Excess olivine and positive FeO-MgO trend in bulk compositions of abyssal peridotites as a consequence of porous melt migration beneath ocean ridges: A clarification

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For your historical interest: Those who are interested in once hotly debated "abyssal peridotite problems", I suggest that you read on as this paper will never be published. Simplified versions were published as conference abstracts:

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Abstract

Niu, Langmuir and Kinzler [Earth Planet. Sci. Lett. 152 (1997) 251-265] (NLK97) show that a positive FeO-MgO trend exists in bulk compositions of abyssal peridotites reconstructed using mineral modes and analyses in the literature. Such a positive trend is inconsistent with abyssal peridotites being simple melting residues, but consistent with these peridotites being melting residues plus excess olivine. This interpretation built on unambiguous observations has been questioned because of the apparently sophisticated arguments by Baker and Beckett [Earth Planet. Sci. Lett. 171 (1999) 49-61] (BB99). Using their *averages* of reconstructed bulk-rock abyssal peridotite compositions, BB99 counter that the positive FeO-MgO correlation by NLK97 is an artifact and there is no evidence for significant olivine accumulation in abyssal peridotites. A clarification is necessary: (1) excess olivine in abyssal peridotites is evident in the original modal data; (2) excess olivine is also observed petrographically as reported in the literature; (3) the *averages* by BB99 cannot be readily derived from their own unaveraged data; and (4) the unaveraged data by BB99 do show a positive FeO-MgO trend. The positive FeO-MgO trend in reconstructed bulk compositions of abyssal peridotites results from excess olivine that *already exists* in these rocks, which is *not interpreted* from the positive FeO-MgO trend. The excess olivine in abyssal peridotites results from cooling of ascending melts migrating through advanced residues in the "cold" thermal boundary layer beneath ocean ridges. As the excess olivine is observed on thin-section scales, abyssal peridotites record porous melt migration beneath ocean ridges although channeled flows inferred from dunite bodies in ophiolites may be volumetrically more important.

Keywords: peridotites; ocean ridge processes; mantle melting; ocean crust formation

1. Introduction

Abyssal peridotites (AP) are mantle melting residues for mid-ocean ridge basalts (MORB) [1-4]. Recent studies [5-8] have confirmed the complementary relationship between MORB and AP, but also revealed the hidden complexities in these peridotites such as olivine addition [5-7] and melt refertilization [7,9,10,37]. These same studies [5,6] have immediately excited serious debates on AP petrogenesis [11-15]. These debates are stimulating and healthy towards an improved understanding of ocean ridge magmatic processes. However, a simple interpretation by Niu, Langmuir and Kinzler

(NLK97) [5] has been misunderstood because of the sophisticated counter-arguments by Baker and Beckett (BB99) [13]. NLK97 [5] show that modal proportions and reconstructed bulk AP compositions have far more olivine than would be predicted from melting models. BB99 [13] use *site averages* of their reconstructed bulk AP compositions to argue that there is "no evidence for significant olivine accumulation" in AP. Such a dispute arrives because AP are extensively serpentinized and not all four phases (olivine [ol], orthopyroxene [opx], clinopyroxene [cpx], spinel) may be present or analyzed for each sample even though their modal proportions can be reasonably estimated by detailed petrography [1,3,7]. In this case, compositions of missing phases must be predicted before bulk compositions can be reconstructed. NLK97's [5] prediction is based on statistically significant compositional (e.g., SiO_2, FeO, MgO, Al_2O_3, CaO, Na_2O, TiO_2) correlations within and between phases of the data set [3,4] (see Appendix of [5]). BB99 [13] take a rather sophisticated approach in predicting compositions of missing phases by considering averages, partition coefficients, polynomial regressions, mineral structural formulae, end-member components etc.

The purpose of this short paper is not to discuss the differences of technical details between the two approaches, but to show in simplest forms that (1) a positive FeO-MgO trend in bulk AP compositions is real, (2) AP do have excess olivine relative to expected melting residues, (3) the excess olivine is an inevitable consequence of cooling of the ascending melts through the advanced residues beneath ocean ridges as demonstrated previously [5,6], and (4) AP record porous melt flows beneath ocean ridges.

2. Excess olivine in abyssal peridotites is evident in mineral modes

While a number of AP data suites existed prior to NLK97 [5], NLK97 use the largest data set by Dick and co-workers [3,4] for consistency in modal estimates. BB99 [13] use the same data set [3,4] plus some newly available data by Dick and Natland [16] on drilled samples from the Hess Deep and data from a few Atlantic locations in the literature. Because the two studies [5,13] mostly use the same largest data set [3,4], the contrasting conclusions by the two studies require a careful re-examination. BB99 [13] state that the positive FeO-MgO trend in reconstructed bulk AP compositions by NLK97 [5] is an artifact, hence there is no significant excess olivine in AP.

However, readers should note that NLK97 [5] demonstrate that AP have far more *modal olivine* than predicted from melting experiments and melting models [5,6]. Therefore, the presence of excess olivine in AP is what is observed, not an interpretation of the positive FeO-MgO trend in reconstructed bulk AP compositions. Figure 1 (modified from Fig. 2 of [5]), which is an observation, *not* an interpretation, compares AP modal data with melting paths defined by residues of isobaric melting experiments at conditions relevant to ocean ridge mantle melting (e.g., 10 and 20 kbars). Clearly, the modal systematics of AP are not consistent with isobaric melting residues nor with residues produced by polybaric near-fractional melting models (not shown) [6]: AP have far more olivine and higher ol/opx ratios at a given cpx abundance level.

