

Comments on Some Misconceptions in Igneous and Experimental Petrology and Methodology: a Reply

YAOLING NIU

DEPARTMENT OF EARTH SCIENCES, THE UNIVERSITY OF QUEENSLAND, BRISBANE, QLD. 4072, AUSTRALIA

RECEIVED OCTOBER 20, 1998; REVISED TYPESCRIPT ACCEPTED JANUARY 15, 1999

INTRODUCTION

I recently showed (Niu, 1997) that proportions of residual minerals in abyssal peridotites (e.g. Dick, 1989; Johnson *et al.*, 1990; Johnson & Dick, 1992) exhibit systematic variations with whole-rock MgO content. I also showed that the whole-rock MgO content in melting residues is linearly related to the overall extent of melting or melt depletion [see fig. 8 of Niu (1997)]. These observations thus allow an explicit examination of how residual mineral proportions change in response to varying extents of melting as shown in Fig. 1 [fig. 12 of Niu (1997)], and allow an insightful understanding of the chemical and mineralogical consequences of *actual* mantle melting processes beneath ocean ridges. Figure 1 can be expressed in terms of a simple mathematical form [equation (8) of Niu (1997)]:

$$0.466 \text{ cpx} + 0.652 \text{ opx} + 0.049 \text{ spl} \\ = 1.000 \text{ melt} + 0.167 \text{ ol.} \quad (1)$$

Equation (1) says that the *abyssal peridotite data* (vs *models*) tell us that in order to produce 1.000 mass unit of a basaltic melt, approximately 0.466 mass unit of *cpx*, 0.652 mass unit of *opx*, and 0.049 mass unit of *spinel* are required to melt whereas about 0.167 mass unit of *olivine* is required to crystallize. Equation (1) is identical in form to isobaric melting reactions determined experimentally (e.g. Kinzler & Grove, 1992a; Baker & Stolper, 1994): $a \text{ cpx} + b \text{ opx} + c \text{ spl} = d \text{ ol} + 1 \text{ Melt}$, suggesting that mantle melting is indeed incongruent. What differs between equation (1) and the isobaric melting reactions is the relative ‘melting

rate’ of *cpx* and *opx*. Isobaric melting experiments show $a > b$, but the abyssal peridotite data suggest $b > a$, i.e. *opx* would contribute more than *cpx* to the melt during melting beneath ocean ridges. As abyssal peridotites are apparently metamorphosed and deformed under subsolidus conditions (e.g. Niu, 1997; Niu *et al.*, 1997) this could have resulted in mineral modal and compositional re-equilibration. In this case, equation (1) could be an artifact of such a post-melting equilibration. The effect of this equilibration may exist, but it is not petrographically evident, and it cannot explain the observed modal changes with increasing extent of melting (see Dick *et al.*, 1984; Niu *et al.*, 1997). As the abyssal peridotites studied are from many locations (not a single location), and define much of the data range on a global scale, I thus interpreted equation (1), with $b > a$, as representing the *net effect* of most likely complex *polybaric* (vs isobaric) melting processes beneath ocean ridges (Niu, 1997). This interpretation is supported by decompression melting model results in which $b > a$ [see fig. 6 of Niu (1997)], and by the polybaric phase equilibria analysis which shows that *opx* (vs *cpx*) melting is further assisted by the incongruent melting of $\text{opx} \Rightarrow \text{ol} + \text{SiO}_2$ with decreasing pressure [see fig. 7 of Niu (1997)]. Importantly, this interpretation is consistent with, and required by, the fact that melting can occur beneath ocean ridges only because of fertile mantle *upwelling and decompression* (i.e. polybaric vs isobaric) in response to plate separation.

My observation [Fig. 1 and equation (1)] and interpretations have received aggressive criticisms from Walter (1999) because my *observation* differs from isobaric melting experiments and his model melting reactions [see his equations (2)–(5), table 1 and fig. 2]. In this reply, I

*Telephone: +61-7-3365-2372. Fax: +61-7-3365-1277.
e-mail: niu@earthsciences.uq.edu.au

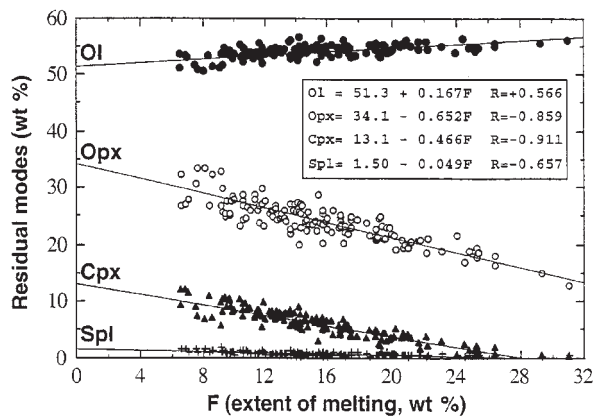


Fig. 1. Weight percent of residual mineral phases (calculated to a total mass of $100 - F\%$) in abyssal peridotites plotted against the extent of melting (F , wt %) estimated from the whole-rock MgO content [see fig. 8 of Niu (1997)]. The inset shows the linear regression equations of olivine (ol), orthopyroxene (opx), clinopyroxene (cpx) and spinel (spl) against the estimated extent of melting with R values being the respective correlation coefficients, all significant at $>99\%$ confidence level. This plot is modified from fig. 12 of Niu (1997).

welcome Walter's criticisms and would like to agree that Walter's isobaric melting reactions derived from simplified CMAS systems could be correct. I would also like to say that actual mantle melting reactions may be rather complex and variable depending on many factors (e.g. P - T paths and bulk compositions, etc.). However, we can readily see that my observation is valid, and my interpretation that this observation is consistent with polybaric mantle melting is valid. Equation (1) thus can be used to evaluate first-order trace element systematics during mantle melting beneath ocean ridges. In contrast, Walter's polybaric melting model in the spinel peridotite stability field (his fig. 2) has the form of $cpx \Rightarrow opx + melt$ that involves no olivine and spinel (see Fig. 5b, below, for details), which is supported neither by experimental data nor by observations. Clearly, it is inappropriate to use Walter's model to evaluate trace element systematics during mantle melting beneath ocean ridges.

