**Concerning Olivine-melt and Olivine-spinel-melt Geothermometry: A Precís**

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**Abstract**

Two methods have been developed to estimate crystallization temperatures of olivine and, from there, potential temperatures of melting in the mantle. These are 1) olivine-melt FeO-MgO backtracking; and 2) olivine-spinel-melt (OSM) equilibria. Iceland and the North Atlantic Igneous Province have figured strongly in application of these techniques. This will be a critique of those procedures. The principal difficulty with backtracking, even using sophisticated computer programs such as Primelt3, is magma mixing, especially that between primitive liquids and differentiated liquids that fall along a low-pressure cotectic. Discriminants within Primelt3 identify most cases of magma mixing, but not all. Mixing, and disequilibrium crystallization of spinel in boundary layers in somewhat undercooled but still faceted olivine, confounds OSM equilibria. Such equilibrium is not a state achieved in nature.

This is incomplete, and depends on further work with Malcolm Hole. It gives my point of view, not necessarily his. At this stage, he is NOT to be implicated in the views expressed. We anticipate working it out. I describe difficulties with procedures, and some of the geological reasons for them.

**Introduction**

Olivine-melt FeO-MgO backtracking takes the compositions of natural olivine and host melt and computes them back to nominal equilibrium in a mantle usually presumed to have Fo91, slightly more or less, which is taken to be the olivine composition in the peridotite mantle source. The computation is done by adding incremental amounts of successively more magnesian olivine to the composition of the host liquid; then calculating the liquid composition from the mixture that should be in equilibrium with each successively more magnesian olivine until Fo91 is reached. The calculations are conventionally done in increments of 0.1 mol % Fo. It presumes a standard distribution coefficient between FeO/MgO (e.g., Roeder and Emslie, 1970) between the liquid and the olivine. It REQUIRES that the liquid(s) be on an olivine-alone fractionation pathway.

The procedure thus applies only to picritic lavas (those with none other than olivine phenocrysts). The magma is presumed to have followed a closed-system crystallization and differentiation history controlled only by olivine, and which has neither reacted with mantle or crustal rocks during its ascent. Also, it has not mixed with any other compositionally different magma. Mixing with a more differentiated cotectic magma having plagioclase or clinopyroxene on the liquidus is forbidden.

The procedure can be (and has been) applied to any relatively primitive basalt, so long as it is properly identified either petrographically or by high MgO contents as picritic. Neither approach is foolproof. A more sophisticated procedure is to use a program such as Primelt3 (Herzberg and Asimov, 2015) to identify whether a picritic composition nevertheless indicates mixing with a differentiated melt, an interval of clinopyroxene crystallization somewhere during its crystallization history, or whether it might have come from a carbonated peridotite. In this respect, it is a bit of a filter. If these tests fail, Primelt3 is unsatisfactory to use to estimate either primary melt compositions or potential temperatures.

An alternative procedure is based on an experimentally determined relationship between the Al concentration in olivine, and the Al2O3 content of intergrown chromian spinel, both in equilibrium with melt. The relationship depends on temperature. Clearly, all three phases must be in equilibrium. But it is not strictly necessary to have the melt composition once the compositions of olivine and spinel in natural rocks are known.

**Olivine-melt MgO-FeO backtracking**

The most serious difficulty with this procedure is determining whether magma mixing has occurred. Clague et al (1995), for example, established that most picritic lavas from Kilauea volcano, Hawaii, are hybrids between an olivine-rich primitive magma, and an olivine-poor differentiated magma that had attained the level of cotectic crystallization of plagioclase, clinopyroxene, or both, in addition to olivine. Such mixing modifies the differentiation trajectories of all elements, but most particularly total iron (as FeOT) and MgO. Hybrid host liquids consequently backtrack to a parental liquid with too much iron, for which the calculated potential temperature and parental MgO content must necessarily be too high.