3. A positive FeO-MgO trend in abyssal peridotites results from varying amounts of excess olivine

Because olivine is the most abundant phase in AP (ol: 73.64±6.25 vol.% [Mean±1σ]; opx: 20.68±4.41 vol.%; cpx: 4.92±2.62 vol.%; spinel: 0.68±0.35 vol.%), and because olivine has significantly higher FeO (9.45±0.36 wt.%) and MgO (49.25±0.36 wt.%) than opx (FeO: 5.91±0.36 wt.%; MgO: 32.25±0.93 wt.%) and cpx (FeO: 2.81±0.44 wt.%; MgO: 17.01±1.35 wt.%) [5], it is straightforward that *both* FeO and MgO in bulk AP compositions increase with increasing modal olivine. Hence, a positive FeO-MgO trend in bulk AP compositions results from varying modal olivine.

If we define relative variability as RSD = one standard deviation / mean (i.e., RSD = 1σ/mean), we can denote relative variability of olivine mode, and olivine FeO and MgO contents as $RSD_{ol\text{-}Mode}$, $RSD_{ol\text{-}FeO}$, $RSD_{ol\text{-}MgO}$ etc. This allows us to see explicitly that mineral modal variability is significantly greater than mineral compositional variability and the bulk AP compositional variations are largely determined by mineral modes, *not* mineral compositions (Table 1 of [5] and Fig. 3 of [6]). For example, $RSD_{ol\text{-}FeO}/RSD_{ol\text{-}Mode} = 0.45$, $RSD_{ol\text{-}MgO}/RSD_{ol\text{-}Mode} = 0.09$, $RSD_{opx\text{-}FeO}/RSD_{opx\text{-}Mode} = 0.71$, $RSD_{opx\text{-}MgO}/RSD_{opx\text{-}Mode} = 0.34$, $RSD_{cpx\text{-}FeO}/RSD_{cpx\text{-}Mode} = 0.29$, $RSD_{cpx\text{-}MgO}/RSD_{cpx\text{-}Mode} = 0.15$ [5,6]. All these observations lead to an explicit conclusion that a positive FeO-MgO trend in bulk AP compositions with varying olivine modes is inevitable as illustrated in Figure 2.

4. Baker and Beckett also obtain a positive FeO-MgO trend but discard it

The above analysis and reasoning suggest that bulk AP compositions reconstructed from the original modal and mineral compositional data by any reasonable method, either simple [5] or complex one [13], should lead to a positive FeO-MgO trend. Indeed, BB99 [13] also produce a positive FeO-MgO trend in their reconstructed bulk AP compositions as clearly shown in Figure 3. This positive trend gives a linear correlation coefficient of R = 0.787, which is statistically significant at > 99.9% confidence levels. However, BB99 [13] state " … we find no statistically significant correlation between FeO and MgO … …" BB99 also argue "… the large grain size and heterogeneous distributions of phases within abyssal peridotites make it unlikely that individual thin section [sample] modes accurately reflect phase proportions in meter-sized dredge-haul samples" [13]. Using the latter argument, BB99 [13] discard the positive FeO-MgO trend seen in Figure 3 without discussing its statistical significance, but chose to use *site-averages*, instead of individual samples, to discuss AP petrogenesis. The difficulty, however, is the fact that the *site-averages* by BB99 [13] cannot be readily derived from their own unaveraged individual samples as explicitly shown in Figure 4. A straightforward analysis says that averages, regardless of how the averaging is done (e.g., arithmetic means, geometrical means, or even "site averaging"), must be confined within the field defined by the original unaveraged data points with the same slope (the slope may vary only slightly depending on data density distribution in this 2-D space). If, for example, we choose to average the entire data set into a single data point, then this single data point must be at the very weight center, *not outside*, of the original data trend. In other words, it is *impossible* to have averages that go beyond the field defined by the original unaveraged data. Therefore, BB99's [13] averages (open circles in Fig. 4) do not represent the original data (Fig. 3) they discard. This underscores that any interpretation based on BB99's averages of unknown origin must be considered with caution.

5. The cause of difference in FeO-MgO slope between NLK97 and BB99 studies

Although a statistically significant positive FeO-MgO trend is conspicuous (Fig. 3) in BB99's unaveraged data, the slope in Figure 3 is much less steep than the slope by NLK97 (Fig. 5a; reproduced from [5]). The difference comes from the differences in ways how the concentration of an element in an unanalyzed mineral is calculated, hence how the bulk-rock concentration of that element in samples with incomplete mineral analysis is "predicted". As described in Section 1 above, once a prediction method is developed, whether it is simple [5] or complex [13], it is necessary to test first whether the method can effectively reproduce bulk compositions for samples with all 4 mineral data available. This is done for each element by plotting "predicted" values against "observed" values (directly calculated from the modes and mineral analyses of all 4 phases) on one-to-one plots. NLK97 [5] have almost perfect reproducibility for SiO_2, TiO_2, Al_2O_3, Cr_2O_3, MgO, CaO and Na_2O, but not for FeO (see Appendix Fig. 2A of [5]). BB99 [13] have almost perfect reproducibility for Al_2O_3 and SiO_2, but their reproducibility for TiO2, Cr_2O_3, MgO, CaO, Na_2O is not reported. However, they do show that their reproducibility for FeO is rather poor. Figure 6a shows that while bulk-rock FeO varies from ~ 8.2 to 8.7 wt. % calculated from samples with known modes and compositions of all 4 phases, their predicted FeO values in bulk compositions of the same samples vary little, within a narrow range of ~ 8.3-8.4 wt. %. The simple linear regression gives a slope of 0.0526, which is essentially zero for 11 data points. This indicates that the calculated FeO in bulk AP compositions by BB99 [13] is necessarily higher for low-FeO samples and lower for FeO-rich samples than should be.

Figure 6b shows that the prediction of bulk-rock FeO by NLK97 [5] is not perfect either, but does show a scattered yet positive trend parallel to the one-to-one line. A simple linear regression gives a slope of 0.4925, which is less than unity, but is significantly non-zero at > 99.9% confidence levels. Assuming BB99 also have nearly perfect MgO reproducibility (unknown), then the difference in FeO predictions by the two methods explains why BB99 have less steep FeO-MgO trend (Fig. 3) than NLK97 do (Fig. 5a). This explanation is correct because of the following.