REPLY TO AND COMMENT ON WALTER'S CRITICISMS

(1) *'The "polybaric melting reaction" for MORB proposed by Niu (1997) is erroneous ... the concept of a single "polybaric melting reaction" is not correct'*—by Walter

The 'polybaric melting reaction [i.e. equation (1)]' by Niu (1997) is a valid *observation* (see Fig. 1), not a proposed model. Actual (vs model) melting reactions may be complex and variable depending on many factors (e.g. P - T

paths and bulk compositions, etc.), but Niu's observation is the consequence of *actual* mantle melting, and represents the *net effect* of most likely complex polybaric (vs isobaric) melting processes beneath ocean ridges (Niu, 1997).

(2) *'The modal abundances of minerals in abyssal peridotites that have equilibrated at low pressures and temperatures cannot be used to calculate high-pressure and -temperature melting reactions'*—by Walter

I did not say anywhere in Niu (1997), either implicitly or explicitly, that modal abundances of abyssal peridotite minerals *can* be used to calculate *high-pressure and -temperature* melting reactions (although they could be approximated). Nor did I say model residual minerals could. In this context, I stated the opposite. For example, I said 'As Fig. 6 uses low-pressure modes to reveal high-pressure signatures, the position of cpx-opx cross-over (Fig. 6b) may differ from that of actual polybaric melting residues without experiencing subsolidus equilibration (undetermined yet)' [p. 1054 of Niu (1997)]. I also said 'One of the major difficulties is the lack of a sound thermodynamic means for evaluating both proportions and compositions of residual minerals from a given bulk composition as a function of temperature and pressure' [p. 1051 of Niu (1997)].

On the other hand, the high pressure-temperature (P - T) melting signatures are still preserved in the whole-rock compositions of melting residues if post-melting equilibration is isochemical. This is because whole-rock compositions of melting residues vary as a function of the melting conditions or paths (in a P - T space) and the extent of melting (Niu, 1997). Therefore, the norms calculated from the compositions of the whole-rock peridotite residues, which are essentially the same as the low P - T modes [see fig. 5 of Niu (1997)], preserve the P - T signatures at the melting conditions [see equations (5) and (6), and related discussion of Niu (1997)]. In other words, the set of model melting reactions in fig. 6 of Niu (1997) are 'polybaric melting reactions' that high P - T melting residues would have when equilibrated at low pressures. To understand the observed data (e.g. Fig. 1), we need to effectively compare the model results with the data. The only proper way to compare the two is to use *norms* or *low- P modes* because they are equivalent [see fig. 5 of Niu (1997)], and because we do not have the actual pressure information on the data. The similarity between the model polybaric melting reactions [fig. 6 and equation (1) of Niu (1997) vs isobaric melting reactions] and the observed data (Fig. 1) indicates that equation (1) is consistent with polybaric melting processes as expected.

It is important to note that the Niu's (1997) 'polybaric melting reaction' [equation (1)] is derived from the modal data (Fig. 1), not from CIPW norm calculations.

(3) *'The change in mineral proportions along the solidus of lherzolite has a profound effect on melting reactions . . . The low temperature modes of abyssal peridotites fail to account for these changes, and this inaccurate assessment of mineral modes. . . . When this misinterpretation of mineral modes is perpetuated into the calculation of a melting reaction, the result is an overestimation in the amount of opx, and an underestimation in the amount of cpx, that dissolves into the melt'*—by Walter

Pyroxenes are complex solid solutions, and the compositions of the coexisting opx and cpx in a rock vary as a function of both temperature and pressure (e.g. Lindsley, 1983). In terms of the enstatite (En, $\text{Mg}_2\text{Si}_2\text{O}_6$) and diopside (Di, $\text{CaMgSi}_2\text{O}_6$) endmembers, the compositions of the two coexisting pyroxenes are constrained to lie on the two-pyroxene miscibility gap (e.g. Lindsley, 1983). For example, En content in cpx and Di content in opx increase with rising temperature. Consequently, the coexisting opx and cpx formed at a high temperature will change their compositions with the associated change of the relative modal proportions of the two minerals when temperature falls. Under subsolidus conditions, this is the process known as exsolution, i.e. opx exsolves Di-rich cpx-lamellae whereas cpx exsolves En-rich opx-lamellae. Exsolution of this type has been observed in some abyssal peridotite samples, but is volumetrically insignificant (Dick *et al.*, 1984; Dick & Natland, 1996; Niu & Hékinian, 1997a). At relatively higher temperatures, some of these lamellae could coalesce into discrete grains of opx and cpx in a process known as 'granular exsolution' (Lindsley & Anderson, 1983). It is possible that cpx in cpx-poor (<2%) abyssal peridotites may be the result of granular exsolution, but there is no textural evidence that cpx in cpx-rich (>2%) rocks and any opx in abyssal peridotites could be the result of granular exsolution (Henry Dick, personal communication, 1998). This is not surprising because the compositions of opx and cpx in abyssal peridotites are consistent with their equilibration being at magmatic conditions (>1100°C) (e.g. Dick & Fisher, 1984; Komor *et al.*, 1990) (also see Fig. 2b).

If, on the other hand, significant pyroxene compositional changes occurred at magmatic conditions along a melting path (falling temperature and decreasing pressure), and these changes were accompanied by a significant increase in opx mode (converted from cpx), then Walter would probably (not necessarily) be correct, and there could be an overestimation of opx and underestimation of cpx that dissolve into the melt from abyssal peridotite data. Walter shows in his fig. 4a that the effect of temperature and pressure on CMASN solidus pyroxenes is huge (e.g. En in cpx decreases from ~75% at 25 kbar and 1500°C to ~35% En at ~5 kbar and 1250°C, ~40% difference), and that the relative modes

