slow and equilibration between the pyroxenite-derived melt and peridotite is unlikely. When the lherzolite is partially molten, the dissolution mechanism changes from simple dissolution to reactive dissolution (involving diffusive mixing, dissolution, and reprecipitation of several phases) and resulting in significant increase in equilibration and dissolution rates. Using these experiments I was able to derive kinetic parameters that I subsequently introduced into a reactive porous flow model where I explored the fractionation of incompatible trace elements during melt

transport. The results of this simulation suggest that if enriched signals in ocean-floor basalt originate from pyroxenite-derived melts, then the melt migration rate through the uppermost mantle must be very fast (on the order of mm to cm/sec).

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I wish to thank my PhD advisory committee for guidance and flexibility during these many years. My advisor, Yan Liang, has provided me with continued support for nearly seven years and has taught me everything I know about kinetic processes in igneous systems. Paul Hess has been one of the best teacher I've ever had, expanded my knowledge of petrology, and taught me everything I know about thermodynamics. I wish to thank Marc Parmentier for introducing me to geodynamics and to numerical modeling techniques. I would also like to thank Alberto Saal for sharing with me his great deal of knowledge in geochemistry and for providing me with free therapy sessions in his office :-). I wish to thank Nobumichi Shimizu for introducing me to the ion probe at Woods Hole, for his enormous help during the analyses, and for his help at the end of my thesis. I also can't thank enough Peter Kelemen for taking me twice to the Josephine and Trinity ophiolites, and for giving me the only opportunity I had during my PhD to taste what field work is like.

My many friends have also been crucial in helping me adapt not only to graduate school but also to North American culture. Mike Nicholis has been (and is) one of my best friends and together we have endured graduate school while sharing the office. My good friend Caleb Holyoke has managed to avoid a heart attack every time I "borrowed" his Oldsmobile and I can't thank him enough for all of his help in and outside the lab. Nancy Fjeldheim has been my great therapist and friend who would make me laugh even if we were

at a funeral. Peter Gromet has always been great to me and I thank him for having me over his house during many holidays that I would have spent alone otherwise. I wish to thank Bill Collins for his tremendous help and support in and outside of work, and for including me in the amazing Geochron saga! Joseph Devine has been amazing to me, patiently taught me how to use the microprobe at Brown, and provided me with much needed comic relief during my PhD. I would also like to thank Jan Tullis for her moral support and great advice throughout my PhD. I can't thank enough Ruth Crane, Gloria Correra, Pauline Fennelly, Lisa Sheehan, and Margaret Doll who have provided me with an incredible amount of help and support while at Brown. I would like to thank Malcolm Rutherford for his support and for showing me the greatest rock ever during my prelims: what a minette! Reid Cooper has been a fantastic teacher and I thank him for introducing me to material sciences and for stimulating discussions in his office. I wish to thank Zlatko, Nena, and Maja for their encouragements and continued support during the last stretch of my thesis. Mark Abbott and Gail Ruggieri have kept me physically healthy and I thank them both for being great teachers. Finally, I would like to thank, in no particular order, the many people I've had the pleasure to interact, go out, crash wedding parties, dance, eat and drink, play some insane football, bush diving, swim in frozen lakes in Maine, and overall helped me stay sane while in graduate school: Kate Rychert, Cliff Claflin, Nicholas Harmon, Josh Schwartz, Winfield Wilson, Shiri Avnery, Rob and Eustacia Jacob, Marshall Sundberg, Amandine Cagnioncle, Sarah Zaranek, Christine McCarthy, Ryan Weisshaar, Zach Morgan, Alyssa Beck, Andrew Huebner, David and Dawn Abt, Giulio Di Toro, Elena Narduzzo, David Goldsby, Michael Harrison, Jenni Junger, Brian Football King, Angie Roach (my first office mate ever!), and last but not least The Graduate Center Bar....you guys just rock! I would also like to thank the National Science Foundation for providing me the support that funded my PhD under grants EAR-0208141, EAR-9902684, and EAR-0510606 awarded to Yan Liang.

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CHAPTER 1

Grain-scale processes during isothermal-isobaric melting of lherzolite

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Abstract

The grain-scale processes of peridotite partial melting were examined at 1340°C and 1.5 GPa using reaction couples formed by juxtaposing pre-synthesized clinopyroxenite against pre-synthesized harzburgite. Reaction between clinopyroxenite and harzburgite produces a melt-enriched, orthopyroxene-free, olivine + clinopyroxene reactive boundary layer. Clinopyroxene compositions vary systematically across the reactive boundary layer with compositional trends similar to the published clinopyroxene core-to-rim compositional variations in the bulk lherzolite partial melting studies conducted at similar P-T conditions. The growth of the reactive boundary layer is at the expense of the harzburgite and is consistent with grain-scale processes that involve dissolution, reprecipitation, and diffusive exchange between the interstitial melt and surrounding crystals.

1. Introduction

At moderate pressures, partial melting of spinel lherzolite produces olivine and melt at the expense of pyroxenes via the reaction $\text{cpx} + \text{opx} + \text{sp} \rightarrow \text{ol} + \text{melt}$. This melting relation has been extensively studied in the laboratory using natural and synthetic starting compositions (e.g., Kushiro, 2001, and references therein). Most of the studies have focused on the composition of the melt produced at prescribed P-T conditions, and equilibrium was assumed when the melt composition did not change with time (e.g., Stolper, 1980; Takahashi and Kushiro, 1983; Baker and Stolper, 1994). Although significant progress has been made through laboratory studies, in detail, the grain-scale processes through which peridotite partially melts are still not fully understood. For example, a feature common to most laboratory melting studies using natural starting materials is that residual pyroxenes are chemically zoned (e.g., Stolper, 1980; Takahashi and Kushiro, 1983; Baker and Stolper, 1994; Robinson et al., 1998; Pickering-Witter and Johnston, 2000; Wasylenski et al., 2003). This zonation has typically been attributed to solid-state diffusion, though the validity of this interpretation has not been carefully examined. Recent theoretical studies have shown that during isothermal-isobaric melting of solid solution forming minerals more complicated processes such as dissolution and reprecipitation are likely to take place (Liang, 2003).

In order to better understand the grain-scale processes of lherzolite melting, we conducted a set of partial melting experiments at 1340°C and 1.5 GPa using reaction couples formed by juxtaposing pre-synthesized harzburgite and clinopyroxenite. The advantage of the reaction couple method is the production of a thick reaction zone that provides a unique opportunity to study the grain-scale processes of lherzolite melting. As will be shown below, dissolution and reprecipitation play an important role in controlling the distributions of various elements in the melt and residual minerals during lherzolite melting.

2. Experimental Methods

Melting experiments were carried out in two steps: Melting experiments were carried out in two steps: (1) syntheses of harzburgite and clinopyroxenite, and (2) reaction between the pre-synthesized clinopyroxenite and harzburgite (ol:opx = 54:46, by weight), all at 1340°C and 1.5 GPa. Starting materials were prepared by mixing handpicked optically clean mineral separates from a fertile spinel lherzolite xenolith from central Mexico (sample XDJ16 from Liang and Elthon, 1990). For simplicity, spinel was not included in this study.

All experiments were conducted using a 19.1 mm piston cylinder apparatus with a NaCl-Pyrex-graphite-MgO furnace assembly, and a molybdenum capsule consisting of a graphite inner sleeve lined with platinum, similar to those described by Morgan and Liang (2003). Synthesis experiments were run at 1340°C and 1.5 GPa for 48 hrs. After quenching, the cylindrical capsule was cross sectioned, the exposed surfaces were polished to 5 µm finish and dried for at least 24 hrs at 200°C under vacuum. Harzburgite and clinopyroxenite cylindrical half-capsules were then juxtaposed, jacketed with platinum tube to form a reaction couple. To start a melting experiment, the reaction couple was first annealed at 1200°C and 1.5 GPa for 24 hrs, the temperature was then increased to 1340°C at 150°C/min and held at the run condition for 47–79 hrs. Each run product was mounted in epoxy, sectioned longitudinally and polished to 0.3 µm finish.

Chemical analyses were conducted using a Cameca SX-100 electron microprobe at Brown University. Analytical conditions common to all the analysis were an accelerating voltage of 15 kV, a 20 nA focused beam for minerals, a 10 nA slightly defocused beam for glass, and a 50 nA focused beam for X-ray intensity maps.

3. Results and Discussion

3.1 Experimental charge

At the run condition (1340°C and 1.5 GPa), the pre-synthesized clinopyroxenite and harzburgite contain small amounts of melt (<5% and 1%, respectively). Thus our reaction couple consists of melt-bearing harzburgite and clinopyroxenite. Results from two experiments are presented here (duration of 47 and 79 hrs, respectively). Each experimental charge consists of three distinct zones (Figure 1a): (1) clinopyroxene + melt, (2) an orthopyroxene-free reactive boundary layer consisting of olivine + clinopyroxene + melt, and (3) orthopyroxene + olivine + melt. The opx-free reactive boundary layer is located on the harzburgite side of the original clinopyroxenite-harzburgite interface (marked by capsule offset in Figure 1a), suggesting that the reactive boundary layer was formed at the expense of the harzburgite. The thickness of the reactive boundary layer increases with time (up to 250 μm for the 79 hr run). Modal abundance of clinopyroxene appears to decrease in the reactive boundary layer with run time (from 48% to 29%), whereas those of olivine and the melt increase (50% to 57%, and 3% to 14%, respectively). As highlighted by the X-ray intensity map in Figure 1d, the melt (15%) is concentrated in the reactive boundary layer.

3.2 Mineral and Melt Compositions

Both cpx and opx grains are chemically zoned in the clinopyroxenite and the harzburgite (Figures 1b–1d). Detailed microprobe traverses show that the core-to-rim chemical variations in cpx grains are much smaller than the cpx compositional differences across the reactive boundary layer, especially for the longer duration run. As shown in Figure 2, SiO_2 , MgO , and FeO in cpx increase towards the reaction front, whereas CaO , Al_2O_3 , and Na_2O in cpx decrease from the clinopyroxenite to the harzburgite. In general, opx cores have lower CaO and slightly higher Al_2O_3 content (asterisks in Figure 3) than opx

rims (open triangles in Figure 3). The extent of core-to-rim variation in opx is not correlated with distance from the reaction boundary layer. The olivine composition, in contrast, does not vary significantly throughout the charge.

Although compositional variations in residual pyroxenes have been noted in most lherzolite melting experiments, core-to-rim compositional variations were reported in only a few studies. Figure 3 compares our measured pyroxene compositions across the clinopyroxenite-harzburgite reaction couple with the pyroxene core-to-rim compositions reported by Robinson et al. (1998) and Pickering-Witter and Johnston (2000). The most striking feature of this plot is that the compositional variations in pyroxenes across our reactive boundary layer are very similar to the pyroxene core-to-rim compositional variations observed in the lherzolite melting experiments. The pyroxene rim compositions from the bulk melting studies (stars in Figure 3) correspond to the pyroxene compositions around the harzburgite-clinopyroxenite interface, whereas the pyroxene core compositions from the previous studies correspond to the pyroxene compositions far away from the reactive boundary layer (i.e., in the interiors of the clinopyroxenite and harzburgite).

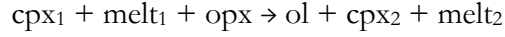
Although small dendritic crystals were observed in the reactive boundary layer, the presence of several large melt pockets in the reactive boundary layer (Figure 1d) allows us to measure the melt composition in that region. In contrast to the systematic variations in cpx across the reactive boundary layer, the melt compositions in this region are more scatter (Figure 2), reflecting the role of local mineralogy and the disequilibrium nature of our experiment. In compositional space, SiO_2 (50.8~52.5%), Al_2O_3 (15.5~17.8%), Na_2O (4.8~5.7%), and TiO_2 (0.9~1.05%) define negative but weak correlations with the MgO content of the melt (6.1~8.4%), where ranges of melt composition are given in the parentheses. No clear correlations were observed for CaO (10.7~12.4%) and FeO (4.9~6.6%). The FeO-MgO mineral-melt distribution coefficients are 0.27 to 0.39 for

olivines and 0.27 to 0.42 for clinopyroxenes in the reactive boundary layer, indicating some quench effect. The SiO_2 , TiO_2 , Al_2O_3 , FeO , and CaO abundance in melts from our reaction couple experiments are similar to those reported in bulk lherzolite melting experiments conducted at similar P-T-t conditions (e.g., Baker and Stolper, 1994; Robinson et al., 1998; Pickering-Witter and Johnston, 2000), whereas the high- Na_2O and low- MgO characteristics of our melts are similar to those observed in the peridotite-basalt (pyroxenite) mixture or reaction couple experiments (e.g., Kogiso et al., 1998; Takahashi and Nakajima, 2002). This is not surprising since our experimental charge is in fact a pyroxenite-peridotite reaction couple. A more detailed study of the interstitial melt compositions will be reported elsewhere.

3.3. Grain-Scale Processes

The presence of concentration gradients in our reaction couple experiments suggests that diffusion plays an important role during clinopyroxenite-harzburgite reaction. Nevertheless, given the relatively slow cation diffusion rates in pyroxenes, it is unlikely that the observed concentration gradients in cpx within the reactive boundary layer are produced by solid-state diffusion alone. For instance, a bulk diffusivity of $10^{-14} \text{ m}^2/\text{s}$ would be needed to account for the observed concentration variations of Ca, Mg, and Fe in cpx in the reactive boundary layer. This apparent bulk diffusivity is 3–5 orders of magnitude larger than the Mg^{2+} - Fe^{2+} chemical diffusivity in cpx (Brady and McCallister, 1983) and 3-4 orders of magnitude smaller than the effective binary diffusivities of MgO and FeO in basalt at 1300°C (Leshner, 1994). Hence diffusion in the melt and in the solid must both contribute to the development of the reactive boundary layer in our experiments.

The development of the reactive boundary layer is consistent with the following reaction:



where subscripts 1 and 2 designate material in the clinopyroxenite and reactive boundary layer, respectively. The original melt in the clinopyroxenite (melt_1) is undersaturated in orthopyroxene and enriched in jadeite component. Hence melt_1 reacts with (or dissolves) opx at the clinopyroxenite-harzburgite reaction front. The rate of this reaction is limited by the rate of diffusion in the interstitial melt (Morgan and Liang, 2003). Incongruent dissolution of opx produces a silica-rich liquid and olivine, as is evident by the increase in olivine grain size in the reactive boundary layer (Figures 1a and 1b). Part of the dissolved opx components mix with melt_1 , resulting in cpx reprecipitation in the reactive boundary layer (cpx_2), as is evident by the increase in cpx grain size in this region (Figures 1b–1d). Hence composition of melt_2 is the net result of $\text{opx} + \text{melt}_1$ reaction, olivine precipitation, and cpx_2 reprecipitation in the reactive boundary layer. Similarly, diffusive infiltration of small amount of melt_2 into the harzburgite results in opx reprecipitation in the harzburgite. The extent of opx reprecipitation is likely small due to the small fraction of melt in the harzburgite. This interpretation is consistent with the theoretical and numerical analyses of the grain-scale processes of crystal dissolution-reprecipitation in partially molten systems (Liang, 2003). It also confirms speculation of Kogiso and Hirschmann (2001) regarding the processes of cpx reequilibration in their study of clinopyroxenite melting. The mechanisms outlined here can be used to better understand the grain-scale processes of lherzolite melting in general.

3.4. Applications to Lherzolite Partial Melting in the Laboratory

It is well known that pyroxenes are chemically zoned in isothermal-isobaric partial melting experiments using natural lherzolite starting compositions (e.g., Stolper, 1980; Takahashi and Kushiro, 1983; Baker and Stolper, 1994; Robinson et al., 1998; Pickering-

Witter and Johnston, 2000). The zoning persists even in long duration runs, while the composition of the melt appears to be homogeneous. The fact that the pyroxene core-to-rim compositional variations in bulk lherzolite melting experiments are similar to the pyroxene compositional variations in our reaction couple experiments (Figure 3) suggests that these systematic variations are produced by similar grain-scale processes, involving dissolution and reprecipitation, in addition to solid-state diffusion.

The development of pyroxene core-to-rim compositional variations can be understood as follows. During initial stage of partial melting of a spinel lherzolite (e.g., within the first few minutes of an experiment), a transient melt was first produced by disequilibrium melting of pyroxenes at their grain boundaries and grain junctions. The disequilibrium melt dissolves pyroxenes and precipitates olivine. The rate of pyroxene dissolution depends on the rate of chemical diffusion in the melt and the extent of under-saturation between the crystals and the melt. With continuing dissolution and diffusive reequilibration in the melt, compositions of the interstitial melt become uniform throughout the charge. This usually takes a few hours to a day, a time scale defined by cation diffusion in the interstitial melt with length scale given by the mean distance between the pyroxenes. Since cation diffusion rates in minerals are much slower than those in the melt, only the surface of the crystals are in chemical equilibrium with the melt, as noted in numerous experimental studies. It can be shown through a simple mass balance calculation that the weight fraction of pyroxene dissolved is larger than expected by the lever rule. In other words, pyroxenes are over-dissolved (for a detailed discussion of this topic, see Liang 2003). As the partially molten system continues to equilibrate, over-dissolution is followed by reprecipitation of pyroxenes, which is rate limited by solid-state diffusion. On laboratory time-scales, reprecipitation of pyroxene is too slow to compensate for the initial over-dissolution, giving rise to the observed zoning in pyroxenes. Hence the chemical processes

governing the bulk lherzolite partial melting in the laboratory are identical to those observed in our clinopyroxenite-harzburgite reaction experiments. The differences between the two are the initial and boundary conditions. For example, the effective volume of cpx is much larger than that of opx and hence orthopyroxene was completely consumed in our reaction experiments.

3.5. Implications For Pyroxenite-Peridotite Reaction Studies

Although the primary objective of this study is to understand the grain-scale processes of lherzolite melting, the experimental method developed here can also be used to study the kinetics of pyroxenite-peridotite interaction. The roles of garnet pyroxenite and pyroxenite-peridotite in mantle melting have received considerable attention in experimental petrology lately (e.g., Yaxley and Green, 1998; Kogiso et al., 1998; Rapp et al., 1999; Takahashi and Nakajima, 2002; Hirschmann et al., 2003). The geometry of our reaction couple is similar to those of Yaxley and Green (1998), Rapp et al. (1999), and Takahashi and Nakajima (2002) in their experimental studies of pyroxenite-peridotite or eclogite-peridotite melting/reactions. The main differences are the starting mineral compositions, the use of the molybdenum outer capsule, and the pre-synthesis step in our experiments. The molybdenum capsule helps to preserve the sample geometry and the offset between the two half-capsules marks the original interface between the clinopyroxenite and the harzburgite at the onset of reaction (Figure 1a). The location of the original interface is essential in quantitative studies of the kinetics of pyroxenite-peridotite interactions.

Results from our clinopyroxenite-harzburgite reaction experiments show that disequilibrium reaction between a pyroxenite and a peridotite can create a melt and a new peridotite having geochemical features broadly similar to those observed in the peridotite-eclogite reaction experiments (e.g., Yaxley and Green, 1998; Rapp et al., 1999; Takahashi and

Nakajima, 2002). Although more work is needed, the grain-scale processes discussed in this study may help to understand the development of the orthopyroxenite reactive boundary layer observed in the pyroxenite-peridotite reaction experiments.

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Figure Captions

Figure 1. (a) Back-scattered electron (BSE) image of the central part of a run conducted at 1340°C and 1.5 GPa for 79 hrs. The offset between the two half-capsules marks the original interface between the harzburgite and the clinopyroxenite (arrow on the left). (b)–(d) false-colored Mg, Ca, and Al X-ray intensity maps of the selected portion of the reactive boundary layer outlined by the dashed box in (a). Red represents high concentrations. Black or dark blue corresponds to low concentrations.

Figure 2. Selected oxide concentration profiles as a function of distance for the run shown in Figure 1. The origin ($x = 0$) marks the original interface position between the harzburgite and the clinopyroxenite. Blue circles represent cpx, asterisks the opx cores, open triangles the opx rims, green circles the olivine, and red circles the glass.

Figure 3. Covariation of Ca^{2+} and Al^{3+} in the pyroxenes in this study compared to those reported by Robinson et al. (1998) and Pickering-Witter and Johnston (2000), outlined by ellipses. Stars represent pyroxene rim composition of these two studies, whereas circles represent cpx, asterisks the opx cores, and open triangles the opx rims of this study.

Figure 3b. Correction to Fig. 3: Covariation of Ca^{2+} and Al^{3+} in the pyroxenes of this study compared to those reported by Pickering-Witter and Johnston (2000) and Robinson et al. (1998), outlined by ellipses. The composition of the minerals in this study, are reported as circles for the cpx, asterisks for the opx cores, and open triangles for the opx rims. During partial melting of peridotite (Pickering-Witter and Johnston, 2000) the cpx composition changes from high Ca^{2+} - Al^{3+} cores towards low Ca^{2+} - Al^{3+} rims, similar to the chemical trend observed in our study.

However, during melting with concomitant crystallization of cpx and opx from a basalt layer (the “sandwich” technique used in Robinson et al., 1998), the core-to-rim trends are reversed. This trend is not characteristic to peridotite partial melting but to crystallization from a high-Al content basalt (in this case the liquid composition is located at $\text{Ca} \sim 0.5$ and $\text{Al} \sim 0.7$).

Figure 1.

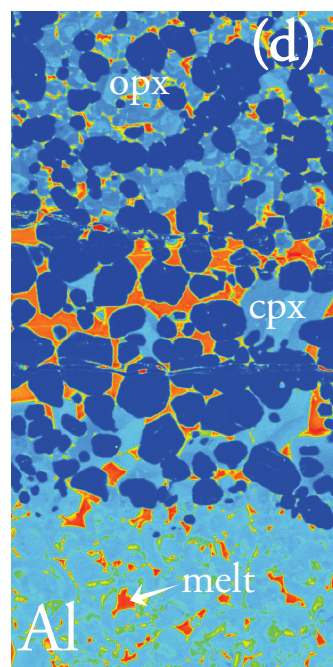
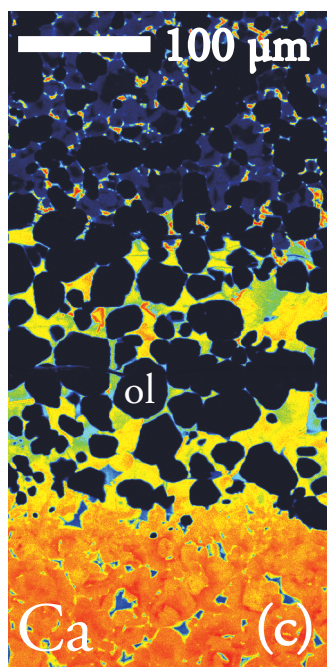
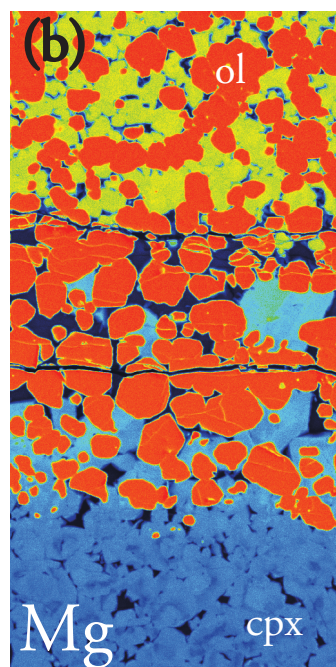
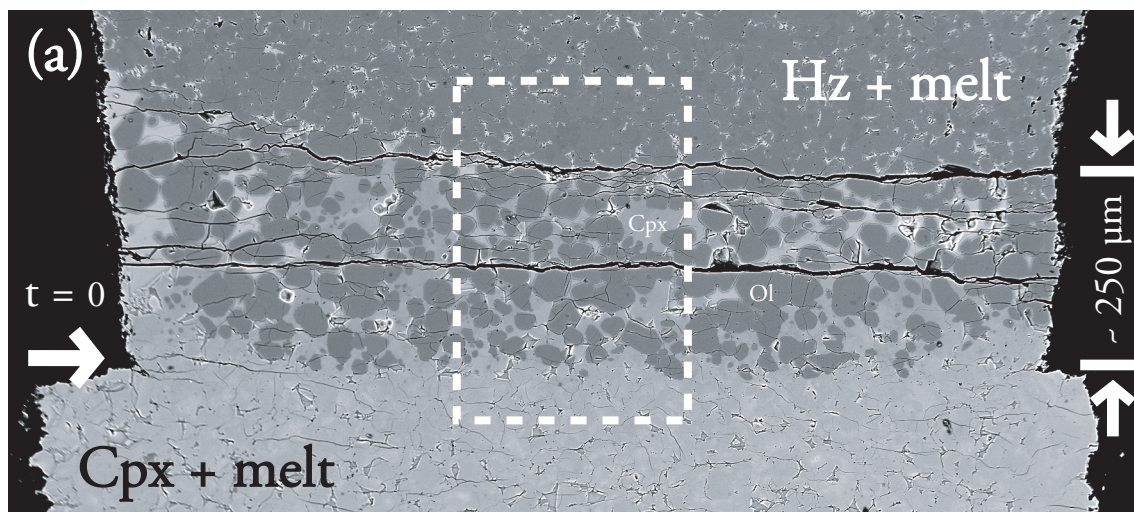


Figure 2.

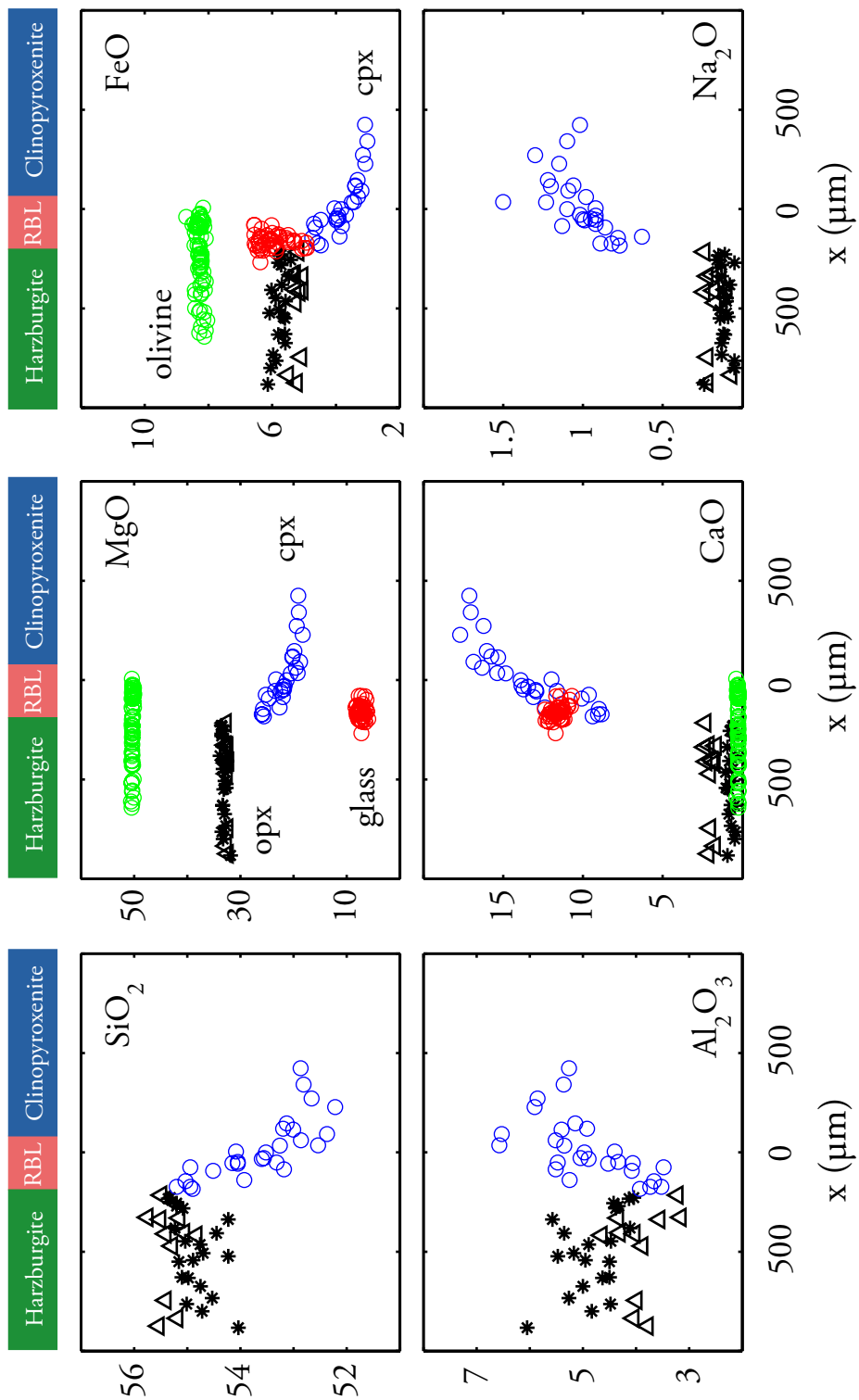
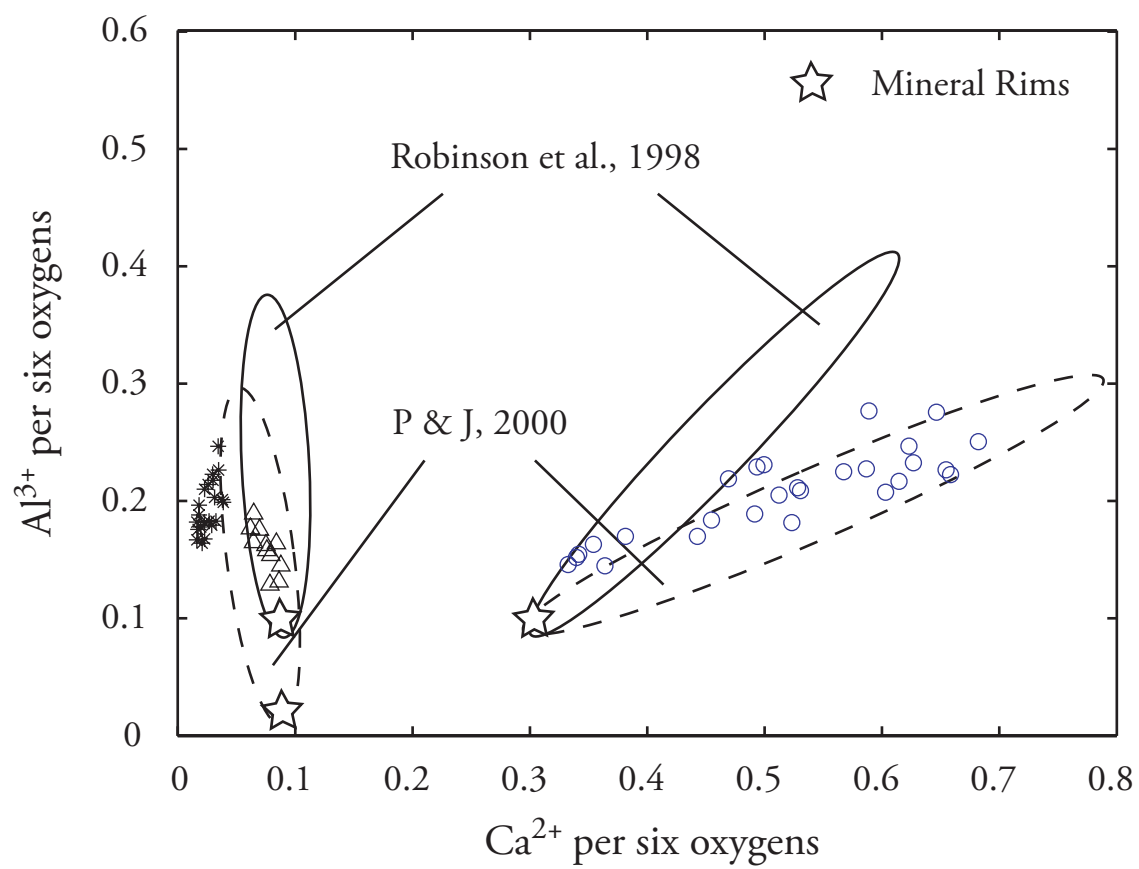
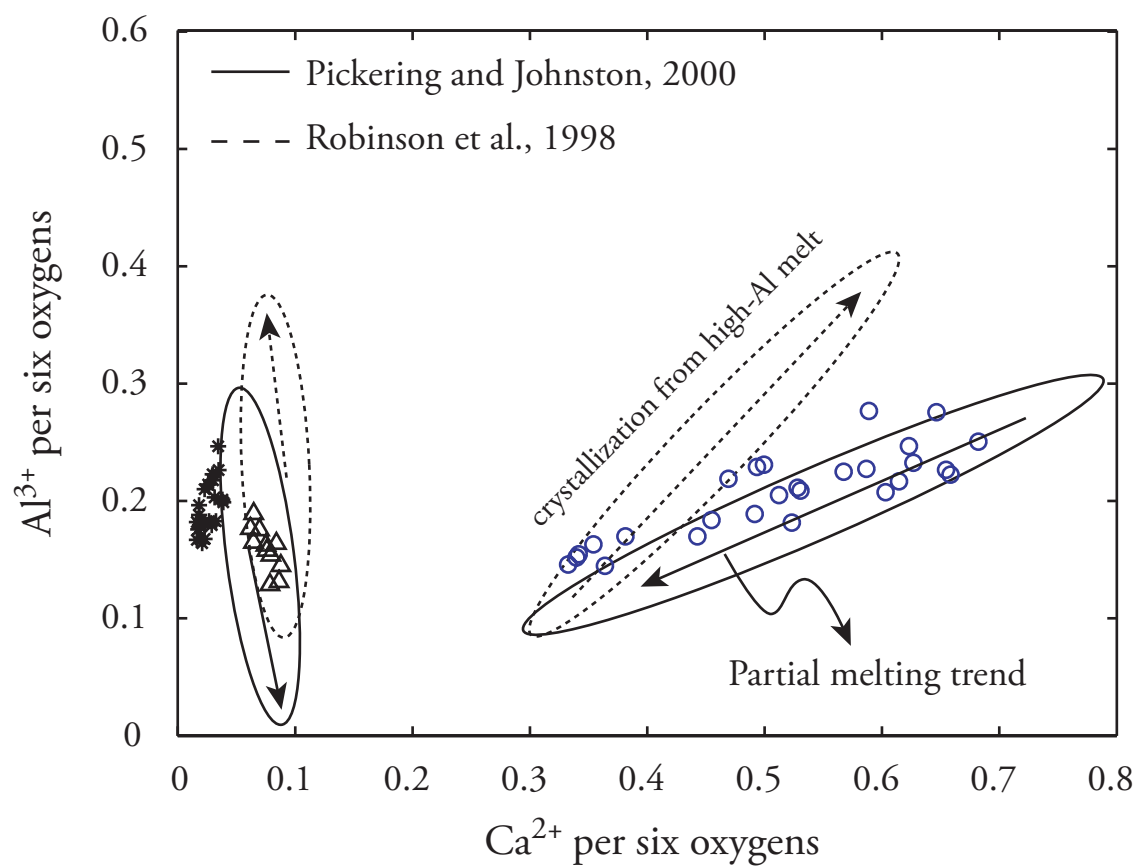


Figure 3.





CHAPTER 2

**An experimental study of the grain-scale processes of peridotite
melting: implications for major and trace element distribution during
equilibrium and disequilibrium melting**

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Abstract

The grain-scale processes of peridotite melting were examined at 1340°C and 1.5 GPa using reaction couples formed by juxtaposing pre-synthesized clinopyroxenite against pre-synthesized orthopyroxenite or harzburgite in graphite and platinum-lined molybdenum capsules. Reaction between the clinopyroxene and orthopyroxene-rich aggregates produces a melt-enriched, orthopyroxene-free, olivine + clinopyroxene reactive boundary layer. Major and trace element abundance in clinopyroxene vary systematically across the reactive boundary layer with compositional trends similar to the published clinopyroxene core-to-rim compositional variations in the bulk lherzolite partial melting studies conducted at similar P–T conditions. The growth of the reactive boundary layer takes place at the expense of the orthopyroxenite or harzburgite and is consistent with grain-scale processes that involve dissolution, precipitation, reprecipitation, and diffusive exchange between the interstitial melt and surrounding crystals. An important consequence of dissolution–reprecipitation during crystal melt interaction is the dramatic decrease in diffusive reequilibration time between coexisting minerals and melt. This effect is especially important for high charged, slow diffusing cations during peridotite melting and melt-rock reaction. Apparent clinopyroxene–melt partition coefficients for REE, Sr, Y, Ti, and Zr, measured from reprecipitated clinopyroxene and coexisting melt in the reactive boundary layer, approach their equilibrium values reported in the literature. Disequilibrium melting models based on volume diffusion in solid limited mechanism are likely to significantly underestimate the rates at which major and trace elements in residual minerals reequilibrate with their surrounding melt.

1. Introduction

Partial melting of the Earth's mantle occurs predominantly in the spinel lherzolite stability field, where clinopyroxene (cpx) and orthopyroxene (opx) are consumed to produce olivine and basaltic melt, i.e., $\text{cpx} + \text{opx} \rightarrow \text{olivine} + \text{melt}$ (e.g., Walter, 2005 and references therein). Although the stoichiometry and melt composition of this reaction has been extensively studied, the grain-scale processes through which pyroxenes undergo partial melting have not yet been examined in detail. These processes are extremely important in controlling how major and trace elements are redistributed between the liquid product and the residual solids during partial melting, melt transport, and melt-rock reaction in the Earth's mantle. To date, most partial melting studies make two common assumptions: (1) equilibration is taken for granted when the melt composition does not change with time even though residual pyroxenes are zoned, and (2) the observed zonations in the pyroxenes are attributed to solid state diffusion. The implications of these assumptions have important consequences beyond laboratory experiments. For instance, diffusion in minerals has often been taken as the dominant rate limiting mechanism for crystal-melt chemical exchange for the trace elements during fluid or melt infiltration, melt-rock reaction, and disequilibrium melting in the upper mantle and lower crust (e.g., Navon and Stolper, 1987; Bodinier et al. 1990; Qin, 1992; Iwamori, 1993, 1994; Hauri, 1997; Korenaga and Kelemen, 1998; Van Orman et al., 2002a; Liang, 2003a). It has been shown that diffusion in solid dominated crystal-melt exchange is important for the slow diffusing trace elements only when the major element in the crystals and their coexisting melt are in chemical equilibrium (e.g., Liang, 2003b).

In a series of numerical and theoretical studies of the grain-scale kinetics of crystal dissolution in molten and partially molten systems, we have shown that dissolution, precipitation, and reprecipitation are inevitable consequences of crystal-melt interaction in

multicomponent partially molten systems (Liang, 2003b, 2005). The processes of dissolution and reprecipitation can be illustrated with the help of a simplified binary phase diagram (Fig. 1). As shown in Fig. 1, if the interstitial melt (L) is initially under-saturated with respect to the solid solution-forming crystal (S), the crystal will dissolve, but only at earlier times. Because the rate of diffusion in the melt is much faster than the rate of diffusion in the solid, the bulk melt composition quickly evolves to the liquidus of the dissolving crystal (L_e). Since only the surface of the dissolving crystal (S_e) is in chemical equilibrium with melt L_e , the interior of the crystal appears over-saturated with respect to the melt. Dissolution then reverses to precipitation that finally stops when the concentration gradients in the solid are eliminated (animations showing the processes of dissolution and reprecipitation in a crystal-melt aggregate can be found in Liang, 2003b). When the crystal-melt aggregate is open to mass transfer with their surrounding (via diffusion and advection), reprecipitation can also take place in another part of the system, away from where dissolution originated. In systems where mineral grain size is not uniform, small grains may dissolve completely before reprecipitation starts, resulting in a reduction in crystal number density. Depending on the extent of undersaturation, the reprecipitated mineral grain size may be considerably larger, as will be shown in this study. The rate of dissolution is determined by the rate of the slowest major diffusing component in the melt (usually SiO_2 , referred to as Regime I dissolution in Liang, 2003b), whereas the rate of reprecipitation is dominated by the rate of the fastest major diffusing component in the crystal. An important consequence of dissolution and reprecipitation is the acceleration of crystal-melt re-equilibration rates for both major and trace elements in partially molten silicates. This point will be further demonstrated experimentally in the present study.

In a preliminary study, we examined the major element chemistry and the kinetics of reaction between a clinopyroxenite and a harzburgite at 1340°C and 1.5 GPa using a reaction

couple method (Lo Cascio et al., 2004). The basic idea behind our reaction couple method is that if peridotite melting takes place through the reaction $\text{cpx} + \text{opx} \rightarrow \text{olivine} + \text{melt}$, the melting process then can be conveniently studied by examining the reaction between a cpx-rich aggregate and an opx-rich aggregate. Indeed, reaction between the clinopyroxenite and the harzburgite produced a reactive boundary layer (RBL) that consists of new olivine, new cpx, and melt. The formation of the RBL is consistent with a grain-scale process that involves dissolution of cpx and opx, precipitation of olivine, and reprecipitation of cpx. Major element variations of cpx across the RBL are similar to the core-to-rim compositional trends observed in cpx from bulk lherzolite partial melting studies, suggesting that the grain-scale mass transfer processes during bulk lherzolite melting in the laboratory and natural are governed by the same dissolution and reprecipitation processes documented in our reaction couple experiments. The grain size of the reprecipitated cpx (up to 50 μm long) and melt pocket (over 100 μm wide) in the RBL are sufficiently large that it would be possible to measure the REE and other incompatible trace element abundance in coexisting cpx and melt in the RBL using an ion microprobe.

In this study, we further expanded our experimental investigation of the grain-scale processes associated with peridotite melting by reacting presynthesized clinopyroxenite with presynthesized orthopyroxenite, by including spinel and small amount of basaltic melt in our reacting couple, and by analyzing both major and trace element (REE, Y, Sr, Ti, and Zr) abundance in coexisting phases in our reaction products. Since kinetic processes are path dependent and the geometry of the reaction couple in our earlier experiments (clinopyroxenite against harzburgite, Lo Cascio et al., 2004) are significantly different from that of the bulk peridotite melting studies, it is important to check if the grain scale processes summarized above and outlined in Lo Cascio et al. (2004) are sensitive to the choices of reaction couples, as well as the presence of spinel. The general conclusions of

Lo Cascio et al. (2004) may not be applicable to peridotite melting in the mantle if the grain-scale melting processes are sensitive to (or different among) the choices of reaction couples. As will be shown below this is not the case. Spinel is the main Al-bearing mineral in spinel peridotite and including spinel in our reaction couple experiments will allow us to explore the distribution of Al_2O_3 in reprecipitated cpx. Addition of small amount of basalt not only further increases the Al content of the starting material but also speed up reaction rates.

It is well known that partition coefficients of REE and high field strength elements (HFSE) between cpx and coexisting basaltic liquid depend strongly on the Al_2O_3 abundance in cpx (e.g. Lundstrom et al., 1994; Gaetani and Grove, 1995; Hill et al., 2000). Measuring REE and selected incompatible trace element abundance in interstitial melt and reprecipitated cpx of variable Al_2O_3 abundance in our reaction couples will allow us to identify the dominant mass transfer processes governing the distribution and partitioning of the high charge, slow diffusing cations during partial melting and melt-rock reaction. One of the major objectives of the present study is to evaluate the extent of chemical equilibrium or disequilibrium between clinopyroxene and its coexisting melt for the REE and HFSE during melt-peridotite interaction. We will show that disequilibrium melting models based on volume diffusion in solid alone are likely to significantly underestimate the rates at which major and trace elements in residual minerals reequilibrate with their surrounding melt.

2. Experimental and analytical methods

2.1 Starting materials

Starting materials for this study were prepared from mineral separates of two fertile spinel lherzolite xenoliths from central Mexico, XDJ-16 and XDJ-11, described by Liang and Elthon (1990). Olivine, cpx, and opx were separated from XDJ-16 and the spinel (sp) was collected from XDJ-11 because of its larger grain size and similar composition to XDJ-16.

For one experiment, we used a basaltic glass from the Herdubreid volcano in Iceland (sample HBT01) in order to increase the Al_2O_3 content of the system. The major element compositions of the starting materials are reported in Table 1.

Coarse mineral separates (0.5-1 mm) were obtained from sieved and optically clean handpicked minerals from the disaggregated nodules. The separates were then ground for 20 minutes in ethanol, dried under a heating lamp and sieved again to obtain a range in grain size of 25-38 μm . Five sets of starting materials were obtained by mixing the processed mineral separates and basaltic glass in desired proportions: (1) pure cpx, (2) opx with less than 5% (by volume) olivine, (3) 54% (by weight) olivine and 46% opx, (4) 94% opx and 6% sp, and (5) 76% cpx, 6% spinel and 17% basaltic glass.

2.2 Experimental methods

All experiments were conducted using a 19.05 mm piston cylinder apparatus using straight-walled graphite furnace, NaCl pressure medium, Pyrex tubing, crushable MgO spacers and insulators, and a molybdenum capsule. The cylindrical molybdenum capsule (6.5 mm OD, 4.1 mm ID, 10 mm long) is lined with a platinum tube (4.0 mm OD, 3.8 mm ID), which in turn is lined with a graphite inner sleeve (3.8 mm OD, 2.0 mm ID), as shown in Fig. 2a. In this assembly the sample is in contact only with the graphite inner sleeve and therefore the oxygen fugacity of the experiments is maintained at or below the graphite-CO buffer, which corresponds to a $\log f\text{O}_2 \leq \text{FMQ}-1$ log unit at 1340°C and 1.5GPa (e.g., Jacobsson and Oskarsson, 1994). One of the advantages of using the Mo-Pt-C capsule is that the strength of Mo assures a reasonably good geometry for both synthesis and dissolution runs, while preventing the sample and the graphite capsule from reacting with the Mo.

Melting experiments were carried out in several steps. First we synthesized the five starting materials in a Mo-Pt-C capsule at 1.5 GPa for 48 hours. Four of the syntheses (cpx, opx, harzburgite, and opx + sp) were run at 1340°C while the synthesis of the cpx + spinel + glass and one set of the opx + spinel mixture were run at 1300°C, due to the lower melting point of the cpx + spinel + glass mixture. After quenching each synthesis run, the capsule was sectioned perpendicular to its cylindrical axis with the exposed surfaces polished down to 1 μm finish and dried for at least 24 hrs at 200°C in a vacuum oven. Cylindrical half-capsules were then juxtaposed and jacketed with a platinum tube to form a reaction couple. Pt and Mo form a solid solution at high pressure and high temperature which helps to prevent the two half capsules from separating during quench. The complete furnace assembly is then stored at 200°C in a vacuum oven again for at least 24 hours before actual melting or reaction experiment.

To conduct a melting experiment, the reaction couple was first cold pressurized to a pressure of ~ 1.6 GPa. The temperature was then raised at a rate of 75°C/min to either 1100°C (for the cpx + spinel + glass vs. opx + spinel assembly) or 1200°C (for all other assemblies). After an annealing period of 24 hours, the temperature was then increased at a rate of 150°C/min to the desired temperature, and held at the run conditions for 72 to 79 hours. The run was quenched to room temperature and the capsules were then mounted in epoxy, sectioned longitudinally, and polished down to 0.3 μm finish for electron microprobe and ion probe analyses. Due to the slight difference in diameters between the two half cylindrical capsules containing the pre-synthesized material, a small offset at the original interface is visible after quench, and is used as a marker for distance measurements. In general the offset between the two half capsules is less than 15-20% of the total width of the sample. Runs with larger offset were not included in this report.

The temperature was monitored using a W₉₇-Re₃/W₇₅-Re₂₅ thermocouple and a Eurotherm 818 controller. No pressure correction was applied to the measured e.m.f. Uncertainties in the temperature measurements were about 10°C due mainly to a temperature gradient in the solid medium assembly (e.g., Ayers et al., 1992; Liang et al., 1996; Watson et al., 2002). The nominal pressure was not corrected for friction because the slight pressure fluctuations (~30 MPa) during a run are comparable to the 25 MPa friction correction measured by Ayers et al. (1992) for a similar furnace assemblage.

2.3 Analytical methods

Backscattered electron (BSE) images, X-ray intensity maps, and mineral and melt chemical analyses were collected at Brown University using a Cameca SX-100 electron microprobe. An accelerating voltage of 20 kV and a beam current of 50 nA were used to collect BSE images and X-ray intensity maps. An accelerating voltage of 15 kV was used for the mineral and glass analyses. A focused beam (1-2 μm) of 20 nA was used for the mineral analyses, and a slightly defocused beam (5 μm) of 10 nA was employed for the glass. Counting times were 20 s for peak and 10 s for background on each side of the peak. Natural glass and mineral standards were used for all analyses and the PAP correction procedure was employed (Pouchou and Pichoir, 1984). To minimize sodium loss during the analyses, Na₂O was analyzed first. Raw oxide sums for the individual analyses were above 98.8 wt.% for minerals and above 95.6 wt.% for the glasses. Grain-size and volume fractions of all the phases present in the reactive boundary layer were measured from BSE images and X-ray intensity maps using the intercept length and point count methods described in Underwood (1970).

In addition, a suite of 11 trace elements (La, Ce, Nd, Sr, Zr, Sm, Ti, Dy, Y, Er, Yb) was determined on the glass and cpx using a Cameca 3f ion probe at the Woods Hole

Oceanographic Institute. Analyses were performed using a 35-40 nA primary beam of O⁻ with a ~20 μ m spot size for Sr, Zr, Ti, Y, a ~50 μ m spot size for REE, and utilizing secondary ions with an energy filtering window of -60 or -90 volts depending on the trace element analyzed (Shimizu and Hart, 1992).

3. Results

3.1 *Experimental charge*

The samples obtained at the end of each melting experiment are approximately 4-5 mm long and ~1.5 mm in diameter. Reflected light and BSE images of the synthesized starting materials indicate that they typically contained small amounts of melts at the run conditions (up to ~5 vol% for the cpx+sp+glass synthesized rod). The opx synthesis also contained 4-5% olivine probably present in the starting material due to incomplete mineral separation.

Four successful melting runs were obtained at 1.5 GPa using the reaction couple: (1) opx against cpx (Run 37, 1340°C for 72 hours, Fig. 3); (2) opx + spinel against cpx+sp+glass (Run 49, 1300°C for 73 hours); (3) opx + spinel against cpx (Run 54, 1340°C for 72 hours); and (4) olivine + opx against cpx (Run 27, 1340°C for 79 hours, Lo Cascio et al., 2004). Reaction between the cpx-rich lithology and the opx-rich lithology at 1300-1340°C and 1.5 GPa produces a RBL that consists of new olivine, cpx, and melt ($\pm$ spinel depending whether spinel is present in the starting material). The width of these RBL's is about 250 μ m for Run 27, 180 μ m for Run 37, 200 μ m for Run 49, and 240 μ m for Run 54. The lithological or mineralogical boundary between the RBL and the unreacted pyroxenite or harzburgite is sharp and planar (Fig. 3), similar to the sharp dunite-harzburgite interface observed in the harzburgite or lherzolite dissolution experiments (e.g., Morgan and Liang,

2003 and 2005). The opx-free RBL is always located on the opx-rich side of the original capsules interface, suggesting that the RBL grows at the expense of opx.

3.2 Textures

Olivine is euhedral to subhedral in the RBL with a median grain size of 40 μm . Clinopyroxene crystals in the RBL are typically anhedral with a median grain size of ~ 60 μm . In areas where olivine grains are abundant, cpx grain-size is typically smaller. We also observe at the edge of the RBL, near the opx-rich side of the capsule, few small anhedral opx grains (5-10 μm in diameter), representing incompletely dissolved opx crystals. In runs where spinel was added to the starting material, there are only few small grains (up to ~ 10 μm) of spinel present in the RBL. These small spinels are usually trapped inside large olivine grains. Far from the RBL, spinel is homogeneously distributed and has a grain size of 20 to 35 μm (Fig. 4). In general, melt in the RBL tends to localize in those areas where olivine grains are more densely accumulated (Fig. 3; see also Fig. 1 of Lo Cascio et al., 2004). Quench growth of cpx is also more abundant in those areas where cpx crystals are more abundant and much less in areas where olivine is present. These help to explain why some melt pockets can be as wide as 150 μm and are less affected by quench growth. The precise grain size of pyroxenes far from the RBL is difficult to determine. Nevertheless, using the melt distribution as a phase boundary and the chemical zonations present in some pyroxenes, it is possible to make a rough estimate of 30-40 μm for opx and cpx in the orthopyroxenite (or harzburgite) and clinopyroxenite, respectively.

3.3. Mineral compositions

Detailed microprobe traverses across all experimental runs show that the composition of olivine is essentially uniform. Opx shows some scatter in composition due

to the presence of grains with unreacted cores but the variation is not related to distance from the RBL (Fig. 5). The compositions of cpx (Figs. 5 and 6, see also Fig. A1 in the supplementary material) and spinel (Fig. 8) vary systematically with distance from the RBL and both minerals have compositional gradients that extend beyond the mineralogical boundaries that define the RBL (Fig. 5, see also an enlarged plot of the boxed area is shown in Fig. A2 in the supplementary materials). In general, the Mg^{2+} , Fe^{2+} and Si^{4+} contents of cpx per six oxygens increase towards the reaction front, whereas Ti^{4+} , Al^{3+} , Cr^{3+} , Ca^{2+} , Na^{+} , REE^{3+} , Y^{3+} , Zr^{4+} , and Sr^{2+} contents decrease (Figs. 5 and 6, see also Fig. A1 in the supplementary materials). Electron microprobe traverses across selected single crystals of cpx show that grains far away from the RBL have systematic core-to-rim variations that account for the scatter in the observed compositional trends away from the RBL (labeled as “core” and “rim” in Figs. 5 and 6). These core-to-rim compositional variations are very similar to those observed in pyroxenes in the unreacted lherzolite in the melt-peridotite reaction experiments of Morgan and Liang (2005, their Figs. 7 and 9). In contrast, compositional variations of cpx in the RBL are more systematic, indicating a lack of significant zoning parallel to the original interface. Compositional traverses across the entire reaction couple also show that the chemical gradients for different elements levels off at approximately the same distance from the original interface, regardless of the size and charge of the cation (Figs. 5 and 6). In addition we observe a linear correlation between cations of different size and charge (Fig. 7), such as Ce^{3+} *vs.* Yb^{3+} and Sr^{2+} *vs.* Zr^{4+} , with low concentrations in the RBL.

The Mg^{2+} and Al^{3+} contents of spinel decrease towards the RBL, whereas the Ti^{4+} , Fe^{2+} , and Cr^{3+} increase. The net effect of these trends on the spinel composition is an increase in the Cr# [molar $100 \times \text{Cr}/(\text{Cr} + \text{Al})$] and a decrease in the Mg# [molar $100 \times \text{Mg}/(\text{Mg} + \text{Fe})$] from the original spinel composition far from the RBL (Mg# ~82 and 85 and Cr# ~10

and 12 for runs 49 and 54, respectively) towards the reaction front ($Mg\# \sim 79$ and 81 and $Cr\# \sim 22$ and 25 for runs 49 and 54, respectively; Fig. 8). The dominant effect of adding spinel or basalt to the starting material is to increase the average Al_2O_3 content of the bulk starting composition (Fig. 5, see also cpx compositions in Run 49 and 54 in Fig. A1), resulting in higher Al_2O_3 content in cpx in the presynthesized starting materials. During the melting reaction, the composition of the cpx in the RBL becomes depleted in Al_2O_3 relative to the cpx composition far from the RBL (Figs. 5 and A1 and A2). For Run 49 where basalt was added to the cpx-rich aggregate in addition to the spinel, clinopyroxene composition is homogeneous throughout the charge, due to faster equilibration during the synthesis run. For Run 54 where spinel was only added to the opx-rich aggregate, the Al_2O_3 abundance in cpx increases from the clinopyroxenite towards the RBL, as a result of spinel dissolution in the RBL. Detailed compositional variations of MgO, FeO, CaO, and Al_2O_3 across the four melting/reaction charges are presented in Fig. 1A in the supplementary materials.

3.4. Melt compositions

Partial melts in the RBL are ne-normative alkali basalts and do not show significant variations in composition with respect to distance (see Fig. 2 of Lo Cascio et al., 2004). However, there is compositional scatter in major elements, reflecting quench modification. The average Fe-Mg exchange coefficient between olivine and melt (K_d^{Fe-Mg}) in our experiments is 0.21 (± 0.04), 0.25 (± 0.03), 0.16 (± 0.02), and 0.13 (± 0.01) for runs 27, 37, 49, and 54, respectively. However this average is not meaningful since the composition of olivine is essentially constant, and the change is due solely to the quench modification in the glass composition. Table 2 shows the average glass, olivine, opx, cpx, and spinel compositions for all runs. The deviation from the mean in the glass composition indicates that quench growth does affect our Fe-Mg exchange coefficient.

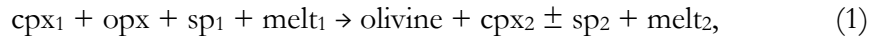
The trace element abundance of the glasses in all runs shows less scatter than major elements, due to the larger volume sampled by the ion probe (~ 20 to $50\ \mu\text{m}$ wide beam spot, compared to the $< 5\ \mu\text{m}$ wide beam of the microprobe) and to the fact that their abundances are less sensitive to quench modifications compared to those of major elements. Table 3 lists selected trace element abundance in cpx and melt located in the RBL, and the apparent cpx-melt apparent partition coefficients (K_d) calculated directly using the measured data. As shown in Fig. 9, the apparent partition coefficients are correlated with the Al^{IV} content of the residual cpx, as has been observed in a number of partitioning studies (e.g., Hart and Dunn, 1993; Hauri et al., 1994; Lundstrom et al., 1994; Gaetani and Grove, 1995; Blundy et al., 1998; Hill et al., 2000; Gaetani, 2004). This point will be further discussed in Section 5.2 below.

4. Grain-Scale Processes of Lherzolite Melting

The presence of concentration gradients in all of our experiments suggests that diffusion plays an important role during the formation of the RBL. The question then is whether the development of the RBL is dominated by diffusion in the solid, in the melt, or by a combination of the two. Given that cation diffusivities in pyroxenes and spinel are very small compared to those in the melt, it is unlikely that the observed cpx and spinel concentration gradients developed over a distance of $200\ \mu\text{m}$ in less than 80 hours are produced by solid-state diffusion alone. For instance, to account for the observed concentration gradients of CaO, MgO, and FeO in the cpx across the RBL, a bulk diffusivity of $\sim 10^{-13}$ – $10^{-15}\ \text{m}^2/\text{s}$ would be needed (see Fig. A1 in the supplement materials). This bulk diffusivity for major elements is 3-5 orders of magnitude larger than the Mg^{2+} - Fe^{2+} chemical diffusivity in cpx (Brady and McCallister, 1983) and 3-4 orders of magnitude smaller than the effective binary diffusivities of MgO and FeO in basaltic melt at 1300°C (e.g., Richter et

al., 2003). This indicates that diffusion in both the solid and the melt, via dissolution and reprecipitation, must contribute to the development of the RBL. In addition, textural evidence such as the presence of large olivine crystals in the RBL for runs where minor amounts of olivine were present in the starting material (Run 37, Fig. 3), the absence of opx and decrease in spinel grain-size in the RBL, and the presence of cpx on the side of the capsule where it was initially absent, all suggests that dissolution and precipitation occur simultaneously during the development of the RBL. This grain-scale process is independent of the choice of reaction couples, nor the presence/absence of spinel, and hence common to melt-peridotite interaction in general.

The development of the RBL involves dissolution of cpx, opx, and spinel, followed by reprecipitation of cpx, and precipitation of olivine and is consistent with the following reaction:



where subscripts 1 and 2 designate the presynthesized material before melting and the product in the RBL, respectively. The volume of melt₂ (> 15% within the RBL) is greater than that of melt₁ (< 5% within the cpx-rich capsule), indicating that net melting occurs during this reaction (Fig. 3). The original melt in the clinopyroxenite (melt₁) is undersaturated in opx and spinel and enriched in jadeite component. Hence melt₁ dissolves opx and spinel at the clinopyroxenite-orthopyroxenite or clinopyroxenite-harzburgite reaction front. Incongruent dissolution of opx produces olivine and a silica-rich liquid, while partial dissolution of spinel elevates the Al₂O₃ abundance in the interstitial melt in the RBL (Table 2). Parts of the dissolved opx and spinel components mix with melt₁, resulting in cpx reprecipitation in the RBL (cpx₂, Fig. 3; see also Figs. 1b-1d in Lo Cascio et al., 2004). The composition of melt₂ is the net result of melt₁ and opx + spinel reaction, olivine precipitation, and cpx₂ reprecipitation in the RBL. The composition of spinel is also

significantly affected by dissolution and reprecipitation before reacting out completely (Fig. 8); its Cr# increases while its Mg# decreases towards the RBL, resulting in an increase in the FeO and Al₂O₃ content of the melt in the RBL.

A salient feature of dissolution, precipitation, and reprecipitation is that the rates of opx and spinel dissolution, as well as olivine and cpx₂ precipitation, are limited by the rates of diffusion of the major components in the interstitial melt and the solid (e.g., SiO₂ and Al₂O₃, Liang, 2003b; Morgan and Liang, 2003). Hence, the crystal-melt equilibration time scales in the RBL are significantly reduced, in spite of the expected slow diffusion rates of high charge cations such as REE³⁺, Y³⁺, Ti⁴⁺, and Zr⁴⁺ in pyroxenes (e.g., Van Orman et al., 2001; Cherniak and Liang, 2007; Cherniak and Liang, unpublished data). This helps to explain the large apparent diffusion distances of Sr²⁺, Sm³⁺, and Zr⁴⁺ as well as the nearly linear and positive correlations between Sr²⁺ and Zr⁴⁺ in Figs. 6 and 7.

5. Implications for Trace Element Distribution During Peridotite Melting

Through numerical calculations, theoretical analyses, and laboratory dissolution, melting, and melt-rock reaction experiments (Liang 2003a, 2005; Morgan and Liang, 2003, 2005; Lo Cascio et al., 2004; and this study) we have shown that dissolution, precipitation, and reprecipitation are an inevitable consequence of crystal-melt reaction and reequilibration in multicomponent crystal-melt aggregate. These grain-scale reequilibration processes have important implications for the distribution of major and trace elements in coexisting minerals and melt during melting and melt-rock reaction. Implications for major element compositional zoning in residual pyroxenes observed in isothermal-isobaric partial melting experiments was discussed by Lo Cascio et al. (2004). In this section, we will focus on trace element distributions by considering two examples: one commonly observed in laboratory

melting studies and the other frequently used in modeling studies of disequilibrium mantle melting and melt transport.

5.1. Trace element fractionation during disequilibrium melting in nature

Disequilibrium melting takes place when the rate of melting is greater than the rate of solid-melt chemical exchange, through volume diffusion in the solid and/or dissolution and reprecipitation. For an incompatible trace element, this can be conveniently measured by a dimensionless melting Damköhler number, (e.g., Liang, 2003a; Cherniak and Liang, 2007),

$$D_m^k = \frac{[\rho_f \phi + \rho_s (1 - \phi)]k}{\Gamma} R \quad (2)$$

where ρ_f and ρ_s are the densities of the melt and solid, respectively; ϕ is the volume fraction of melt in the residuum; k is the mineral-melt partition coefficient for the element of interest; Γ is the rate of melting of the bulk matrix as defined by McKenzie (1984); and R is the chemical exchange rate between the solid and the melt for a given element of interest. The melting Damköhler number in Eq. 2 was obtained from an analysis of the disequilibrium dynamic melting model of Liang (2003a). It can be shown that disequilibrium melting is important for the incompatible trace element of interest when $D_m^k < 1$.

Previous studies of trace element distribution during disequilibrium mantle melting focused almost exclusively on cases in which the rate of crystal-melt mass exchange is limited by the rate of volume diffusion in the solids (e.g., Qin, 1992; Iwamori, 1993, 1994; Van Orman et al., 2002). The crystal-melt chemical exchange rate in this case can be estimated using the simple expression (e.g., Vermeulen, 1953),

$$R = \frac{\beta D_s}{a^2} \quad (3)$$

where a is the average grain size or radius of the mineral of interest; D_s is diffusion coefficient in the mineral for the element of interest; and β is a geometry factor ranging from 3 to 15 (e.g., Vermeulen, 1953; Navon and Stolper, 1987; Bodinier et al., 1990; Liang, 2003b). Since diffusion is a thermally activated process one would expect that disequilibrium melting plays an important role at moderate to low temperatures ($< 1100^\circ\text{C}$). Such environments can be found during wet or flux melting in the upper mantle or lower crust, where the solidi of the mantle or crust materials are low and the rates of volume diffusion in residual minerals are small. Consider an example of REE fractionation during wet melting of a peridotite at 1100°C and 2 GPa. Van Orman et al. (2002a) and Cherniak and Liang (2007) measured the diffusion coefficients of REE in diopside and enstatite, respectively. Assuming a grain size of 1 mm, a bulk density normalized melting rate of 10^{-14} to 10^{-15} s^{-1} (e.g., Iwamori, 2000), the melting Damköhler numbers are approximately 0.1 to 1 for the REE in enstatite, and 0.01 to 0.1 for La and 1 to 10 for Yb in diopside. Hence a significant component of disequilibrium melting would be expected for the LREE during wet melting of peridotite if volume diffusion in solid were the dominant mass transfer mechanism for crystal-melt chemical exchange. Using a similar argument, we have recently shown that the effect of diffusion in solid limited disequilibrium melting can still be observed for the REE in melts produced by dehydration melting of a subducting slab even when the grain sizes of garnet and cpx in the residual eclogite are as small as $100 \mu\text{m}$ (Liang, 2003a). In spite of these theoretical predictions, significant components of disequilibrium melting have not been reported for the REE in magmas produced in the aforementioned tectonic settings. This, of course, does not rule out the possibility of diffusion in solid limited disequilibrium melting in either tectonic environment. The paucity of trace element data in support of disequilibrium melting, however, does imply that other mass transport processes such as dissolution and reprecipitation are likely to play a dominant role in distributing and

equilibrating slow diffusing species between residual minerals and their surrounding melt during partial melting. As discussed in Section 4, dissolution, precipitation, and reprecipitation are most likely to occur during disequilibrium melting of solid solution forming minerals (Liang, 2003a, 2003b, 2005; Lo Cascio et al., 2004; and this study). These grain-scale processes significantly accelerate the rates at which slow diffusing cations in residual minerals reequilibrate with their surrounding melt. Disequilibrium melting models based on volume diffusion in solid alone are likely to significantly underestimate the rates at which major and trace elements in residual minerals reequilibrate with their surrounding melt. This can be further demonstrated by the apparent trace element partition coefficients for cpx and its coexisting melt in the RBL in Section 5.2.

One simple way to incorporate dissolution and reprecipitation into the disequilibrium melting models is to replace the average grain size, a , in Eq. 3 by an effective grain size that is defined as the average size of the unreacted cores of a mineral of interest. Although dissolution and reprecipitation can increase mineral grain size, as demonstrated in this study, it is the regions that are not affected by reprecipitation (i.e., mineral cores) that are likely to be significantly out of chemical equilibrium with the surrounding melt during melt-rock interaction. This approach was used by Liang (2003a) in his study of disequilibrium melting of a subducting slab. The effective grain size can be significantly smaller than the actual grain size (Liang, unpublished numerical results). Further studies are needed to constrain the effective grain size during mantle melting and melt-peridotite interaction.

5.2. Apparent clinopyroxene-melt trace element coefficients from this study

Partition coefficient of incompatible trace element between cpx and basaltic melt is a critical parameter to understand melting and melt transport processes in the upper mantle (e.g., Blundy and Wood, 2003 and references therein). Although in principle one could

measure the elemental abundance in coexisting cpx and melt after a peridotite partial melting experiment, it has never been done before due to analytical difficulties such as small crystal and melt pocket sizes, crystal zoning, as well as quench modification. This is the main reason why the trace element partition coefficients between cpx and melt are generally determined through crystal growth experiments. According to the dissolution and reprecipitation processes discussed in Sections 4, it is reasonable to assume that the large cpx grains in the RBL produced in our reaction couple experiments are compositionally equivalent to the cpx rim in bulk lherzolite melting studies. An important question then is how far the apparent cpx-melt partition coefficients reported in this study (Table 3 and Fig. 9) deviate from the cpx-melt (equilibrium) partition coefficients obtained by other experimental methods (e.g., cpx crystallization in controlled cooling experiments). Here the word “apparent” is used to distinguish our measured cpx-melt partition coefficients from the equilibrium partition coefficients. The former is identical to the latter when chemical equilibrium is established.

It is well known that cpx-basaltic melt partition coefficients for REE and HFSE depend strongly on the abundance of tetrahedrally coordinated Al (Al^{IV}) in cpx, whereas cpx-melt partition coefficient for Sr is insensitive to the Al^{IV} abundance in cpx (e.g., McKay, 1986; Hart and Dunn, 1993; Hauri et al., 1994; Lundstrom et al., 1994; Gaetani and Grove, 1995; Blundy et al., 1998; Hill et al., 2000; Gaetani, 2004). Figure 9 shows the cpx-melt partition coefficients for REE, Y, Ti, Zr, and Sr as a function of Al^{IV} abundance in cpx reported in recent laboratory partitioning studies (references given in the caption to Fig. 9). Deviations from the general trends among the published data shown in this figure could be due to differences in melt composition, temperature and pressure, as well as experimental and analytical uncertainties among different studies. For comparison, we also plot the cpx-melt apparent partition coefficients obtained from our reaction couple experiments, shown

as larger symbols in Fig. 9. In general, our apparent partition coefficients agree reasonably well with the published values. In detail, however, we note that our apparent partition coefficients for larger ions (La, Ce, Sr, and to a lesser extent, Nd) and Ti in Runs 27 (large red circle) and 37 (large blue circle, Fig. 9) are slightly but systematically lower than the general trends established by other partitioning studies. It is unlikely that these lower than expected apparent partition coefficients are a result of analytical error, given the similarities in the major and trace element abundance between Runs 27 and 37. Possible explanations for this deviation include (1) differences in melt composition between our study and other partitioning studies; (2) fast cpx growth or precipitation rate in the RBL; (3) ionic charge and size dependent cation diffusion in cpx; and (4) incomplete crystal-melt reequilibration in the RBL in spite of dissolution and reprecipitation. We will briefly address each possible cause below.

Both Gaetani et al. (2003) and McDade et al. (2003) have shown that the presence of more than 1 wt% of H₂O in coexisting silicate melt can reduce the cpx-melt partition coefficients for the REE and HFSE relative to values obtained from anhydrous partitioning studies. Gaetani (2004) has further demonstrated that cpx-melt partition coefficients for the REE also depend on melt structure and hence melt composition. According to these studies, variations in melt composition not only affect the cpx-melt partition coefficients for the light REE (LREE) but also the mid to heavy REE and the HFSE, which is not the case in the present study: our apparent partition coefficients for the LREE are lower than the systematic trend established by the published data, whereas our apparent cpx-melt partition coefficients for the mid to heavy REE, Y, and Zr are in good agreement with the published data (Fig. 9). Although the exact amount of H₂O in the melt coexisting with cpx in our experimental charges is not known, we conclude that differences in melt composition are unlikely the cause to the systematic deviations shown in Fig. 9.

It is well known that fast crystal growth can lead to trapping or enrichment of slow diffusing incompatible trace elements in a growing crystal. The amount of enrichment are positively correlated with the growth Péclet number (e.g., Aziz, 1982; Watson and Liang, 1995), a dimensionless number that measures the relative crystal growth rate to the trace element diffusion rate across the near surface layer of the crystal. The run duration and cpx crystal size in the RBL in our reaction couple experiments are comparable to those reported in crystal growth/partitioning studies. Hence it is unlikely the reprecipitation rate of cpx in the RBL in our reaction couple experiments is significantly different from those in other partitioning studies. Furthermore, near surface trapping always results in an increase in the apparent crystal-melt partition coefficient for the incompatible trace elements (e.g., Aziz, 1982; Watson and Liang, 1995), which is the opposite of the systematic deviation observed in this study.

Van Orman et al. (2001) have shown that tracer diffusivities of the REE in diopside increase systematically from La to Lu. Hence it is possible that the lower than expected apparent partition coefficients for La, Ce, and Nd obtained from our reaction couple experiments are due to the slow diffusion rates of these elements relative those of the mid to heavy REE and Y in cpx, despite of dissolution and reprecipitation in the RBL. Although tracer diffusivities of Ti and Zr in cpx have not been measured directly, trace element zoning patterns preserved in cpx in plagioclase lherzolite from Horoman peridotite (Takazawa et al., 1996) suggest that the apparent or effective diffusivity of Ti in cpx is smaller than the apparent diffusivity of Zr in cpx. Typically, the width of the concentration boundary layer thickness for Ti in cpx in Horoman plagioclase lherzolite is comparable to that for Nd in the cpx, but the concentration boundary layer thickness for Zr in cpx is comparable to those for Dy, Y, and Er in the same cpx (see Figs. 4 and 5 in Takazawa et al., 1996). Hence it is possible that the apparent diffusivity of Zr in cpx is larger than the apparent diffusivity of Ti

in cpx. This may help to explain our lower than expected apparent partition coefficient of Ti but effectively normal partitioning behavior of Zr in Runs 27 and 37.

It is well known that tracer diffusivity of Sr in diopside is significantly larger than those of REE in diopside (e.g., Sneeringer et al., 1984). If sluggish diffusion of Sr in cpx is significant in affecting its reequilibration time, then why does it not affect the HREE whose diffusivities are smaller than that of Sr in cpx? The answer probably lies in the cpx-melt partition coefficient. Hart (1993) pointed out that diffusive reequilibration time for a trace element in crystal-melt aggregate also depends on crystal-melt partition coefficient. This is why the melting Damköhler number defined in Eq. 2 is also a function of partition coefficient. According to Hart (1993) and our numerical calculations (Liang, unpublished results), the crystal-melt reequilibration time is longer for more incompatible trace element than for less incompatible one, though its exact functional form depends on boundary conditions and whether other transport processes such as melting, advection, and melt-rock reaction also present during crystal-melt diffusive reequilibration. Given the relative small cpx-melt partition coefficient for Sr (0.06, according to Fig. 9) compared to HREE, it is possible that the cpx-melt reequilibration time for Sr is slightly longer than that for the HREE such that Sr has still not fully equilibrated at the end of our experiments.

The lower than expected apparent partition coefficients of La, Ce, Sr, and to a lesser extent, Nd and Ti in Runs 27 and 37 can be understood in terms of the grain scale processes discussed in Section 4 and in Lo Cascio et al. (2004). Partial melting of the fertile clinopyroxenite during both synthesis and melting reaction experiments produced an incompatible element enriched melt (melt₁ in Eq. 1). Reaction between melt₁ and opx produced a RBL that consists of precipitated olivine and cpx (cpx₂ in Eq. 1) and an incompatible element depleted melt (melt₂ in Eq. 1). Because the depleted melt₂ in the RBL exchanges chemically with the enriched melt₁ in the clinopyroxenite via diffusion through

interstitial melt, its incompatible trace element abundance is elevated relative to the melt at the RBL-orthopyroxenite or RBL-harzburgite interface. If diffusion in the near surface region of cpx₂ cannot keep up with melt₁-melt₂ diffusive exchange in the growing RBL, the apparent cpx-melt partition coefficients for the incompatible trace elements will be lower than their equilibrium values. An important implication of this open system behavior is that dissolution and reprecipitation, though significantly faster than simple solid state diffusion in minerals, are still not fast enough on laboratory time scales such that small but measurable amounts of disequilibrium between reprecipitated cpx and its coexisting melt can still exist, especially for the highly incompatible trace elements. Depending on the time scale of magmatic processes, grain-scale isotopic and chemical heterogeneities can be preserved at least in some mantle rocks.