An objection to this procedure can be summarized as follows. Take a diagram of FeO versus MgO (Figure 1). Imagine an olivine fractionation pathway, AB (I’ve made it linear here, but it won’t quite be). Arrows indicate down-temperature directions of differentiation. At B, clinopyroxene and/or plagioclase join the liquidus, initiating cotectic crystallization. With continued cooling, its pathway becomes BC. This is true, for example, for both Hawaiian lavas and those from West Greenland and Baffin Bay.  Now, there are two sides of a triangle.  Assume that two identical liquids produce the same two lines. Superimpose the two pairs of lines.  Here I’ve slightly displaced the two, one being in black the other in blue. Somewhere along the olivine fractionation pathway of the black line, call it point A, draw a mixing line to another composition on the steeper side of the triangle, representing liquid B, on the blue line.  That forms a third side to the triangle, AB, here shown in red with double-headed arrows. Any point along that mixing line will have higher FeO than A. Then if olivine is incrementally added to any point along AB, to get back to a melt composition "in equilibrium with" a mantle with Fo91, (this time the arrowhead indicates increasing temperature) the result is a composition with higher FeO than the mantle composition that partially melted to produce either of the original identical relatively flatter baselines.  The estimated mantle composition has more iron (higher MgNo) than it actually does. More incremental olivine must be added to the liquid get back to Fo91, and the resultant parental MgO content is higher than it should be.  The hybrid composition, with its enhanced FeO content, results in both higher T and Tp.

Most points along the mixing trend AB, with MgO contents higher than in cotectic liquids, will likely have only olivine phenocrysts in thin section. With no further evaluation, they will likely be perceived as picrites along an olivine-fractionation pathway. Mixing has pulled the hybrid liquid away from cotectic differentiation.

At best, ONLY THE BASELINES CAN BE USED FOR BACKTRACKING TO GIVE TP. And that assumes the identical mantle composition and identical CLOSED-SYSTEM fractionation pathways. But are picrites themselves single melts from the mantle, or do they represent mixing ALONG THE BASELINES at high temperature and pressure between different primitive magma stems?

**Some Hawaiian Volcanology**

Wright and Fiske's (1970) paper on Kilauea volcano, Hawaii, documents extensive mixing between magmas arriving at a cauldron just beneath the summit (they called this a staging area), with others stagnating and differentiating along the Kilauea East Rift.  They established this through a series of historic eruptions.  The physical reason for existence of a “staging area” about 3 km below the summit is that ascending magmas, buoyant at first, encounter a region where the formation density is determined by fracture porosity and spaces between lava flows and within them. At that depth, usually 2-4 km, the formation and magma density match, the magma is no longer buoyant, and further inflation simply forces the magma sideways into lateral rift zones (e.g., Ryan, 1987; 1988). Eruption occurs when inflation rates exceed the capacity of the summit magma reservoir, and lateral rift zones cannot handle the rate of magma supply. They expand, almost like a balloon, but with a steady leak, or an arterial aneurism, and usually at the point of least superincumbent load, leading to lateral flank eruption. Considerable cooling of magma occurs, however, along the rift zones between eruptions, leading to their differentiated (cotectic) compositions. The gravitational loading structure of the volcano leads to consistent dike-on-dike injection, thus frequent opportunity for magma mixing (Fisk and Jackson, 1970). Ryan (993) proposed a similar mechanism for Iceland.

Assume now that a flank eruption produces differentiated cotectic liquid A, pushed out ahead of magma moving into the cauldron staging area.  If the latter pulse is big enough, then a range of mixtures erupts. Call these AB, recognizing that there is a spectrum of mixed compositions, and that A and B are end-members. Finally, if the eruption is a whopper, out comes primitive "olivine-controlled" end-member lava B.  The cycle repeats itself.  Differentiated magma B during an eruption cycle precedes mixtures BC, which then are followed by C, the magma plumbing system effectively being purged.  If the eruptions are truly large, primitive liquid C might ultimately erupt at the summit.  In one case, Wright and Fiske (1970) documented that the differentiated flank liquid had over 60% SiO2.  That never erupted, but was implicated in mixing by a least squares mixing program. The procedure also revealed that the parental compositions of separate magma inflation events were never identical.  Wright (1971) later modeled the range of calculated parental liquids to conclude that differences in parental compositions between Kilauea and Mauna Loa reflected different degrees and probably average depths of partial melting.  Even this assumed an identical starting mantle composition.  But models have to start somewhere.

One consequence of this magma transport system is that, when magma reaches the region of neutral buoyancy, most olivine is shed from it before it can even begin to ascend again. The olivine accumulates in cumulus dunite masses far below ground level (e.g., Clague and Denlinger, 1994).