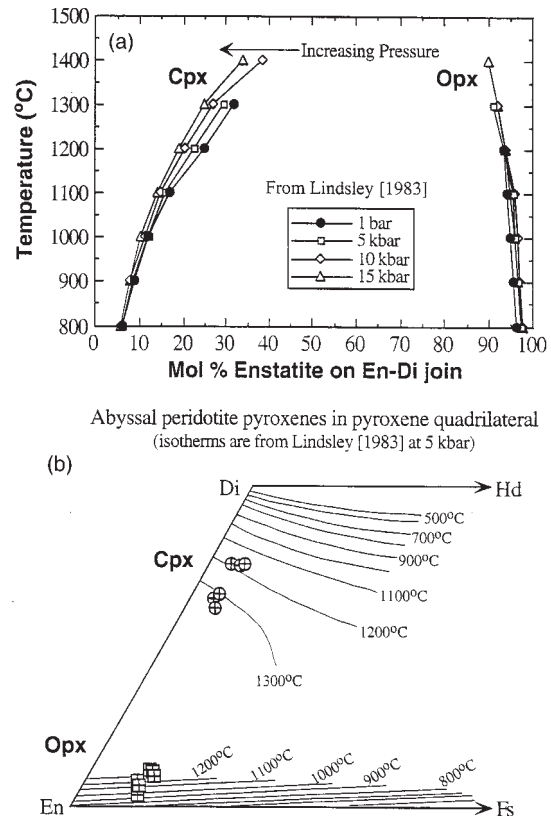


Fig. 2. (a) Enstatite (En) content (mol %) in coexisting cpx and opx as a function of temperature and pressure. Data are derived from the En-Di joins of pyroxene quadrilaterals of Lindsley (1983). (b) Averages of six suites of abyssal peridotite pyroxenes [see fig. 9 of Niu (1997)] plotted onto the 5 kbar pyroxene quadrilateral of Lindsley (1983) following the projection scheme of Lindsley (1983) and Lindsley & Anderson (1983).

of coexisting opx and cpx change dramatically along a decompression melting path as shown in his fig. 4b. Is Walter really correct? The answer is simply, 'No'. First, Walter's figs 4a and 4b are schematic representations, albeit based on experimental data. Second, Walter did not seem to have realized that it is well established experimentally that the effect of pressure on the compositions of coexisting pyroxenes is opposite to that of temperature (e.g. Lindsley, 1983). Thus, Walter's fig. 4a is conceptually misleading without properly evaluating the relative effects of pressure and temperature on the compositions of coexisting opx and cpx.

Let us now examine the data (vs Walter's fig. 4), and see how pyroxene compositions change in response to the changing P - T along a melting path. We know that pyroxenes (cpx in particular) are complex in composition and have many major endmember components (e.g. En— $\text{Mg}_2\text{Si}_2\text{O}_6$, Di— $\text{CaMgSi}_2\text{O}_6$, Hd— $\text{CaFeSi}_2\text{O}_6$, Fs— $\text{Fe}_2\text{Si}_2\text{O}_6$, Jd— $\text{NaAlSi}_2\text{O}_6$, Ct— $\text{CaAl}_2\text{SiO}_6$, etc.), but in terms of the effects of temperature and pressure on

the compositions of coexisting pyroxenes, the so-called quadrilateral pyroxenes (En–Di–Hd–Fs) are mostly considered, and the En–Di join is best studied both experimentally and theoretically (e.g. Lindsley, 1983). Figure 2a shows the compositions of coexisting opx and cpx in terms of En content on the En–Di join derived from fig. 9 of Lindsley (1983). It is clear that the En content in cpx increases with rising temperature at all temperatures, but decreases, at a given temperature, with increasing pressure at $T > 1000^\circ\text{C}$. The En content in opx decreases slightly with rising temperature, and is essentially independent of pressure. That is, cpx composition is more sensitive and reliable than opx composition in reflecting the equilibration P – T conditions. Figure 2b plots average abyssal peridotite pyroxenes onto the pyroxene quadrilateral following the projection scheme of Lindsley (1983). Given the uncertainties of the isotherms (~ 20 – 30°C) (Lindsley & Anderson, 1983), we can say that the average abyssal peridotite pyroxenes represent equilibration temperatures of ~ 1200 – 1300°C , which are indeed magmatic temperatures. Figure 3a shows in a P – T space the probable ‘locations’ of abyssal peridotite pyroxenes with respect to decompression melting conditions beneath ocean ridges. The mantle ascends along the adiabat in response to plate separation, and begins to melt when intersecting the solidus at ~ 25 kbar. Melting continues as the mantle rises along a melting path until it reaches the thermal boundary layer atop the mantle where conductive cooling becomes important. The melting path is a function of the heat of fusion of the solid mantle material, and is constrained to be between path A ($H_f = 100$ cal/g) and path B ($H_f = 180$ cal/g) (Langmuir *et al.*, 1992). The thickness of the thermal boundary layer or the depth of melting cessation is not precisely known, but should increase with decreasing spreading rate (e.g. Shen & Forsyth, 1995; Niu & Hékinian, 1997b), and can be as deep as ~ 30 km beneath very slow-spreading ridges (Niu, 1997).

Figure 3b, a portion of Fig. 3a, shows how En content in cpx (mol %) varies as a function of temperature and pressure [after Lindsley (1983); also see Fig. 2a above]. It should be noted that Lindsley graphically reported the data at four pressures (1 bar, 5 kbar, 10 kbar and 15 kbar), but the contours are extrapolated to 20 and 25 kbar by using a second-order polynomial fit to 25% and 30% En data, respectively, with the rest of the contours drawn parallel to the 25% and 30% En contours and passing through the respective data points. We can now readily see that in the course of decompression melting, cpx compositional change as a result of P – T change only is very limited. For example, if the mantle begins to melt at ~ 25 kbar, and takes melting path A, then the En content of cpx in this ascending and melting mantle is essentially constant at $\sim 30\%$ (from $\sim 29\%$ to $\sim 31\%$). If the melting takes path B, the En content in the cpx may