Asimow [14] (A99) pointed out that the published version of NLK97's reconstructed bulk AP compositions differs from the version he obtained from my co-author C.H. Langmuir (his "C. Langmuir, pers. commun."). Here is the brief history. I started this work when I was at Lamont in 1993 working with C.H. Langmuir and R.J. Kinzler. I was not satisfied with the calculated FeO because on one-to-one plots (33 samples have all phases analyzed) all the major element oxides are good with slopes close or very close to unity (SiO_2, TiO_2, Al_2O_3, MgO, CaO, Na_2O) except for FeO, the slope is 0.2456 (see Fig. 6c; although it is still better than the rather flat 0.0516 of BB99 as shown in Fig. 6a), i.e., calculated values vary very little (vertical axis) despite the relatively larger observed values (horizontal axis). The difficulty in getting acceptably good FeO calculation lies in the fact that the relative variation range of FeO is smaller than other major element oxides. While BB99 was satisfied with a flat $FeO_{[calc]}$-$FeO_{[obs]}$ slope of 0.0516, I did not consider a slope of 0.2456 to be valid because it is far from unity, and the calculated FeO would be in ***huge error***. There is no straightforward way to perfect the $FeO_{[calc]}$-$FeO_{[obs]}$ slope, i.e, to make the slope unity mathematically. However, the slope can be improved. This was done by rotating the 33 data points in $FeO_{[calc]}$-$FeO_{[obs]}$ space (Fig. 6c) counter clockwise with respect to a chosen pivot of FeO = ~ 8.31 (the average of the 33 data points) until the bulk of the 33 data points give an ***apparent/visual*** slope of unity. This is the result in Figure 6b. This rotation is equivalent to applying the equation of $FeO_{[improved]} = -8.33+2.005*FeO_{[originally\ calculated]}$. Application of this equation to all other samples with all oxides normalized to the original totals results in the improvement of calculated FeO values used in NLK97. Therefore, Slope $[FeO_{[calc]}\text{-}FeO_{[obs]}]_{IMPROVED\ (NLK97)}$ = 0.4925 (> Slope $[FeO_{[calc]}\text{-}FeO_{[obs]}]_{ORIGINAL\ (NLK97\ unused)}$ = 0.2456 >>> Slope $[FeO_{[calc]}\text{-}FeO_{[obs]}]_{BB99}$ = 0.0516) results in the steeper FeO-MgO trend in NLK97. I do not know what Slope $[FeO_{[calc]}\text{-}FeO_{[obs]}]_{A99}$ A99 [14] produced, but if his calculated FeO-MgO slope is as gentle as that by BB99 and that by unpublished version of NLK97 [14], then Slope $[FeO_{[calc]}\text{-}FeO_{[obs]}]_{A99}$ must be small. Note that the slope of 0.4925 is significantly better, and thus the steeper FeO-MgO slope of NLK97 is more realistic than the gentler slopes by BB99, A99 and by unpublished version of NLK97. Also note that although the Slope $[FeO_{[calc]}\text{-}FeO_{[obs]}]_{IMPROVED\ (NLK97)}$ = 0.4925 is a significant improvement, it is still far from unity. Therefore, the calculated FeO-MgO slope by NLK97 is theoretically not as steep as it should be although probably close.

In summary, neither BB99 nor NLK97 can predict bulk-rock FeO precisely, but NLK97 is significantly better in that its predicted FeO values increase as the actual bulk-rock FeO values increase (Fig. 6b). In contrast, the predicted bulk-rock FeO values by BB99 stay constant regardless of actual FeO variation in bulk AP compositions (Fig. 6a). The constancy of BB99's FeO prediction not only leads to the gentle FeO-MgO slope in reconstructed bulk AP compositions (Figs. 3 and 5a), but also overestimates bulk-rock $Mg^{\#}$ of olivine rich samples. This is because olivine has the highest FeO among major silicate phases (i.e., ol, opx and cpx), and the increase in modal olivine will increase both MgO and FeO in bulk AP compositions (Fig. 2), yet the constant FeO values predicted by BB99 will increase MgO/FeO ratio, and thus $Mg^{\#}$, in olivine rich samples (see below).

6. $Mg^{\#}$ of olivine, opx, cpx and bulk compositions of abyssal peridotites

$Mg^{\#}$, $Mg/[Mg+Fe^{2+}]$, in residual olivine, opx, cpx and bulk-rock melting residues increases with increasing extents of melting or melt extraction [6,17-21]. This is true for minerals in AP [3,4,6,7,13]. This should also be true for bulk AP compositions if they were true melting residues. As modal olivine increases as melting proceeds [6,17-21], $Mg^{\#}$ of residual olivine, opx, cpx and bulk-rock residues should correlate positively with modal olivine. However, as AP are not simple residues, but have excess amounts of olivine (see Sections 2 and 3 above) [5-7] with greater amounts of excess olivine in the progressively more depleted residues (see Fig. 11 of [6]), $Mg^{\#}$ in bulk AP compositions may not necessarily show significant positive trend with increasing modal olivine in contrast to what is expected for pure melting residues. This is because $Mg^{\#}_{[ol,\ 0.9029\pm0.0037]} < Mg^{\#}_{[opx,\ 0.9068\pm0.0055]} < Mg^{\#}_{[cpx,\ 0.9156\pm0.0086]}$ whereas $Mode_{[ol]} > Mode_{[opx]} > Mode_{[cpx]}$ (Table 1 of [5]). The latter modal relationship is true for a given sample and is also further enhanced with increasing modal olivine in AP. There is thus a simple counter-balance towards bulk-rock AP $Mg^{\#}$. For example, in the most depleted samples dominated by olivine, the bulk-rock $Mg^{\#}$ will be largely determined by $Mg^{\#}$ of olivine, thus lower ($Mg^{\#}_{[ol]}$), *not higher* ($Mg^{\#}_{[cpx]}$ and $Mg^{\#}_{[opx]}$), bulk-rock AP $Mg^{\#}$ is expected. Therefore, $Mg^{\#}$ varies very little in the properly calculated bulk AP compositions. The steep bulk-rock $Mg^{\#}$ increase with increasing modal olivine predicted by BB99 [13] largely results from their constant FeO (Fig. 6a); the bulk-rock $Mg^{\#}$ would, of course, increase rapidly with increasing modal olivine if bulk-rock AP MgO increases while FeO is kept constant (Fig. 6a). Figure 7a compares the predicted trend of bulk-rock AP $Mg^{\#}$ by BB99 and NLK97. I maintain that a steep positive trend must be true for genuine melting residues [5-7], but such trend is not obvious in abyssal peridotites (see above). Figure 7b is not typical, but is a good example of an inverse correlation between modal olivine abundance and olivine forsterite ($Mg^{\#}$) content in the AP suite from the Garrett transform [7]. The low Fo values in olivine rich samples are consistent with the interpretation that (1) there exists excess olivine in this sample suite, and (2) the excess olivine precipitated from the ascending and cooling melts in the advanced residues in the "cold" thermal boundary layer atop the mantle beneath ocean ridges. The key point is that $Mg^{\#}$ of bulk-rock peridotites does not always increase with increasing modal olivine abundance (vs. [13]), depending on specific histories the peridotites in question may have experienced.