6. Summary and Conclusions

We have shown that partial melting of lherzolite of varying bulk compositions can be studied in great detail by analyzing the formation of a reactive boundary layer between cpx-rich and opx-rich aggregates, as long as the peridotite melting reaction consumes pyroxenes and produces olivine and melt. We found that the RBL growth at constant temperature and pressure takes place by melting, and by dissolution and reprecipitation of several phases. These grain-scale processes significantly reduce the diffusive equilibration time between solid-solution forming minerals and the surrounding melt and affect the distribution of major and trace elements, especially for cations with relatively slow diffusion coefficients. We showed that during mineral-melt equilibration, volume diffusion in minerals is not the dominant mechanism of chemical exchange, but rather dissolution and reprecipitation. This conclusion led us to speculate that these grain-scale processes might be responsible for the lack of disequilibrium melting component in arc magmas and melts from

back arc basins. Detailed analysis of coexisting cpx and melt in our runs also show that the cpx/melt partition coefficient for incompatible trace elements is primarily controlled by the Al^{IV} content of the cpx, as noted in previous studies. However, for larger cations and Ti we observe a partition coefficient lower than expected, indicating that dissolution and reprecipitation are not fast enough to eliminate completely small degrees of disequilibrium during our experiments. Depending on the timescale of melting and melt migration relative to the timescale of melt-rock reequilibration, chemical and isotopic heterogeneities can be preserved in mantle rocks.

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Figure Captions

Figure 1. Schematic binary phase diagram showing the processes of dissolution and reprecipitation. Fields of solid solutions are labeled as α_{ss} and β_{ss} . The initial melt and crystal compositions are at L and S, respectively. The final equilibrium crystal and melt compositions are at Se and Le, respectively, and are fixed at a given temperature and pressure. See text for details.

Figure 2. Schematic diagram showing the platinum-molybdenum-graphite capsule (a) and the four types of melting couples used in this study (b). The sample is only in contact with graphite.

Figure 3. (a) Back-scattered electron image of the central part of Run 37 (cpx vs. opx $\pm$ ol, 72 hours at 1340°C, 1.5 GPa). (b) False colored X-ray intensity map of Mg corresponding to the same area. Red represents high concentrations (ol) and dark blue represents low concentrations (melt). Light to medium blue corresponds to the cpx from the reactive boundary layer (RBL, center) and far field (top). The yellow area represents the opx grains in the lower capsule. The RBL is confined in between the two dashed lines in (a). The upper dashed line marks the approximate location of the initial interface of the reaction couple.

Figure 4. Backscattered electron image of spinel (sp) in the reactive boundary layer (a), and in the clinopyroxenite, far away from the RBL (b). The spinel grains in the RBL are completely dissolved into the melt unless olivine and/or cpx crystallize around them.

Figure 5. Plots of selected cation concentration per six oxygen for cpx (circles) and opx (triangles) as a function of distance for runs 37 (cpx vs. opx) and 49 (cpx+sp+gl vs. opx+sp). The origin ($x = 0$) marks the initial location of the interface position between the two half capsules. Note that far away from the origin, the

composition of cpx is scattered due to core-to-rim zonation (shown as arrows). However, the composition of the cpx in the RBL is distinct from this chemical variation. The dashed region in the cpx composition is enlarged in the supplementary material (Fig. A2) where the RBL and concentration gradient widths are compared.

Figure 6. Plot of selected trace element abundance (normalized to C1 chondrite) of cpx (circles) as a function of distance for runs 27 (cpx vs. opx+ol) and 37 (cpx vs. opx $\pm$ ol). The origin ($x = 0$) marks the initial location of the interface position between the two half capsules. The data was not collected for single grains but as traverses across the capsule and we observed that some large cpx grains are typically enriched in incompatible elements (“cores”) and that smaller grains are depleted in those elements (“rims”), indicating local effects of dissolution and reprecipitation. The numbers shown in the panels represent apparent diffusion coefficients determined by least squares fits to the measured data using an error function solution that includes the movement of the reaction couple interface (e.g., Zhang et al., 1989).

Figure 7. Covariation of Ce^{3+} and Yb^{3+} (a), and Zr^{3+} and Sr^{2+} (b), in cpx from runs 27 and 37. The positive correlation between light and heavy REE, and between cations of very different charge cannot be explained by volume diffusion in cpx. The nearly linear correlations between the light and heavy REE, and between cations of different charge can be explained by a grain-scale process that involves dissolution and reprecipitation (see text a detailed discussion).

Figure 8. Plot of Mg# of spinel vs. Cr# of spinel. Melting and melt-rock reaction decrease the Mg# and increase the Cr# of spinel in the RBL (data enclosed in the dashed ellipses). Trends of melt-rock reaction are shown as an arrow.

Figure 9. Variation of cpx/melt partition coefficients for selected trace elements as a function of the Al^{IV} content in the residual cpx of this study and other partitioning studies. This logarithmic correlation is not observed for Na^+ , Ca^{2+} , or any other cation present in the cpx structure, indicating that the Ca-Tschermak substitution dominates the REE partitioning as suggested by previous studies (e.g., Hauri et al., 1994). The wide range of P-T conditions and melt compositions of the selected partitioning studies, indicates that pressure, temperature, and melt composition do not control directly the REE cpx/melt K_d directly but affect instead the Al^{IV} content of cpx. The Al^{IV} content of cpx is most likely the dominant control on the REE content that can be accommodated in the cpx structure.

Figure 1.

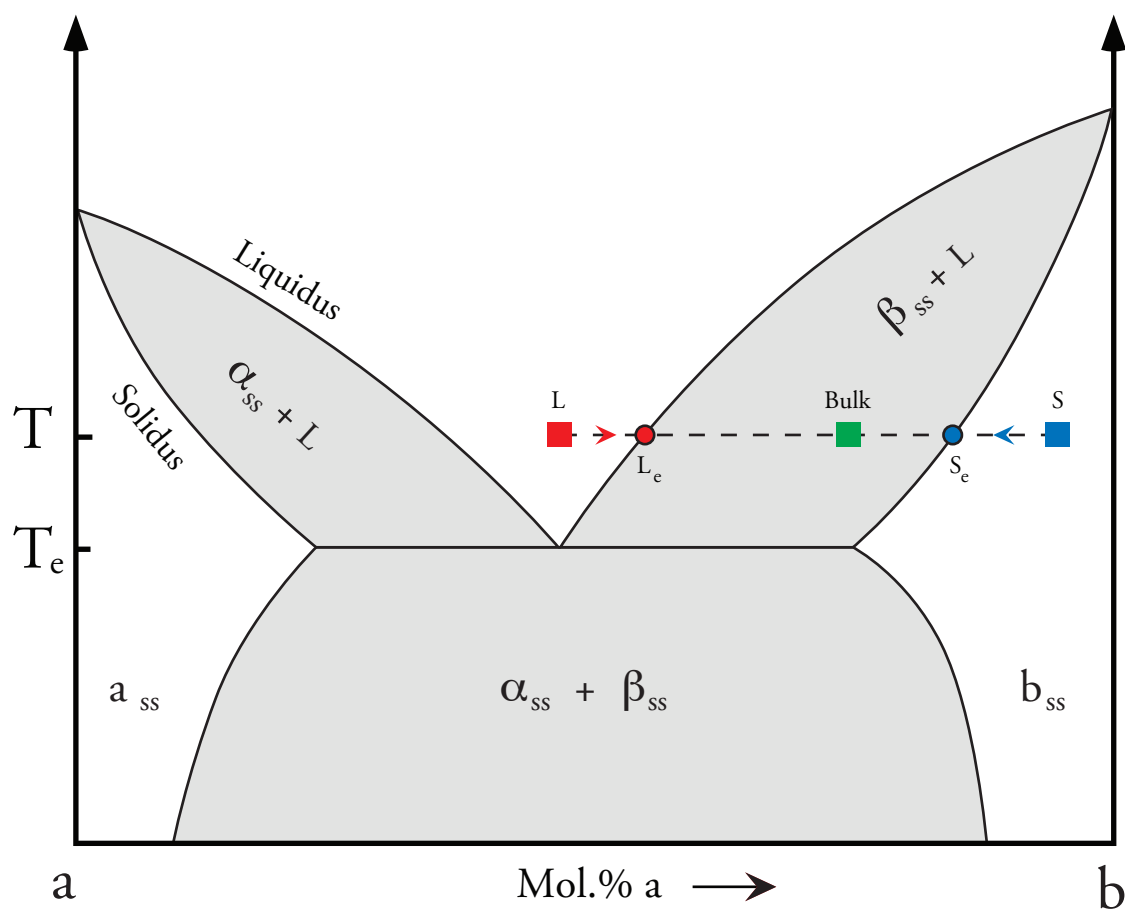
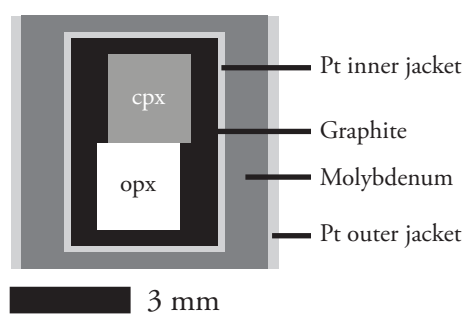


Figure 2.



(a)

Run 27	Run 37	Run 49	Run 54
cpx	cpx	cpx+sp +gl	cpx
opx + ol	opx	opx + sp	opx + sp

(b)

Figure 3.

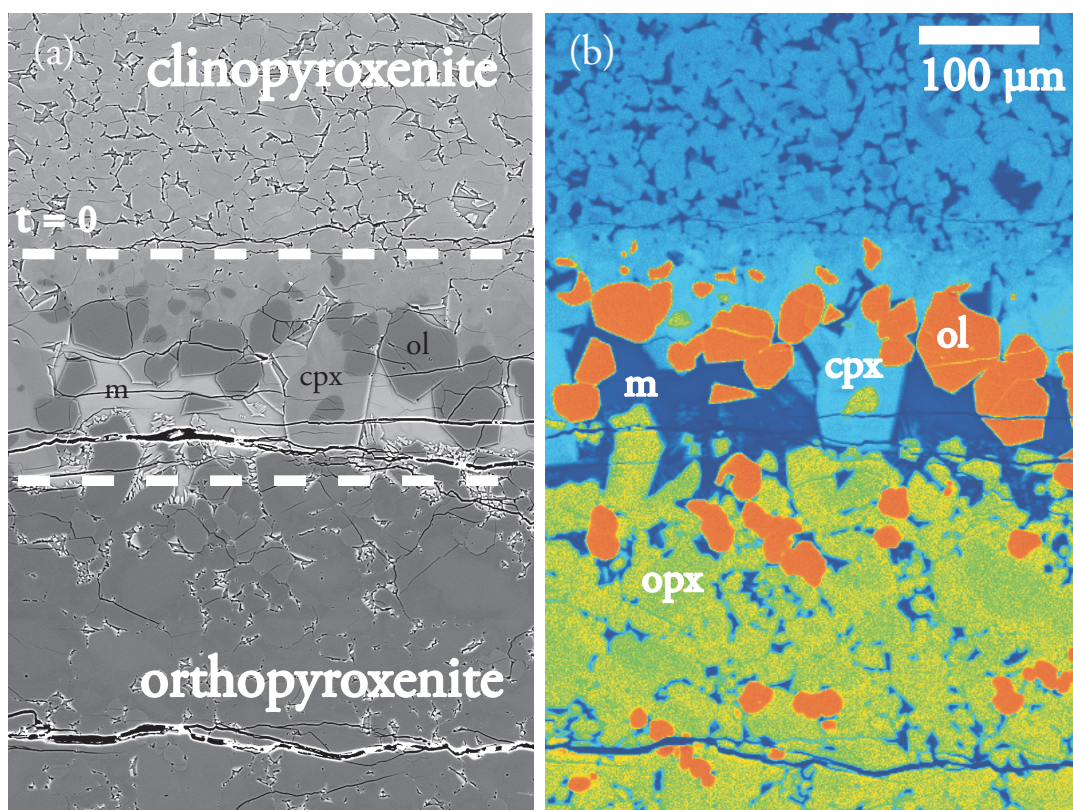


Figure 4

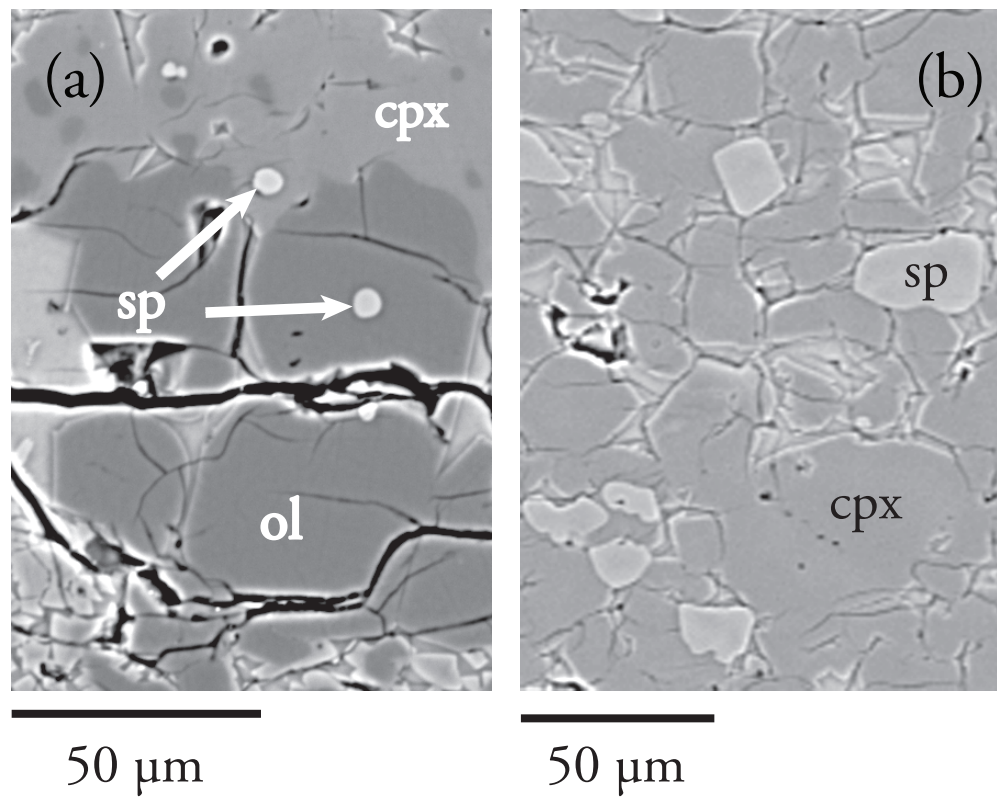


Figure 5

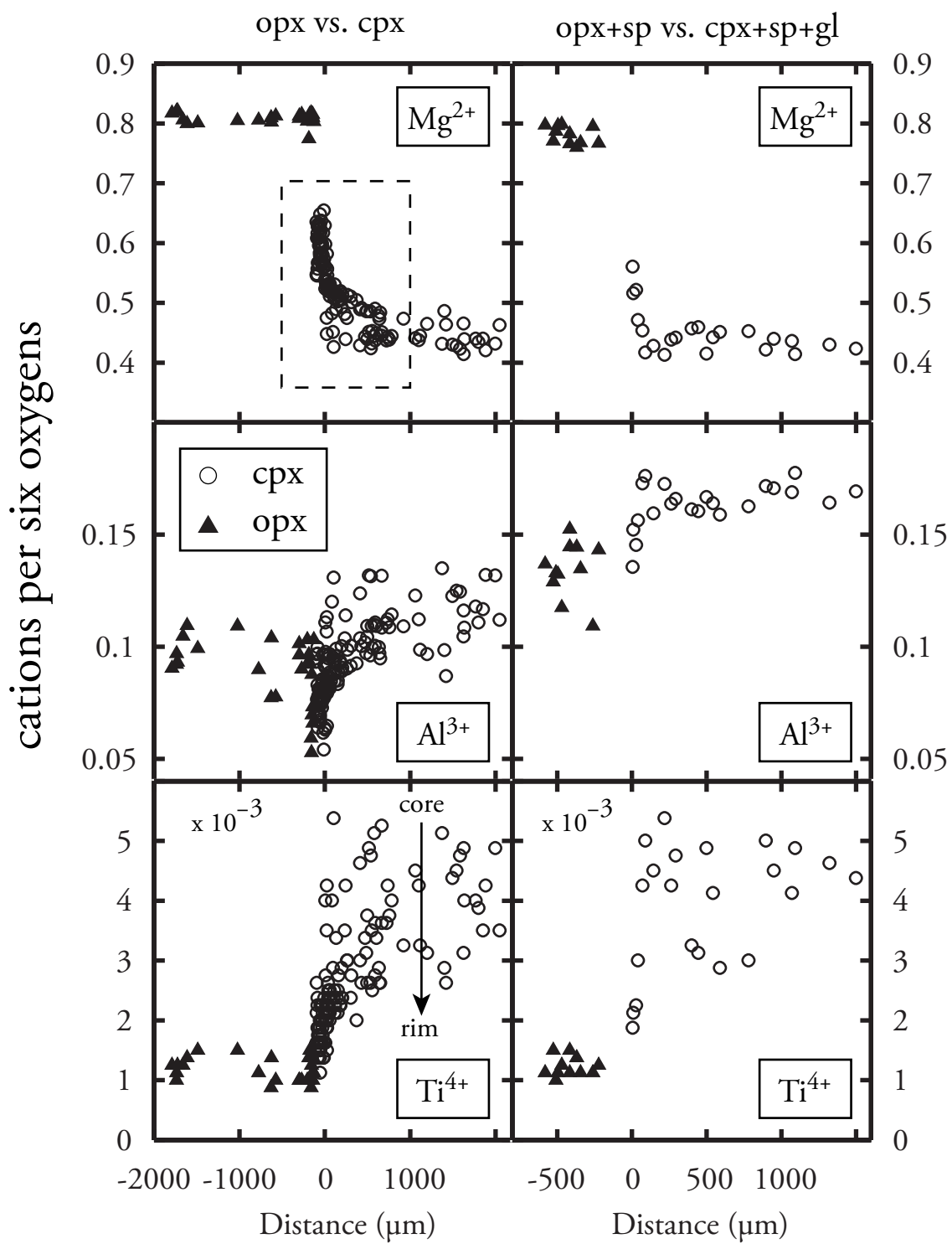


Figure 6

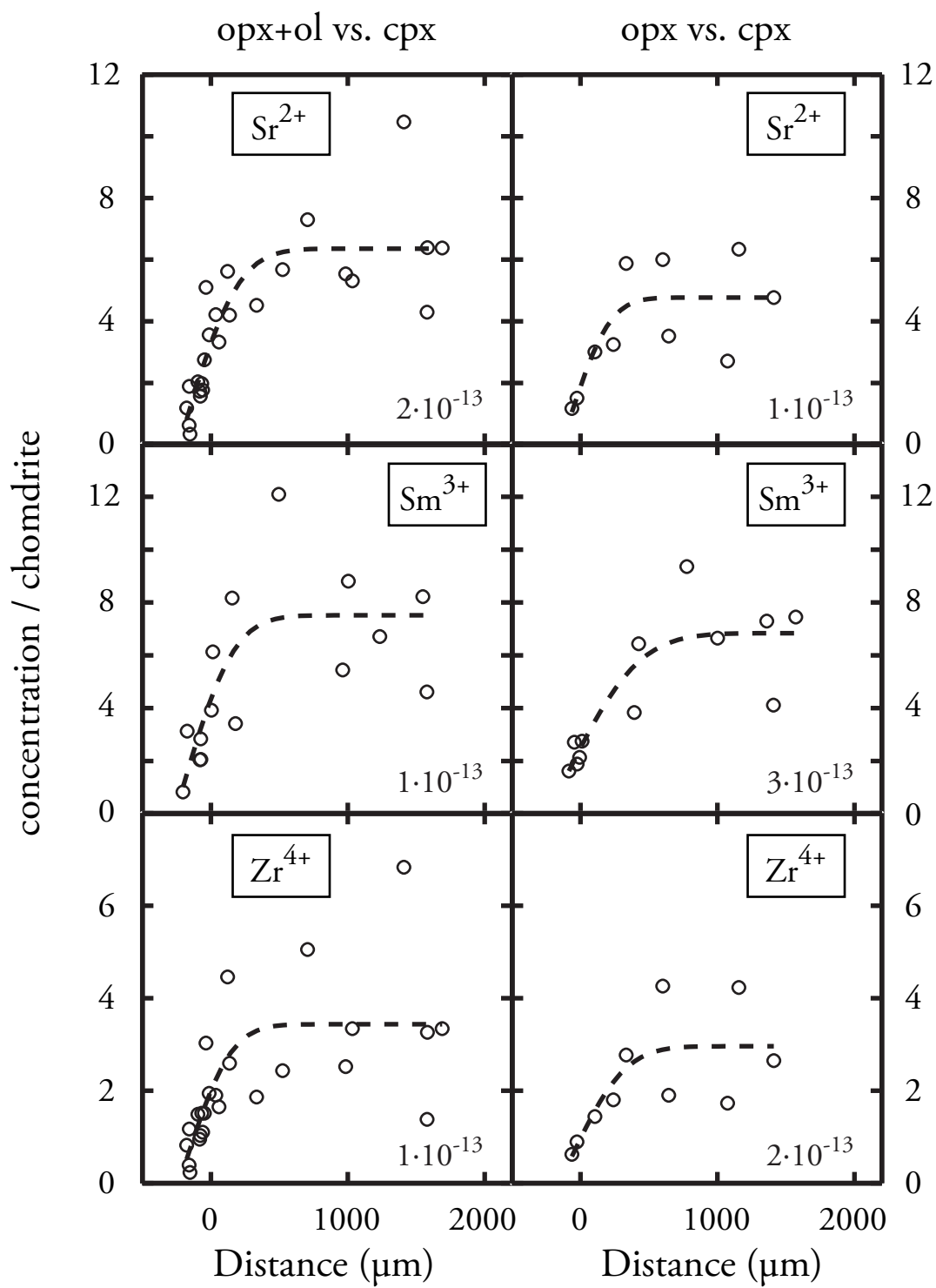


Figure 7

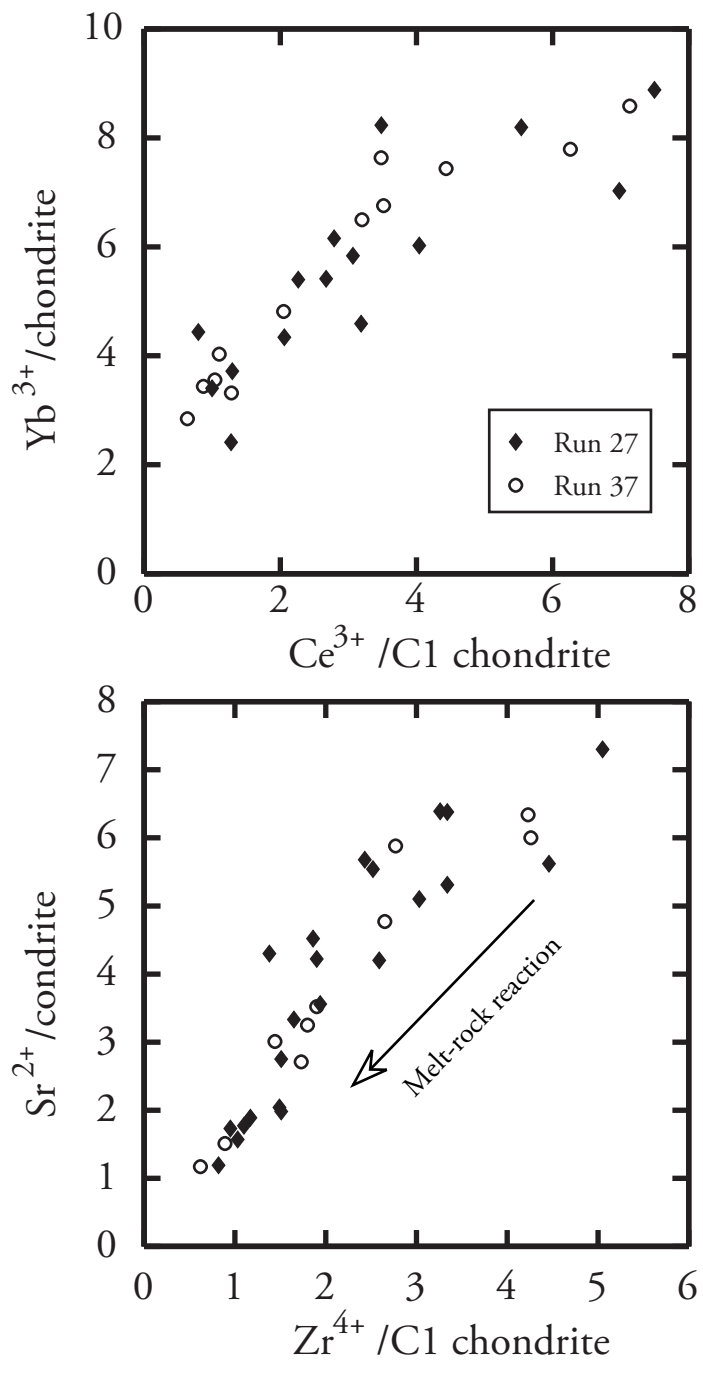


Figure 8

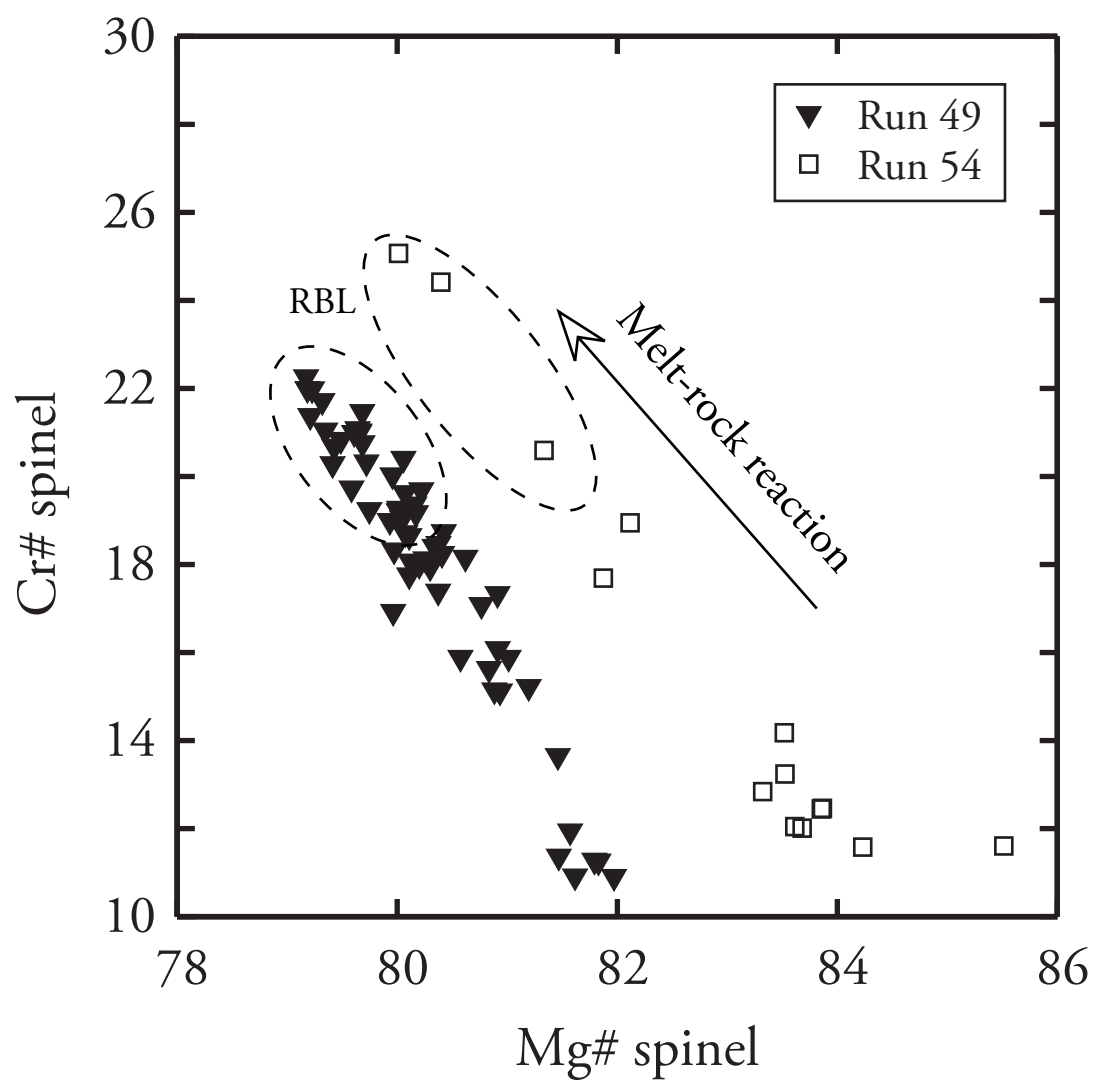


Figure 9

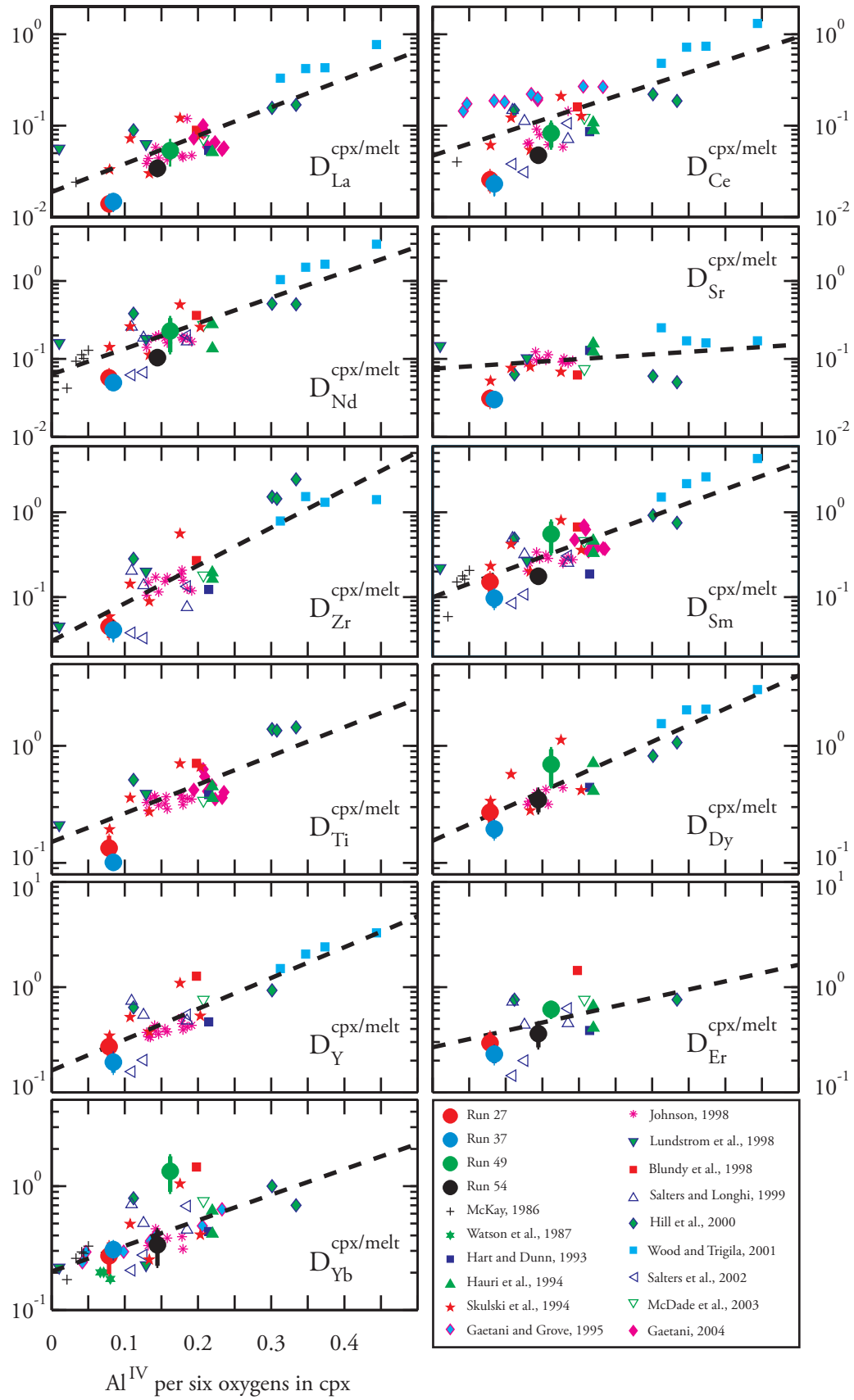


Table 1. Starting compositions

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	ΣFeO	NiO	MnO	MgO	CaO	Na ₂ O	Total
XDJ-16 ^a											
olivine	40.04				11.01	0.39	0.18	47.58	0.08		99.28
orthopyroxene	54.94	0.09	4.71	0.45	6.91		0.17	32.07	0.80	0.21	100.35
clinopyroxene	52.32	0.39	7.30	0.93	3.47		0.13	14.78	17.97	2.48	99.77
spinel	0.08	0.24	53.25	13.72	13.41		0.13	20.18			101.13
XDJ-11 ^a											
spinel	0.09	0.15	57.88	10.87	10.44		0.12	21.21			100.86
HBT01 ^b											
pillow lava	47.94	0.91	15.40		10.69		0.17	10.13	12.58	1.91	99.26

^aLiang and Elthon, 1990

^bSample by N. Shimizu; LOI = -0.68

Table 2. Electron microprobe analyses of run products (in wt%)

Run ^a	n	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
Run 27: 1350°C, 79.15 hrs														
glass	64	51.60 (0.54)	0.97 (0.05)	16.42 (0.76)	na	6.03 (0.46)	0.16 (0.04)	7.81 (1.39)	11.29 (0.66)	5.29 (0.29)	0.27 (0.03)	0.27 (0.04)	100.13	0.70
olivine	111	41.09 (0.16)	na ^d	na	na	8.33 (0.13)	0.15 (0.03)	50.64 (0.17)	0.28 (0.03)	na	na	na	100.49	0.92
orthopyroxene	14	55.60 (0.39)	0.08 (0.02)	4.28 (0.67)	0.52 (0.05)	5.38 (0.35)	0.15 (0.03)	32.58 (0.39)	1.82 (0.69)	0.28 (0.10)	na	na	100.69	0.92
clinopyroxene "core"	18	53.01 (0.25)	0.22 (0.02)	5.34 (0.30)	1.13 (0.08)	3.16 (0.13)	0.11 (0.03)	19.41 (0.52)	16.70 (0.66)	1.13 (0.14)	na	na	100.22	0.92
clinopyroxene RBL	32	54.37 (0.60)	0.14 (0.03)	4.28 (0.62)	0.81 (0.11)	4.24 (0.36)	0.16 (0.04)	23.70 (1.64)	11.52 (1.85)	0.99 (0.16)	na	na	100.20	0.91
Run 37: 1350°C, 72.00 hrs														
glass	36	49.16 (0.26)	1.05 (0.05)	15.41 (0.37)	na	7.56 (0.36)	0.17 (0.04)	10.55 (0.97)	10.72 (0.48)	4.77 (0.26)	0.28 (0.02)	0.11 (0.03)	99.79	0.71
olivine	53	40.96 (0.16)	na	na	na	8.96 (0.14)	0.16 (0.04)	49.37 (0.14)	0.29 (0.02)	na	na	na	99.73	0.91
orthopyroxene	26	55.22 (0.53)	0.09 (0.02)	4.57 (0.78)	0.52 (0.04)	5.79 (0.47)	0.18 (0.12)	32.63 (0.38)	1.34 (0.59)	0.22 (0.07)	na	na	100.55	0.91
clinopyroxene "core"	46	52.37 (0.36)	0.29 (0.07)	5.64 (0.62)	1.14 (0.08)	2.93 (0.22)	0.11 (0.11)	18.24 (0.93)	18.65 (1.01)	0.99 (0.10)	na	na	100.37	0.92
clinopyroxene RBL	43	54.43 (0.45)	0.14 (0.03)	3.98 (0.51)	0.91 (0.08)	4.23 (0.25)	0.15 (0.03)	24.07 (1.23)	11.79 (1.41)	0.82 (0.09)	na	na	100.52	0.91
Run 49: 1300°C, 72.75 hrs														
glass	7	47.78 (0.78)	0.94 (0.03)	17.90 (0.40)	na	8.16 (0.71)	0.15 (0.04)	6.83 (0.60)	11.92 (0.58)	3.68 (0.46)	0.23 (0.03)	0.27 (0.03)	97.85	0.60
olivine	12	40.80 (0.25)	na	na	na	9.51 (0.10)	0.15 (0.02)	49.31 (0.13)	0.30 (0.03)	na	na	na	100.05	0.90
orthopyroxene	11	53.16 (0.43)	0.10 (0.01)	6.85 (0.64)	0.89 (0.16)	5.95 (0.22)	0.15 (0.02)	31.47 (0.60)	1.54 (0.49)	0.17 (0.03)	na	na	100.28	0.90
clinopyroxene "core"	15	50.41 (0.23)	0.34 (0.06)	8.49 (0.26)	1.18 (0.16)	3.75 (0.17)	0.11 (0.02)	17.57 (0.63)	16.97 (0.66)	0.94 (0.10)	na	na	99.75	0.89
clinopyroxene RBL	3	51.60 (0.42)	0.17 (0.02)	7.36 (0.43)	1.46 (0.10)	4.43 (0.21)	0.13 (0.02)	21.48 (0.98)	12.62 (0.92)	0.78 (0.09)	na	na	100.04	0.90
spinel in cpx	5	na	0.17 (0.01)	58.79 (0.56)	11.11 (0.39)	8.58 (0.08)	na	21.56 (0.14)	na	na	na	na	100.21	0.82
spinel in opx	16	na	0.15 (0.02)	52.58 (1.40)	17.10 (1.47)	9.08 (0.17)	na	20.93 (0.25)	na	na	na	na	99.85	0.80
spinel in RBL	23	na	0.16 (0.01)	50.63 (1.19)	19.32 (1.10)	9.35 (0.15)	na	20.58 (0.22)	na	na	na	na	100.05	0.80
Run 54: 1350°C, 72.00 hrs														
glass	5	45.51 (0.40)	1.21 (0.05)	19.65 (0.93)	na	8.55 (0.44)	0.17 (0.01)	6.39 (0.60)	8.34 (0.49)	6.05 (0.19)	0.42 (0.05)	0.23 (0.02)	96.52	0.57
olivine	12	41.17 (0.24)	na	na	na	8.49 (0.08)	0.15 (0.02)	50.20 (0.19)	0.28 (0.03)	na	na	na	100.28	0.91
orthopyroxene	12	54.33 (0.38)	0.09 (0.01)	5.72 (0.44)	0.71 (0.19)	5.75 (0.41)	0.14 (0.02)	32.58 (0.23)	1.08 (0.36)	0.16 (0.03)	na	na	100.56	0.91
clinopyroxene "core"	6	52.34 (0.69)	0.27 (0.06)	5.70 (0.85)	1.15 (0.06)	2.88 (0.25)	0.10 (0.02)	18.35 (0.67)	18.23 (1.27)	0.92 (0.07)	na	na	99.93	0.92
clinopyroxene RBL	22	52.23 (0.30)	0.22 (0.03)	6.97 (0.41)	1.23 (0.07)	3.99 (0.20)	0.14 (0.02)	21.18 (0.40)	13.51 (0.51)	0.85 (0.03)	na	na	100.32	0.90
spinel in opx	9	na	0.14 (0.01)	57.61 (1.04)	12.24 (0.71)	7.68 (0.29)	na	22.46 (0.27)	na	na	na	na	100.13	0.84
spinel RBL	3	na	0.19 (0.02)	48.55 (2.11)	22.02 (2.04)	8.89 (0.17)	na	20.69 (0.51)	na	na	na	na	100.34	0.81

Units in parentheses represent 1σ standard deviation on the basis of replicate analyses. ^aTherefore, 40.96 (0.16) should be read as 40.96 ± 0.16 wt%.

^bRun 27: opx+ol vs. cpx; Run 37: opx vs. cpx; Run 49: opx+sp vs. cpx+sp+glass; Run 54: opx+sp vs. cpx, all at 1.5 GPa

^cTime reflects the time spent at the specified temperature and pressure. In addition, there are 24 hrs of preanneal period at 1.5 GPa and 1200°C (runs 27, 37, 54) or 1100°C (run 49)

^dAverage chemical composition in different locations of the experiment. "Core" refers to far away concentration from the interface. RBL refers to Reactive Boundary Layer

^ena stands for not analyzed

Table 3. Ion microprobe analyses of run products (in ppm)

Run ^a	Run 27: 1350°C, 79.15 hrs				Run 37: 1350°C, 72.00 hrs			
^b Phase (n)	Cpx (3)	Glass (2)	K _d ^c		Cpx (5)	Glass (4)	K _d	
La	0.10 (0.02)	7.00 (0.45)	0.01 (0.00)		0.13 (0.03)	8.85 (0.17)	0.01 (0.00)	
Ce	0.67 (0.15)	26.19 (3.21)	0.03 (0.01)		0.60 (0.15)	26.21 (1.23)	0.02 (0.01)	
Nd	0.70 (0.15)	12.32 (1.67)	0.06 (0.01)		0.71 (0.07)	14.44 (0.45)	0.05 (0.01)	
Sm	0.36 (0.09)	2.36 (0.14)	0.15 (0.04)		0.33 (0.07)	3.39 (0.22)	0.10 (0.02)	
Dy	0.91 (0.16)	3.34 (0.30)	0.27 (0.05)		0.70 (0.09)	3.59 (0.44)	0.19 (0.03)	
Er	0.71 (0.15)	2.42 (0.33)	0.29 (0.07)		0.49 (0.08)	2.14 (0.20)	0.23 (0.04)	
Yb	0.56 (0.14)	2.05 (0.32)	0.27 (0.08)		0.55 (0.07)	1.80 (0.15)	0.31 (0.05)	
Run 49: 1300°C, 72.75 hrs								
^b Phase (n)	Cpx (2)	Glass (2)	K _d		Cpx (3)	Glass (1)	K _d	
La	0.17 (0.05)	3.27 (0.45)	0.05 (0.02)		0.31 (0.06)	9.05	0.03 (0.01)	
Ce	0.76 (0.09)	9.22 (2.60)	0.08 (0.03)		1.41 (0.12)	29.74	0.05 (0.00)	
Nd	1.05 (0.47)	4.63 (0.55)	0.23 (0.11)		1.69 (0.15)	16.33	0.10 (0.01)	
Sm	0.61 (0.03)	1.10 (0.44)	0.55 (0.22)		0.77 (0.11)	4.36	0.18 (0.03)	
Dy	2.49 (0.77)	3.58 (0.57)	0.69 (0.24)		5.07 (1.12)	14.64	0.35 (0.08)	
Er	0.24 (0.02)	0.39 (0.05)	0.61 (0.09)		0.55 (0.14)	1.54	0.36 (0.09)	
Yb	0.61 (0.19)	0.46 (0.02)	1.32 (0.42)		0.71 (0.23)	2.13	0.34 (0.11)	
Run 54: 1350°C, 72.00 hrs								
^b Phase (n)	Cpx (7)	Glass (6)	K _d		Cpx (3)	Glass (6)	K _d	
Sr	13 (2)	401 (67)	0.03 (0.01)		10 (1)	334 (35)	0.03 (0.00)	
Ti	924 (195)	6,880 (1,187)	0.13 (0.04)		675 (47)	6,664 (606)	0.10 (0.01)	
Zr	4 (1.0)	97 (15)	0.05 (0.01)		3 (1)	81 (7)	0.04 (0.01)	
Y	8 (2)	29 (6)	0.27 (0.08)		6 (1)	29 (3)	0.19 (0.04)	

Units in parentheses represent 1s standard deviation on the basis of replicate analyses

^aRun 27: opx+ol vs. cpx; Run 37: opx vs. cpx; Run 49: opx+sp vs. cpx+sp+glass; Run 54: opx+sp vs. cpx

^bAnalyzed phase and number of analysis in parentheses

^cStandard deviations are calculated as total fractional uncertainty for independent random errors (Taylor, 1982)

Table 4: Linear regression parameters[†]

	K_d°	slope	R^2
$K_d = K_d^\circ * \log_{10}(m * Al_{cp\infty}^{IV})$			
La	0.018711	3.0902	0.82
Ce	0.046897	2.6007	0.68
Nd	0.063224	3.2802	0.85
Sm	0.099807	3.1792	0.83
Dy	0.154250	2.8246	0.89
Er	0.237500	1.5703	0.38
Yb	0.204630	2.0656	0.69
Lu	0.227430	2.1781	0.60
Sr	0.074453	0.6204	0.35
Ti	0.150850	2.4535	0.76
Zr	0.030297	4.4562	0.85
Y	0.160940	2.9322	0.84

[†]Data from our experiments was excluded in the calculation

Supplementary Materials

Figure A1. Major element composition of cpx across the four experiments. This figure shows that if the concentration gradients in cpx were produced by volume diffusion alone, a diffusivity of 10^{-13} – 10^{-15} m²/s would be needed. The numbers shown in the panels represent apparent diffusion coefficients determined by least squares fits to the measured data using an error function solution that includes the movement of the reaction couple interface (e.g., Zhang et al., 1989). For Al₂O₃ we show the fitted model for reference but the data fit is very poor. All runs start with a cpx composition having an Al₂O₃ content of ~6 wt.% except for Run 49 where we added spinel and basalt to the cpx-aggregate. The composition of the cpx in Run 49 readjusted during the synthesis to about 8.5 wt.% Al₂O₃ and to a FeO content that is also slightly higher compared to the other runs. Note that for Run 54, where spinel was added only to the opx-aggregate, the cpx composition increases towards the RBL, in contrast to all other experiments.

Figure A2. Enlarged plot showing the boxed region in Fig. 5 where the width of the concentration gradient and RBL can be compared. The RBL is defined mineralogically (melt+cpx+oliv, see Fig. 3) and is 180 μ m thick, whereas the concentration gradient is ~400 μ m. This decoupling between mineralogy and chemistry is typical of dissolution and reprecipitation.

Figure A1

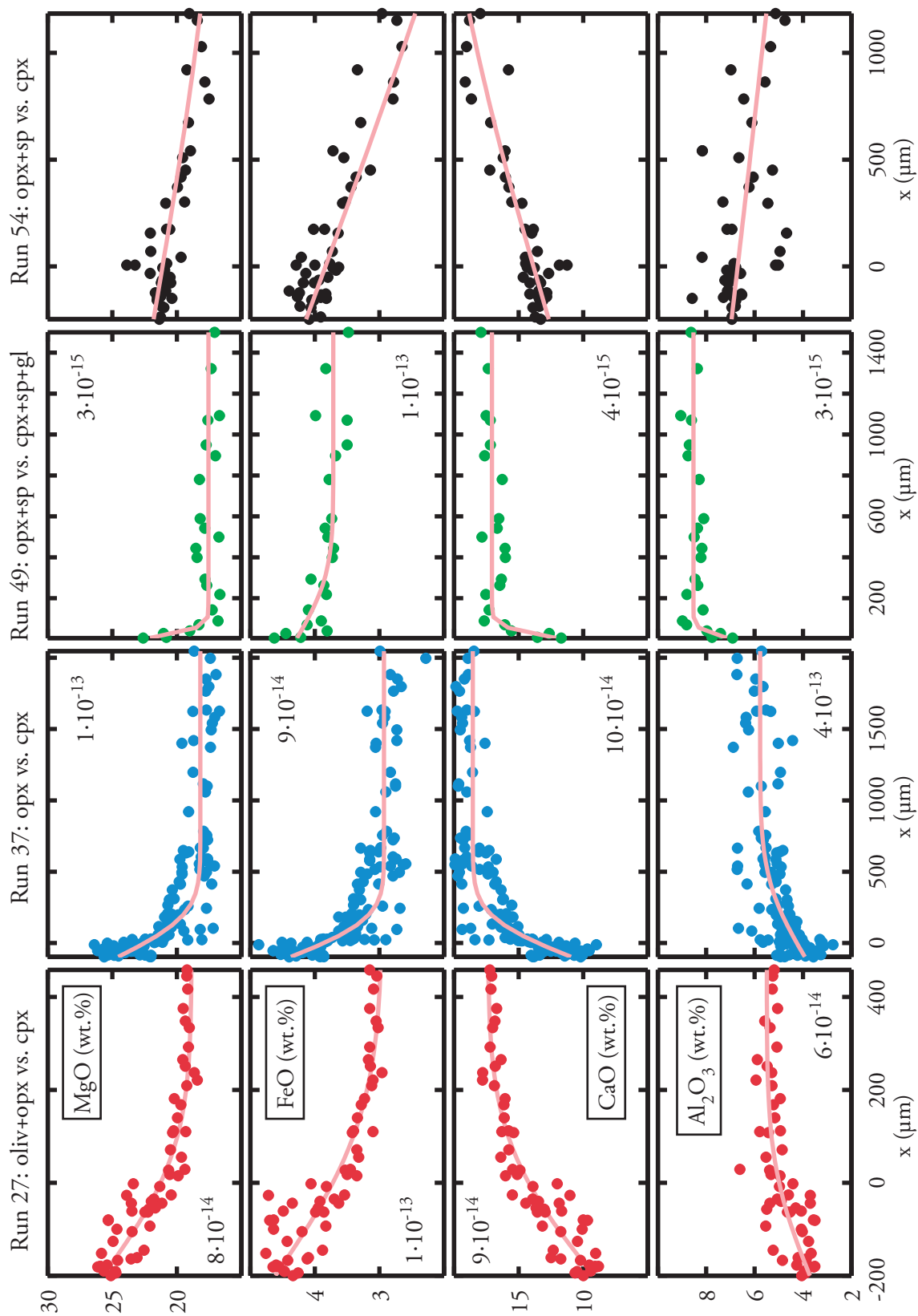
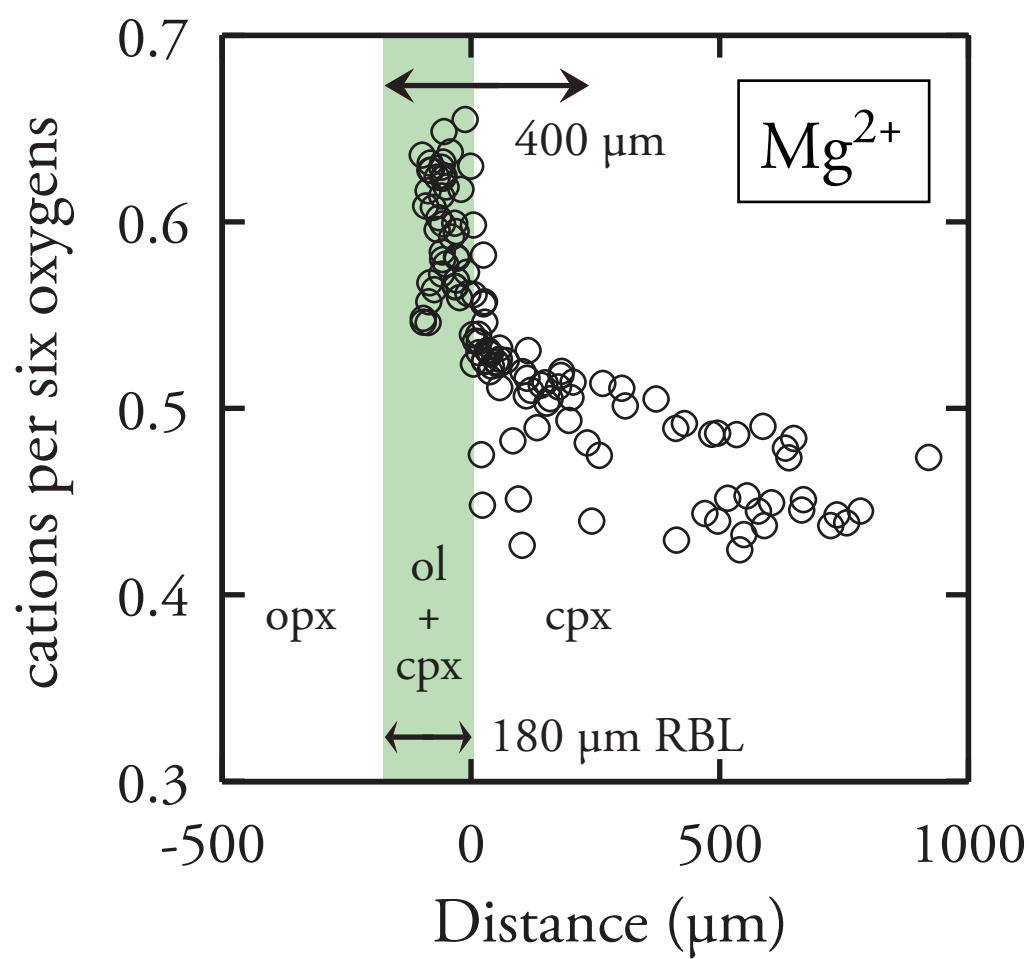


Figure A2



CHAPTER 3

**Kinetics of peridotite and pyroxenite-derived melts interaction:
Implications for the style and extent of melt-rock reaction in the Earth's
mantle**

Abstract

The kinetics of lherzolite dissolution in a pyroxenite-derived melt were examined at 2 GPa and 1300°C to 1375°C using the reaction couple method. Dissolution of lherzolite in a pyroxenite-derived melt is primarily controlled by the physical state of the peridotite and is characterized by two distinct dissolution regimes that are related to different grain-scale processes taking place. At lherzolite subsolidus conditions we observe very small dissolution rates and the precipitation of garnet at the melt-rock interface. In contrast, when the lherzolite is partially molten we observe the development of orthopyroxene-rich peridotites between the melt and the original lherzolite and very high dissolution rates, even though the orthopyroxene-rich bands have a lower porosity than the internal peridotites. In both cases, dissolution is driven by the degree of undersaturation of the melt with respect to the lherzolite and is rate-limited by the diffusion of the slowest major diffusing components in the melt. However, when the lherzolite is partially molten reactive dissolution dominates. Reactive dissolution is a grain-scale process that involves dissolution, precipitation, reprecipitation, and diffusive transport in the interstitial melts and surrounding minerals, and has the net effect of increasing the initial degree of undersaturation and hence the dissolution rates. In the Earth's mantle it is unlikely that a partially molten pyroxenite vein would remain out of equilibrium with the surrounding mantle. This suggests that the existence of heterogeneous geochemical signatures in the source region of ocean floor basalts imply that melt migration to the surface must take place by fast transport mechanisms.

1. Introduction

The Earth's upper mantle is known to be compositionally heterogeneous based on field observations of mantle-derived rocks (e.g., Nicolas and Boudier, 2003), and on major elements, trace elements, and isotopic features of ocean floor basalts (e.g., Zindler and Hart, 1986; Hauri, 1996; Hirschmann and Stolper, 1996; Hofmann, 1997; Sobolev et al., 2007). For example, the observed elevated SiO_2 , FeO , and NiO contents in lavas (e.g., Sobolev et al., 2007), combined with their enrichments in LREE/HREE ratios and $(^{230}\text{Th}/^{238}\text{U})$ excesses, have been attributed to the presence of garnet in the source region of ocean islands basalts (Beattie, 1993; Blundy and Wood, 2003). To satisfy both the crustal thickness constraints that limit partial melting of the mantle to the spinel stability field and the ocean island basalts chemistry, it is necessary to partially melt a hybrid mantle composed predominantly of peridotite with minor amounts of garnet pyroxenites (e.g., Hirschmann and Stolper, 1996 and references therein). The source of these heterogeneities being related to subduction processes and recycling of either old oceanic crust (Hofmann, 2003) or deep portions of oceanic lithosphere (see Niu and O'Hara, 2004 for a review), which turn into a garnet pyroxenite at high-pressure (e.g., Yasuda et al., 1994; Kogiso et al., 2004).

These findings have led to extensive studies on the melting phase relations of a variety of possible pyroxenite compositions that could be present in the mantle (e.g., Yaxley and Green, 1998; Takahashi et al., 1998; Rapp et al., 1999; Takahashi and Nakajima, 2002; Hirschmann et al., 2003; Kogiso et al., 2003; Petermann and Hirschmann, 2003; Keshav et al., 2004; Kogiso and Hirschmann, 2006). As can be seen in Fig. 1a, the partial melts obtained in these phase equilibria studies show a major element compositional range spanning from alkali-basalts to trachytes and dacites, depending on the starting composition and the temperature (T) and pressure (P) conditions of the experiments (Fig. 1b). Typically, pyroxenite-derived melts obtained in these experiments are low in MgO and silica-saturated

(Fig. 2) but some studies have shown that nepheline-normative melts, such as alkali basalts, can also be produced by certain types of pyroxenites (e.g., Kogiso et al., 2003; Keshav et al., 2004; Kogiso and Hirschmann, 2006). These compositional differences are important since they can determine whether melt infiltration is promoted or hindered in the mantle (e.g., Kogiso et al., 2004).

Several melt-rock reaction studies showed that at relatively low pressures (0.3 to 1 GPa) reaction of basalts with partially molten peridotites resulted in an increase of melt fraction through the development of high-porosity dunite bands at the expense of pyroxenes (Daines and Kohlstedt, 1994; Morgan and Liang, 2003; Morgan and Liang, 2005; Beck et al., 2006), boosting infiltration and reaction. In contrast, melt-rock reaction studies between pyroxenite-derived melts with peridotites at elevated pressures (2.5 to 3.8 GPa), suggested that the reaction consumes melt and crystallizes an orthopyroxene and garnet-rich lithology at the expense of olivine (Yaxley and Green, 1998; Rapp et al., 1999; Takahashi and Nakajima, 2002), potentially inhibiting infiltration and further reaction. Therefore, the nature of the interface that separates peridotites and pyroxenites (Fig. 3) appears to control the mechanisms and time-scales of melt segregation during partial melting of this hybrid mantle.

Although the goals, starting materials, and P - T conditions of the aforementioned melt-rock reaction studies were different, the reaction being considered at high-pressure (i.e., peridotite vs. garnet pyroxenite) was identical. The general conclusion of these studies is that interactions between eclogite-derived melts and peridotite result in crystallization of an orthopyroxene rich lithology at the melt-rock interface, and equilibration between the melt and the lherzolite is not achieved. This reaction takes place at the expense of melt and olivine, thus increasing the orthopyroxene:olivine ratio and decreasing the melt:rock ratio as reaction proceeds. These conclusions have led to the widely accepted notion that the

formation of orthopyroxene-rich bands between peridotites and eclogite-derived melts creates a permeability barrier thereby impeding melt infiltration and limiting mass exchange to volume diffusion between the two reacting lithologies (e.g., Kogiso et al., 2004). However, the stability of this reactive boundary layer has not been addressed yet. Furthermore, a number of important issues related to peridotite and pyroxenite-derived melt interaction remained unanswered. For example, do the style and mechanism of reaction change when peridotite is at subsolidus conditions or partially molten? Does the style of dissolution changes as a function of depth or pressure? What controls the dissolution rates? Finally, to what extent does an orthopyroxene-rich lithology hinder infiltration and reaction? The answers to these questions are very important in our understanding of how melt-rock reaction takes place in the mantle and its implications for melt transport.

In an attempt to address these important questions, we conducted two sets of dissolution experiments: one by reacting a pyroxenite-derived melt with a subsolidus lherzolite and the other by reacting a pyroxenite-derived melt with a melt-bearing lherzolite. These experiments will allow us to test whether small degrees of lherzolite melting make a difference in the style and extent of melt-rock reaction between the pyroxenite-derived melt and the lherzolite. In section 2 we will describe our experimental and analytical methods, and justify the choice of our starting material. In section 3, we will present our experimental and analytical results, and show that there are two melt-rock reaction regimes. In the last part of the chapter (Section 4), we will discuss the grain-scale processes associated with dissolution (§4.1), and we will show that the kinetics of lherzolite dissolution in a pyroxenite-derived melt are characterized by two melt-rock reaction regimes (§4.2). Finally we will speculate on the style and extent of melt-rock reaction in the Earth's uppermost mantle (§4.3), and its implications for the trace element content of enriched melts in the Earth's mantle, using a reactive transport model (§4.4).

2. Experimental and analytical methods

2.1 Starting materials

The starting materials used in the present study were made from mineral separates of a fertile spinel lherzolite xenolith from Kilbourne Hole, New Mexico (sample KBH-1 provided by Drs. L. Huang and D. Bell), and from a powdered basaltic andesite from Montserrat (sample Mont 147 provided by Dr. J.D. Devine). The major element compositions of the starting materials are reported in Table 1. The basaltic andesite was chosen as an analogue to a pyroxenite-derived mel. As shown in Fig. 1, the composition of our starting basaltic andesite is within the range of pyroxenite-derived melts that were obtained in experimental studies conducted between 1100°C to 1650°C, and 1.25 GPa to 3.80 GPa. The phase equilibria studies of Peterman and Hirschmann (2003) and Takahashi and Nakajima (2002) that result in a similar melt composition, indicate that our starting material has clinopyroxene and garnet on the liquidus. However, at the pressure-temperature conditions of this study, the basaltic andesite is fully molten.

Coarse mineral separates (0.5-1 mm) were obtained from sieved and optically clean handpicked minerals from the disaggregated nodule of KBH-1. The separates were then ground for 15 minutes in ethanol, dried under a heating lamp and sieved again to obtain a range in grain size of 25-38 μm . The lherzolite starting material was obtained by mixing the processed mineral separates in the following proportions (by weight): 49.0% olivine, 35.5% orthopyroxene, and 15.5% clinopyroxene. For simplicity, spinel was not included in this study. The basaltic andesite was also ground for 15 minutes in ethanol and dried under a heating lamp. Although we did not measure the water content in the basaltic andesite, we expect the water content to be less than 0.5 wt.% based on the degassed nature of the magma (Dr. J. D. Devine, personal communication, 2004). The starting materials were heat-

treated to drive off adsorbed water (200°C in a vacuum oven for >48 hrs) and then stored in the vacuum oven at 110°C.

2.2 Experimental methods

Synthesis and reaction experiments were conducted in a molybdenum capsule using a 19.05 mm piston cylinder apparatus with straight-walled graphite furnace, Pyrex® tubing, crushable MgO spacers and insulators, and NaCl pressure medium. The cylindrical molybdenum capsules (6.5 mm OD, 4.1 mm ID, 10.0 to 10.5 mm long) are lined with a platinum tube (4.0 mm OD, 3.8 mm ID), which in turn is lined with a graphite inner sleeve (3.8 mm OD, 2.0 mm ID). See Fig. 2 in chapter 2 for more details. In this assembly the sample is in contact only with the graphite inner sleeve and therefore the oxygen fugacity of the experiments is maintained at the graphite-CO buffer, which corresponds to FMQ to FMQ-1 at 1300-1375°C and 2.0 GPa (Jakobsson and Oskarsson 1994). One of the advantages of using the Mo-Pt-C capsule is that the strength of Mo assures a reasonably good geometry for both synthesis and dissolution runs, while preventing the graphite capsule from reacting with the Mo.

The synthesis of lherzolite and basaltic andesite cylindrical rods was done at 2 GPa. One set of lherzolite and basaltic andesite synthesis was prepared at 1300°C, where the basaltic andesite was fully molten and the lherzolite was completely solid. The other set of lherzolite and glass rods was prepared at 1375°C to obtain a melt-bearing lherzolite. Run durations ranged from 30 minutes to 74 hours. The details of run durations and conditions of the synthesis experiments are reported in Table 2. Each quenched synthesis run was sectioned perpendicular to their cylindrical axis with the exposed surfaces polished down to 1 µm finish (Al₂O₃ polishing compound in H₂O) and dried for at least 24 hrs at 200°C in a vacuum oven. Cylindrical half-capsules were then juxtaposed and jacketed with a platinum

tube to form a reaction couple. The complete furnace assembly was stored at 200°C in a vacuum oven for at least 24 hours before an actual dissolution experiment. We juxtapose the melt on top of the lherzolite to maintain stable density stratification during the reaction. The glass density as a function of position in the capsule was calculated based on the major element chemistry of the glass (see §3.2) and we found that the density stratification is stable.

Dissolution experiments were first cold pressurized to a pressure of ~ 2.1 GPa. The temperature was then raised to 1000°C at 75°C/min. After a 2 hour annealing period at 1000°C and 2 GPa, the temperature was increased to either 1300°C or 1375°C again at 75°C/min, and held at the run conditions for 2 to 74 hours (Table 2). At the end of a run, the experiment was quenched to room temperature by shutting off the power. The capsule was then mounted in epoxy, sectioned longitudinally, and polished down to 0.3 μm finish. Due to the slight difference in diameters between the two half cylindrical capsules containing the pre-synthesized material, a small offset at the original interface is visible after quench, and is used as a marker for distance measurements (Fig. 4b).

The temperature was monitored using a W₉₇-Re₃/W₇₅-Re₂₅ thermocouple and a Eurotherm 818 controller. No pressure correction was applied to the measured e.m.f. Uncertainties in the temperature measurements were about 10°C due mainly to a temperature gradient in the solid medium assembly (e.g., Ayers et al., 1992; Liang et al., 1996; Watson et al., 2002). The nominal pressure was not corrected for friction because the slight pressure fluctuations (~ 30 MPa) during a run are comparable to the 25 MPa friction correction measured by (Ayers et al., 1992) for a similar furnace assemblage.

2.3 Microprobe analysis

Back-scattered electron (BSE) images, X-ray intensity maps, and mineral and melt chemical analyses were conducted at Brown University using a Cameca SX-100 electron microprobe. An accelerating voltage of 20 kV and a beam current of 50 nA were used to collect BSE images and X-ray intensity maps. Chemical analyses were conducted using an accelerating voltage of 15 kV, a current of 10 nA, and a slightly defocused beam (5 μm) for the glass analyses. For the minerals analyses, we used an accelerating voltage of 20 kV, a current of 25 nA, and a focused beam (1-2 μm). Counting times were 20 s for peak and 10 s for background on each side of the peak. Natural glass and mineral standards were used for all analyses and the PAP correction procedure was employed (Pouchou and Pichoir 1984). To minimize sodium loss during the analyses, sodium was analyzed first.

2.4 Image analysis

BSE images were used to measure the dissolution distance, modal abundance, and grain size. Individual phases were traced manually in Photoshop® from the BSE images and the measurements of area and grain-size were made from the traced images using ImageJ, the NIH image analysis software (Abramoff et al., 2004).

3. Results

We carried out two sets of experiments in this study: one at 1300°C in which the lherzolite was below its solidus temperature, and another set at 1375°C in which the lherzolite was partially molten (< 5%), resulting in a total of nine successful basaltic andesite-lherzolite dissolution runs. We will show that the reaction between the basaltic andesite and lherzolite differs greatly depending on whether the lherzolite is subsolidus or partially molten. Experiments where Fe-loss was detected due to leaks in the graphite inner

capsule, or where we observed oxidation of the thermocouple, or where the offset between the two half capsules was larger than 15-20% of the total width of the interface, were excluded from this report.

3.1 Experimental charge and textures

Each dissolution experiment is composed of two juxtaposed cylindrical half-capsules (basaltic andesite on top of lherzolite) and the dimensions of the run are typically 3-4 mm long and 1.0-1.5 mm in diameter. However, the individual lengths of the lherzolite and basaltic andesite half-capsules are different for each experiment (Table 2) due to the way we cut each synthesis run. At 1300°C the lherzolite is below its solidus temperature and we observe small amounts of dissolution of the lherzolite in the melt. A few garnet grains were observed on the melt side of the reaction front (Figs. 4a and 4b). The dissolution distance is small and varies very little with time (Table 2 and Fig. 10) but the garnet grain-size (up to 150 μm) and number of garnet grains at the interface increase dramatically over time (Fig. 4). The boundary between the melt and lherzolite is mineralogically and chemically sharp, even though we observe a narrow transition region of one mineral grain width, composed of clinopyroxenes and olivine at the interface between the melt and the lherzolite (Fig. 4a and inset). In §3.2 we will show that this layer is compositionally distinct from the rest of the peridotite. The interior of the lherzolite is mineralogically and texturally (and chemically, see §3.2) unaffected by this reaction. In general, we do not observe any change with distance of grain size or phase modal abundance. Olivine and orthopyroxene are euhedral throughout the lherzolite with a median grain size of 40 and 30 μm respectively. Clinopyroxene crystals are typically anhedral with a median grain size of 40 μm except right at the interface between the lherzolite and the melt, where the grain size becomes very small ($< 10 \mu\text{m}$). The basaltic

andesite appears to be quench-free, even at the reaction interface located between the melt and the lherzolite.

At 1375°C, the lherzolite is partially molten with less than 5 vol.% of melt and the kinetics of dissolution are very different from the 1300°C experiments. Garnet is not present in this set of experiments (Figs. 5 to 9) and we observe a significant increase in the dissolution rate compared to the 1300°C experiments (Fig. 10). In addition, the peridotite develops distinct internal lithological regions (and chemical gradients that extend across the mineralogical zones, see §3.2). The sequence of lithologies going from the melt to the lherzolite is: (1) orthopyroxene-rich harzburgite, (2) harzburgite + melt, and (3) lherzolite $\pm$ melt. Lithologies (1) and (2) are both clinopyroxene free. For the longest duration run (74 hrs; Fig. 9), the whole capsule is clinopyroxene-free and we observe an orthopyroxene-rich region surrounding the central harzburgite. The width of each lithology changes with time such that the lherzolite width decreases in time while the harzburgite and orthopyroxene-rich harzburgite widths increase. Olivine and orthopyroxene are euhedral to subhedral with median grain size of 50 and 45 μm respectively. Clinopyroxenes crystals are typically anhedral with a median grain size of 25 μm . In the peridotite, the distribution of the melt is inhomogeneous and is found primarily in the harzburgite (Figs. 7 and 8), between the orthopyroxene-rich harzburgite and the lherzolite, and is heavily affected by quench even for relatively large ($\sim 30\ \mu\text{m}$) melt pockets. Within the basaltic andesite, the melt is not affected by quench growth, except at the peridotite-melt interface region where we observe a relatively thick zone (up to $\sim 40\ \mu\text{m}$) of clinopyroxene quench.

3.2. Mineral and melt compositions

Detailed microprobe traverses across each run were performed for all phases present and the major element analyses as a function of position in the charge are reported in

Appendix A. The composition of each phase for a given position in the capsule is shown in Figures 11 to 19.

3.2.1 Olivine

The olivine composition at 1300°C is essentially constant across the lherzolite with an average Mg# of 90.5, except at the melt/lherzolite interface where the FeO, Al₂O₃, and CaO increase whereas the MgO and Mg# decrease (Fig. 11). In contrast, the MgO, FeO, and Mg# of olivine at 1375°C changes gradually with distance while other elements remain relatively constant but not CaO (Fig. 12). Note that the initial composition of olivine in the 1375°C experiments is different from the starting material (dashed line) due to small amounts of melting during the synthesis (arrow in Fig. 12). The NiO content of olivine is shown in Figure 13 as a function of distance from the initial melt/peridotite interface. Although the shortest run at 1300°C shows a non-negligible content of NiO throughout the capsules, for longer duration runs and for the 1375°C experiments the NiO content of olivines becomes nearly undetectable. This decrease in NiO content in olivine results from the reaction with the melt which dilutes the NiO content of the olivine in the peridotite.

3.2.2 Orthopyroxene

The orthopyroxene compositional changes are analogue to the olivine, in that at 1300°C they are essentially constant (Mg# 91.4; Fig. 14) and at 1375°C the MgO, FeO, Mg#, and to a lesser extent SiO₂ and Al₂O₃ vary with distance (Fig. 15). However, the orthopyroxene has a larger compositional scatter compared to olivine reflecting the role of local core-to-rim chemical equilibration, which is expected due to slower diffusion rates in orthopyroxene compared to olivine (*e.g.*, Cherniak, 2001). The orthopyroxene composition at 1375°C is typically more enriched in SiO₂ and CaO compared to the 1300°C experiments,

and shows an Al_2O_3 enrichment and SiO_2 , MgO , and $\text{Mg \#}$ depletion near the melt-rock interface for the longest duration runs (Fig. 15).

3.2.3 *Clinopyroxene*

The 1300°C clinopyroxene composition is also relatively constant across the capsule ($\text{Mg\#}$ 91) except at the melt-lherzolite interface (Fig. 16) where Cr_2O_3 , $\text{Mg\#}$, CaO , and Na_2O decrease while Al_2O_3 , FeO , and MnO increase. The 1375°C clinopyroxene composition does not vary with distance, even though the core-to-rim scatter is larger than at 1300°C (Fig. 17) due, in part, to partial melting of the lherzolite. The composition of clinopyroxene is typically more enriched in SiO_2 and FeO at 1375°C and depleted in Al_2O_3 , CaO , Na_2O , and MgO , relative to the composition at 1300°C . In both sets of experiments, the composition of clinopyroxene does not appear to change systematically with distance, even though it is being dissolved.

3.2.4 *Garnet*

The composition of garnet in the 1300°C experiments changes with time (see Appendix A for details of all mineral and glass analyses). Initially (Run 3) the garnet molecular proportions in pyrope, almandine, spessartine, and grossular are respectively 54%, 29%, 1%, and 16%. However, as the garnet grain-size increases (Run 11), we observe a change in composition with cores rich in FeO and CaO , and rims rich in SiO_2 and MgO . This results in a range of molecular proportions of pyrope, almandine, spessartine, and grossular of 47-59%, 17-33%, 0.5-1.5%, and 14-27% respectively, with cores enriched in almandine and grossular, and rims enriched in pyrope and spessartine (Appendix C, Tables C1-5 and C3-5).

3.2.5 Melt

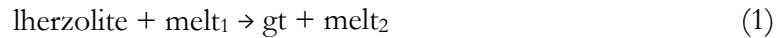
The starting glass composition (Table 1) is quartz-normative and the melt compositional profiles for the two set of experiments is different due to different processes operating at the melt-lherzolite interface. At 1300°C (subsolidus lherzolite), the reaction between the pyroxenite-derived melt and lherzolite increases the SiO₂, Na₂O, MgO, and Mg# while decreasing the Al₂O₃, FeO, and CaO content of the glass (Fig. 18). The arrows in Fig. 18, show how the melt composition located at the melt-rock interface changes with time. At 1375°C (when the lherzolite is partially molten), we observe a decrease in SiO₂, TiO₂, Al₂O₃, FeO, and Na₂O content of the glass and an increase in MgO and Mg# (Fig. 19). Again, the arrows indicate how the melt composition at the interface changes with time. The main differences between the two sets of experiments are (1) the SiO₂ content of the melt at the rock-melt interface increases (up to 57%) in the 1300°C runs whereas it decreases in the 1375°C runs (down to 54%); (2) a small increase in the Mg# of the interface melt composition in the 1300°C runs (up to 55) compared to the high Mg# of the melt-rock interface in the 1375°C runs (up to 72); and (3) the larger Al₂O₃ depletion of the 1375°C experiments (down to ~15.6%) relative to the 1300°C ones (down to 17.4%). The glass compositional differences is also illustrated in Figure 20, which shows the normative composition of the glass in the pseudo-ternary system Forsterite–Calcium Tschermak–Quartz projected from Diopside (O'Hara 1968). Along with our data, we also show the composition of pyroxenite-derived melts obtained in published experimental studies (Takahashi et al., 1998; Yaxley and Green, 1998; Rapp et al., 1999; Takahashi and Nakajima, 2002; Kogiso et al., 2003; Hirschmann et al., 2003; Petermann and Hirschmann, 2003; Keshav et al., 2004; Kogiso and Hirschmann, 2006). This figure shows that the melt chemistry of the 1300°C experiments is primarily controlled by garnet crystallization, while the composition of the melt in the 1375°C experiments is controlled by dissolution of the

lherzolite (see § 4.1 for a detailed description of the process). These compositional differences between the two sets of experiments are also reflected in the calculated melt density and viscosity, shown as a function of position in the capsule in Figure 21. For all runs, we observe a decrease in viscosity and a small increase in the density at the melt/peridotite interface relative to the upper capsule. However, the absolute values of density for the 1300°C melts decrease with time while the 1375°C melts increase. The viscosity change is also very different for both regimes, with the 1375°C melts decreasing in viscosity down to 0.5 Pa sec. As mentioned in § 2.2, the density stratification of the melt is stable in this configuration.