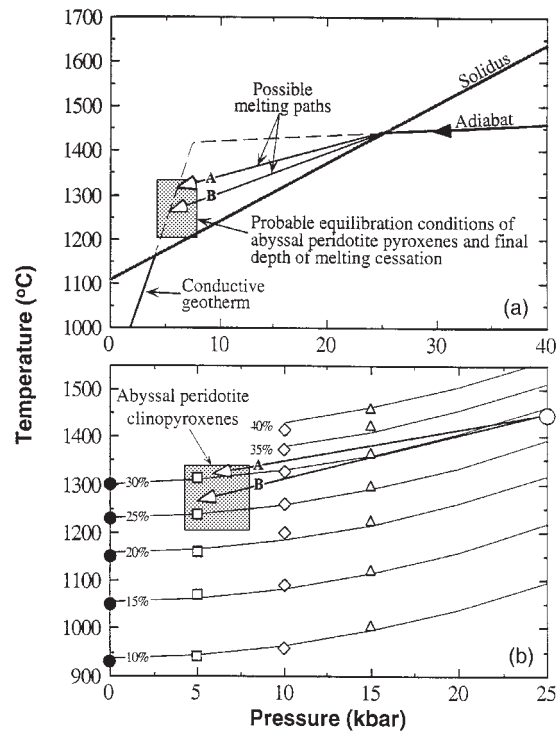


Fig. 3. (a) The probable equilibration conditions of abyssal peridotite pyroxenes (see Fig. 2) in P – T space in the context of decompression melting beneath ocean ridges. The solidus is taken from McKenzie & Bickle (1988) and is based on averaged experimental data. The possible melting paths, assuming melting begins at 25 kbar, are approximated (using straight vs curved lines for simplicity) after Langmuir *et al.* (1992) as constrained by the heat of fusion of the fertile mantle varying from $H_f = 100$ cal/g for path A to $H_f = 180$ cal/g for path B. The adiabatic and conductive thermal gradients are schematic. (b) is a portion of (a) with contours of En content (mol %) in cpx plotted to show the extent to which pyroxene compositions may change along the decompression melting path as a result of only changes in temperature and pressure (i.e. the effect of melt depletion is not considered). The data at pressures of 1 bar, and 5, 10 and 15 kbar are plotted using the same symbols as in Fig. 2a. The En contours are second-order polynomial fits to the data of 25% and 30% En, and extrapolated to pressures of 20 and 25 kbar. The contours for other En % are drawn parallel to the contours of 25% and 30% En and passing through the respective data points. It is clear that the cpx at the onset of melting at 25 kbar that has $\sim 29\%$ En will still have $\sim 29 \pm 2\%$ En. This indicates that the relative modal abundance change of the coexisting cpx and opx, as a result of only P – T dependent pyroxene compositional change along the melting path, is insignificant. This contrasts markedly with what is shown in Walter's schematic representations (his fig. 4).

decrease only slightly (may not be practically discernible) from onset of melting ($\sim 29\%$) to the conditions preserved in abyssal peridotites ($\sim 27\%$). This does not mean that the cpx will not change in composition during melting, but means that the cpx compositional change as a result of only the changing P – T along the melting path is trivial because of the canceling effects of temperature and pressure. It should be noted that although we do not have data at 20 and 25 kbar (Fig. 3b), the maximum En content change in cpx along the decompression melting

path is predicted to be significantly $<5\%$, in which case the En contours would have to be extrapolated linearly. This small value ($<5\%$) contrasts with the huge (40%) cpx En-content change in Walter's schematic representation (his fig. 4a). Consequently, opx-cpx modal abundance change resulting from their compositional change is minimal. Therefore, the observed opx-cpx modal variations in abyssal peridotites are not caused by changing temperature and pressure along the melting path, but result from varying extents of melting, as has been well established (Dick & Fisher, 1984; Dick *et al.*, 1984; Michael & Bonatti, 1985; Niu *et al.*, 1997). Therefore, equation (1) [equation (8) of Niu (1997)], the observation, is to a first order a valid mineralogical expression of decompression melting beneath ocean ridges.

In summary, Walter's figs 4a and 4b are schematic representations albeit based on experimental data. In particular, Walter's fig. 4b clearly neglects the opposing effects of temperature and pressure on pyroxene compositions (see Figs 2 and 3), which has been well established experimentally (e.g. Lindsley, 1983; Lindsley & Anderson, 1983). Figure 4 compares Walter's polybaric melting residues (derived from his fig. 2) with several natural peridotite suites. The positive correlation between olivine and opx modes in Walter's model spinel lherzolite residue contrasts with the negative olivine-opx correlations observed in natural peridotites: abyssal peridotites, massif peridotites, and cratonic peridotites. Walter may choose to interpret the negative olivine-opx correlations in natural peridotites as resulting from P - T dependent pyroxene compositional and modal changes, but this interpretation cannot be correct as demonstrated above (see Figs 2a and 3b). Therefore, Walter's polybaric melting model (his fig. 2) is questionable (see below).

(4) 'This reaction [Niu's equation (12)], with opx contributing more by weight than cpx to the melt, is very different from melting reactions obtained for melting of spinel lherzolite on the basis of experimental data from both natural and simplified systems'—by Walter

We know that doing experiments is one approach, and making observations is another. If the conclusions of the two approaches differ, then further efforts are needed to reconcile the differences. The 'Niu's reaction' is the observation, and is the consequence of the natural processes, whereas doing experiment is an attempt to simulate and to understand the natural processes. As partial melting can occur beneath ocean ridges only because of mantle upwelling and decompression (polybaric), application of isobaric melting experiments to polybaric natural processes is not straightforward (e.g. Niu & Batiza, 1991; Kinzler & Grove, 1992b; Langmuir *et al.*, 1992; Niu, 1997). Therefore, it is not surprising

