

*Crystallization temperatures of tholeiite parental liquids: Implications for the existence of thermally driven mantle plumes*

by

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Electronic supplement to the authors' reply to discussion comments

We copy the comments of others in plain text and insert our responses in *italics*.

*1st January 2007, Dean C. Presnall*

“The only unequivocal magma composition is one that is produced from a direct analysis of a glass. The validity of calculated compositions, such as those produced by Falloon et al. (this volume) is always dependent on a series of assumptions.” *We have used glass compositions, analysed by electron microprobe, and calculated parental compositions by incremental addition of equilibrium olivine where the glass contains both its liquidus olivine and more magnesian olivine, using the latter as the target or limit justified by the petrography. We make no other assumptions.*

“Despite thousands of microprobe analyses of MORB glasses, no compositions that show a trend of olivine-controlled crystallization have ever been reported, either from “normal” ridge segments or Iceland (over 400 glass analyses just from Iceland).” *This statement is not true. It is repeated in Presnall and Gudfinnsson (submitted), but it arises from inadequate coverage of published work and from the way Presnall and Gudfinnsson (submitted) select their glass data for petrogenetic interpretation. In our chapter we plot 190 glass analyses from MOR settings with >9.5% MgO, from the PetDB database. Among these, there are clearly glasses that lie in the Ol+Liq field at eruption pressures and temperatures (e.g., high-magnesian glasses from Siqueiros; Figure 2). In addition we have clear mineral-composition evidence from selected sites (Siqueiros, ODP Hole 896A) which demonstrate the sequence of appearance of phases as ol (+rare spinel), ol+plag, ol+plag+cpx. Experimental demonstration of this sequence goes back at least to the paper of Green et al. (1979). We are not the first to identify this range of MORB glasses extending into the ol+liq field. In the petrogenetic analysis of global MORB glass chemical compositions of Presnall and Gudfinnsson (submitted), the authors state that ‘the LKP (Langmuir et al., 1992) procedure of retaining only analyses with MgO values between 5 and 8.5% has been followed’. The authors further restrict their dataset to the Smithsonian database. Langmuir et al. (1992) wished to select glasses lying on the ol+plag+cpx fractionation surface*

*at low pressure, and approximating to a linear trend in several oxide vs oxide variation diagrams, particularly MgO vs FeO and MgO vs Na<sub>2</sub>O, they wished to avoid more magnesian glasses (> 8.5% MgO) which depart from this multiply-saturated surface. Presnall and Gudfinnsson (submitted) exclude higher temperature, MgO-rich glasses from their consideration and then state that there is no evidence for them, in spite of other authors' publications of such glasses.*

*“This is in contrast to the situation at Kilauea, Hawaii, where direct analyses have shown the existence of a clear trend of olivine-controlled crystallization (Clague et al., 1991; 1995). MORB generation (including Iceland) at low and relatively uniform pressures (0.9-1.5 GPa) and potential temperatures (~1240-1260°C) (Presnall et al., 1979; 2002; Presnall and Gudfinnsson, submitted) explains both the inverse and positive Na<sub>8</sub>-Fe<sub>8</sub> correlations as direct melts from a heterogeneous mantle.” Presnall and Gudfinnsson (submitted) argue that parental MORB lie on the ol, opx, cpx, plag and/or sp saturation surface at 0.9-1.5 GPa, based on consideration of compositions interpolated at MgO=8.0%. Neither these nor higher-temperature glasses with >9.5%MgO lie precisely on the 1 GPa ol, opx, cpx, plag, sp multiply-saturated surface when projected into multi-component normative projections as in our chapter, Green et al. (2001), or Green and Falloon (2005)—they lie at higher normative diopside and lower normative olivine than the multiphase cotectic. In addition the glasses Presnall and Gudfinnsson (submitted) at MgO= 8% are not sufficiently magnesian to be in equilibrium with mantle olivine (>Fo<sub>89</sub>). The more magnesian parental glasses derived in our paper by olivine addition to Fo<sub>91-91.5</sub> have eruption temperatures greater than the restricted T<sub>p</sub>=1240-1260°C of Presnall and Gudfinnsson (submitted), further demonstrating the error in the low-T MORB model.*

*“In addition, it avoids the conundrum of the complete absence of olivine-controlled fractionation.” There is no conundrum, as such fractionation is documented (see Figure above).*  
*January 12th, 2007 James H. Natland*