4. Discussion

4.1 Grain-scale processes of lherzolite and pyroxenite-derived melt interaction

The reaction between a fertile lherzolite and a basaltic andesite melt at 2 GPa is characterized by two dissolution regimes depending on whether the lherzolite is subsolidus or partially molten. At 1300°C the lherzolite is at subsolidus conditions and the reaction involves simple dissolution of the lherzolite with crystallization of garnet at the rock-melt interface. As described in §3, the lherzolite composition does not change with time, therefore based on the BSE images (Fig. 3) and measured chemical profiles across our experiments (Figs. 11, 14, 16, and 18) the reaction taking place at 1300°C can be written as follows



where melt₁ designates the starting basaltic andesite and melt₂ the new melt composition at the lherzolite-melt interface. The composition of melt₂ is controlled in part by the crystallization of garnet at the melt-rock interface, which drives the melt towards a more qz-normative composition (Fig. 20). Although the composition of olivine and clinopyroxene

changes right at the melt-lherzolite interface (for just one grain-width) the bulk of the lherzolite is chemically unaffected by the reaction. Therefore, dissolution is primarily controlled by the interface melt composition that changes with time (red arrows in Fig. 18). This process of crystal-melt interaction is characteristic of diffusive dissolution, a crystal-melt equilibration process that is rate-limited by the slowest major diffusing component in the melt (Liang 1999; Liang, 2003a). Nevertheless, the analysis of Liang (2003a) must be modified to account for garnet precipitation at the melt-rock interface such that the flux balance or Stefan condition becomes

$$\phi D_f \frac{\partial C_f}{\partial x} \Big|_{x=X_b^-} + V[\phi C_f^b + (1 - \phi)C_{Gt}] = V C_{Lhz} \quad (2)$$

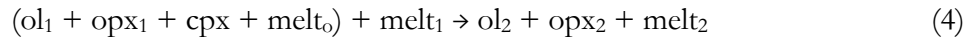
where D_f is the diffusion coefficient of the rate limiting component, C_f is the melt composition, V is the interface velocity or dissolution rate, C_{Gt} is the garnet composition, and C_{Lhz} is the bulk lherzolite composition at the melt-rock interface. The terms in the square bracket on the left hand side of equation (2) represent the bulk composition of the layer made of garnet + melt, and the porosity ϕ is relative to this layer. The dissolution rate can therefore be written as

$$V = \frac{\phi}{C_{Lhz} - [\phi C_f^b + (1 - \phi)C_{Gt}]} D_f \frac{\partial C_f}{\partial x} \Big|_{x=X_b^-} \quad (3)$$

Equation 3 suggests that the equilibration process is rate-limited by both the slowest diffusing component in the melt, the concentration gradient at the melt-rock interface, and by the amount of crystallized garnet (i.e., $1-\phi$). This partially explains why when garnet crystallizes at the melt-rock interface, the dissolution rate is very small. Equilibration between the melt and lherzolite is also sluggish and incomplete even at the melt-peridotite interface, where the individual mineral/melt Fe-Mg exchange coefficients are below 0.15.

The melt therefore is not likely to reach chemical equilibrium with the surrounding peridotite, even though its chemical composition changes due to garnet crystallization at the interface.

At 1375°C, when the lherzolite is partially molten, we observe dramatic mineralogical changes and the development of compositional gradients in the reaction couple that extend beyond the newly developed lithological zones. This decoupling between mineralogy and mineral composition is characteristic of reactive dissolution, a grain-scale process that involves dissolution, precipitation, and reprecipitation of several phases (Liang 2003a; Morgan and Liang 2003; Lo Cascio et al., 2004; Morgan and Liang, 2005; Lo Cascio et al., 2008). Dissolution-reprecipitation not only speeds up equilibration between minerals and melt, but also changes the distribution of mineral phases in the rock. Based on the BSE images and chemical profiles of our experiments, we can write the reaction between the partially molten lherzolite and the pyroxenite-derived melt as follows



where subscripts 1 and 2 designate the material before and after the reaction, and melt₀ indicates the melt produced by partial melting of the lherzolite during the synthesis step. This reaction involves diffusive mixing between melt₁ and melt₀, resulting in a liquid composition at the melt-rock interface that is depleted in SiO₂, Al₂O₃, Na₂O and enriched in FeO and MgO (Fig. 19) with respect to the melt composition observed in the 1300°C experiments (Fig. 18). This change of melt composition results in the dissolution of pyroxenes and olivine, followed by reprecipitation of a compositionally distinct layer of olivine and orthopyroxene, located between the original lherzolite and the melt. During this reaction, the volume of melt₂ increases dramatically with time (Fig. 10), indicating substantial amounts of assimilation of the lherzolite into the melt relative to amount of reprecipitation. However, the absolute value of the dissolution distance (Fig. 10a) and dissolution rate (Fig.

22) depends, primarily, on the initial length of the glass rod (Table 2), as shown in Fig. 10b. We see that after 24 hours reaction, Run 17 has the the smallest dissolution distance (160 μm) and started with shortest initial glass length (721 μm), while Run 27 has the highest dissolution distance (348 μm) and started with the longest initial glass length (2230 μm). This can be understood in terms of the volumetric capability of the melt to assimilate lherzolite. This observation can also be rationalized by modeling these experiments as a 1-D column of length L with melt present for $0 \leq x \leq X_b$ and solid for $X_b \leq x \leq L$ such that the overall mass conservation of a chemical specie can be written as

$$C_f(t_o)X_b(t_o) + C_s(t_o)(L - X_b(t_o)) = \bar{C}_f(t)X_b(t) + \bar{C}_s(t)(L - X_b(t))$$

$$\text{or} \quad X_b(t) = \frac{C_f(t_o) - C_s(t_o)}{\bar{C}_f(t) - \bar{C}_s(t)} X_b(t_o) + (C_s(t_o) - \bar{C}_s(t))L \quad (5)$$

where $C_f(t_o)$ and $C_s(t_o)$ are respectively the melt and solid concentrations at t_o , $\bar{C}_f(t)$ and $\bar{C}_s(t)$ are the average melt and solid concentrations for a given time t . Equation (5) shows that the dissolution distance $X_b(t)$ is a function of concentrations, initial dissolution distance $X_b(t_o)$, and the overall length of the system L (glass + lherzolite). For our experiments, the second term on the right hand side of equation (5) is negligible at small times given that the change of solid composition is much slower than that of the melt (i.e., $C_s(t_o) \sim \bar{C}_s(t)$ for small times). Therefore, to a first approximation the dissolution distance is dominated by the first term of the right hand side of equation (5) and the dominant length-scale of this problem becomes the initial glass length, $X_b(t_o)$. This is what we show in Fig. 10b, where the dissolution distance is normalized to the initial glass length and experiments 16, 17, and 27 collapse, within error, onto the same dissolution curve. Hence, the differences in these two grain-scale processes results in two very different dissolution regimes, depending on whether the lherzolite is at subsolidus conditions or partially molten. To simplify the discussion we

will refer to the 1300°C lherzolite subsolidus experiments where simple dissolution takes place as the low-T regime, and to the 1375°C lherzolite suprasolidus experiments where reactive dissolution dominates as the high-T regime.

4.2 Kinetics of lherzolite dissolution by a pyroxenite-derived melt

In both the low-T and high-T regimes, none of the minerals in the lherzolite are in equilibrium with the basaltic andesite, even at the melt-rock interface, and we would expect that in both cases olivine, orthopyroxene, and clinopyroxene would dissolve, at least partially, in the reacting melt. Yet, the low-T regime shows very small dissolution rates compared to the high-T regime (Fig. 22) which can be linked to (1) the temperature difference, accounting for different diffusivities in the melt (see below for values), (2) differences in the grain-scale processes taking place during dissolution as discussed in §4.1, which also results in (3) differences in the degrees of undersaturation between the two dissolution regimes, caused by the differences in melt composition at the melt-rock interface.

The dissolution rate for a simple crystal-melt system depends on the transport properties of the melt (i.e., diffusion and viscosity) and the chemical potential difference between the dissolving melt and the solid. The latter is related to the degree of undersaturation (Θ , defined below) of the rate-limiting species in the melt with respect to the crystal (Liang, 2003a; Liang 1999; Zhang et al., 1989). The concentrations profiles of the glass in our experiments can be used to estimate oxides diffusivities in the melt and viscosities which in turn can help us deduce what are the rate-limiting species during dissolution. For multicomponent molten silicates, coupled chemical diffusion can lead to non-linear effects such as uphill diffusion (Liang 1999), however, in this study we do not observe evidence of such coupling (Figs. 18 and 19). Therefore, we choose to use the simplest method of describing diffusion in a multicomponent system: the effective binary

diffusion coefficient or EBDC (Cooper 1968; Watson 1982; Zhang et al., 1989). Using the composition of the glass in the shortest duration runs of the low-T (Pyx 3, Figure 18) and high-T (Pyx 26, Figure 19) regimes, we can estimate the EBDC for several oxides. The analysis was done by least-squares fitting of the data to the following relationship that accounts for the moving boundary X_b

$$C_f(x, t) = C_f^o + (C_f^\infty - C_f^o) \operatorname{erf}\left(\frac{x + X_b}{\sqrt{4D_f t}}\right) \quad (6)$$

where C_f^o is the concentration of the melt at the melt-rock interface, C_f^∞ is the concentration of the melt far from the interface, and D_f is the EBDC. The data suggests that SiO_2 and Al_2O_3 are the rate-limiting species in our experiments (*i.e.*, they have the smallest values of diffusion coefficients of all oxides). However, for SiO_2 the errors are very large ($R^2 < 0.3$ for the low-T regime and $R^2 < 0.7$ for the high-T regime) due to the small changes in concentrations during reaction relative to the microprobe analysis errors. Therefore, in this chapter for simplicity we will use the calculated EBDC of Al_2O_3 whose value is $7.39 \cdot 10^{-12} \text{ m}^2/\text{sec}$ for the low-T regime ($R^2 \sim 0.961$) and $2.87 \cdot 10^{-11} \text{ m}^2/\text{sec}$ for the high-T regime ($R^2 \sim 0.997$). This estimate is on the same order of magnitude as the EBDC values of Richter et al. (2003) for a similar temperature and composition range.

Although the difference in diffusivities between the two regimes can partially account for the different dissolution rates (by a factor of 4), the driving force in both cases, Θ , is also very different. As mentioned earlier, during diffusive dissolution the dissolution rate is proportional to the degree of undersaturation Θ of the rate-limiting species in the melt with respect to the crystal (*e.g.*, Liang 1999; Zhang et al., 1989) and is defined as

$$\Theta = \frac{C_f^b - C_f^\infty}{C_s^b - C_f^\infty} \quad (7)$$

where C_i^b is the melt composition at the interface, C_i^∞ is the average melt composition far from the interface, and C_s^b is the average solid composition at the interface. Using the EBDC obtained earlier, we can assume that Al_2O_3 is the rate-limiting specie, and therefore will control dissolution rates. For a multicomponent system, the melt and solid concentrations at the interface will change with time (Liang 2003b), and we should see the degree of undersaturation also change with time. Figure 23 shows how the degree of undersaturation of the melt in Al_2O_3 in our experiments (calculated at the melt-rock interface) varies as a function of the square root of time. The main difference between the two dissolution regimes is the initial degree of undersaturation (Θ), being at least 50% greater in the high-T regime compared to the low-T regime. These differences in degrees of undersaturation result in an order of magnitude difference in dissolution rates (Fig. 22) between the low-T and high-T regime. In addition, the decrease of Θ with time corresponds to sharp decreases in the dissolution rates. These observations can be quantified using the diffusive dissolution analysis of Liang (1999), where the dissolution rate is expressed as a function of the measured degree of undersaturation in Al_2O_3 (Θ)

$$V = \alpha \sqrt{\frac{D_f}{t}} \quad (8)$$

where $\alpha \simeq -0.7763(1 - \sqrt{1 + \Theta})$, and D_f is the EBDC of Al_2O_3 . The results of this calculation are shown in Figures 10 and 22, where the experimental data (solid lines) is compared to equation 8 (dashed lines). As expected for the low-T regime there is an excellent agreement between the experiments and the model, whereas for the high-T regime the dissolution model underestimates the dissolution rates by $\sim 30\%$ because it does not account for dissolution and reprecipitation. However, equation 8 does an excellent job in recovering the measured dissolution distance, calculated as $X_b = 2\alpha \sqrt{D_f t}$, in both

regimes (Fig. 10) and can be used to extrapolate our experimental data to longer time scales, provided we know how the degree of undersaturation varies with time.

In summary, the high dissolution rates of the high-T regime are linked to a grain-scale process that results in a high degree of undersaturation and high diffusivities, compared to the low-T regime. Diffusive dissolution (low-T regime) and reactive dissolution (high-T regime) between lherzolite and pyroxenite-derived melt have very different effects on the mineralogy, dissolution rates, and equilibration times. Hence, these equilibration processes place important constraints on how pyroxenite-derived melts interact physically and chemically with the surrounding mantle lherzolite.

4.3 Style and extent of melt-rock reaction in the Earth's uppermost mantle

During mantle upwelling, pyroxenite-rich regions will likely start to melt at greater depths than the surrounding mantle peridotite (e.g., Ringwood and Green, 1966; Yasuda et al., 1994; Hirschmann and Stolper, 1996; Yaxley and Green, 1998; Petermann and Hirschmann, 2003). As this heterogeneous region ascends, peridotite will also start melting but the degree of melting of the pyroxenite will be larger than the peridotite for a given depth. Therefore, we can anticipate the existence of at least two regimes of chemical and mechanical interaction between lherzolites and pyroxenites during decompressional melting: one at high-P in which pyroxenite is partially molten while lherzolite is subsolidus, and another one at low-P in which both lithologies are partially molten (Fig. 24). Although this evolution takes place during mantle decompression, our isobaric experiments conducted at two different temperatures represent snap shots of reaction regimes that can take place in the upwelling mantle. Hence at depth greater than peridotite solidus we have simple dissolution of peridotites in pyroxenite-derived melts with garnet crystallization at the interface; whereas at depth shallower than peridotite solidus we have reactive dissolution of

peridotites in pyroxenite-derived melts. The net outcome of the melt-rock reaction creates an orthopyroxene-rich reactive boundary layer between the original lherzolite and the pyroxenite-derived melt.

In this study we have demonstrated that the necessary condition for infiltration and reaction of a pyroxenite-derived melt into the surrounding mantle is that the mantle must be partially molten. We have shown that during this reaction, the P-T conditions and the composition of the pyroxenite-derived melt determine the mineralogy of the reaction boundary layer (*i.e.*, orthopyroxene-rich at high pressure for high-SiO₂ melts *vs.* olivine-rich at low pressure for low-SiO₂ melts), the dissolution rates, and the time-scales of equilibration. These findings contradict previous studies suggesting that an orthopyroxene-rich reactive boundary layer would inhibit infiltration and reaction (e.g., Yaxley and Green, 1998; Takahashi and Nakajima, 2002). The formation of an orthopyroxene-rich reactive boundary layer during reactive dissolution in the high-T regime is also associated with a higher degree of undersaturation, which drives dissolution, and compensates for this permeability barrier. We have also shown that if the temperature is below the lherzolite solidus, the reaction involves small dissolution and equilibration rates between the melt and the peridotite. Because the bulk of the lherzolite is unaffected by the reaction, the partially molten pyroxenites is likely to remain out of chemical equilibrium with the surrounding mantle. Therefore, for partially molten pyroxenite veins, due to the lack of infiltration into the peridotite, there could be an increase in fluid partial pressure leading to spontaneous melt segregation into the surrounding mantle by ductile or even elastic deformation (e.g., Sleep, 1998; Stevenson, 1989; Rubin, 1995).

This study also shows that the extent of melt-rock reaction and equilibration time is controlled by the dissolution rate relative to the size of the partially molten pyroxenite body. For example, given the range in composition of pyroxenite-derived melts proposed in

previous studies (Figs. 1 and 2), an estimate of the degree of undersaturation for these melts with respect to a given peridotite composition shows that the dissolution rates by high-SiO₂/low-MgO/high-Al₂O₃ melts (i.e., quartz-normative) will be much higher than for the low-SiO₂/high-MgO/low-Al₂O₃ melts (i.e., hypersthene-normative). These differences in dissolution rates will further expand depending of the style of melt-rock reaction: slowest for diffusive dissolution and faster for reactive dissolution. As shown in §4.1, during diffusive dissolution of lherzolite by an eclogite-derived melt, equilibrium is not attained. However, during mantle upwelling the mechanism of dissolution changes when the surrounding peridotite partially melts (Fig. 24), which dramatically speeds up equilibration. This means that a necessary condition for preserving geochemical signatures from melts generated at depth is that the melt flow to the surface must take place faster than equilibration during reactive dissolution. In the next section we will discuss this point based on our numerical analysis of trace-element fractionation during porous flow in a hypothetical 1D mantle column.

4.4 Implications for the trace element content of enriched melts in the Earth's mantle

In this section we explore the fractionation of trace elements through numerical simulations of an enriched source percolating through a reactive porous mantle column composed of a depleted mantle (DMM of Workman and Hart, 2005). For simplicity, we will consider a constant porosity and partition coefficient during transport but in a separate chapter we will evaluate the effect of varying partition coefficient due to changes in the mineral mode and/or individual mineral/melt partition coefficients. The equations used here are similar to those of McKenzie (1984), Navon and Stolper (1986), Richter and DePaolo (1987), and Bodinier et al. (1990), and are applicable to a representative element

volume (REV) that is much larger than individual mineral grains. Mass conservation of the fluid and solid can then be written as

$$\frac{\partial(\rho_f \phi)}{\partial t} + \nabla \cdot [\rho_f \phi \mathbf{V}_f] = \Gamma \quad (9)$$

$$\frac{\partial[\rho_s(1 - \phi)]}{\partial t} + \nabla \cdot [\rho_s(1 - \phi) \mathbf{V}_s] = -\Gamma \quad (10)$$

where ϕ is the porosity or interconnected volume fraction of the fluid, ρ_f and ρ_s are the fluid and solid densities, V_f and V_s are the fluid and solid velocities respectively, and Γ is the rate at which mass is transferred from the matrix to the melt ($\text{kg m}^{-3} \text{sec}^{-1}$) and measured in a frame fixed to the matrix (McKenzie, 1984). Conservation of chemical species in the melt and the solid can be written as

$$\frac{\partial(\rho_f \phi C_f)}{\partial t} + \nabla \cdot [\rho_f \phi C_f V_f] = \nabla \cdot [D_f \nabla(\rho_f \phi C_f)] + Q + C_s \Gamma \quad (11)$$

$$\frac{\partial[\rho_s(1 - \phi)C_s]}{\partial t} + \nabla \cdot [\rho_s(1 - \phi)C_s V_s] = \nabla \cdot [D_s \nabla(\rho_s(1 - \phi)C_s)] - Q - C_s \Gamma \quad (12)$$

where D_f and D_s are respectively the fluid and solid diffusivities, and $C_s \Gamma$ is the source/sink term due to melting (Liang, 2003b). $Q = \rho_s(1 - \phi)R(C_s - kC_f)$ is the change in composition due to chemical exchange between the melt and the solid by dissolution and reprecipitation (Richter and DePaolo, 1987; Liang, 2003a), where R is a linear rate of reaction between solid and liquid in fraction of solid per unit time (1/sec), and k is the bulk solid-liquid partition coefficient for a given element.

Combining equations (7) to (10) and neglecting solid diffusion at the REV scale, we obtain the following equations

$$\frac{\partial C_f}{\partial t} + \mathbf{V}_f \cdot \nabla C_f = D_f \nabla^2 C_f + \frac{\rho_s(1-\phi)}{\rho_f \phi} R(C_s - kC_f) + \frac{\Gamma}{\rho_f \phi} (C_s - C_f) \quad (13)$$

$$\frac{\partial C_s}{\partial t} + \mathbf{V}_s \cdot \nabla (C_s) = -R(C_s - kC_f) \quad (14)$$

Equations (11) and (12) are non-dimensionalized using the time scale $t_0 = L/V_f$, where L is the length of the melting column,

$$\frac{\partial C_f}{\partial t} + \nabla C_f = \frac{1}{Pe} \nabla^2 C_f + D_r \frac{\rho_s(1-\phi)}{\rho_f \phi} (C_s - kC_f) + D_m \frac{\rho_s(1-\phi)}{\rho_f \phi} (C_s - C_f) \quad (15)$$

$$\frac{\partial C_s}{\partial t} + W \nabla C_s = -D_r (C_s - kC_f) \quad (16)$$

where Pe is the Péclet number (ratio of the fluid flow rate to the diffusive rate, $Pe = V_f L / D_f$), D_r is the reaction Damköhler number (ratio of the reaction rate to the fluid flow rate, $D_r = R L / V_f$), and D_m is the melting Damköhler number (ratio of the melting rate to the fluid flow rate, $D_m = \Gamma L / [\rho_s(1-\phi)V_f]$), and $W = V_s/V_f$.

For the Earth's mantle we can assume the following ranges in values for L ranging from 50 to 100 km, V_s ranging from 10 to 100 mm/yr, and V_f ranging from V_s to 1 m/yr (assuming porous flow in a mantle that has an average grain size of 1 mm). Therefore, it is reasonable to assume that in the mantle $V_s/V_f \ll 1$. Additionally the $Pe \gg 10^3$ given that diffusivities in silicate liquids are on the order of $10^{-12} \text{ m}^2/\text{s}$. Hence, the concentration of a given element in the melt and solid will be primarily controlled by two Damköhler numbers, the bulk partition coefficient, and the porosity. To place some limits on the time required for a melt to go through a porous column while preserving its original geochemical signature, we can use a semi-quantitative approach to constrain the melting Damköhler number based on the maximum degree of melting in the mantle. For a 1-D steady-state mantle, the degree of melting is defined as the ratio of the total melt production flux to the flux of solid that enters the base of the column (*e.g.*, Spiegelman and Elliott, 1993) such that

$$F(z) = \frac{\int_0^L \Gamma dz}{\rho_s V_s} \quad (17)$$

where V_s in this case is the initial upwelling rate of the mantle. In this study we assume that the mantle upwelling rate is constant, making this V_s equivalent to the one in equation 12. Therefore if the melting rate is also assumed constant and the maximum degree of melting at the top of the column is $F_{\max}$, the melting rate can be written as

$$\Gamma = \frac{\rho_s V_s F_{\max}}{L} \quad (18)$$

The melting Damköhler number then becomes

$$D_m = \frac{\Gamma L}{\rho_s (1 - \phi) V_f} = \frac{V_s}{V_f} \frac{F_{\max}}{1 - \phi} \quad (19)$$

Therefore, $D_m < 0.2$, assuming a mantle with residual porosity $\phi \sim 1\%$, a velocity ratio $V_s/V_f < 1$, and a maximum degree of melting of $F = 0.2$. In this study we will use a value of $D_m = 0.005$ that corresponds to a degree of melting that of 0.5%. However, this value could range from 0.5% to 50% depending on whether V_s/V_f is equal to 1 or 1/100 respectively. We will also use two end-member values for D_r , one for complete non-reacting flow ($D_r = 0$) and one having exchange rates comparable to flow rates ($D_r = 1$). Table 3 reports all the parameters used in this model and selected results are shown in Figs. 26 to 28, where the upper panels indicates the concentration of the solid and the fluid leaving the top of the porous column, and the lower panel shows the concentration of La and Dy for different times as a function of position in the column. The initial and boundary conditions are given in Table 3 and Figure 25.

Figure 26a shows how trace elements migrate in the column without reacting with the solid. The key point here is that the solid composition does not change with time and

that, given enough time (here $t > 1.4$), the initial melt present in the column will adjust to the pyroxenite-derived melt composition (assuming an infinite source of enriched material coming from below). Figure 26b shows how the melt evolves when melting is introduced. First we observe a depletion in the melt composition leaving the column due to partial melting of the solid, but with increasing time the composition of the enriched melt overwhelms the signal inside the column. The melt leaving at the top will eventually have an enriched-like signature but will be more depleted than the original pyroxenite-derived melt. In both cases we have assumed that the surrounding peridotite does not re-equilibrate with the melt.

Figures 27 and 28 show two simulations with equilibration taking place between the peridotite and the percolating melt. The difference between the two cases is the residual porosity: 1% for Fig. 20a and 0.1% for Fig. 20b. The decrease in porosity, increases the solid

to melt mass ratio $\frac{\rho_s(1-\phi)}{\rho_f\phi}$ in Eq. (15) by a factor inversely proportional to the porosity change. This change increases the product of the mass ratio to the Damköhler numbers, which results in effective higher melting and reaction Damköhler numbers. For a large residual porosity (Fig. 27), we see a very small melt depletion at first due to melting but quickly both the melt and the solid composition become more enriched as they equilibrate with the incoming pyroxenite-derived melt. For a small residual porosity (Fig. 28), we see large depletions in both the solid and the melt. This has the net effect of producing a steady-state flow of an almost U-shape melt composition that leaves the mantle, even though at the base there is a strong enriched source. The solid composition in this case becomes depleted, in contrast to the large porosity case.

These melt-rock reaction calculations show that the residual solids are a better record of the effect of melting vs. melt-rock reaction than partial melts. Enriched solids will likely

have been in a system where the effects of melt-rock reaction dominate relative to partial melting. Alternatively, more depleted solids indicate that the effects of melting dominate those of melt-rock reaction. This simplified model also shows that to preserve the geochemical signature of a deep enriched source in an erupted ocean-floor basalts, it is necessary to have a system with relatively large residual porosities and small reaction rates relative to the flow of melt ($D_r \ll 1$), which means that $V_f \gg R L$. To determine V_f , an estimate of R is necessary. When crystal-melt exchange is limited by the rate of volume diffusion in the solids, the exchange rate R , can be estimated using the expression (e.g., Vermeulen, 1953)

$$R = \beta \frac{D_s}{a^2} \quad (17)$$

where a is the average grain size or radius of the mineral of interest; D_s is diffusion coefficient in the mineral for the element of interest; and β is a geometry factor ranging from 3 to 15 (e.g., Vermeulen 1953; Navon and Stolper 1987; Bodinier et al. 1990; Liang 2003b). However, we have shown that dissolution and reprecipitation are the dominant mass transfer mechanism in this system and the value of R will be orders of magnitude higher than the one obtained using (17). Our experiments show that the decrease in dissolution rate (Fig. 22) is a proxy for equilibration rates, as the melt assimilates more lherzolite and changes the residual peridotite into an orthopyroxene-rich harzburgite. Therefore, normalizing the dissolution rate to the initial glass length provides a first order estimate of R . Figure 29 shows how the normalized dissolution rate changes with the square root of time from $2 \cdot 10^{-5}$ to 10^{-6} s^{-1} for the high-T regime. Using the value closest to steady state (Pyx 20 at 10^{-6} s^{-1}) and a 50-100 km mantle melting column, where dissolution and reprecipitation dominate mass exchange between minerals and melt, the condition for preserving a deep geochemical signal requires a flow speed of $V_f > R L > 1 \text{ cm/sec}$. This

first order estimate indicates that either enriched signals observed in oceanic islands are not derived from pyroxenite-derived melts, given the unrealistically high flow velocities for porous flow, or that the melt transport takes place at very high flow rates and does not take place by porous flow. Considering that the geochemical evidence for the presence of enriched components in the mantle is very strong (Hofmann, 2003), melt flow rates in a heterogenous mantle are likely to be extremely high. Processes that satisfy these flow rates could range from high-porosity conduits (though rich in SiO_2 at high-pressure, i.e., harzburgites) to diking. It is beyond the scope of this study to evaluate whether porous conduits can sustain these high flow rates or whether diking is possible at mantle pressures of over 1 GPa. This study, however, shows how the geochemistry of oceanic basalts, based on experimental and numerical evidence, has the potential to place strong constraints on mantle flow dynamics.

5. Conclusions

This study has shown that reaction between pyroxenite-derived melts and peridotites is characterized by two dissolution regimes: simple and reactive dissolution. The former process is very slow and results in garnet precipitation and a lack of chemical equilibrium between the melt and the peridotite. The latter process, instead, is extremely fast and results in high equilibration rates, even though orthopyroxene-rich bands develop at the melt-rock interface. Therefore it is unlikely that a partially molten pyroxenite will remain out of equilibrium with the surrounding mantle, regardless of its size, as suggested by previous studies. Consequently, observed enriched signals in ocean-floor basalt must result from very fast melt propagation mechanisms in the mantle.

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Figure Captions

Figure 1. (a) Total alkali vs. silica diagram of the starting glass composition used in this study (yellow star) compared to pyroxenite-derived melts obtained in other experimental studies. Classification and nomenclature follow those of Le Maître (1989). The alkalinity boundary (heavy solid line) is given by MacDonald and Katsura (1964) and MacDonald (1968). (b) Silica and alkali content of the glasses as a function of pressure and temperature. Although starting materials vary for different studies, typically high- P /low- T glasses are rich in alkali and SiO_2 , whereas low- P /high- T glasses have lower alkali and SiO_2 contents. Our starting composition falls well within the range of pyroxenite-derived melts obtained experimentally at the same P - T conditions. In our experiments we have one starting composition but our experiments were done at 1300°C and 1375°C , this is why two stars are shown in (b).

Figure 2. Harker diagram of the starting glass composition used in this study (yellow star) compared to pyroxenite-derived melts obtained in other experimental studies. Our starting composition falls within the range of pyroxenite-derived melts obtained in previous experimental studies. Symbols are identical to those of Fig. 1.

Figure 3. Illustration on the role of the interface separating peridotites and melt in controlling the mechanisms and time-scales of melt segregation. (a) Shows how alkali basalts react with lherzolites at low pressure, forming high-porosity dunite channels in the mantle (e.g., Morgan and Liang, 2005). In this study, the question being tested is whether at higher pressures the reaction between peridotites and pyroxenite-derived melts (b) forms of an orthopyroxene-rich lithology which hinders infiltration, reaction, and melt segregation (c) or does this opx-rich region

allow melt to flow and segregate into the surrounding mantle. The reaction zone for case (c) would follow the melt flow field and create a hybrid lithology having the geochemical signature of both peridotite and pyroxenite.

Figure 4. Back-scattered electron images of the central parts of two runs conducted at 1300°C experiments and 2GPa, during which the lherzolite was below its solidus temperature. The white dashed lines denote the initial location of the interface between the two capsules before reaction. The light gray mineral in the peridotite is the cpx, the medium is gray is the olivine, and the darker gray is the opx. The large crystals in the glass are pyrope-rich garnets formed by reaction between the melt and the lherzolite. The two insets are X-ray intensity maps of Ca and show the mineralogy at the melt-rock interface (a), and the compositional zoning of garnets and presence of small cpx grains in the garnet (b). The dissolution rates are very small in these experiments and the lherzolite is unaffected by the reaction, even though a small layer of distinct cpx are visible at the interface between the melt and the lherzolite as shown in the inset in (a). The grain numbers and the dashed lines in the garnet grains show the electron microprobe traverses reported in Appendix C.

Figure 5. Back-scattered electron image of the central part of run Pyx 26. The white dashed line denotes the initial location of the interface between the two capsules before reaction. The light gray mineral in the peridotite is the cpx, the medium is gray is the olivine, and the darker gray is the opx. In this run we do not observe crystallization of garnets at the interface, and we see a small amount of dissolution, with quench growth at the melt-rock interface, and cpx dissolution at the top of the peridotite.

Figure 6. Back-scattered electron image of the central part of run Pyx 21. The inset shows an enlarged view of the melt-rock interface. For this run we see a higher dissolution length and the presence of larger pockets of melt.

Figure 7. (a) Back-scattered electron image of the central part of run Pyx 27. In this run we observe a dramatic increase in dissolution, with a clear change of mineralogy due to the reaction taking place at melt-rock interface. Near this interface, the lithology is richer in orthopyroxene but the change towards the harzburgite is gradual and the boundary is shown for reference only. The boundary between the harzburgite and the lherzolite is defined by the absence or presence of clinopyroxene.

Figure 8. Hand-traced melt distribution across the central part of the run as shown by the orange dashed rectangle of Fig. 7. Melt distribution is focused in the harzburgite layer located between the opx-rich harzburgite and lherzolite.

Figure 9. (a) Back-scattered electron image of the central part of run Pyx 20. In this run we observe complete disappearance of cpx throughout the peridotite and an increase in the mode of olivine and opx. Dissolution of the peridotite is also much larger than in the previous runs.

Figure 10. (a) Dissolution distance as a function of the square root of time for the 1300°C and 1375°C experiments. The dashed line is calculated using equation 8 and matches well the experimental data for both sets of experiments. The 1300°C experiments show very small to negligible increase of dissolution distance with time in contrast to the 1375°C experiments. Runs Pyx 26, Pyx 21, and Pyx 27 show a dissolution trend that is nearly-linear, as would be expected for a semi-infinite medium. However, the effect of finite boundary slows down dissolution to a plateau (Run 20). (b) Runs Pyx 16 and Pyx 17 have a much lower dissolution

distance due to their shorter initial glass length. Normalizing the dissolution distance by the initial glass length shows that within error, experiments Pyx 27, Pyx 16, and Pyx 17 collapse onto the same point. See text for a detailed discussion.

Figure 11. Olivine composition in the 1300°C experiments as a function of position in the capsule from the interface ($x = 0$) between the lherzolite and the glass. The dashed lines indicate the starting material composition. The composition of the olivine is essentially constant across the lherzolite even though the longer duration run shows a change in composition right at the interface. In particular, the content in Al_2O_3 , CaO , MgO , and FeO is affected due to the reaction with the melt and crystallization of garnet.

Figure 12. Olivine composition in the 1375°C experiments as a function of position in the capsule from the interface ($x = 0$) between the lherzolite and the glass. The arrow shows how the composition in the 1375°C experiments changes first due to partial melting during synthesis, then due to the reaction with the melt. Therefore, the pre-reaction composition for the 1375°C experiments should correspond approximately to the one of run Pyx 26. This will be valid for all other minerals as well. The composition of the 1375°C olivine shows a gradual change in composition in space, going from a relatively unchanged composition in the lherzolite ($x < -1000 \mu\text{m}$ for longer runs) to a modified composition near the interface ($x = 0$). This change indicates that melt is present throughout the peridotite, and that dissolution and reprecipitation are taking place to account for the large changes, especially in FeO and MgO , in chemistry over a $2000 \mu\text{m}$ length-scale in less than 74 hours.

Figure 13. NiO content in olivines from 1300°C and 1375°C experiments. This figure shows the dilution effect of Ni during the reaction with the melt.

Figure 14. Orthopyroxene composition in the 1300°C experiments as a function of position in the capsule from the interface ($x = 0$) between the lherzolite and the glass. The composition of the 1300°C orthopyroxenes is essentially constant across the lherzolite, even though for a given position we have core-to-rim chemical zonation.

Figure 15. Orthopyroxene composition in the 1375°C experiments as a function of position in the capsule from the interface ($x = 0$) between the lherzolite and the glass. The orthopyroxene composition shows chemical gradients that extend from the interface throughout the capsule, in particular Al_2O_3 , FeO, and MgO (and Mg#), resulting from diffusive mixing, dissolution and precipitation of opx (see text § 4.2).

Figure 16. Clinopyroxene composition of the 1300°C experiments as a function of position in the capsule from the interface ($x = 0$) between the lherzolite and the glass. The composition of the clinopyroxenes is essentially constant across the lherzolite, except at the melt-rock interface, where a compositionally distinct thin layer of clinopyroxene + olivine crystallizes during reaction with the melt.

Figure 17. Clinopyroxene composition of the 1375°C experiments as a function of position in the capsule from the interface ($x = 0$) between the lherzolite and the glass. Contrary to orthopyroxene and olivine, the composition of clinopyroxene does not change with time and position. However we see more compositional scatter than in the 1300°C runs, due to partial melting during the synthesis. This affects clinopyroxene composition more than olivine and orthopyroxene due to smaller diffusivities in clinopyroxene. The composition (and BSE images) of

clinopyroxenes in the 1375°C experiments suggests that clinopyroxene simply dissolves during reaction with the melt.

Figure 18. Glass composition of the 1300°C (a) experiments as a function of position in the capsule from the interface ($x = 0$) between the lherzolite and the glass. The pyroxenite-derived melt composition becomes more SiO_2 , Na_2O , and MgO rich when reacting with the lherzolite, while being depleted in Al_2O_3 and FeO . These chemical trends are dominated by the crystallization of a pyrope-rich garnet at the melt-rock interface, that moves the melt composition towards a more *qz*-normative composition (up to 7 wt.% *qz*- and 21 wt.% *hy*- normative). The red arrows show how the interface melt composition changes with time during reaction.

Figure 19. Glass composition of the 1375°C (a) experiments as a function of position in the capsule from the interface ($x = 0$) between the lherzolite and the glass. The 1375°C experiments show not only that the range in composition of the pyroxenite-derived melt is greater than at 1300°C, but also becomes depleted in SiO_2 , Na_2O , Al_2O_3 , and FeO while becoming more enriched in MgO . These trends are dominated by the net dissolution of olivine and orthopyroxene, moving the melt towards a more *hy*-normative composition (down to 1.6 wt.% *qz*- and up to 35 wt.% *hy*- normative). The red arrows show how the interface melt composition changes with time during reaction.

Figure 20. Normative composition in the pseudoternary system Forsterite–Calcium Tschermak–Quartz projected from Diopside (O' Hara 1968). (a) The glass (yellow star) and lherzolite (green star) starting compositions used in this study are shown along with the composition of pyroxenite-derived melts obtained in published experimental studies (references listed in the figure legend). Also

shown are dashed lines connecting the glass starting composition to Fo and En. (b) Inset showing the composition of the glasses obtained in this study and how they relate to the garnet composition for the 1300°C runs, and to Fo and En for the 1300°C runs. Crystallization of garnet drives the 1300°C glasses towards a more qz -normative composition. Net dissolution of orthopyroxene and olivine is what controls the composition of the 1375°C glasses, increasing their hy-normative content. The gray dashed line connecting An-En denotes the limit of the qz -stability field.

Figure 21. Calculated density and viscosity profiles in the glass as a function of position in the capsule. Densities and viscosities were calculated using the methods of Lange and Carmichael (1990) and Shaw (1972), respectively. The origin in position denotes the original melt-rock interface and during the experiments the glass was oriented as in the figure (on top of the lherzolite) to maintain a stable density stratification. Note how during the 1300°C dissolution experiments densities decrease while in the 1375°C runs they increase. In the 1375°C experiments the viscosity decreases by an order of magnitude during the reaction, suggesting that this melt has a better capability of infiltrating the surrounding peridotite. For experiments Pyx 17 and Pyx 27 (both run for 24 hrs), the difference in chemistry and physical properties arises from the difference in initial glass lengths: run 17 had an initial glass length that was 1/3 of run Pyx 27 (Table 2) and therefore it's chemical composition reaches equilibrium more rapidly.

Figure 22. Plot of measured dissolution rates (solid lines) as a function of the square root of time compared to the dissolution rates calculated using equation 8 (dashed lines). These two plots show that even though the 1300°C experiments are completely out of equilibrium even after 74 hours, the dissolution rates are very small. In

contrast, the 1375°C experiments are closer to equilibrium from the start and reach chemical equilibrium at the melt-rock interface relatively quickly. Yet the dissolution rates of the 1375°C experiments are up to an order of magnitude higher compared to the 1300°C runs indicating that the driving force for dissolution is not due to chemical equilibration.

Figure 23. Degree of undersaturation of the melt in Al_2O_3 , with respect to the composition of the peridotite located at the melt-rock interface, as a function of the square root of time. The degree of undersaturation is a proxy for the chemical potential gradient driving dissolution and given that the current definition of Θ uses the solid composition at the interface. The difference in dissolution rates between the 1300°C and 1375°C experiments (Fig. 22) correlates in time with the changes in the degree of undersaturation. Note that run Pyx 17 has very small values of Θ due to the initial glass length being 1/3 of run 27 (Table 2). Therefore the glass composition reaches saturation more quickly.

Figure 24. Schematic illustration of melt-rock reaction processes in the mantle. The first panel to the left, shows how dunite channels are formed during reactive dissolution of lherzolite into alkali basalts (e.g., Kelemen et al., 2000; Morgan and Liang, 2005) and form dunite-harburgite-lherzolite sequences. This process depletes the surrounding mantle from both major and trace elements, as pyroxenes are consumed and melt is sucked into the high-porosity conduits and segregates to the surface. This scenario is likely to take place at mid-ocean ridges at relatively low pressures. In contrast for ocean islands, the involvement of garnet pyroxenites during partial melting would change the dynamics of the melting column. In this case, partial melting of pyroxenites (red blobs) at the eclogite solidus would result in recrystallization of garnet when reacting with the

lherzolite. By the time the pyroxenites veins reach the lherzolite solidus, up to 70% melting in the veins has taken place. When the lherzolite solidus is crossed, reactive dissolution of the lherzolite into the pyroxenite-derived melt results in the creation of an orthopyroxene rich lithology. In this scenario, the pyroxenite-derived melt and the host peridotite are likely to re-equilibrate very fast, relative to melt flow. This process would create a residual mantle that is depleted in major elements (i.e., an orthopyroxene-rich harzburgite) and enriched in trace elements due to the metasomatic effect of the melt.

Figure 25. Primitive upper mantle (PUM) normalized spider diagram of the initial and boundary conditions used in solving equations (13) and (14). The melt composition and the solid composition are initially in chemical equilibrium throughout the 1D column. The lower boundary condition assumes a constant flux of an enriched pyroxenite-derived melt. The top and bottom boundary conditions are no flux boundaries ($\partial C/\partial z = 0$). The bottom boundary however has a source term included that represents the incoming enriched melt. In this model, porosity, partition coefficient, and fluid and solid velocities are assumed constants.

Figure 26. Primitive upper mantle (PUM) normalized spider diagram for a reactive porous flow model of a 1D column where the fluid and solid are interacting chemically through diffusion, advection, melting, and reaction (DAMR model). In these plots we show the fluid (blue diamonds) and solid (green squares) that were initially in chemical equilibrium with each other, and the hypothetical enriched composition (e.g., pyroxenite-derived melt) coming into the porous column from the bottom. The upper panel represents the composition of the material leaving the column (e.g., mid-ocean ridge basalt) and the lower panels show the

composition of La and Dy as a function of time and position in the column. We also show the maximum non-dimensional time (scaled to the melt velocity) up to which each simulation is run, typically to steady-state. (a) Shows how in the absence of melting and reaction, the melt composition in the column adjusts relatively quickly to the composition of the incoming enriched melt. (b) The effect of a small increase in the melting Damköhler number on the melt composition leaving at the top (upper panel) and on the distribution of composition throughout the column (lower panels). Arrows show the time evolution of the melt composition leaving the column. The initial melt depletion is due to melting.

Figure 27. Primitive upper mantle (PUM) normalized spider diagrams showing variations of melt (blue lines) and solid composition (green lines) as a function of time. Concentrations were calculated using the 1-D model discussed in §4.5 with a residual porosity of 1%. The melt is initially depleted due to melting but quickly evolves towards the enriched composition. The solid composition follows that of the melt and is progressively more enriched by reacting with the melt.

Figure 28. Primitive upper mantle (PUM) normalized spider diagrams showing variations of melt (blue lines) and solid composition (green lines) as a function of time. Concentrations were calculated using the 1-D model discussed in §4.5 with a residual porosity of 0.1%. This calculation shows how melt-rock reaction proceeds when the residual porosity is decreased by an order of magnitude, down to 0.1%. The integrated degree of melting is identical to Fig. 27 but the product of the melting and reaction Damköhler numbers with the solid/melt ratio is increased by an order of magnitude (see Eq. 15). This has the net effect of increasing the degree of depletion of the fluid and solid by almost 2 orders of

magnitude (for the melt) before the effect of the enriched component is felt in the column. See text for discussion.

Figure 29. Normalized dissolution rates as a function of the square-root of time for the 1300°C and 1375°C experiments. The data for the 1375°C experiments was used as a first order proxy for the linear rate of mass exchange, R , used in our reactive porous flow model.

Figure 1.

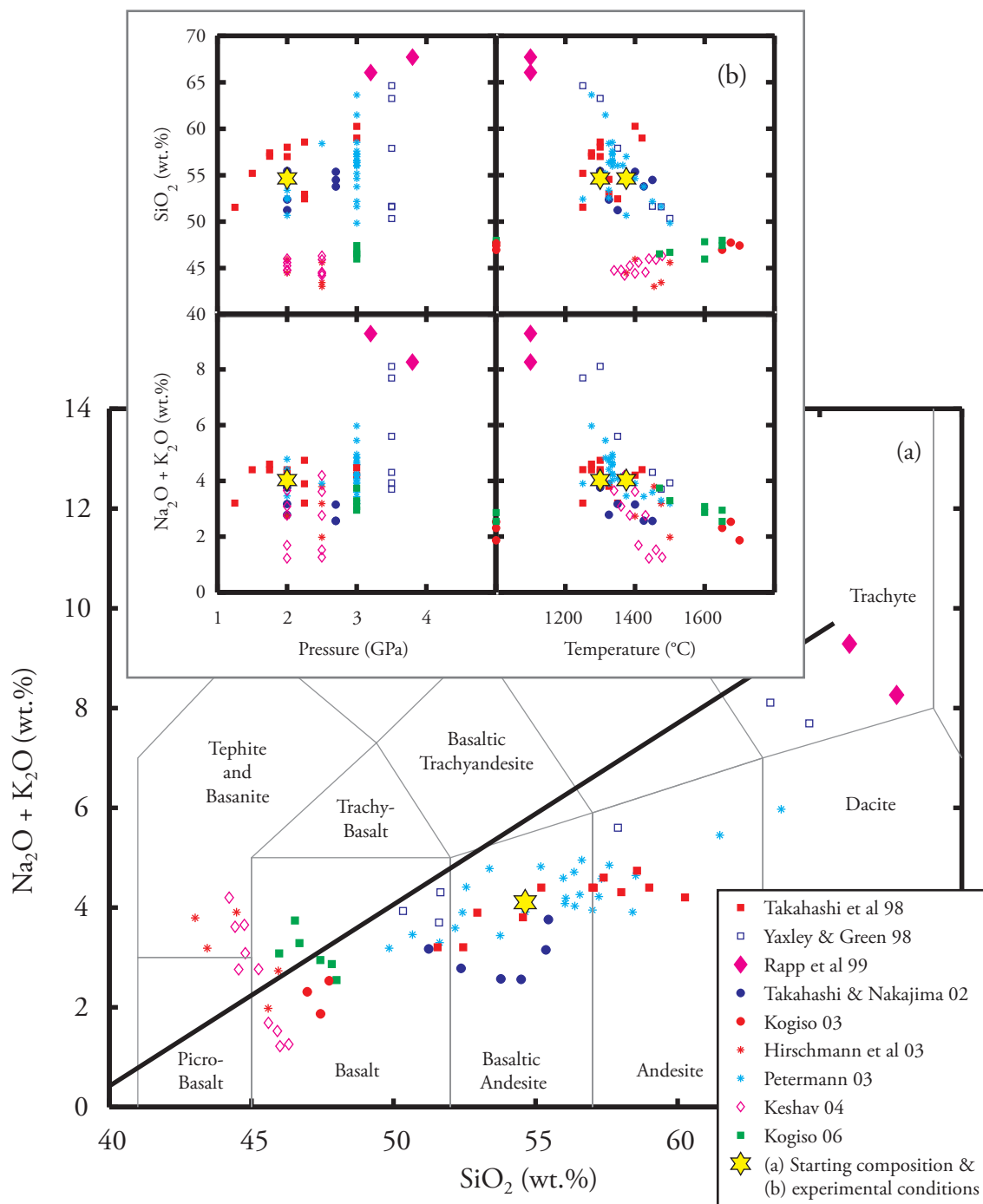
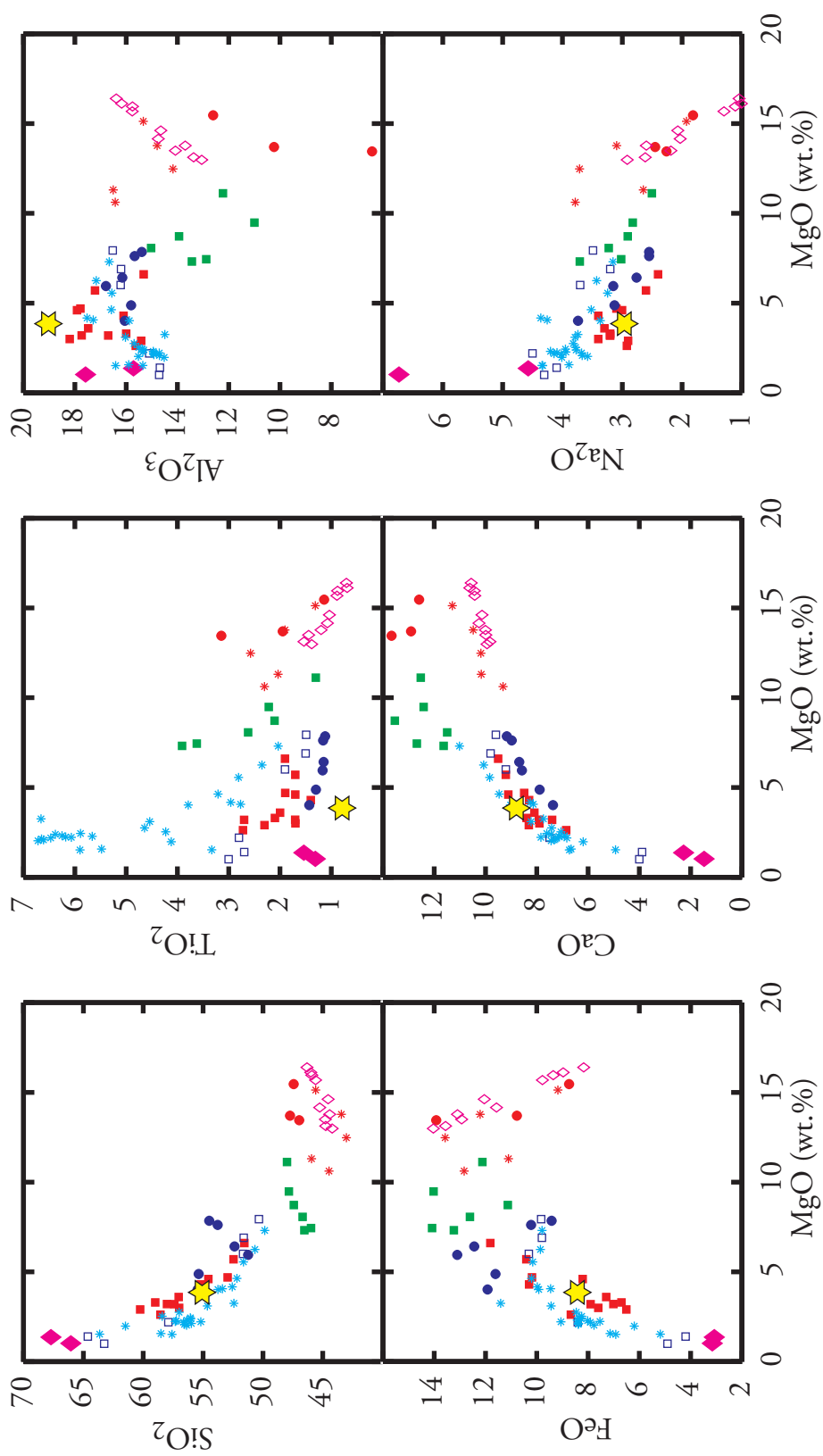


Figure 2.



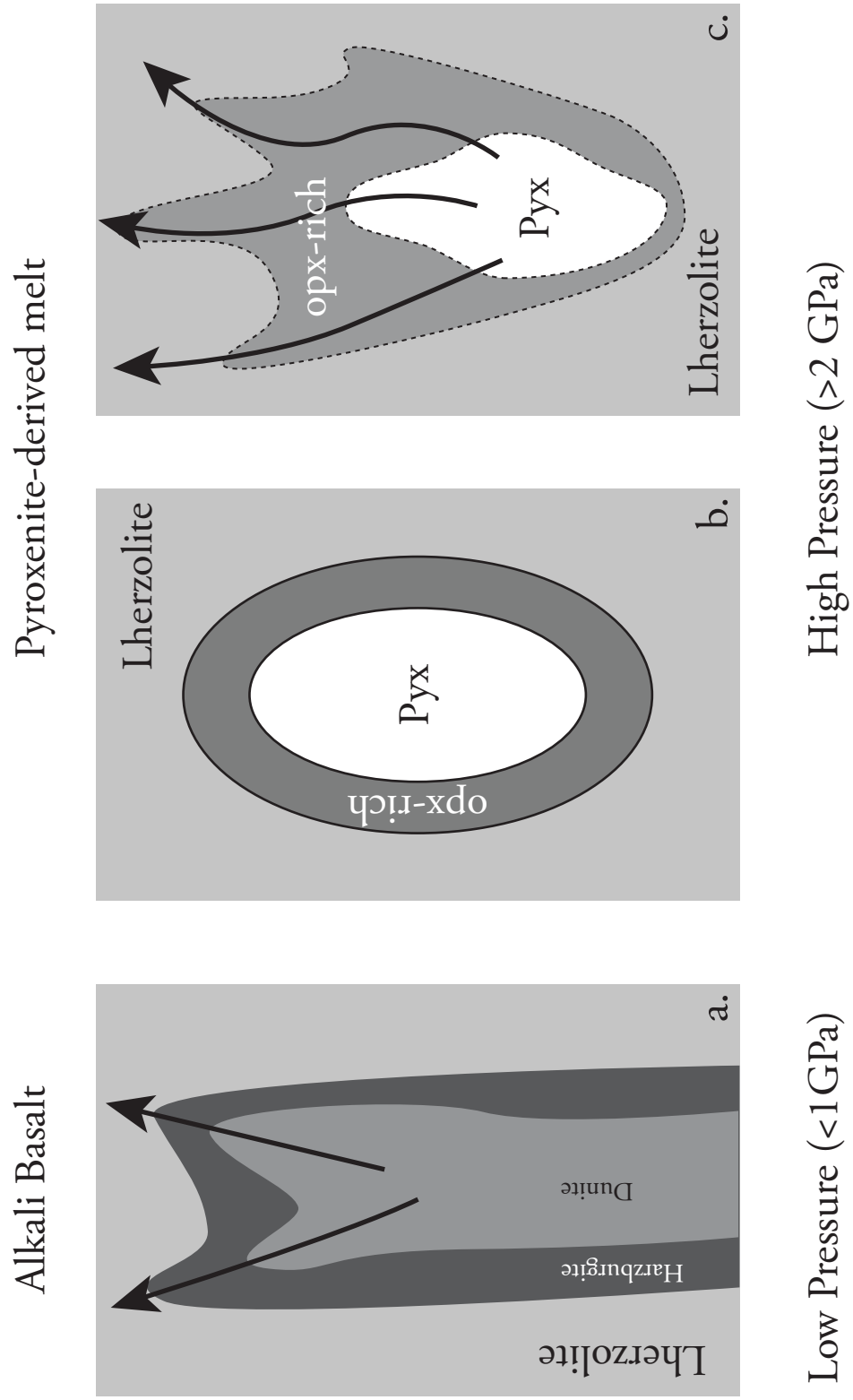


Figure 3.

Figure 4.

1300°C, 2 GPa

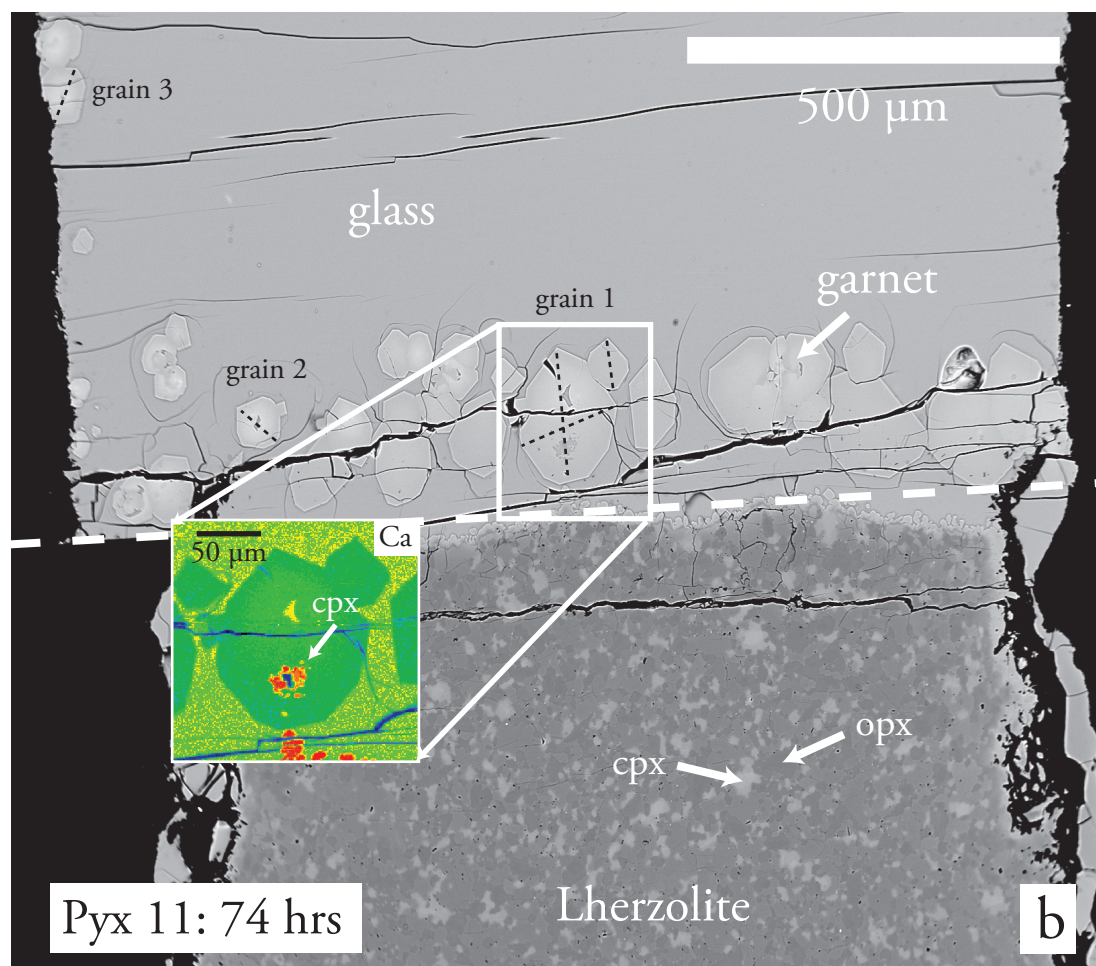
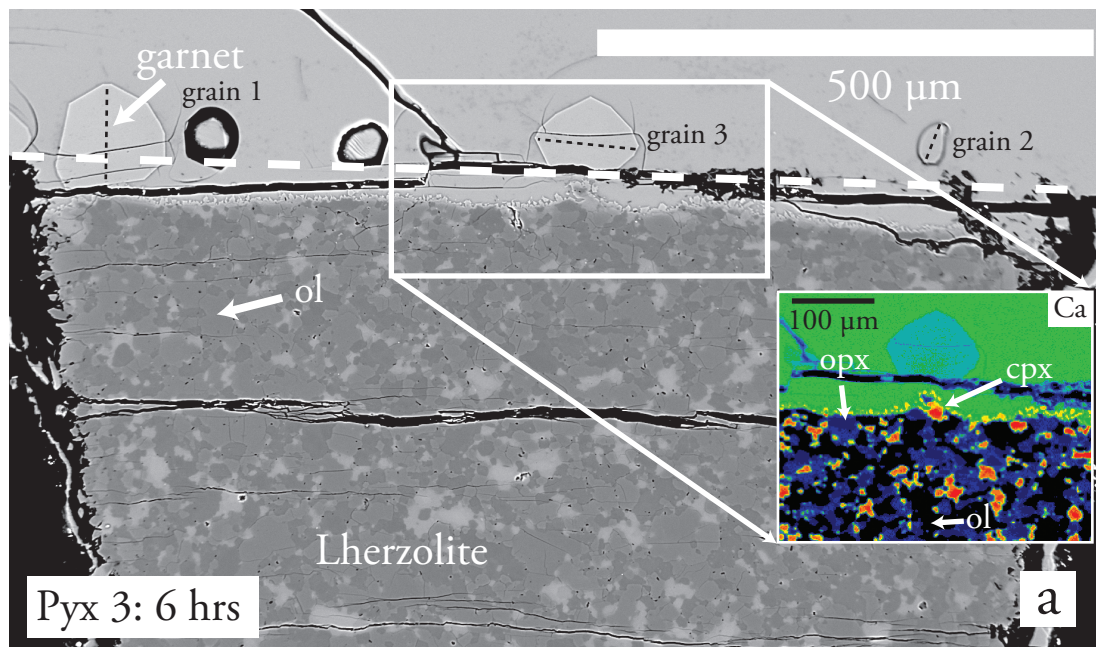


Figure 5.

Pyx 26: 0.5 hrs, 1375°C, 2 GPa

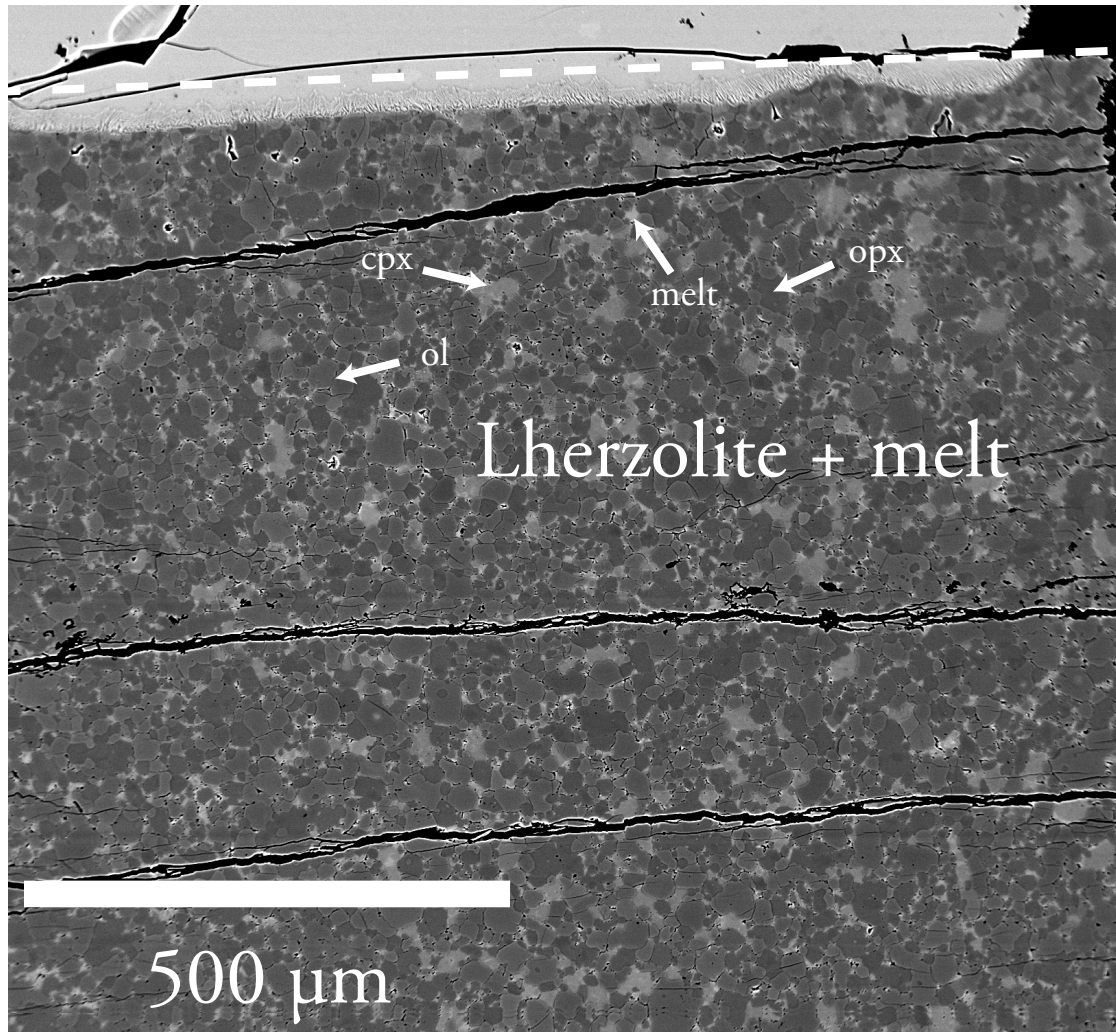


Figure 6.

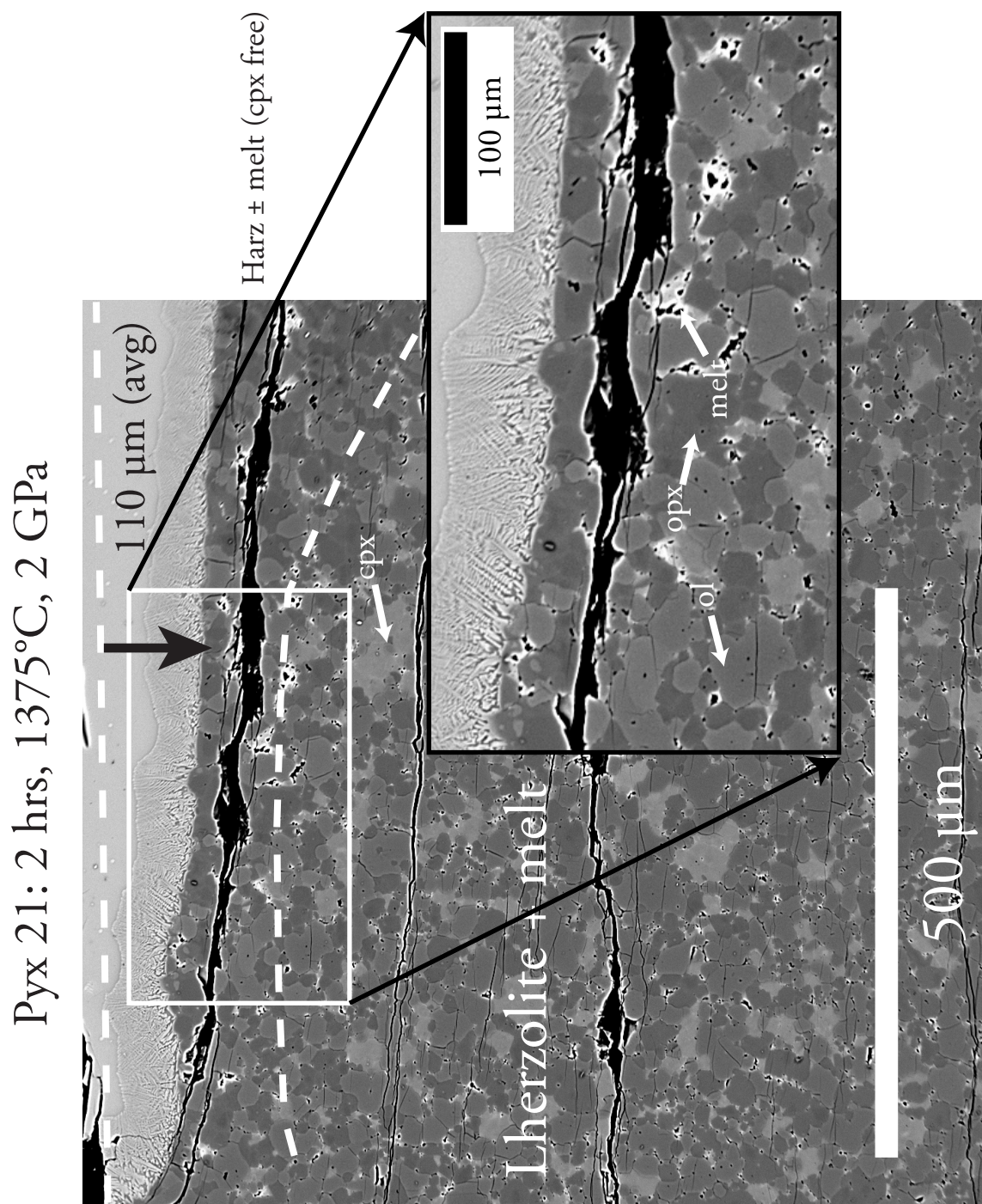
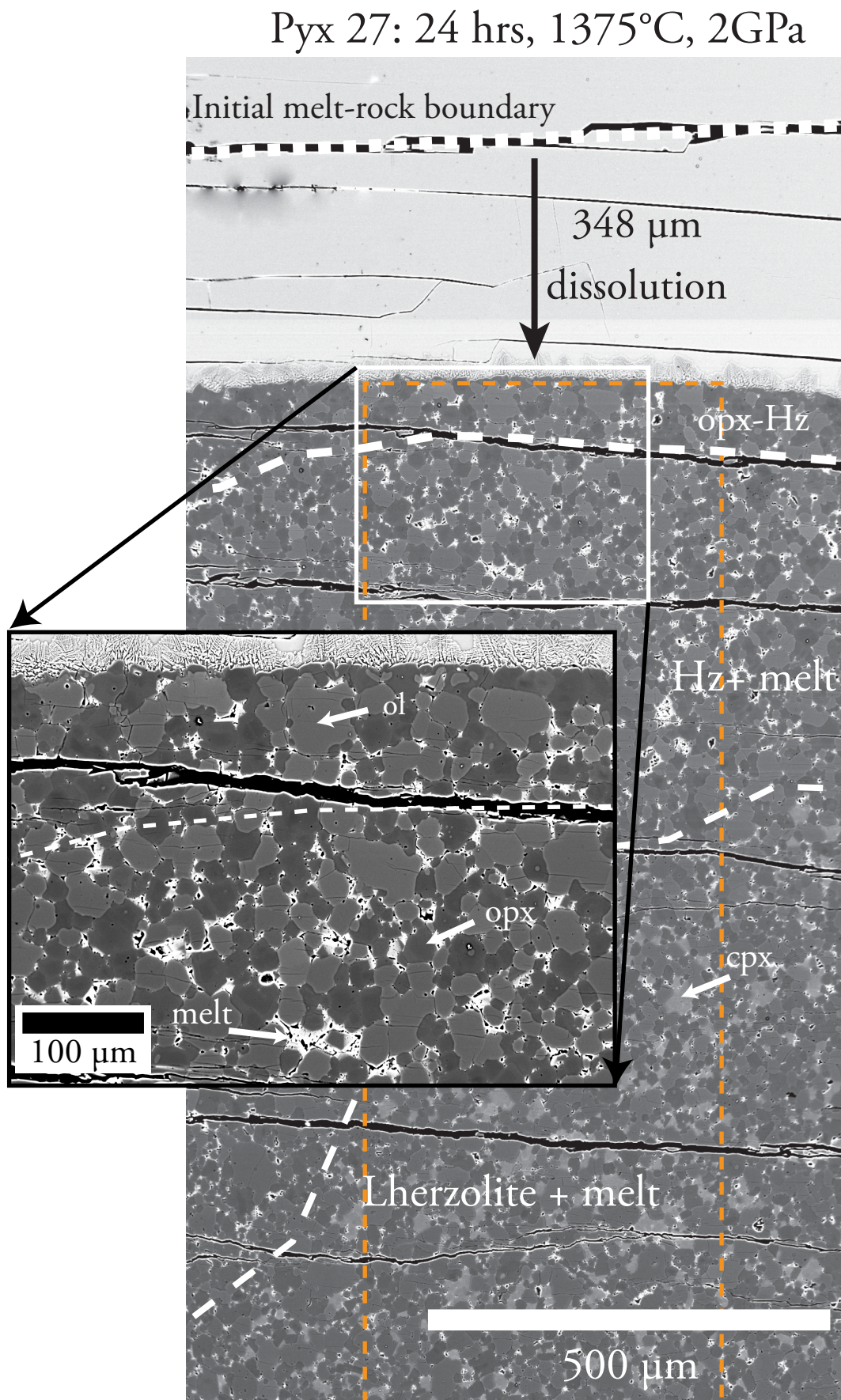


Figure 7.