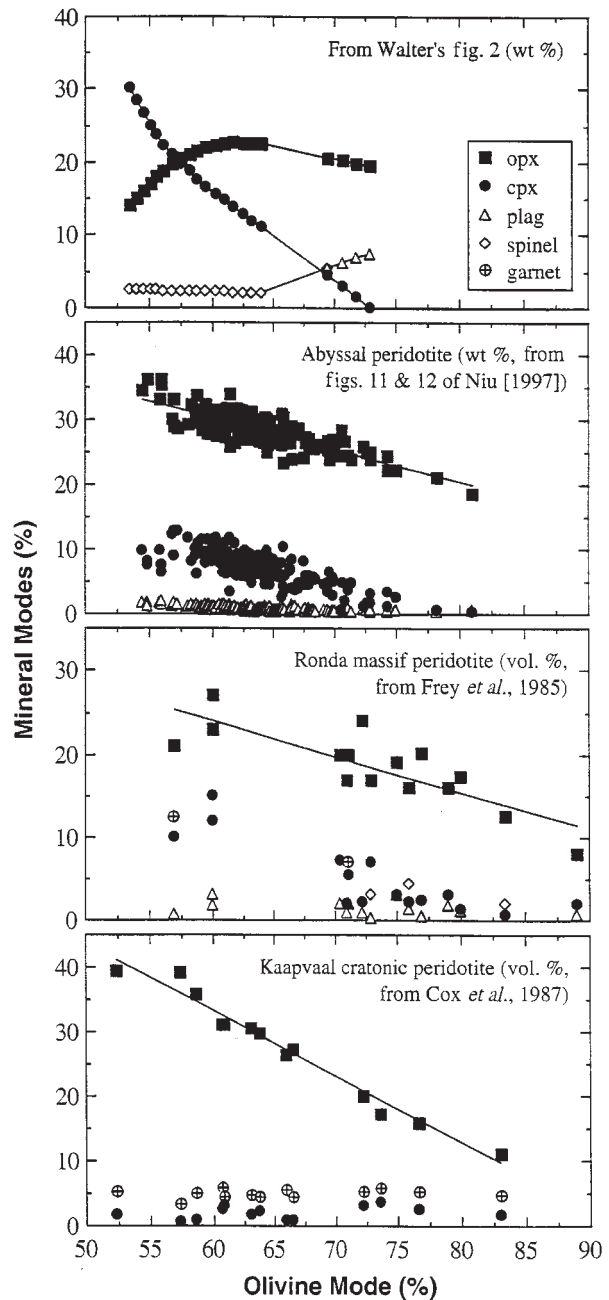


Fig. 4. Comparison of modal systematics of Walter's polybaric melting residues (his fig. 2) with modal systematics in several natural peridotite suites: abyssal peridotites [Dick (1989); also see figs 11 and 12 of Niu (1997), massif peridotite from Ronda (Frey *et al.*, 1985), and Kapaavaal cratonic peridotites (Cox *et al.*, 1987)]. It should be noted that Walter's positive olivine-opx correlation in the 'spinel lherzolite' field is not observed in any natural suites. Walter would ascribe the differences between his model results and the observations to P - T dependent pyroxene compositional, and hence modal changes, but as demonstrated in Fig. 3, his interpretation is unsupported by experimental data.

that isobaric experiments differ from the observations. However, the observation is consistent with Niu's (1997)

polybaric melting model results [see figs 6 and 7 of Niu (1997)], and is similar to those of Walter following Niu's approach (see Walter's figs 3, 5a and 5b), but is inconsistent with Walter's 'correct' polybaric melting reaction (his fig. 2; see below).

(5) *'Experimental data show that the complexity of phase relations as a function of pressure and temperature leads to a rich variety of melting reactions in polybaric melting paths. A single "polybaric melting reaction" is not realistic. Only high-pressure and -temperature phase relations can yield reliable melting reactions'*—by Walter

Walter's P - T dependent rich variety of reactions [his equations (2)–(5), and table 1] could be correct, although the correctness of these reactions is difficult to evaluate. This is because of the lack of sufficient data, and because his polybaric melting model (his fig. 2) derived from these reactions is in error (see below). The relevance of his CMASN-derived reactions to natural systems is also questionable. The fact is that there are no real-world observations that require invoking Walter's *realistic* reactions. Walter did not seem to have realized that making observations is a valid scientific approach. Walter takes an experimental approach, and examines the details of possible melting reactions in simplified systems, but I try to understand the first-order observations—the consequences of *actual* processes. It is probably true that a single polybaric melting reaction may not be realistic, but I emphasize the implications of the first-order observations, and the observations are *realistic*. We are still in the process of understanding the first-order problems, and our goal is to explain the first-order observations. The data [equation (1) and Fig. 1] are from many locations (Dick, 1989; Johnson *et al.*, 1990; Johnson & Dick, 1992), and thus do not reflect melting from a single melting regime. However, as the data define much of the range on a global scale, Fig. 1 and equation (1) tell us to a first order what mantle melting looks like beneath ocean ridges, which is the very point stressed by Niu (1997). In comparison, Walter's detailed reactions [his equations (2)–(5)] do not have the same power as the observations [Fig. 1 and equation (1)] that speak about nature.

(6) *'Figure 2 shows residual mineral modes as a function of degree of melt depletion for polybaric melting of model lherzolite from 25 to 6 kbar. In this model, 1% melt is extracted at 1 kbar pressure. . . . Mineral modes for the sequentially depleted residues are calculated by mass balance . . . at the pressures and temperatures of melt extraction'*—by Walter

Walter presents his 'correct' polybaric melting model in his fig. 2 with the purpose to argue against Niu's proposal that Fig. 1 and equation (1) are the expressions of the mineralogical consequences of natural decompression

melting processes. We can readily see that Walter's polybaric melting model contradicts all the experimental data and all the observations. Figure 5a is a reproduction of Walter's fig. 2, which shows the relative modal proportions of minerals in melting residues after a certain amount (wt %) of melt has been produced and extracted. This plot, however, does not explicitly show the behavior of mineral phases during melting, i.e. if a mineral melts or crystallizes as melting proceeds. To show the behavior of a mineral phase during melting, we need to recast the mineral proportions to

$$\text{cpx} + \text{opx} + \text{spl} + \text{ol} + \text{melt depletion} = 100\% \quad (2)$$

and then plot the percent of each of the minerals against the percent of melt depletion (see Baker & Stolper, 1994; Niu, 1997) as done in Fig. 5b. Figure 5b explicitly shows that Walter's polybaric melting process in the spinel lherzolite stability conditions does not involve olivine and spinel because both olivine and spinel modes do not change (zero slope) with melting. The modal increase of opx and decrease of cpx with melting indicate that Walter's polybaric melting process is essentially the melting of cpx only with the accompanied crystallization of opx, i.e. $\text{cpx} \Rightarrow \text{opx} + \text{melt}$. This model result contradicts the well-established concept in igneous and experimental petrology over the last 80 years (e.g. Bowen & Anderson, 1914; Bowen, 1928; Green & Ringwood, 1967; O'Hara, 1968; Chen & Presnall, 1975; Hanson & Langmuir, 1978; Presnall *et al.*, 1979; Jaques & Green, 1980; Stolper, 1980; Langmuir & Hanson, 1981; Falloon & Green, 1988; Kinzler & Grove, 1992a; Baker & Stolper, 1994; Kinzler, 1997) that olivine plays a key role in basalt genesis. For example, the incongruent melting relationship of $\text{opx} \Rightarrow \text{ol} + \text{SiO}_2$ is essential in basalt genesis, and is further assisted by decreasing pressure [see fig. 7 of Niu (1997)]. It should be noted also that Walter's $\text{cpx} \Rightarrow \text{opx} + \text{melt}$ even contradicts his own melting reactions in the spinel lherzolite field [his equations (2) and (3)] in which *olivine is involved*, and crystallizes with melting. In addition, Walter's model result (Fig. 5b) contradicts petrological observations. For example, crystallization of opx, which has a higher SiO_2 content ($\sim 54.3 \pm 0.7\%$ in abyssal peridotites) than average primary basalt melts ($< \sim 51\%$) and cpx ($\sim 50.8 \pm 0.6\%$ in abyssal peridotites), during decompression melting would produce melt that is progressively depleted in SiO_2 with decreasing pressure of melting. This is opposite to what is expected, and is opposite to what is observed both in nature (e.g. Klein & Langmuir, 1987, 1989; Niu & Batiza, 1991, 1993, 1994; Kinzler & Grove, 1992b; Langmuir *et al.*, 1992) and in peridotite melting experiments (e.g. Jaques & Green, 1980; Falloon & Green, 1988; Kinzler & Grove, 1992a; Hirose & Kushiro, 1993).