7. A positive FeO-MgO trend observed in bulk-rock analyses of abyssal and some ophiolitic peridotites

We have known for many years that bulk-rock compositions of upper mantle peridotites inferred from massif peridotites, mantle xenoliths, and ophiolites [22-27] show scattered yet flat or slightly negative trend on FeO-MgO plots. Residues of peridotite melting experiments [17-21] and empirical melting models [5,6,28-30] show the same. Hence, the steep positive FeO-MgO trend (Fig. 5a; also Figs. 6-8 of [5]) defined by reconstructed bulk AP compositions [5] has surprised many. As such a steep trend is rarely reported in the literature and is rarely observed in peridotites other than in abyssal peridotites, it is understandable to cast doubt on the significance of such a steep FeO-MgO trend [5,6,13,24,31] in AP. Nevertheless, bulk-rock analyses of an AP suite from Southwest Indian Ridge, where AP were best sampled and studied [3,4], show a scattered yet positive trend (open squares), particularly when plotted on an anhydrous basis (gray-filled squares) (Figs. 5b,c) [37]. Bulk-rock analyses of Erro-Tobbio ophiolites, particularly the granular suite [32] define a nice positive trend that parallels the steep FeO-MgO trend by NLK97 [5] (Fig. 5b,c). These rare examples tell us that the positive FeO-MgO trend remains apparent in some serpentinized AP and some ophiolitic suites.

8. The uniqueness of abyssal peridotites – an important concept

AP are mostly cpx-depleted harzburgites, which are consistent with being melting residues. However, harzburgites are not unique to AP. Many massif peridotites, most ophiolitic peridotites and subcontinental lithospheric mantle are harzburgitic. Melting residues of mantle plumes, and mantle wedge peridotites above subduction zones are also likely to be harzburgitic. What are unique to AP are (1) where they are from and (2) their peculiar histories that many of these aforementioned rocks may have never experienced. AP are from ocean-ridge-transform systems and represent the upper-most mantle materials that have been processed during sub-ridge mantle melting, melt extraction, and melt-residue interactions before tectonically exposed on the seafloor to be sampled. The fact that AP are partially or entirely serpentinized, and that serpentinization is a hydration (or hydrothermal) metamorphism at ~ 250-400°C tells us that this process is shallow - constrained by some maximum depth of seawater penetration and hydrothermal fluid development as a result of seawater circulation induced cooling of magmas and residual peridotites. Accepting all these, we can illustrate processes that are likely to take place beneath ocean ridges as schematically shown in Figure 8.

Plate separation causes the asthenosphere to rise and melt when crossing the solidus, P_o, by decompression. Melting stops at a depth, P_f, due to conductive cooling to the seafloor [6,7,34]. Residual mantle (thick arrowed blue lines) flows upwards and sideways away from beneath the ridge, but newly formed melts (thin arrowed red lines) continue to rise, pass through the advanced residues in the cold thermal boundary layer (the region labeled "2" in Fig. 8), and focus towards the very narrow (< 2 km) axial zone of crustal accretion [5-7]. Serpentinization takes place at shallow depths beneath ridge axis and nearby (labeled "3" in Fig. 8) – forming serpentinized peridotites that could be sampled on the seafloor as "abyssal peridotites". Residual peridotites formed at regions labeled "1" in Figure 8 will not rise but flow sideways at depths. They will not be serpentinized at such deep levels, and will be *fresh*. They will never be sampled on the seafloor as "abyssal peridotites", but could very well be sampled as "fresh" ophiolitic or massif harzburgitic peridotites in geological record [23,24,31,32].

It is important to note that in the "cold" thermal boundary layer (TBL; "2" in Fig. 8), before serpentinization taking place at shallow levels, the "old" advanced residues will be in constant interaction with ascending melts, which will cool and crystallize whatever liquidus minerals out adding to the residues and will also refertilize the residues in terms of incompatible elements by either active chemical interactions or passive melt entrapment. This very well explains why abyssal peridotites are necessarily serpentinized, have excess olivine [5-7], and have higher-than-expected abundances of incompatible elements [7,10,33,37]. It is necessary to emphasize that even if petrology and geochemistry of some fresh massif or ophiolitic peridotites in geological record are consistent with being residues for paleo-ocean ridge melting (i.e., residues in locations labeled "1" in Fig. 8), these peridotites cannot be compared in any straightforward way with present-day AP given the discussion above and as illustrated in Figure 8. This is because AP experienced very complex histories beneath ocean ridges ("2" and "3" in Fig. 8) whereas fresh massif or ophiolitic peridotites (if they were indeed sub-ridge melting residues, i.e., residues in locations labeled "1" in Fig. 8) are more or less simple residues [23,24]. The apparent incompatible element refertilization as seen in the Horoman peridotites [24] may very well be the consequence of low-degree melt metasomatism at the interface between seismic low velocity zone and the cooling and growing oceanic lithosphere [35].