Pyx 27: 24 hrs, 1375°C, 2GPa

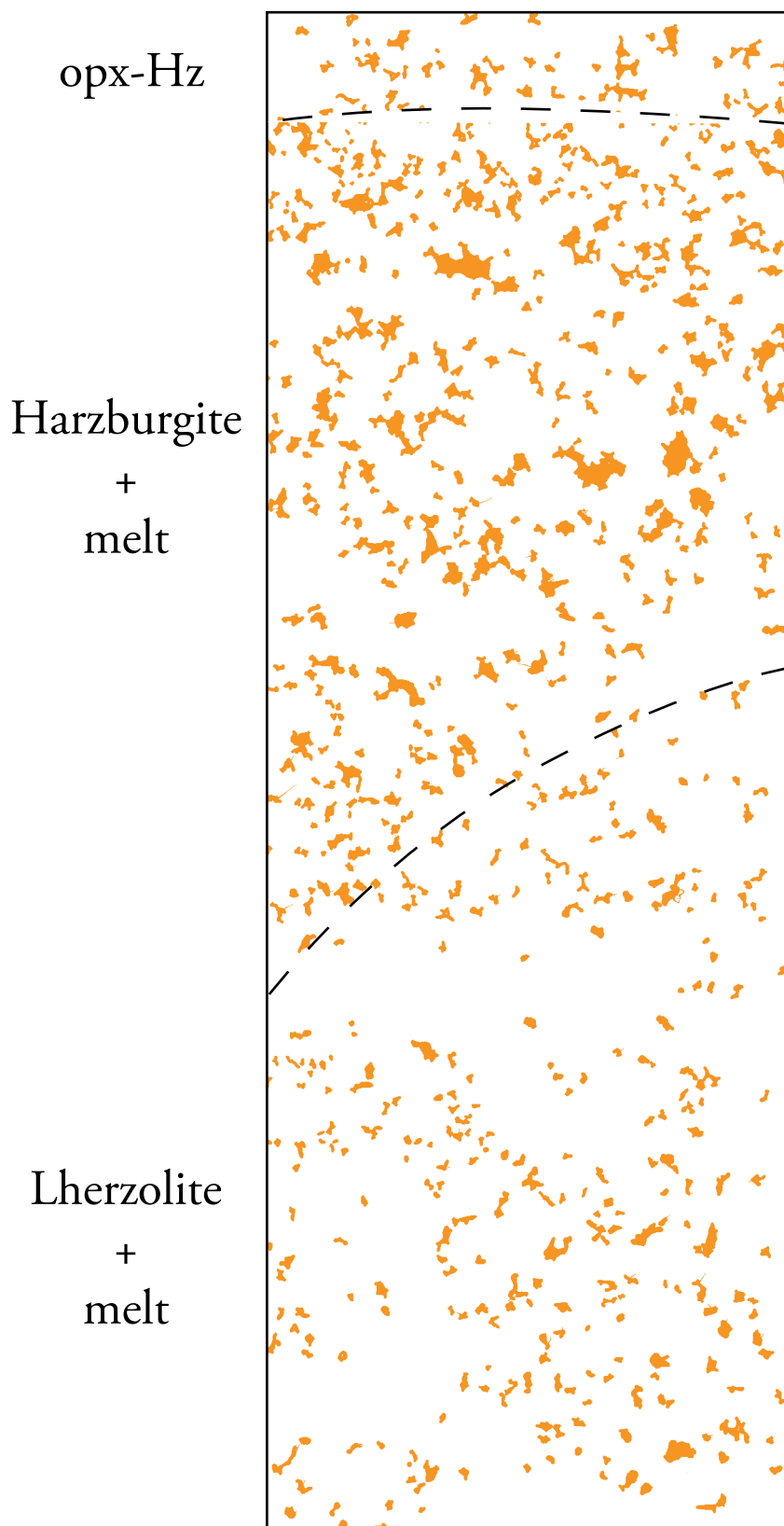


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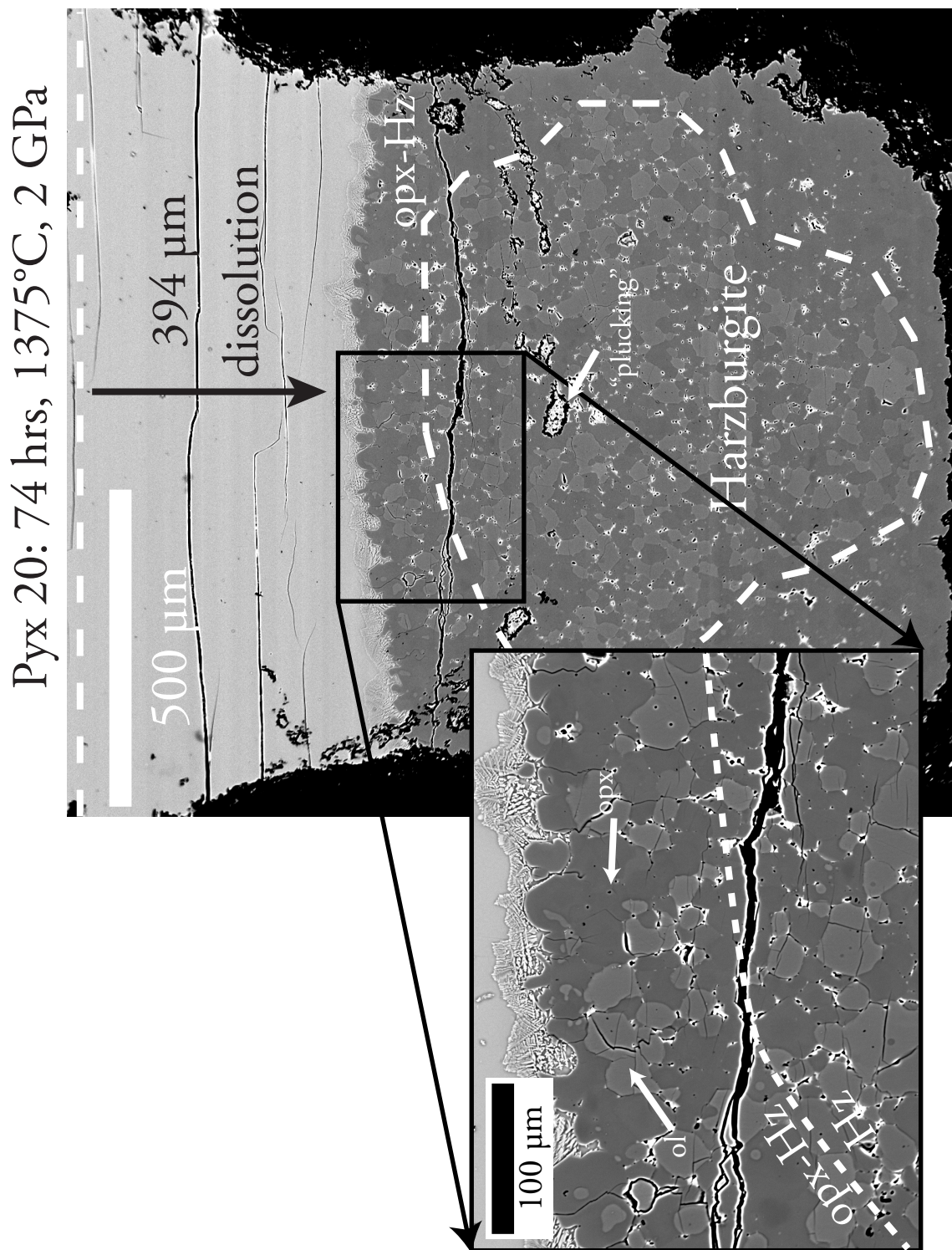


Figure 10.

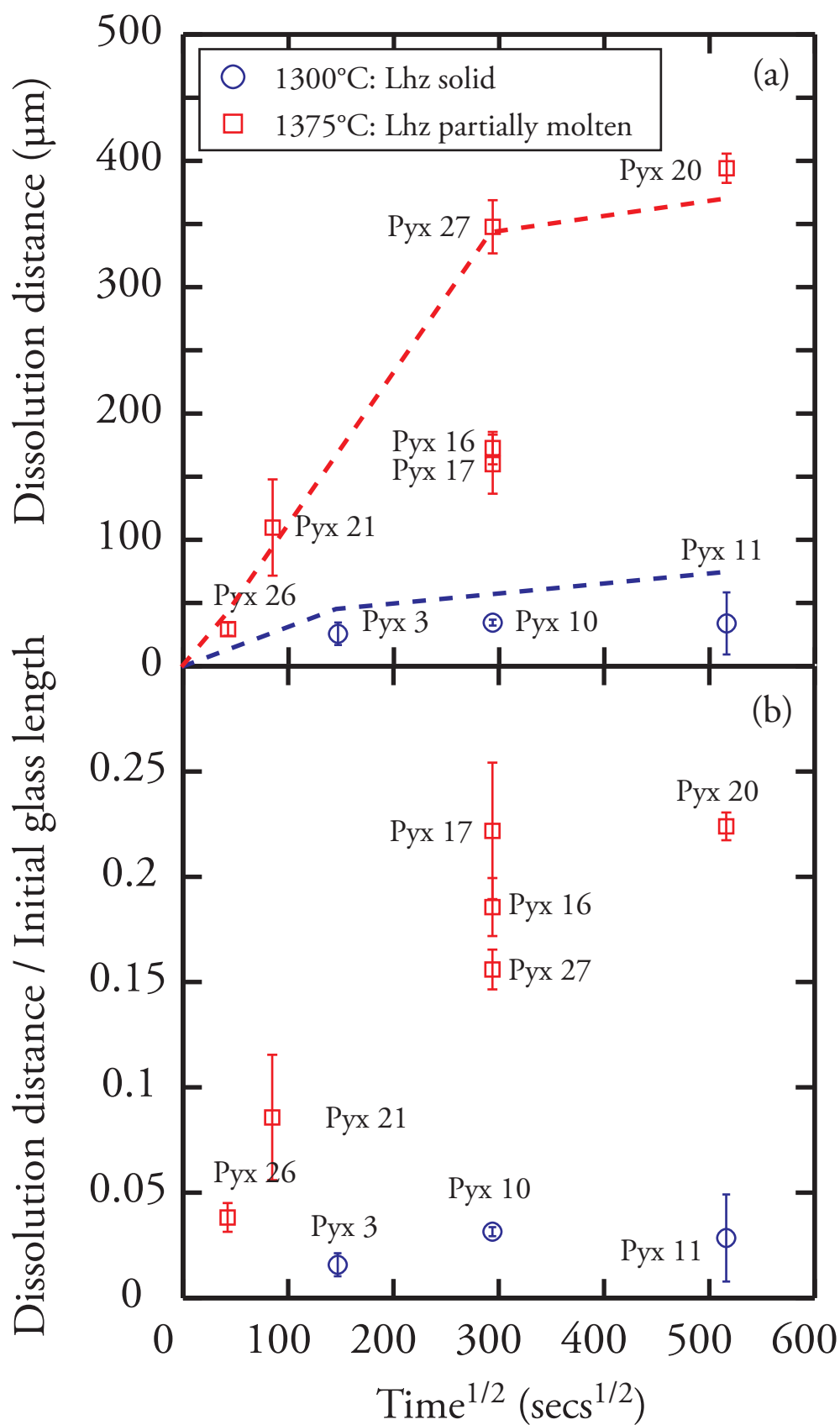


Figure 11.

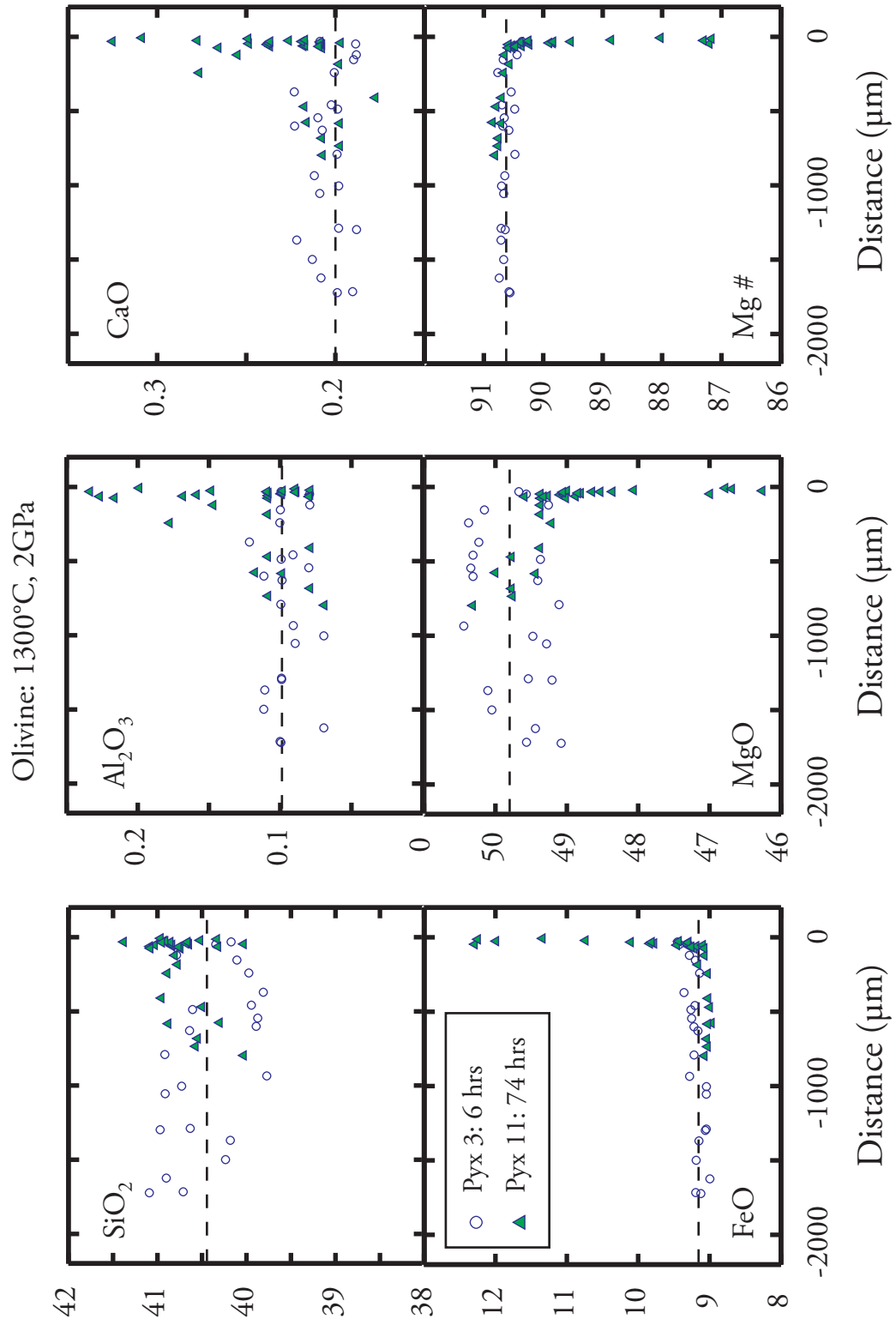


Figure 12.

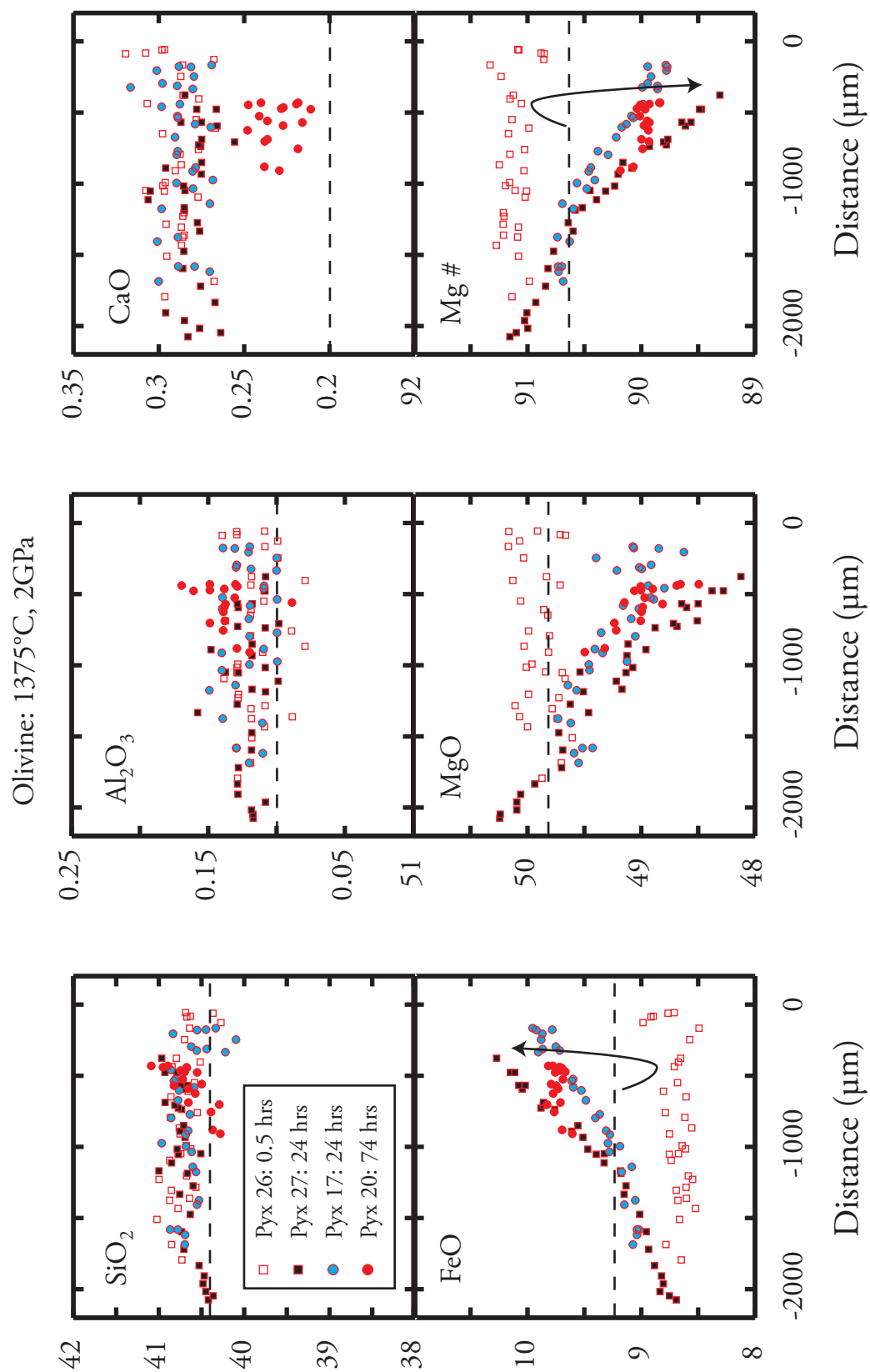


Figure 13.

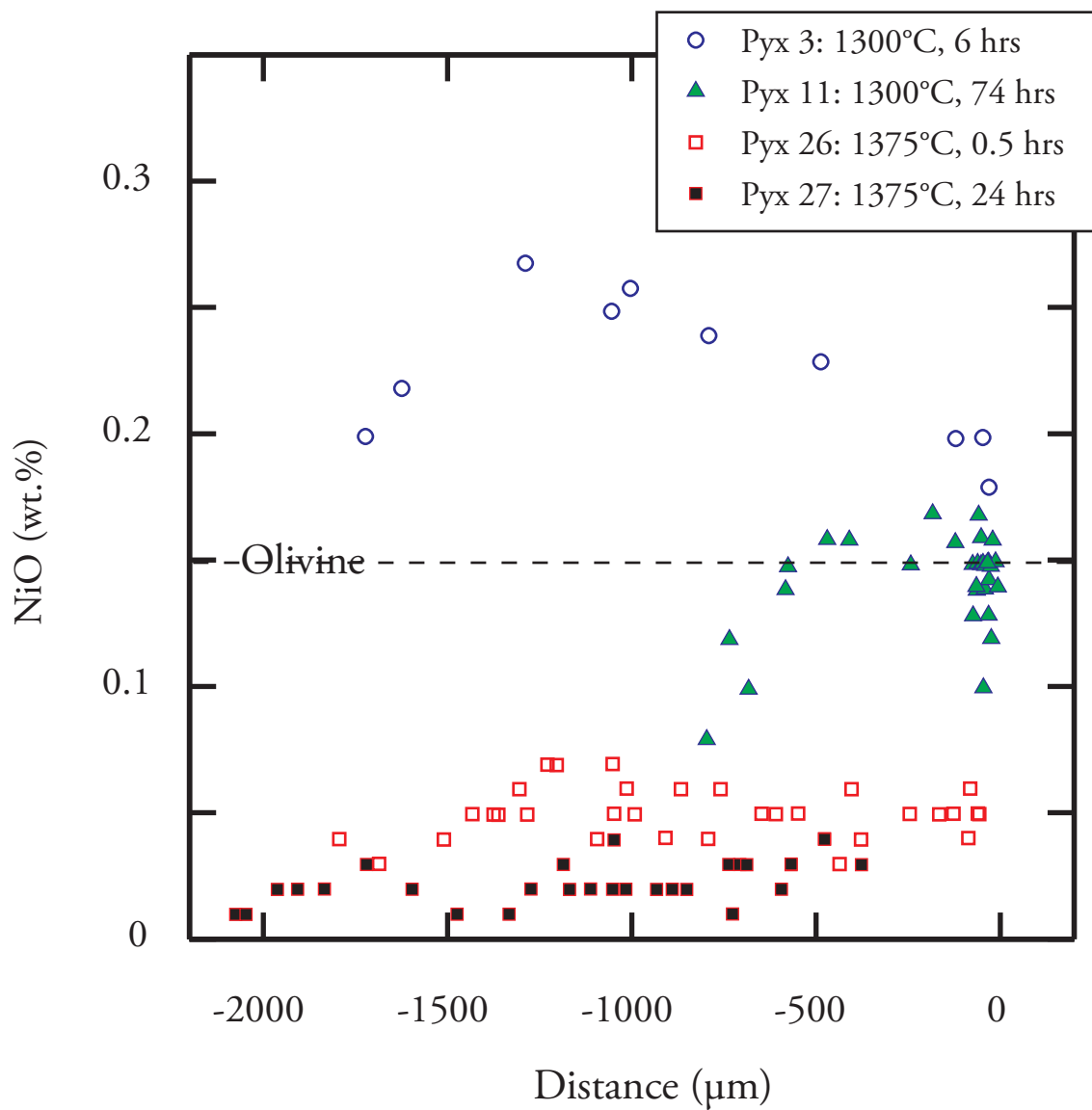
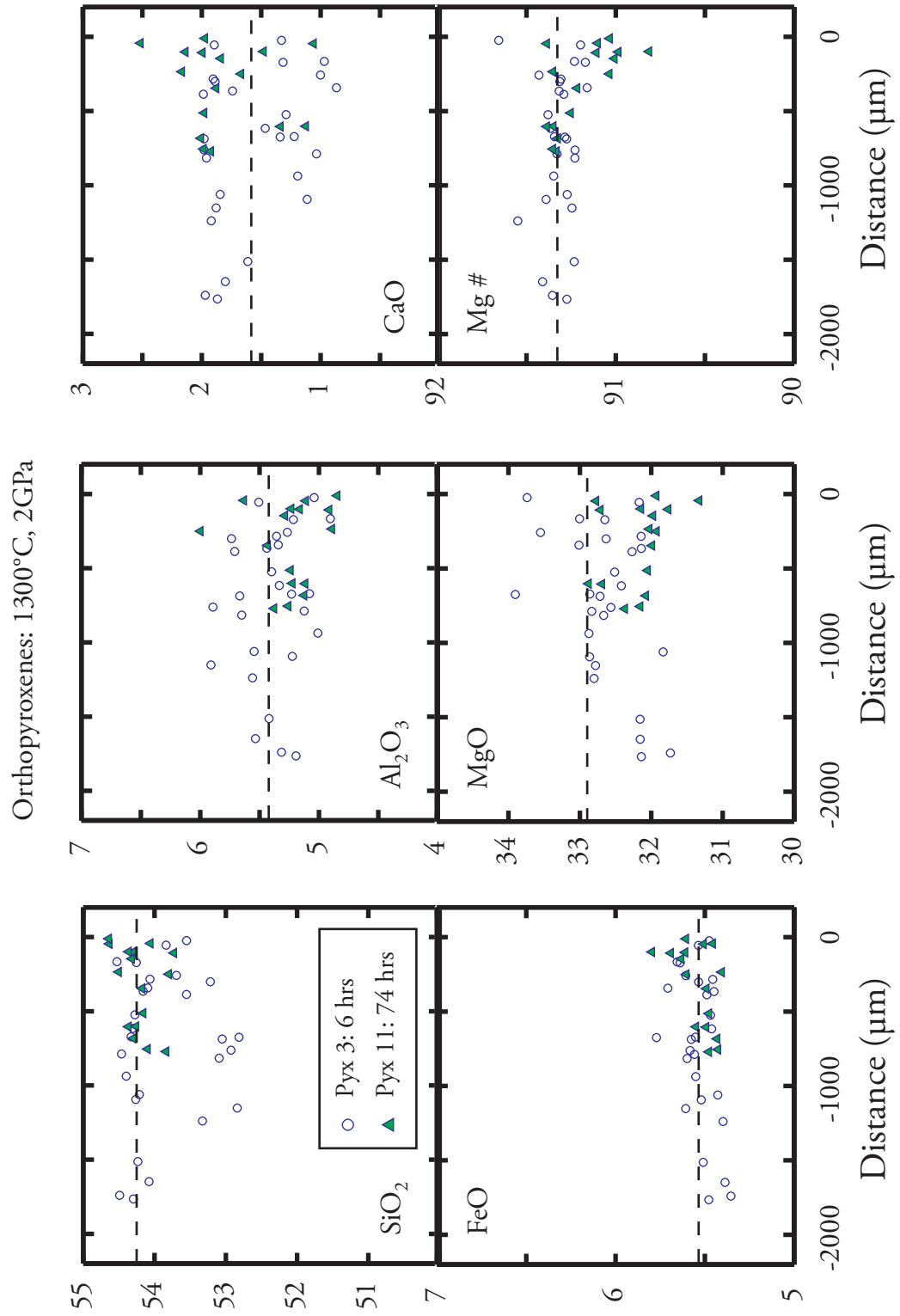


Figure 14.



Distance (μm)

Figure 16.

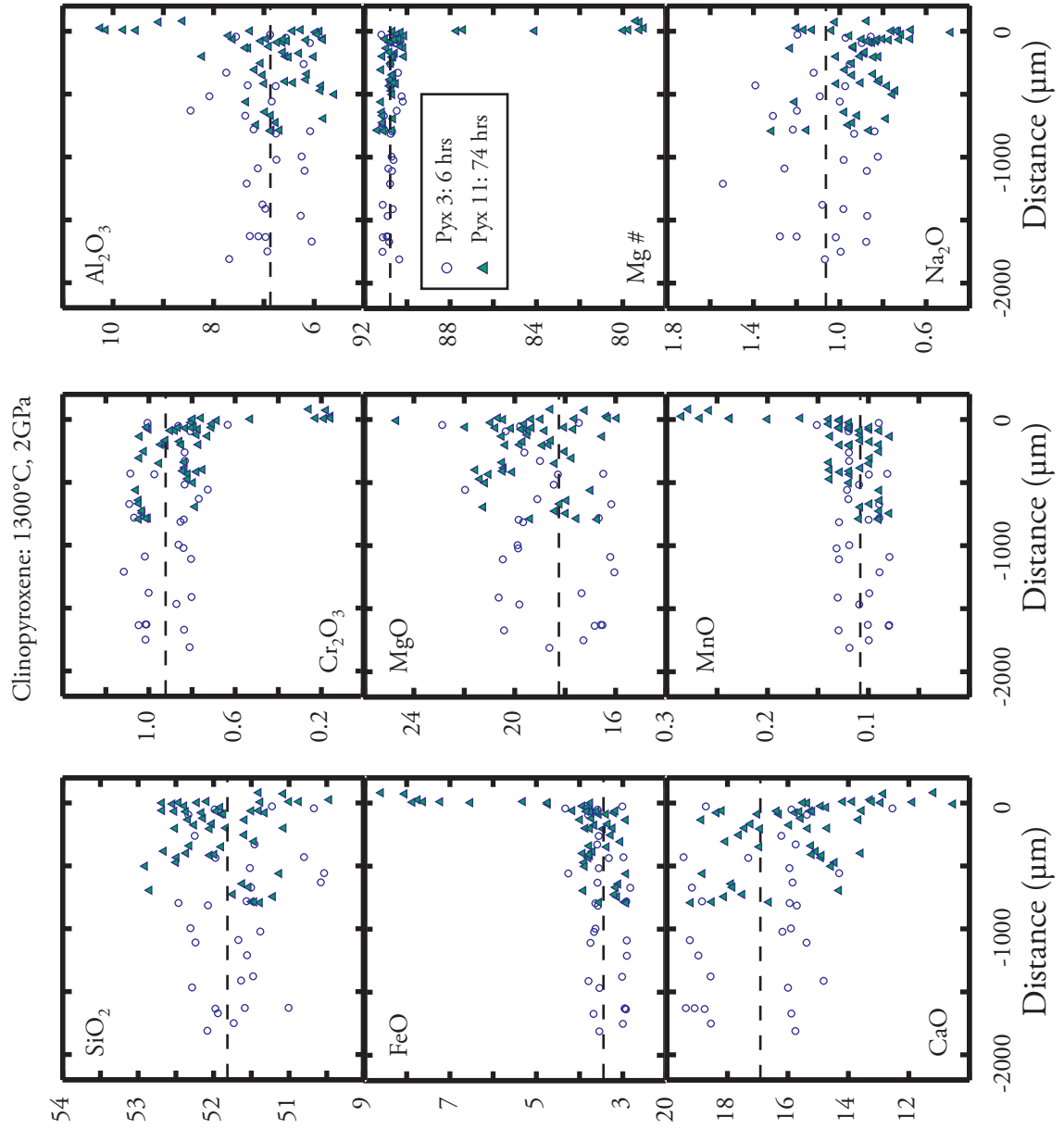


Figure 17.

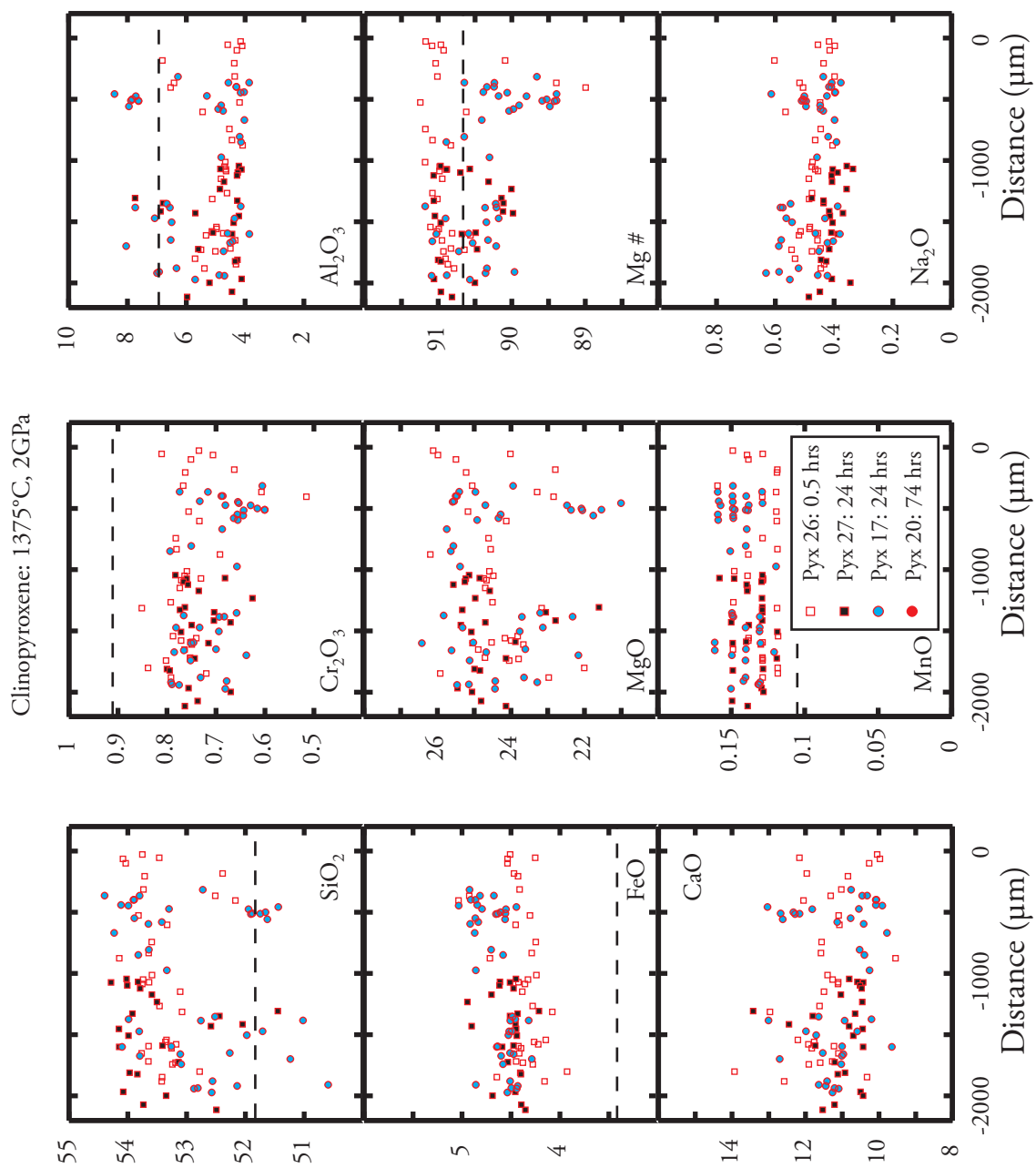


Figure 18.

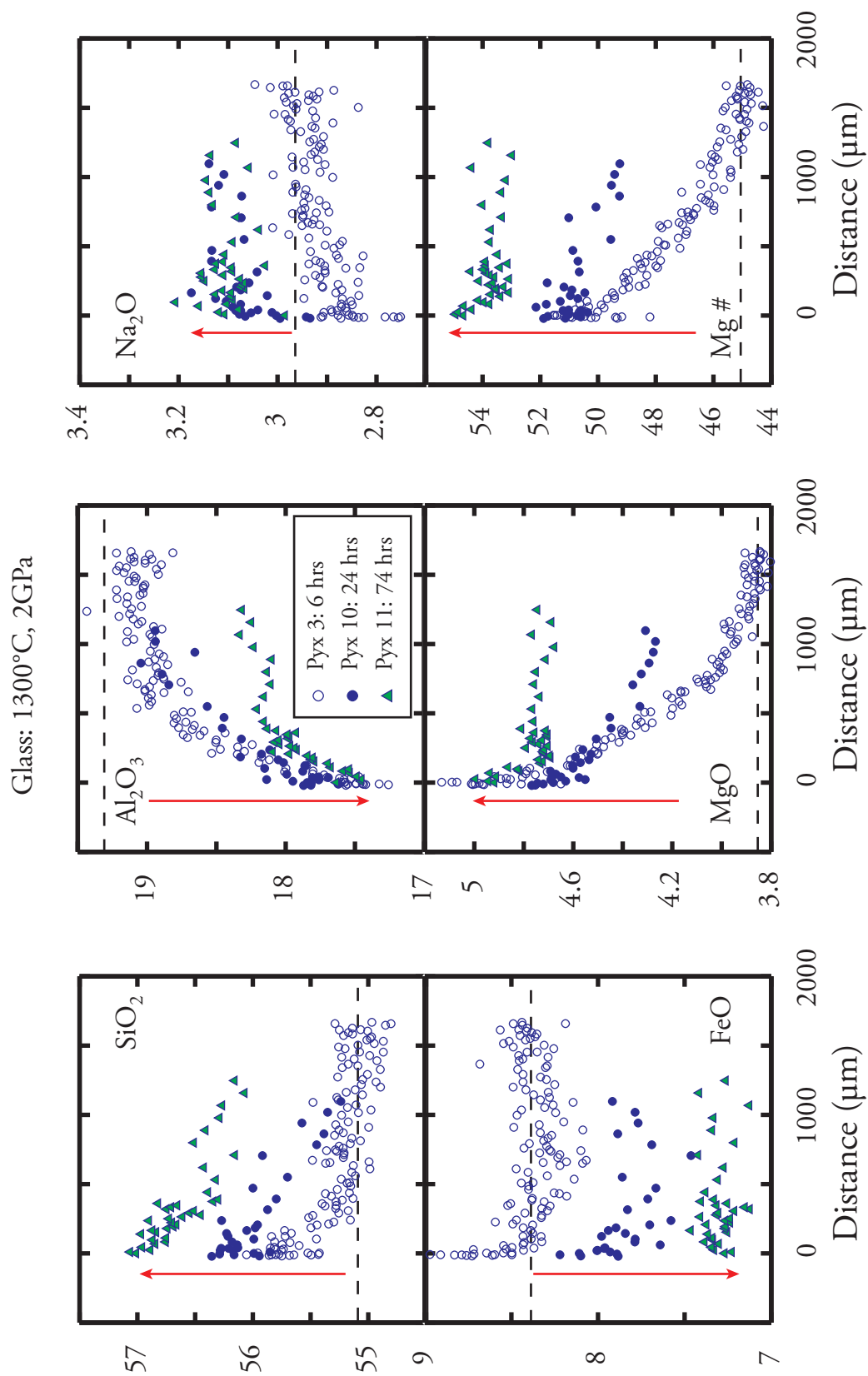


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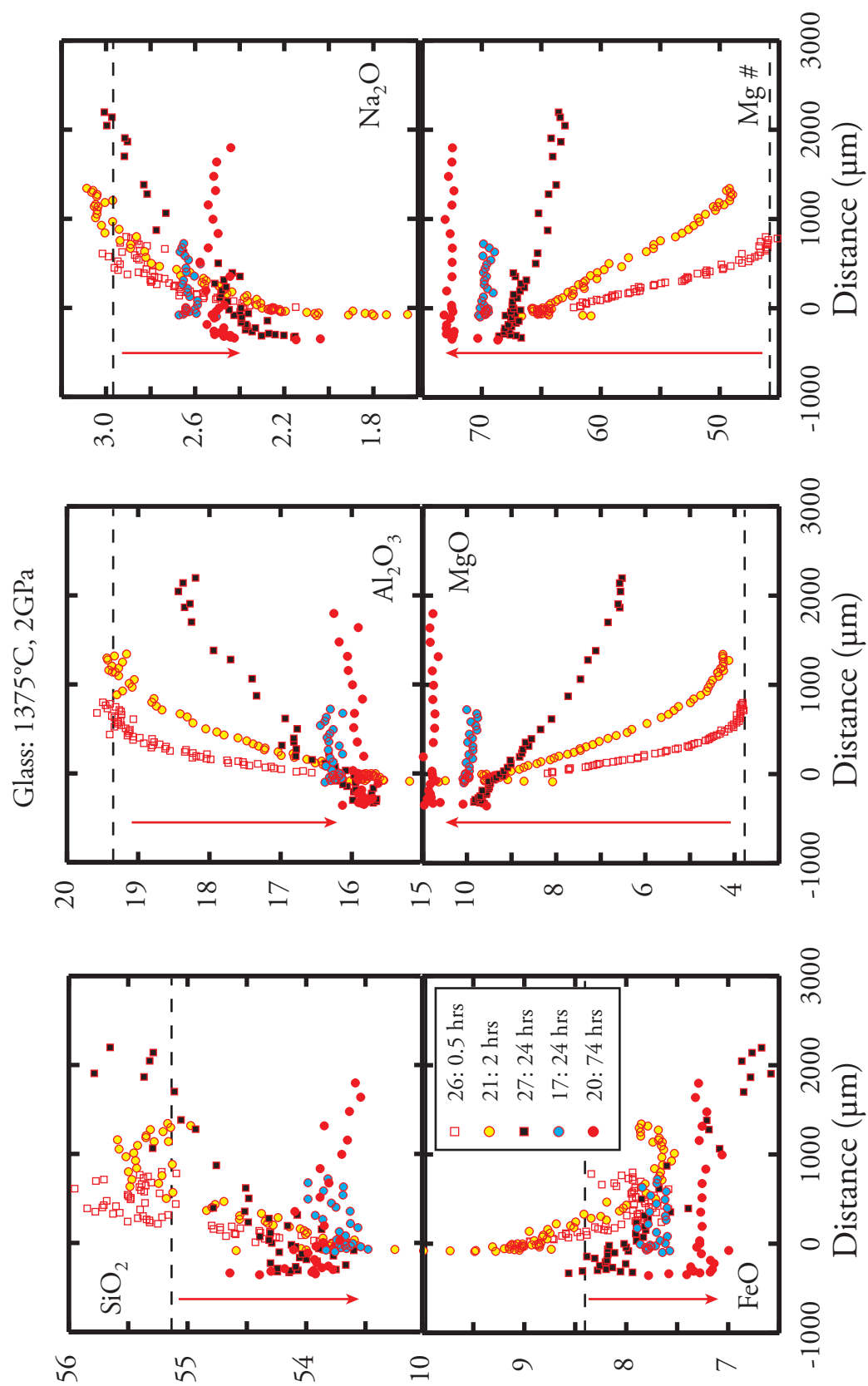


Figure 20.

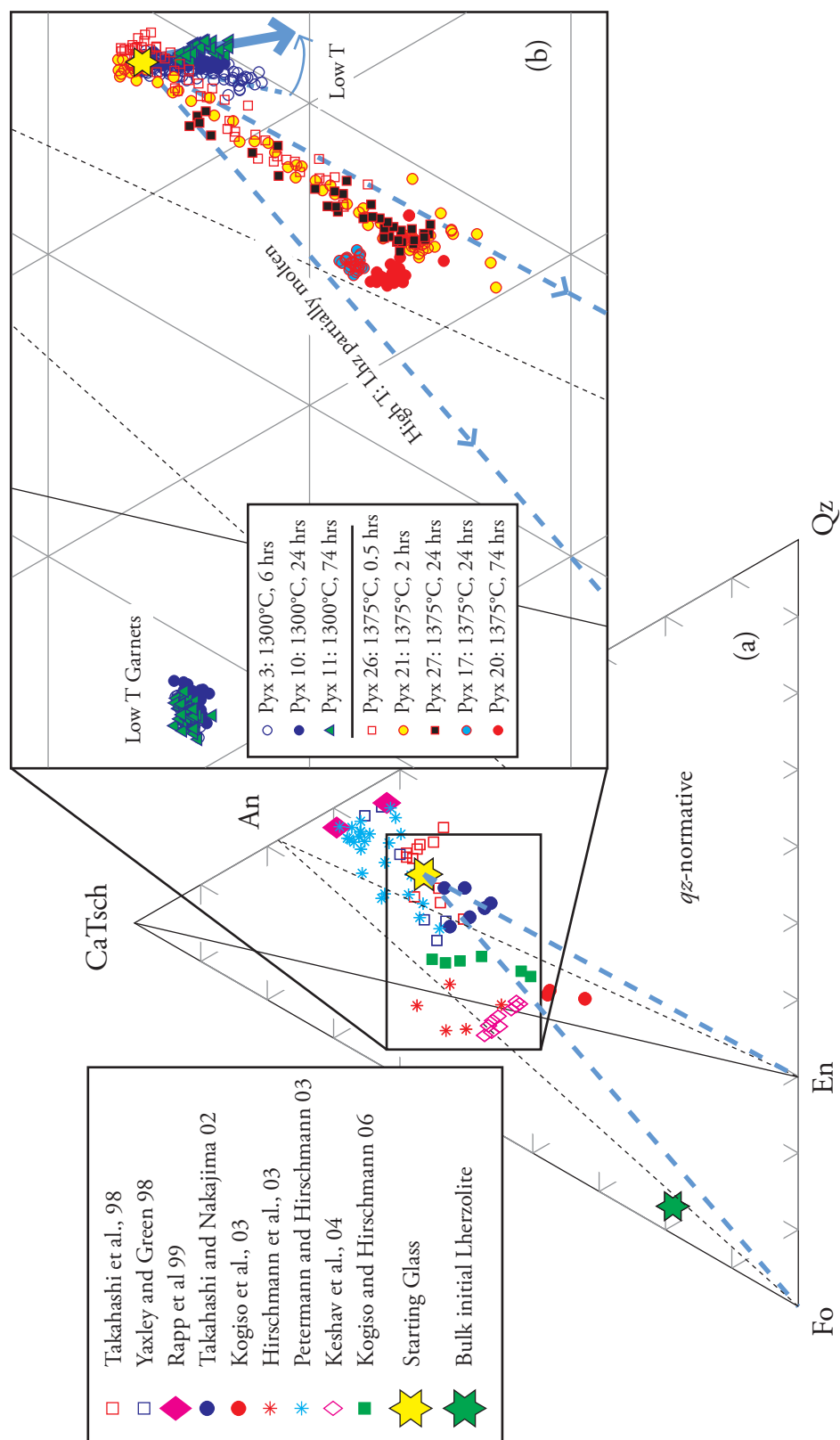


Figure 21.

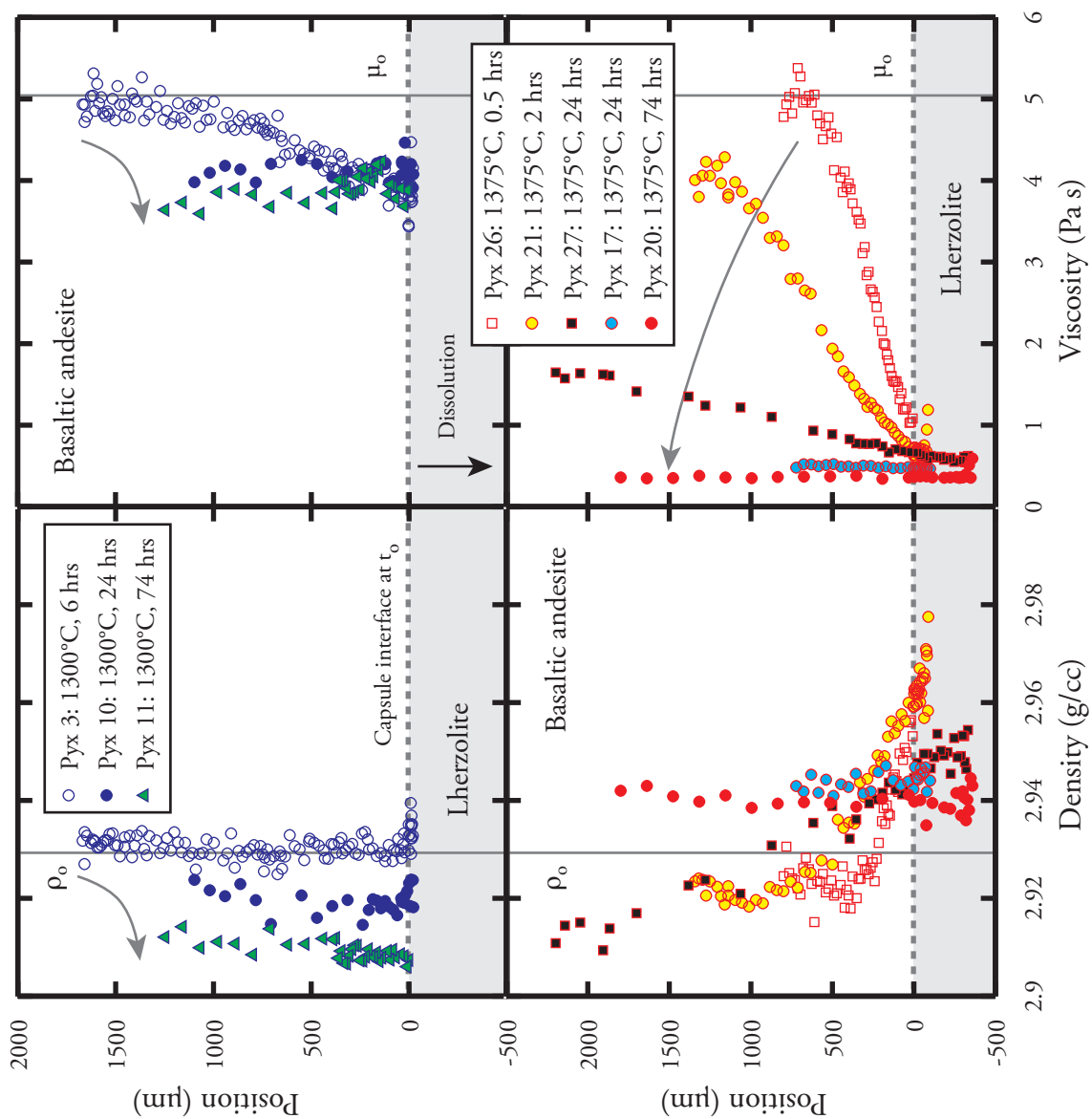


Figure 22.

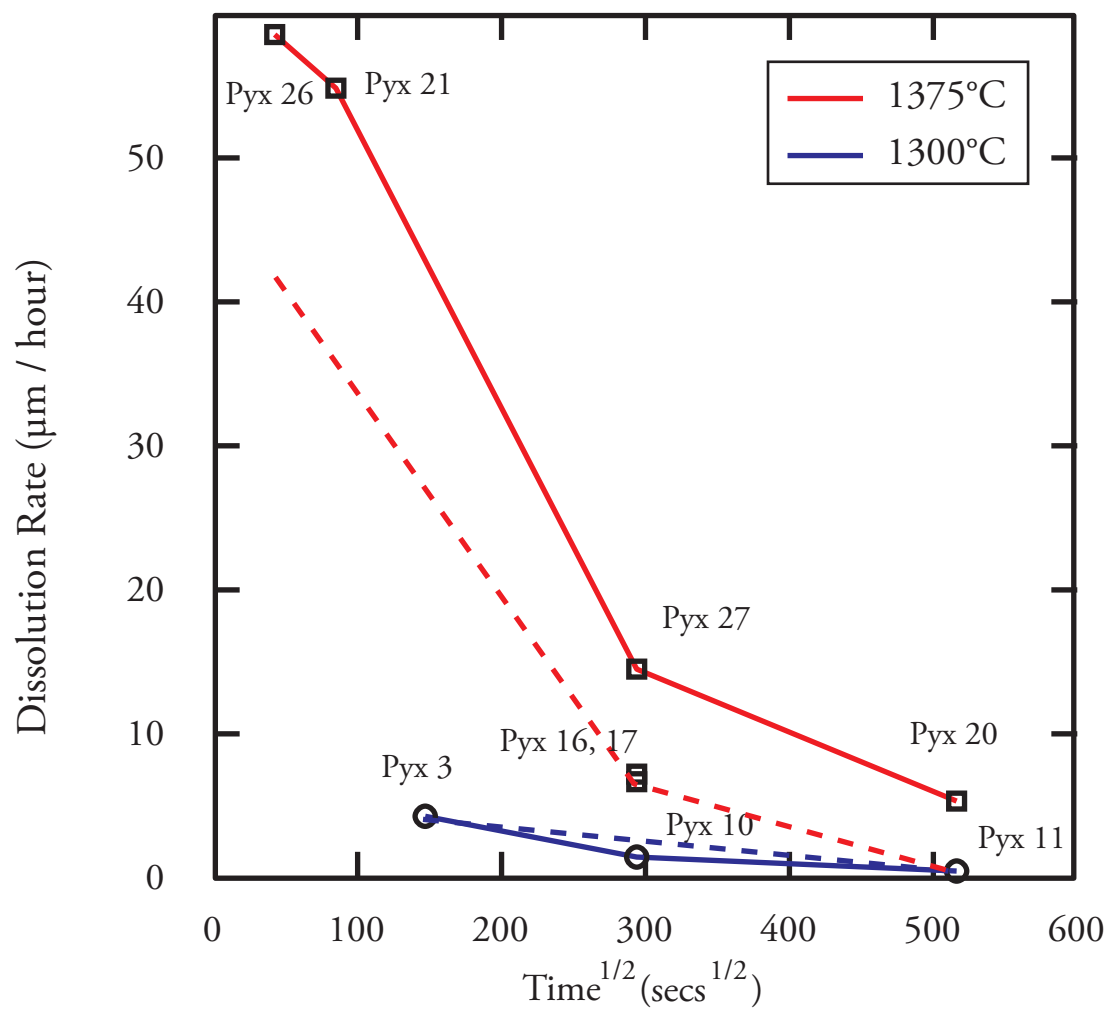


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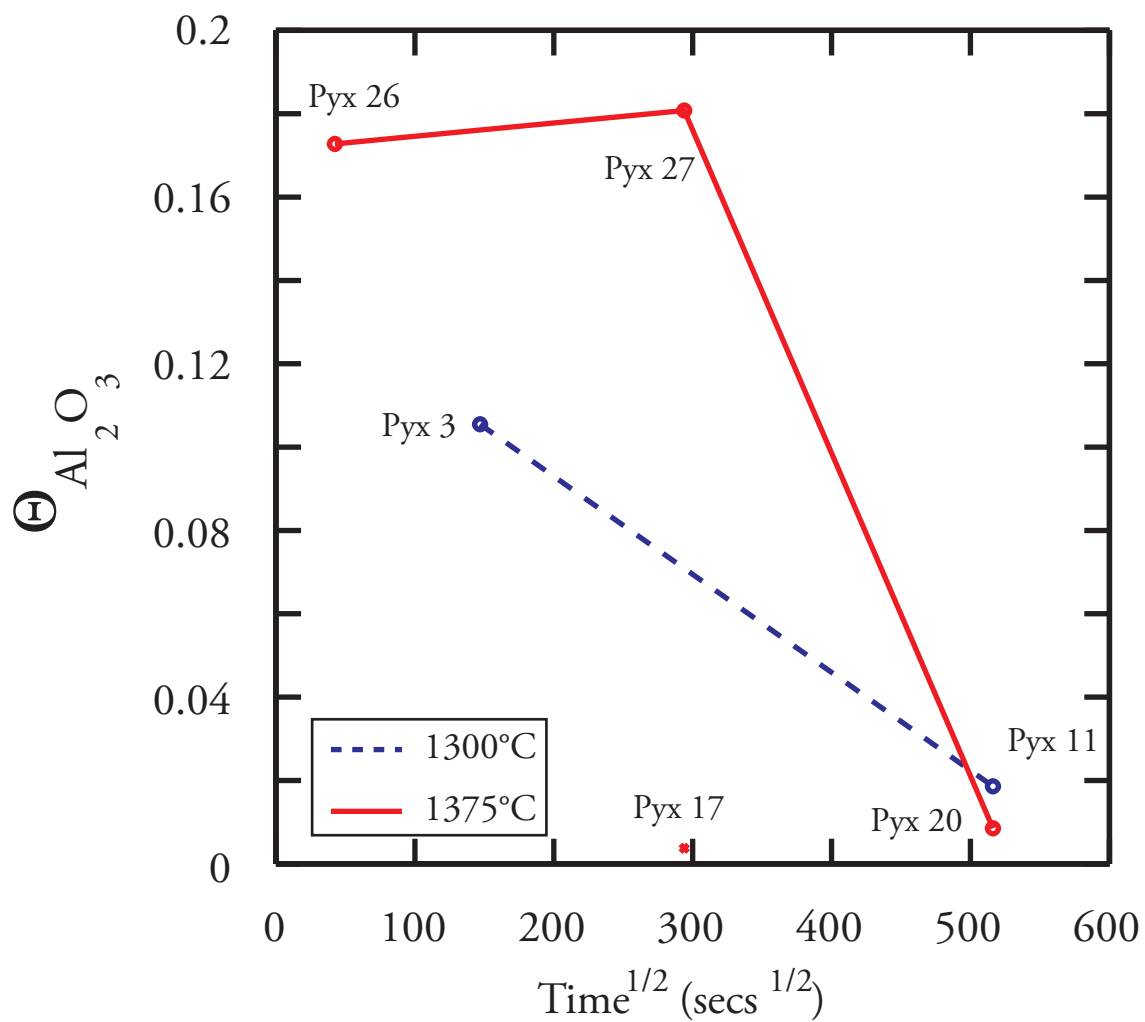


Figure 24.

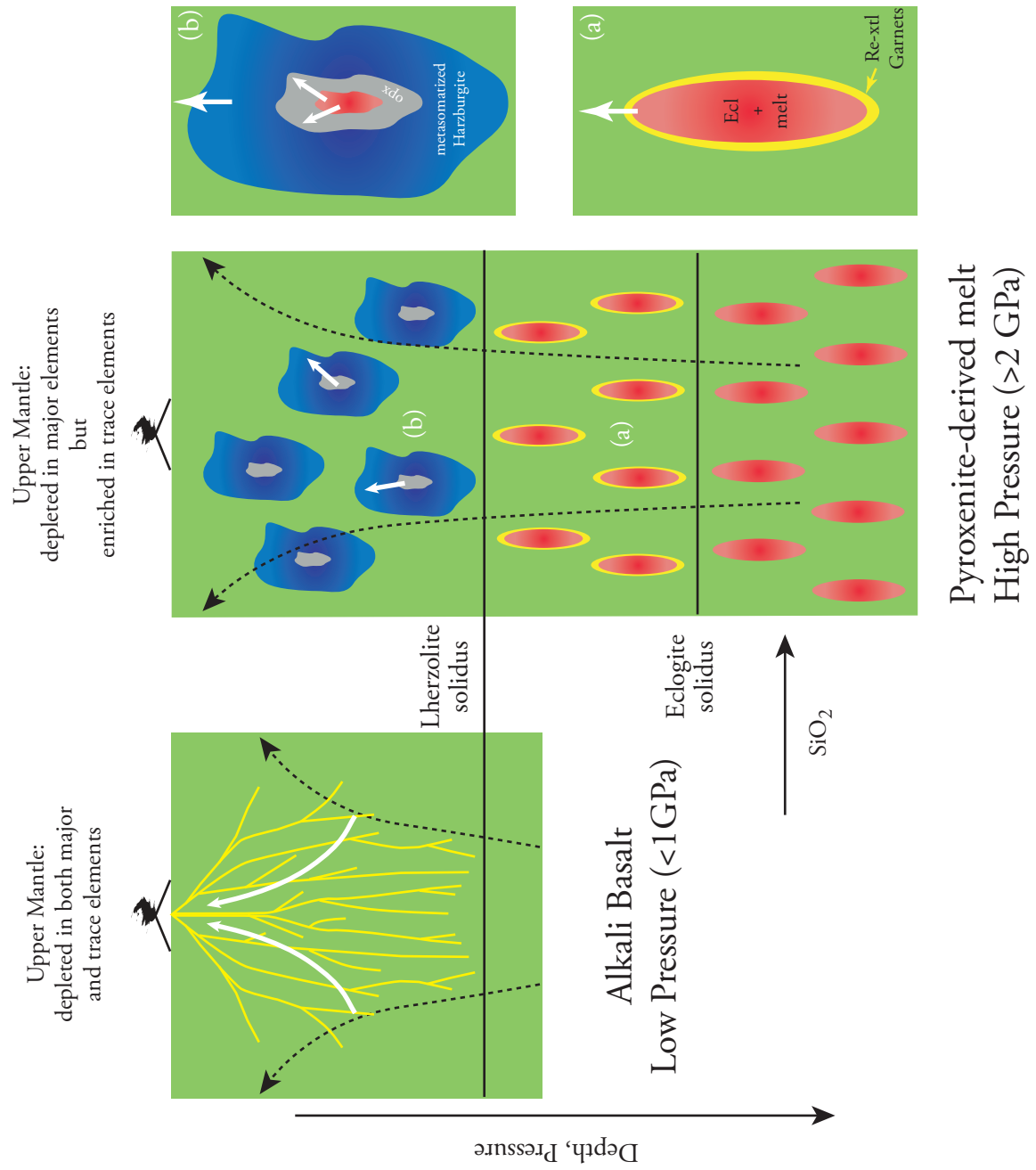


Figure 25.

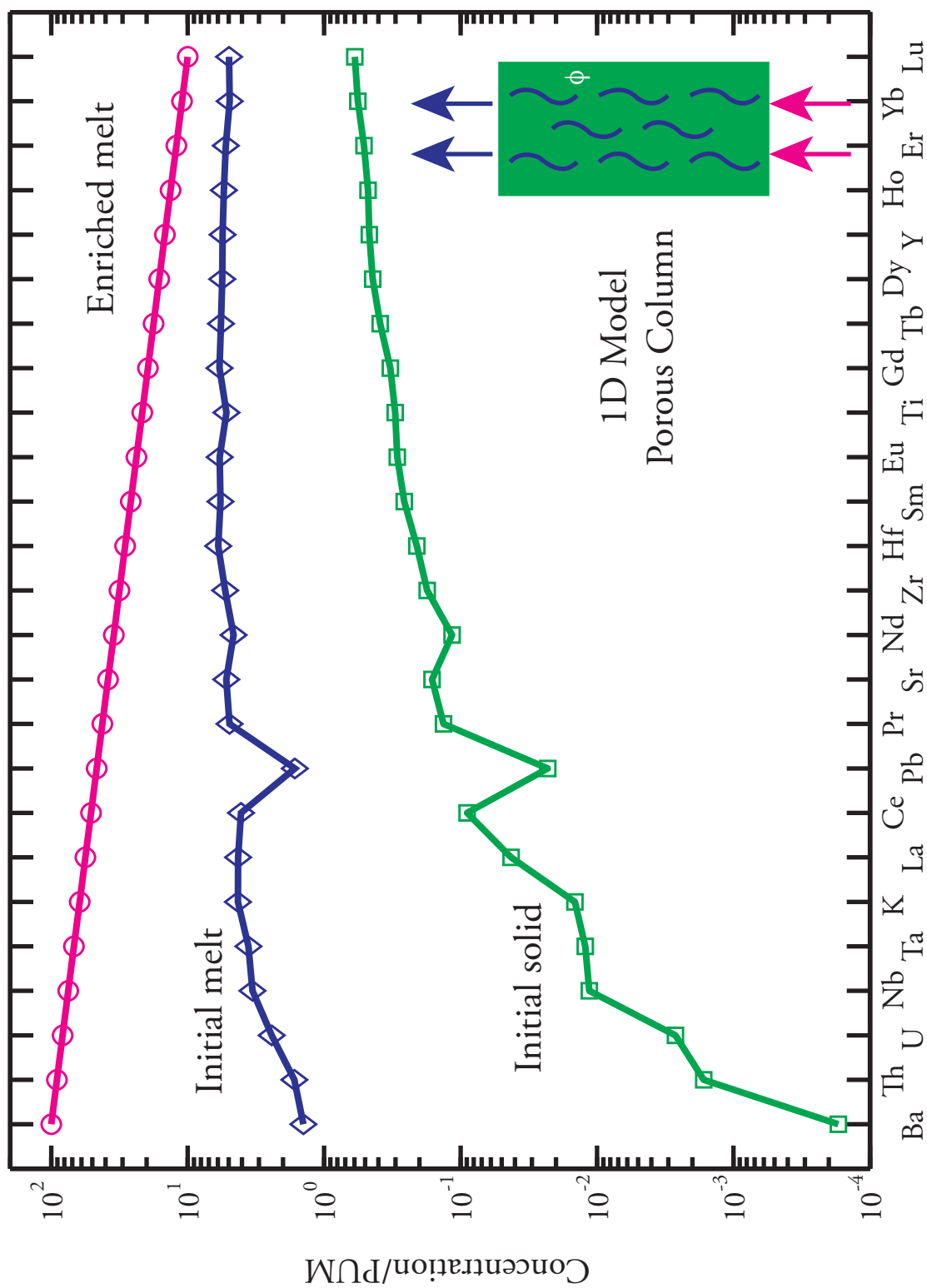


Figure 26.

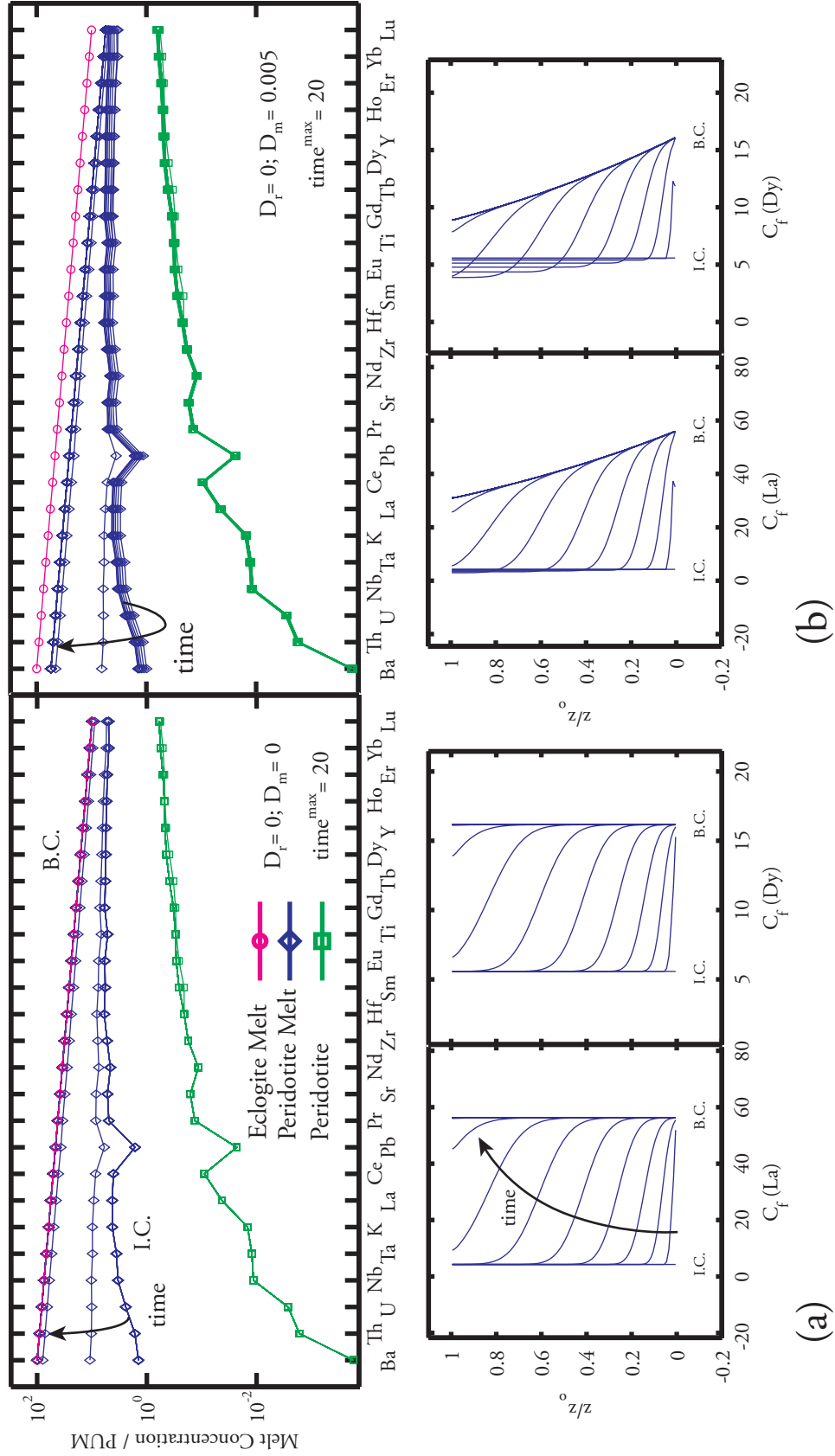


Figure 27.

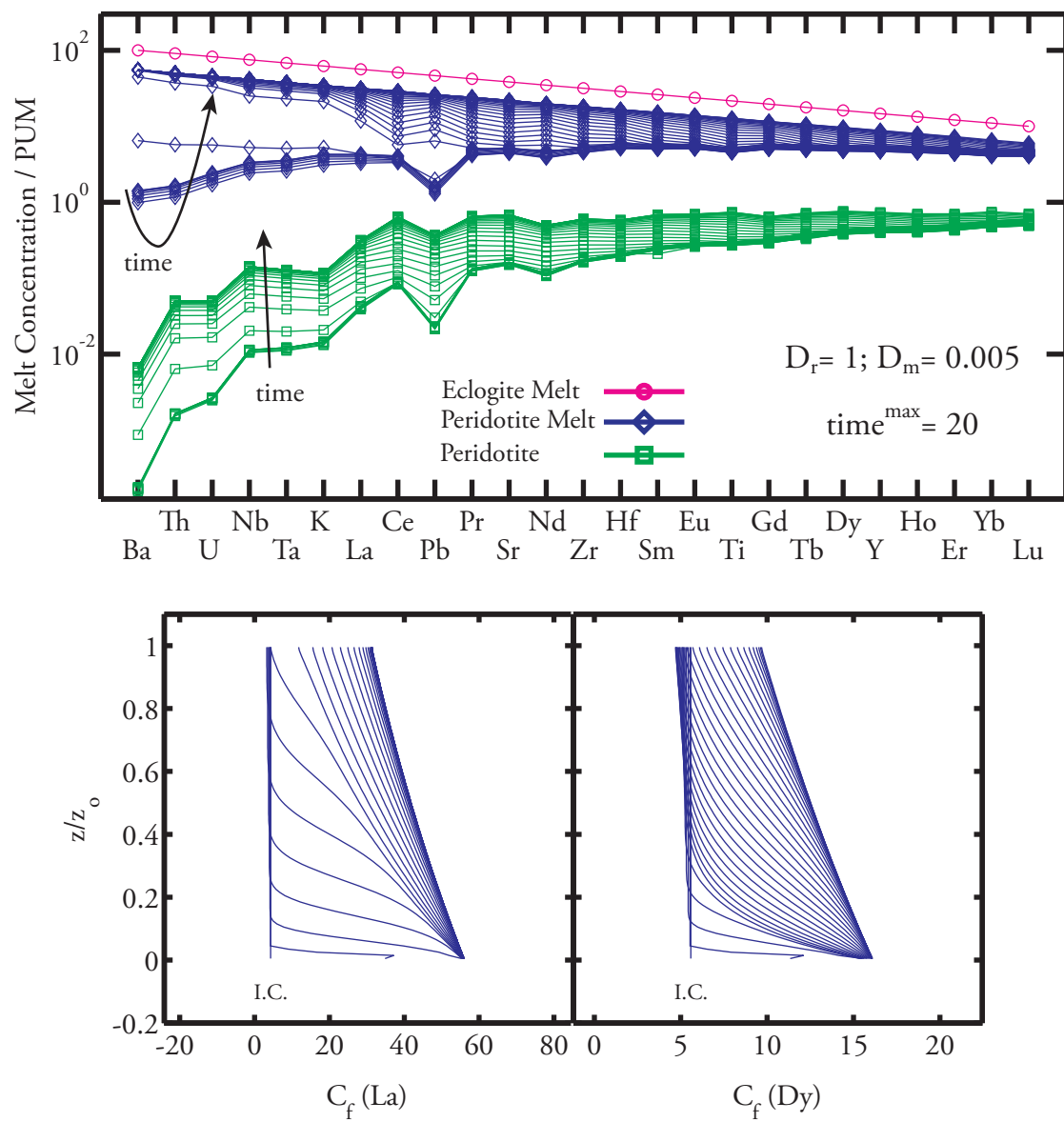


Figure 28.

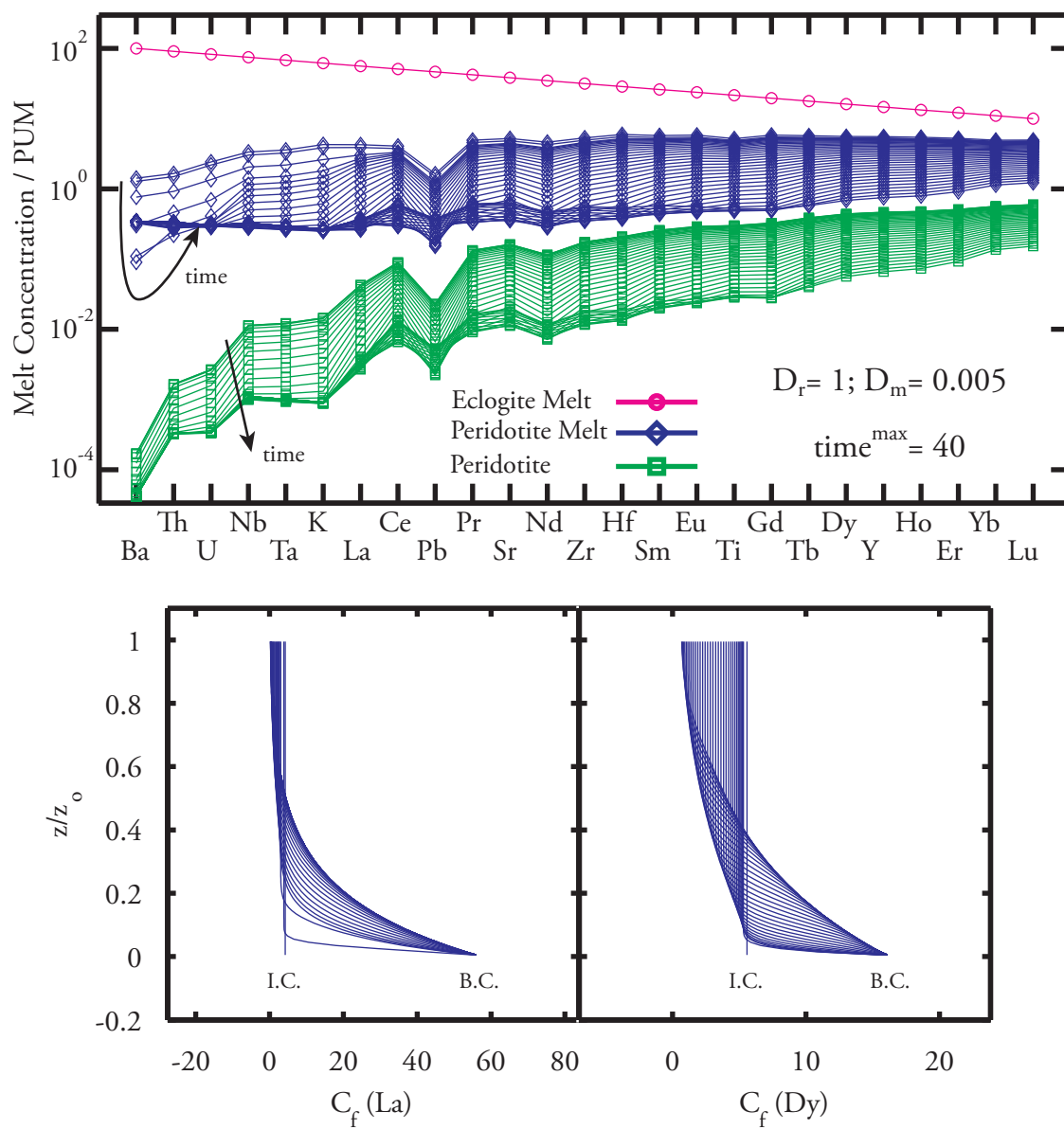


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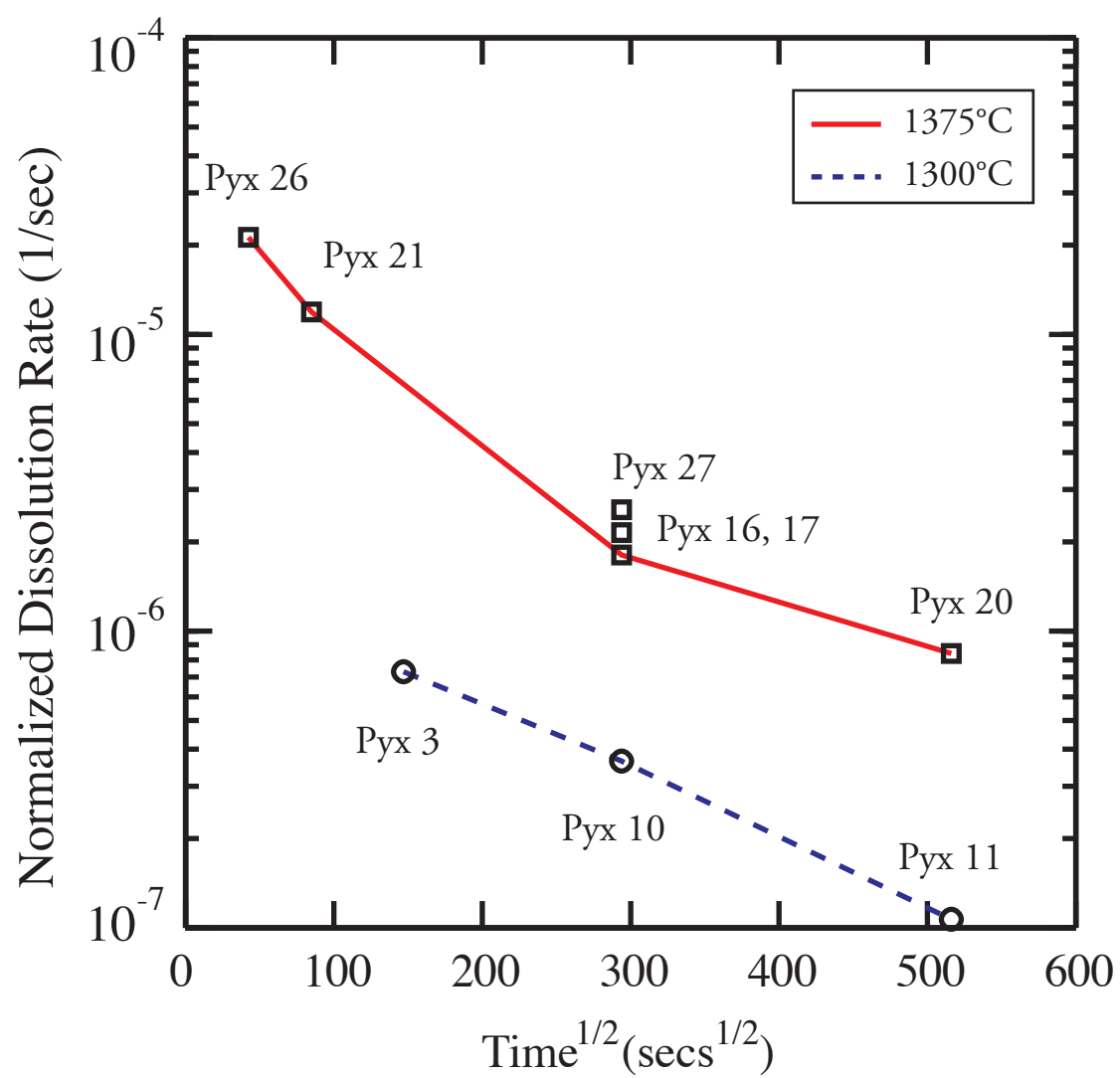


Table 1. Starting materials composition

Oxide	Basaltic andesite ^a	olivine ^b	orthopyroxene ^b	clinopyroxene ^b
SiO ₂	55.09 (0.29)	40.47 (0.74)	54.25 (1.05)	51.82 (0.81)
TiO ₂	0.79 (0.02)	0.01 (0.00)	0.11 (0.01)	0.29 (0.09)
Al ₂ O ₃	19.03 (0.15)	0.10 (0.01)	5.43 (0.24)	6.98 (0.62)
Cr ₂ O ₃		0.06 (0.01)	0.56 (0.04)	0.91 (0.13)
ΣFeO	8.42 (0.11)	9.21 (0.13)	5.57 (0.09)	3.42 (0.41)
NiO		0.23 (0.03)	0.09 (0.01)	0.05 (0.01)
MnO	0.22 (0.03)	0.14 (0.01)	0.13 (0.01)	0.11 (0.02)
MgO	3.86 (0.04)	49.80 (0.29)	32.87 (0.52)	18.76 (1.82)
CaO	8.80 (0.13)	0.20 (0.01)	1.58 (0.38)	16.94 (1.87)
Na ₂ O	2.97 (0.04)	0.01 (0.03)	0.16 (0.02)	1.07 (0.18)
K ₂ O	0.71 (0.03)			
P ₂ O ₅	0.13 (0.02)			
Total	100.01	100.22	100.75	100.35
Mg#	0.4496	0.9061	0.9132	0.9072

^aSample from Dr. J. Devine, average on 10 analyses of 2GPa glass at 1300°C in the unmodified portion of run Pyx3

^bSample from Drs. Huang and Bell. Averages on analyses for run Pyx3 of 22, 27, and 30 points for ol, opx, and cpx respectively

Table 2. Summary of Lherzolite dissolution experiments by Eclogite-derived melts at 2.0 GPa

Run #	Synthesis (hrs) ^a Glass / Lhz	T (°C) Anneal / Reaction	Duration (hrs) Anneal / Reaction	Dissolution (μm) ^b	Glass length t_g (μm) ^c	Lherzolite length t_l (μm) ^c	Glass / Lhz initial ratio	Dissolution/Glass ratio
Low T°								
Pyx 3	6 / 48	1000 / 1300	2 / 6	26 (9)	1627	1764	0.92	0.016
Pyx 10	6 / 48	1000 / 1300	2 / 24	34 (2)	1094	2059	0.53	0.031
Pyx 11	6 / 48	1000 / 1300	2 / 74	34 (25)	1187	827	1.43	0.028
High T°								
Pyx 21	24 / 48	1000 / 1375	2 / 2	110 (38)	1280	1440	0.89	0.086
Pyx 16	24 / 48	1000 / 1375	2 / 24	173 (13) ^d	930	164	5.66	0.186
Pyx 17	24 / 48	1000 / 1375	2 / 24	160 (23)	721	2049	0.35	0.222
Pyx 20	24 / 48	1000 / 1375	2 / 74	394 (12)	1760	1112	1.58	0.224
Pyx 26	6 / 48	800 / 1375	4 / 0.5	29 (5)	766	1845	0.42	0.038
Pyx 27	6 / 48	800 / 1375	4 / 24	348 (21)	2230	2068	1.08	0.156

^aSynthesis runs are done at the same temperature of the reaction runs (e.g., for Pyx 3 the starting glass and lherzolite were synthesized separately at 1300°C)^bOne standard deviation estimated from at least 10 optical (1.6X) and 15 back scattered electron images measurements around the central portion of each charge^cOptical (1.6X) length measurements done around the central portion of each charge to estimate the original lengths of each glass or lherzolite rod^dObtained only from optical measurements (2.5X)

Table 3. Parameters used to solve equations 13 and 14 using a porosity of 1% and 0.1%.