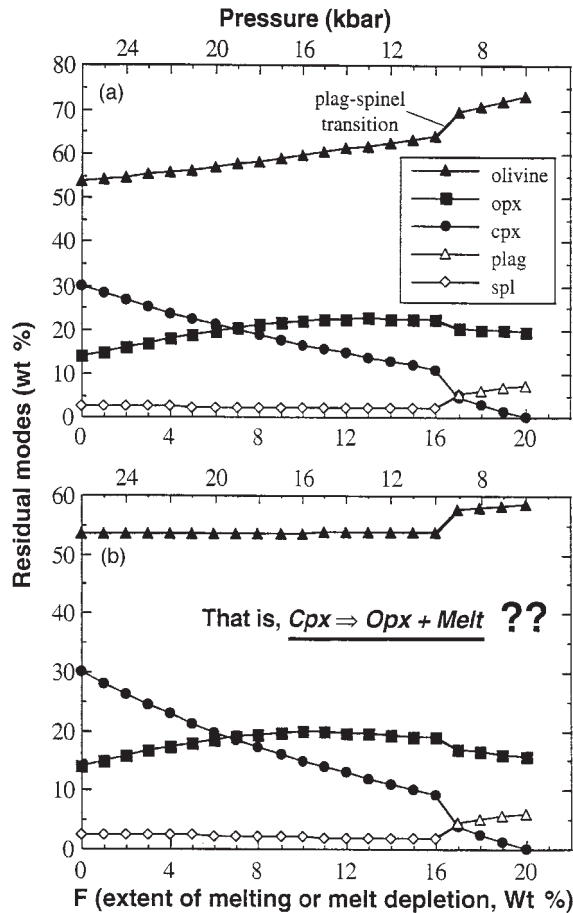


Fig. 5. (a) A reproduction of Walter's fig. 2, showing modal variations of minerals in his model melting residues after a certain amount (wt %) of melt has been extracted. This plot cannot, however, show the behavior of mineral phases during actual melting. (b) replots (a) after recasting residual mineral modes to a total mass of (100 - melt depletion)% [see equation (2)] to show whether a mineral enters the melt or crystallizes out of the melt with increasing overall extent of melting. The essentially zero slope of olivine and spinel indicates that in Walter's polybaric melting model these two mineral phases do not participate in the melting process. His polybaric melting is characterized by melting cpx only with accompanied opx crystallization. This model result is consistent neither with petrological observations nor with experimental data of any kind in terms of peridotite melting and basaltic magma genesis.

Walter seems to emphasize the importance of decompression melting in the plagioclase peridotite depth range (see his figs 2 and 4a). It is important to note that such melting may not take place in nature. Plagioclase is rare in abyssal peridotites, and all the plagioclase observed results from melt impregnation (Dick, 1989; Hékinian *et al.*, 1992, 1993; Dick & Natland, 1996; Niu & Hékinian, 1997a). Physically, the plagioclase peridotite stability field is equivalent to the thermal boundary layer atop the mantle beneath ocean ridges, particularly at slow-spreading ridges, where conductive cooling dominates over the adiabat so that no significant melting

would be possible (Niu, 1997; Niu & Hékinian, 1997b; Niu *et al.*, 1997).

(7) 'The point here is that the 'polybaric melting reaction' presented by Niu (1997) is wrong on phase equilibrium grounds, and that it can lead to quantitatively significant errors in trace element modeling. . . . Thus, conclusion (2) of Niu (1997) is refuted by experimentally determined phase relations for melting of lherzolite'—by Walter

These statements are clearly not well thought out. Niu's (1997) 'polybaric melting reaction' is the observation, which tells us to a first order what *actual* decompression melting looks like beneath ocean ridges. As it is what is observed, this *reaction* is objective, independent of models, and has few assumptions. It is therefore straightforward and logical to use this *observed reaction* to model first-order trace element systematics during mantle melting beneath ocean ridges. In contrast to this observation, Walter's polybaric melting model (his fig. 2) has the form $cpx \Rightarrow opx + melt$ (see Fig. 5b), which is supported neither by observations nor by experimental data of any kind (see discussion above). It is therefore obvious that Walter's polybaric melting model cannot be used to properly and realistically model trace elements.

It should be noted that Walter's fig. 2 is his polybaric melting model, which is not 'experimentally determined phase relations for melting of lherzolite'. We know that we have not yet been able to conduct truly polybaric melting experiments. We thus take the approach to *model* the polybaric melting processes by using isobaric experimental data (e.g. Niu & Batiza, 1991; Kinzler & Grove, 1992b; Langmuir *et al.*, 1992; Niu, 1997). Both Walter's fig. 2 and fig. 6 of Niu (1997) are such polybaric melting models. The difference between these two models is that Niu's polybaric melting model is consistent with the observation [Fig. 1 and equation (1)], but Walter's model is not.

It should be noted also that Walter's fig. 6 shows different results by the two different approaches, which itself is not evidence in favor of one approach over the other. I hope Walter did not reason from his fig. 6 that 'calculations that differ from his are in error'. It should be noted that Niu's 'polybaric melting reaction' [Fig. 1 and equation (1)] is the observation, *not* models or 'normative method' as mislabeled in Walter's fig. 6.