*“The fatal assumption behind estimation of temperatures of crystallization using olivine-liquid FeO-T-MgO relationships is that the most forsteritic olivine in a rock, or surmised to be representative of a liquid in equilibrium with the mantle, is probably not related to the host liquid composition along a single closed-system liquid line of descent. That assumption is the entire basis for the procedure of adding incrementally more forsteritic olivine into liquid compositions until an “equilibrium” liquid is reached, but it is wrong.” In our paper we use only glass (liquid) compositions which contain olivines*

*matching liquidus olivine compositions (derived from experimentally calibrated Fe/Mg partitioning; Ford et al., 1983) and contain in addition, more magnesian olivine phenocrysts and microphenocrysts. Our interpretation is consistent with the petrographic observations and is the simplest interpretation, requiring no assumption of addition and complete solution of some other 'mixing component'.*

*"This is because most picrites are hybrid rocks, the results of magma mixing." We are not using compositions of picrite rocks i.e. rocks with >10-15% modal olivine. We are using glasses and only the highest temperature and most magnesian glasses lying in the ol+liq phase field at their liquidus temperatures.*

*"This can be established by careful studies of crystallization histories. The mixing is of two types: 1) mixing between primitive magma strains near or somewhere above their melt sources in the mantle, and 2) mixing between primitive and differentiated magma strains." We agree with Natland that most MORB glasses are evolved and the processes of evolution includes crystal fractionation, 'AFC' (assimilation, fractionation, crystallization) processes, reactive porous flow, magma mixing etc.. This complexity clouds the interpretations of Presnall and Gudfinnsson (submitted) and of Langmuir et al. (1992) using arrays of evolved glasses with 5-8.5% MgO. However, by choosing the glasses as discussed we identify the highest temperature melts, i.e., the most primitive observed liquids. There is no conflict between the recognition of the complexity of processes which a high-temperature picritic magma may undergo as it cools, reacts, crystallizes and quenches to crystals+glass, and the identification of the highest temperature liquid, i.e., the liquid approaching or reaching an end-member 'primitive magma'.*

*"An example of mixing of primitive magma strains is sample D20-3 in Table 1 of Falloon et al. (this volume), from Siqueiros Fracture Zone on the East Pacific Rise. The glass analysis is from Danyushevsky et al. (2003), but an interesting aspect of the history of this sample is that it was obtained from almost exactly the location of an earlier dredged picrite (Batiza et al., 1977) with a glass composition (Natland, 1989, Table 1, Analysis SD7-C) that is identical to within parameters considered by Melson et al. (1976) to represent material from the same eruption." As described, this is a picrite i.e. >15-20% crystalline olivine. The rock contains 16.7% MgO, with olivine phenocryst cores to Fo90.5, in glass with 9.58% MgO.*

*"The glass contains olivine dendrites and plagioclase spherulites (Natland, 1980), thus is on a two-phase cotectic" This is not necessarily so, as the liquid was ol+sp saturated but dendrites of*

*olivine(?Fo) and spherulites of plagioclase(?An) are quench phases nucleating between the liquidus T for the glass and the glass transition temperature. See also the Figure, that clearly shows that most primitive glasses from Siquieros are within an olivine-only field..*

“Even though the rock is a picrite, the glass is not an olivine-controlled liquid. Nor indeed is even the most magnesian MORB glass (Presnall et al., 2002)” *This incorrect statement was addressed previously.*

“Olivine in SD7-C, at least, commonly occludes Cr-spinel within skeletal embayments that also contain glass. Some of the spinel is zoned. But most importantly it has a substantial range in Cr# but little in Mg# (Natland, 1989, Figure 3), indicating crystallization from similarly magnesian parental liquids but with significant differences in Al<sub>2</sub>O<sub>3</sub> content (Poustovetov and Roeder, 2000). Such differences cannot be the result of olivine crystallization, and must reflect mixing at about the same temperature of melt strains derived from a heterogeneous source.” *The description accords with the reactions between a high temperature, olivine-saturated melt and wall-rock or admixed crystalline material. Natland (1989) has documented evidence for mixing and reaction of high-temperature melts with crystalline inclusions, notably An-rich plagioclase. For a liquid already crystallizing olivine(+spinel) the energy required to dissolve phases with which the liquid is undersaturated is provided by exothermic olivine+/-spinel crystallisation at the site of dissolution. This also may lead to entrapment of ephemeral and local melt inclusions and zoned spinels, reflecting the competition between diffusive homogenization of melt and growth of olivine (Danushevsky et al., (2003).*