Elements	${}^iC_f^o / PUM$	${}^iC_o^o / PUM$	${}^{*}K_d = C_o / C_f$	${}^{*+}C_f^{enriched} / PUM$	$D_o = R L / V_f$	$D_m = \Gamma L / \rho_o (1-\phi) V_f$	$P\dot{\epsilon} = V_f L / D_f$
Ba	1.4190	0.0002	0.0001	100.00	0 or 5	0.01	100
Th	1.6513	0.0017	0.0010	90.85	0 or 5	0.01	100
U	2.4213	0.0027	0.0011	82.54	0 or 5	0.01	100
K	3.3494	0.0114	0.0034	74.99	0 or 5	0.01	100
Nb	3.5832	0.0122	0.0034	68.13	0 or 5	0.01	100
Ta	4.2767	0.0145	0.0034	61.90	0 or 5	0.01	100
La	4.2694	0.0427	0.0100	56.23	0 or 5	0.01	100
Ce	4.0699	0.0895	0.0220	51.09	0 or 5	0.01	100
Pb	1.6402	0.0230	0.0140	46.42	0 or 5	0.01	100
Pr	4.9339	0.1332	0.0270	42.17	0 or 5	0.01	100
Nd	5.2143	0.1616	0.0310	38.31	0 or 5	0.01	100
Sr	4.6123	0.1153	0.0250	34.81	0 or 5	0.01	100
Zr	5.3175	0.1755	0.0330	31.62	0 or 5	0.01	100
Hf	5.9717	0.2090	0.0350	28.73	0 or 5	0.01	100
Sm	5.7543	0.2589	0.0450	26.10	0 or 5	0.01	100
Eu	5.8259	0.2913	0.0500	23.71	0 or 5	0.01	100
Ti	5.1907	0.3011	0.0580	21.54	0 or 5	0.01	100
Gd	5.8424	0.3272	0.0560	19.57	0 or 5	0.01	100
Tb	5.7059	0.3880	0.0680	17.78	0 or 5	0.01	100
Dy	5.5807	0.4409	0.0790	16.16	0 or 5	0.01	100
Ho	5.5542	0.4666	0.0840	14.68	0 or 5	0.01	100
Y	5.4229	0.4772	0.0880	13.34	0 or 5	0.01	100
Er	5.2555	0.5098	0.0970	12.12	0 or 5	0.01	100
Yb	4.9236	0.5662	0.1150	11.01	0 or 5	0.01	100
Lu	4.9726	0.5967	0.1200	10.00	0 or 5	0.01	100

^oThe initial melt and solid concentrations are in chemical equilibrium.

⁺Partition coefficients by Workman and Hart (2005). Data is reported relative to primitive upper mantle (PUM) of McDonough and Sun (1995)

⁺Enriched pyroxenite-derived model melt based on the isotopically enriched, Si-rich melt component of Koolau lavas (Hauri and Kurtz, 1997)

Here we assume that the values of the $P\dot{\epsilon}$ and D_a numbers are identical for all trace elements. This assumption is valid for processes that are rate-limited by mineral-melt exchange processes in the presence of melt, such as dissolution and reprecipitation.

CHAPTER 4

**The behavior of rare-earth elements
during partial melting in the Earth's upper mantle**

Abstract

Using two phase flow theory, we have derived the mathematical expression for a general dynamic melting model, that takes into account variations in the source mineral proportions and individual mineral/melt partition coefficients. We show how the clinopyroxene/melt partition coefficient changes during partial melting of peridotite, and how to parameterize the bulk-rock/melt partition coefficient as a function of the degree of melting. Combining available experimental partitioning data and the thermodynamic algorithm pMELTS [Ghiorso MS, Hirschmann MM, Reiners PW, Kress VC (2002) The pMELTS: A revision of MELTS for improved calculation of phase relations and major element partitioning related to partial melting of the mantle to 3 GPa. *Geochem Geophys Geosys* 3, 5: 10.1029/2001GC000217], we applied the dynamic equations to mantle melting. The results of this study show how rare-earth elements become progressively more incompatible as partial melting of the mantle takes place. Therefore, the major element compositional dependence of incompatible trace element partitioning during partial melting, must be accounted for in studies of igneous rock petrogenesis.

1. Introduction

The abundance of incompatible trace elements in mafic and ultramafic rocks has been extensively used to study the chemical composition and the processes of melting and melt segregation that take place in the Earth's upper mantle (*e.g.*, Langmuir et al. 1977; Johnson et al. 1990; Kelemen et al. 1995). However, petrogenetical interpretations based on trace element fractionation during igneous processes are very sensitive (1) to the mathematical model used to describe melting and melt segregation (*e.g.*, Gast, 1968; Shaw 1970; Hertogen and Gijbels, 1976; Richter and McKenzie, 1984; McKenzie 1985; Richter, 1986; Navon and Stolper 1987; Albarède, 1995; Zou, 2000), and (2) to the value of the solid/melt partition coefficient (*e.g.*, Blundy and Wood, 2003; Gaetani, 2004; Hauri et al., 2006). The partition coefficient (K) is defined as the mass ratio between the equilibrium abundance of a specific element in a solid divided by its abundance in the coexisting liquid.

There have been two types of mathematical melting models developed in the last 40 years, one used by geochemists based on Rayleigh distillation theory (Gast, 1968), and another used by geophysicists based on the fluid dynamics of two phase flow (McKenzie, 1984 and references therein). Physically, however, geochemical processes are influenced by the dynamics of the mantle (McKenzie and O'Nions, 1991) and in the last few year there have been several attempts to reconcile both approaches (see Shaw, 2000 for a review). However, an examination of modal melting following two-phase flow theory (Zou, 1998) failed to extend the analysis to non-modal melting or to a general case where the partition coefficient varies during melting (Shaw, 2000). Therefore, even though the change of the bulk-rock partition coefficient, due to changes in mineral modes and in individual mineral/melt partition coefficients, has been treated mathematically by several geochemistry groups along the lines of distillation theory (Hertogen and Gijbels, 1976; Zou, 2000), the analysis has not been extended to two phase flow theory yet. In this study we have expanded the

treatment of McKenzie (1984) to include the effect of varying partition coefficient by using known compositional dependences on individual mineral/melt partition coefficients, and we have used the thermodynamic algorithm pMELTS (Ghiorso et al., 2002) to constraint mineral chemistry during partial melting of the mantle.

2. Model derivation

The governing equations are derived in the same way as McKenzie (1984), namely mass conservation of the fluid and the solid,

$$\frac{\partial(\rho_f \phi)}{\partial t} + \nabla \cdot [\rho_f \phi \mathbf{V}_f] = \Gamma$$

$$\frac{\partial[\rho_s(1 - \phi)]}{\partial t} + \nabla \cdot [\rho_s(1 - \phi) \mathbf{V}_s] = -\Gamma$$

and conservation of chemical species in the melt and the solid

$$\frac{\partial(\rho_f \phi C_f)}{\partial t} + \nabla \cdot [\rho_f \phi C_f \mathbf{V}_f] = \nabla \cdot [D_f \nabla(\rho_f \phi C_f)] + Q + C_s \Gamma$$

$$\frac{\partial[\rho_s(1 - \phi) C_s]}{\partial t} + \nabla \cdot [\rho_s(1 - \phi) C_s \mathbf{V}_s] = \nabla \cdot [D_s \nabla(\rho_s(1 - \phi) C_s)] - Q - C_s \Gamma$$

where ρ_f and ρ_s are the fluid and solid densities, V_f and V_s are the fluid and solid velocities respectively, ϕ is the porosity (volume of interconnected liquid/total volume), Γ is the rate at which mass is transferred from the solid matrix to the melt ($\text{kg m}^{-3} \text{sec}^{-1}$) and measured in a frame fixed to the matrix, D_f and D_s are respectively the fluid and solid diffusivity tensors, $C_s \Gamma$ is the source/sink term due to melting (Liang, 2003b), $Q = \rho_s(1 - \phi)R(C_s - KC_f)$ is the change in composition due to chemical exchange between the melt and the solid by dissolution and reprecipitation (Richter and DePaolo, 1987; Liang, 2003a), where R is a linear rate of reaction between solid and liquid in fraction of solid per unit time (s^{-1}), and K is the

bulk solid-liquid partition coefficient for a given element. These four equations can be simplified by combining the conservation of mass with the conservation of a chemical specie to obtain

$$\rho_f \phi \left[\frac{\partial C_f}{\partial t} + \mathbf{V}_f \cdot \nabla C_f \right] = \nabla \cdot [\rho_f \phi D_f \nabla C_f] + (C_s - C_f) \Gamma + Q$$

$$\rho_s (1 - \phi) \left[\frac{\partial C_s}{\partial t} + \mathbf{V}_s \cdot \nabla C_s \right] = \nabla \cdot [\rho_s (1 - \phi) D_s \nabla C_s] - Q$$

If we assume that diffusion of the solid can be neglected, a valid assumption for a representative elemental volume much larger than the average grain-size, and assume local equilibrium (i.e. $C_s = K C_f$), we obtain the following equation

$$\begin{aligned} [\rho_f \phi + \rho_s (1 - \phi) K] \frac{\partial C_f}{\partial t} + C_f \rho_s (1 - \phi) \frac{\partial K}{\partial t} + [\rho_f \phi \mathbf{V}_f \cdot \nabla C_f + \rho_s (1 - \phi) \mathbf{V}_s \cdot \nabla (K C_s)] \\ = \nabla \cdot [\rho_f \phi D_f \nabla C_f] + C_f (K - 1) \Gamma \end{aligned} \quad (1)$$

Equation (1) is similar to equation (A42) of McKenzie (1984), except that here we also consider the variation of the bulk-rock partition coefficient with time. It is possible to simplify equation (1) by making a few reasonable assumptions pertinent to the Earth's mantle. In chapter 3, we have shown that the *Péclet* number ($Pe = V_f L / D_f$) is likely to be very large in the mantle ($\gg 10^3$), and that the melting Damköhler number ($D_m = \Gamma L / [\rho_s (1 - \phi) V_f]$) is likely to be much smaller than 1, where L is the length over which melting takes place. We can therefore assume that, to a first approximation, C_f and C_s are only a function of time. Equation (1) then simplifies to

$$\frac{1}{C_f} \frac{dC_f}{dt} + \frac{\rho_s (1 - \phi)}{\rho_f \phi + \rho_s (1 - \phi) K} \frac{dK}{dt} = \frac{K - 1}{\rho_f \phi + \rho_s (1 - \phi) K} \Gamma$$

which can be written as an ordinary differential equation with separable terms,

$$\frac{dC_f}{C_f} + \frac{\rho_s(1-\phi)}{\rho_f\phi + \rho_s(1-\phi)K} dK = \frac{K-1}{\rho_f\phi + \rho_s(1-\phi)K} \Gamma dt \quad (2)$$

Using the relation between the melting rate and the degree of melting for a closed system (McKenzie, 1985)

$$\Gamma = \frac{\rho_f\phi + \rho_s(1-\phi)}{1-F} \frac{dF}{dt}$$

equation (2) becomes

$$\frac{dC_f}{C_f} = (1+A) \frac{K-1}{1+AK} \frac{dF}{1-F} - \frac{A}{1+AK} dK \quad (3)$$

where $A = \frac{\rho_s(1-\phi)}{\rho_f\phi}$, and the general solution to (3) is

$$\ln \frac{C_f}{C_f^o} = (1+A) \int_0^F \frac{K-1}{1+AK} \frac{dF}{1-F} - \ln \frac{1+AK}{1+AK^o} \quad (4)$$

where K^o is the bulk-rock partition coefficient for $F = 0$. To a first approximation, equation (4) can recover the dynamic melting model of Shaw (2000, equation 20), which is equivalent to the many melting models that have been proposed to date (e.g., Shaw, 1970; Langmuir et al. 1977; Sobolev and Shimizu, 1993; Albarède, 1995; Zou, 1998). In detail, however, the solution to equation (4) for non-modal melting with constant mineral/melt partition coefficients, deviates from the solution of Shaw (2000) for large residual porosities and for large degrees of melting (Fig. 12). This is due to our simplified analysis of the source/melting term $C_s\Gamma$. Nevertheless, for the porosity and degree of melting we will be dealing with here, equation (4) offers excellent numerical results combined with the flexibility of handling any functional form of the bulk-rock/melt partition coefficient (K). This feature is particularly useful since current available analytical solutions of melting models, that include changes in the mineral/melt partition coefficients, only consider linear changes of K with respect to the degree of melting (e.g., Hertogen and Gijbels, 1976; Zou, 2000). In

the next section we will discuss what are the most important parameters controlling K . We will also show that the K dependence on the degree of melting is highly non-linear, due to the changes in individual mineral/melt partition coefficients with increasing degree of melting. Finally, we will show how different melting models fractionate REE during partial melting and its implication for the Earth's mantle.

3. Results and Discussion

3.1 Crystal-chemistry control on the variation of individual mineral/melt partition coefficients

Partial melting of the Earth's mantle occurs predominantly above the garnet stability field, where clinopyroxene is the crystalline phase that holds most incompatible trace elements. Hence, the clinopyroxene/melt K is the dominant parameter controlling how incompatible trace elements behave during melting and melt transport processes in the Earth's upper mantle. The partitioning of trace elements into a crystalline structure is controlled by the size and the charge of the cation compared to the size and charge of the lattice site which varies with mineral composition, pressure, and temperature (e.g., Goldschmidt, 1937; Nagasawa, 1966; Brice, 1975; Blundy and Wood, 2003). The partitioning of rare earth elements (REE) in particular has been extensively studied because these elements have similar chemical and physical properties arising from the fact that they typically form 3+ cations of similar ionic size. Their small decrease in ionic size with increasing atomic number, however, is sufficient to fractionate them relative to each other and valuable information on the source mineralogy and melting processes can be extracted from this fractionation. The effect of the Al^{3+} content of clinopyroxene is also known to have strong effect on the clinopyroxene crystal chemistry and on the amount of REE and HFSE that clinopyroxene can accommodate in its structure (e.g. Blundy and Wood, 2003; Hill et al., 2000; Lundstrom et al., 1998; Gaetani and Grove, 1995; Lundstrom et al., 1994),

possibly through the substitution $\text{Ca}^{2+}_{\text{M2}} + \text{Si}^{4+}_{\text{T}} \rightarrow \text{REE}^{3+}_{\text{M2}} + \text{Al}^{3+}_{\text{T}}$, where the subscript represents the cation location in the crystal site of clinopyroxene (the large irregular 8-fold M_2 site and the tetrahedral site T).

The clinopyroxene/melt K is generally determined experimentally and although in principle one could measure the elemental abundance in coexisting clinopyroxene and melt after a peridotite partial melting experiment, it has never been done before due to analytical difficulties such as small crystal sizes and melt pockets, with severe quench modification. As a result, typical partitioning studies are performed through crystal growth experiments from a basaltic liquid composition to enhance spatial resolution and equilibration. When comparing the major element composition of clinopyroxene obtained in these partitioning studies, we observe a large compositional scatter in the major elements (Figures 1). In particular, the Al^{3+} content in clinopyroxene from partitioning studies is significantly higher than in the residual clinopyroxene from partial melting experiments and abyssal peridotites. Crystallization experiments aimed at simulating partial melting fall somewhere in between, with an intermediate Al^{3+} content. In addition to these differences in major element chemistry, the partitioning of Al^{3+} between the octahedral site (Al^{VI}) and the tetrahedral site (Al^{IV}) in clinopyroxene is different between different studies (Fig. 2). For example, the clinopyroxene composition from partial melting studies are dominated by the Ca-Tschermak ($\text{CaAl}^{\text{VI}}[\text{Al}^{\text{IV}}\text{Si}]\text{O}_6$, CaTs for short) substitution (i.e. they lie on the line $\text{Al}^{\text{VI}}/\text{Al}^{\text{IV}}=1$), whereas many partitioning studies have also a strong Jadeite ($\text{NaAl}^{\text{VI}}\text{Si}_2\text{O}_6$, Jd for short) component ($\text{Al}^{\text{VI}}/\text{Al}^{\text{IV}}>1$) in their clinopyroxene. Note however, that a few partitioning studies have been highlighted separately in Fig. 2 and also follow the CaTs substitution. Even though the composition of clinopyroxene in the mantle is not known with certainty, abyssal peridotites can be used as a first approximation to the residual oceanic mantle (e.g., Johnson et al., 1990; Workman and Hart, 2005) and they tend to have Al^{3+} contents comparable to partial melting

studies and a low Jadeite component (i.e., $Al^{VI}/Al^{IV} \leq 1$) in contrast to partitioning studies. However, there is no correlation between the Al^{VI} and Al^{IV} in clinopyroxene for abyssal peridotites. This is likely due to subsolidus re-equilibration. Hence, an assessment of the dominant substitution of Al in clinopyroxene in the mantle is difficult.

These crystal chemistry characteristics suggest that the REE clinopyroxene/melt K obtained from partitioning experiments are expected to be higher than those from partial mantle melting studies due to both higher CaTs and Jd contents in clinopyroxene derived from crystal growth experiments. As expected (e.g., Lundstrom et al., 1994; Gaetani and Grove, 1995; Hill et al., 2000; Blundy and Wood, 2003), Figure 3 shows a very good correlation between the Al^{IV} content of clinopyroxene and the partition coefficient of REE. Even though these studies were done over a wide range in P - T conditions (1 *atm* to 3.2 GPa, and $\sim 1200^{\circ}\text{C}$ to 1500°C) and for different starting compositions, to a first approximation the REE clinopyroxene/melt K is controlled by the Al^{IV} of clinopyroxene alone. Therefore, in order to be able to use the relationships shown in Figure 3, we will need to assess the change in clinopyroxene Al^{IV} with increasing degree of melting. In chapter 2, we showed that the Ca^{2+} and Al^{3+} content of clinopyroxene also changes during partial melting, namely decreasing its Ca^{2+} and Al^{3+} content at a constant ratio and follows the CaTs substitution (Figure 4). This also suggests, that the REE clinopyroxene/melt K should change during melting, as shown by the red arrows in Figures 3 and 4.

3.2 The change of clinopyroxene composition as a function of the degree of melting and its effects on REE distribution during partial melting of the mantle

The degree of melting (F) is an important parameter that determines both the thickness of the oceanic crust and the composition of basalts produced by mantle melting (Planck et al., 1995). Although the definition of F varies depending on how partial melting of the

mantle is treated as a function of depth (e.g., Plank and Langmuir, 1992; Forsyth, 1993; Plank et al., 1995), the classic definition of F as the mass ratio of melt to the initial unmelted rock (Shaw, 1970) will be used here in order to compare calculations to experimental data. To derive the relationship between the REE clinopyroxene/melt K and the degree of melting, we will use the correlation of the K with tetrahedral Al in clinopyroxenes (Al^{IV}_{cpx}) and assess what is the change of Al^{IV}_{cpx} as a function of F .

A recent study by Hauri et al (2006) suggested that the partitioning of REE and H_2O varied significantly only near the exhaustion of clinopyroxene. This conclusion was based on results obtained from the thermodynamic model pMELTS (Ghiorso et al., 2002) using the menu-driven front-end Adibat_1ph (Smith and Asimow, 2005). The thermodynamic model of clinopyroxene in pMELTS is formulated using a regular solution model (Sack and Ghiorso, 1994a; Sack and Ghiorso, 1994b; Sack and Ghiorso, 1994c). However, as reported in Sack and Ghiorso (1994c), for high-Al clinopyroxenes, this regular solution model is not consistent with the experimental data probably due to the simplified molecular approximation for the configurational entropy of Ti^{4+} , Al^{3+} , and Fe^{3+} substituted in pyroxenes. Therefore, using this regular solution model to determine Al^{IV}_{cpx} , a non quadrilateral component in pyroxenes whose substitution is highly non-ideal, must be done with caution. To be able to use the results given by pMELTS (where p stands for peridotite composition), a comparison with known experimental partial melting studies is necessary first (e.g., Hirschmann et al., 1998; Hirschmann, 2000). Several isobaric partial melting experiments on peridotites report both the composition of each individual phase and the degree of melting (e.g., Baker and Stolper, 1994; Robinson et al., 1998; Pickering-Witter and Johnston, 2000; Schwab and Johnston, 2001) and show an approximate linear decrease in Al^{IV}_{cpx} for increasing values of F (Figure 5). Therefore, before applying the pMELTS algorithm to mantle melting we will compare it to these experimental results.

Several studies have successfully used the MELTS algorithm and its derivatives to constraint the degree of melting of a given mantle source, melt productivities, melt compositions, and even water partitioning during mantle melting (e.g., Hirschmann et al., 1998; Hirschmann et al., 1999; Asimow et al., 2001; Asimow et al., 2004; Hauri et al., 2006). However, very little attention has been paid to the mineral chemistry, in particular the non-quadrilateral components of pyroxenes. To test pMELTS capability of reproducing experimental results, I compared it to the isobaric partial melting studies of Robinson et al. (1998, composition MPY). Table 1 reports all the modeling parameters used in this study. The results show that, although pMELTS does an excellent job in predicting the modes and melt chemistry as a function of temperature and/or melt fraction in isobaric calculations, the Al^{IV} of clinopyroxene (Figs. 6) remains constant and does not match the experimental data. On the other hand if spinel is omitted from the calculation (Figs. 8), the Al^{IV} of clinopyroxene simulated with pMELTS shows a trend that is comparable to the one observed in isobaric experiments (Fig. 5). This probably indicates that either the calibration of pMELTS with respect to spinel/clinopyroxene equilibria is incomplete (*i.e.*, not enough experimental data), or that the regular solution model used for calculating non-quadrilateral pyroxenes is not appropriate. Given the difficulties in modeling spinel chemistry especially if Cr_2O_3 is added to the system (e.g., Asimow et al, 1995; Hirschmann et al., 1998), we will assume that pMELTS calculates clinopyroxene composition more accurately in the absence of spinel, even though we are aware that the calculation of non-quadrilateral components is simplistic (Sack and Ghiorso, 1994c).

The same calculations were also performed for isentropic melting in the presence (Fig. 7a) or absence (Fig. 7b) of spinel. In this set of calculations we observe similar results for the modes but different melt productivities and clinopyroxene chemistry. In particular, the Al^{IV} of clinopyroxene is buffered until spinel runs out (Fig. 7a) just as in the isobaric melting

models. In Figure 8, we compare the Al^{IV}_{cpx} as a function of F for isobaric experiments and isentropic calculations in the presence and absence of spinel. Using a polynomial approximation for the isentropic trend in the absence of spinel, and the change of REE clinopyroxene/melt K as a function of Al^{IV}_{cpx} (Fig. 3), we can calculate the change in clinopyroxene/melt and bulk-rock melt K for REE as a function of F (Fig. 13). This figure shows that the effect of Al^{IV}_{cpx} on the clinopyroxene/melt K is substantial (Fig. 13a) but not very strong for the bulk-rock/melt K (Fig. 13b, modal abundances given in Table 1). If we were to use the parameterizations between $K^{cpx/oliv}$ and $K^{cpx/opx}$ of Lee et al. (2007) and Witt-Eickschen and O'Neill (2005), to calculate the individual $K^{oliv/melt}$ and $K^{opx/melt}$ we would find a more significant effect on the bulk-rock/melt K and Al^{IV}_{cpx} . This calculation unfortunately would not depend directly on the individual orthopyroxene and olivine crystal chemistry controls and would inherit the Al^{IV} functional form of clinopyroxene, which is known not to be the only substitution mechanism operating in these minerals (e.g., Hauri et al., 2006).

The Al^{IV}_{cpx} effect has a non-negligible effect on the behavior of REE as shown in Figs. 13 to 15, where we used the results of Figures 3, 10, and 11 to solve equation (4) for Yb in clinopyroxene as a function of the degree of melting. The field of abyssal peridotites (from PETDB) is shown as reference, and the starting composition corresponds to the DMM composition of Workman and Hart (2005). At low degrees of melting both non-modal melting models agree well but for higher degrees of melting, the standard non-modal melting model slightly overestimates the degree of melting (Fig. 13). Inferences on the degree of melting and composition of the source based on high and constant mineral/melt K 's values will therefore result in a mantle source that has an overestimated total degree of melting or that is too depleted in REE abundance. In addition, comparing the different melting models to the composition of clinopyroxene in abyssal peridotites (Figs. 13 and 14),

shows that equation (4) develops the largest compositional range and depletes REE more significantly than other melting models due to the Al^{IV}_{cpx} effect on clinopyroxene.

4. Summary

The change in major element composition of rock-forming minerals during partial melting of the Earth's upper mantle, has a very strong effect on the amount of REE that minerals can accommodate in their structure. We have used available partitioning dataset and pMELTS to parameterize the change of the REE bulk-rock/melt partition coefficient, K , as a function of the degree of melting, F . The change of K with F is not linear and can be incorporated into a dynamic melting that was developed using two-phase flow theory. The preliminary findings reported in this chapter indicate that REE are very likely to become more incompatible as partial melting of the mantle takes place. A comparison between our model to the available data on abyssal peridotites, shows that the observed compositional span could be explained by smaller degrees of melting than previously thought. However, further calibrations and improvement of the pMELTS algorithm will be necessary in order to determine with more confidence what is the change of mineral chemistry during partial melting of peridotites.

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Figures captions

Figure 1. Covariation of Ca^{2+} and Al^{3+} on the basis of 6 oxygens in the residual clinopyroxenes from published partial melting and partitioning studies. The pink field denotes partial melting experiments *sensu stricto* (Baker and Stolper, 1994; Pickering and Johnston, 2000; Schwab and Johnston, 2001; Wasylenski et al., 2003). The orange/yellow field encloses partitioning studies performed by crystal growth experiments (Blundy et al., 1998; Hart and Dunn, 1993; McDade et al., 2003; Hauri et al., 1994; Gaetani, 2004; Johnson, 1998). Melting studies performed by crystal growth or sandwich technique experiments are outlined in the blue field (Falloon et al., 1997; Falloon et al., 1999; Falloon et al., 2001; Kinzler and Grove, 1992; Robinson et al., 1998). Other partitioning studies performed on the CMAS system or non-terrestrial compositions (Hill et al., 2000; Gaetani and Grove, 1995; McKay, 1986; Watson et al., 1987) are shown individually. The green field of abyssal peridotites is shown as reference (PETDB: Arai, 1998; Bonatti, 1986, Bonatti, 1992; Bonatti, 1993; Dick, 1989; Dick, 1996; Fujii, 1990; Hamlyn, 1980; Hellerbrad, 2002; Hodges, 1976; Johnson, 1990; Johnson, 1992; Komor, 1990; Melson, 1972; Michael, 1985; O'Hara, 2002; Piccardo, 1988; Prinz, 1976; Roden, 1984; Seyler, 2003; Shibata, 1986; Tartarotti, 2002).

Figure 2. Covariation of tetrahedrally (Al^{IV}) and octahedrally (Al^{VI}) coordinated Al^{3+} in the residual clinopyroxenes referred in Fig. 1, showing how Al^{3+} is partitioned between the tetrahedral and octahedral sites.

Figure 3. Variation of the clinopyroxene/melt partition coefficients for rare-earth elements as a function of the Al^{IV} content in the residual clinopyroxene. Regression

parameters are given in Table 1. Range of Al^{IV} in abyssal peridotites is shown as hatched area.

Figure 4. Covariation of Ca^{2+} and Al^{3+} , and of Al^{IV} and Al^{VI} in residual clinopyroxenes from partial melting experiments described in Chapters 1 and 2.

Figure 5. Variation of Al^{IV} in the residual clinopyroxenes as a function of the degree of melting in published isobaric partial melting experiments.

Figure 6. Isobaric melting calculations using pMELTS for the starting composition MPY in the absence of spinel. Calculated mineral modes and glass chemistry match relatively well the experimental data of Robinson et al., (1998). However, the change in $\text{Al}^{\text{IV}}_{\text{cpx}}$ as a function of the degree of melting can is not well matched.

Figure 7. Isobaric melting calculations using pMELTS for the starting composition MPY in the absence of spinel. Calculated mineral modes and glass chemistry match relatively well the experimental data of Robinson et al., (1998). Note however that the excess Al_2O_3 is then taken care by feldspar and corundum, two unlikely phases present in the mantle at the prescribed P - T conditions. However, the change in $\text{Al}^{\text{IV}}_{\text{cpx}}$ as a function of the degree of melting matches very well the experimental data, suggesting that pMELTS spinel-clinopyroxene equilibria buffers the $\text{Al}^{\text{IV}}_{\text{cpx}}$ incorrectly.

Figure 8. Isentropic melting calculations using pMELTS for the starting composition DMM of Workman and Hart (2005) in the presence of spinel. Note how the presence of spinel buffers the Al^{IV} content of the residual clinopyroxene.

Figure 9. Isentropic melting calculations using pMELTS for the starting composition DMM of Workman and Hart (2005) in the absence of spinel. In this calculation Al^{IV} decreases significantly with increasing degree of melting.

Figure 10. A comparison of the change in Al^{IV}_{cpx} as a function of the degree of melting for three different models. The isobaric trend should be considered as a minimum variation in Al^{IV}_{cpx} considering that the melt is in continuous contact with the mineral. In the isentropic case, the melt escapes from the system and therefore Al^{IV}_{cpx} should decrease more dramatically as F increases. The results obtained by pMELTS when spinel is suppressed from the calculation show a small decrease. However, a more rigorous treatment of the spinel/clinopyroxene equilibria needs to be done to better constraint the change of Al^{IV}_{cpx} during partial melting of peridotites.

Figure 11. Clinopyroxene/melt and bulk-rock/melt partition coefficients of selected REE as a function of the degree of melting. Both calculations take into account the change in modal proportions.

Figure 12. Residual clinopyroxene Yb concentration difference between equation (4) and the dynamic melting model of Shaw (2000) as a function of the degree of melting. The difference is given in percentage relative to Shaw's values. Both models were calculated using the melting coefficients of Baker and Stolper (1994), with constant individual mineral/melt partition coefficients. Variations in the bulk partition coefficient are therefore solely due to changes in mode proportions during melting. The numbers next to the curve show the residual porosity used for each comparison. The difference between the two models is not too significant (<2%) for small residual porosities and for a degree of melting below 10%.

Figure 13. Yb content in residual clinopyroxene during partial melting for different mantle melting models, compared to the clinopyroxene composition of abyssal peridotites (PETDB). The DMM mantle of Workman and Hart (2005) was used

as starting point here. The left panel shows the case for 0% residual porosity. As expected, the fractional (green-dashed line), dynamic (green solid line), and equation 4 with constant mineral/melt partition coefficients (black dashed line) overlap. In contrast when we take into account the change in cpx/melt partition coefficient (red solid line), we see a stronger depletion in Yb in the residual cpx as melting proceeds. The right panel shows the case for 5% residual porosity and as mentioned in section 2 and shown in Fig. 13, the dynamic melting model (green solid line) and equation 4 with constant mineral/melt partition coefficients (black dashed line) do not overlap for large degrees of melting. Fractional melting (green dashed line) depletes the cpx more than the standard melting model. However, when taking into account the change in cpx/melt partition coefficient as a function of the degree of melting (red solid line), we see a depletion in Yb that is even stronger than in the fractional melting case.

Figure 14. Covariation of Ce and Yb (left panel) in residual clinopyroxene during partial melting for different mantle melting models, compared to the clinopyroxene composition of abyssal peridotites (PETDB). The DMM mantle of Workman and Hart (2005) was used as starting point here. The calculation was run up to cpx exhaustion around 21% melting with a residual porosity of 0%. The right panel only shows the results of equation (4) for every ~2% melting. Note how equation (4) show the largest compositional range and the most depleted trend. However, the abyssal peridotite trend cannot be reproduced by any of the models.

Figure 15. Equivalent to Fig. 14, except that the calculation here was done for a residual porosity of 5%. Note how LREE are less fractionated and less depleted than the

case shown in Fig. 14, and how the abyssal peridotite trend can be best reproduced by equation (4).

Figure 1.

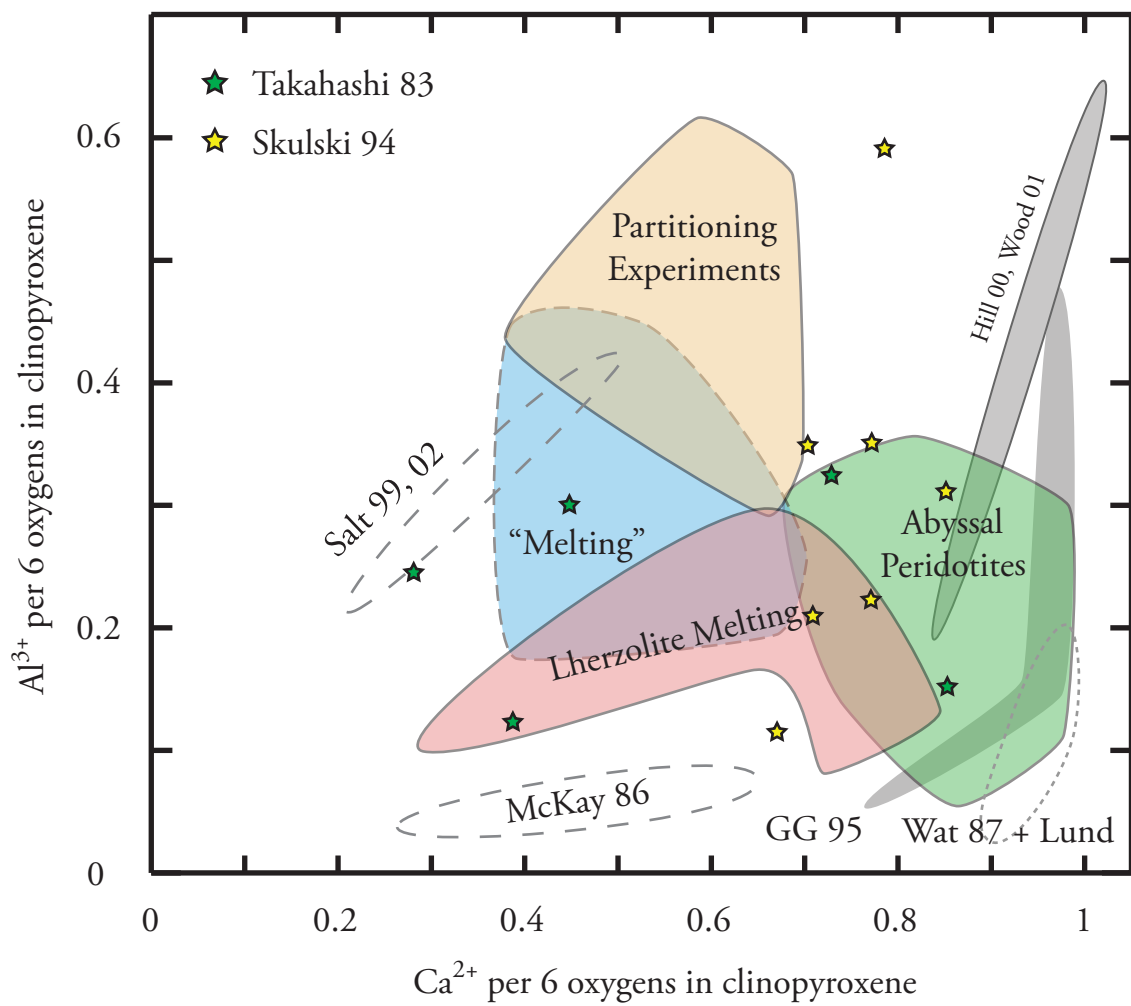


Figure 2.

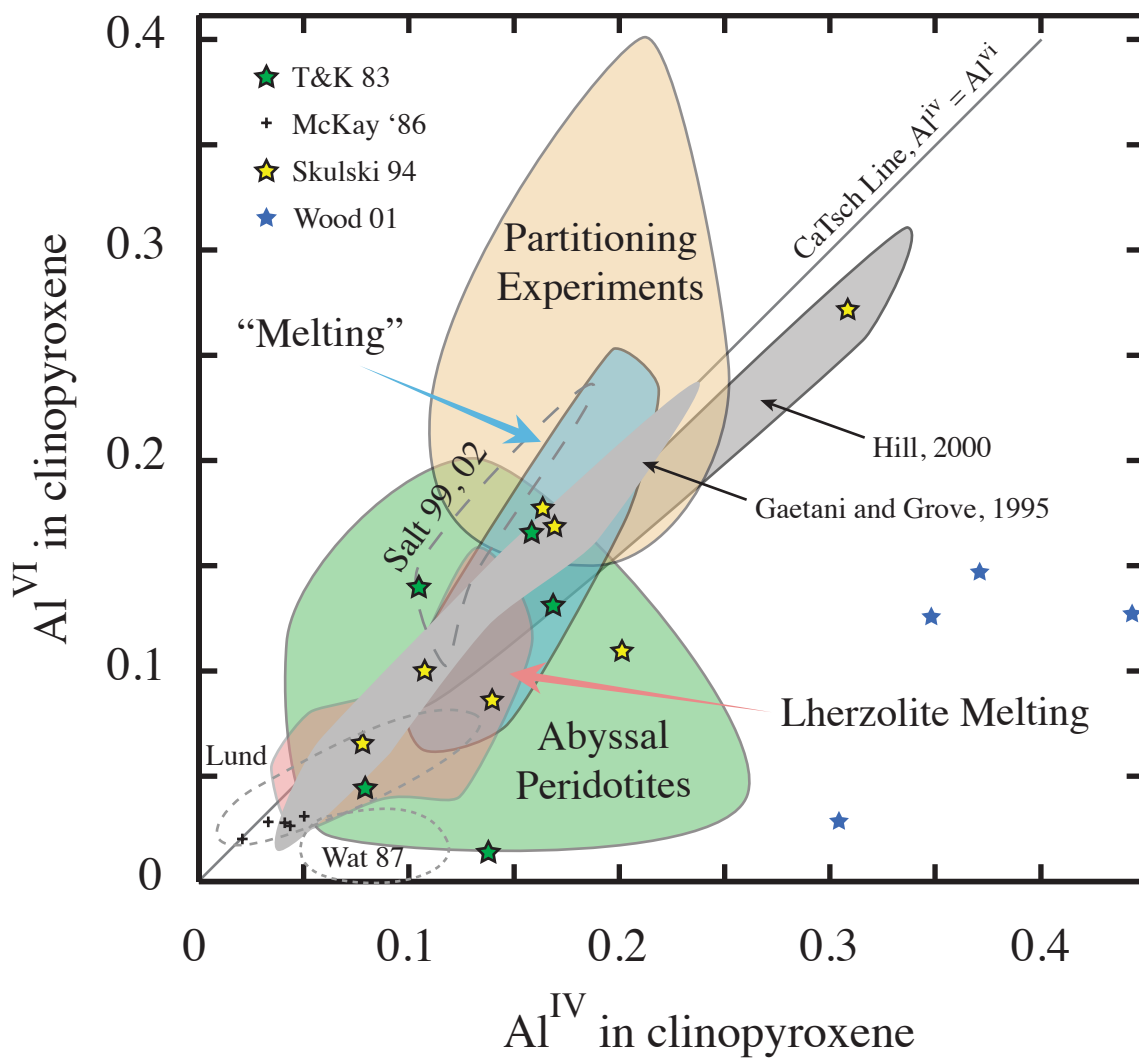


Figure 3.

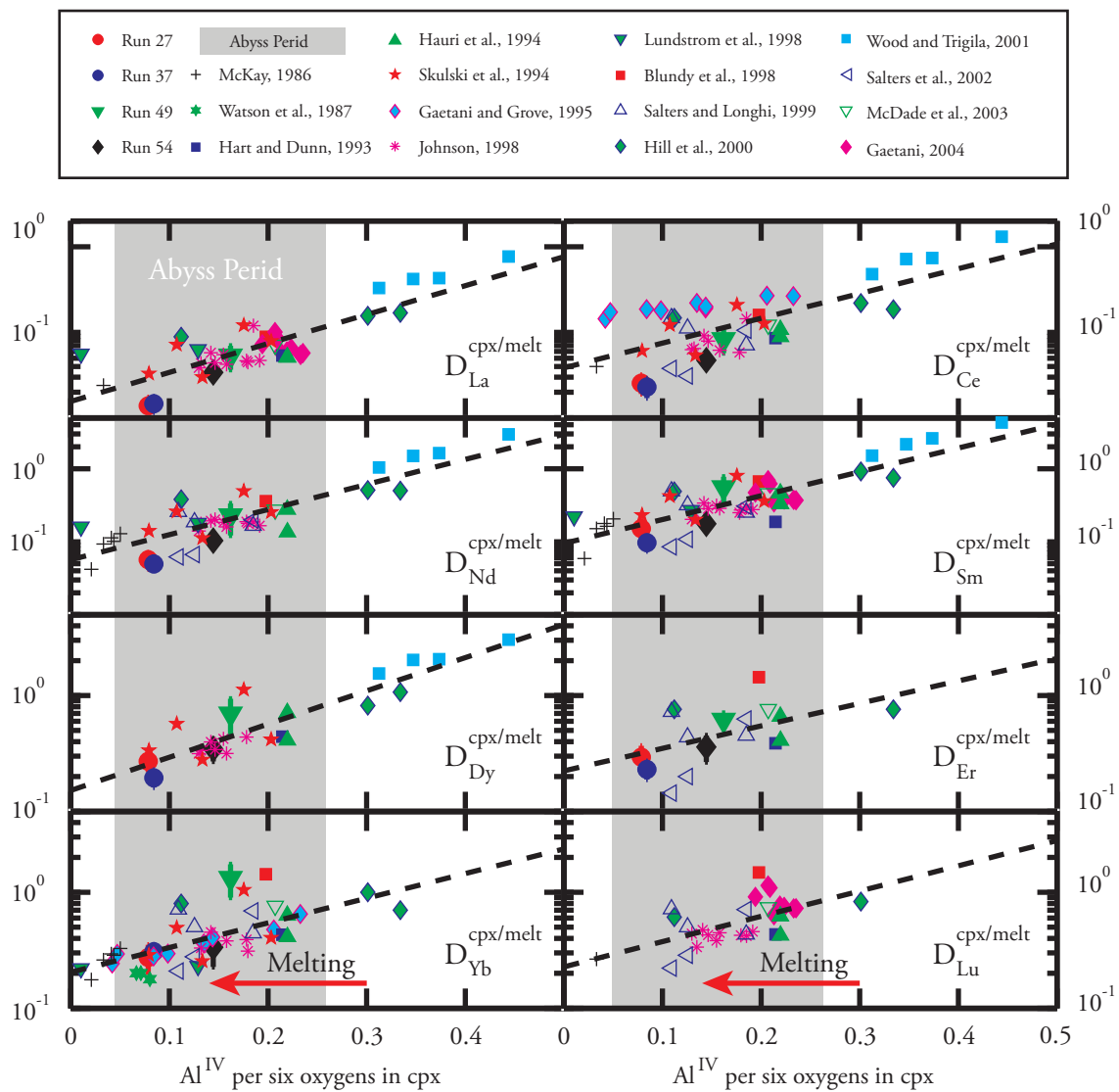


Figure 4.

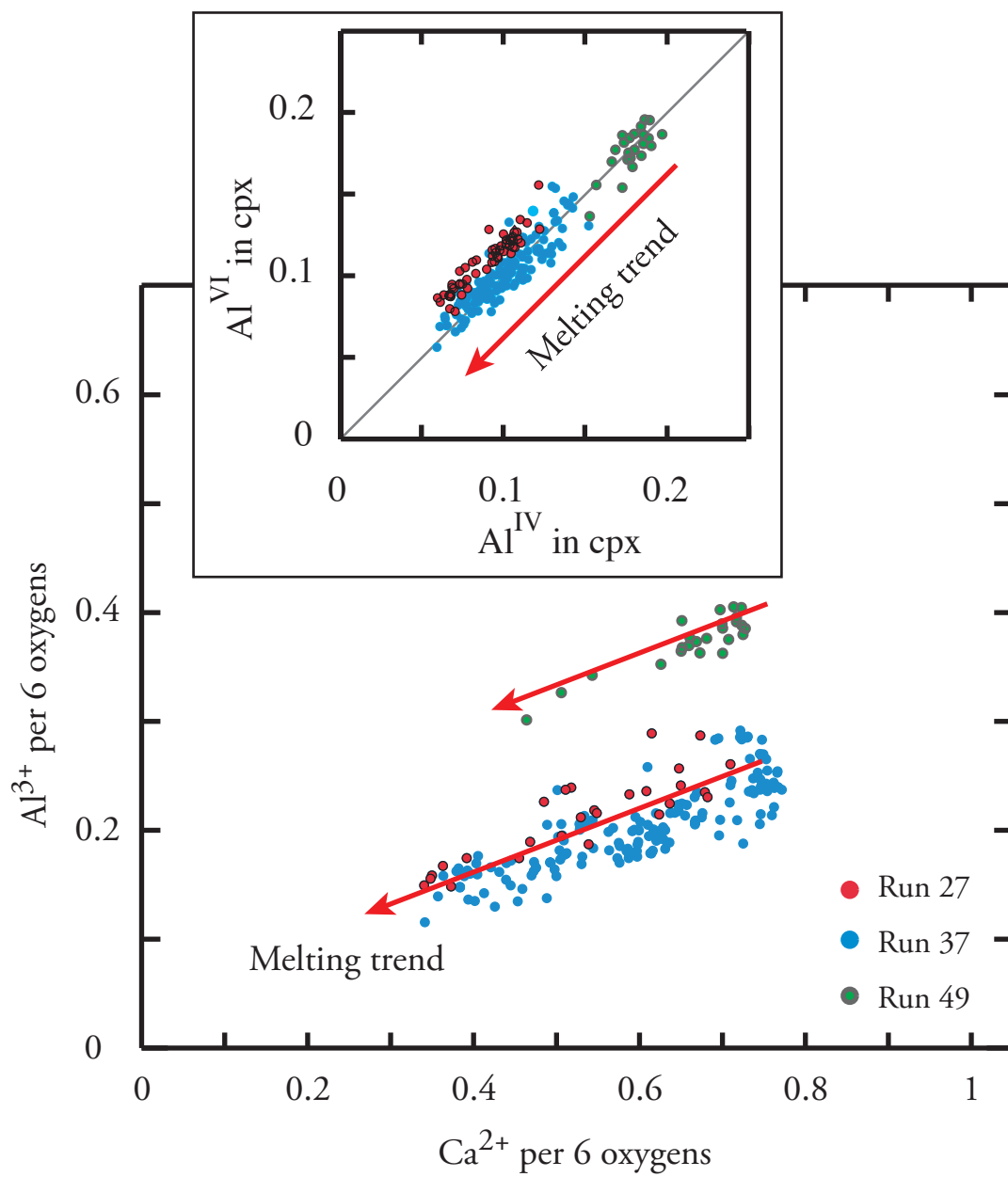


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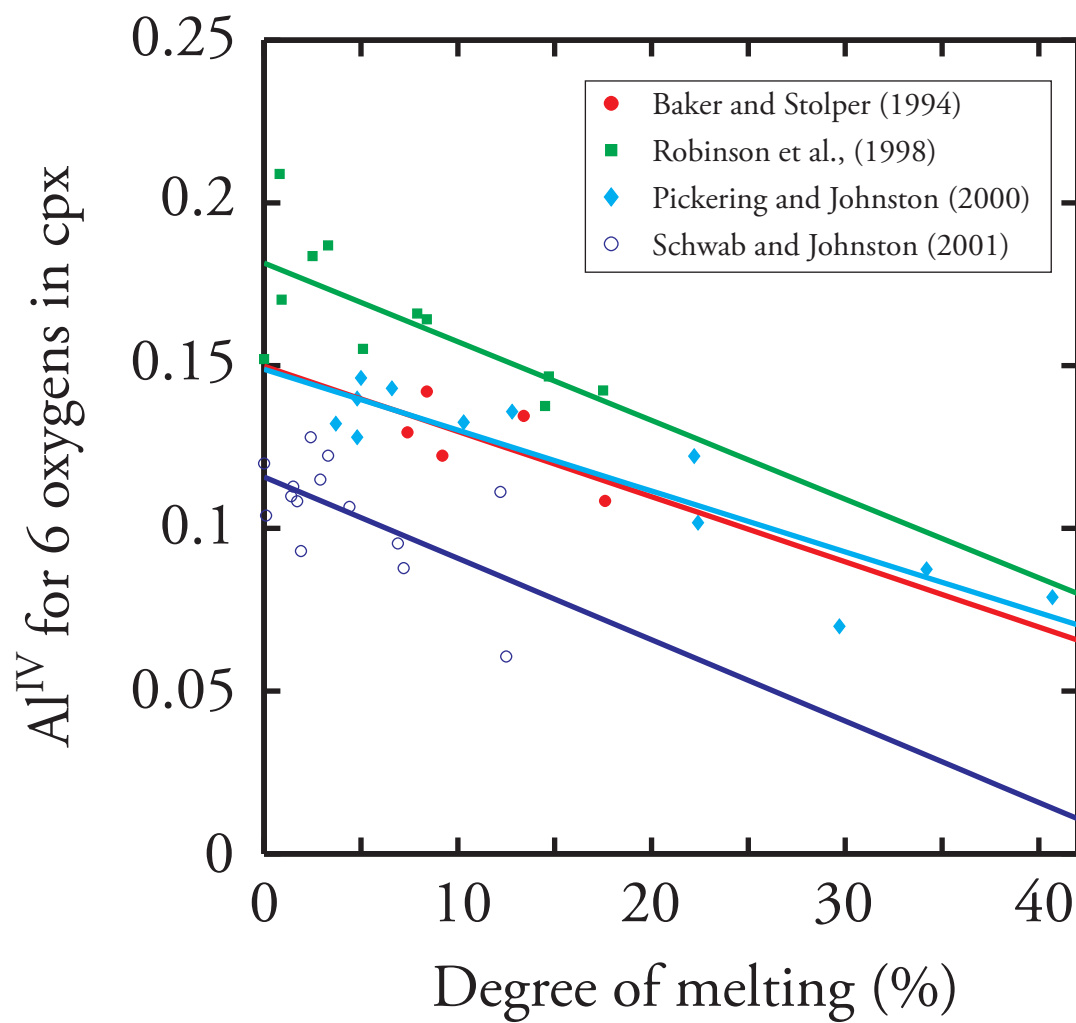


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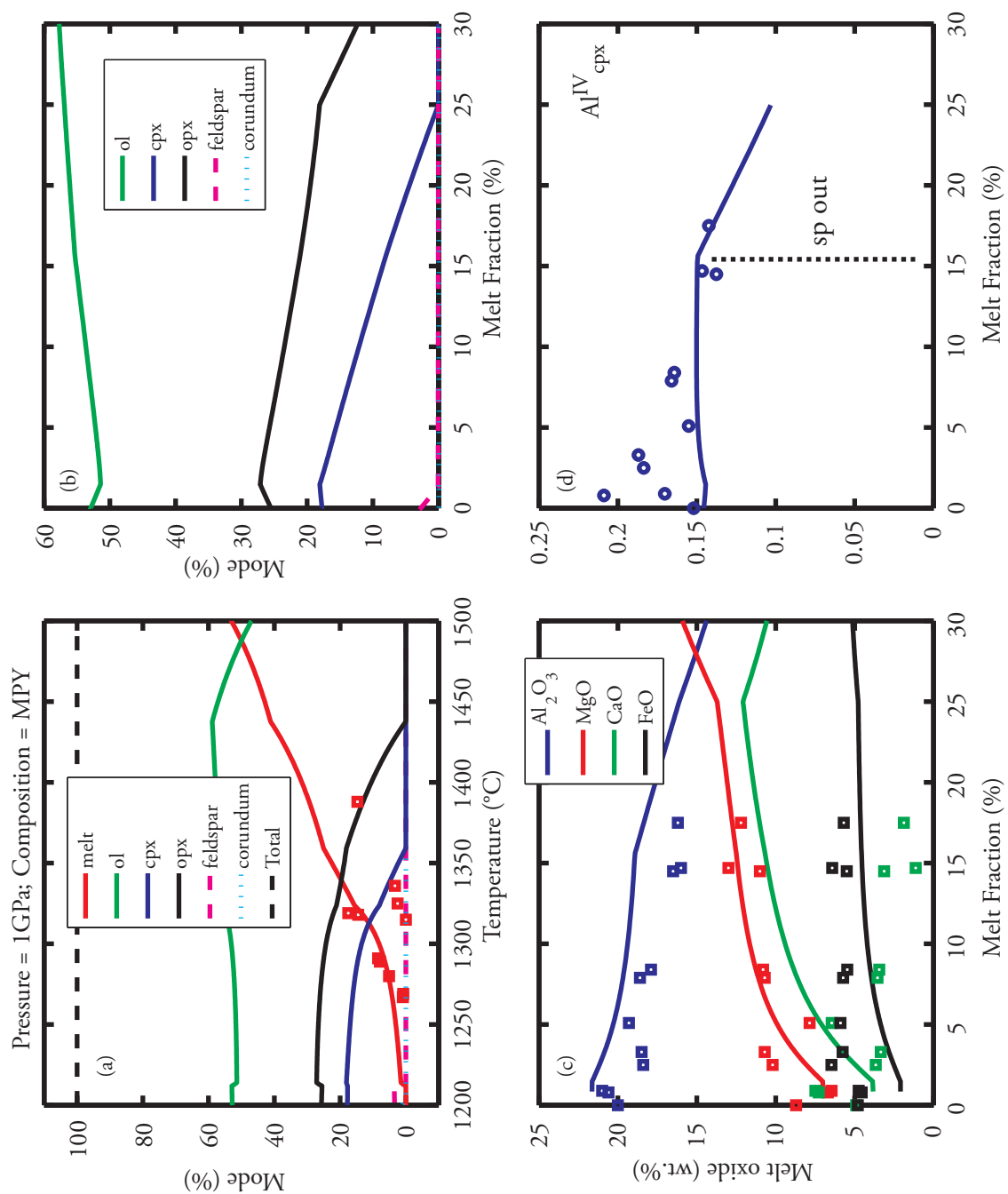


Figure 7.

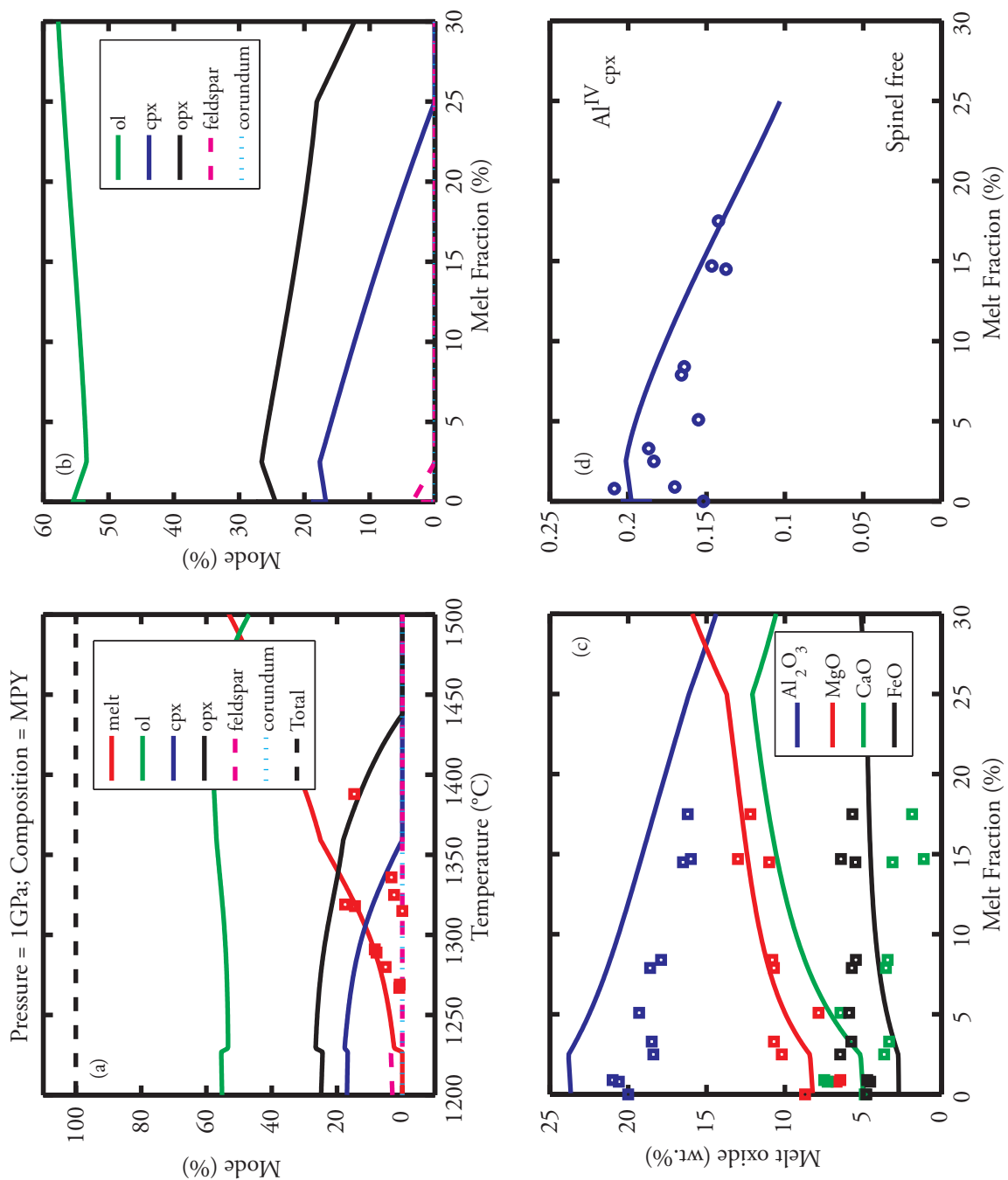


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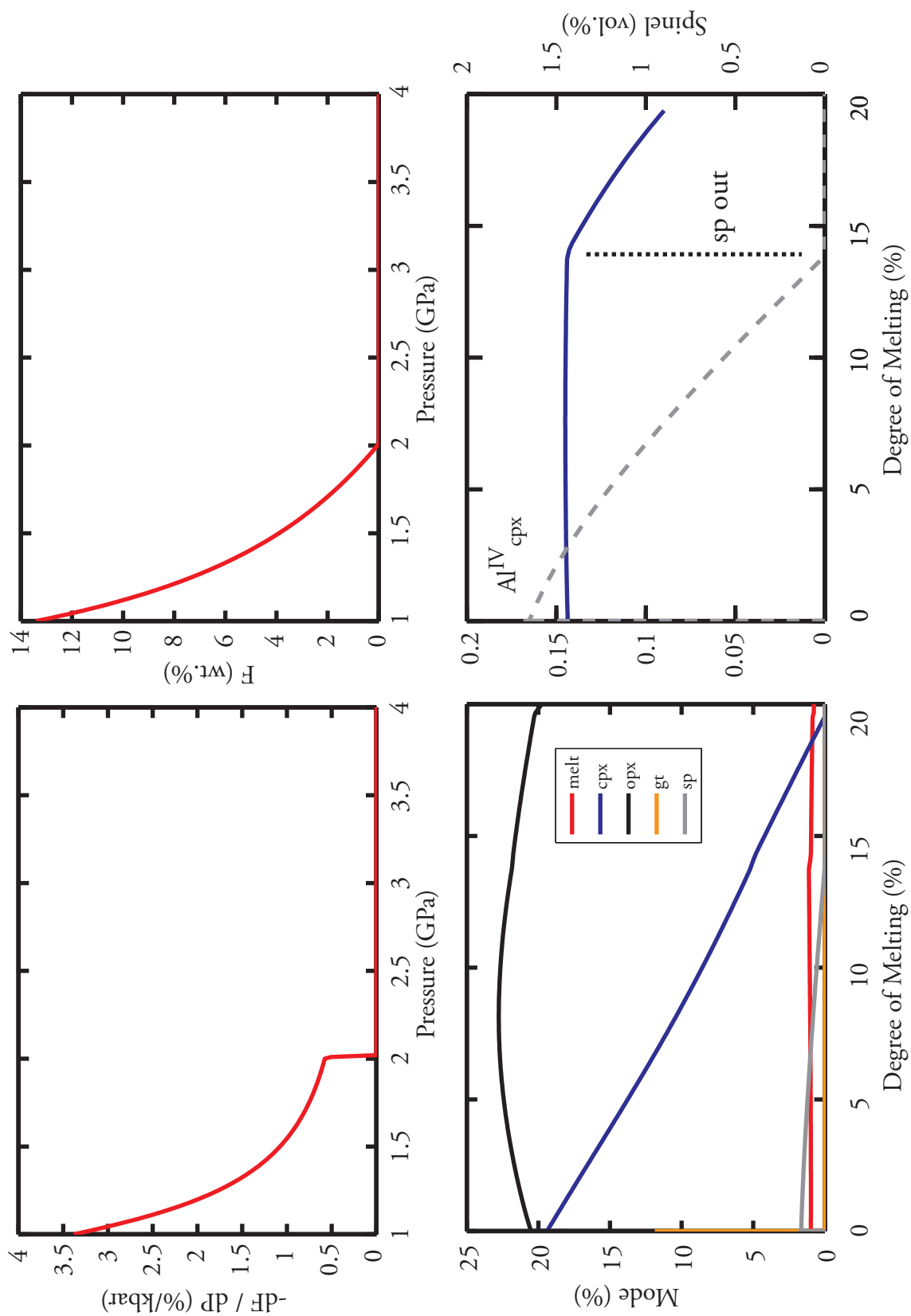


Figure 9.

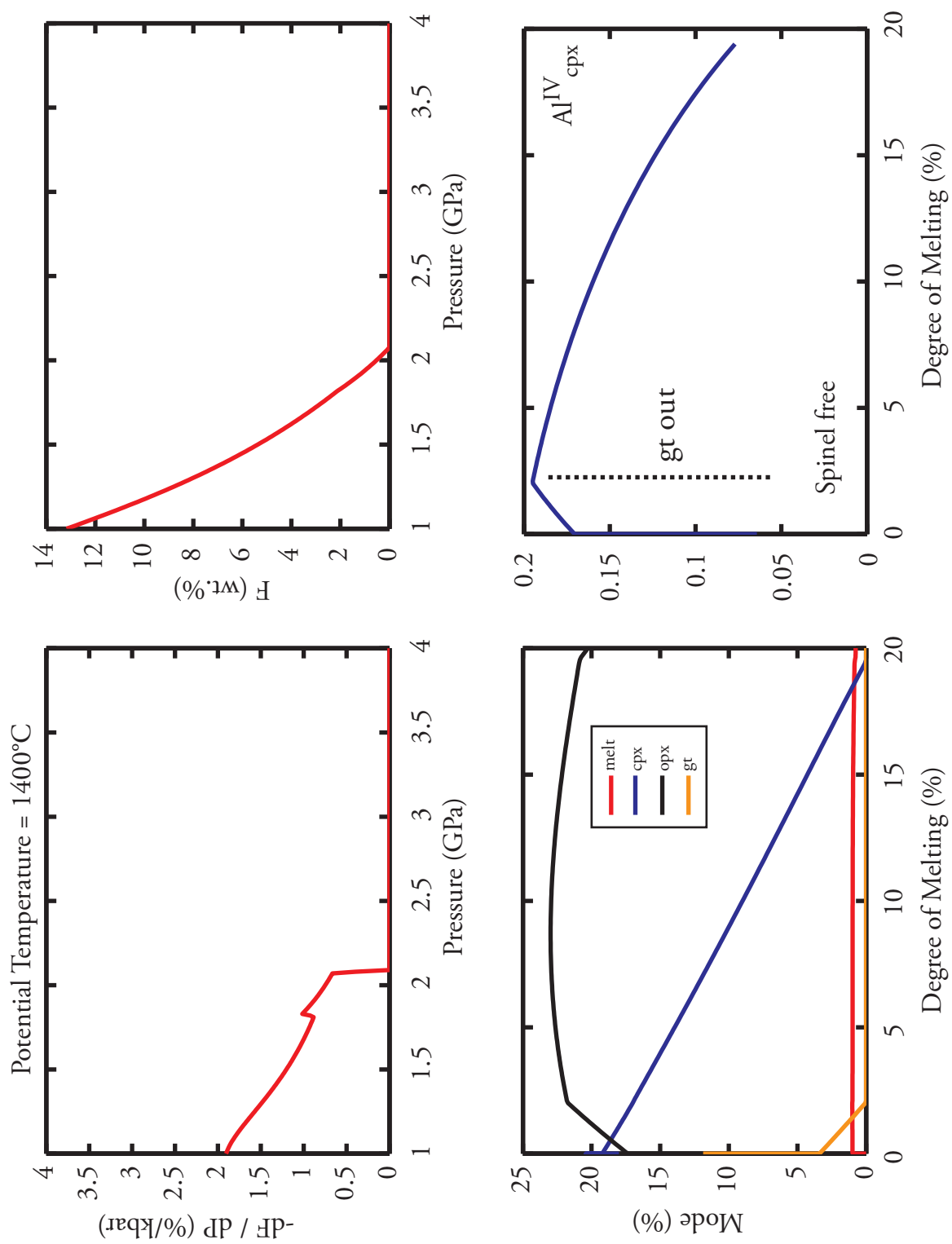


Figure 10.

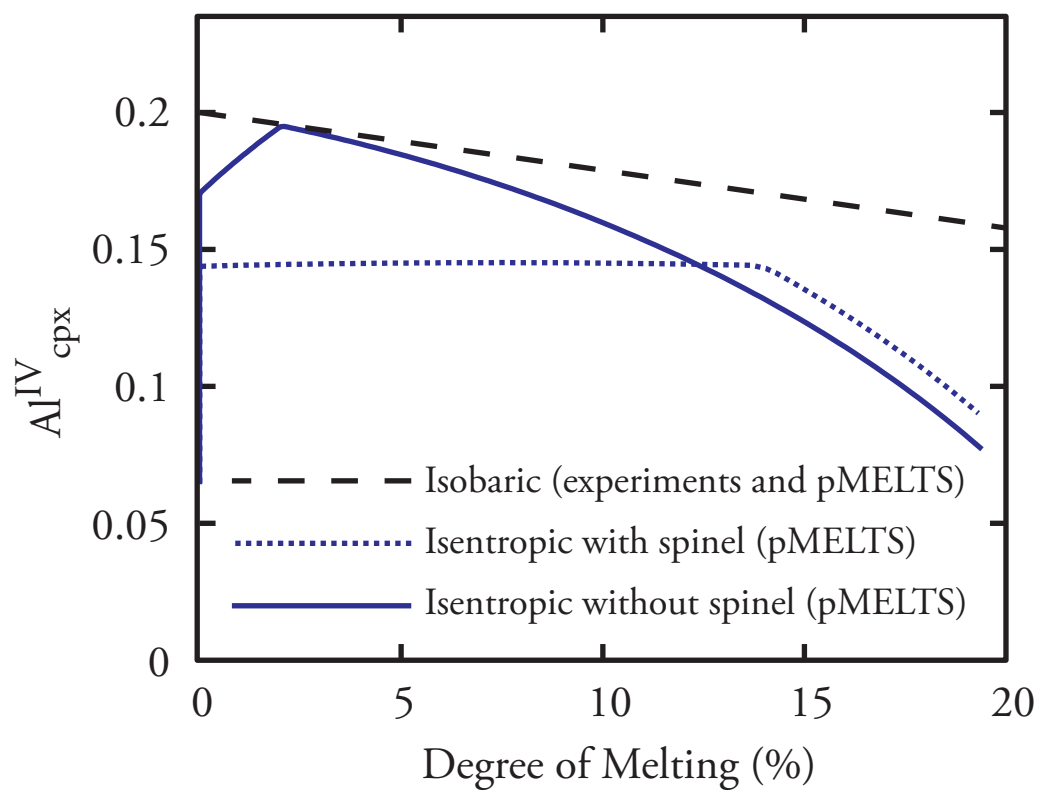


Figure 11.

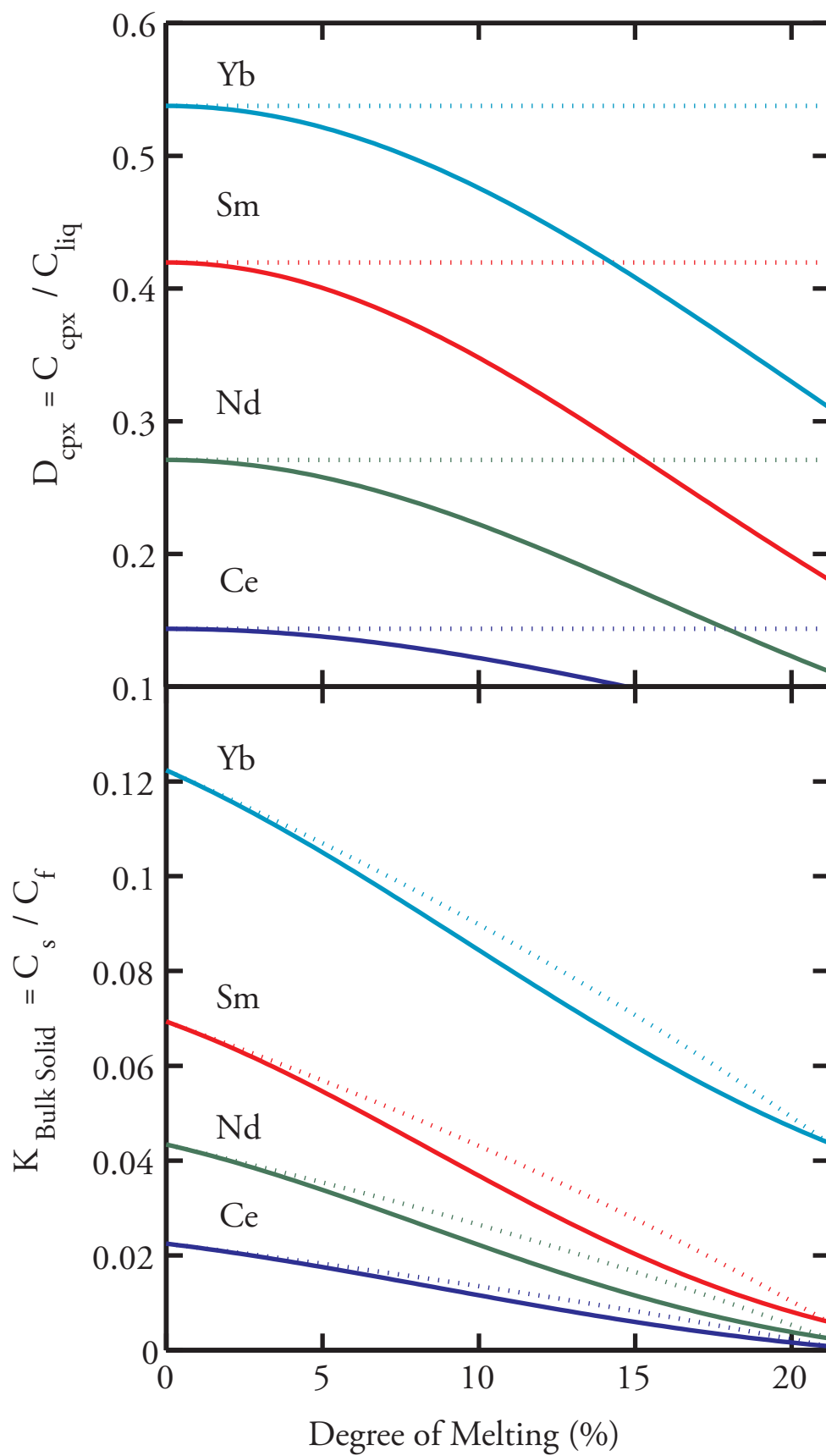


Figure 12.