(8) *Some typographic(?) errors*—by Walter

Walter's equation (1) was meant to be the reproduction of Niu's (1997) equation (8), but he introduced an error so that his equation (1) is mass unbalanced. For example, my equation (1) is mass balanced with 1.167 mass units on both sides of the equation, but Walter's equation (1) is not; 117 on the left-hand side of the equation does not equal 18 on the right-hand side. This could be a

typographic error, but he keeps this same error in his figs 3, 5a and 5b, where both sides of the equations are mass unbalanced. It should be noted also that Walter used incorrect La–Sm–Nd–Dy–Yb plotting order in his fig. 6. The correct order is La–Nd–Sm–Dy–Yb. Wouldn't Walter have negative Sm anomalies if plotting Nd on the left of Sm? What would cause these Sm anomalies?

SUMMARY

The major conclusions of this reply are:

(1) In contrast to Walter's schematic interpretation (his fig. 4), the experimental data (Figs 2a and 3b) show that temperature and pressure have opposing effects on the compositions (in terms of En content) of coexisting opx and cpx. Therefore, pyroxene compositional change, and the resulting opx–cpx abundance change, along a melting path as a result of only the changing temperature and pressure is minimal (Fig. 3b).

(2) Therefore, contrary to Walter's opinion, equation (1) and Fig. 1 [equation (8) and fig. 12 of Niu (1997)] are valid observations, and are the first-order expression of mantle melting processes beneath ocean ridges.

(3) Niu's equation (1) hence can be used to model trace element systematics during decompression near-fractional melting beneath ocean ridges. Given the extreme fertile mantle compositional variations on various scales beneath ocean ridges (e.g. Niu & Batiza, 1997), we can at present confidently model only the first-order systematics of trace elements as a result of decompression melting.

(4) Walter's polybaric melting model in the spinel lherzolite field (his fig. 2) has the form $\text{cpx} \Rightarrow \text{opx} + \text{melt}$ (see Fig. 5). This 'reaction' involves neither olivine nor spinel, and thus violates the well-established concept in igneous and experimental petrology over the last ~80 years that olivine plays a key role in basalt genesis. Therefore, Walter's polybaric melting reaction model, $\text{cpx} \Rightarrow \text{opx} + \text{melt}$, cannot be used to model trace elements.

(5) Doing experiments, making observations, and conducting theoretical modeling are different scientific approaches. An effort is needed to reconcile the conclusions of these approaches if they conflict. This is a recommended scientific methodology.

ACKNOWLEDGEMENTS

I thank Michael Walter for his criticisms, which give me this opportunity to further clarify some fundamental concepts in igneous and experimental petrology, and in magma generation processes. I thank Mike O'Hara and

Marjorie Wilson for constructive comments and suggestions that helped improve the paper. I also thank Pam Stuart and Marjorie Wilson for editorial effort.

REFERENCES

- Baker, M. B. & Stolper, E. M. (1994). Determining the composition of high-pressure mantle melts using diamond aggregates. *Geochimica et Cosmochimica Acta* **58**, 2811–2827.
- Bowen, N. L. (1928). *The Evolution of the Igneous Rocks*. Princeton, NJ: Princeton University Press, 332 pp.
- Bowen, N. L. & Anderson, O. (1914). The binary system MgO–SiO₂. *American Journal of Science, 4th series* **37**, 487–500.
- Chen, C.-H. & Presnall, D. C. (1975). The system MgSiO₄–SiO₂ at pressures up to 25 kilobars. *American Mineralogist* **60**, 398–406.
- Cox, K. G., Smith, M. R. & Beswetherick, S. (1987). Textural studies of garnet lherzolites: evidence of exsolution origin from high-temperature harzburgites. In: Nixon, P. H. (ed.) *Mantle Xenoliths*. New York: John Wiley, pp. 537–550.
- Dick, H. J. B. (1989). Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism. In: Saunders, A. D. & Norry, M. J. (eds) *Magmatism in the Ocean Basins. Geological Society, London, Special Publication* **42**, 71–105.
- Dick, H. J. B. & Fisher, R. L. (1984). Mineralogic studies of the residues of mantle melting: abyssal and alpine-type peridotites. In: Kornprobst, J. (ed.) *The Mantle and Crustal–Mantle Relationships—Mineralogical, Petrological, and Geodynamic Processes of the Third International Kimberlite Conference, Vol. II*. New York: Elsevier, pp. 295–308.
- Dick, H. J. B. & Natland, J. H. (1996). Late-stage melt evolution and transport in the shallow mantle beneath the East Pacific Rise. In: Mével, C., Gills, K. M. & Allan, J. F. (eds) *Proceedings of the Ocean Drilling Program, 147*. College Station, TX: Ocean Drilling Program, pp. 103–134.
- Dick, H. J. B., Fisher, R. L. & Bryan, W. B. (1984). Mineralogical variability of the uppermost mantle along mid-ocean ridges. *Earth and Planetary Science Letters* **69**, 88–106.
- Falloon, T. J. & Green, D. H. (1988). Anhydrous partial melting of peridotite from 8 to 35 kb and the petrogenesis of MORB. *Journal of Petrology*, Special Lithosphere Issue, 379–414.
- Frey, F. A., Suen, C. J. & Stockman, H. (1985). The Ronda high temperature peridotite: geochemistry and petrogenesis. *Geochimica et Cosmochimica Acta* **49**, 2469–2491.
- Green, D. H. & Ringwood, A. E. (1967). The genesis of basaltic magmas. *Contributions to Mineralogy and Petrology* **15**, 103–190.
- Hanson, G. N. & Langmuir, C. H. (1978). Modeling of major elements in mantle systems using trace element approaches. *Geochimica et Cosmochimica Acta* **42**, 725–741.
- Hékinian, R., Bideau, D., Cannat, M., Francheteau, J. & Hébert, R. (1992). Volcanic activity and crust–mantle exposure in the ultrafast Garrett transform fault near 13°28'S in the Pacific. *Earth and Planetary Science Letters* **108**, 259–273.
- Hékinian, R., Bideau, D., Francheteau, J., Cheminee, J. J., Armijo, R., Lonsdale, P. & Blum, N. (1993). Petrology of the East Pacific Rise crust and upper mantle exposed in Hess Deep (eastern equatorial Pacific). *Journal of Geophysical Research* **98**, 8069–8094.
- Hirose, K. & Kushiro, I. (1993). Partial melting of dry peridotites at high pressures: determination of compositions of melts segregated from peridotite using aggregates of diamonds. *Earth and Planetary Science Letters* **114**, 477–489.
- Jaqes, A. L. & Green, D. H. (1980). Anhydrous melting of peridotite at 0–15 kb pressure and the genesis of tholeiitic basalts. *Contributions to Mineralogy and Petrology* **73**, 287–310.