“Pertinent here is that two other chemically distinctive picrites were obtained in the same dredge haul (one of these during the later expedition). The one studied by Natland (1989) in detail (SD- 7A) has spinel with a similar range in Cr# as SD7-C but at systematically lower Mg#; associated olivine is also a bit more iron rich, and there are rare plagioclase phenocrysts. The glass has higher FeOT, and if one were to add olivine incrementally back into it to, say, a nominal primitive olivine composition of Fo91, then the estimated parental crystallization temperature (and glass MgO content) would be higher than that of SD-7C. But from the minerals actually in the rock, there’s no indication that it even makes sense to do this. The cooler picrite is the more iron-rich. The two samples did not derive from the same mantle composition, even though they erupted side by side and maybe at almost the same time. They simply sampled the array of primitive liquid compositions across the melting domain in two different ways.” *We also argue for significant source heterogeneity and complex evolution of primitive magmas at crustal and subcrustal depths. From the brief details above we would infer SD-*

*7A glass was more evolved than D-23 and the simplest attempt at a parental magma would reverse ol+plag, and then ol crystallization to a liquidus olivine of choice—but we would need a model of melt crystallization such as PETROLOG (Danushevsky, 2001) to back-calculate the ol+plag crystallization.*

“A second example is provided by Icelandic picrites. Many, including samples from the Borgarhraun flow studied by Falloon et al. (this volume), contain phenocrysts of plagioclase and clinopyroxene (e.g., Slater et al., 2001; MacLennan et al., 2003). Primitive basalt from Site 896 on the Costa Rica Rift also contains plagioclase phenocrysts (Shipboard Scientific Party, 1993). These are proof positive that the liquids did not follow olivine-controlled liquid lines of descent. Besides the phenocrysts, melt inclusions in Icelandic picrites provide substantial evidence for mixing of primitive melt strains as well as evidence for pyroxenite in the melt source (Sigurdsson et al., 2000; Slater et al., 2001; Foulger et al., 2005).” *As noted, we recognise complexity in evolution of primitive melts but our methodology, using both petrography and the PETROLOG modeling, identifies the highest temperature melts in each sampled setting and explores the implications of such melts for constraining the actual melting and melt segregation process (P, T, and residual phases) from a lherzolite or harzburgite source.*

“Next, Hawaii, particularly Kilauea and Puna Ridge, provides examples of mixing between primitive and differentiated liquids” *Significantly, Natland identifies primitive liquids—these are our focus.*

“Such mixing has been amply demonstrated by petrological studies of the Kilauea rift system (e.g., Wright and Fiske, 1971). It has the effect of elevating FeOT contents of the hybrid beyond that which the primitive mixing component could have reached by differentiation of olivine alone. This results in artificially high temperature estimates. Clague et al. (1995) discussed this mixing in the paper that also presented the composition of the most primitive Hawaiian glass (a grain with no phenocrysts in a cored, thinly-bedded sand). This type of mixing is also evident in the mineralogy of similar but more iron-rich, tholeiitic picrites from the Juan Fernandez Islands (Natland, 2003). Another possibility is that some Hawaiian and Icelandic melt strains derive from eclogitic components in mantle sources (e.g., Sobolev et al., 2002, 2005; Natland, this volume) that may be either more or less iron-rich than commonly construed mantle peridotite.” *Pyroxenitic or eclogite heterogeneity in mantle sources of MORB and particularly OIB, may permit melting at temperatures below the peridotite solidus but such melts can rarely reach the surface. Normally they react out of existence in the enclosing peridotite, ‘fertilising’ the latter and possibly fluxing melting of the new ‘refertilised mantle’—such liquids will be picritic, controlled in their major element composition by the residual phases of*

*lherzolite/harzburgite but reflecting in their trace element (incompatible elements) and isotopic composition their precursor (eclogite+residual peridotite) histories (Yaxley and Green, 1998; Yaxley, 2000). This will contribute to heterogeneity of melt strains contributing to erupted picrites, and add further complexity to estimation of crystallization and potential temperatures. Therefore, no-one should try to estimate these until the full crystallization histories of the rocks are understood.*