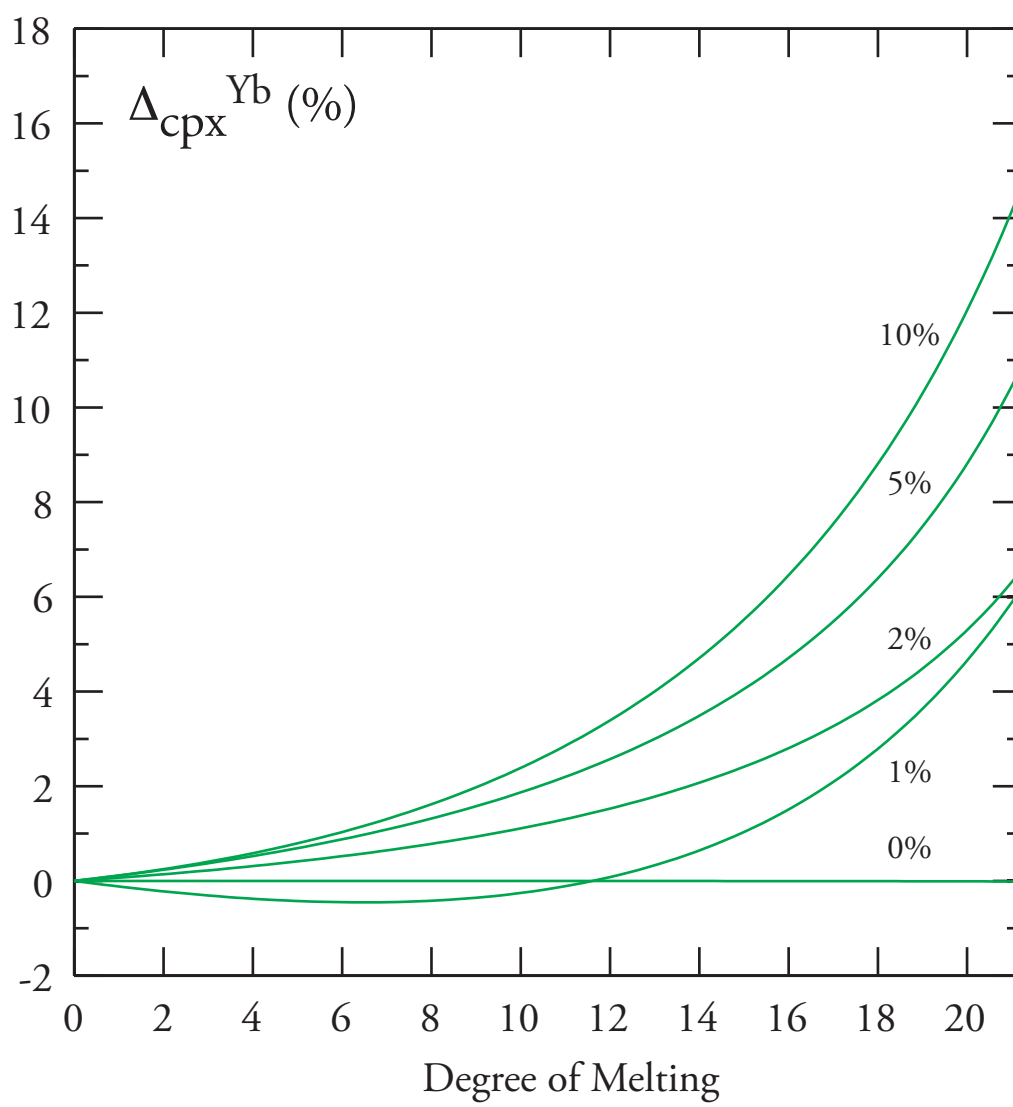


Figure 13.

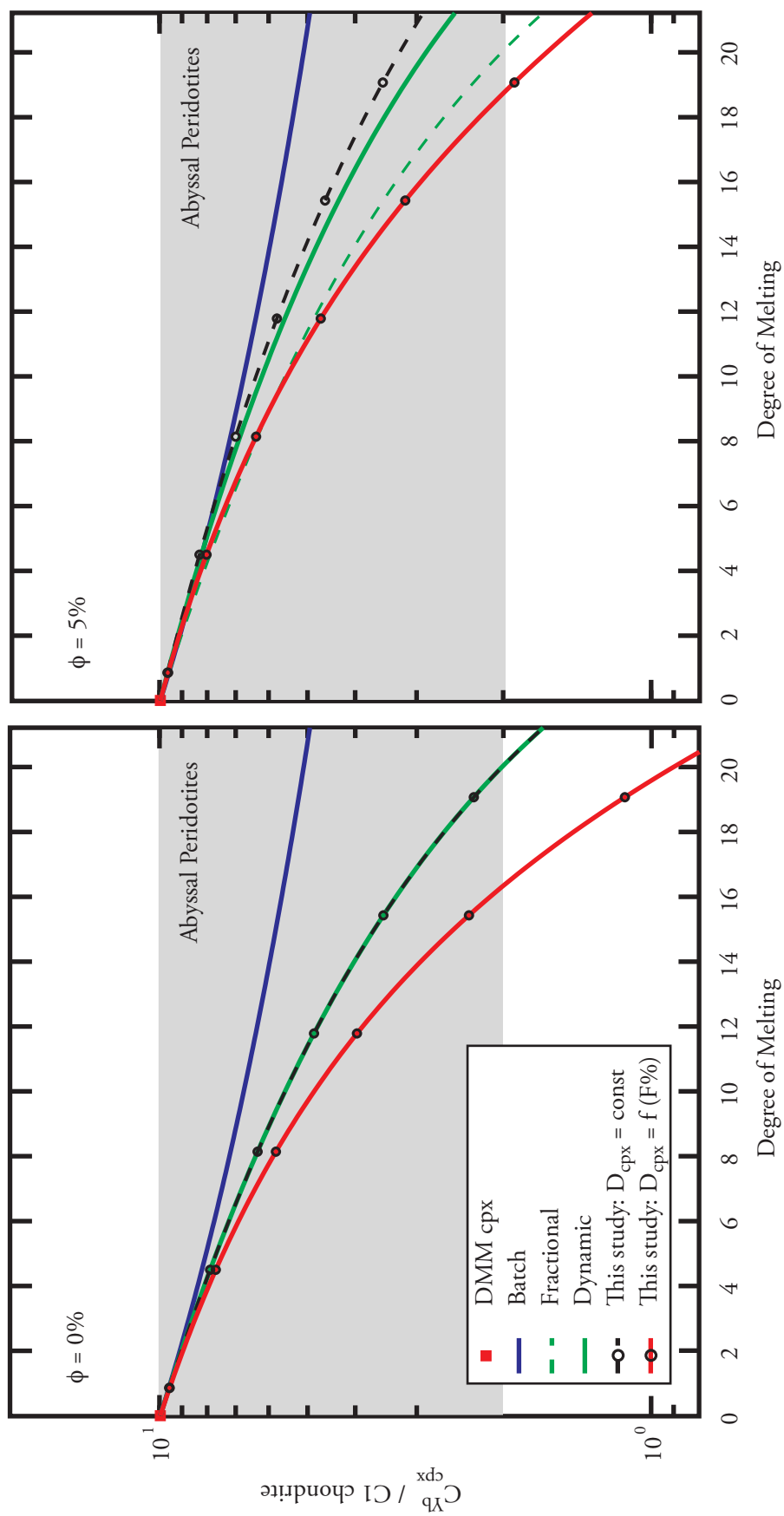


Figure 14.

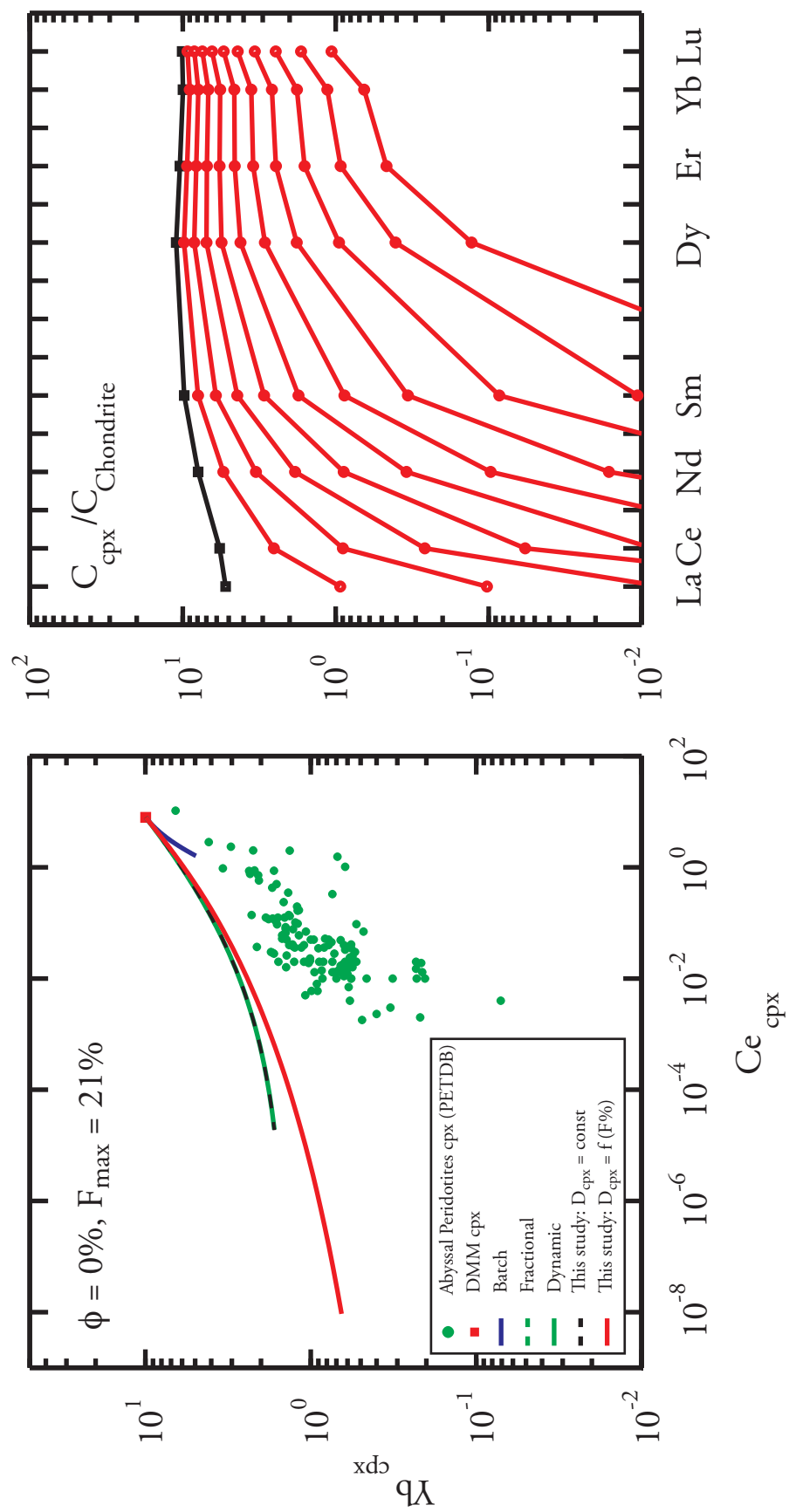


Figure 15.

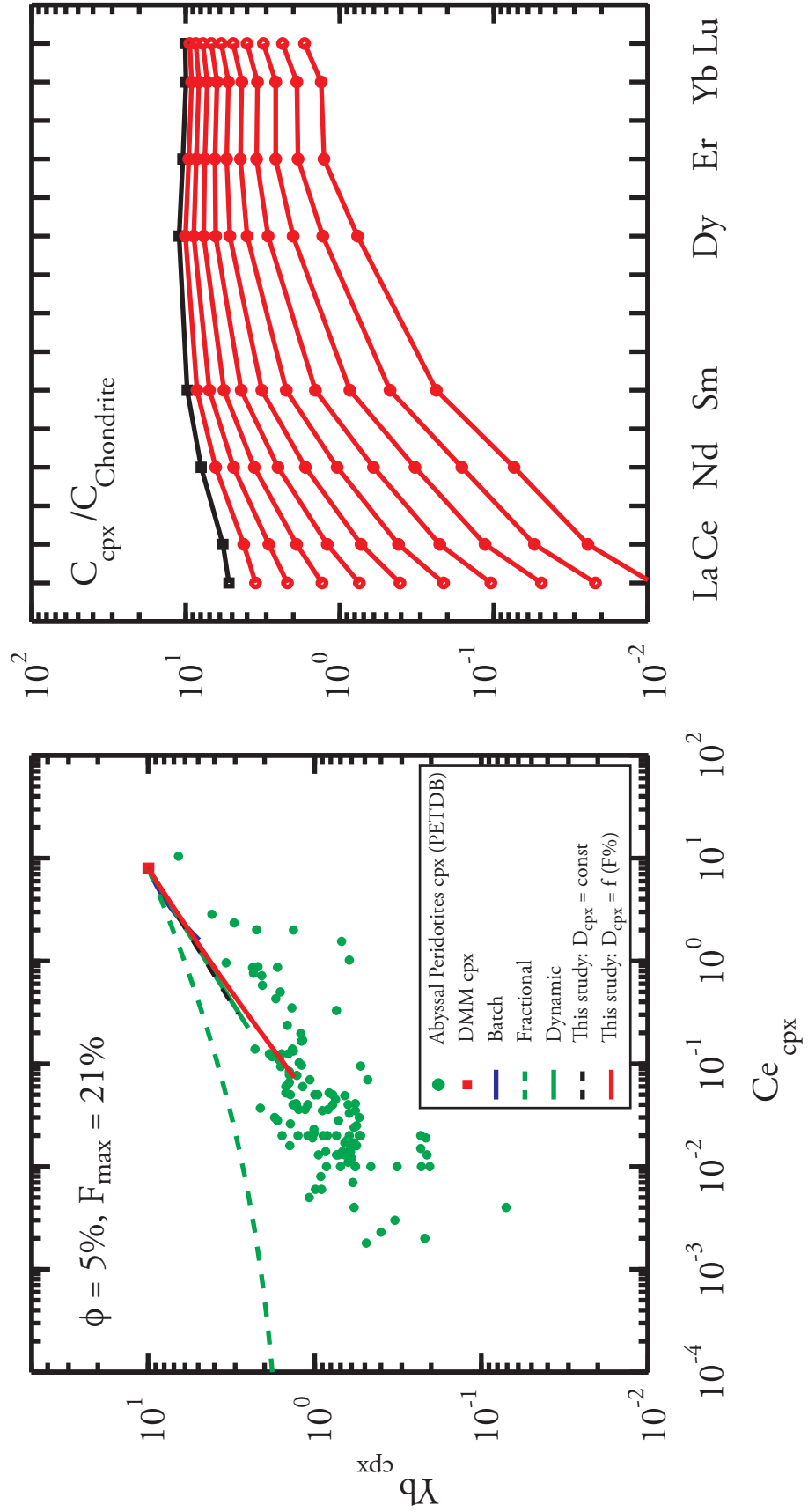


Table 1: Parameters used to solve equation 4

	K_d°	m	R^2
$K_d = K_d^\circ * \log_{10}(m * Al_{cpx}^{IV})$			
La	0.018711	3.0902	0.82
Ce	0.046897	2.6007	0.68
Nd	0.063224	3.2802	0.85
Sm	0.099807	3.1792	0.83
Dy	0.154250	2.8246	0.89
Er	0.237500	1.5703	0.38
Yb	0.204630	2.0656	0.69
Lu	0.227430	2.1781	0.60
<i>pMELTS quadratic parameters for</i>			
$Al_{cpx}^{IV} = p_1 * F^2 + p_2 * F + p_3$; where F is in wt. %			
p_1	-2.4958		
p_2	-0.1256		
p_3	0.2		
<i>Initial mineral mass fractions in the solid</i>			
olivine	0.50		
clinopyroxene	0.15		
orthopyroxene	0.30		
spinel	0.05		
<i>Melting coefficients by Baker and Stolper (1994)</i>			
olivine	-0.22		
clinopyroxene	0.71		
orthopyroxene	0.38		
spinel	0.13		
<i>Porosity</i>	0% and 5%		

APPENDIX A

Electron Microprobe Data for Chapters 1 and 2

Table A1-1: Glass composition of Run 27, conducted at 1340°C and 1.5 GPa for 79.15 hours

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-293	51.01	0.89	15.48	6.61	0.16	9.78	11.16	4.86	0.25	0.21	100.42	72.51
-278	51.10	1.01	16.00	6.17	0.19	8.07	11.25	4.99	0.28	0.25	99.29	69.99
-268	51.77	1.00	15.97	6.37	0.11	7.21	11.71	5.25	0.24	0.29	99.92	66.87
-264	50.63	0.96	15.40	6.56	0.16	8.95	11.63	4.73	0.23	0.21	99.46	70.87
-252	51.63	0.96	16.15	6.09	0.22	7.84	11.66	5.14	0.22	0.27	100.18	69.65
-227	50.07	0.87	14.68	6.54	0.12	10.92	10.99	4.72	0.22	0.24	99.37	74.85
-213	51.86	1.05	16.63	5.87	0.14	6.51	11.85	5.40	0.29	0.29	99.91	66.41
-209	51.70	1.02	16.30	6.31	0.11	7.06	12.18	5.00	0.24	0.26	100.18	66.61
-208	51.23	1.06	15.71	6.42	0.19	7.23	12.12	4.95	0.25	0.26	99.42	66.75
-204	51.03	1.03	15.76	6.29	0.18	7.23	12.23	4.88	0.25	0.16	99.03	67.21
-200	51.77	0.89	16.71	6.14	0.16	7.74	11.38	5.48	0.27	0.26	100.80	69.21
-198	52.34	0.96	17.43	5.08	0.19	6.65	11.35	5.57	0.30	0.34	100.22	70.00
-196	53.21	0.97	17.90	5.02	0.23	5.98	11.26	5.77	0.30	0.32	100.94	67.99
-195	51.94	0.98	16.92	4.92	0.15	7.92	11.44	5.47	0.27	0.30	100.32	74.16
-194	51.38	0.97	16.50	5.86	0.25	7.55	11.37	5.43	0.27	0.32	99.87	69.67
-184	51.59	1.05	16.27	5.98	0.22	6.81	12.20	5.07	0.27	0.27	99.73	67.00
-184	52.39	0.97	16.30	6.57	0.24	7.17	11.63	5.10	0.27	0.33	100.96	66.05
-183	51.92	1.01	16.37	6.31	0.20	6.92	11.91	5.14	0.28	0.28	100.34	66.16
-180	50.62	0.89	15.11	6.40	0.17	10.64	11.13	4.76	0.22	0.29	100.23	74.77
-175	51.25	0.96	15.88	6.57	0.18	8.12	11.69	5.07	0.27	0.27	100.28	68.78
-170	51.38	0.98	16.59	6.18	0.14	6.44	12.08	5.32	0.28	0.28	99.67	65.01
-169	51.49	0.96	16.27	6.48	0.26	8.06	11.66	5.00	0.24	0.29	100.71	68.92
-169	52.70	0.95	17.13	4.96	0.09	6.75	11.84	5.58	0.25	0.33	100.58	70.81
-168	52.22	1.00	17.10	5.32	0.19	6.83	11.96	5.45	0.26	0.27	100.60	69.59
-167	51.28	0.88	17.65	5.24	0.16	6.02	10.78	5.96	0.33	0.40	98.71	67.19
-166	51.68	1.03	16.21	5.89	0.16	7.59	11.62	5.27	0.26	0.28	99.99	69.67
-165	51.75	0.93	17.10	5.56	0.16	7.37	11.73	5.50	0.30	0.30	100.71	70.27
-161	51.38	1.03	16.38	6.11	0.20	7.86	11.52	5.27	0.26	0.28	100.27	69.64
-160	51.18	0.96	15.60	6.23	0.17	9.30	10.90	4.88	0.27	0.27	99.76	72.69
-160	51.31	0.97	15.87	6.22	0.24	8.96	11.03	5.09	0.25	0.24	100.19	71.98
-160	52.24	0.94	17.52	5.07	0.10	6.77	11.13	5.61	0.30	0.29	99.97	70.42
-160	52.22	1.00	17.63	5.37	0.12	6.23	11.80	5.59	0.28	0.33	100.57	67.41
-160	51.44	1.04	16.38	6.46	0.18	7.24	11.99	5.34	0.26	0.28	100.60	66.65

Table A1-1 continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-159	51.77	0.99	17.09	5.35	0.07	8.19	11.40	5.41	0.25	0.27	100.79	73.19
-158	51.49	0.97	16.34	6.09	0.15	7.93	11.43	5.32	0.27	0.26	100.25	69.89
-156	52.40	0.98	17.48	5.56	0.17	6.20	11.47	5.54	0.27	0.33	100.40	66.53
-154	51.68	0.94	15.72	6.18	0.20	9.46	9.69	5.17	0.28	0.20	99.52	73.18
-154	51.55	1.01	16.14	5.81	0.18	8.53	10.89	5.17	0.27	0.24	99.79	72.36
-154	51.23	0.94	16.00	6.35	0.17	9.47	11.25	5.06	0.27	0.20	100.94	72.67
-153	51.59	1.00	16.75	6.14	0.24	7.70	11.54	5.29	0.25	0.28	100.77	69.10
-149	51.40	0.98	15.33	6.36	0.20	7.68	12.37	5.11	0.26	0.26	99.94	68.28
-148	51.78	0.96	16.78	6.11	0.17	7.66	11.42	5.36	0.28	0.25	100.76	69.09
-148	51.72	0.99	16.03	6.36	0.15	7.19	12.01	5.14	0.24	0.27	100.11	66.84
-146	51.90	0.96	17.09	5.58	0.17	7.38	11.29	5.35	0.29	0.27	100.28	70.22
-141	51.96	0.99	17.23	6.09	0.17	6.00	9.84	6.09	0.35	0.27	99.00	63.72
-140	52.06	0.98	16.67	5.80	0.13	7.21	11.55	5.28	0.28	0.29	100.25	68.91
-138	50.36	0.87	14.78	6.54	0.06	11.81	10.07	4.65	0.24	0.25	99.63	76.30
-138	51.75	1.02	17.12	5.75	0.13	6.42	11.58	5.39	0.30	0.32	99.77	66.56
-138	51.35	0.94	16.20	6.43	0.22	8.44	11.61	5.16	0.21	0.28	100.82	70.06
-136	51.69	0.94	16.75	5.89	0.13	7.09	11.54	5.51	0.27	0.27	100.07	68.21
-132	52.10	0.96	16.87	6.20	0.20	7.29	10.82	5.70	0.31	0.27	100.73	67.70
-130	52.35	0.95	17.27	5.55	0.20	7.50	11.02	5.42	0.29	0.27	100.80	70.67
-129	51.57	0.94	16.31	6.59	0.16	8.10	11.01	5.28	0.25	0.27	100.49	68.67
-127	51.69	0.92	16.65	5.84	0.08	8.16	10.96	5.59	0.26	0.29	100.43	71.36
-123	50.97	0.92	15.82	5.98	0.10	10.05	10.72	5.12	0.29	0.27	100.23	74.98
-120	51.78	1.00	16.70	6.01	0.17	6.98	11.36	5.68	0.30	0.25	100.24	67.43
-104	50.70	0.89	15.00	6.41	0.14	11.33	10.10	5.10	0.26	0.25	100.18	75.91
-104	51.09	0.85	15.35	6.03	0.17	10.82	10.21	5.19	0.27	0.23	100.21	76.19
-99	51.81	1.00	17.41	6.34	0.15	6.32	10.84	5.63	0.32	0.32	100.14	63.99
-93	51.21	0.95	15.49	6.55	0.15	10.05	9.38	5.53	0.28	0.28	99.87	73.23
-86	51.96	0.96	18.10	5.85	0.18	5.66	9.35	5.23	0.43	0.23	97.95	63.30
-81	51.63	1.02	16.62	6.00	0.11	6.55	11.63	5.50	0.28	0.27	99.60	66.06
-79	51.57	0.98	16.42	6.59	0.13	7.73	10.71	5.61	0.28	0.26	100.30	67.65
-79	51.58	1.05	16.42	6.60	0.13	7.31	11.48	5.39	0.27	0.32	100.55	66.38

Table A1-2: Clinopyroxene composition of Run 27, conducted at 1340°C and 1.5 GPa for 79.15 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
-200	55.01	0.12	0.67	4.05	4.34	0.21	25.10	9.98	1.22	100.71	91.16
-194	54.78	0.11	0.67	3.88	4.26	0.13	24.72	10.63	0.89	100.08	91.19
-191	54.66	0.11	0.69	3.91	4.47	0.15	24.75	10.47	1.14	100.34	90.80
-190	55.04	0.10	0.68	3.94	4.48	0.16	25.65	9.42	0.77	100.24	91.08
-181	55.18	0.11	0.69	3.55	4.65	0.15	26.12	9.01	1.07	100.52	90.92
-180	55.03	0.11	0.70	3.51	4.56	0.17	25.91	8.81	0.89	99.69	91.02
-180	55.07	0.10	0.70	3.73	4.59	0.19	25.93	9.08	0.82	100.20	90.97
-177	55.10	0.14	0.66	4.26	4.60	0.13	25.40	9.52	0.83	100.63	90.78
-167	54.26	0.13	0.81	4.85	4.42	0.17	24.58	10.20	1.07	100.48	90.84
-164	54.44	0.10	0.75	3.86	4.12	0.21	23.55	11.73	1.17	99.94	91.06
-161	54.40	0.14	0.75	4.20	4.10	0.07	23.08	12.48	1.21	100.43	90.94
-152	55.12	0.10	0.73	3.66	4.76	0.14	25.83	9.03	0.78	100.15	90.63
-145	53.71	0.17	0.92	5.23	3.88	0.15	22.54	12.32	0.63	99.55	91.20
-126	55.03	0.09	0.73	3.77	4.43	0.18	24.94	10.44	0.91	100.52	90.94
-105	54.38	0.11	0.80	4.03	4.20	0.12	23.47	11.73	1.20	100.04	90.88
-100	54.44	0.11	0.88	4.07	4.64	0.16	24.64	10.07	0.86	99.87	90.45
-93	53.39	0.20	0.87	5.54	3.83	0.17	22.09	13.16	1.13	100.38	91.14
-81	55.14	0.10	0.79	3.50	4.70	0.21	25.31	9.66	0.92	100.33	90.57
-80	54.77	0.10	0.78	3.57	4.64	0.22	25.30	10.00	0.89	100.27	90.67
-63	54.12	0.16	0.78	4.53	3.99	0.15	22.47	12.94	0.99	100.12	90.94
-63	54.31	0.15	0.83	4.64	3.86	0.13	22.24	13.55	1.00	100.70	91.13
-61	54.26	0.13	0.98	4.07	4.49	0.16	23.48	11.67	0.92	100.16	90.31
-57	53.55	0.20	0.88	5.50	3.94	0.16	22.19	13.01	1.00	100.43	90.94
-54	53.73	0.16	0.94	4.30	3.95	0.07	21.66	13.64	0.94	99.40	90.72
-44	54.42	0.12	0.85	3.70	4.35	0.19	23.52	11.85	0.87	99.86	90.60
-44	53.24	0.17	0.85	5.37	3.63	0.11	21.16	14.44	1.12	100.10	91.22
-40	53.66	0.17	0.97	4.90	3.92	0.12	21.97	13.46	0.93	100.09	90.90
-35	53.76	0.18	0.82	5.06	3.70	0.17	21.77	13.91	1.02	100.38	91.30
-27	54.67	0.13	0.76	3.70	4.72	0.15	23.89	11.02	1.24	100.27	90.02
-26	53.56	0.19	1.04	4.60	3.54	0.17	20.44	15.48	1.31	100.32	91.15
-8	53.48	0.18	1.05	4.97	3.82	0.09	21.32	13.89	1.10	99.91	90.87
-2	54.27	0.16	0.89	4.42	4.06	0.22	23.37	12.01	0.93	100.32	91.12
15	53.20	0.19	1.16	4.95	3.35	0.14	19.90	16.01	1.03	99.94	91.37

Table A1-2 continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
18	52.95	0.19	0.97	5.32	3.50	0.13	20.55	15.10	1.26	99.98	91.28
27	53.48	0.19	0.94	5.38	3.53	0.14	20.64	14.90	1.23	100.43	91.25
29	52.88	0.28	0.96	6.61	3.45	0.11	19.37	15.46	1.50	100.62	90.92
55	53.01	0.23	0.97	5.53	3.32	0.14	19.64	16.38	0.98	100.19	91.34
71	53.79	0.18	1.04	4.86	3.35	0.17	20.49	15.76	1.34	100.98	91.60
108	53.24	0.21	1.06	5.43	3.42	0.12	20.33	15.38	1.20	100.39	91.38
110	52.76	0.23	1.07	5.79	3.10	0.14	19.31	16.30	1.20	99.90	91.74
112	53.32	0.20	1.15	4.93	3.40	0.12	20.25	15.77	1.06	100.20	91.39
140	53.42	0.21	1.00	5.16	3.34	0.11	19.95	16.11	1.23	100.55	91.42
168	52.72	0.22	1.10	5.22	3.28	0.09	19.68	16.13	0.91	99.35	91.45
181	53.36	0.19	1.10	4.94	3.23	0.11	20.19	16.04	1.08	100.23	91.77
209	52.86	0.21	1.10	5.28	3.12	0.12	19.23	16.87	1.33	100.10	91.66
221	52.48	0.26	1.25	5.94	3.10	0.12	18.41	17.79	1.16	100.51	91.37
237	52.91	0.23	1.25	5.29	2.96	0.08	18.64	17.78	0.88	100.01	91.82
251	52.93	0.22	1.12	5.48	3.14	0.12	19.34	16.81	1.34	100.51	91.65
265	53.04	0.29	1.00	5.89	3.17	0.09	19.54	16.36	1.31	100.69	91.66
292	52.96	0.22	1.23	5.08	3.15	0.06	19.10	17.21	0.99	99.99	91.53
334	52.74	0.23	1.22	5.36	3.02	0.15	19.03	17.01	1.09	99.86	91.83
348	53.00	0.24	1.10	5.58	3.05	0.17	19.34	16.83	1.02	100.32	91.87
375	53.14	0.22	1.11	5.05	3.15	0.11	19.51	16.70	1.06	100.06	91.70
417	52.91	0.22	1.15	5.27	3.09	0.11	19.15	17.14	1.02	100.06	91.70
445	53.20	0.21	1.11	5.25	3.04	0.10	19.23	17.09	1.25	100.47	91.86
458	53.21	0.21	1.22	5.19	3.15	0.10	19.21	17.23	1.28	100.80	91.58

Table A1-3: Orthopyroxene composition of Run 27, conducted at 1340°C and 1.5 GPa for 79.15 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
-607	55.72	0.05	0.50	4.19	5.77	0.20	33.11	1.20	0.24	100.99	91.10
-502	55.97	0.07	0.53	3.49	5.43	0.17	32.45	2.19	0.06	100.35	91.42
-483	55.93	0.08	0.52	3.93	5.08	0.15	32.61	2.22	0.33	100.84	91.96
-467	55.04	0.09	0.47	5.29	6.10	0.13	32.81	0.72	0.22	100.87	90.56
-458	55.01	0.12	0.56	5.13	4.99	0.16	31.93	2.23	0.41	100.55	91.94
-435	55.50	0.08	0.59	4.28	5.17	0.16	32.07	2.51	0.39	100.75	91.71
-426	55.30	0.10	0.60	5.19	5.25	0.14	32.29	1.65	0.23	100.76	91.64
-409	55.66	0.09	0.53	4.32	5.30	0.14	32.70	1.58	0.25	100.57	91.67
-370	55.76	0.11	0.52	4.11	5.02	0.14	32.18	2.46	0.46	100.75	91.95
-322	56.03	0.06	0.53	3.49	5.20	0.12	32.62	2.35	0.30	100.69	91.79
-321	56.11	0.09	0.55	3.66	5.13	0.21	32.44	2.28	0.25	100.72	91.85
-311	55.93	0.06	0.39	3.92	5.92	0.16	33.33	0.62	0.25	100.58	90.94
-273	55.13	0.08	0.46	5.22	5.72	0.12	32.89	0.96	0.35	100.94	91.11
-273	55.26	0.10	0.56	3.64	5.29	0.14	32.65	2.47	0.20	100.30	91.67

Table A1-4: Olivine composition of Run 27, conducted at 1340°C and 1.5 GPa for 79.15 hours

Distance (μm)	SiO ₂	FeO	MnO	MgO	CaO	Total	Mg#
-642	41.27	8.21	0.16	50.96	0.26	100.85	91.71
-622	41.16	8.36	0.16	50.83	0.25	100.76	91.55
-611	41.23	8.16	0.18	51.05	0.27	100.89	91.77
-601	41.10	8.29	0.18	50.87	0.26	100.70	91.62
-591	41.27	8.28	0.13	50.35	0.40	100.43	91.56
-576	41.07	8.33	0.16	50.74	0.28	100.58	91.57
-566	41.22	8.20	0.15	50.64	0.28	100.49	91.67
-560	41.17	8.06	0.15	50.60	0.24	100.22	91.80
-556	41.24	8.21	0.17	50.66	0.27	100.55	91.67
-519	41.16	8.38	0.12	50.92	0.25	100.83	91.55
-518	41.27	8.21	0.16	50.94	0.26	100.84	91.71
-509	41.11	8.33	0.16	50.78	0.26	100.64	91.57
-508	41.06	8.20	0.13	50.61	0.23	100.23	91.67
-499	41.18	8.47	0.19	50.39	0.26	100.50	91.38
-431	41.21	8.30	0.13	50.81	0.23	100.68	91.61
-428	41.21	8.49	0.12	50.62	0.28	100.72	91.40
-422	41.24	8.30	0.13	50.72	0.27	100.66	91.59
-408	41.09	8.51	0.18	50.74	0.26	100.78	91.40
-407	41.01	8.15	0.14	50.76	0.26	100.31	91.74
-383	41.21	8.32	0.11	50.77	0.29	100.70	91.58
-374	41.16	8.23	0.14	50.56	0.24	100.33	91.63
-366	41.09	8.19	0.17	50.69	0.25	100.38	91.69
-364	41.19	8.13	0.11	50.85	0.28	100.56	91.77
-354	41.26	8.22	0.18	50.72	0.24	100.61	91.67
-335	41.16	8.16	0.13	50.80	0.29	100.54	91.74
-326	41.22	8.44	0.16	50.76	0.24	100.84	91.47
-325	41.19	8.33	0.17	50.78	0.27	100.74	91.57
-316	41.17	8.15	0.19	50.74	0.27	100.51	91.74
-315	41.22	8.22	0.14	50.77	0.27	100.62	91.67
-306	40.77	8.20	0.14	50.61	0.27	99.97	91.67
-305	40.97	8.49	0.15	50.82	0.26	100.68	91.43
-297	40.97	8.37	0.18	50.67	0.24	100.44	91.52
-294	41.18	8.34	0.19	50.83	0.24	100.78	91.57

Table A1-4 continued

Distance (μm)	SiO ₂	FeO	MnO	MgO	CaO	Total	Mg#
-287	40.83	8.23	0.14	50.47	0.26	99.94	91.62
-284	41.00	8.28	0.14	50.54	0.28	100.24	91.58
-284	41.21	8.36	0.17	50.81	0.25	100.80	91.55
-283	41.02	8.27	0.11	50.44	0.23	100.08	91.58
-283	40.99	8.29	0.15	50.65	0.29	100.37	91.59
-274	41.09	8.09	0.13	50.78	0.28	100.38	91.80
-271	41.01	8.34	0.12	50.47	0.25	100.19	91.52
-271	41.07	8.31	0.17	50.73	0.29	100.57	91.59
-268	41.00	8.22	0.15	50.33	0.35	100.05	91.61
-265	40.96	8.23	0.15	50.31	0.28	99.94	91.60
-261	40.97	8.39	0.15	50.49	0.25	100.25	91.47
-258	41.14	8.28	0.20	50.77	0.25	100.65	91.62
-251	40.66	8.39	0.17	50.65	0.31	100.19	91.50
-251	40.92	8.28	0.18	50.53	0.28	100.19	91.58
-249	41.33	8.32	0.18	50.66	0.27	100.76	91.57
-247	41.25	8.34	0.08	50.81	0.27	100.74	91.57
-241	41.02	8.42	0.13	50.42	0.29	100.28	91.44
-239	41.15	8.30	0.17	50.77	0.26	100.65	91.60
-230	41.18	8.40	0.10	50.74	0.29	100.71	91.50
-229	40.95	8.32	0.12	50.38	0.31	100.07	91.52
-229	40.68	8.17	0.09	50.05	0.30	99.30	91.61
-223	41.11	8.30	0.16	50.81	0.26	100.64	91.61
-198	40.83	8.29	0.17	50.44	0.25	99.97	91.56
-188	40.79	8.26	0.14	50.28	0.27	99.73	91.56
-183	41.32	8.35	0.18	50.60	0.25	100.70	91.53
-182	40.86	8.46	0.11	50.45	0.28	100.16	91.40
-182	41.18	8.40	0.10	50.62	0.25	100.55	91.48
-180	41.36	8.32	0.15	50.53	0.26	100.61	91.55
-177	40.70	8.33	0.17	50.58	0.29	100.07	91.54
-160	40.87	8.26	0.10	50.73	0.31	100.26	91.63
-149	41.17	8.13	0.16	50.60	0.30	100.35	91.73
-142	40.65	8.21	0.18	50.39	0.28	99.70	91.63
-142	40.70	8.39	0.17	50.51	0.27	100.05	91.48

Table A1-4 continued

Distance (μm)	SiO ₂	FeO	MnO	MgO	CaO	Total	Mg#
-142	40.87	8.76	0.18	50.57	0.31	100.69	91.14
-138	41.38	8.43	0.18	50.39	0.27	100.65	91.42
-137	40.91	8.28	0.15	50.73	0.28	100.35	91.61
-121	41.07	8.56	0.17	50.78	0.32	100.89	91.36
-114	41.26	8.48	0.11	50.34	0.26	100.45	91.37
-109	40.81	8.53	0.17	50.44	0.29	100.24	91.34
-95	41.29	8.45	0.18	50.59	0.28	100.78	91.43
-94	41.28	8.35	0.19	50.76	0.28	100.86	91.55
-93	41.06	8.33	0.16	50.88	0.27	100.71	91.59
-91	41.11	8.28	0.16	50.69	0.30	100.55	91.61
-90	41.21	8.17	0.10	50.60	0.27	100.35	91.70
-89	41.06	8.45	0.16	50.71	0.26	100.64	91.45
-87	41.37	8.56	0.11	50.44	0.27	100.76	91.31
-85	40.87	8.40	0.19	50.38	0.28	100.13	91.45
-85	41.07	8.45	0.19	50.71	0.27	100.69	91.45
-84	41.11	8.38	0.16	50.69	0.25	100.59	91.51
-83	41.03	8.30	0.19	50.65	0.35	100.52	91.58
-80	41.09	8.38	0.12	50.67	0.28	100.54	91.51
-79	41.04	8.43	0.16	50.67	0.29	100.59	91.46
-79	41.21	8.41	0.14	50.77	0.31	100.84	91.50
-78	41.17	8.58	0.15	50.64	0.30	100.85	91.32
-77	41.14	8.44	0.17	50.70	0.35	100.81	91.46
-76	40.93	8.12	0.13	50.63	0.31	100.12	91.75
-74	40.96	8.40	0.15	50.66	0.31	100.48	91.49
-74	41.12	8.43	0.15	50.59	0.29	100.57	91.45
-74	41.10	8.44	0.13	50.84	0.28	100.80	91.48
-73	41.27	8.40	0.15	50.60	0.28	100.70	91.48
-71	41.03	8.68	0.14	50.52	0.32	100.68	91.21
-70	41.39	8.53	0.16	50.47	0.27	100.81	91.34
-63	40.94	8.17	0.21	50.53	0.25	100.11	91.69
-61	41.11	8.36	0.20	50.49	0.31	100.48	91.50
-61	41.20	8.25	0.17	50.61	0.30	100.54	91.62
-55	41.26	8.39	0.18	50.58	0.24	100.65	91.49

Table A1-4 continued

Distance (μm)	SiO ₂	FeO	MnO	MgO	CaO	Total	Mg#
-53	41.14	8.33	0.15	50.46	0.33	100.43	91.53
-50	41.21	8.29	0.14	50.79	0.34	100.78	91.61
-50	41.30	8.46	0.12	50.54	0.38	100.80	91.42
-48	41.11	8.31	0.14	50.60	0.28	100.43	91.57
-47	40.98	8.35	0.13	50.72	0.30	100.48	91.55
-40	41.17	8.29	0.11	50.69	0.29	100.56	91.60
-39	40.98	8.75	0.12	50.31	0.32	100.47	91.11
-30	41.07	8.32	0.16	50.42	0.29	100.26	91.53
-25	41.18	8.33	0.17	50.52	0.31	100.50	91.53
-22	41.09	8.34	0.19	50.81	0.29	100.72	91.57
-13	41.02	8.32	0.17	50.94	0.29	100.74	91.61
7	40.98	8.22	0.13	50.71	0.40	100.45	91.67

Table A2-1: Glass composition of Run 37 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-158	49.11	1.05	15.24	7.93	0.13	10.98	10.42	4.79	0.32	0.14	100.10	71.17
-148	49.00	1.06	15.26	7.53	0.26	11.31	10.62	4.90	0.29	0.10	100.34	72.81
-146	48.98	1.00	15.07	7.04	0.14	12.12	10.73	4.72	0.27	0.09	100.16	75.43
-135	48.95	1.07	15.29	8.26	0.16	10.65	9.73	4.94	0.31	0.06	99.41	69.69
-133	49.41	1.02	15.26	7.47	0.17	11.37	9.95	4.82	0.31	0.10	99.88	73.07
-132	49.04	1.01	15.01	7.64	0.16	11.75	10.34	4.80	0.30	0.11	100.15	73.28
-131	49.07	0.95	15.09	7.23	0.22	11.86	10.24	4.87	0.26	0.08	99.87	74.52
-131	49.05	1.02	15.22	7.87	0.14	10.61	10.80	5.04	0.26	0.07	100.09	70.62
-131	48.91	1.01	15.13	7.31	0.16	11.61	10.29	5.04	0.26	0.06	99.79	73.90
-128	48.99	1.09	15.63	8.40	0.22	9.63	9.44	5.57	0.29	0.09	99.34	67.15
-128	49.54	1.00	15.12	7.26	0.12	11.03	10.95	4.46	0.27	0.10	99.85	73.04
-121	49.10	1.06	14.69	7.56	0.19	11.41	10.59	4.53	0.27	0.12	99.50	72.91
-120	48.93	1.02	15.16	7.35	0.14	11.95	10.80	4.58	0.26	0.14	100.34	74.35
-120	49.03	1.03	14.92	7.15	0.20	11.76	10.69	4.65	0.27	0.16	99.85	74.57
-109	49.64	1.06	15.63	7.44	0.18	9.56	11.46	4.51	0.27	0.08	99.83	69.61
-105	49.52	1.09	15.92	7.23	0.16	9.86	11.42	4.67	0.27	0.06	100.21	70.86
-102	49.14	1.06	15.42	7.49	0.20	10.35	10.64	5.00	0.32	0.11	99.74	71.13
-100	49.19	1.04	15.41	7.86	0.17	10.22	10.24	5.16	0.30	0.10	99.69	69.86
-97	49.71	1.11	16.00	7.38	0.16	9.03	11.15	4.92	0.28	0.14	99.90	68.57
-96	48.90	1.08	15.62	7.56	0.18	10.28	11.16	4.68	0.27	0.12	99.85	70.80
-96	49.25	1.04	15.15	7.22	0.11	11.56	11.03	4.37	0.26	0.14	100.13	74.06
-90	48.92	1.03	15.12	7.55	0.13	10.32	11.00	4.56	0.26	0.17	99.04	70.90
-88	49.03	1.10	15.80	8.26	0.21	9.22	10.64	5.02	0.32	0.10	99.72	66.56
-87	49.21	1.06	16.03	7.05	0.18	10.08	11.01	4.90	0.30	0.16	99.98	71.82
-84	49.64	1.10	15.81	7.68	0.16	8.75	11.51	4.65	0.28	0.10	99.69	67.01
-84	48.85	1.05	15.49	7.47	0.11	10.20	10.58	4.72	0.27	0.09	98.84	70.88
-82	49.35	1.04	15.44	7.46	0.25	10.57	10.96	4.65	0.28	0.12	100.11	71.64
-81	48.98	0.98	15.36	7.46	0.15	10.55	10.89	4.59	0.29	0.08	99.33	71.60
-80	48.87	1.02	15.05	7.24	0.22	10.64	11.01	4.51	0.28	0.10	98.93	72.38
-80	48.67	1.05	15.10	8.11	0.15	10.17	10.89	4.73	0.28	0.16	99.31	69.10
-79	49.24	1.10	15.88	7.78	0.18	10.23	9.94	4.88	0.33	0.05	99.63	70.10
-79	49.24	1.18	15.87	7.58	0.19	8.93	11.11	4.92	0.28	0.07	99.37	67.75
-76	49.43	1.01	15.12	7.44	0.17	11.76	10.52	4.50	0.25	0.14	100.35	73.81

Table A2-1: continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-75	49.30	1.07	15.46	7.24	0.18	10.98	11.22	4.42	0.29	0.10	100.25	73.00
-69	49.63	1.03	15.69	7.42	0.18	9.93	11.32	4.53	0.23	0.12	100.08	70.47
-42	49.02	1.16	16.41	8.34	0.14	8.46	10.44	5.27	0.30	0.13	99.69	64.39

Table A2-2: Clinopyroxene composition of Run 37 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
-98	54.96	0.13	0.78	3.57	4.40	0.17	25.62	10.19	0.95	100.78	91.21
-96	53.86	0.17	0.90	4.93	3.92	0.11	22.01	13.90	1.04	100.85	90.92
-96	53.45	0.21	0.87	4.76	3.86	0.13	22.09	13.81	0.89	100.07	91.07
-91	54.69	0.13	0.78	3.90	4.29	0.15	24.52	11.42	0.73	100.61	91.06
-86	53.49	0.19	0.96	5.09	3.87	0.12	22.00	14.03	0.95	100.71	91.02
-86	54.10	0.15	0.88	4.23	4.31	0.16	24.85	10.69	0.79	100.18	91.13
-85	54.00	0.18	0.94	4.94	4.04	0.12	22.45	13.37	0.84	100.88	90.83
-83	53.96	0.15	0.93	4.57	3.96	0.17	22.86	13.43	0.89	100.92	91.14
-83	54.76	0.15	0.77	3.91	4.39	0.13	25.29	10.04	0.73	100.18	91.13
-82	54.53	0.11	0.86	3.26	4.38	0.12	25.45	10.36	0.76	99.83	91.20
-80	54.72	0.14	0.81	3.86	4.53	0.22	25.29	10.52	0.74	100.82	90.87
-76	54.60	0.12	0.82	3.99	4.33	0.14	24.49	11.13	0.84	100.47	90.98
-74	54.42	0.14	0.86	4.14	3.99	0.16	22.71	13.30	0.86	100.59	91.03
-68	54.18	0.15	0.81	4.12	4.19	0.10	24.01	11.71	0.77	100.04	91.08
-68	54.66	0.13	0.95	3.80	4.50	0.14	25.14	10.30	0.92	100.54	90.88
-65	54.43	0.13	0.96	3.58	4.34	0.18	24.27	11.72	0.78	100.39	90.88
-59	54.50	0.15	0.94	4.07	4.34	0.15	24.74	10.67	0.68	100.22	91.04
-59	54.53	0.16	0.97	4.09	4.07	0.15	23.05	13.03	0.81	100.86	90.99
-59	54.69	0.13	0.87	3.99	4.48	0.16	25.36	10.14	0.90	100.71	90.98
-58	54.49	0.14	0.95	4.11	4.13	0.16	23.53	12.51	0.92	100.95	91.04
-57	54.27	0.13	0.90	3.78	3.94	0.19	23.36	13.16	0.80	100.52	91.36
-57	54.43	0.12	0.94	3.50	4.17	0.13	24.13	12.08	0.87	100.38	91.16
-56	54.84	0.11	0.90	3.43	4.48	0.19	25.12	10.94	0.81	100.81	90.91
-56	54.98	0.11	0.79	3.56	4.55	0.20	25.47	10.18	0.83	100.68	90.89
-54	55.47	0.09	0.81	3.38	4.64	0.11	26.13	9.53	0.77	100.93	90.94
-54	54.57	0.12	0.98	3.93	4.65	0.22	25.17	10.42	0.74	100.79	90.61
-51	54.03	0.18	1.09	4.09	4.21	0.18	23.27	12.98	0.83	100.86	90.79
-50	54.76	0.16	0.95	3.85	4.43	0.15	24.93	10.73	0.73	100.68	90.94
-42	54.98	0.13	0.91	3.82	4.49	0.13	25.69	9.67	0.74	100.57	91.07
-39	54.47	0.13	0.89	3.80	4.03	0.13	23.85	12.40	0.73	100.43	91.34
-33	54.72	0.13	0.95	3.71	4.37	0.13	24.15	11.61	0.80	100.58	90.79
-32	53.89	0.18	0.98	4.28	3.94	0.11	22.79	13.47	0.80	100.43	91.16
-31	53.76	0.16	1.07	4.24	3.99	0.15	22.77	13.38	0.74	100.26	91.05

Table A2-2 continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
-30	54.06	0.15	1.00	4.05	4.15	0.16	23.97	11.54	0.77	99.85	91.15
-29	54.12	0.14	0.93	3.96	4.19	0.13	23.42	12.49	0.89	100.27	90.88
-29	54.26	0.16	0.88	4.36	3.91	0.16	22.92	13.31	0.81	100.77	91.27
-28	54.32	0.14	0.95	3.88	4.08	0.13	23.39	12.41	0.76	100.06	91.09
-23	54.12	0.17	0.83	4.92	4.14	0.10	22.54	12.89	0.99	100.71	90.66
-20	55.35	0.11	1.00	3.14	4.09	0.16	24.88	11.31	0.92	100.95	91.56
-12	54.84	0.11	0.90	2.76	4.87	0.10	26.39	8.98	0.63	99.56	90.62
-9	54.42	0.13	0.97	3.93	3.91	0.16	23.09	13.12	0.84	100.58	91.33
-6	53.90	0.19	0.92	4.68	3.93	0.16	22.63	13.36	0.84	100.61	91.12
-1	54.96	0.13	0.82	3.25	4.37	0.10	25.38	10.62	0.68	100.32	91.19
3	53.45	0.17	0.98	4.92	3.89	0.16	21.74	14.02	0.83	100.15	90.88
5	54.48	0.13	0.95	3.21	4.12	0.15	24.11	11.88	0.75	99.78	91.25
5	53.49	0.32	0.93	5.65	4.51	0.18	21.11	13.15	1.21	100.54	89.30
6	53.76	0.16	0.93	4.63	3.87	0.16	22.61	13.17	0.85	100.15	91.24
9	53.39	0.22	1.02	4.98	3.83	0.10	21.60	14.22	0.85	100.22	90.95
15	53.80	0.17	1.01	4.33	3.57	0.08	21.75	14.77	0.84	100.32	91.57
16	53.35	0.18	0.98	4.71	3.80	0.14	21.35	14.69	0.97	100.18	90.92
17	53.73	0.15	1.09	4.04	3.45	0.14	21.59	15.03	0.93	100.16	91.77
21	52.59	0.28	1.25	5.44	3.08	0.06	19.15	17.30	0.99	100.14	91.73
23	52.23	0.34	1.18	5.77	2.90	0.12	18.06	18.38	0.98	99.96	91.74
25	54.74	0.12	1.02	3.30	3.91	0.16	23.46	12.85	0.83	100.38	91.45
25	53.69	0.16	1.07	4.18	3.23	0.70	22.41	13.90	0.78	100.13	92.52
27	54.13	0.15	1.08	4.04	3.81	0.15	22.45	13.95	0.95	100.72	91.31
27	53.74	0.17	1.14	4.31	3.41	0.18	21.16	15.64	0.96	100.70	91.71
27	53.84	0.17	1.10	4.19	3.50	0.15	21.18	15.65	0.85	100.62	91.52
28	54.04	0.18	1.04	4.39	3.87	0.15	22.01	14.33	0.81	100.83	91.02
33	53.72	0.18	1.15	4.14	3.39	0.13	21.40	15.35	0.85	100.31	91.84
35	53.15	0.18	1.05	4.33	3.57	0.12	21.40	15.24	0.86	99.90	91.44
37	53.58	0.21	1.14	4.23	3.58	0.12	21.35	15.49	0.89	100.58	91.40
38	53.66	0.17	1.13	4.26	3.47	0.13	20.94	16.05	0.87	100.68	91.50
39	53.75	0.19	1.01	4.83	3.73	0.11	21.32	14.94	1.02	100.91	91.06
41	53.44	0.20	1.13	4.43	3.51	0.13	21.06	15.62	0.85	100.37	91.45
51	53.51	0.20	1.17	4.25	3.46	0.11	21.15	15.52	0.98	100.34	91.60

Table A2-2 continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
55	53.57	0.20	1.10	4.51	3.37	0.13	21.09	15.68	0.87	100.53	91.77
57	53.78	0.16	1.07	4.41	3.44	0.14	21.21	15.08	1.17	100.45	91.66
58	53.24	0.20	1.07	4.93	3.55	0.12	20.60	15.69	1.02	100.43	91.19
58	53.75	0.17	1.15	4.15	3.53	0.11	21.45	14.97	0.84	100.11	91.55
71	53.89	0.19	1.11	4.31	3.37	0.13	21.18	15.31	0.93	100.40	91.81
84	52.75	0.32	1.04	6.12	3.63	0.10	19.45	15.91	0.99	100.30	90.52
95	53.01	0.23	1.28	4.86	2.73	0.05	18.19	19.37	0.93	100.65	92.24
103	51.83	0.43	1.06	6.67	3.12	0.08	17.19	18.71	1.24	100.32	90.76
104	53.52	0.19	1.05	4.76	3.42	0.21	20.94	15.71	0.85	100.64	91.61
111	52.96	0.20	1.07	4.80	3.47	0.11	20.42	16.37	0.92	100.32	91.30
113	53.59	0.18	1.14	4.31	3.34	0.12	20.80	16.10	0.84	100.43	91.74
115	53.62	0.17	1.11	4.48	3.55	0.10	21.40	15.05	0.80	100.29	91.49
120	53.40	0.18	1.08	4.74	3.40	0.12	20.54	16.33	0.97	100.76	91.50
133	52.74	0.27	1.19	5.05	3.33	0.15	19.73	17.04	1.03	100.52	91.35
141	53.47	0.19	1.12	4.89	3.43	0.15	20.65	16.00	1.03	100.93	91.48
149	53.79	0.17	1.18	4.25	3.40	0.14	20.70	16.07	0.86	100.55	91.56
152	53.52	0.20	1.15	4.33	3.35	0.12	20.26	16.44	0.90	100.26	91.51
159	53.54	0.22	1.20	4.52	3.26	0.15	20.36	16.20	0.93	100.37	91.76
176	53.35	0.18	1.09	4.78	3.39	0.12	20.61	16.13	1.05	100.69	91.55
181	53.42	0.18	1.06	4.76	3.52	0.12	20.86	15.53	1.10	100.55	91.35
182	53.30	0.18	1.03	4.73	3.63	0.15	20.95	15.44	0.98	100.38	91.14
197	53.02	0.23	1.11	5.11	3.31	0.04	19.89	16.60	1.07	100.37	91.46
201	53.28	0.19	1.21	4.54	3.21	0.14	20.38	16.40	1.10	100.46	91.88
205	53.31	0.19	1.13	4.62	3.43	0.13	20.72	15.96	0.92	100.40	91.50
234	52.95	0.28	1.09	5.29	3.17	0.13	19.40	17.12	1.08	100.52	91.60
243	52.12	0.34	1.17	5.81	2.68	0.07	17.71	19.28	0.99	100.17	92.18
258	52.96	0.24	1.27	4.60	2.95	0.09	19.13	18.06	0.90	100.20	92.04
265	53.07	0.24	1.07	5.03	3.40	0.15	20.69	15.52	0.93	100.10	91.56
303	53.26	0.19	1.22	4.66	3.29	0.16	20.58	16.23	0.94	100.53	91.77
310	53.17	0.22	1.12	5.12	3.40	0.06	20.20	16.18	0.93	100.39	91.37
372	52.76	0.16	1.17	4.72	3.31	0.09	20.35	16.36	0.97	99.89	91.64
412	52.80	0.24	1.06	5.29	3.34	0.08	19.72	16.84	0.91	100.28	91.32
413	52.09	0.37	0.98	6.31	3.01	0.07	17.30	19.40	1.21	100.72	91.11

Table A2-2 continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
429	52.95	0.21	1.13	5.11	3.25	0.10	19.82	16.73	0.97	100.27	91.58
470	52.32	0.27	1.12	5.20	2.79	0.12	17.88	19.71	0.95	100.36	91.95
484	52.83	0.25	1.26	4.95	3.19	0.15	19.59	17.37	0.82	100.41	91.63
496	52.88	0.21	1.07	5.32	3.29	0.11	19.61	16.97	0.99	100.45	91.40
496	52.47	0.30	1.19	5.57	2.69	0.11	17.71	19.58	1.16	100.78	92.15
516	52.18	0.39	0.93	6.72	3.07	0.25	18.21	18.03	1.11	100.89	91.36
534	52.95	0.21	1.25	4.90	2.99	0.11	19.58	17.34	0.94	100.27	92.11
540	51.94	0.38	1.08	6.70	2.83	0.15	17.09	18.63	1.15	99.95	91.50
549	52.16	0.28	1.16	5.57	2.63	0.06	17.42	19.93	0.97	100.16	92.19
555	52.70	0.20	1.17	5.07	2.59	0.09	18.26	19.34	0.81	100.22	92.63
578	52.17	0.41	1.20	5.60	3.15	0.13	17.93	19.36	0.82	100.77	91.03
587	52.45	0.22	1.15	5.12	3.15	0.12	19.76	16.73	1.00	99.70	91.79
590	52.27	0.29	1.12	5.65	2.74	0.09	17.62	19.91	1.05	100.76	91.98
604	52.17	0.27	1.17	5.57	2.79	0.11	18.11	19.02	0.93	100.13	92.05
632	52.65	0.23	1.22	5.09	3.15	0.07	19.29	17.53	0.90	100.11	91.61
639	52.69	0.21	1.27	4.95	3.01	0.12	19.08	18.10	0.99	100.42	91.87
649	52.76	0.21	1.19	4.83	3.14	0.08	19.50	17.28	0.90	99.89	91.72
665	51.80	0.42	1.10	6.71	3.29	0.09	17.95	18.04	1.01	100.41	90.68
668	52.40	0.29	1.13	5.53	2.98	0.10	18.18	19.18	0.99	100.79	91.58
723	52.32	0.29	1.11	5.64	2.79	0.10	17.62	19.30	1.00	100.18	91.84
736	52.03	0.34	1.19	5.72	2.77	0.14	17.85	19.50	0.87	100.40	91.99
755	52.44	0.30	1.12	5.54	2.95	0.11	17.68	18.91	1.02	100.07	91.44
783	51.99	0.32	1.16	5.83	2.89	0.09	17.93	19.06	1.00	100.26	91.71
920	52.77	0.26	1.12	5.56	3.06	0.07	19.09	17.43	1.04	100.40	91.75
1059	51.93	0.36	1.09	6.26	2.90	0.09	17.78	19.01	1.04	100.46	91.62
1100	51.93	0.34	1.09	5.72	2.75	0.08	17.65	19.67	0.95	100.17	91.96
1116	52.46	0.26	1.17	5.03	2.75	0.14	17.95	19.64	0.87	100.26	92.09
1197	52.51	0.25	1.23	4.93	2.83	0.11	18.74	18.57	1.01	100.18	92.19
1372	51.81	0.41	1.08	6.88	3.06	0.12	17.40	18.72	1.05	100.53	91.02
1400	52.97	0.23	1.14	5.02	3.05	0.10	19.61	17.61	0.95	100.69	91.98
1419	53.16	0.21	1.19	4.43	2.73	0.06	18.70	18.80	0.99	100.28	92.43
1494	52.06	0.35	1.16	6.25	2.73	0.07	17.34	19.52	1.02	100.51	91.89
1542	52.13	0.36	1.06	6.37	2.95	0.12	17.25	19.34	1.03	100.61	91.25

Table A2-2 continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
1583	52.05	0.38	1.05	6.35	2.92	0.04	17.06	19.41	1.25	100.50	91.24
1624	52.62	0.25	1.16	5.33	2.91	0.09	18.76	18.42	0.90	100.44	92.00
1626	52.06	0.39	1.01	5.92	3.19	0.13	16.70	19.75	1.12	100.27	90.32
1634	52.43	0.32	1.05	5.53	2.96	0.09	17.71	19.01	0.93	100.04	91.43
1766	52.03	0.32	1.16	6.01	2.78	0.07	17.75	19.57	0.95	100.63	91.92
1798	52.52	0.31	1.38	5.65	2.66	0.07	17.52	19.85	0.99	100.94	92.15
1851	52.09	0.28	1.13	5.95	2.72	0.05	17.74	19.20	0.91	100.06	92.08
1882	51.98	0.34	1.11	6.73	2.83	0.08	16.96	18.90	1.31	100.24	91.44
1996	51.83	0.39	1.07	6.72	2.28	0.79	17.41	18.92	1.01	100.42	93.16
2046	52.36	0.28	1.16	5.71	2.99	0.07	18.66	18.46	1.00	100.70	91.75

Table A2-3: Orthopyroxene composition of Run 37 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
-1790	55.15	0.10	0.49	4.61	5.90	0.09	32.95	0.84	0.20	100.33	90.87
-1738	55.13	0.08	0.47	4.70	5.55	0.04	33.05	1.23	0.24	100.50	91.39
-1736	54.78	0.09	0.51	4.94	6.24	0.23	33.05	0.82	0.19	100.84	90.42
-1726	54.88	0.10	0.47	4.75	5.90	0.31	33.10	0.86	0.15	100.52	90.91
-1661	54.77	0.10	0.47	5.34	6.32	0.03	32.49	0.84	0.21	100.57	90.16
-1612	54.35	0.11	0.51	5.58	6.19	0.05	32.24	0.82	0.18	100.02	90.28
-1487	54.82	0.12	0.52	5.06	5.75	0.12	32.28	1.41	0.21	100.29	90.92
-1023	54.39	0.12	0.48	5.57	5.72	0.04	32.44	0.95	0.14	99.86	91.00
-776	55.36	0.09	0.50	4.58	4.66	0.58	32.48	1.27	0.20	99.72	92.55
-630	55.64	0.07	0.51	3.94	6.04	0.29	32.63	1.43	0.18	100.72	90.59
-625	54.47	0.11	0.50	5.30	6.52	0.16	32.34	0.84	0.36	100.61	89.84
-574	55.74	0.08	0.50	3.96	5.45	0.38	32.76	1.42	0.20	100.49	91.47
-301	55.25	0.08	0.48	5.17	5.63	0.14	32.59	1.03	0.20	100.54	91.17
-298	54.96	0.08	0.53	4.91	6.13	0.28	32.76	0.73	0.33	100.70	90.50
-270	55.30	0.08	0.53	4.59	5.28	0.25	32.86	1.00	0.20	100.08	91.73
-205	54.88	0.08	0.47	5.26	6.55	0.20	32.41	0.88	0.19	100.92	89.82
-188	55.47	0.11	0.55	4.77	5.52	0.26	31.22	2.54	0.49	100.92	90.98
-187	55.24	0.08	0.50	4.92	6.10	0.12	32.64	1.06	0.15	100.80	90.51
-176	55.23	0.12	0.53	4.70	5.60	0.18	32.88	1.36	0.18	100.77	91.28
-159	55.78	0.07	0.52	3.02	5.48	0.16	32.96	2.02	0.17	100.17	91.47
-157	56.39	0.10	0.55	2.69	5.18	0.15	32.81	2.52	0.19	100.58	91.87
-153	55.36	0.12	0.50	4.47	5.80	0.16	32.82	1.33	0.17	100.75	90.98
-150	55.82	0.11	0.63	3.55	5.31	0.13	32.75	2.36	0.21	100.85	91.66
-142	55.87	0.09	0.57	3.73	5.71	0.13	32.87	1.76	0.20	100.93	91.12
-141	56.06	0.08	0.63	3.36	5.28	0.12	32.64	2.53	0.26	100.95	91.68
-129	54.59	0.09	0.50	5.26	6.63	0.13	32.38	0.87	0.27	100.72	89.70

Table A2-4: Olivine composition of Run 37 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	SiO ₂	FeO	MnO	MgO	CaO	Total	Mg#
-868	41.02	8.84	0.15	49.52	0.23	99.76	90.90
-862	40.68	9.01	0.21	49.27	0.26	99.43	90.70
-686	41.14	8.80	0.17	49.63	0.23	99.97	90.95
-215	40.86	8.96	0.08	49.29	0.27	99.46	90.75
-183	40.89	8.98	0.12	49.36	0.27	99.62	90.74
-138	40.82	9.23	0.15	49.62	0.28	100.11	90.55
-132	41.12	9.04	0.18	49.47	0.30	100.12	90.70
-113	40.99	8.89	0.16	49.51	0.29	99.85	90.85
-111	41.34	8.99	0.12	49.59	0.27	100.31	90.77
-105	40.94	9.11	0.16	49.26	0.29	99.76	90.60
-102	41.00	8.85	0.16	49.57	0.26	99.85	90.90
-101	41.03	8.83	0.20	49.16	0.28	99.49	90.85
-99	41.01	8.63	0.18	49.26	0.26	99.34	91.05
-96	40.89	9.00	0.12	49.56	0.26	99.83	90.76
-93	41.23	8.86	0.13	49.32	0.30	99.85	90.85
-92	40.81	8.90	0.16	49.34	0.28	99.49	90.81
-86	41.19	9.15	0.22	49.42	0.31	100.28	90.59
-85	41.00	8.98	0.14	49.43	0.28	99.84	90.75
-84	40.85	9.01	0.16	49.35	0.30	99.66	90.71
-78	41.02	8.73	0.12	49.39	0.28	99.53	90.98
-77	41.00	9.13	0.21	49.48	0.27	100.09	90.62
-77	40.98	9.01	0.16	49.46	0.32	99.93	90.73
-77	40.96	9.06	0.19	49.17	0.30	99.68	90.63
-77	41.03	8.97	0.16	49.36	0.31	99.83	90.75
-74	40.98	9.12	0.20	49.26	0.32	99.87	90.59
-72	41.34	8.91	0.15	49.24	0.29	99.94	90.79
-70	41.01	8.96	0.20	49.12	0.29	99.58	90.72
-69	40.86	9.28	0.11	49.30	0.32	99.86	90.45
-65	40.76	8.84	0.15	49.48	0.29	99.52	90.89
-63	40.93	8.85	0.02	49.04	0.29	99.13	90.81
-62	40.92	9.04	0.10	49.06	0.31	99.44	90.63
-59	41.17	8.81	0.15	49.37	0.28	99.78	90.90
-59	40.85	8.89	0.14	49.30	0.31	99.49	90.81

Table A2-4 continued

Distance (μm)	SiO ₂	FeO	MnO	MgO	CaO	Total	Mg#
-59	41.03	8.76	0.20	49.30	0.30	99.58	90.94
-58	41.07	9.06	0.20	49.59	0.33	100.25	90.71
-57	41.00	9.07	0.14	49.49	0.28	99.98	90.68
-55	40.77	8.78	0.14	49.45	0.28	99.41	90.94
-54	40.99	9.02	0.07	49.24	0.29	99.61	90.68
-51	40.73	8.85	0.19	49.33	0.30	99.40	90.86
-51	41.02	9.04	0.18	49.16	0.31	99.70	90.65
-49	40.92	8.88	0.19	49.51	0.30	99.80	90.86
-45	41.15	8.92	0.17	49.50	0.30	100.04	90.82
-45	40.98	8.80	0.17	49.40	0.31	99.66	90.92
-43	40.51	9.20	0.13	49.47	0.29	99.59	90.55
-40	40.86	8.90	0.17	49.33	0.31	99.57	90.81
-38	40.84	9.03	0.15	49.41	0.30	99.74	90.70
-37	41.04	8.93	0.24	49.36	0.30	99.87	90.79
-37	41.00	8.94	0.14	49.30	0.31	99.69	90.77
-35	40.87	9.02	0.12	49.40	0.27	99.69	90.71
-30	40.80	8.98	0.13	49.36	0.32	99.60	90.74
-22	40.82	8.97	0.19	49.41	0.34	99.73	90.76
-21	41.15	8.84	0.15	49.11	0.30	99.55	90.83
-20	40.72	9.26	0.16	49.34	0.31	99.78	90.48

Table A3-1: Glass composition of Run 49 conducted at 1300°C and 1.5 GPa for 72.75 hours

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-23	47.50	0.96	17.72	8.86	0.19	7.55	11.92	3.47	0.21	0.28	98.66	60.31
-8	49.21	0.94	17.73	7.68	0.21	7.29	12.37	3.36	0.25	0.28	99.31	62.86
-2	47.73	0.92	17.43	9.36	0.14	6.87	10.84	3.85	0.27	0.21	97.62	56.68
59	48.30	0.98	18.65	8.07	0.13	5.71	11.47	4.56	0.23	0.27	98.37	55.78
60	47.43	0.91	17.85	8.11	0.16	6.96	12.23	3.44	0.21	0.27	97.57	60.48
70	47.50	0.92	18.16	7.61	0.12	7.01	12.08	3.87	0.25	0.26	97.79	62.15
75	46.77	0.92	17.75	7.43	0.11	6.45	12.50	3.22	0.19	0.29	95.62	60.75

Table A3-2: Clinopyroxene composition of Run 49 conducted at 1300°C and 1.5 GPa for 72.75 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
5	52.03	0.15	1.35	6.91	4.63	0.12	22.60	11.70	0.71	100.19	89.69
9	51.19	0.17	1.54	7.76	4.22	0.13	20.81	13.54	0.74	100.11	89.79
28	51.59	0.18	1.50	7.41	4.45	0.15	21.03	12.63	0.88	99.81	89.39
40	51.27	0.24	1.39	7.97	3.81	0.08	19.00	15.56	0.88	100.21	89.89
70	50.45	0.34	1.05	8.81	4.12	0.10	18.29	16.07	0.90	100.13	88.78
89	49.77	0.40	1.12	8.98	3.90	0.12	16.81	17.66	0.95	99.72	88.49
143	50.81	0.36	1.04	8.13	4.10	0.11	17.26	17.28	0.93	100.02	88.24
218	50.16	0.43	1.07	8.80	3.82	0.14	16.66	17.54	1.02	99.63	88.60
263	50.62	0.34	1.21	8.35	3.86	0.14	17.68	16.45	1.04	99.69	89.09
293	50.82	0.38	0.95	8.46	4.06	0.12	17.81	16.33	1.05	99.98	88.66
399	50.48	0.26	1.42	8.22	3.73	0.13	18.43	16.02	0.79	99.48	89.81
444	50.69	0.25	1.40	8.18	3.71	0.11	18.52	16.05	0.87	99.77	89.90
499	50.55	0.39	1.09	8.50	3.80	0.12	16.74	17.84	1.05	100.07	88.71
542	49.99	0.33	1.10	8.36	3.84	0.09	17.84	16.65	0.94	99.14	89.23
589	50.35	0.23	1.39	8.10	3.74	0.11	18.19	16.53	0.84	99.49	89.66
780	50.66	0.24	1.40	8.29	3.78	0.09	18.25	16.27	0.83	99.81	89.59
896	50.33	0.40	1.06	8.75	3.68	0.12	17.01	17.63	1.04	100.03	89.18
949	50.18	0.36	1.19	8.70	3.50	0.10	17.73	17.19	0.84	99.79	90.03
1070	50.29	0.33	1.30	8.61	3.50	0.08	17.59	17.20	0.83	99.73	89.96
1092	50.25	0.39	1.08	9.05	3.99	0.09	16.70	17.52	1.09	100.16	88.18
1322	50.26	0.37	1.02	8.37	3.83	0.11	17.34	17.35	0.91	99.58	88.98
1499	50.52	0.35	1.02	8.63	3.48	0.08	17.07	17.92	0.90	99.96	89.74

Table A3-3: Orthopyroxene composition of Run 49 conducted at 1300°C and 1.5 GPa for 72.75 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
-581	53.20	0.09	0.82	6.98	5.87	0.12	32.14	1.11	0.16	100.50	90.71
-526	53.04	0.12	1.01	6.57	5.79	0.16	31.06	2.15	0.21	100.10	90.53
-509	53.26	0.08	0.91	6.78	5.64	0.14	31.72	1.58	0.16	100.26	90.93
-495	52.90	0.09	0.74	6.75	6.15	0.15	32.11	0.83	0.14	99.87	90.30
-469	53.89	0.10	0.70	5.99	5.78	0.19	32.20	1.46	0.16	100.46	90.85
-416	52.79	0.12	0.83	7.77	6.36	0.17	31.54	0.79	0.13	100.50	89.84
-416	52.63	0.09	0.86	7.37	6.17	0.18	30.88	1.54	0.18	99.90	89.92
-369	52.87	0.11	1.09	7.36	5.85	0.17	30.64	2.17	0.22	100.48	90.33
-344	53.03	0.09	1.11	6.87	5.75	0.14	30.95	2.08	0.18	100.20	90.56
-262	54.01	0.09	0.64	5.57	6.14	0.13	32.05	1.40	0.15	100.16	90.30
-222	53.13	0.10	1.04	7.30	6.00	0.14	30.92	1.79	0.17	100.61	90.18

Table A3-4: Olivine composition of Run 49 conducted at 1300°C and 1.5 GPa for 72.75 hours

Distance (μm)	SiO ₂	FeO	MnO	MgO	CaO	Total	Mg#
-71	40.50	9.68	0.15	49.02	0.36	99.70	90.03
-59	40.97	9.49	0.12	49.20	0.31	100.09	90.24
-54	40.25	9.64	0.14	49.21	0.32	99.55	90.10
-40	40.63	9.44	0.16	49.20	0.30	99.73	90.28
-39	40.75	9.57	0.15	49.37	0.30	100.15	90.19
-32	41.10	9.41	0.18	49.38	0.28	100.35	90.34
-25	40.88	9.54	0.12	49.44	0.32	100.30	90.23
-24	40.70	9.53	0.16	49.48	0.26	100.13	90.25
-22	41.11	9.46	0.15	49.32	0.29	100.33	90.29
-17	40.97	9.50	0.15	49.37	0.28	100.27	90.26
-5	40.90	9.34	0.15	49.41	0.28	100.08	90.41
-5	40.78	9.46	0.12	49.34	0.26	99.96	90.29

Table A3-5: Spinel composition of Run 49 conducted at 1300°C and 1.5 GPa for 72.75 hours