Clague et al (1995) showed that most picrites from Kilauea and its submarine extension, Puna Ridge, were actually like hybrid liquids AB and BC.  These cannot be used for backtracking.  Any use of only FeO-MgO diagrams to select "olivine controlled" liquids (Putirka, 2008) fails to take this into account.  You need to use at least Al2O3-MgO (e.g., West Greenland and Padloping Is; Figure 2) to see how mistaken this procedure is.  Or, just look at thin sections to see if minerals other than olivine are present (Samoa is near the top of Putirka's list, second only to Hawaii in TP. Every Samoan thin section I have - dozens, many of them what Macdonald termed "picrites of the ankaramite type" - have at least cpx and often plag phenocrysts, no matter how high the MgO of the analysis).   Picrites are more than tables of analyses, and they all are, as I believe, mixtures.

**Primelt3**

PRIMELT3 does basically the same thing.  The phase projection for Baffin Island and West Greenland calculated from PRIMELT3 (Figure 3), prepared by Malcolm Hole, is essentially a multiphase version of the FeO-MgO diagram. The difference in potential temperatures calculated for Padloping and West Greenland (contrast upper and lower diagonal lines) is 60o. On this basis, no backtracked temperature is realistic.  PRIMELT3 may circumstantially hit about where it should, but there is no way to know this. The result doesn’t mean anything, unless 60o is inconsequential.

The problem is that no one has worked out crystallization histories properly.  Lotte Larsen came close, as did Natland (2006, and unpublished for Samoa). This means calibrating compositions of all coexisting phases – olivine, spinel, glass inclusions, clinopyroxene, plagioclase, Fe-Ti oxides - in any multiphase intergrowth.  For example, such a calibration allows comparison of olivine Fo content and spinel MgNo and/or cpx MgNo, and/or plag An.    This almost always reveals that extensive mixing has occurred. It is, in my experience, ubiquitous.

For starters, doing crystallization histories properly means acknowledging that minerals are almost always intergrowths, and those who, for example, stick strictly to olivine are being misled about the complexities of olivine crystallization.  Thus, almost all olivine has intergrown spinel.   In picrites, people rarely notice or document the presence of the odd plagioclase or clinopyroxene, but therein is the story. It is proof that something in that lava crystallized along a cotectic.  Thor Hansteen, for example, sent me an outcrop photo of a large (maybe 10 cm), skeletal plagioclase megacryst in an olivine-only Icelandic picrite, as described in the literature.  Whoever it was, missed it.

Clague et al (1995) identified high-MgO picritic (>11%MgO) glasses from sand grains taken in a box core near Puna Ridge. These appear to lie on or near olivine fractionation pathway, but were a minority among glass grains in the core, most of which have cotectic, differentiated compositions. Full crystallization histories cannot be worked out. At my suggestion, Dr. Clague recently undertook to determine olivine and spinel compositions on these grains, if they existed. Unfortunately, neither mineral is intergrown with a glass shard having MgO = 15%, the highest found in any Hawaiian glass. Dave determined that Cr-spinel does not occur in olivine more magnesian than Fo88, although it clearly does in picrites from Baffin Bay and West Greenland. The high-MgO glass has a crystallization temperature of 1325°, using the glass geothermometer of Beattie (1991).

**A Test of Primelt 3**

Between Baffin Island and West Greenland, 26 picrites have determinations of the compositions of host (quenched) glass and their associated whole rocks, which contain much olivine. In Figure 7, these are plotted in terms of FeO and MgO, where FeO = 0,9\*FeO(T). West Greenland (Larsen and Pedersen, 2000) is shown in A, Padloping Island, on the western side of the Labrador Sea, in B (Francis, 1985; Yaxley et al., 2004; Starkey et al., 2008). From Padloping Island, only samples studied by Francis (1985) have analyzed glass. The glass compositions have the steep slopes of cotectic compositions.  Lines link them to the corresponding whole-rock compositions. Of the 26 linked pairs, Primelt3 successfully identified 16 whole-rocks, and all glasses, as having either experienced clinopyroxene fractionation, or having MgO < 9.5%, indicating plagioclase fractionation. The remaining ten whole-rock compositions, five each from Padloping Island and WestGreenland, passed all tests, thus appear to be “olivine controlled”. This, however, is despite the fact that they contain cotectic glass. Primelt3 therefore discriminates mixtures fairly well, but not perfectly (62%of thetime).