*January 27th, 2007 Keith D. Putirka & J. Michael Rhodes*

“Falloon et al. (this volume) attempt to show that magmas from mid-ocean ridges (MORB) and ocean islands (OIB), or “plumes”, have similar mantle potential temperatures ( $T_p$ ). Their strategy contains five errors and an inconsistency. Errors 1) and 5) derive from a misunderstanding of the thermal implications of the plume model, errors 2) and 3) lead to overestimates of ambient mantle  $T_p$ , error 4) leads to an underestimate of hot spot  $T_p$ , and all errors minimize mantle excess temperatures ( $T_{ex}=T_p$  OIB- $T_p$  MORB):

1) Their physical model is wrong. Plumes represent “point sources”, so only the highest temperatures at any OIB are relevant to  $T_p$  OIB, which repeats an error in Green et al. (2001). Falloon et al. (this volume) also presume that only the highest MORB temperatures represent ambient mantle, contradicting our understanding of the linkages between mantle temperatures, bathymetry and geochemistry (Langmuir et al., 1993)—and no alternative explanation is provided.” *See Anderson’s and Presnall’s comments; we are careful to document the sequential steps which we have followed to infer:*

- (1) liquidus temperature for most magnesian glasses (Table 1)*
- (2) parental magmas to these glasses and P,T conditions of compatibility with peridotite residue (Tables 2, 3, 4)—assuming that any prior melting and melt migration is on grainscale and by porous flow so that at melt pooling/melt segregation, the aggregated melt is in equilibrium with peridotitic residue. Numerical modeling which calculates ‘depth point averages’ for instantaneous melt increments over a large and variably melting volume is relevant for strongly incompatible elements. However, is not a physically realistic representation of porous flow in which a small liquid fraction with large surface contact with peridotite mineralogy, will back-react and be compositionally buffered by peridotite mineralogy appropriate to the changing P,T along the flow paths prior to segregation.*
- (3) mantle potential temperatures, with emphasis on the assumptions with respect to melt fraction/source composition and latent heat of melting and their effect on  $T_p$  estimation (Table 5). We do not use ‘mean’ temperatures or compositions as these are meaningless when each magma batch,*

*upwelling column or diapir, ridge segment, seamount or volcano may have different compositional, source  $P,T$  or non-adiabatic ascent path to eruption. We reject the numerical and computational approach which compiles and manipulates thousands of analyses of rocks and glasses to seek arithmetic algorithms to define geodynamic models and ignores petrological information and physical reality. A more detailed discussion of Putirka (2005) and Putirka et al., (2007) is presented in Falloon et al. (2007). Also, we have been unable to reproduce their published  $T,P$  estimates (appendices A1 and A2) from their published algorithms.*

*“2) In Falloon et al. (this volume) MORB with low-moderate FeOt are ignored. However, it is impossible to generate low-moderate FeOt MORB from high FeOt MORB by fractionation of olivine  $\pm$  plagioclase (their 1243°C and 1320°C trends cannot be derived by fractionation from their 1351°C trend). These low-moderate FeO MORB must reflect differences in ambient  $T_p$  MORB and cannot be ignored when estimating ambient  $T_p$ ; source heterogeneity does not alleviate the problem because olivine thermometry is independent of source composition (Putirka, 2005).” The comment is wrong. We illustrate 3 MORB of different FeO, different eruption and source  $T,P$  and thus inferred  $T_p$ ’s. We do not advocate a unique ‘ambient mantle’  $T_p$  or ‘plume  $T_p$ ’ but demonstrate the lack of any evidence for differences between the range of eruption  $T$ ’s or source  $T,P$  for MORB and Hot-spot primitive magmas.*

*“3) Falloon et al. (this volume) over-estimate mean MORB FeOt (at 9.3% FeOt, for MORB glasses with  $>9.5\%$  MgO ( $n=80$ )). But there are at least 137 glasses in PetDB with  $\text{MgO}>9.5\%$ , and they average 8.5% FeOt. And because olivine fractionation does not affect FeOt,...” This is an extraordinary and incorrect statement and in fact the basis of problems with the approaches of Putirka (2005) and Putirka et al. (2007). They derive from lack of understanding of the difference between olivine fractional crystallization and mixing lines due to olivine accumulation—discussed in detail by Natland below,*

*“...there is no reason to exclude whole rocks with  $>9.5\%$  MgO,” Putirka includes cumulates with up to 30% MgO—see Natland below.*