Distance (μm)	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MgO	Total	Mg#	Cr#
-491	0.16	17.28	52.27	8.97	20.93	99.61	80.62	18.16
-478	0.19	18.34	51.56	9.27	20.82	100.18	80.02	19.27
-478	0.14	19.76	49.81	9.34	20.51	99.58	79.65	21.03
-468	0.15	15.35	53.77	8.87	21.09	99.23	80.91	16.08
-371	0.17	16.54	52.95	8.93	21.23	99.82	80.91	17.33
-370	0.11	15.3	54.39	9.03	21.01	99.85	80.58	15.88
-369	0.16	17.16	52.04	9.14	20.84	99.34	80.26	18.12
-368	0.14	16.38	53.36	9.04	21.29	100.22	80.76	17.08
-364	0.15	17.94	52.21	9.11	20.99	100.4	80.42	18.74
-355	0.17	19.09	50.22	9.27	20.44	99.19	79.72	20.33
-336	0.15	18.69	51.38	9.19	20.71	100.11	80.07	19.62
-298	0.16	17.33	52.74	9.21	20.82	100.26	80.12	18.07
-297	0.15	17.32	52.98	9.16	20.81	100.41	80.20	17.99
-273	0.14	15.32	54.46	8.83	21.13	99.88	81.01	15.88
-234	0.16	17.13	52.57	9.19	21.01	100.05	80.30	17.94
-163	0.14	14.6	54.58	8.8	21.31	99.43	81.19	15.22
-163	0.18	14.54	54.8	8.9	21.19	99.61	80.93	15.12
-140	0.16	19.24	50.37	9.15	20.6	99.51	80.06	20.40
-138	0.16	19.71	50.49	9.3	20.46	100.12	79.68	20.76
-109	0.15	18.62	50.96	9.22	20.97	99.92	80.22	19.69
-82	0.17	17.04	52.97	9.35	21.12	100.65	80.11	17.76
-80	0.15	18.32	51.69	9.25	20.77	100.17	80.01	19.22
-65	0.17	18.46	52.01	9.26	20.45	100.33	79.75	19.24
-59	0.15	19.24	50.75	9.48	20.51	100.13	79.41	20.28
-59	0.15	19.58	50.41	9.5	20.57	100.21	79.43	20.68
-31	0.17	20.9	48.99	9.47	20.19	99.72	79.17	22.26
-31	0.18	20.53	48.88	9.52	20.31	99.41	79.18	21.99
-29	0.17	20.12	49.4	9.32	20.5	99.51	79.68	21.47
-28	0.19	19.94	49.22	9.56	20.43	99.34	79.21	21.38
-27	0.17	19.9	50.01	9.39	20.6	100.07	79.64	21.08
-26	0.18	20.59	49.81	9.52	20.48	100.57	79.32	21.72
-25	0.17	19.94	50.2	9.5	20.47	100.28	79.35	21.05
-25	0.16	20.64	49.16	9.56	20.45	99.97	79.23	21.98

Table A3-5 continued

Distance (μm)	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MgO	Total	Mg#	Cr#
-23	0.16	17.54	52.75	9.08	20.9	100.44	80.41	18.24
-20	0.13	19.17	51.36	9.26	20.72	100.64	79.96	20.03
-1	0.16	20.04	50.59	9.34	20.51	100.64	79.65	21.00
0	0.15	20.08	50.72	9.38	20.54	100.87	79.61	20.99
20	0.17	19.52	49.77	9.34	20.3	99.08	79.49	20.84
67	0.17	17.78	51.83	9.26	20.87	99.91	80.07	18.71
80	0.17	17.53	52.16	9.01	20.65	99.52	80.34	18.40
83	0.17	18.41	51.44	9.11	20.64	99.77	80.16	19.37
85	0.16	18.7	51.06	9.38	20.51	99.82	79.59	19.73
88	0.18	18.21	51.92	9.21	20.72	100.24	80.04	19.05
91	0.18	17.69	52.41	9.02	20.72	100.02	80.37	18.47
99	0.17	18.16	51.99	9.22	20.6	100.15	79.93	18.99
107	0.2	18.25	51.64	9.19	20.84	100.13	80.17	19.17
127	0.18	17.55	52.51	9.23	20.67	100.14	79.97	18.32
139	0.19	16.79	53.55	9.13	20.97	100.63	80.37	17.38
189	0.19	17.79	52.09	9.19	20.76	100.02	80.11	18.65
308	0.18	18.12	52.01	9.23	20.74	100.28	80.02	18.95
429	0.16	16.28	53.63	9.35	20.93	100.35	79.96	16.93
463	0.17	14.62	54.99	8.95	21.24	99.98	80.88	15.14
686	0.16	13.36	56.73	8.68	21.39	100.32	81.46	13.65
826	0.16	11.23	58.77	8.78	21.65	100.59	81.47	11.37
852	0.16	15.07	54.59	8.94	21.15	99.91	80.84	15.63
1177	0.18	11.75	58.18	8.68	21.55	100.34	81.57	11.94
1470	0.19	11.02	58.2	8.62	21.72	99.75	81.79	11.28
1589	0.16	10.82	59.35	8.47	21.6	100.4	81.97	10.90
1594	0.18	10.8	59.15	8.57	21.34	100.05	81.62	10.92
1600	0.16	11.16	59.08	8.54	21.57	100.5	81.83	11.25

Table A4-1: Glass composition of Run 54 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-41	45.21	1.17	20.01	8.36	0.15	6.40	8.56	5.87	0.39	0.25	96.38	57.71
-40	45.21	1.17	20.45	8.52	0.16	5.71	7.64	6.26	0.47	0.20	95.80	54.44
-34	45.75	1.29	19.30	8.69	0.16	7.09	8.81	6.19	0.38	0.22	97.88	59.26
-30	45.28	1.18	20.31	8.00	0.18	5.87	8.03	6.07	0.48	0.26	95.66	56.68
202	46.10	1.25	18.20	9.19	0.18	6.88	8.64	5.84	0.40	0.22	96.90	57.17

Table A4-2: Clinopyroxene composition of Run 54 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
-248	52.35	0.19	1.38	6.94	4.09	0.12	21.35	13.29	0.84	100.55	90.30
-237	52.60	0.20	1.26	6.93	3.91	0.13	21.27	13.71	0.86	100.86	90.65
-193	52.13	0.21	1.33	6.94	4.06	0.13	21.00	13.89	0.83	100.52	90.22
-187	52.40	0.21	1.30	6.80	4.23	0.18	21.19	13.38	0.80	100.50	89.93
-160	52.44	0.21	1.23	6.78	4.02	0.12	21.50	13.13	0.81	100.23	90.51
-157	52.52	0.19	1.27	6.80	4.05	0.14	21.52	13.36	0.82	100.67	90.45
-150	52.20	0.26	1.09	8.58	3.82	0.12	20.38	13.34	0.85	100.63	90.49
-145	52.35	0.25	1.15	7.29	3.91	0.16	21.32	13.43	0.90	100.77	90.67
-142	52.42	0.21	1.27	6.89	4.27	0.10	21.52	12.83	0.88	100.40	89.99
-139	52.20	0.19	1.24	6.73	3.93	0.18	21.24	13.10	0.84	99.65	90.60
-133	52.57	0.20	1.21	6.53	3.90	0.15	21.48	13.11	0.81	99.96	90.76
-129	52.66	0.20	1.23	6.55	3.83	0.14	21.21	14.13	0.84	100.79	90.80
-124	52.31	0.20	1.27	6.95	4.24	0.16	21.67	12.81	0.82	100.44	90.11
-115	51.87	0.20	1.24	7.12	4.40	0.15	20.86	13.44	0.85	100.14	89.42
-77	52.03	0.24	1.14	7.10	4.01	0.14	21.20	13.29	0.86	100.00	90.41
-77	51.78	0.23	1.28	7.07	4.18	0.12	20.47	14.13	0.89	100.14	89.72
-65	51.48	0.29	1.13	7.23	3.94	0.15	21.13	13.44	0.88	99.66	90.53
-51	51.98	0.23	1.31	6.89	3.80	0.12	20.53	14.64	0.83	100.33	90.59
-33	52.42	0.19	1.18	6.58	4.14	0.14	22.06	12.67	0.82	100.20	90.48
-18	52.17	0.26	1.15	7.15	3.67	0.16	20.95	13.95	0.88	100.35	91.05
-7	51.84	0.20	1.19	6.81	3.72	0.13	21.09	13.78	0.87	99.63	91.00
-4	52.38	0.21	1.23	6.78	3.63	0.14	20.97	14.33	0.87	100.52	91.15
6	53.28	0.13	1.46	5.02	4.29	0.13	23.88	11.25	0.71	100.14	90.85
6	53.40	0.11	1.89	5.13	4.00	0.16	23.24	11.84	0.84	100.61	91.20
13	52.08	0.23	1.22	6.85	3.77	0.12	20.78	14.45	0.89	100.38	90.76
43	51.04	0.26	1.13	8.17	4.21	0.13	19.67	14.47	0.98	100.07	89.28
70	53.08	0.15	1.70	4.95	3.73	0.12	22.02	13.55	0.83	100.13	91.32
156	53.20	0.13	1.43	4.68	3.64	0.16	22.05	13.98	0.75	100.04	91.53
174	51.86	0.22	1.22	6.94	3.85	0.12	20.55	14.50	0.87	100.12	90.49
174	52.13	0.28	1.14	7.14	4.02	0.15	20.79	13.86	0.86	100.37	90.22
296	52.87	0.18	1.24	5.45	3.57	0.12	20.86	14.74	0.84	99.86	91.24
302	51.49	0.30	1.15	7.31	3.53	0.09	19.40	15.52	0.99	99.78	90.74
371	52.30	0.22	1.25	6.23	3.44	0.13	19.95	15.75	0.89	100.16	91.18

Table A4-2 continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
418	52.03	0.22	1.25	6.06	3.36	0.11	19.67	16.02	0.84	99.56	91.26
451	52.62	0.19	1.40	5.26	3.14	0.08	19.32	17.23	0.85	100.09	91.65
509	51.61	0.29	1.10	6.65	3.55	0.12	19.55	16.19	0.86	99.92	90.76
541	50.68	0.51	1.02	8.16	3.72	0.12	18.94	16.04	0.88	100.06	90.08
674	52.11	0.24	1.18	6.11	3.29	0.08	19.10	17.16	0.88	100.14	91.19
784	51.22	0.32	1.17	6.45	2.79	0.09	17.51	18.66	1.02	99.24	91.80
864	52.12	0.36	1.15	5.57	2.78	0.11	17.83	19.13	0.98	100.02	91.96
921	52.14	0.27	1.03	6.98	3.34	0.13	19.22	15.78	0.93	99.81	91.12
1029	52.41	0.25	1.17	5.34	2.65	0.08	18.09	19.03	0.88	99.90	92.41
1152	53.13	0.21	1.14	4.74	2.73	0.10	18.41	18.80	0.86	100.14	92.32
1184	53.00	0.21	1.22	5.13	2.96	0.11	19.03	17.97	0.84	100.46	91.98

Table A4-3: Orthopyroxene composition of Run 54 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	Total	Mg#
-1073	54.44	0.09	0.49	5.38	6.63	0.12	32.39	0.86	0.15	100.54	89.70
-976	54.43	0.10	0.51	5.51	6.23	0.14	32.51	0.89	0.15	100.46	90.29
-972	53.28	0.06	0.90	6.59	5.58	0.15	32.39	1.04	0.16	100.16	91.19
-736	54.35	0.09	0.79	6.23	5.72	0.13	32.33	1.03	0.15	100.82	90.97
-664	54.00	0.11	0.56	5.59	5.88	0.17	32.83	0.82	0.13	100.08	90.87
-349	54.43	0.07	0.72	5.87	6.09	0.12	32.53	0.78	0.14	100.77	90.50
-284	54.53	0.09	0.50	5.49	5.91	0.18	32.67	0.89	0.13	100.39	90.79
-263	54.28	0.09	0.63	5.48	5.56	0.11	32.78	1.08	0.15	100.15	91.31
-260	54.67	0.08	0.66	5.38	5.51	0.14	32.98	1.02	0.15	100.58	91.43
-220	54.34	0.10	0.83	6.08	5.27	0.13	32.42	1.56	0.23	100.94	91.64
-217	54.68	0.09	1.12	5.05	5.24	0.13	32.32	2.02	0.19	100.84	91.66
-162	54.55	0.09	0.81	6.03	5.41	0.13	32.83	0.93	0.17	100.95	91.54

Table A4-4: Olivine composition of Run 54 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	SiO ₂	FeO	MnO	MgO	CaO	Total	Mg#
-353	41.18	8.51	0.13	50.20	0.25	100.28	91.32
-330	41.04	8.51	0.15	50.27	0.24	100.20	91.33
-328	41.16	8.53	0.13	49.92	0.28	100.03	91.25
-324	41.37	8.32	0.14	50.11	0.25	100.19	91.48
-298	41.02	8.58	0.17	50.49	0.25	100.51	91.30
-279	40.75	8.50	0.14	50.26	0.30	99.94	91.34
-260	41.24	8.47	0.16	50.21	0.26	100.35	91.36
-257	41.16	8.40	0.15	50.37	0.29	100.37	91.45
-201	41.07	8.40	0.17	50.48	0.28	100.40	91.46
-192	40.97	8.57	0.17	50.08	0.27	100.05	91.24
-189	41.50	8.51	0.13	50.09	0.32	100.55	91.30
-160	41.61	8.53	0.16	49.92	0.31	100.53	91.25

Table A4-5: Spinel composition of Run 54 conducted at 1340°C and 1.5 GPa for 72 hours

Distance (μm)	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MgO	Total	Mg#	Cr#
-1332	0.14	11.84	58.22	7.82	22.49	100.50	83.68	12.01
-1328	0.13	12.28	57.92	7.69	22.42	100.44	83.87	12.46
-1303	0.15	12.64	57.58	7.93	22.22	100.52	83.32	12.84
-1285	0.12	11.42	58.38	6.98	23.11	100.02	85.51	11.60
-1192	0.12	12.18	57.53	7.70	22.43	99.96	83.85	12.44
-1186	0.16	13.67	55.55	7.87	22.37	99.62	83.52	14.17
-1182	0.14	12.81	56.34	7.80	22.18	99.26	83.52	13.24
-1180	0.13	11.48	58.85	7.53	22.56	100.55	84.23	11.58
-1177	0.14	11.86	58.12	7.82	22.38	100.32	83.61	12.05
-1125	0.14	18.76	52.50	6.92	22.09	100.40	85.06	19.34
-978	0.15	17.02	53.15	8.49	21.51	100.32	81.87	17.69
-971	0.16	17.98	51.63	8.36	21.53	99.65	82.12	18.94
-747	0.17	19.70	50.98	8.69	21.24	100.78	81.34	20.59
-608	0.20	22.86	47.50	8.96	20.61	100.13	80.40	24.41
-527	0.19	23.51	47.16	9.01	20.23	100.11	80.01	25.07

APPENDIX B

Ion Microprobe Data for Chapter 2

Table B1-1: Ion microprobe analyses of partial melting experimental runs. All data relative to C 1 chondrite of McDonough and Sun (1995).

Distance (μm)	La	Ce	Nd	Sm	Dy	Er	Yb
<i>Clinopyroxene Run 27</i>							
-203	0.3679	0.7953	1.2015	0.8270	3.0423	3.1031	4.4373
-173	0.3156	1.2930	1.2906	3.1284	4.3272	5.3200	3.7155
-79	0.4063	0.9962	1.9048	2.0453	3.2508	4.5681	3.4031
-73	0.5527	1.2752	1.7276	2.0615	4.1069	4.8331	2.4112
-74	0.8443	2.0589	3.9742	2.8351	5.2663	4.3163	4.3410
4	1.7173	3.1866	3.7004	3.9250	7.3183	5.2588	4.5907
15	2.1633	4.0413	5.0989	6.1331	6.8179	5.1363	6.0261
156	1.5354	3.4837	5.4779	8.1703	9.8634	8.6319	8.2335
180	0.7443	2.6726	3.1956	3.4182	6.8512	9.8656	5.4137
496	3.6190	7.4953	9.9923	12.0919	8.1598	10.7388	8.8814
963	3.5169	5.5396	7.8278	5.4486	7.9528	6.6050	8.1938
1004	4.2582	6.9798	8.4204	8.8041	7.4081	11.7969	7.0273
1234	1.0802	2.7910	4.9514	6.7135	8.2317	7.3769	6.1571
1548	1.6211	3.0661	4.7508	8.2196	7.0663	6.2663	5.8354
1578	1.3582	2.2644	2.7298	4.6142	5.4077	4.0913	5.3975
<i>Glass Run 27</i>							
-134	29.5454	42.7223	26.9643	15.9545	13.5841	15.1420	12.7523
-187	26.8333	35.3179	21.7836	17.2453	11.8744	12.2231	9.9398
<i>Clinopyroxene Run 37</i>							
-85	0.5481	1.0383	1.4668	1.6187	2.8605	3.27	3.555
-25	0.7068	1.2825	1.6184	1.8882	3.0393	3.116	3.3175
-45	0.4089	0.6334	1.3325	2.7132	2.25	2.2569	2.8446
-6	0.4679	1.1023	1.7044	2.1409	2.9458	3.3582	4.0306
12	0.6072	0.8692	1.6916	2.7504	3.126	3.4194	3.4385
393	1.3198	2.0494	3.2698	3.8334	4.396	4.6764	4.8116
1360	1.7759	3.5168	4.9902	7.2966	7.9868	6.4355	6.7571

Table B1-1: continued

Distance (μm)	La	Ce	Nd	Sm	Dy	Er	Yb
424	4.0717	6.2604	5.4545	6.4387	7.4787	6.572	7.7919
776	3.8793	7.1333	7.3572	9.3599	8.8383	7.0524	8.5853
1572	2.1599	4.4351	5.6977	7.4516	8.0326	8.3323	7.4389
1409	1.6738	3.1992	4.3012	4.1159	6.0879	6.2422	6.4989
1001	1.6363	3.4811	4.2287	6.6497	6.7673	6.226	7.6352
<i>Glass Run 37</i>							
-112	36.4392	41.5258	32.4571	23.1507	15.652	13.4713	11.5609
-70	38.0203	41.7248	32.1411	23.9655	13.7179	12.3981	10.9447
-89	37.8688	42.046	30.216	20.7243	16.452	15.1063	10.0099
-110	37.1093	45.7427	31.5869	23.6878	12.5394	12.6031	12.1957

Table B1-2: Ion microprobe analyses of partial melting experimental runs.

Distance (μm)	Sr	Ti	Zr	Y	Na	Cr
<i>Clinopyroxene Run 27</i>						
-177	1.19	1.43	0.82	3.31	1.43	0.63
-159	0.63	0.28	0.39	0.32	0.36	0.11
-158	1.89	2.22	1.17	5.55	2.23	1.02
-152	0.34	0.20	0.23	0.35	0.39	0.05
-95	2.04	2.61	1.49	6.12	2.62	1.04
-82	1.73	1.73	0.95	3.89	1.37	0.82
-77	1.57	2.08	1.03	4.81	2.18	0.92
-66	1.98	2.65	1.51	6.06	2.19	1.05
-60	1.77	1.98	1.10	4.88	2.29	0.95
-47	2.75	2.72	1.51	7.57	2.64	1.23
-35	5.10	3.16	3.03	6.91	2.13	1.32
-12	3.56	3.30	1.94	7.39	2.43	1.19
-95	2.04	3.79	1.90	9.12	3.55	1.26
-82	1.73	3.04	1.65	7.05	2.20	1.33
-77	1.57	5.52	4.46	12.79	2.84	1.30
-66	1.98	3.90	2.59	9.00	2.75	1.25
-60	1.77	3.48	1.86	8.02	3.75	1.08
-47	2.75	3.99	2.43	8.90	3.81	1.06
-95	2.04	7.25	5.05	15.47	2.90	1.27
-82	1.73	4.73	2.52	11.17	3.47	1.22
1034	5.31	5.00	3.34	11.71	3.47	1.28
1579	4.30	2.88	1.38	6.53	4.07	0.97
1582	6.39	4.91	3.26	9.62	4.03	1.23
1689	6.38	5.40	3.34	13.45	3.53	1.28
<i>Glass Run 27</i>						
-188	65.17	18.82	30.10	22.80	0.29	7.39
-170	56.96	15.29	26.16	17.07	0.25	6.81

Table B1-2: continued

Distance (µm)	Sr	Ti	Zr	Y	Na	Cr
-159	56.06	15.44	24.63	18.31	0.33	6.67
-149	64.41	18.41	29.24	22.74	0.28	7.22
-145	42.00	11.55	19.83	13.62	0.23	5.87
-71	47.07	14.32	22.48	14.60	0.12	7.39
<i>Clinopyroxene Run 37</i>						
-63	1.17	1.41	0.62	2.94	1.45	0.64
-26	1.51	1.58	0.89	4.16	1.8	0.75
22	6	3.78	4.26	6.09	1.38	1.62
105	3.01	2.58	1.44	6.07	2.14	0.7
240	3.25	2.96	1.8	5.5	2.01	0.65
334	5.88	3.59	2.77	6.59	1.93	1.11
644	3.52	3.28	1.9	7.14	2.12	0.68
1074	2.71	2.88	1.73	5.85	1.97	0.75
1156	6.34	4.24	4.23	8.91	1.75	1.02
1411	4.77	3.76	2.65	8.13	2.28	1.36
<i>Glass Run 37</i>						
-136	41.23	14.19	18.52	16.89	0.16	7.04
-78	38.89	12.81	18.99	16.47	0.17	4.96
-80	49.49	16.08	23.01	16.7	0.13	7.04
-108	48.84	16.42	22.29	19.05	0.18	7.04
-49	50.37	15.81	22.02	20.87	0.13	7.04
-126	47.79	15.56	22.28	21.48	0.18	7.04

APPENDIX C

Electron Microprobe Data for Chapter 3

Table C1-1: Glass composition of run Pyx3, conducted at 1300°C and 2.0 GPa for 6 hours

Distance (µm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-19	55.32	0.71	17.43	8.66	0.27	4.73	8.50	2.85	0.64	0.11	99.23	49.34
-15	55.56	0.74	17.22	8.74	0.19	4.95	8.76	2.75	0.75	0.12	99.78	50.24
-14	55.34	0.79	17.26	8.53	0.14	4.96	8.45	2.81	0.66	0.12	99.07	50.90
-12	55.19	0.80	17.34	8.78	0.20	4.94	8.50	2.81	0.74	0.15	99.45	50.08
-11	55.41	0.79	17.48	8.75	0.13	4.79	8.47	2.90	0.65	0.21	99.58	49.39
-10	56.20	0.73	17.37	8.52	0.22	5.01	8.53	2.79	0.72	0.16	100.26	51.18
-10	55.72	0.76	17.58	8.89	0.13	4.64	8.49	2.84	0.67	0.07	99.79	48.20
-9	55.89	0.76	17.52	8.61	0.23	5.02	8.55	2.77	0.68	0.13	100.16	50.97
-8	55.00	0.79	17.31	8.90	0.27	4.83	8.68	2.73	0.60	0.11	99.22	49.18
-5	55.99	0.78	17.56	8.75	0.27	5.00	8.36	2.92	0.65	0.12	100.39	50.47
2	55.08	0.81	17.49	8.59	0.22	5.10	8.38	2.86	0.70	0.16	99.38	51.42
3	55.84	0.76	17.54	8.48	0.22	5.06	8.35	2.85	0.58	0.12	99.79	51.55
3	55.74	0.73	17.64	8.58	0.24	5.11	8.62	2.86	0.70	0.16	100.39	51.50
23	55.82	0.75	17.60	8.44	0.23	4.86	8.64	2.91	0.70	0.17	100.12	50.66
27	55.42	0.75	17.41	8.66	0.15	4.86	8.49	2.87	0.65	0.07	99.31	50.01
31	55.73	0.75	17.61	8.53	0.23	4.87	8.56	2.86	0.75	0.11	99.99	50.44
38	56.25	0.74	17.83	8.43	0.21	4.84	8.72	2.90	0.67	0.12	100.72	50.58
43	56.16	0.72	17.58	8.55	0.23	4.95	8.66	2.91	0.70	0.17	100.62	50.79
56	55.56	0.78	17.71	8.54	0.21	4.75	8.66	2.86	0.76	0.10	99.93	49.79
63	55.73	0.75	17.80	8.43	0.19	4.79	8.58	2.87	0.70	0.13	99.97	50.32
78	55.50	0.76	17.95	8.40	0.18	4.69	8.51	2.84	0.72	0.12	99.68	49.89
84	56.18	0.74	17.92	8.38	0.20	4.82	8.63	2.89	0.73	0.15	100.66	50.63
104	55.61	0.74	18.05	8.41	0.19	4.79	8.77	2.86	0.75	0.12	100.29	50.38
122	56.05	0.74	17.93	8.36	0.25	4.63	8.82	2.88	0.62	0.11	100.38	49.68
124	56.16	0.73	17.99	8.50	0.19	4.66	8.67	2.97	0.74	0.18	100.79	49.43
145	55.75	0.77	18.22	8.39	0.19	4.60	8.56	2.84	0.69	0.14	100.15	49.43
165	56.07	0.75	18.23	8.44	0.18	4.64	8.57	2.90	0.71	0.13	100.62	49.50
185	55.88	0.73	18.30	8.49	0.23	4.60	8.66	2.89	0.74	0.17	100.69	49.13
205	55.66	0.75	18.42	8.41	0.17	4.52	8.70	2.92	0.70	0.15	100.39	48.93
212	55.72	0.76	18.66	8.55	0.18	4.53	8.61	2.93	0.68	0.07	100.68	48.58
226	55.73	0.73	18.44	8.66	0.18	4.55	8.77	2.90	0.71	0.12	100.78	48.37
241	55.21	0.75	18.49	8.48	0.22	4.58	8.67	2.84	0.73	0.14	100.10	49.06
258	55.80	0.79	18.44	8.37	0.18	4.50	8.62	2.96	0.73	0.12	100.51	48.94

Table C1-1 continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
274	55.78	0.77	18.34	8.37	0.19	4.53	8.75	2.93	0.72	0.15	100.54	49.11
291	55.57	0.75	18.61	8.47	0.22	4.44	8.68	2.94	0.74	0.15	100.57	48.31
308	55.29	0.76	18.54	8.31	0.22	4.48	8.83	2.91	0.73	0.15	100.21	49.01
325	55.58	0.74	18.81	8.37	0.20	4.47	8.58	2.92	0.73	0.14	100.54	48.77
342	55.53	0.77	18.67	8.30	0.20	4.38	8.70	2.87	0.75	0.13	100.28	48.48
346	55.40	0.72	18.78	8.54	0.20	4.41	8.49	2.84	0.70	0.15	100.22	47.93
359	55.50	0.75	18.47	8.52	0.14	4.41	8.59	2.91	0.73	0.16	100.18	47.99
373	55.34	0.71	18.61	8.32	0.17	4.40	8.71	2.94	0.71	0.19	100.11	48.53
384	55.54	0.75	18.78	8.43	0.20	4.43	8.69	2.93	0.69	0.14	100.57	48.37
397	55.27	0.76	18.82	8.40	0.22	4.32	8.62	2.93	0.75	0.16	100.25	47.83
413	55.38	0.74	18.68	8.19	0.19	4.35	8.82	2.88	0.72	0.15	100.11	48.64
431	55.62	0.74	18.89	8.26	0.17	4.30	8.71	2.84	0.74	0.18	100.45	48.14
437	55.34	0.76	18.78	8.28	0.20	4.34	8.79	2.89	0.77	0.18	100.32	48.31
462	55.39	0.79	18.83	8.42	0.20	4.35	8.46	2.94	0.68	0.15	100.22	47.95
486	55.61	0.76	18.96	8.47	0.20	4.24	8.78	2.91	0.73	0.15	100.83	47.16
508	55.30	0.78	18.72	8.46	0.18	4.32	8.72	2.91	0.68	0.14	100.21	47.66
511	55.46	0.80	18.84	8.42	0.19	4.31	8.76	2.89	0.74	0.12	100.54	47.72
536	55.25	0.75	19.08	8.14	0.19	4.20	8.71	2.87	0.72	0.12	100.03	47.91
560	55.36	0.74	19.07	8.33	0.20	4.18	8.81	2.95	0.69	0.12	100.45	47.22
585	55.38	0.75	19.05	8.44	0.23	4.19	8.55	2.99	0.72	0.13	100.43	46.95
610	55.36	0.75	19.12	8.53	0.22	4.23	8.65	2.92	0.77	0.13	100.68	46.92
634	55.13	0.76	18.97	8.22	0.23	4.22	8.60	3.01	0.69	0.16	100.00	47.79
650	55.17	0.77	18.81	8.06	0.22	4.15	8.69	2.94	0.69	0.16	99.64	47.86
656	55.62	0.72	18.80	8.36	0.18	4.17	8.80	2.93	0.76	0.19	100.52	47.07
661	55.18	0.78	19.08	8.21	0.24	4.18	8.85	2.94	0.74	0.15	100.34	47.58
672	55.70	0.77	19.09	8.10	0.22	4.06	8.72	2.95	0.66	0.12	100.39	47.19
692	55.47	0.77	19.07	8.27	0.19	4.08	8.79	2.94	0.74	0.14	100.46	46.80
713	55.41	0.75	19.14	8.25	0.21	4.08	8.64	2.96	0.74	0.17	100.36	46.86
725	55.43	0.77	18.83	8.37	0.21	4.11	8.87	2.96	0.73	0.14	100.40	46.68
737	55.46	0.72	19.02	8.30	0.18	4.08	8.79	2.98	0.71	0.09	100.34	46.71
742	55.71	0.73	19.26	8.15	0.22	4.07	8.68	2.94	0.70	0.16	100.63	47.10
748	55.55	0.77	18.97	8.32	0.20	4.12	8.78	2.91	0.71	0.16	100.48	46.89
760	55.56	0.74	19.00	8.48	0.21	4.05	8.83	2.97	0.68	0.10	100.62	45.99

Table C1-1 continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
774	55.54	0.75	19.02	8.34	0.15	4.08	8.79	2.96	0.72	0.16	100.52	46.59
793	55.31	0.77	18.97	8.42	0.21	4.02	8.75	2.91	0.76	0.18	100.28	45.98
813	55.31	0.79	19.19	8.35	0.23	4.01	8.68	2.96	0.74	0.19	100.44	46.13
832	55.22	0.73	18.96	8.30	0.24	4.01	8.91	2.92	0.72	0.13	100.14	46.28
852	55.17	0.78	18.81	8.25	0.21	4.01	8.75	2.93	0.69	0.18	99.78	46.43
871	54.93	0.77	18.89	8.29	0.14	3.99	8.65	2.93	0.73	0.17	99.48	46.18
891	55.27	0.79	18.95	8.09	0.28	4.04	8.74	2.97	0.74	0.16	100.03	47.10
910	54.76	0.79	18.80	8.45	0.18	3.98	8.85	2.93	0.69	0.14	99.57	45.64
929	55.42	0.76	18.96	8.36	0.19	3.99	8.76	2.97	0.73	0.11	100.25	45.97
949	54.92	0.75	18.89	8.16	0.21	3.97	8.71	2.95	0.78	0.20	99.54	46.45
998	55.64	0.78	19.09	8.53	0.18	3.98	8.74	2.91	0.74	0.15	100.74	45.41
1016	54.92	0.79	19.09	8.22	0.21	3.93	8.67	3.00	0.70	0.16	99.70	46.02
1035	54.90	0.74	19.07	8.43	0.21	3.93	8.75	2.91	0.74	0.17	99.86	45.39
1053	55.66	0.77	19.13	8.38	0.21	3.91	8.95	2.97	0.73	0.17	100.87	45.41
1071	55.31	0.76	19.05	8.29	0.21	3.98	8.87	2.98	0.75	0.16	100.37	46.12
1090	55.59	0.77	19.18	8.16	0.17	3.97	8.64	2.91	0.72	0.09	100.20	46.45
1108	55.31	0.78	18.91	8.34	0.22	3.99	8.72	2.95	0.69	0.17	100.09	46.03
1126	55.67	0.78	19.09	8.34	0.17	3.96	8.84	2.94	0.73	0.19	100.72	45.84
1145	55.04	0.81	19.06	8.37	0.18	3.99	8.74	2.97	0.67	0.13	99.98	45.94
1163	55.34	0.80	19.09	8.31	0.17	3.98	8.74	2.94	0.76	0.16	100.27	46.06
1181	55.40	0.81	19.20	8.46	0.21	3.91	8.76	2.94	0.73	0.12	100.52	45.18
1200	54.57	0.77	19.09	8.44	0.23	3.87	8.73	2.89	0.72	0.11	99.41	44.98
1218	55.33	0.78	19.22	8.29	0.20	3.94	8.95	2.93	0.72	0.15	100.49	45.87
1237	54.52	0.78	19.29	8.37	0.18	3.86	8.47	2.89	0.73	0.15	99.25	45.12
1255	55.33	0.80	19.21	8.34	0.22	3.95	8.85	2.95	0.72	0.14	100.51	45.78
1273	55.32	0.80	19.06	8.34	0.22	3.89	8.68	2.93	0.69	0.18	100.10	45.40
1292	55.25	0.76	19.23	8.47	0.24	3.89	8.82	2.92	0.71	0.14	100.44	45.02
1328	55.39	0.76	19.39	8.54	0.22	3.90	8.89	2.98	0.70	0.12	100.90	44.88
1341	55.54	0.78	19.25	8.35	0.24	3.92	8.70	2.99	0.71	0.10	100.57	45.56
1354	55.20	0.78	19.09	8.31	0.19	3.93	8.91	2.93	0.73	0.15	100.20	45.75
1366	55.35	0.75	19.09	8.71	0.20	3.88	8.63	2.94	0.64	0.12	100.32	44.27
1391	55.15	0.80	19.30	8.49	0.26	3.86	8.79	2.90	0.68	0.17	100.41	44.77
1403	55.42	0.75	19.13	8.48	0.20	3.87	8.82	2.99	0.73	0.14	100.54	44.86

Table C1-1 continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
1416	55.44	0.76	19.10	8.32	0.22	3.83	8.86	2.99	0.72	0.14	100.38	45.08
1428	54.74	0.78	18.93	8.42	0.19	3.88	8.86	2.91	0.74	0.10	99.55	45.10
1453	55.33	0.82	19.25	8.48	0.25	3.88	8.95	3.01	0.73	0.14	100.84	44.93
1454	55.13	0.82	19.15	8.36	0.23	3.87	8.76	3.01	0.68	0.09	100.10	45.22
1478	55.03	0.77	19.02	8.23	0.25	3.88	8.75	2.92	0.70	0.14	99.69	45.67
1490	55.39	0.77	19.14	8.51	0.16	3.88	8.57	2.97	0.73	0.11	100.24	44.84
1503	55.15	0.78	18.94	8.32	0.15	3.91	9.06	2.84	0.77	0.19	100.11	45.59
1515	55.36	0.77	19.31	8.61	0.21	3.84	8.82	2.99	0.72	0.11	100.75	44.29
1531	55.04	0.74	19.28	8.54	0.19	3.87	8.75	2.97	0.76	0.17	100.31	44.69
1541	55.15	0.78	18.98	8.44	0.20	3.86	9.02	2.99	0.71	0.11	100.25	44.92
1552	54.84	0.79	19.10	8.37	0.21	3.90	8.80	2.93	0.67	0.13	99.74	45.38
1563	55.34	0.79	19.33	8.42	0.20	3.89	8.90	2.94	0.71	0.15	100.67	45.17
1573	55.28	0.80	18.92	8.46	0.18	3.91	8.70	2.99	0.73	0.15	100.12	45.18
1584	55.18	0.79	19.03	8.36	0.24	3.87	8.85	2.93	0.72	0.13	100.08	45.22
1594	55.42	0.82	19.18	8.42	0.22	3.82	8.76	2.95	0.71	0.14	100.45	44.72
1605	55.05	0.78	19.03	8.42	0.21	3.85	8.91	2.98	0.74	0.11	100.08	44.91
1613	55.35	0.78	19.00	8.58	0.22	3.85	8.61	2.97	0.68	0.13	100.18	44.44
1615	54.95	0.78	19.08	8.44	0.28	3.84	8.75	2.91	0.67	0.09	99.79	44.79
1626	55.21	0.80	19.12	8.42	0.23	3.88	8.77	2.89	0.68	0.11	100.13	45.10
1647	55.13	0.82	19.08	8.48	0.25	3.85	8.97	3.03	0.77	0.12	100.51	44.73
1658	55.00	0.78	19.29	8.52	0.21	3.92	8.76	3.00	0.70	0.17	100.36	45.06
1659	55.10	0.74	18.75	8.16	0.20	3.83	9.02	2.97	0.72	0.17	99.66	45.56
1668	54.32	0.78	18.89	8.34	0.21	3.80	8.67	3.01	0.65	0.14	98.82	44.82

Table C1-2: Clinopyroxene composition of run Pyx3, conducted at 1300°C and 2.0 GPa for 6 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-27	51.40	0.38	1.01	6.90	3.02	0.09	17.52	0.03	18.78	1.20	100.34	37.28
-43	50.30	0.37	0.63	7.50	4.30	0.15	22.71	0.00	12.45	0.85	99.27	0.00
-52	52.36	0.22	0.87	6.61	3.61	0.12	19.93	0.03	16.00	0.98	100.72	30.83
-93	52.46	0.19	0.81	6.10	3.81	0.12	20.41	0.04	15.41	0.90	100.24	37.28
-261	52.58	0.20	0.84	6.25	3.58	0.12	19.74	0.05	16.32	0.96	100.63	90.77
-329	51.87	0.33	0.84	7.81	3.62	0.12	19.15	0.05	15.87	1.13	100.80	90.41
-430	50.03	0.38	1.07	7.21	2.94	0.08	16.24	0.00	19.16	1.37	98.48	90.78
-436	52.24	0.26	0.98	6.80	3.34	0.10	18.38	0.04	17.40	0.98	100.51	90.75
-517	51.87	0.36	0.84	8.14	3.58	0.11	18.58	0.03	16.06	1.10	100.68	90.25
-558	50.05	0.23	0.72	6.78	4.22	0.12	21.76	0.00	14.17	0.99	99.04	90.19
-631	50.65	0.34	0.77	8.47	3.59	0.12	19.13	0.00	15.87	1.20	100.14	90.48
-672	51.91	0.41	1.10	7.43	2.85	0.09	16.30	0.05	19.33	1.32	100.79	91.07
-781	52.10	0.37	1.08	7.28	2.95	0.09	16.84	0.06	19.04	1.23	101.04	91.05
-795	52.55	0.18	0.84	6.09	3.64	0.10	19.88	0.06	15.97	0.84	100.16	90.69
-814	52.45	0.23	0.86	6.81	3.60	0.13	19.81	0.06	15.82	0.94	100.72	90.75
-996	52.73	0.18	0.87	6.30	3.66	0.12	20.05	0.04	16.03	0.83	100.81	90.71
-1022	50.77	0.21	0.83	6.67	3.62	0.13	19.63	0.00	15.99	0.97	98.81	90.63
-1090	52.24	0.41	1.03	7.20	2.94	0.08	16.39	0.06	19.46	1.27	101.10	90.86
-1109	52.57	0.16	0.81	6.23	3.77	0.13	20.60	0.00	15.48	0.88	100.63	90.69
-1211	52.17	0.38	1.13	7.43	2.94	0.09	16.24	0.06	19.19	1.56	101.19	90.78
-1378	51.92	0.36	1.01	7.09	3.04	0.10	17.50	0.05	18.72	1.09	100.86	91.12
-1412	51.47	0.23	0.80	6.95	3.78	0.13	20.57	0.00	14.77	0.98	99.68	90.66
-1467	52.72	0.19	0.88	6.32	3.57	0.11	19.98	0.06	16.13	0.88	100.83	90.89
-1629	50.72	0.41	1.01	7.24	2.93	0.10	16.49	0.00	19.27	1.27	99.44	90.94
-1630	52.02	0.39	1.02	7.17	2.98	0.08	16.66	0.06	19.25	1.21	100.84	90.88
-1636	52.07	0.35	1.05	6.98	2.93	0.08	16.86	0.05	18.79	1.02	100.18	91.12
-1672	52.11	0.17	0.84	6.07	3.69	0.13	20.49	0.00	15.94	0.88	100.32	90.83
-1751	51.95	0.36	1.02	6.96	3.01	0.10	17.35	0.05	18.63	1.00	100.42	91.13
-1811	52.63	0.28	0.82	7.77	3.58	0.12	18.82	0.03	15.92	1.08	101.05	90.36

Table C1-3: Orthopyroxene composition of run Pxx3, conducted at 1300°C and 2.0 GPa for 6 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-24	53.98	0.10	0.49	5.08	5.52	0.13	34.01	0.00	1.34	0.14	100.80	91.66
-55	54.56	0.13	0.55	5.58	5.61	0.13	32.60	0.06	1.92	0.19	101.34	91.20
-166	55.15	0.10	0.47	4.96	5.72	0.14	33.38	0.10	0.98	0.14	101.14	91.23
-172	53.99	0.11	0.52	5.19	5.61	0.13	32.49	0.00	1.31	0.17	99.51	91.17
-258	53.63	0.11	0.51	5.26	5.60	0.13	33.51	0.00	1.00	0.13	99.88	91.43
-284	54.80	0.10	0.59	5.43	5.53	0.13	32.58	0.09	1.93	0.16	101.36	91.31
-301	52.69	0.10	0.60	5.68	5.48	0.12	32.31	0.00	1.87	0.16	99.01	91.31
-343	54.88	0.12	0.54	5.42	5.79	0.11	33.49	0.11	0.88	0.11	101.45	91.16
-365	55.07	0.13	0.55	5.53	5.54	0.13	32.68	0.08	1.77	0.20	101.68	91.32
-387	53.37	0.10	0.59	5.69	5.47	0.13	32.16	0.00	1.98	0.18	99.66	91.29
-524	55.09	0.12	0.56	5.48	5.55	0.12	33.00	0.10	1.31	0.17	101.50	91.38
-616	55.18	0.10	0.56	5.42	5.55	0.11	32.94	0.10	1.49	0.16	101.61	91.37
-672	55.09	0.09	0.52	5.15	5.63	0.11	33.32	0.10	1.24	0.14	101.40	91.34
-675	52.81	0.10	0.54	5.23	5.77	0.13	33.90	0.00	1.34	0.16	99.99	91.29
-687	52.52	0.10	0.58	5.61	5.52	0.14	32.39	0.00	1.96	0.18	99.00	91.28
-762	52.90	0.13	0.57	5.89	5.58	0.13	32.55	0.00	1.98	0.21	99.95	91.23
-788	55.27	0.10	0.54	5.20	5.64	0.12	33.32	0.10	1.05	0.14	101.48	91.33
-816	52.53	0.11	0.57	5.59	5.54	0.14	32.32	0.00	1.94	0.19	98.94	91.23
-937	55.17	0.10	0.53	5.08	5.63	0.12	33.34	0.10	1.21	0.15	101.42	91.35
-1061	54.94	0.10	0.64	5.62	5.50	0.13	32.26	0.12	1.87	0.18	101.34	91.27
-1094	55.05	0.10	0.55	5.30	5.60	0.13	33.34	0.10	1.13	0.14	101.45	91.39
-1152	52.58	0.12	0.57	5.88	5.58	0.12	32.62	0.00	1.87	0.18	99.51	91.25
-1239	53.05	0.10	0.58	5.53	5.37	0.12	32.63	0.00	1.91	0.18	99.48	91.55
-1513	54.83	0.11	0.58	5.48	5.57	0.15	32.51	0.08	1.63	0.17	101.10	91.23
-1648	54.91	0.11	0.62	5.62	5.47	0.12	32.65	0.08	1.83	0.12	101.54	91.41
-1740	55.57	0.10	0.64	5.42	5.46	0.14	32.36	0.09	2.01	0.18	101.98	91.35
-1765	55.21	0.09	0.60	5.28	5.57	0.12	32.68	0.08	1.90	0.15	101.68	91.27

Table C1-4: Olivine composition of run Pyx3, conducted at 1300°C and 2.0 GPa for 6 hours

Distance (μm)	SiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Total	Mg#
-31	40.43	0.04	0.10	9.51	0.15	49.99	0.18	0.21	100.64	90.36
-48	40.64	0.05	0.08	9.49	0.15	49.93	0.20	0.19	100.73	90.37
-121	41.17	0.05	0.08	9.37	0.15	49.72	0.20	0.19	100.94	90.44
-154	40.16	0.06	0.10	9.21	0.16	50.22	0.00	0.19	100.13	90.67
-241	39.85	0.06	0.10	9.11	0.11	50.22	0.00	0.20	99.69	90.76
-371	39.27	0.06	0.12	9.23	0.15	49.55	0.00	0.22	98.64	90.54
-458	39.49	0.06	0.09	9.10	0.16	49.74	0.00	0.20	98.86	90.69
-487	40.87	0.05	0.10	9.32	0.14	49.69	0.23	0.20	100.65	90.48
-545	39.91	0.05	0.08	9.26	0.15	50.39	0.00	0.21	100.09	90.66
-601	39.38	0.06	0.11	9.10	0.15	49.67	0.00	0.22	98.72	90.68
-791	41.11	0.06	0.10	9.26	0.13	49.34	0.24	0.20	100.47	90.48
-935	39.43	0.05	0.09	9.20	0.13	50.01	0.00	0.21	99.14	90.65
-1004	41.12	0.06	0.07	9.13	0.14	49.95	0.26	0.20	100.96	90.70
-1055	41.16	0.06	0.09	9.10	0.12	49.58	0.25	0.21	100.60	90.67
-1289	41.01	0.06	0.10	9.13	0.14	50.00	0.27	0.20	100.93	90.71
-1369	39.88	0.06	0.11	9.08	0.13	49.73	0.00	0.22	99.25	90.71
-1499	39.68	0.06	0.11	9.06	0.13	49.36	0.00	0.21	98.62	90.67
-1624	41.29	0.05	0.07	9.08	0.14	49.91	0.22	0.21	100.95	90.74
-1716	40.65	0.06	0.10	9.18	0.14	49.49	0.00	0.19	99.85	90.58
-1723	41.31	0.06	0.10	9.17	0.14	49.34	0.20	0.20	100.53	90.56

Table C1-5: Garnet composition of run Pyx3, conducted at 1300°C and 2.0 GPa for 6 hours

Distance (µm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Total	Mg#	Pyrope %	Almandine %	Spessartine %	Grossular
Grain 1: rim-core-rim traverse														
0	40.24	0.38	0.17	23.30	14.36	0.63	15.31	6.11	100.51	65.53	54.46	28.64	1.27	15.63
8	40.31	0.40	0.16	23.37	14.34	0.60	15.17	6.15	100.49	65.35	54.23	28.76	1.22	15.79
15	40.37	0.41	0.16	23.24	14.38	0.61	15.09	6.26	100.52	65.17	53.88	28.81	1.24	16.06
22	40.49	0.33	0.14	23.41	14.37	0.61	14.96	6.31	100.62	64.99	53.63	28.89	1.23	16.25
36	40.33	0.53	0.14	23.22	14.37	0.64	14.85	6.55	100.63	64.82	53.07	28.81	1.30	16.82
42	40.28	0.55	0.14	23.21	14.30	0.60	14.79	6.62	100.48	64.84	53.01	28.74	1.21	17.04
51	40.47	0.56	0.13	23.34	14.32	0.64	14.75	6.76	100.97	64.74	52.68	28.69	1.29	17.34
Grain 2: rim-core-rim traverse														
0	40.75	0.40	0.22	23.43	13.82	0.55	15.32	6.06	100.56	66.40	55.23	27.93	1.13	15.70
9	40.59	0.45	0.25	23.44	13.95	0.60	15.30	6.26	100.84	66.16	54.72	27.98	1.21	16.09
14	40.63	0.47	0.23	23.45	14.09	0.58	15.26	6.38	101.08	65.88	54.36	28.14	1.17	16.32
28	40.64	0.47	0.19	23.52	14.21	0.58	14.96	6.52	101.10	65.24	53.53	28.52	1.18	16.77
44	40.62	0.41	0.16	23.77	14.39	0.62	14.94	6.44	101.35	64.92	53.38	28.84	1.25	16.53
54	40.92	0.44	0.15	23.55	14.46	0.64	15.05	6.42	101.62	64.98	53.48	28.83	1.30	16.39
67	40.76	0.41	0.14	23.63	14.38	0.61	15.03	6.29	101.25	65.08	53.77	28.85	1.23	16.16
76	40.99	0.40	0.15	23.74	14.41	0.62	15.41	6.24	101.96	65.60	54.40	28.53	1.25	15.82
78	41.45	0.36	0.15	24.02	14.32	0.60	15.75	6.19	102.84	66.23	55.14	28.11	1.19	15.56
Grain 3: rim-core-rim traverse														
0	40.57	0.35	0.17	23.66	14.22	0.60	15.13	6.16	100.86	65.48	54.29	28.62	1.22	15.87
3	40.94	0.38	0.16	23.63	14.09	0.61	15.10	6.17	101.08	65.64	54.35	28.44	1.24	15.97
5	40.95	0.38	0.16	23.83	14.34	0.62	15.17	6.21	101.66	65.35	54.12	28.70	1.25	15.93
9	41.09	0.40	0.16	23.89	14.23	0.61	15.09	6.17	101.64	65.41	54.18	28.66	1.25	15.91
19	41.15	0.40	0.16	23.71	14.26	0.59	15.04	6.35	101.67	65.28	53.82	28.64	1.20	16.33
32	41.29	0.38	0.15	23.83	14.15	0.61	15.09	6.28	101.80	65.53	54.11	28.46	1.24	16.19
37	41.30	0.38	0.15	23.99	14.34	0.59	15.14	6.20	102.08	65.31	54.13	28.76	1.19	15.92
38	41.44	0.40	0.15	24.07	14.32	0.59	14.97	6.30	102.26	65.08	53.71	28.82	1.21	16.25
48	41.65	0.30	0.14	24.28	14.29	0.63	15.12	6.20	102.62	65.36	54.10	28.68	1.27	15.94
60	41.72	0.40	0.15	24.26	14.22	0.59	15.08	6.31	102.73	65.41	54.00	28.57	1.20	16.24
63	42.07	0.38	0.16	24.38	14.14	0.60	15.29	6.17	103.20	65.85	54.61	28.33	1.22	15.84
68	42.61	0.37	0.16	24.60	14.13	0.59	15.64	6.19	104.30	66.37	55.16	27.96	1.18	15.69

Table C2-1: Glass composition of run Pyx10, conducted at 1300°C and 2.0 GPa for 24 hours

Distance (µm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-21	56.26	0.71	17.84	7.87	0.15	4.76	8.41	2.99	0.69	0.14	99.83	51.88
-19	55.67	0.73	17.73	8.06	0.21	4.73	8.57	2.92	0.75	0.14	99.51	51.13
-10	55.55	0.75	17.43	8.13	0.18	4.67	8.37	2.91	0.75	0.18	98.91	50.60
-5	55.64	0.72	17.61	7.80	0.18	4.69	8.37	3.03	0.68	0.12	98.85	51.74
0	55.38	0.73	17.65	8.02	0.18	4.63	8.47	2.97	0.75	0.14	98.91	50.72
10	55.36	0.74	17.79	7.86	0.21	4.59	8.67	3.05	0.70	0.14	99.12	51.01
20	55.92	0.78	17.68	7.97	0.20	4.67	8.39	3.04	0.74	0.16	99.55	51.09
22	56.26	0.69	18.13	8.00	0.17	4.55	8.26	3.01	0.73	0.17	99.96	50.35
36	55.76	0.75	17.55	7.90	0.14	4.54	8.67	3.05	0.75	0.08	99.20	50.61
37	56.19	0.77	17.78	7.95	0.19	4.68	8.35	3.08	0.70	0.16	99.85	51.21
41	56.13	0.69	17.76	7.96	0.20	4.65	8.69	3.04	0.74	0.14	100.00	51.02
61	56.13	0.78	17.99	7.64	0.18	4.67	8.64	3.09	0.74	0.13	99.99	52.15
82	55.91	0.73	17.79	7.75	0.21	4.67	8.54	3.06	0.72	0.15	99.52	51.79
103	55.74	0.71	18.07	7.75	0.19	4.58	8.55	3.09	0.75	0.12	99.55	51.31
123	55.94	0.72	17.77	7.94	0.12	4.58	8.47	3.11	0.76	0.10	99.51	50.70
144	56.21	0.73	18.01	7.84	0.14	4.57	8.49	3.02	0.79	0.17	99.97	50.96
165	55.98	0.74	18.03	7.93	0.10	4.53	8.47	3.17	0.75	0.16	99.87	50.46
185	56.08	0.74	18.36	7.91	0.18	4.60	8.37	3.08	0.74	0.13	100.18	50.90
206	55.73	0.74	18.10	7.67	0.20	4.51	8.64	3.07	0.77	0.17	99.59	51.18
237	56.13	0.74	18.07	7.56	0.19	4.55	8.60	3.05	0.74	0.12	99.75	51.76
315	55.66	0.74	18.25	7.80	0.20	4.49	8.51	3.03	0.77	0.16	99.62	50.65
393	55.20	0.75	18.26	7.63	0.17	4.40	8.52	3.10	0.78	0.13	98.93	50.69
471	55.59	0.71	18.31	7.61	0.18	4.42	8.39	3.11	0.75	0.19	99.27	50.87
550	55.56	0.72	18.52	7.84	0.15	4.32	8.64	3.06	0.75	0.19	99.75	49.56
706	55.67	0.75	18.76	7.43	0.20	4.34	8.53	3.06	0.70	0.13	99.56	51.01
784	55.38	0.70	18.87	7.68	0.15	4.32	8.75	3.13	0.72	0.17	99.88	50.07
863	55.34	0.73	19.03	7.88	0.15	4.29	8.64	3.07	0.67	0.12	99.92	49.25
941	55.23	0.77	18.54	7.72	0.18	4.25	8.71	3.10	0.76	0.12	99.38	49.53
1019	55.38	0.76	18.95	7.79	0.20	4.27	8.68	3.11	0.75	0.15	100.05	49.43
1097	55.26	0.74	18.95	7.92	0.18	4.31	8.66	3.14	0.77	0.12	100.04	49.24

Table C2-2: Garnet composition of run Pyx10, conducted at 1300°C and 2.0 GPa for 24 hours

Distance (µm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Total	Mg#	Pyrope %	Almandine %	Spessartine %	Grossular
Grain 1: rim-core-rim traverse 1														
0	40.46	0.33	0.24	23.19	13.77	0.57	15.14	6.10	99.78	66.22	54.92	28.02	1.17	15.90
11	40.43	0.36	0.20	23.34	14.18	0.58	14.88	6.40	100.36	65.17	53.60	28.65	1.18	16.56
23	40.44	0.38	0.20	23.27	14.32	0.62	14.66	6.64	100.53	64.60	52.71	28.88	1.27	17.14
45	40.52	0.44	0.14	23.43	14.91	0.59	14.07	7.06	101.16	62.72	50.54	30.03	1.21	18.22
56	40.61	0.40	0.13	23.53	14.85	0.63	14.24	7.03	101.42	63.09	50.89	29.77	1.28	18.07
68	40.48	0.43	0.09	23.56	15.34	0.65	13.54	7.07	101.18	61.15	49.07	31.18	1.33	18.42
79	40.86	0.32	0.02	23.60	17.27	0.74	12.79	6.79	102.39	56.90	46.04	34.88	1.51	17.58
102	40.28	0.40	0.11	23.45	14.91	0.62	14.05	6.89	100.72	62.69	50.69	30.17	1.27	17.87
Grain 1: rim-core-rim traverse 2 perpendicular to 1														
0	39.93	0.30	0.20	22.96	14.01	0.61	14.90	6.22	99.12	65.47	54.03	28.51	1.25	16.21
12	40.05	0.34	0.18	23.21	14.15	0.58	14.72	6.38	99.62	64.97	53.39	28.79	1.20	16.62
24	40.93	0.39	0.16	23.35	14.37	0.57	14.39	6.68	100.85	64.10	52.18	29.23	1.18	17.41
35	40.28	0.42	0.17	23.28	14.34	0.58	14.60	6.64	100.29	64.48	52.63	28.99	1.18	17.20
47	40.66	0.38	0.19	23.48	14.29	0.56	14.84	6.51	100.91	64.93	53.28	28.78	1.15	16.79
59	40.94	0.35	0.21	23.62	14.10	0.60	15.06	6.37	101.26	65.57	54.01	28.35	1.22	16.42
71	41.74	0.33	0.23	24.05	13.79	0.57	15.44	6.16	102.31	66.62	55.30	27.71	1.15	15.84
Grain 2: rim-core-rim traverse														
0	41.38	0.36	0.10	23.98	14.81	0.61	14.16	7.04	102.44	63.03	50.80	29.80	1.24	18.16
16	40.87	0.27	0.02	23.93	15.84	0.73	13.74	6.33	101.75	60.73	49.80	32.20	1.51	16.48
20	40.32	0.37	0.01	23.40	16.40	0.70	12.82	7.18	101.19	58.22	46.49	33.36	1.45	18.70
27	40.28	0.38	0.08	23.37	14.90	0.63	13.99	6.98	100.62	62.60	50.48	30.14	1.29	18.09
Grain 3: rim-core-rim traverse														
0	40.68	0.33	0.14	23.50	14.45	0.59	14.78	6.59	101.05	64.58	52.88	29.00	1.19	16.93
12	40.13	0.51	0.04	23.34	15.62	0.64	12.99	7.50	100.76	59.72	47.23	31.85	1.32	19.59
50	40.43	0.40	0.20	23.23	14.41	0.59	14.27	6.62	100.16	63.84	52.00	29.45	1.22	17.33
62	40.45	0.35	0.20	23.28	14.14	0.61	14.75	6.21	99.99	65.03	53.66	28.85	1.26	16.23
Grain 4: rim-core-rim traverse														
0	39.77	0.40	0.08	23.08	15.08	0.62	13.88	6.75	99.66	62.14	50.40	30.71	1.28	17.60
10	39.67	0.54	0.03	22.94	16.02	0.70	12.73	7.32	99.94	58.62	46.49	32.83	1.46	19.22
20	39.98	0.25	0.04	23.17	15.54	0.65	13.35	6.85	99.83	60.50	48.80	31.87	1.35	17.98
29	40.46	0.23	0.12	23.37	14.22	0.61	14.82	6.11	99.94	65.01	53.83	28.96	1.25	15.95
39	40.20	0.29	0.10	22.91	14.59	0.63	13.88	6.60	99.19	62.91	51.10	30.13	1.31	17.47
49	40.15	0.32	0.08	23.32	15.00	0.63	13.74	6.79	100.04	62.02	50.16	30.71	1.31	17.82
69	40.45	0.33	0.14	23.37	14.68	0.60	14.18	6.58	100.32	63.26	51.59	29.96	1.23	17.22
78	40.62	0.31	0.16	23.42	14.32	0.60	14.71	6.33	100.46	64.68	53.23	29.07	1.23	16.47
88	40.55	0.48	0.15	23.65	14.84	0.62	13.63	7.04	100.96	62.09	49.81	30.41	1.29	18.49

Table C2-2: continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Total	Mg#	Pyrope %	Almandine %	Spessartine %	Grossular
Grain 5: rim-core-rim traverse														
0	40.86	0.28	0.13	23.88	14.30	0.60	15.05	6.27	101.37	65.23	53.92	28.73	1.21	16.13
6	40.39	0.34	0.13	23.45	14.31	0.57	14.51	6.42	100.12	64.38	52.81	29.22	1.19	16.79
13	40.46	0.32	0.15	23.38	14.21	0.63	14.58	6.53	100.25	64.66	52.82	28.88	1.29	17.01
19	40.94	0.34	0.15	23.26	13.97	0.55	14.61	6.37	100.18	65.09	53.44	28.68	1.14	16.74

Table C3-1: Glass composition of run Pyx11, conducted at 1300°C and 2.0 GPa for 74 hours

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
1	57.48	0.74	17.78	7.33	0.15	4.96	8.47	3.01	0.76	0.13	100.82	54.68
10	57.47	0.75	17.58	7.28	0.17	4.98	8.45	3.13	0.75	0.13	100.71	54.95
25	57.27	0.72	17.57	7.38	0.16	5.03	8.46	3.14	0.83	0.12	100.67	54.86
44	57.16	0.77	17.55	7.37	0.17	4.93	8.49	3.09	0.75	0.07	100.35	54.39
69	57.21	0.75	17.65	7.35	0.21	4.97	8.44	3.18	0.78	0.11	100.64	54.66
83	57.25	0.74	17.74	7.45	0.18	4.86	8.58	3.13	0.79	0.15	100.87	53.77
97	57.28	0.72	17.67	7.39	0.18	4.86	8.46	3.23	0.79	0.13	100.72	53.97
111	57.28	0.73	17.84	7.41	0.16	4.91	8.61	3.12	0.74	0.12	100.93	54.16
139	56.69	0.75	17.61	7.33	0.14	4.71	8.28	3.08	0.77	0.15	99.51	53.39
153	57.27	0.77	17.93	7.31	0.19	4.76	8.46	3.15	0.75	0.17	100.76	53.72
166	56.98	0.68	17.85	7.48	0.19	4.75	8.26	3.10	0.78	0.11	100.19	53.10
180	57.07	0.76	17.91	7.31	0.17	4.72	8.57	3.13	0.80	0.14	100.58	53.51
194	56.74	0.72	17.86	7.27	0.18	4.70	8.58	3.07	0.82	0.15	100.09	53.54
208	56.93	0.75	18.06	7.41	0.19	4.74	8.36	3.09	0.76	0.16	100.47	53.28
222	57.03	0.76	18.20	7.28	0.14	4.75	8.42	3.09	0.76	0.14	100.58	53.77
236	56.93	0.75	17.93	7.27	0.13	4.72	8.35	3.07	0.78	0.12	100.05	53.65
250	56.58	0.73	17.89	7.22	0.17	4.78	8.28	3.14	0.82	0.13	99.74	54.14
264	56.68	0.72	17.99	7.42	0.17	4.71	8.43	3.08	0.78	0.13	100.12	53.09
278	56.56	0.78	18.08	7.33	0.16	4.75	8.50	3.16	0.74	0.13	100.19	53.60
292	56.73	0.73	18.14	7.33	0.10	4.78	8.46	3.12	0.79	0.14	100.32	53.76
306	56.79	0.75	18.14	7.25	0.18	4.75	8.46	3.17	0.84	0.16	100.49	53.88
319	56.71	0.78	17.97	7.12	0.16	4.77	8.43	3.09	0.76	0.16	99.93	54.43
333	56.76	0.77	17.99	7.16	0.21	4.71	8.47	3.13	0.75	0.13	100.09	53.98
347	56.60	0.73	17.97	7.31	0.14	4.70	8.51	3.09	0.76	0.11	99.90	53.41
361	57.09	0.74	18.01	7.29	0.09	4.78	8.45	3.04	0.81	0.16	100.47	53.90
375	56.44	0.74	18.10	7.42	0.18	4.72	8.54	3.13	0.76	0.15	100.17	53.14
389	56.29	0.75	18.13	7.33	0.12	4.81	8.50	3.11	0.77	0.16	99.98	53.92
441	56.61	0.79	18.23	7.41	0.17	4.78	8.40	3.12	0.77	0.12	100.39	53.49
531	56.48	0.72	18.26	7.33	0.22	4.78	8.45	3.10	0.81	0.14	100.28	53.76
620	56.46	0.78	18.17	7.28	0.16	4.74	8.49	3.04	0.77	0.18	100.06	53.72
710	56.28	0.76	18.15	7.44	0.20	4.77	8.65	3.09	0.77	0.12	100.22	53.34
799	56.49	0.74	18.13	7.21	0.17	4.75	8.43	3.13	0.76	0.15	99.96	54.01
889	56.62	0.74	18.17	7.37	0.19	4.73	8.58	3.15	0.69	0.13	100.37	53.36

Table C3-1: continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
978	56.56	0.75	18.32	7.37	0.16	4.70	8.52	3.16	0.77	0.17	100.48	53.20
1068	56.29	0.78	18.34	7.13	0.16	4.77	8.63	3.06	0.78	0.11	100.04	54.40
1158	56.32	0.79	18.33	7.45	0.14	4.71	8.70	3.15	0.73	0.11	100.44	52.99
1247	56.44	0.76	18.41	7.30	0.18	4.77	8.78	3.10	0.67	0.10	100.50	53.81

Table C3-2: Clinopyroxene composition of run Pyl1, conducted at 1300°C and 2.0 GPa for 74 hours

Distance (µm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
82	51.66	0.20	0.26	8.66	8.64	0.28	18.68	0.00	11.24	0.88	100.50	79.40
73	51.45	0.25	0.18	9.16	8.11	0.26	17.35	0.01	12.94	1.03	100.73	79.23
26	51.29	0.24	0.16	10.42	7.87	0.29	16.63	0.00	13.50	1.22	101.63	79.02
12	52.86	0.18	0.77	6.36	5.39	0.17	20.97	0.02	14.08	0.68	101.47	87.40
11	51.53	0.23	0.23	9.90	7.30	0.24	16.12	0.01	14.33	1.14	101.04	79.74
11	51.40	0.24	0.16	10.25	7.70	0.27	16.47	0.00	13.36	1.18	101.04	79.23
7	51.93	0.22	0.19	9.65	7.95	0.24	17.82	0.00	12.01	1.05	101.07	79.99
3	52.17	0.20	0.53	7.27	6.52	0.20	19.33	0.01	12.92	0.76	99.90	84.09
3	52.69	0.19	0.80	6.46	4.76	0.14	19.06	0.02	15.57	0.74	100.43	87.71
0	53.46	0.16	0.81	5.98	3.81	0.13	20.76	0.03	15.59	0.74	101.47	90.67
-8	52.93	0.16	0.69	6.02	4.77	0.13	24.88	0.04	10.61	0.49	100.73	90.29
-24	52.73	0.15	0.81	5.98	3.96	0.12	21.10	0.05	15.01	0.72	100.65	90.48
-35	52.14	0.37	0.71	7.74	3.85	0.14	19.71	0.02	14.80	0.96	100.44	90.13
-60	53.23	0.15	0.80	5.89	4.21	0.13	22.20	0.04	13.70	0.68	101.04	90.39
-61	51.88	0.31	1.02	7.02	3.20	0.10	18.21	0.02	18.36	0.81	100.93	91.03
-63	52.18	0.43	0.72	7.72	3.83	0.12	19.90	0.03	15.47	0.91	101.32	90.26
-64	52.21	0.28	0.87	6.65	3.62	0.12	19.42	0.03	16.45	0.83	100.47	90.53
-66	52.91	0.16	0.81	5.87	3.87	0.13	20.92	0.03	15.31	0.73	100.74	90.60
-69	52.86	0.19	0.84	6.22	3.79	0.13	20.34	0.04	15.77	0.78	100.94	90.54
-77	51.74	0.37	1.01	7.12	3.23	0.10	17.82	0.04	18.51	0.88	100.81	90.77
-77	52.62	0.28	0.78	6.60	3.76	0.12	19.92	0.04	15.91	0.84	100.88	90.43
-88	52.51	0.26	0.89	6.71	3.60	0.11	19.70	0.04	16.49	0.86	101.18	90.70
-88	52.35	0.30	0.91	6.80	3.42	0.09	18.99	0.02	17.17	0.87	100.92	90.83
-121	52.88	0.29	0.79	7.00	3.78	0.11	19.78	0.04	15.80	0.95	101.42	90.32
-132	53.13	0.29	0.74	7.48	4.05	0.14	20.83	0.03	13.87	0.95	101.51	90.17
-134	52.42	0.40	1.06	7.43	2.98	0.08	16.80	0.03	19.17	1.25	101.61	90.95
-166	52.96	0.28	0.94	6.74	3.41	0.11	18.90	0.01	17.55	0.90	101.80	90.81
-175	52.98	0.23	0.87	6.39	3.71	0.10	19.96	0.06	16.18	0.90	101.38	90.56
-199	52.06	0.28	0.95	6.60	3.25	0.09	18.74	0.04	17.51	0.91	100.43	91.14
-200	51.70	0.41	0.78	8.33	3.91	0.12	20.05	0.03	14.88	1.03	101.23	90.14
-202	53.11	0.17	0.86	6.08	3.80	0.13	20.61	0.03	15.52	0.83	101.14	90.63
-205	52.48	0.24	0.93	6.56	3.49	0.12	19.06	0.03	17.06	0.85	100.82	90.69
-254	51.93	0.32	1.03	7.11	3.30	0.09	18.14	0.03	17.74	0.95	100.65	90.74

Table C3-2: continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-306	52.20	0.34	1.06	7.29	3.10	0.10	18.00	0.04	18.33	0.99	101.43	91.19
-340	52.62	0.18	0.84	6.18	3.80	0.14	20.62	0.03	15.32	0.85	100.57	90.63
-348	52.31	0.29	0.96	7.08	3.40	0.10	18.56	0.05	17.08	0.95	100.79	90.68
-384	53.64	0.17	0.85	6.28	3.77	0.11	20.82	0.04	15.36	0.83	101.86	90.78
-399	52.93	0.24	0.76	6.65	3.97	0.14	21.80	0.03	13.74	0.83	101.08	90.73
-409	52.39	0.22	0.85	6.47	3.81	0.12	20.64	0.03	15.33	0.91	100.77	90.62
-416	52.77	0.26	0.79	7.09	3.81	0.13	20.38	0.04	15.09	1.03	101.38	90.51
-434	53.10	0.16	0.83	5.93	3.84	0.12	21.28	0.04	15.08	0.79	101.16	90.81
-472	53.07	0.16	0.83	5.94	3.94	0.14	21.62	0.03	14.61	0.75	101.09	90.73
-502	53.18	0.14	0.80	5.63	3.90	0.12	21.29	0.05	14.65	0.76	100.51	90.68
-561	51.59	0.39	1.07	7.42	2.95	0.09	17.15	0.03	19.00	1.22	100.90	91.20
-642	52.22	0.32	1.06	7.06	3.14	0.09	18.16	0.03	18.09	0.99	101.16	91.16
-669	52.13	0.30	1.06	6.94	3.20	0.10	18.43	0.02	18.04	0.93	101.15	91.13
-694	53.78	0.16	0.80	5.92	3.98	0.11	21.62	0.03	14.56	0.80	101.76	90.64
-726	52.16	0.30	1.04	6.82	3.22	0.09	18.56	0.01	17.65	0.95	100.80	91.13
-744	51.68	0.33	1.04	7.22	3.16	0.08	18.14	0.02	18.28	0.97	100.91	91.10
-785	51.75	0.35	1.01	6.88	2.97	0.09	17.64	0.03	18.61	1.16	100.49	91.37
-787	51.77	0.26	1.02	6.73	3.57	0.11	19.51	0.03	16.73	0.87	100.60	90.69
-792	51.53	0.39	1.05	6.89	2.93	0.09	16.78	0.04	19.27	1.32	100.28	91.08

Table C3-3: Orthopyroxene composition of run Pyx11, conducted at 1300°C and 2.0 GPa for 74 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-11	55.36	0.10	0.59	4.91	5.68	0.14	32.35	0.05	2.00	0.15	101.31	91.03
-43	54.99	0.15	0.53	5.73	5.55	0.13	31.87	0.03	2.56	0.18	101.72	91.10
-45	51.06	0.15	0.44	5.19	6.68	0.12	36.58	0.07	1.58	0.10	101.96	90.71
-46	55.16	0.11	0.51	5.16	5.56	0.14	33.09	0.06	1.07	0.10	100.96	91.39
-79	53.73	0.20	0.52	6.33	6.80	0.15	30.57	0.03	2.75	0.14	101.22	88.91
-99	55.05	0.11	0.56	5.30	5.87	0.13	32.55	0.04	1.50	0.12	101.26	90.81
-102	54.59	0.11	0.60	5.19	5.64	0.12	31.93	0.04	2.15	0.14	100.52	90.99
-107	54.66	0.11	0.54	5.00	5.79	0.13	33.28	0.04	2.03	0.15	101.73	91.11
-146	54.87	0.14	0.54	5.34	5.69	0.10	32.30	0.04	1.86	0.14	101.01	91.01
-235	55.05	0.08	0.60	4.94	5.46	0.10	32.35	0.08	2.19	0.14	101.00	91.35
-250	54.43	0.15	0.51	6.07	5.67	0.14	32.30	0.04	1.69	0.16	101.17	91.04
-346	54.75	0.13	0.55	5.49	5.55	0.12	32.33	0.05	1.90	0.18	101.06	91.22
-513	54.68	0.11	0.60	5.29	5.53	0.14	32.36	0.06	2.00	0.17	100.96	91.25
-602	54.94	0.10	0.52	5.29	5.62	0.15	33.29	0.09	1.14	0.10	101.25	91.35
-604	54.83	0.11	0.55	5.16	5.54	0.12	32.97	0.07	1.35	0.14	100.85	91.39
-683	54.88	0.11	0.59	5.18	5.49	0.12	32.42	0.06	2.03	0.18	101.07	91.33
-755	55.03	0.10	0.64	5.35	5.52	0.15	32.71	0.03	2.02	0.19	101.72	91.35
-771	54.55	0.13	0.55	5.45	5.55	0.13	32.80	0.04	1.95	0.17	101.32	91.33

Table C3-4: Olivine composition of run Pyx11, conducted at 1300°C and 2.0 GPa for 74 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-7	41.14	0.02	0.05	0.20	11.39	0.17	46.98	0.14	0.31	0.01	100.42	88.03
-13	40.50	0.01	0.05	0.09	12.30	0.17	46.88	0.15	0.25	0.01	100.41	87.17
-21	41.05	0.02	0.05	0.08	10.88	0.15	48.69	0.16	0.22	0.01	101.30	88.86
-25	41.29	0.02	0.05	0.15	12.10	0.18	46.67	0.12	0.28	0.02	100.88	87.30
-26	41.59	0.01	0.05	0.10	9.59	0.13	49.81	0.15	0.23	0.01	101.65	90.25
-31	40.72	0.01	0.06	0.23	9.15	0.14	47.59	0.14	0.32	0.02	98.40	90.27
-32	40.88	0.01	0.05	0.11	10.16	0.15	48.79	0.15	0.22	0.01	100.53	89.54
-32	41.43	0.01	0.05	0.09	9.95	0.15	49.33	0.13	0.24	0.01	101.40	89.84
-35	41.24	0.01	0.06	0.09	9.37	0.14	49.40	0.15	0.21	0.02	100.70	90.38
-41	41.27	0.00	0.05	0.11	9.92	0.16	49.55	0.15	0.20	0.02	101.44	89.90
-42	41.08	0.01	0.05	0.10	9.94	0.14	49.31	0.14	0.24	0.02	101.03	89.84
-46	40.25	0.02	0.03	0.10	12.36	0.17	47.25	0.10	0.25	0.01	100.54	87.21
-47	41.01	0.01	0.05	0.10	9.40	0.14	49.81	0.15	0.21	0.01	100.89	90.43
-52	41.32	0.01	0.06	0.16	9.16	0.13	49.44	0.16	0.24	0.02	100.70	90.59
-52	41.32	0.01	0.04	0.08	9.57	0.14	49.62	0.15	0.21	0.02	101.18	90.24
-59	41.38	0.01	0.05	0.11	9.31	0.14	49.92	0.17	0.22	0.02	101.32	90.53
-62	41.45	0.01	0.05	0.17	9.37	0.14	49.31	0.15	0.22	0.01	100.88	90.37
-64	40.87	0.01	0.06	0.23	9.39	0.14	50.27	0.14	0.24	0.01	101.36	90.52
-65	40.90	0.01	0.05	0.08	9.29	0.15	49.49	0.14	0.21	0.01	100.33	90.47
-74	41.74	0.01	0.05	0.22	9.22	0.14	49.80	0.13	0.27	0.02	101.60	90.59
-75	41.21	0.00	0.06	0.11	9.32	0.14	49.93	0.15	0.21	0.01	101.14	90.52
-122	41.60	0.01	0.05	0.15	9.25	0.13	50.33	0.16	0.26	0.01	101.94	90.65
-184	41.16	0.00	0.06	0.11	9.25	0.15	49.84	0.17	0.20	0.02	100.94	90.57
-243	41.40	0.02	0.07	0.18	9.14	0.14	49.83	0.15	0.28	0.02	101.24	90.67
-410	41.50	0.01	0.05	0.08	9.14	0.14	50.03	0.16	0.18	0.02	101.32	90.71
-470	40.96	0.00	0.07	0.11	9.10	0.14	50.34	0.16	0.22	0.01	101.13	90.79
-576	41.01	0.01	0.07	0.12	9.13	0.15	50.88	0.15	0.22	0.01	101.75	90.86
-583	41.36	0.02	0.06	0.10	9.13	0.12	50.02	0.14	0.20	0.02	101.17	90.71
-683	41.00	0.01	0.06	0.08	9.14	0.16	50.33	0.10	0.21	0.02	101.11	90.76
-735	41.07	0.01	0.06	0.11	9.14	0.13	50.37	0.12	0.20	0.02	101.22	90.76
-797	40.55	0.00	0.06	0.07	9.19	0.14	50.97	0.08	0.21	0.01	101.29	90.82