- Johnson, K. T. M. & Dick, H. J. B. (1992). Open system melting and the temporal and spatial variation of peridotite and basalt compositions at the Atlantis II F. Z. *Journal of Geophysical Research* **97**, 9219–9241.
- Johnson, K. T. M., Dick, H. J. B. & Shimizu, N. (1990). Melting in the oceanic upper mantle: an ion microprobe study of diopside in abyssal peridotites. *Journal of Geophysical Research* **95**, 2661–2678.
- Kinzler, R. J. (1997). Melting of mantle peridotite at pressures approaching the spinel to garnet transition: application to mid-ocean ridge basalt petrogenesis. *Journal of Geophysical Research* **102**, 853–874.
- Kinzler, R. J. & Grove, T. L. (1992a). Primary magmas of mid-ocean ridge basalts, 1, experiments and methods. *Journal of Geophysical Research* **97**, 6885–6906.
- Kinzler, R. J. & Grove, T. L. (1992b). Primary magmas of mid-ocean ridge basalts, 2, applications. *Journal of Geophysical Research* **97**, 6907–6926.
- Klein, E. M. & Langmuir, C. H. (1987). Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness. *Journal of Geophysical Research* **92**, 8089–8115.
- Klein, E. M. & Langmuir, C. H. (1989). Local versus global variation in ocean ridge basaltic composition: a reply. *Journal of Geophysical Research* **94**, 4241–4252.
- Komor, S., Grove, T. L. & Hébert, R. (1990). Abyssal peridotites from ODP Hole 670A (21°10'N, 45°02'W): residues of mantle melting exposed by non-constructive axial divergence. *Proceedings of Ocean Drilling Program, 106/109*. College Station, TX: Ocean Drilling Program, pp. 85–101.
- Langmuir, C. H. & Hanson, G. N. (1981). Calculating mineral–melt equilibria with stoichiometry, mass balance, and single component distribution coefficients. In: Newton, R. C., Navrotsky, A. & Wood, B. J. (eds) *Thermodynamics of Minerals and Melts. Advances in Physical Chemistry* **1**, 247–271.
- Langmuir, C. H., Klein, E. M. & Plank, T. (1992). Petrological systematics of mid-ocean ridge basalts: constraints on melt generation beneath ocean ridges. In: Phipps Morgan, J., Blackman, D. K. & Sinton, J. M. (eds) *Mantle Flow and Melt Generation at Mid-ocean Ridges. American Geophysical Union Monograph* **71**, 183–280.
- Lindsley, D. H. (1983). Pyroxene thermometry. *American Mineralogist* **68**, 477–493.
- Lindsley, D. H. & Anderson, D. J. (1983). A two-pyroxene thermometer. In: *Proceedings of the 13th Lunar and Planetary Science Conference, Part 2. Journal of Geophysical Research* **88**, Supplement, A887–A906.
- McKenzie, D. & Bickle, M. J. (1988). The volume and composition of melt generated by extension of the lithosphere. *Journal of Petrology* **29**, 625–679.
- Michael, P. J. & Bonatti, E. (1985). Peridotite composition from the North Atlantic: regional and tectonic variations and implications for partial melting. *Earth and Planetary Science Letters* **73**, 91–104.
- Niu, Y. (1997). Mantle melting and melt extraction processes beneath ocean ridges: evidence from abyssal peridotites. *Journal of Petrology* **38**, 1047–1074.
- Niu, Y. & Batiza, R. (1991). An empirical method for calculating melt compositions produced beneath mid-ocean ridges: application for axis and off-axis (seamounts) melting. *Journal of Geophysical Research* **96**, 21753–21777.
- Niu, Y. & Batiza, R. (1993). Chemical variation trends at fast and slow spreading ridges. *Journal of Geophysical Research* **98**, 7887–7902.
- Niu, Y. & Batiza, R. (1994). Magmatic processes at the Mid-Atlantic Ridge ~26°S. *Journal of Geophysical Research* **99**, 19719–19740.
- Niu, Y. & Batiza, R. (1997). Trace element evidence from seamounts for recycled oceanic crust in the eastern equatorial Pacific mantle. *Earth and Planetary Science Letters* **148**, 471–484.
- Niu, Y. & Hékinian, R. (1997a). Basaltic liquids and harzburgitic residues in the Garrett transform: a case study at fast-spreading ridges. *Earth and Planetary Science Letters* **146**, 243–258.
- Niu, Y. & Hékinian, R. (1997b). Spreading rate dependence of the extent of mantle melting beneath ocean ridges. *Nature* **385**, 326–329.
- Niu, Y., Langmuir, C. H. & Kinzler, R. J. (1997). Origin of abyssal peridotites: a new perspective. *Earth and Planetary Science Letters* **52**, 251–265.
- O'Hara, M. J. (1968). The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks. *Earth-Science Review* **4**, 69–133.
- Presnall, D. C., Dixon, T. H., O'Connell, T. H. & Dixon, S. A. (1979). Generation of mid-ocean ridge tholeiites. *Journal of Petrology* **20**, 3–35.
- Shen, Y. & Forsyth, D. W. (1995). Geochemical constraints on initial and final depth of melting beneath mid-ocean ridges. *Journal of Geophysical Research* **100**, 2211–2237.
- Stolper, E. (1980). A phase diagram for mid-ocean ridge basalts: preliminary results and implications for petrogenesis. *Contributions to Mineralogy and Petrology* **74**, 13–27.
- Walter, J. W. (1999). Comments on 'Mantle melting and melt extraction processes beneath ocean ridges: evidence from abyssal peridotites' by Yaoling Niu. *Journal of Petrology* **40**, 1187–1193.