9. Abyssal peridotites record porous melt migration beneath ocean ridges

Excess olivine in AP is conspicuous in the original modal data [3,4] (Fig. 1). Excess olivine is also directly observed petrographically with the amount of excess olivine correlated positively with elevated abundances of incompatible elements in the bulk-rock samples [7]. These observations led Niu and Hékinian [7] to conclude "the excess olivine and incompatible element enrichment are both the result of melt-solid re-equilibration" (p.243 of [7]). The buoyant melts that ascend and percolate through advanced residues crystallize olivine as a result of cooling (Figs. 7a and 8). Entrapment of these melts leads to bulk-rock incompatible element enrichment [6,7,10,33,37]. As these are observed on thin-section scales, it is clear that AP record porous melt flow beneath ocean ridges [6,7,10,15,36,37]. It is possible that dunite dikes/veins as probable melt channels may exist in the TBL and may be volumetrically significant in melt transport [38,39], but abyssal peridotites, which are harzburgitic, are arguably materials sampled away from those probable dunite bodies.

The above interpretations, which require further testing, are consistent with petrographic [7,37], petrologic [5-7], and geochemical observations [7,10,33,37]. Recently, Lundstrom [15] suggested that the observed excess olivine in abyssal peridotites may result from alkali diffusion induced precipitation of olivine at the expense of opx during melt ascent atop the mantle, equivalent to the TBL (Fig. 8). On the other hand, Asimow [14] (A99) proposed that polybaric melting can explain both major and trace elements in AP without the need of invoking excess olivine. This is a very useful exercise. However, in terms of major elements, A99 succeeded in modeling the gentle FeO-MgO correlation (see Figs. 3,5), which is itself in error (see Figs. 5-6 and Section 5 above). In terms of trace elements, A99 succeeded in modeling residual cpx data [4]. However, cpx trace element data do not represent bulk AP trace element compositions in both abundances and systematics [10,33,37].

10. Summary

1. As demonstrated previously [5-7], AP possess excess olivine compared to simple melting residues produced by isobaric melting experiments and polybaric melting models (Fig. 1). The excess olivine is evident in the original modal data [3,4] (Fig. 1) and is also *observed* petrographically [7] (Fig. 7b).
2. The positive FeO-MgO trend in reconstructed bulk AP compositions is *not* an artifact of calculations, but a *straightforward* result of excess olivine in these rocks (Fig. 2).

Addition/crystallization of olivine in AP is an inevitable consequence of cooling of ascending melts migrating through advanced residues in the "cold" TBL beneath ocean ridges [5-7,37] (Figs. 7b,8).

3. As excess olivine is observed on thin-section scales (Figs. 1,7b), AP record snapshots of porous melt flow beneath ocean ridges [7,37] although channeled flows inferred from dunite dikes/veins in ophiolites may be volumetrically more important in melt transport [38,39].
4. AP are unique because of their uniquely complex histories beneath ocean ridges. These include: (a) being simple decompression melting residues rising to the cold TBL beneath ridges; (b) receiving olivine crystallized (with some trapped melts) from the ascending and cooling melts in the TBL; (c) variously serpentinized when rising to shallow levels; (d) tectonically exposed on the seafloor; and (e) sampled as AP.
5. Sub-ridge mantle melting residues that flow laterally at deep levels without experiencing TBL processes and serpentinization will not be exposed on the seafloor to be sampled as AP. These "deep" and "fresh" residues will differ in mineralogy, petrology and geochemistry from AP, and could be sampled as ophiolitic or massif peridotites in geological record. Therefore, if "fresh" ophiolitic or massif peridotites can be demonstrated to be deep level melting residues for MORB, they will necessarily differ from AP.

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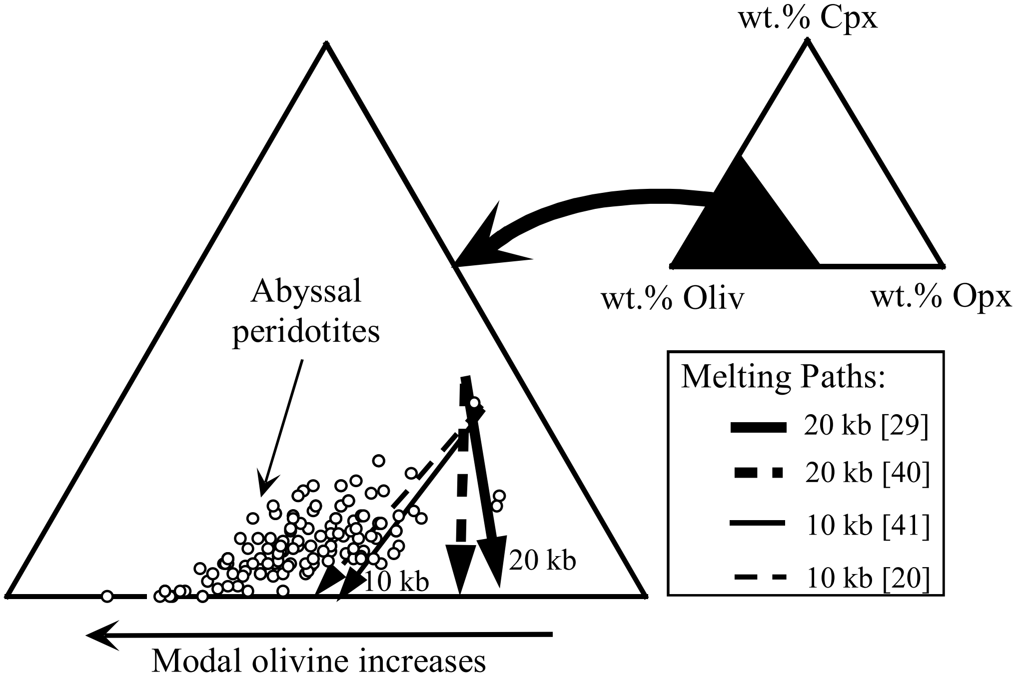

Fig. 1. Weight percent modes [3,4] (converted from volume percent) to show that AP have much more olivine than can be produced by isobaric melting experiments. Not shown, the excess olivine in AP cannot be produced by polybaric melting models either [6]. The key point here is that excess olivine in AP is *observed* in the original modal data, not interpreted from reconstructed bulk compositions. The figure is modified from [5].