*“...which combined with glasses yield an average of 8.2% FeOt for MORB ( $n=192$ ).” This comment is false—we do not use or attach meaning to ‘mean’ or average compositions—each magma batch has its own story—see Natland comments.*

*“4) Falloon et al. (this volume) assume a very low  $\text{Fe}_2\text{O}$  for Hawaii. At Mauna Loa, sample 182-7 has 9.38% FeO—much lower than Hawaiian picrites, which average 10.4-10.6%  $\text{Fe}_2\text{O}$  (Herzberg*

and O'Hara, 2002; Putirka et al., 2007). This underestimate of  $\text{Fe}^{2+}/\text{O}$  at Hawaii artificially reduces  $T_p$  Hawaii by  $>70^\circ\text{C}$ ." *The comment is wrong—we discuss the use of correct  $f\text{O}_2$  (Fe oxidation state) in our paper.*

"5) The authors state that plume  $T_{ex}$  must be  $200\text{--}300^\circ\text{C}$ . Some models of excess bathymetry suggest that  $T_{ex}>160^\circ\text{C}$  (Sleep, 1990; Schilling, 1991), but the thermal plume model only requires that over a given depth range, the Rayleigh number is above critical. At Iceland, where acoustic anomalies extend to 670 km (Foulger et al., 2005),  $T_{ex}$  of a few  $10\text{'s }^\circ\text{C}$  would be more than sufficient to support thermally driven active upwelling." *Advocates of the 'deep mantle plume' hypothesis have weakened the constraints of fixed point source (plumes are deflected, flow along ridge axes, are intermittent) and the unique source compositions (depleted mantle in plumes, E-MORB on ridges, 'OIB' chemistry in rifts, seamounts, ridges) but the prediction and assertion of high magma eruption temperatures at 'hot spots' has remained firm (e.g., Campbell, 2005). Although in this comment Putirka and Rhodes appear to weaken this difference to within the spread of MORB sources (see also Anderson's comments below), elsewhere (Putirka, 2005; Putirka et al., 2007) support  $T_p$  for MORB of  $>1400^\circ\text{C}$  and excess  $T_p$  for 'plumes' of  $\sim 200^\circ\text{C}$ . Such values for  $T_p$  should produce peridotitic komatiite magmas at hot spots with  $\sim 60\text{--}70\%$  melting of mantle lherzolite and residual dunite of  $\text{Fo}_{93\text{--}4}$ —these are not seen.*

"6) The inconsistency: Falloon et al. (this volume) use the highest  $\text{FeO}$  (and  $T$ ) at MORB but not at OIB." *This is a wrong statement—we use the observed range at both and derive a similar range of eruption and segregation temperatures and pressures for both settings).*

"7) Concluding statements aside, Falloon et al. (this volume) present a convincing case that some ocean islands have very high  $T_{ex}$ . If we eliminate only error 6), they derive a *minimum*  $T_{ex}$  of  $122^\circ\text{C}$  at Hawaii; taking the average of their  $T$  estimates at Hawaii and MORB, their *minimum*  $T_{ex}$  is  $126^\circ\text{C}$  (Table 5). Had Falloon et al. (this volume) used observed  $f\text{O}_2$  and  $\text{FeO}$  for Mauna Loa (Rhodes and Vollinger, 2004), their primitive magma would have 20.6%  $\text{MgO}$  (assuming their implied  $\text{KD}(\text{Fe-Mg})_{\text{ol-liq}}=0.318$ ; Table 2), and their *minimum*  $T_{ex}$  would be  $\sim 70^\circ\text{C}$  hotter." *This is a distortion of our paper, see comments above on  $f\text{O}_2$  and refer to Table 5.*

"This is the third attempt by this group to argue that at Hawaii  $T_{ex}=0^\circ\text{C}$ . Green et al. (2001) suggested that because Siqueiros (along the East Pacific Rise) and Hawaii yield olivine phenocrysts with similarly high forsterite ( $\text{Fo}$ ) contents, that  $T_p$  must be similar..." *This is not an adequate summary of our paper!*



“...Putirka (2005), however, showed that because Hawaiian lavas contain more FeO, Hawaiian *Tex* is at least 220°C. *i.e.*  $T_p > 1620^\circ\text{C}$ ?