Table C3-5: Garnet composition of run Pys11, conducted at 1300°C and 2.0 GPa for 74 hours

Distance (µm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Total	Mg#	Pyrope %	Almandine %	Spessartine %	Grossular
Grain 1: rim-core-rim traverse 1														
0	41.44	0.29	0.16	24.07	13.75	0.55	15.38	5.96	101.61	66.60	55.54	27.86	1.13	15.47
9	40.81	0.33	0.15	23.74	14.47	0.61	14.67	6.35	101.13	64.39	52.97	29.30	1.26	16.47
18	40.69	0.41	0.13	23.59	14.80	0.60	14.26	6.77	101.26	63.21	51.36	29.90	1.23	17.52
26	40.53	0.41	0.11	23.63	15.01	0.65	14.00	6.92	101.26	62.45	50.44	30.32	1.32	17.92
35	40.78	0.43	0.06	23.85	15.45	0.68	13.76	7.03	102.03	61.36	49.37	31.10	1.39	18.14
53	40.25	0.40	0.05	23.55	15.55	0.65	13.64	6.83	100.92	60.99	49.33	31.56	1.34	17.76
70	40.86	0.38	0.18	23.66	14.65	0.60	14.61	6.49	101.44	64.00	52.49	29.53	1.22	16.76
79	40.89	0.42	0.23	23.63	14.18	0.61	15.11	6.41	101.49	65.51	53.93	28.39	1.23	16.45
88	41.20	0.37	0.23	23.36	13.94	0.55	15.53	6.27	101.46	66.50	55.13	27.77	1.12	15.99
114	41.29	0.32	0.26	23.75	13.56	0.52	16.13	5.63	101.45	67.97	57.45	27.08	1.06	14.41
123	41.97	0.29	0.23	22.82	12.77	0.54	16.32	6.61	101.54	69.50	57.19	25.10	1.07	16.64
132	41.28	0.30	0.21	23.83	13.08	0.52	16.72	5.61	101.55	69.51	58.90	25.84	1.04	14.21
Grain 1: rim-core-rim traverse 2														
0	40.39	0.30	0.22	23.53	13.09	0.54	15.86	5.62	99.56	68.36	57.57	26.65	1.11	14.66
10	41.01	0.32	0.23	23.76	13.83	0.61	15.76	5.84	101.36	67.02	56.17	27.64	1.23	14.96
20	40.81	0.34	0.24	23.52	14.04	0.58	15.37	6.00	100.90	66.12	55.12	28.23	1.18	15.47
30	40.99	0.39	0.23	23.60	14.33	0.60	15.11	6.31	101.56	65.28	53.92	28.68	1.22	16.18
40	41.06	0.37	0.19	23.85	14.57	0.59	14.81	6.44	101.87	64.44	53.01	29.25	1.19	16.55
50	42.84	0.40	0.14	25.02	14.73	0.60	13.64	6.64	104.01	62.28	50.49	30.58	1.26	17.66
60	39.56	0.45	0.10	23.39	14.90	0.59	14.30	6.50	99.79	63.11	51.68	30.21	1.21	16.90
81	40.37	0.46	0.02	23.41	16.14	0.70	13.05	6.93	101.08	59.04	47.49	32.94	1.44	18.12
91	40.55	0.45	0.11	23.39	15.13	0.63	14.04	6.94	101.23	62.33	50.38	30.46	1.28	17.89
101	40.73	0.38	0.15	23.58	14.53	0.58	14.65	6.33	100.92	64.26	52.92	29.45	1.19	16.43
111	41.59	0.28	0.16	24.20	13.48	0.57	16.19	5.68	102.15	68.17	57.49	26.86	1.16	14.50
121	41.36	0.30	0.17	24.03	13.72	0.58	15.80	5.69	101.65	67.25	56.61	27.57	1.19	14.64
131	41.53	0.30	0.17	24.08	13.77	0.56	15.78	5.84	102.03	67.14	56.33	27.56	1.14	14.97
141	41.37	0.26	0.15	24.08	13.40	0.53	15.68	5.64	101.11	67.60	56.91	27.28	1.10	14.71
151	42.84	0.29	0.15	24.84	13.33	0.55	16.25	5.79	104.04	68.49	57.62	26.51	1.10	14.77
Grain 1: rim-core-rim traverse 3														
0	41.83	0.29	0.17	24.43	13.13	0.54	16.74	5.69	102.80	69.45	58.73	25.85	1.08	14.34
9	41.39	0.29	0.16	23.83	13.54	0.55	15.97	5.70	101.42	67.77	57.09	27.14	1.12	14.65
18	43.56	0.30	0.17	24.97	14.27	0.57	16.73	6.09	106.66	67.64	56.85	27.19	1.10	14.86
26	41.60	0.26	0.15	24.24	13.67	0.58	15.89	5.75	102.13	67.45	56.71	27.36	1.17	14.76
35	41.91	0.27	0.15	24.37	13.51	0.55	15.90	5.75	102.41	67.72	56.95	27.14	1.12	14.79
44	42.15	0.30	0.15	24.54	13.33	0.54	16.00	5.84	102.84	68.15	57.18	26.72	1.10	15.00

Table C3-5: continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	CaO	Total	Mg#	Pyrope %	Almandine %	Spessartine %	Grossular
Grain 2: rim-core-rim traverse														
0	42.19	0.27	0.15	24.42	13.36	0.55	16.04	5.68	102.66	68.16	57.45	26.82	1.12	14.61
7	41.88	0.28	0.15	24.24	13.80	0.57	15.79	5.79	102.50	67.10	56.37	27.62	1.16	14.85
15	41.42	0.29	0.17	24.08	14.05	0.59	15.62	5.93	102.15	66.47	55.59	28.06	1.19	15.16
22	41.45	0.27	0.17	23.91	13.92	0.56	15.72	5.84	101.85	66.82	56.05	27.84	1.14	14.97
30	41.41	0.27	0.15	23.99	13.52	0.54	16.20	5.77	101.86	68.12	57.37	26.85	1.09	14.69
Grain 3: rim-core-rim traverse														
0	40.32	0.32	0.15	23.41	13.13	0.51	15.97	5.88	99.69	68.44	57.35	26.44	1.03	15.18
14	40.98	0.32	0.14	23.76	13.59	0.56	15.93	6.01	101.30	67.64	56.51	27.04	1.12	15.33
31	40.50	0.33	0.12	23.73	14.07	0.58	15.16	6.22	100.71	65.77	54.43	28.33	1.19	16.05
44	40.47	0.33	0.10	23.79	14.29	0.63	14.91	6.28	100.81	65.04	53.65	28.84	1.29	16.23
57	39.39	0.31	0.05	22.94	14.40	0.61	13.96	6.42	98.08	63.35	51.72	29.92	1.28	17.08
77	40.56	0.31	0.09	23.62	14.54	0.60	14.61	6.42	100.75	64.18	52.72	29.42	1.22	16.64
86	40.28	0.33	0.12	23.52	14.11	0.63	14.90	6.28	100.17	65.31	53.82	28.58	1.29	16.31
98	40.57	0.33	0.12	23.36	13.82	0.59	15.16	6.13	100.09	66.17	54.82	28.04	1.21	15.94
104	40.97	0.32	0.14	23.74	13.72	0.53	15.52	6.13	101.06	66.85	55.58	27.56	1.07	15.78
110	41.13	0.33	0.14	24.02	13.64	0.58	15.57	6.17	101.57	67.05	55.64	27.34	1.18	15.84
116	40.98	0.32	0.14	23.68	13.52	0.55	15.61	6.16	100.95	67.30	55.88	27.15	1.12	15.84
124	40.57	0.32	0.13	23.36	13.12	0.54	15.42	5.99	99.47	67.69	56.30	26.86	1.13	15.72

Table C4-1: Glass composition of run Pyx26, conducted at 1375°C and 2.0 GPa for 0.5 hours

Distance (µm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
8	53.96	0.71	16.42	8.77	0.19	8.12	8.11	2.13	0.55	0.16	99.14	62.27
18	53.70	0.68	16.72	8.91	0.21	8.05	8.44	2.37	0.49	0.09	99.65	61.70
27	54.02	0.67	16.71	8.96	0.23	8.11	8.40	2.36	0.61	0.11	100.16	61.74
47	54.16	0.67	16.93	8.68	0.23	7.69	8.32	2.30	0.54	0.14	99.65	61.23
57	54.02	0.67	17.03	8.69	0.13	7.69	8.40	2.38	0.47	0.14	99.62	61.21
67	54.21	0.66	17.20	8.56	0.24	7.68	8.33	2.33	0.57	0.13	99.92	61.53
77	54.73	0.67	17.15	8.46	0.22	7.35	8.45	2.43	0.53	0.12	100.10	60.77
87	54.23	0.67	17.50	8.66	0.21	7.30	8.66	2.39	0.59	0.15	100.35	60.05
97	54.43	0.67	17.46	8.36	0.28	7.14	8.15	2.50	0.58	0.12	99.70	60.36
107	54.73	0.67	17.36	8.61	0.27	7.10	8.27	2.57	0.54	0.10	100.23	59.52
117	54.37	0.67	17.73	8.59	0.23	7.04	8.12	2.50	0.56	0.15	99.97	59.37
127	54.31	0.71	17.53	8.48	0.17	6.87	8.63	2.56	0.57	0.19	100.01	59.09
137	54.57	0.73	17.65	8.42	0.21	6.74	8.55	2.68	0.70	0.07	100.32	58.80
147	55.06	0.63	17.86	8.23	0.18	6.65	8.59	2.61	0.66	0.14	100.61	59.03
157	54.53	0.65	17.90	8.18	0.13	6.48	8.42	2.58	0.60	0.09	99.54	58.55
166	54.91	0.73	18.16	8.33	0.19	6.37	8.43	2.58	0.79	0.15	100.65	57.69
176	54.43	0.69	18.14	8.07	0.22	6.14	8.38	2.65	0.66	0.09	99.46	57.56
186	54.77	0.70	18.17	8.33	0.21	6.19	8.48	2.63	0.67	0.11	100.26	56.99
196	54.72	0.72	18.16	8.19	0.22	6.02	8.40	2.63	0.65	0.14	99.86	56.72
216	54.72	0.69	17.86	7.97	0.23	5.97	8.29	2.53	0.64	0.16	99.04	57.18
229	55.28	0.72	18.22	7.89	0.24	5.78	8.34	2.67	0.67	0.13	99.93	56.64
241	55.61	0.73	18.38	7.67	0.21	5.66	8.32	2.70	0.72	0.19	100.19	56.82
253	55.52	0.70	18.62	7.94	0.18	5.57	8.25	2.70	0.78	0.11	100.36	55.57
265	55.29	0.68	18.31	7.88	0.22	5.51	8.32	2.77	0.76	0.16	99.90	55.49
278	55.68	0.71	18.71	7.83	0.20	5.35	8.42	2.73	0.70	0.12	100.47	54.92
290	55.43	0.71	18.89	7.85	0.18	5.29	8.36	2.81	0.74	0.13	100.39	54.58
302	55.68	0.74	18.71	7.93	0.20	5.05	8.60	2.81	0.73	0.11	100.55	53.17
315	55.34	0.71	18.86	8.02	0.20	5.07	8.39	2.81	0.76	0.15	100.32	52.99
327	55.69	0.73	18.72	7.90	0.23	4.97	8.29	2.74	0.70	0.15	100.11	52.87
339	55.51	0.75	18.90	7.86	0.25	4.90	8.18	2.76	0.70	0.09	99.89	52.64
351	55.52	0.70	18.69	7.67	0.24	4.80	8.25	2.77	0.77	0.12	99.54	52.74
376	55.51	0.71	19.11	7.95	0.18	4.66	8.37	2.91	0.69	0.11	100.20	51.10
388	55.65	0.73	18.74	7.56	0.16	4.57	8.45	2.82	0.78	0.19	99.65	51.87
400	55.64	0.75	18.95	7.73	0.15	4.55	8.37	2.85	0.73	0.15	99.86	51.21
413	55.97	0.71	19.20	7.83	0.19	4.54	8.58	2.81	0.76	0.07	100.66	50.83
425	55.21	0.74	18.98	7.56	0.28	4.43	8.14	2.92	0.70	0.14	99.11	51.09

Table C4-1: continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
437	54.73	0.76	19.27	7.87	0.18	4.37	8.49	2.80	0.75	0.11	99.33	49.75
450	55.12	0.76	19.05	7.78	0.15	4.31	8.51	2.95	0.79	0.14	99.57	49.69
473	55.47	0.73	19.06	7.79	0.25	4.21	8.43	2.78	0.74	0.17	99.62	49.07
490	54.97	0.72	18.94	7.64	0.20	4.26	8.55	2.91	0.73	0.17	99.08	49.85
507	55.20	0.74	19.08	7.90	0.21	4.11	8.55	2.80	0.73	0.19	99.50	48.12
524	55.17	0.73	19.22	7.86	0.19	4.00	8.38	2.93	0.73	0.21	99.41	47.57
541	55.45	0.81	19.22	7.72	0.23	4.06	8.70	2.85	0.64	0.21	99.90	48.39
558	54.81	0.73	19.14	7.89	0.24	3.99	8.73	2.84	0.74	0.11	99.23	47.41
576	55.57	0.73	19.35	7.97	0.21	3.97	8.78	3.00	0.70	0.10	100.37	47.04
593	55.37	0.77	19.24	7.92	0.20	3.90	8.73	2.87	0.83	0.15	99.96	46.75
610	55.84	0.76	19.03	7.57	0.22	3.94	8.49	3.01	0.77	0.17	99.80	48.13
627	55.25	0.76	19.28	7.89	0.19	3.86	8.68	2.92	0.69	0.19	99.72	46.59
644	55.38	0.79	19.38	8.10	0.22	3.88	8.56	2.85	0.75	0.15	100.05	46.06
662	55.06	0.75	19.12	8.19	0.23	3.93	8.63	2.72	0.70	0.08	99.41	46.11
679	55.25	0.75	19.56	8.11	0.14	3.87	8.49	2.89	0.74	0.09	99.90	45.97
696	55.65	0.76	19.20	7.84	0.22	3.85	8.66	2.81	0.68	0.12	99.78	46.68
713	55.66	0.78	19.25	7.93	0.20	3.79	8.68	2.85	0.69	0.09	99.92	46.01
730	55.25	0.78	19.39	7.96	0.20	3.80	8.55	2.93	0.77	0.14	99.78	45.98
747	54.94	0.75	19.18	7.88	0.21	3.85	8.74	2.84	0.76	0.14	99.29	46.55
765	54.81	0.73	19.25	7.96	0.20	3.79	8.70	2.84	0.65	0.00	98.93	45.91
782	54.94	0.76	19.34	8.32	0.19	3.84	8.70	2.88	0.69	0.05	99.72	45.14
799	55.03	0.74	19.43	7.91	0.14	3.80	8.83	2.90	0.76	0.12	99.66	46.14

Table C4-2: Clinopyroxene composition of run Pyx26, conducted at 1375°C and 2.0 GPa for 0.5 hours

Distance (µm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-28	54.13	0.09	0.74	4.18	4.54	0.15	26.30	0.03	10.12	0.42	100.70	91.17
-55	54.06	0.10	0.82	4.64	4.30	0.13	24.28	0.02	12.30	0.46	101.11	90.96
-64	54.38	0.07	0.71	4.12	4.56	0.14	26.13	0.01	10.03	0.40	100.55	91.08
-100	54.68	0.08	0.76	4.33	4.59	0.14	25.80	0.02	10.39	0.42	101.19	90.93
-183	52.98	0.17	0.67	6.89	4.52	0.12	23.05	0.02	12.10	0.61	101.13	90.09
-206	54.23	0.08	0.77	4.41	4.47	0.12	25.46	0.02	10.95	0.44	100.96	91.04
-314	53.96	0.08	0.77	4.37	4.43	0.16	25.16	0.02	11.07	0.40	100.42	91.01
-366	52.77	0.25	0.61	6.45	4.95	0.12	23.40	0.01	11.37	0.52	100.49	89.39
-404	52.63	0.20	0.52	6.59	5.08	0.13	23.04	0.01	12.16	0.51	100.88	88.99
-526	54.12	0.08	0.76	4.21	4.33	0.12	25.31	0.02	11.16	0.45	100.56	91.24
-603	53.78	0.12	0.74	5.49	4.49	0.12	24.33	0.02	11.17	0.57	100.84	90.62
-743	54.14	0.09	0.79	4.58	4.29	0.13	24.86	0.03	11.68	0.45	101.02	91.18
-833	54.30	0.09	0.79	4.50	4.34	0.12	24.85	0.02	11.72	0.47	101.22	91.08
-876	54.78	0.07	0.70	4.13	4.77	0.14	26.50	0.02	9.66	0.41	101.17	90.83
-1013	54.34	0.09	0.77	4.74	4.30	0.15	24.93	0.03	11.56	0.48	101.40	91.18
-1050	54.16	0.09	0.77	4.74	4.36	0.14	24.67	0.01	11.35	0.48	100.78	90.98
-1072	54.32	0.10	0.74	4.71	4.48	0.13	25.05	0.02	11.25	0.47	101.27	90.88
-1086	54.40	0.10	0.78	4.70	4.41	0.13	24.96	0.02	11.25	0.46	101.20	90.98
-1149	53.54	0.09	0.78	4.86	4.42	0.14	24.90	0.00	11.59	0.49	100.81	90.95
-1266	53.98	0.09	0.80	4.66	4.32	0.15	24.74	0.02	11.73	0.48	100.97	91.08
-1314	53.62	0.12	0.86	5.17	4.12	0.12	23.40	0.02	13.10	0.49	101.02	91.01
-1543	54.18	0.10	0.80	5.05	4.21	0.12	24.19	0.02	12.40	0.49	101.57	91.11
-1559	54.06	0.10	0.75	5.04	4.32	0.14	24.48	0.01	11.92	0.49	101.31	90.99
-1579	53.79	0.10	0.78	5.19	4.27	0.14	24.27	0.02	12.06	0.52	101.15	91.02
-1594	54.20	0.09	0.76	4.79	4.47	0.13	24.78	0.01	11.34	0.46	101.03	90.81
-1611	53.30	0.12	0.75	5.33	4.40	0.13	23.68	0.02	11.84	0.52	100.08	90.56
-1652	54.18	0.09	0.77	4.37	4.45	0.15	25.08	0.02	11.19	0.46	100.77	90.95
-1718	54.16	0.08	0.76	4.54	4.49	0.13	24.94	0.02	11.38	0.45	100.95	90.83
-1729	53.70	0.11	0.76	5.55	4.42	0.13	24.02	0.01	11.71	0.55	100.96	90.64
-1742	53.78	0.10	0.81	5.06	4.32	0.13	24.29	0.01	12.03	0.48	101.01	90.93
-1802	53.49	0.16	0.85	5.78	3.98	0.12	22.30	0.02	14.12	0.54	101.35	90.90
-1847	54.17	0.08	0.73	4.37	4.71	0.12	26.29	0.02	10.47	0.44	101.41	90.87
-1881	53.98	0.10	0.80	5.44	4.20	0.13	23.21	0.02	12.71	0.45	101.04	90.79

Table C4-3: Orthopyroxene composition of run Pxx26, conducted at 1375°C and 2.0 GPa for 0.5 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-23	55.26	0.06	0.59	3.79	5.17	0.12	33.33	0.02	2.55	0.10	101.01	92.00
-23	55.23	0.06	0.63	3.89	5.18	0.14	33.45	0.03	2.55	0.12	101.28	92.01
-44	55.50	0.06	0.64	4.05	5.12	0.13	33.00	0.01	2.49	0.04	101.05	91.99
-44	55.19	0.06	0.62	4.21	5.23	0.11	32.98	0.03	2.50	0.13	101.07	91.83
-75	55.46	0.07	0.58	4.53	5.42	0.12	32.68	0.01	2.48	0.10	101.46	91.49
-75	55.97	0.05	0.63	3.83	5.14	0.11	33.06	0.03	2.65	0.14	101.63	91.98
-125	55.13	0.07	0.66	4.37	5.11	0.13	33.05	0.04	2.56	0.12	101.26	92.02
-144	55.23	0.06	0.65	4.18	5.19	0.13	32.78	0.02	2.51	0.13	100.89	91.84
-153	55.18	0.07	0.65	4.33	5.22	0.13	32.82	0.02	2.56	0.13	101.12	91.81
-234	55.76	0.06	0.63	3.84	5.13	0.13	32.80	0.04	2.56	0.11	101.05	91.94
-267	55.34	0.08	0.64	4.93	5.13	0.10	33.45	0.03	1.60	0.08	101.38	92.08
-532	55.06	0.06	0.64	4.07	5.15	0.12	33.03	0.03	2.41	0.12	100.69	91.96
-592	54.75	0.12	0.58	5.48	5.73	0.14	33.40	0.08	0.98	0.09	101.35	91.22
-719	55.55	0.07	0.65	4.31	5.19	0.14	33.09	0.03	2.57	0.12	101.72	91.91
-723	55.40	0.06	0.63	4.03	5.19	0.12	33.02	0.07	2.51	0.13	101.15	91.90
-792	55.10	0.10	0.59	5.19	5.27	0.13	33.52	0.03	1.16	0.07	101.18	91.90
-880	55.37	0.07	0.64	4.77	5.21	0.14	32.86	0.03	2.12	0.12	101.35	91.83
-1020	55.52	0.07	0.63	4.21	5.11	0.12	33.01	0.03	2.46	0.12	101.28	92.01
-1323	56.01	0.07	0.61	4.14	5.25	0.13	32.80	0.04	2.63	0.12	101.81	91.76
-1341	55.61	0.06	0.64	4.35	5.18	0.13	32.99	0.04	2.52	0.13	101.66	91.91
-1369	55.14	0.10	0.52	5.23	5.62	0.12	33.70	0.08	0.97	0.09	101.57	91.45
-1456	55.41	0.06	0.63	4.27	5.15	0.13	32.86	0.05	2.49	0.13	101.17	91.92
-1482	55.53	0.08	0.64	5.01	5.25	0.11	32.94	0.03	1.93	0.05	101.57	91.79
-1570	55.44	0.09	0.55	5.05	5.44	0.13	33.63	0.07	1.23	0.10	101.74	91.68
-1715	55.52	0.10	0.56	5.22	5.37	0.12	33.41	0.03	1.19	0.11	101.65	91.73

Table C4-4: Olivine composition of run Pyx26, conducted at 1375°C and 2.0 GPa for 0.5 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-57	41.15	0.00	0.11	0.11	8.81	0.13	50.48	0.05	0.30	0.00	101.14	91.08
-61	40.62	0.00	0.12	0.13	8.82	0.14	50.48	0.05	0.30	0.00	100.63	91.07
-82	40.93	0.01	0.11	0.13	8.96	0.13	50.08	0.06	0.31	0.01	100.74	90.88
-87	40.74	0.01	0.10	0.14	8.93	0.13	49.75	0.04	0.32	0.01	100.17	90.85
-127	40.61	0.00	0.11	0.10	9.06	0.13	50.49	0.05	0.27	0.02	100.84	90.86
-166	41.20	0.00	0.13	0.11	8.61	0.14	50.86	0.05	0.29	0.00	101.38	91.33
-246	41.11	0.01	0.12	0.10	8.66	0.12	50.54	0.05	0.29	0.01	101.01	91.23
-378	41.39	0.01	0.13	0.12	8.78	0.14	50.56	0.04	0.29	0.01	101.46	91.12
-404	41.01	0.01	0.12	0.08	8.78	0.12	50.74	0.06	0.28	0.02	101.22	91.15
-436	41.27	0.00	0.12	0.12	8.80	0.13	50.23	0.03	0.31	0.02	101.04	91.05
-549	40.86	0.01	0.11	0.11	8.74	0.13	50.40	0.05	0.28	0.00	100.68	91.14
-609	41.14	0.00	0.10	0.12	8.91	0.12	50.45	0.05	0.27	0.02	101.19	90.99
-648	41.16	0.00	0.12	0.12	8.67	0.12	50.19	0.05	0.30	0.01	100.74	91.17
-759	41.02	0.01	0.11	0.09	8.89	0.13	50.57	0.06	0.28	0.00	101.16	91.02
-793	41.21	0.00	0.12	0.12	8.69	0.14	50.23	0.04	0.29	0.00	100.85	91.15
-867	41.21	0.01	0.11	0.08	8.65	0.13	50.58	0.06	0.29	0.00	101.10	91.25
-909	40.70	0.00	0.12	0.11	8.74	0.13	49.75	0.04	0.29	0.01	99.87	91.03
-992	41.19	0.00	0.12	0.13	8.75	0.13	50.59	0.05	0.30	0.01	101.26	91.16
-1014	40.95	0.01	0.12	0.13	8.68	0.13	50.41	0.06	0.30	0.01	100.80	91.19
-1048	41.06	0.00	0.12	0.13	8.74	0.14	50.23	0.05	0.31	0.01	100.78	91.11
-1052	41.22	0.01	0.12	0.13	8.85	0.14	50.24	0.07	0.30	0.03	101.10	91.01
-1094	41.31	0.00	0.12	0.14	8.83	0.15	50.20	0.04	0.28	0.01	101.07	91.02
-1204	41.35	0.00	0.12	0.13	8.73	0.14	50.82	0.07	0.29	0.01	101.66	91.21
-1229	41.58	0.00	0.12	0.13	8.67	0.14	50.43	0.07	0.29	0.00	101.42	91.21
-1284	41.15	0.00	0.12	0.11	8.73	0.14	50.83	0.05	0.30	0.00	101.44	91.21
-1305	41.31	0.00	0.11	0.12	8.79	0.14	50.34	0.06	0.29	0.00	101.12	91.08
-1362	41.34	0.00	0.12	0.09	8.75	0.12	50.93	0.05	0.29	0.02	101.72	91.21
-1375	41.45	0.00	0.12	0.12	8.80	0.12	50.44	0.05	0.29	0.02	101.41	91.09
-1433	41.24	0.00	0.12	0.11	8.62	0.14	50.57	0.05	0.29	0.00	101.14	91.27
-1510	41.67	0.00	0.11	0.12	8.80	0.13	50.39	0.04	0.30	0.02	101.58	91.08
-1686	41.21	0.00	0.11	0.12	8.86	0.13	50.14	0.03	0.27	0.01	100.88	90.98
-1794	41.21	0.01	0.12	0.13	8.75	0.14	50.46	0.04	0.30	0.01	101.18	91.14

Table C5-1: Glass composition of run Pyx21, conducted at 1375°C and 2.0 GPa for 2 hours

Distance (µm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-88	53.09	0.66	15.21	9.50	0.25	10.65	8.59	1.80	0.34	0.05	100.15	66.65
-86	54.47	0.70	15.99	9.26	0.20	8.06	8.47	2.05	0.48	0.10	99.78	60.81
-80	53.68	0.68	15.72	9.67	0.23	8.67	8.37	1.90	0.42	0.07	99.41	61.52
-77	53.75	0.66	15.54	9.47	0.23	9.60	8.48	1.74	0.37	0.10	99.94	64.38
-74	53.38	0.64	15.60	9.07	0.21	10.51	8.74	1.65	0.34	0.09	100.24	67.38
-68	54.00	0.68	15.89	9.12	0.19	9.63	8.43	1.81	0.44	0.06	100.25	65.31
-63	53.95	0.69	16.10	8.72	0.19	9.07	8.45	2.06	0.48	0.12	99.83	64.97
-62	53.86	0.69	15.81	9.16	0.25	9.61	8.47	1.84	0.40	0.08	100.16	65.16
-56	53.09	0.68	15.66	9.08	0.18	9.24	8.33	2.02	0.40	0.06	98.74	64.47
-50	53.63	0.67	15.65	9.05	0.17	9.56	8.64	2.10	0.47	0.13	100.05	65.32
-44	53.70	0.64	15.59	9.02	0.22	9.49	8.42	2.21	0.48	0.13	99.89	65.23
-38	53.43	0.68	15.57	8.79	0.21	9.44	8.46	2.18	0.47	0.08	99.31	65.69
-38	53.38	0.68	15.74	9.11	0.26	9.23	8.45	2.21	0.43	0.12	99.60	64.37
-35	54.07	0.68	15.83	9.35	0.20	9.46	8.47	1.90	0.36	0.10	100.42	64.33
-32	53.49	0.64	15.68	8.99	0.21	9.46	8.56	2.22	0.46	0.13	99.86	65.23
-26	53.41	0.65	15.76	8.97	0.23	9.29	8.41	2.25	0.46	0.07	99.51	64.87
-26	53.50	0.66	15.74	9.00	0.21	9.35	8.46	2.25	0.45	0.11	99.71	64.94
-20	54.14	0.67	15.77	9.18	0.16	9.37	8.44	2.26	0.44	0.10	100.53	64.54
-18	53.97	0.67	15.90	8.89	0.22	9.39	8.56	2.23	0.48	0.10	100.41	65.32
-16	53.59	0.71	15.74	9.09	0.25	9.38	8.31	2.27	0.47	0.09	99.91	64.79
-14	53.51	0.66	15.74	8.91	0.21	9.60	8.43	2.25	0.42	0.08	99.80	65.76
-14	53.95	0.69	15.97	8.91	0.22	9.29	8.44	2.28	0.47	0.10	100.31	65.02
-8	54.03	0.64	15.92	9.17	0.16	9.20	8.61	2.27	0.47	0.06	100.53	64.14
-3	53.66	0.67	15.67	9.02	0.16	9.67	8.36	2.30	0.43	0.09	100.03	65.65
-2	53.92	0.68	15.84	9.09	0.20	9.21	8.50	2.25	0.46	0.09	100.25	64.37
-1	53.74	0.64	15.69	8.84	0.17	9.54	8.36	2.25	0.43	0.12	99.77	65.80
4	53.44	0.68	15.85	8.79	0.26	9.11	8.51	2.24	0.45	0.12	99.44	64.88
33	53.76	0.66	16.28	8.93	0.21	9.04	8.54	2.33	0.48	0.08	100.31	64.35
54	53.95	0.66	16.28	8.79	0.22	8.84	8.48	2.31	0.49	0.17	100.17	64.20
75	53.82	0.71	16.36	8.84	0.20	8.74	8.51	2.37	0.48	0.14	100.20	63.80
96	53.93	0.68	16.38	8.80	0.20	8.62	8.25	2.32	0.57	0.12	99.86	63.59
117	52.90	0.63	16.18	8.57	0.20	8.26	8.28	2.33	0.53	0.11	97.98	63.21
138	54.07	0.68	16.44	8.96	0.19	8.35	8.38	2.37	0.48	0.17	100.10	62.43
159	54.11	0.67	16.65	8.78	0.20	8.14	8.54	2.46	0.50	0.07	100.11	62.31
180	54.25	0.69	16.84	8.53	0.23	8.06	8.49	2.44	0.53	0.13	100.20	62.75
201	54.24	0.66	16.98	8.54	0.16	7.93	8.28	2.47	0.55	0.11	99.93	62.34

Table C5-1: continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
222	54.22	0.67	16.79	8.67	0.19	7.73	8.41	2.46	0.56	0.12	99.81	61.38
243	53.41	0.65	16.74	8.35	0.22	7.47	8.30	2.45	0.59	0.09	98.28	61.46
264	54.60	0.66	17.24	8.20	0.18	7.46	8.45	2.56	0.55	0.17	100.07	61.86
285	54.47	0.69	17.29	8.38	0.19	7.50	8.57	2.58	0.60	0.17	100.43	61.47
306	54.56	0.65	17.31	8.25	0.19	7.33	8.45	2.55	0.60	0.13	100.00	61.30
331	54.54	0.67	17.44	8.44	0.19	7.20	8.52	2.57	0.61	0.12	100.30	60.33
365	54.73	0.64	17.44	8.05	0.17	7.02	8.29	2.66	0.64	0.16	99.80	60.86
399	55.14	0.71	17.71	8.08	0.20	6.88	8.49	2.64	0.62	0.16	100.63	60.29
432	54.91	0.67	17.84	8.02	0.19	6.67	8.51	2.69	0.64	0.13	100.26	59.72
466	54.89	0.68	17.96	8.22	0.24	6.43	8.40	2.77	0.64	0.14	100.36	58.24
500	55.24	0.67	18.07	7.72	0.20	6.31	8.36	2.80	0.61	0.14	100.11	59.30
567	55.09	0.69	18.22	7.80	0.17	5.96	8.39	2.82	0.69	0.11	99.94	57.67
634	55.54	0.69	18.33	7.86	0.19	5.65	8.22	2.83	0.67	0.13	100.10	56.17
669	55.42	0.71	18.47	7.84	0.24	5.50	8.32	2.90	0.73	0.20	100.32	55.57
713	55.48	0.73	18.67	7.65	0.18	5.36	8.22	2.89	0.75	0.09	100.02	55.54
756	55.26	0.70	18.76	7.68	0.17	5.26	8.44	2.94	0.69	0.17	100.08	54.98
800	55.62	0.71	18.85	7.68	0.21	5.00	8.43	2.87	0.74	0.12	100.22	53.72
841	55.70	0.75	18.87	7.76	0.22	4.94	8.31	3.02	0.75	0.16	100.49	53.16
883	55.47	0.72	19.42	7.69	0.23	4.79	8.44	2.96	0.75	0.15	100.62	52.62
926	55.61	0.71	19.28	7.58	0.13	4.64	8.43	3.03	0.77	0.14	100.31	52.18
969	55.88	0.72	19.21	7.70	0.23	4.62	8.41	2.99	0.78	0.10	100.65	51.68
1011	55.32	0.72	19.08	7.51	0.18	4.53	8.47	3.04	0.76	0.13	99.76	51.82
1054	55.56	0.75	19.05	7.63	0.20	4.49	8.44	3.04	0.74	0.07	99.97	51.20
1096	55.61	0.72	19.34	7.68	0.20	4.37	8.51	3.05	0.73	0.13	100.34	50.36
1138	55.53	0.74	19.41	7.68	0.20	4.40	8.54	3.05	0.78	0.13	100.45	50.53
1139	55.10	0.74	19.34	7.73	0.18	4.37	8.51	3.05	0.77	0.10	99.89	50.20
1160	55.64	0.74	19.43	7.69	0.15	4.25	8.25	3.05	0.79	0.11	100.09	49.63
1183	55.45	0.71	19.31	7.69	0.17	4.32	8.60	3.01	0.77	0.15	100.18	50.04
1206	55.72	0.70	19.50	7.91	0.21	4.29	8.45	2.99	0.77	0.13	100.67	49.16
1251	55.35	0.72	19.27	7.88	0.17	4.26	8.69	3.05	0.72	0.15	100.26	49.08
1274	55.49	0.73	19.49	7.71	0.19	4.14	8.70	3.05	0.72	0.11	100.32	48.91
1297	55.06	0.73	19.41	7.86	0.16	4.25	8.47	3.06	0.70	0.14	99.85	49.08
1319	54.99	0.74	19.34	7.79	0.21	4.27	8.73	3.06	0.80	0.11	100.03	49.43
1342	54.87	0.73	19.06	7.81	0.22	4.24	8.62	3.07	0.73	0.13	99.46	49.18

Table C6-1: Glass composition of run Pyxl7, conducted at 1375°C and 2.0 GPa for 24 hours

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-99	53.44	0.62	16.28	7.60	0.11	10.01	8.16	2.49	0.61	0.10	99.41	70.13
-80	53.38	0.64	16.16	7.51	0.15	9.96	8.03	2.65	0.55	0.12	99.16	70.28
-71	53.20	0.64	16.16	7.76	0.23	10.01	8.16	2.64	0.56	0.13	99.48	69.70
-62	53.36	0.65	16.14	7.74	0.21	9.98	8.09	2.58	0.57	0.13	99.44	69.69
-53	53.39	0.65	16.05	7.74	0.18	10.03	8.05	2.63	0.59	0.12	99.41	69.79
-43	53.40	0.62	16.27	7.79	0.19	9.93	8.29	2.62	0.55	0.08	99.74	69.44
-34	53.59	0.60	16.17	7.75	0.13	9.96	8.39	2.64	0.58	0.12	99.93	69.62
-25	53.44	0.64	16.20	7.68	0.20	9.91	8.12	2.63	0.62	0.13	99.57	69.70
-16	53.68	0.60	16.24	7.76	0.22	9.97	8.13	2.60	0.58	0.13	99.92	69.61
-6	53.59	0.66	16.15	7.86	0.20	10.03	8.11	2.64	0.60	0.13	99.97	69.47
3	53.81	0.65	16.17	7.61	0.21	10.03	8.12	2.64	0.60	0.08	99.92	70.15
35	53.55	0.66	16.22	7.64	0.19	9.91	8.20	2.58	0.58	0.12	99.64	69.81
81	53.69	0.62	16.37	7.60	0.19	9.95	8.31	2.59	0.61	0.10	100.04	70.01
127	53.42	0.62	16.17	7.66	0.15	9.96	8.15	2.61	0.61	0.10	99.44	69.86
172	53.28	0.63	16.22	7.85	0.19	9.82	8.16	2.62	0.63	0.08	99.47	69.04
218	53.53	0.63	16.10	7.77	0.21	9.94	8.36	2.63	0.57	0.08	99.82	69.52
264	53.73	0.66	16.29	7.59	0.17	9.84	8.13	2.65	0.60	0.10	99.76	69.80
310	53.67	0.63	16.10	7.58	0.21	9.82	8.19	2.64	0.56	0.12	99.53	69.79
356	53.56	0.61	16.30	7.76	0.16	9.97	8.21	2.60	0.58	0.12	99.87	69.61
401	53.76	0.69	16.35	7.60	0.19	9.88	8.21	2.64	0.58	0.13	100.02	69.86
447	53.76	0.63	16.30	7.70	0.19	9.94	8.07	2.64	0.58	0.14	99.95	69.71
493	53.85	0.63	16.22	7.60	0.23	9.75	8.12	2.57	0.62	0.15	99.75	69.58
539	53.69	0.64	16.44	7.76	0.18	9.80	8.05	2.63	0.63	0.19	100.00	69.25
585	53.73	0.64	16.34	7.59	0.22	9.89	8.00	2.64	0.60	0.12	99.77	69.91
630	53.53	0.64	16.31	7.82	0.16	9.73	8.10	2.66	0.63	0.12	99.71	68.93
676	54.20	0.63	16.19	7.73	0.18	9.82	8.26	2.67	0.60	0.11	100.40	69.37
722	53.58	0.59	16.23	7.66	0.18	9.96	8.06	2.64	0.58	0.09	99.56	69.86

Table C6-2: Clinopyroxene composition of run Pyx17, conducted at 1375°C and 2.0 GPa for 24 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-316	53.12	0.17	0.61	6.33	4.96	0.15	24.12	0.00	10.84	0.44	100.75	89.66
-364	54.81	0.07	0.78	3.89	4.71	0.13	25.60	0.01	10.40	0.38	100.76	90.65
-365	54.07	0.10	0.72	4.59	4.84	0.16	25.09	0.00	10.51	0.41	100.50	90.24
-398	54.21	0.09	0.69	4.32	4.94	0.15	25.62	0.01	10.13	0.42	100.59	90.24
-399	53.98	0.08	0.69	4.30	4.87	0.14	25.54	0.02	10.10	0.41	100.14	90.34
-441	54.63	0.08	0.74	4.07	4.89	0.16	25.79	0.01	10.18	0.40	100.95	90.39
-446	54.38	0.10	0.66	4.18	5.07	0.15	25.77	0.02	9.98	0.40	100.72	90.06
-457	51.97	0.22	0.66	8.53	4.49	0.13	21.22	0.00	13.17	0.62	101.03	89.39
-473	54.02	0.11	0.69	5.37	4.86	0.14	25.03	0.00	10.69	0.43	101.35	90.18
-475	52.84	0.20	0.64	7.85	4.63	0.16	22.86	0.01	12.02	0.51	101.72	89.80
-500	52.03	0.21	0.62	7.90	4.64	0.15	22.24	-0.01	12.42	0.51	100.72	89.52
-510	52.71	0.22	0.61	8.01	4.63	0.15	21.88	-0.01	12.88	0.51	101.60	89.39
-512	51.69	0.21	0.60	7.62	4.63	0.14	22.34	0.00	12.15	0.51	99.89	89.59
-515	52.43	0.20	0.65	7.70	4.70	0.14	22.28	0.01	12.41	0.50	101.01	89.42
-549	54.18	0.10	0.66	4.84	4.89	0.16	24.41	0.02	10.83	0.45	100.54	89.90
-558	52.08	0.19	0.65	8.02	4.60	0.15	21.95	0.00	12.73	0.50	100.88	89.48
-580	53.93	0.11	0.67	4.96	4.88	0.15	24.57	0.00	11.24	0.45	100.95	89.98
-595	54.02	0.10	0.66	4.78	4.95	0.16	25.09	0.00	10.49	0.44	100.69	90.04
-669	54.45	0.08	0.69	4.04	4.89	0.14	25.85	0.01	9.82	0.40	100.40	90.41
-806	53.61	0.06	0.75	4.18	4.70	0.14	25.55	0.01	10.52	0.42	99.94	90.65
-849	53.58	0.07	0.79	4.12	4.56	0.15	25.52	0.02	10.35	0.39	99.55	90.89
-974	53.56	0.09	0.66	4.83	4.88	0.12	25.49	0.01	10.30	0.46	100.42	90.30
-1353	52.69	0.14	0.66	6.68	4.50	0.15	23.28	0.01	11.68	0.55	100.33	90.22
-1374	54.28	0.07	0.77	4.17	4.48	0.15	25.97	0.01	10.26	0.39	100.54	91.18
-1384	50.79	0.20	0.68	7.70	4.30	0.13	22.22	0.00	12.95	0.58	99.55	90.21
-1385	53.27	0.13	0.70	6.62	4.55	0.15	23.93	0.00	11.04	0.58	100.97	90.36
-1472	51.46	0.14	0.73	7.04	4.47	0.13	23.02	0.02	11.93	0.56	99.52	90.18
-1473	53.71	0.08	0.78	4.35	4.51	0.14	25.27	0.00	10.57	0.43	99.82	90.90
-1504	51.67	0.13	0.69	6.46	4.50	0.13	23.62	0.03	11.64	0.54	99.41	90.35
-1595	52.85	0.08	0.74	4.56	4.60	0.16	24.83	0.02	10.92	0.46	99.23	90.59
-1600	54.05	0.07	0.75	3.85	4.64	0.13	26.40	0.01	9.64	0.38	99.91	91.03
-1649	52.27	0.14	0.70	6.53	4.51	0.14	23.61	0.00	11.53	0.58	100.01	90.32
-1659	52.72	0.07	0.76	4.39	4.44	0.16	25.43	0.01	10.89	0.40	99.27	91.08
-1673	53.44	0.08	0.78	4.48	4.57	0.12	24.51	0.00	10.94	0.42	99.34	90.53
-1699	51.39	0.19	0.64	8.07	4.30	0.15	22.23	0.00	12.74	0.59	100.30	90.21
-1741	52.96	0.09	0.75	4.72	4.57	0.14	25.06	0.01	11.00	0.45	99.75	90.72

Table C6-2: continued

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-1880	52.46	0.13	0.73	6.32	4.50	0.14	23.60	0.02	11.39	0.52	99.81	90.34
-1909	49.98	0.15	0.67	6.84	4.80	0.14	24.13	0.01	11.50	0.58	98.79	89.96
-1919	52.02	0.15	0.79	6.98	4.42	0.13	23.23	0.00	11.42	0.63	99.77	90.36
-1936	52.15	0.08	0.78	4.82	4.44	0.13	24.83	0.00	11.07	0.45	98.75	90.88
-1941	52.51	0.08	0.77	4.67	4.41	0.13	25.29	0.01	11.02	0.42	99.31	91.09

Table C6-3: Orthopyroxene composition of run Pxx17, conducted at 1375°C and 2.0 GPa for 24 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-139	54.31	0.09	0.30	5.93	7.12	0.18	31.53	0.00	1.52	0.16	101.13	88.76
-143	53.93	0.10	0.31	6.35	7.29	0.18	31.11	0.01	1.69	0.17	101.13	88.38
-152	53.76	0.09	0.33	5.80	7.17	0.18	31.39	0.00	1.73	0.15	100.60	88.64
-157	53.27	0.15	0.46	6.95	6.04	0.15	31.23	0.01	2.35	0.11	100.72	90.21
-179	53.85	0.15	0.54	6.96	6.00	0.15	31.28	0.02	2.34	0.11	101.39	90.29
-195	54.05	0.14	0.48	6.98	5.97	0.13	31.10	0.01	2.30	0.12	101.28	90.28
-209	54.44	0.12	0.52	6.60	5.96	0.13	31.22	0.01	2.22	0.13	101.35	90.33
-239	55.46	0.05	0.65	3.76	5.16	0.13	33.36	0.02	2.54	0.12	101.25	92.02
-259	54.62	0.07	0.54	4.72	5.76	0.15	32.11	0.00	2.43	0.11	100.53	90.86
-270	55.65	0.06	0.66	3.78	5.15	0.10	32.84	0.02	2.56	0.12	100.94	91.92
-283	55.10	0.09	0.57	4.83	5.31	0.13	33.31	0.04	1.53	0.10	100.99	91.79
-294	53.26	0.14	0.57	7.17	5.97	0.15	31.02	0.01	2.38	0.12	100.80	90.26
-316	55.01	0.06	0.63	3.80	5.26	0.13	32.79	0.02	2.52	0.11	100.33	91.75
-316	55.63	0.06	0.64	3.92	5.55	0.11	32.58	0.01	2.52	0.13	101.16	91.28
-354	55.79	0.06	0.67	3.96	5.17	0.11	32.46	0.01	2.51	0.11	100.86	91.80
-366	54.92	0.10	0.57	5.31	5.24	0.12	33.24	0.04	1.13	0.08	100.76	91.88
-390	55.03	0.06	0.59	3.99	5.55	0.12	32.40	0.03	2.52	0.14	100.42	91.23
-420	55.00	0.05	0.62	3.66	5.33	0.12	32.51	0.00	2.59	0.13	100.00	91.58
-421	55.85	0.05	0.62	3.73	5.13	0.14	33.08	0.01	2.53	0.10	101.24	92.00
-439	56.14	0.05	0.65	3.84	5.14	0.13	32.84	0.01	2.58	0.12	101.49	91.93
-466	53.42	0.11	0.64	7.30	5.64	0.14	30.82	0.00	2.46	0.12	100.65	90.69
-488	55.12	0.06	0.61	4.20	5.18	0.12	33.13	0.00	2.19	0.10	100.71	91.94
-517	54.88	0.07	0.60	4.21	5.30	0.13	32.54	0.01	2.57	0.12	100.44	91.63
-577	55.85	0.06	0.66	3.96	5.14	0.13	32.74	0.00	2.53	0.12	101.19	91.91
-591	55.80	0.08	0.54	4.67	5.63	0.15	32.23	0.01	2.52	0.13	101.76	91.08
-647	55.97	0.06	0.65	3.95	5.29	0.11	32.84	0.01	2.53	0.12	101.53	91.71
-859	54.44	0.09	0.53	5.20	5.37	0.12	33.31	0.04	1.10	0.10	100.30	91.71
-874	54.96	0.05	0.65	3.95	5.05	0.14	32.72	0.02	2.59	0.11	100.24	92.03
-885	54.34	0.08	0.57	5.67	5.42	0.11	31.85	0.03	2.48	0.14	100.71	91.29
-905	54.88	0.07	0.69	5.06	5.37	0.12	32.47	0.00	2.27	0.12	101.05	91.51
-1042	53.76	0.09	0.57	6.29	5.44	0.12	31.48	0.00	2.41	0.13	100.30	91.16
-1927	54.00	0.07	0.69	4.66	5.19	0.13	32.34	0.00	2.71	0.14	99.94	91.74
-1933	54.40	0.06	0.63	3.93	5.21	0.12	32.90	0.02	2.65	0.14	100.06	91.84
-1937	53.90	0.06	0.64	4.35	5.21	0.12	32.25	0.01	2.52	0.13	99.19	91.69

Table C6-4: Olivine composition of run Pyxl7, conducted at 1375°C and 2.0 GPa for 24 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-166	40.48	0.00	0.07	0.12	9.99	0.15	49.25	0.01	0.27	0.02	100.36	89.78
-176	40.69	0.01	0.07	0.14	9.84	0.16	49.36	0.03	0.29	0.01	100.60	89.94
-179	40.38	0.01	0.07	0.13	9.88	0.16	48.64	0.01	0.28	0.02	99.58	89.77
-205	40.67	0.01	0.07	0.12	9.83	0.16	48.43	0.01	0.30	0.01	99.60	89.78
-246	40.18	0.00	0.06	0.10	9.90	0.16	49.50	0.01	0.28	0.02	100.21	89.91
-295	40.91	0.02	0.08	0.13	9.82	0.15	49.26	0.04	0.30	0.01	100.71	89.94
-312	40.54	0.00	0.07	0.13	9.89	0.15	49.14	0.02	0.29	0.02	100.25	89.86
-323	40.99	0.00	0.07	0.12	9.82	0.16	49.52	0.03	0.32	0.01	101.07	89.99
-334	40.20	0.01	0.08	0.10	9.90	0.15	49.19	0.02	0.28	0.01	99.95	89.86
-441	41.00	0.01	0.07	0.11	9.79	0.16	49.33	0.01	0.29	0.02	100.80	89.98
-459	41.08	0.00	0.06	0.11	9.74	0.16	49.06	0.02	0.30	0.02	100.54	89.98
-524	40.94	0.01	0.08	0.14	9.63	0.15	49.08	0.01	0.29	0.00	100.33	90.09
-537	40.99	0.02	0.07	0.10	9.65	0.16	49.09	0.02	0.29	0.01	100.41	90.07
-581	40.77	0.01	0.07	0.12	9.64	0.14	49.38	0.03	0.28	0.02	100.45	90.13
-603	40.82	0.01	0.08	0.14	9.54	0.15	49.09	0.01	0.27	0.02	100.14	90.17
-673	40.70	0.01	0.07	0.12	9.47	0.14	49.00	0.02	0.29	0.00	99.82	90.22
-771	40.79	0.00	0.07	0.10	9.40	0.16	49.54	0.01	0.29	0.01	100.38	90.38
-797	40.93	0.01	0.09	0.12	9.42	0.13	49.14	0.03	0.29	0.01	100.18	90.29
-886	40.88	0.01	0.08	0.11	9.36	0.13	49.68	0.00	0.28	0.01	100.55	90.44
-913	40.66	0.01	0.07	0.14	9.27	0.15	49.31	0.02	0.28	0.01	99.94	90.46
-974	41.22	0.01	0.07	0.10	9.35	0.13	49.43	0.01	0.27	0.02	100.62	90.41
-995	40.74	0.01	0.07	0.12	9.20	0.15	49.53	0.01	0.29	0.02	100.14	90.56
-1035	40.62	0.00	0.08	0.14	9.28	0.14	49.46	0.00	0.28	0.01	100.01	90.48
-1140	40.59	0.01	0.08	0.13	9.08	0.14	49.63	0.02	0.27	0.01	99.97	90.69
-1176	40.78	0.01	0.08	0.15	9.22	0.16	49.83	0.00	0.30	0.01	100.53	90.60
-1375	40.70	0.01	0.08	0.14	9.09	0.14	49.94	0.01	0.29	0.01	100.42	90.74
-1406	40.43	0.01	0.08	0.11	9.12	0.13	49.47	0.02	0.30	0.02	99.70	90.63
-1581	41.06	0.01	0.09	0.13	9.08	0.15	49.66	0.00	0.29	0.01	100.47	90.70
-1582	40.92	0.01	0.09	0.13	9.05	0.14	49.69	0.00	0.28	0.02	100.35	90.73
-1618	40.66	0.01	0.09	0.11	9.03	0.16	49.55	0.03	0.27	0.01	99.92	90.73
-1686	40.68	0.00	0.09	0.12	9.07	0.14	49.53	0.01	0.30	0.02	99.96	90.69

Table C7-1: Glass composition of run Pyx27, conducted at 1375°C and 2.0 GPa for 24 hours

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-331	54.49	0.65	15.80	8.62	0.18	9.68	8.44	2.17	0.51	0.10	100.64	66.69
-321	54.46	0.62	15.87	7.97	0.19	9.75	8.79	2.16	0.48	0.10	100.40	68.56
-313	54.56	0.63	15.78	8.12	0.24	9.92	8.64	2.32	0.46	0.12	100.79	68.53
-308	54.27	0.66	15.90	8.46	0.23	9.69	8.45	2.21	0.38	0.10	100.37	67.13
-299	54.20	0.62	16.12	8.35	0.19	9.77	8.82	2.26	0.46	0.05	100.84	67.60
-288	54.72	0.65	15.79	8.27	0.18	9.90	8.47	2.29	0.50	0.11	100.88	68.09
-267	54.45	0.66	15.83	8.19	0.23	9.81	8.55	2.36	0.47	0.12	100.67	68.11
-247	53.80	0.66	15.91	8.28	0.21	9.73	8.64	2.38	0.50	0.13	100.25	67.69
-226	54.54	0.66	15.79	8.04	0.26	9.61	8.54	2.34	0.53	0.14	100.44	68.06
-206	54.21	0.62	16.06	8.25	0.22	9.61	8.56	2.38	0.52	0.14	100.56	67.50
-185	53.95	0.60	15.93	8.18	0.19	9.65	8.44	2.37	0.48	0.13	99.91	67.78
-144	54.12	0.64	16.17	8.44	0.17	9.56	8.62	2.29	0.51	0.13	100.65	66.88
-124	54.22	0.64	16.18	8.21	0.18	9.54	8.43	2.40	0.47	0.08	100.34	67.44
-103	54.20	0.61	15.94	8.11	0.19	9.47	8.46	2.39	0.47	0.11	99.95	67.55
-62	54.08	0.64	16.23	8.21	0.24	9.43	8.53	2.37	0.55	0.08	100.35	67.19
-42	54.36	0.65	16.22	8.04	0.25	9.39	8.54	2.41	0.50	0.14	100.50	67.56
-21	54.40	0.63	16.05	8.21	0.13	9.24	8.84	2.46	0.50	0.06	100.51	66.74
-1	54.42	0.62	16.18	8.04	0.21	9.29	8.47	2.40	0.50	0.11	100.24	67.32
32	54.53	0.68	16.15	7.93	0.14	9.21	8.65	2.48	0.52	0.10	100.40	67.43
72	54.51	0.64	16.27	7.85	0.19	9.11	8.56	2.46	0.60	0.04	100.22	67.42
113	54.53	0.64	16.44	7.94	0.22	9.05	8.51	2.50	0.56	0.05	100.42	67.02
193	54.59	0.67	16.92	7.88	0.21	8.89	8.48	2.50	0.55	0.10	100.80	66.79
233	54.69	0.60	16.38	7.93	0.25	8.80	8.60	2.47	0.54	0.11	100.37	66.43
274	54.70	0.63	16.90	7.84	0.19	8.81	8.38	2.53	0.56	0.17	100.71	66.71
314	54.48	0.62	17.11	7.88	0.12	8.68	8.62	2.49	0.59	0.16	100.75	66.26
354	54.54	0.63	16.82	7.57	0.20	8.69	8.46	2.40	0.61	0.12	100.04	67.18
394	54.70	0.64	16.79	7.38	0.24	8.54	8.52	2.43	0.51	0.10	99.85	67.35
501	54.56	0.65	16.79	7.86	0.19	8.36	8.51	2.50	0.60	0.14	100.14	65.47
617	54.88	0.64	17.05	7.73	0.20	8.16	8.69	2.67	0.61	0.05	100.68	65.30
872	54.67	0.63	17.31	7.59	0.21	7.72	8.19	2.77	0.63	0.11	99.84	64.46
1064	55.26	0.64	17.39	7.08	0.24	7.45	8.33	2.73	0.66	0.17	99.94	65.23
1279	55.02	0.65	17.73	7.20	0.20	7.30	8.42	2.82	0.66	0.16	100.16	64.38
1701	55.53	0.65	18.39	6.90	0.18	6.89	8.41	2.94	0.73	0.15	100.76	64.03

Table C7-1: continued

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
2046	55.75	0.71	18.58	6.92	0.23	6.61	8.12	3.02	0.73	0.13	100.78	63.00
2197	55.88	0.70	18.27	6.70	0.09	6.55	8.22	3.02	0.84	0.14	100.41	63.54
2140	55.41	0.68	18.41	6.78	0.15	6.59	8.38	2.98	0.70	0.14	100.22	63.41
1906	55.87	0.68	18.30	6.59	0.13	6.62	8.13	2.92	0.81	0.09	100.15	64.17

Table C7-2: Clinopyroxene composition of run Pyx27, conducted at 1375°C and 2.0 GPa for 24 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-1045	54.52	0.07	0.79	4.25	4.49	0.13	25.37	0.01	10.91	0.36	100.92	90.97
-1069	54.50	0.09	0.69	4.90	4.67	0.16	25.16	0.01	10.72	0.34	101.25	90.57
-1073	55.02	0.08	0.77	4.18	4.57	0.15	25.57	0.01	10.57	0.41	101.35	90.89
-1098	54.28	0.08	0.77	4.27	4.64	0.13	25.38	0.00	10.57	0.39	100.50	90.70
-1122	53.99	0.08	0.76	4.29	4.49	0.14	25.66	0.04	10.51	0.41	100.37	91.06
-1173	53.95	0.10	0.74	4.75	4.73	0.14	24.74	0.00	11.11	0.41	100.67	90.32
-1233	53.89	0.15	0.63	4.89	4.98	0.13	25.15	0.01	10.53	0.36	100.72	90.00
-1328	54.38	0.07	0.78	4.30	4.47	0.13	25.54	0.01	10.74	0.44	100.85	91.06
-1453	54.91	0.08	0.76	4.27	4.51	0.14	25.72	0.00	10.59	0.42	101.40	91.05
-1508	54.60	0.09	0.78	4.44	4.49	0.12	25.36	0.01	10.82	0.41	101.13	90.97
-1589	53.48	0.11	0.75	5.10	4.48	0.14	23.91	0.00	11.75	0.41	100.13	90.49
-1600	54.50	0.09	0.72	4.47	4.62	0.15	25.21	0.00	10.50	0.39	100.65	90.68
-1724	53.59	0.12	0.75	5.64	4.57	0.12	24.34	0.01	11.30	0.42	100.85	90.47
-1811	54.64	0.08	0.81	4.31	4.46	0.13	25.30	0.02	11.06	0.45	101.24	91.00
-1823	54.22	0.08	0.80	4.37	4.43	0.15	25.02	0.01	11.20	0.43	100.71	90.97
-1967	54.37	0.08	0.76	4.14	4.48	0.13	25.59	0.01	10.56	0.41	100.54	91.06
-1998	54.16	0.13	0.68	5.29	4.76	0.13	25.44	0.01	10.59	0.35	101.52	90.50
-2072	53.93	0.08	0.74	4.46	4.41	0.15	24.90	0.00	11.25	0.45	100.36	90.96

Table C7-3: Orthopyroxene composition of run Pyx27, conducted at 1375°C and 2.0 GPa for 24 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-349	56.52	0.06	0.58	4.40	5.80	0.14	32.05	0.02	2.46	0.12	102.16	90.79
-349	54.59	0.12	0.56	6.92	6.17	0.14	30.87	0.01	2.46	0.10	101.94	89.92
-363	53.70	0.15	0.50	7.27	6.44	0.15	30.43	0.01	2.47	0.10	101.21	89.39
-369	56.21	0.06	0.63	4.34	5.47	0.13	32.21	0.02	2.49	0.12	101.67	91.30
-385	56.09	0.07	0.67	4.47	5.38	0.13	32.65	0.04	2.45	0.10	102.06	91.54
-416	56.31	0.06	0.64	4.03	5.59	0.13	32.92	0.00	2.51	0.10	102.28	91.30
-454	56.55	0.06	0.59	4.28	5.48	0.14	32.52	0.01	2.48	0.06	102.18	91.36
-501	55.98	0.06	0.59	4.47	5.57	0.13	32.67	0.01	2.51	0.10	102.10	91.27
-550	55.06	0.08	0.58	4.78	5.55	0.14	32.18	0.02	2.48	0.12	100.98	91.18
-624	55.65	0.07	0.60	4.28	5.51	0.13	32.88	0.01	2.54	0.11	101.78	91.41
-633	55.10	0.08	0.62	5.25	5.94	0.13	32.61	0.02	2.14	0.09	101.99	90.73
-674	55.62	0.08	0.61	4.57	5.53	0.16	31.70	0.02	3.08	0.13	101.49	91.09
-748	54.96	0.10	0.53	5.71	5.76	0.14	32.82	0.03	1.61	0.09	101.75	91.04
-767	55.44	0.09	0.57	5.01	5.26	0.14	33.53	0.03	1.28	0.08	101.42	91.91
-842	55.98	0.07	0.70	4.41	5.39	0.12	32.48	0.01	2.44	0.09	101.68	91.48
-949	56.13	0.06	0.57	4.08	5.39	0.10	32.95	0.02	2.50	0.10	101.90	91.60
-1020	55.74	0.06	0.63	3.97	5.28	0.13	32.51	0.01	2.55	0.11	100.98	91.65
-1042	55.77	0.05	0.63	3.83	5.13	0.13	33.13	0.05	2.51	0.12	101.34	92.01
-1056	55.37	0.09	0.58	5.18	5.36	0.11	33.27	0.04	1.48	0.09	101.56	91.71
-1099	55.84	0.07	0.51	4.66	5.59	0.13	32.63	0.01	2.46	0.09	101.99	91.23
-1273	55.56	0.06	0.66	4.12	5.18	0.10	32.62	0.04	2.48	0.12	100.95	91.82
-1340	55.05	0.06	0.64	4.64	5.27	0.11	32.35	0.01	2.51	0.12	100.76	91.63
-1417	56.28	0.06	0.63	3.97	5.17	0.11	32.96	0.03	2.48	0.13	101.81	91.91
-1444	55.86	0.05	0.67	4.22	5.12	0.13	33.07	0.02	2.46	0.07	101.67	92.01
-1723	55.66	0.06	0.67	4.14	5.17	0.12	33.01	0.03	2.51	0.12	101.49	91.92
-1737	54.61	0.08	0.66	5.02	5.33	0.12	32.50	0.02	2.03	0.10	100.46	91.58
-1882	55.82	0.06	0.66	4.05	5.16	0.13	33.36	0.02	2.54	0.10	101.89	92.02

Table C7-4: Olivine composition of run Pyx27, conducted at 1375°C and 2.0 GPa for 24 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-377	41.72	0.01	0.11	0.06	10.46	0.16	49.01	0.03	0.29	0.00	101.84	89.31
-477	41.11	0.01	0.11	0.06	10.23	0.17	48.76	0.04	0.28	0.01	100.79	89.47
-477	41.49	0.01	0.11	0.06	10.25	0.18	48.94	0.04	0.27	0.01	101.37	89.49
-568	41.40	0.01	0.12	0.07	10.20	0.15	49.52	0.03	0.28	0.01	101.80	89.64
-568	41.16	0.01	0.13	0.06	10.18	0.17	49.00	0.03	0.29	0.01	101.03	89.56
-594	41.31	0.00	0.13	0.07	10.20	0.17	49.35	0.02	0.27	0.01	101.54	89.61
-688	41.68	0.01	0.14	0.06	10.04	0.18	49.40	0.03	0.28	0.01	101.84	89.77
-707	41.51	0.00	0.10	0.07	10.03	0.15	49.55	0.03	0.26	0.01	101.71	89.80
-727	41.26	0.01	0.13	0.07	10.00	0.16	49.27	0.01	0.28	0.01	101.20	89.78
-737	41.40	0.00	0.11	0.07	9.92	0.15	49.68	0.03	0.28	0.00	101.64	89.93
-851	41.45	0.01	0.12	0.08	9.73	0.16	50.01	0.02	0.28	0.00	101.82	90.16
-890	41.30	0.01	0.15	0.07	9.74	0.14	49.62	0.02	0.30	0.00	101.35	90.08
-933	41.41	0.01	0.12	0.08	9.68	0.16	49.99	0.02	0.28	0.01	101.76	90.20
-1016	41.43	0.01	0.11	0.08	9.62	0.17	49.85	0.02	0.29	0.00	101.58	90.23
-1048	41.27	0.00	0.14	0.09	9.50	0.15	50.47	0.04	0.29	0.00	101.88	90.45
-1052	41.44	0.01	0.13	0.08	9.55	0.16	49.94	0.02	0.31	0.01	101.64	90.31
-1112	41.35	0.01	0.10	0.07	9.44	0.17	49.82	0.02	0.31	0.00	101.22	90.39
-1169	41.70	0.00	0.12	0.09	9.34	0.15	50.01	0.02	0.29	0.00	101.71	90.52
-1186	41.38	0.00	0.11	0.08	9.34	0.16	50.38	0.03	0.29	0.00	101.76	90.58
-1274	40.98	0.01	0.13	0.08	9.22	0.14	50.09	0.02	0.28	0.01	100.94	90.64
-1333	41.33	0.00	0.16	0.08	9.28	0.12	50.16	0.01	0.28	0.00	101.41	90.60
-1474	41.29	0.00	0.12	0.08	9.16	0.14	50.53	0.01	0.29	0.00	101.62	90.77
-1596	41.30	0.00	0.12	0.08	9.08	0.13	50.38	0.02	0.29	0.00	101.39	90.82
-1720	41.37	0.00	0.13	0.08	9.08	0.13	50.51	0.03	0.28	0.02	101.63	90.84
-1834	40.97	0.00	0.13	0.08	8.98	0.14	50.48	0.02	0.27	0.01	101.09	90.93
-1907	41.01	0.01	0.13	0.08	8.94	0.14	50.73	0.02	0.30	0.00	101.34	91.00
-1962	41.19	0.00	0.11	0.09	8.96	0.13	50.97	0.02	0.29	0.01	101.75	91.03
-2017	41.02	0.01	0.12	0.07	8.96	0.13	50.80	0.00	0.28	0.01	101.41	91.00
-2047	41.32	0.00	0.12	0.08	8.96	0.14	51.43	0.01	0.27	0.03	102.37	91.10
-2075	41.43	0.01	0.12	0.09	8.91	0.13	51.50	0.01	0.29	0.02	102.50	91.15

Table C8-1: Glass composition of run Pyx20, conducted at 1375°C and 2.0 GPa for 74 hours

Distance (μm)	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	Mg#
-358	54.73	0.61	16.23	7.83	0.13	9.62	8.64	2.16	0.56	0.11	100.62	68.66
-348	54.24	0.59	15.92	7.45	0.19	11.02	8.56	2.05	0.51	0.06	100.59	72.51
-338	54.55	0.60	15.83	7.57	0.14	10.07	7.99	2.42	0.54	0.13	99.83	70.34
-328	54.34	0.61	16.02	7.33	0.16	10.84	8.33	2.46	0.56	0.07	100.72	72.50
-319	54.71	0.59	15.97	7.23	0.16	10.68	8.24	2.49	0.58	0.12	100.76	72.48
-309	54.11	0.61	15.85	7.36	0.17	10.83	8.17	2.45	0.61	0.15	100.32	72.40
-299	53.93	0.63	15.79	7.38	0.21	10.86	8.25	2.52	0.58	0.14	100.29	72.40
-289	54.22	0.61	15.78	7.16	0.14	10.85	8.08	2.47	0.64	0.13	100.07	72.99
-279	53.91	0.60	15.72	7.37	0.21	10.90	8.19	2.49	0.62	0.07	100.08	72.50
-260	53.91	0.60	15.87	7.38	0.18	10.82	8.22	2.52	0.57	0.12	100.18	72.33
-223	54.31	0.62	16.03	7.19	0.21	10.90	8.25	2.49	0.58	0.17	100.74	72.99
-186	54.20	0.63	15.94	7.21	0.18	10.91	8.20	2.56	0.57	0.10	100.50	72.96
-113	54.33	0.61	15.73	7.31	0.17	10.89	8.36	2.53	0.61	0.10	100.64	72.65
-76	54.23	0.61	15.95	7.01	0.21	10.72	8.27	2.53	0.57	0.13	100.23	73.16
-39	54.23	0.61	16.00	7.35	0.19	10.83	8.16	2.52	0.57	0.12	100.58	72.43
-2	54.24	0.57	16.02	7.33	0.24	10.85	8.24	2.51	0.60	0.09	100.71	72.52
32	53.94	0.61	16.05	7.31	0.19	10.83	8.24	2.48	0.64	0.13	100.42	72.54
193	53.81	0.61	15.82	7.25	0.13	10.97	8.15	2.55	0.55	0.10	99.93	72.96
353	54.02	0.61	15.90	7.26	0.18	10.74	8.00	2.44	0.58	0.15	99.86	72.51
514	53.91	0.65	15.98	7.26	0.15	10.73	8.08	2.58	0.61	0.09	100.05	72.49
674	53.77	0.60	15.95	7.25	0.18	10.71	8.15	2.54	0.62	0.16	99.93	72.48
835	53.51	0.60	15.74	7.17	0.20	10.69	8.22	2.48	0.58	0.12	99.31	72.66
995	53.70	0.62	15.99	7.06	0.19	10.75	8.39	2.52	0.67	0.12	100.00	73.08
1156	53.62	0.61	16.04	7.28	0.19	10.77	8.11	2.54	0.60	0.17	99.94	72.51
1316	53.88	0.64	16.07	7.26	0.17	10.65	8.13	2.51	0.63	0.11	100.06	72.34
1477	53.71	0.64	16.20	7.22	0.16	10.84	8.12	2.52	0.61	0.13	100.14	72.80
1638	53.68	0.63	15.95	7.34	0.20	10.86	8.36	2.51	0.61	0.13	100.26	72.51
1798	53.58	0.58	16.25	7.29	0.18	10.76	8.20	2.44	0.59	0.11	99.99	72.46

Table C8-2: Orthopyroxene composition of run Pyx20, conducted at 1375°C and 2.0 GPa for 74 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-396	56.03	0.07	4.38	0.61	5.74	0.12	32.35	0.01	2.44	0.10	101.84	90.95
-420	55.40	0.07	4.44	0.56	5.83	0.14	32.21	0.00	2.44	0.12	101.21	90.78
-430	54.50	0.18	6.90	0.46	6.26	0.15	30.71	0.00	2.49	0.11	101.75	89.74
-443	55.39	0.06	4.28	0.62	5.67	0.13	32.38	0.00	2.43	0.11	101.07	91.06
-468	54.29	0.11	6.81	0.48	6.02	0.15	31.92	0.00	2.03	0.10	101.89	90.43
-485	54.17	0.13	7.13	0.46	5.94	0.15	31.81	0.02	1.84	0.07	101.73	90.52
-513	55.17	0.10	5.91	0.45	5.91	0.15	32.12	0.01	2.07	0.08	101.98	90.65
-527	55.58	0.06	4.45	0.61	5.75	0.14	32.28	0.00	2.38	0.10	101.36	90.92
-556	54.84	0.10	5.38	0.57	5.77	0.14	32.49	0.01	1.65	0.09	101.03	90.94
-591	54.15	0.13	6.84	0.45	5.94	0.13	32.11	0.01	1.86	0.09	101.70	90.60
-624	53.92	0.10	6.32	0.51	5.92	0.13	31.65	0.00	2.26	0.10	100.90	90.50
-706	55.61	0.06	3.97	0.60	5.54	0.13	33.07	0.00	2.50	0.11	101.58	91.41
-835	54.49	0.07	4.83	0.54	5.60	0.14	32.48	0.00	2.42	0.11	100.68	91.18
-911	55.05	0.06	4.29	0.62	5.63	0.14	32.79	0.01	2.43	0.11	101.13	91.22

Table C8-3: Olivine composition of run Pyx20, conducted at 1375°C and 2.0 GPa for 74 hours

Distance (μm)	SiO ₂	TiO ₂	Cr ₂ O ₃	Al ₂ O ₃	FeO	MnO	MgO	NiO	CaO	Na ₂ O	Total	Mg#
-431	41.06	0.01	0.13	0.05	9.77	0.16	48.46	0.03	0.24	0.01	99.93	89.84
-431	41.20	0.01	0.15	0.05	9.89	0.17	49.02	0.01	0.22	0.02	100.75	89.83
-440	41.07	0.01	0.17	0.07	9.75	0.15	48.83	0.00	0.22	0.02	100.29	89.93
-446	41.06	0.01	0.13	0.07	9.79	0.16	49.47	0.00	0.25	0.01	100.95	90.01
-464	41.28	0.01	0.14	0.06	9.84	0.16	49.54	0.03	0.23	0.01	101.31	89.98
-472	41.00	0.01	0.15	0.07	9.74	0.15	49.37	0.01	0.23	0.01	100.75	90.04
-477	40.36	0.00	0.16	0.06	9.71	0.18	48.83	0.01	0.21	0.01	99.53	89.97
-525	40.52	0.01	0.13	0.06	9.64	0.15	48.73	0.02	0.24	0.01	99.51	90.01
-559	41.11	0.01	0.09	0.06	9.94	0.15	49.89	0.01	0.24	0.00	101.51	89.95
-570	41.59	0.01	0.14	0.06	9.93	0.17	49.73	0.02	0.22	0.02	101.88	89.93
-591	41.15	0.01	0.14	0.05	9.85	0.16	49.59	0.03	0.23	0.02	101.23	89.98
-625	40.89	0.00	0.14	0.06	9.85	0.17	49.38	0.02	0.25	0.01	100.78	89.94
-688	41.28	0.00	0.14	0.06	9.86	0.17	49.76	0.00	0.24	0.03	101.54	90.00
-703	40.63	0.01	0.15	0.07	9.91	0.16	49.65	0.01	0.24	0.02	100.84	89.93
-755	40.66	0.00	0.14	0.07	9.83	0.16	49.55	0.01	0.22	0.01	100.67	89.99
-881	40.68	0.00	0.13	0.06	9.77	0.17	49.70	0.02	0.24	0.00	100.77	90.07
-908	40.38	0.01	0.12	0.07	9.63	0.17	49.62	0.00	0.23	0.02	100.25	90.18