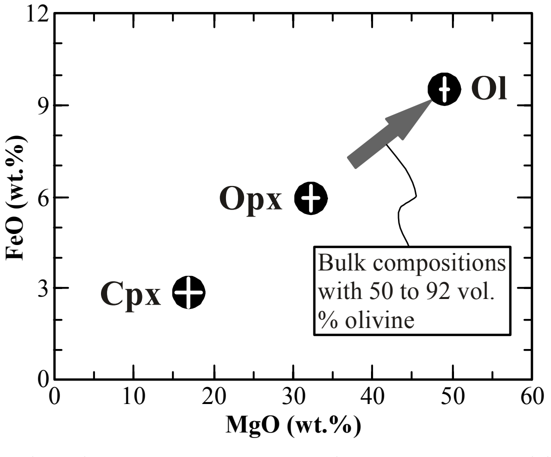

Fig. 2. A quantitative illustration, in FeO-MgO space, of average compositions of AP olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx) [3,4] and likely bulk-rock compositions calculated from analyzed compositions and modes of these minerals. Note that the white crosses within the sold symbols are 2σ variability of FeO and MgO in the entire data set. Given the small mineral compositional variability yet large modal variability, a steep positive FeO-MgO trend (with scatter in reality) in the calculated bulk AP compositions is straightforward. Note that the excess olivine is interpreted to be added to the advanced residues in the "cold" TBL by precipitation from ascending and cooling melts. Hence, a liner mixing trend is expected (see text for details),

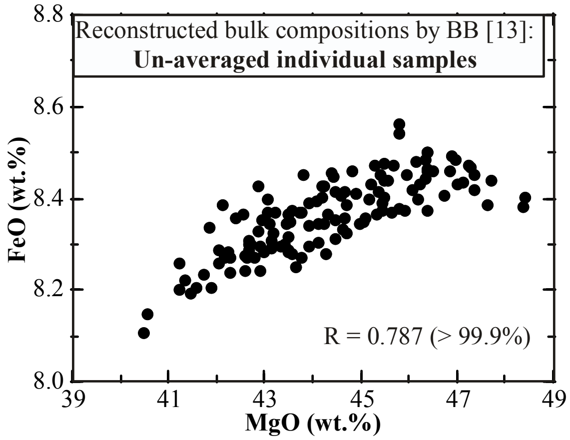

Fig. 3 A statistically significant positive FeO-MgO trend is conspicuous in the reconstructed bulk AP compositions by BB99 [13]. These authors, however, discard the trend, but focus on their *site-averages* (see Fig. 4), which cannot be readily derived from the reconstructed bulk compositions shown here. The important point here is that the reconstructed bulk-rock data by BB99 support, *not* refute, NLK97 [5] that the positive FeO-MgO trend in bulk AP compositions is real, although both parties produce different FeO-MgO slopes. The data are provided by M. B. Baker.

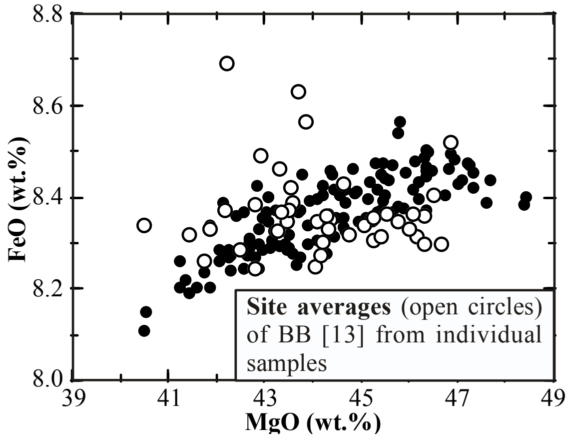

Fig. 4. Comparison of the *site-averages* (open circles) by BB99 [13] with their own unaveraged data (solid circles). Obviously, it is impossible by any means that the *averages* can be obtained from the unaveraged data. Note that BB99 [13] discard the positive trend defined by their own unaveraged data, but focus on their *averages* in discussing AP petrogenesis against the excess olivine observation and interpretations by NLK97 [5]. The data are provided by M. B. Baker.