“More recently, Falloon et al. (2007) suggested that the  $T_p$  estimates of Putirka (2005) at Hawaii were too high due to model error. But Putirka et al. (2007) show that Hawaii, Iceland and Samoa have high *Tex* regardless of which thermometer is used (and that the Ford et al. (1983) thermometer has systematic error not present in Putirka et al. (2007) and Beattie (1993).” *See Falloon et al. (2007) and Danushevsky (2001) for evaluation of ol-liq equilibria and thermometry. Both the Putirka (2005) and Putirka et al. (2007) versions of the olivine thermometer have error towards high temperature with increasing MgO contents.*

“Finally, Putirka et al. (2007) demonstrate that:

- 1) excluding Iceland, MORB exhibit a  $T_p$  range of 140°C, with a standard deviation of  $\pm 34^\circ\text{C}$ ,
- 2) the MORB  $T_p$  range is 210°C when Iceland is included—consistent with Langmuir et al. (1992), and
- 3) Hawaii, Iceland and Samoa have  $T_p$  values that do not overlap with MORB within 2 $\sigma$ . It is thus safe to conclude not just that the mantle thermally convects, but that convection currents drive intra-plate volcanism.

Finally, although we disagree with the conclusions of Falloon et al. (this volume), unlike Natland (see his comment of January 12th), we do not find fault with their general approach. We agree with Natland that the strong linear Hawaiian trends are mixing trends and not liquid lines of descent (Rhodes and Vollinger, 2004). Nonetheless, Natland’s suggestion that parental magmas are lower in FeO, and bear little relationship to the mixing trends, is a red herring. Perusal of Figure 11 in Rhodes and Vollinger (2004) will make this clear.”

*January 28th, 2007, Dean C. Presnall*

“In their comment of 27th January, Putirka and Rhodes accept the arguments of Langmuir et al. (1992) that mantle temperature, bathymetry, and geochemistry are linked. However, a global examination of MORB glass analyses in the Smithsonian database shows no such linkages (Presnall and Gudfinnsson, submitted). Instead, the observed Na<sub>8</sub>-Fe<sub>8</sub> systematics of MORBs match the systematics of melts at the lherzolite  $\square$  basalt solidus of the CaO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-Na<sub>2</sub>O-FeO system in the narrow pressure-temperature range of 0.9-1.5 GPa, 1240-1260°C (Presnall and Gudfinnsson, 2002; submitted). This low and globally uniform potential temperature along all ridges (including Iceland), is not consistent with the existence of hot plumes (Galapagos, Iceland, Azores, Tristan, Bouvet, Afar, Easter) on or close to ridges.” *We infer a range of eruption temperatures and of  $P, T$  and*

*% melting along ridges but consider that attribution of this variability to differences in  $T_p$ , or differences in the departure from adiabatic upwelling, or to source compositions, is premature, awaiting a much greater database of primitive melt compositions as assessed by methods used in our paper.*

*January 28th, 2007 Don L Anderson*

*31st January, 2007 James H. Natland*

*The comments by Anderson (28th January) and Natland (31st January) address the Putirka and Rhodes comment and do not directly address our paper. We are in general agreement with them. Natland provides a figure and discussion illustrating the differences between olivine fractional crystallization and olivine phenocryst accumulation refuting the approach of Putirka (2005; 2007). We agree with Anderson's emphasis on compositional rather than thermal variability as causes for relative density, buoyancy and seismic properties within the upper mantle. In Green et al. (2001) and Green and Falloon (2005), we specifically advocate a key role for refractory, buoyant, old subducted slabs as causes for topographic and magmatic aspects of 'hot spots'. We agree that the fuller exploration of the geodynamic consequences of mantle compositional heterogeneity is timely, having to our satisfaction tested and denied a key prediction (and oft-quoted confirmation) of the deep mantle thermal plume hypothesis (i.e. that their magmatic expression at hot spots is characterized by much higher temperature magmas, and greater depths and extents of melting than provided in the 'normal' mantle upwelling and melting at mid-ocean ridges). We find to the contrary that the range of magmatic temperatures in 'hot spot' and mid-ocean ridge settings are similar and observed differences in magmatic products are a consequence of compositional heterogeneity in the upper mantle.*

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Figure: Composition of glasses from the Siqueiros Transform from Danyushevsky et al. (2003), and a fractionation calculated from the most magnesian glass following the model of Danyushevsky (2001). The plot clearly demonstrates that the most magnesian glasses from Siqueiros are saturated in olivine only.