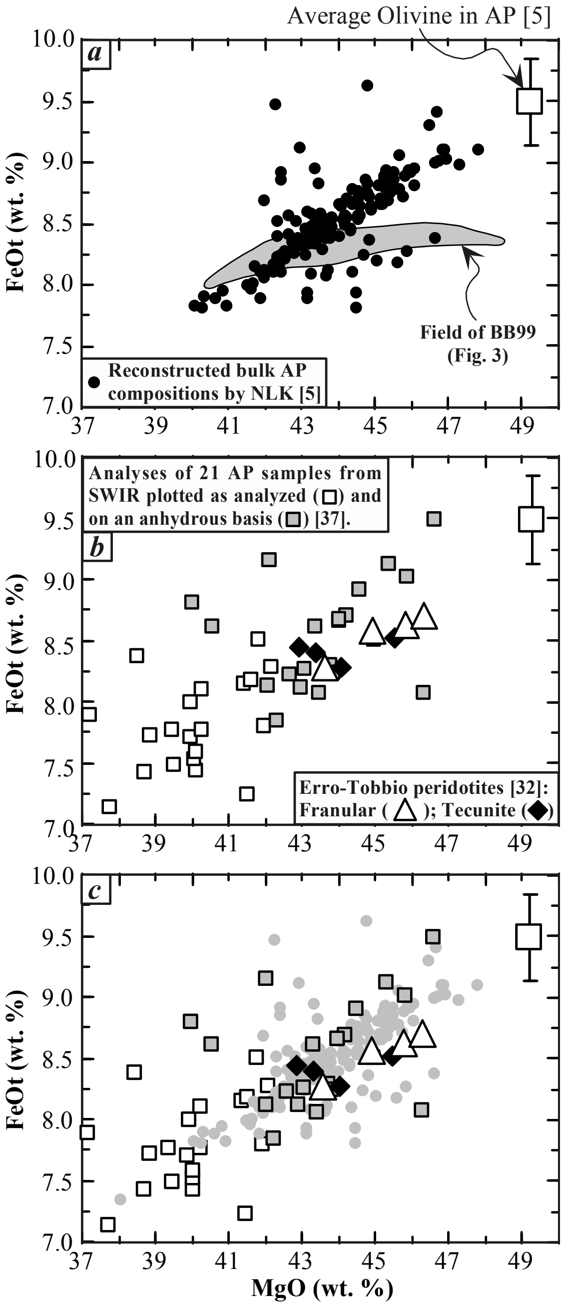

Fig. 5. ***A.*** Reproduction from NLK97 [5], where a steep positive FeO-MgO trend defined by reconstructed bulk AP compositions points to compositions of olivine in these rocks. The field of reconstructed bulk compositions by BB99 [13] is plotted for comparison. ***B.*** Plot of 21 bulk-rock analyses of a Southwest Indian Ridge (SWIR) AP suite [37]: both raw data (open squares) and normalized data on an anhydrous basis (grey-filled squares). Eight Erro-Tobbio ophiolitic harzburgite samples (4 granular, large open triangles, and 4 tectonite, solid diamonds) by Rampone et al. [32] also are plotted for comparison. Despite the rarity of positive FeO-MgO trend defined by commonly studied mantle peridotites, these samples do show scattered yet positive trends on the FeO-MgO plot with the slope quite similar to reconstructed bulk AP compositions by NLK97 as shown in ***C***.

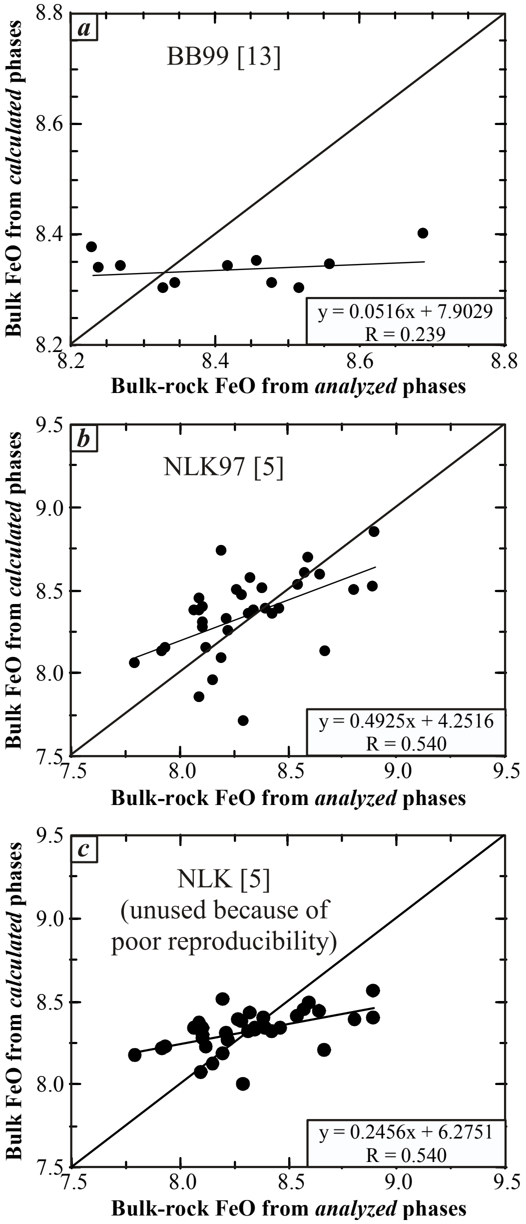

Fig. 6. ***A.*** BB99 [13] are unable to reproduce the bulk-rock FeO (vertical axis) from the same samples with both modes and mineral analyses of all four phases (ol, opx, cpx and spinel) available (horizontal axis). A successful model should yield a positive trend with the slope close to unity (the one-to-one line), but a slope of essentially zero indicates that the calculated bulk-rock FeO values by BB99 are invalid. The essentially constant calculated FeO values will necessarily lead to higher FeO values for FeO poor samples and lower FeO values for FeO rich samples, leading to gentler or flat FeO-MgO slope (see comparison in Fig. 5a). ***B.*** NLK97 [5] calculation for FeO is not perfect either, but a positive trend with a slope of 0.4925 is significantly different from zero [5]. Hence, the calculated FeO in bulk AP compositions by NLK97 [5] is more realistic. The difference by the two methods explains why the positive FeO-MgO trend by BB99 [13] is much gentler (Figs. 3 and 5a) than by NLK97 [5] (Fig. 5a). ***C.*** This shows the unpublished first attempt at calculating FeO by NLK97 [5]. The slope of 0.2456 is too far from unity, and any indiscriminate application of this calculation procedure will lead to huge errors. This is improved by counter-clockwise rotating all the data points with respect to the mean FeO value (~ 8.31 wt.%) until all the data points altogether give a visual slope close to unity, which is Fig. 6b (see text for details).

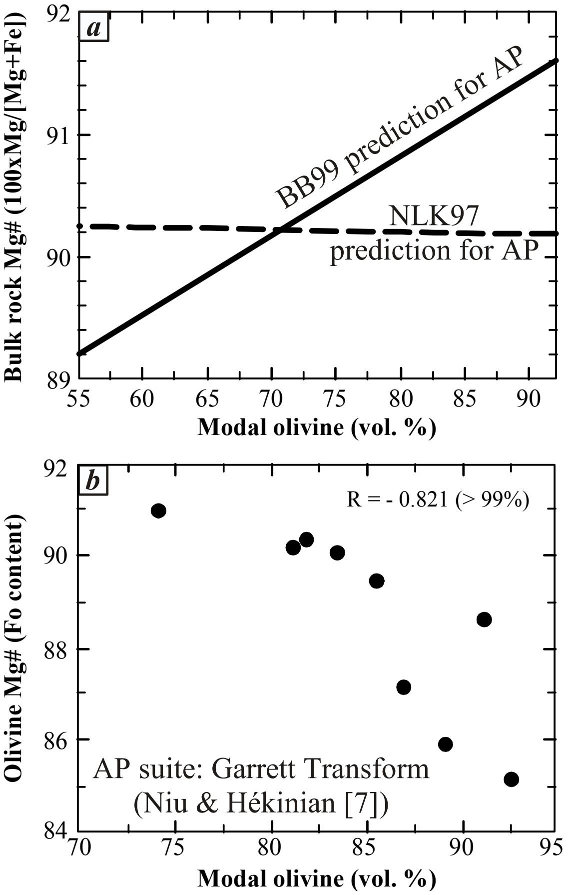

Fig. 7. ***A.*** Comparison of expected trends of bulk-rock AP Mg$^{\#}$ by BB99 [13] and NLK97 [5]. A steep trend is expected if AP are pure melting residues because of the melting phase equilibria control, but this should not be the case because AP are not simple residues but possess added olivine (see text for details). ***B.*** Example of an inverse trend between modal olivine abundance and olivine forsterite (Mg$^{\#}$) content in the AP suite from the Garrett transform [7].

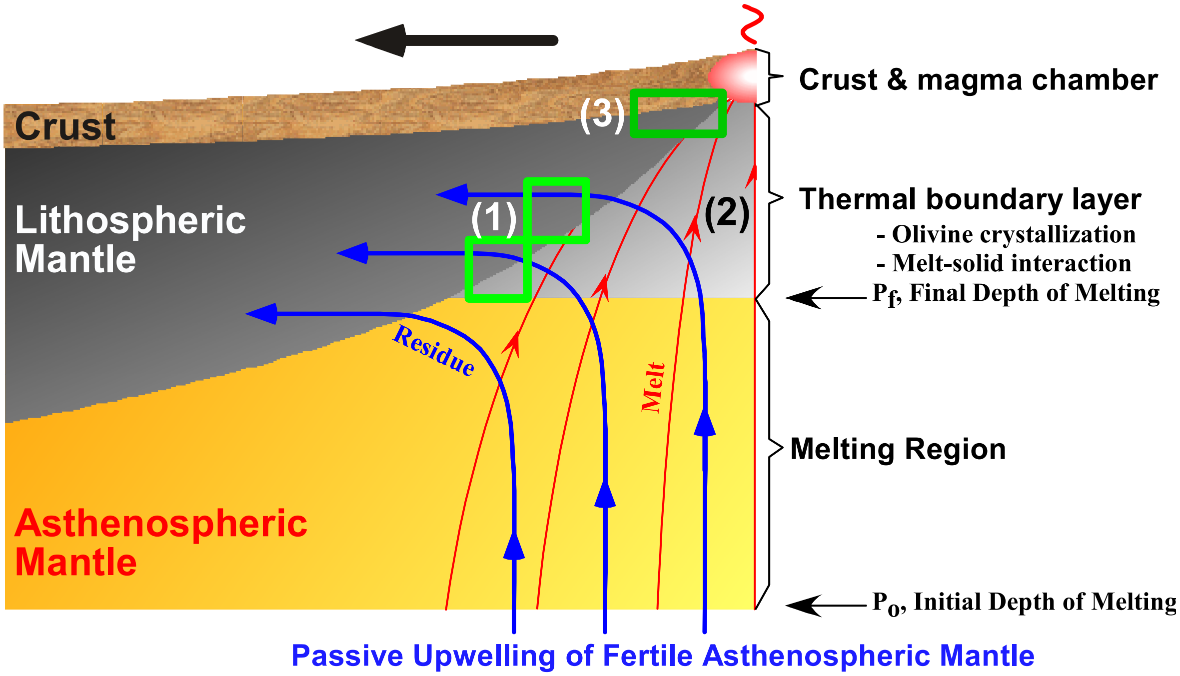

Fig. 8. Cartoon illustrating why AP possess excess olivine. Decompression melting begins when upwelling asthenospheric mantle crosses the solidus, P_o, but stops at a shower depth, P_f, due to conductive cooling to the seafloor. The region between P_f and the base of the crust is the "cold" thermal boundary layer (TBL; labeled "2"), which comprises advanced residues without melting. The advanced residues in the TBL continue to rise or move sideways (think blue arrowed lines). Ascending melts (thin red arrowed lines) rise and percolate through this TBL by crystallizing olivine out due to cooling with some melt trapped. The advanced residues so processed will continue to rise to shallow levels and variably serpentinized (labeled "3") before tectonically exposed on the seafloor to be sampled as AP. On the other hand, melting residues at deep levels that turn laterally will not experience the TBL processes (labeled "1"), never be serpentinized, and never be sampled as AP, but may be sampled as fresh ophiolitic or massif peridotites in geological records. It is thus straightforward to understand that AP are unique and will differ in mineralogy, petrology and geochemistry from fresh melting residues like some ophiolitic [31] and massif peridotites [23,24] even if the latter can be demonstrated to be melting residues produced beneath paleo-spreading centers.