The importance of glass in these samples is that they are from quenched rims to pillow lavas. The lavas either entered seawater or erupted into it. Two examples with glasss rims more than 1 cm thick, from Padloping Island are shown in Figure 8 (from Francis, 1985, Fig. 1, a and b). Glass represents 50-80% of each quenched rim, the rest mainly being olivine and spinel, and is equivalent to the matrix or mesostasis of the more crystalline part of the rock. It is the molten eruptive composition of each sample, and each one has a cotectic composition. The olivine is baggage. The eruptive temperature of each one is the most pertinent to its origin. The average eruptive temperature (Beattie, 1991) of fourteen glasses from West Greenland is 1188° ± 10°C. Twelve glasses from Padloping Island erupted at 1200° ± 8°C. These are near the high end of glass temperatures for MORB (1210°-1230°), but certainly no hotter. Temperatures of crystallization for both places combined, 1211°-1170°, decrease as glass MgNo decreases, and TiO2 increases, as they should if the liquids were on a cotectic.

The olivine in these rocks, which has faceted to skeletal morphologies and diverse composition, was mixed into them along with some accompanying primitive melt. This melt undoubtedly is now incorporated into the present matrix and glass margin to the lava, but ascertaining its composition is not simple. The overwhelming signal of the glass rims, however, is that of differentiated, cotectic liquids.

The heavier green lines link the matching pairs in Figure 7, and project out to a red line that gives olivine compositions. Where the green and black lines intersect that line, the olivine compositions are shown to the right. They have a narrow range, from Fo89.8-88.2. These are average olivine compositions corresponding to the upper quarter of the Fo range in the spectrum of analyzed olivine in all samples (Fo92-77). The green square gives the average olivine composition determined for hundreds of analyses from West Greenland (Larsen and Pedersen, 2000).

**Al in Olivine (Olivine-spinel-melt = OSM Equilibria)**

I once thought that if you could identify the most forsteritic olivine in a picrite, and it had a glass inclusion containing spinel, that you might be able to fiddle with all compositions and get at temperature.  Finding this association in “most magnesian olivine” is obviously difficult in a rock with a diverse population of olivine. Nevertheless, Al-in-Ol (OSM) was a heroic attempt to do this.  But it doesn’t work, because the experimental conditions for equilibrium are not attained in nature. The problem again is magma mixing.

The term Al-in-olivine is shorthand for a procedure that involves simultaneous (equilibrium) crystallization of olivine and Cr-spinel from melt. The compositions of all phases were determined and temperatures estimated assuming that they all were in equilibrium. Thus, technically, the procedure involves melt, and I prefer to term it olivine-spinel-melt (or OSM) equilibria. It is a way to circumvent the difficulties inherent in backtracking, if it works.

OSM equilibria was developed experimentally by Wan et al (2008) and Coogan et al (2014), and applied to Iceland by Matthews et al (2016) and to the North Atlantic region from Baffin-West Greenland to Iceland by Spice et al (2016). The experiments were carried out in air on small bits of basalt glass powders sintered to wires, then using an electrical current subjected to various temperatures near the liquidus, and then quenched. The glasses were spiked with aluminous spinel, olivine and chromite in order to exceed detection limits of electron-probe microanalysis (EPMA).

This raises the first potential objection to application to rocks. It is that spiking shifts everything to higher temperature, based on phase diagrams (Figure 4). Furthermore, most experimental Cr-spinel crystals have higher CrNo (= Cr/[Cr+Al]; Figure 5A) than spinel from the East Pacific Rise, Gorgona, West Greenland (Figure 5B) or Iceland (Figure 5C). The most primitive spinel crystals are from Gorgona and a few from Borgarshraun, Iceland (Figure 5C, blue data field). Of experimental ol-sp intergrowths over a range of temperatures (Figure 6A), spinel with MgNo >85 do not occur at any of those places. The black line separating experimental spinel above and below 1300°C parallels regional data spreads for natural spinel (Figure 6B), that mimic data spreads for individual samples. Olivine isopleths in Figure 5 show that varying spinel MgNo at constant CrNo actually is evidence for mixing between magmas of primitive compositions and differentiated magmas having olivine as iron-rich as Fo80, despite compositions falling above the 1300°C experimental boundary. This is because the olivine isopleths in Figure 4 crosscut spinel MgNo’s. The drop in temperature amounts to almost 200°. Such evidence for mixing thus confounds estimates for crystallization temperatures based on OSM experimental equilibria (Figure 7).

Then there is the matter of olivine zoning. Decades ago, EPMA analysis of olivine did not resolve low concentrations of, e.g., Al. It was treated as below detection limits and usually not included in lists of analyses. Now, with improved beam and current stability, contemporary electron microprobes allow these determinations, although explicit conditions for wavelength location of background measurements, curvature of backgrounds, and standardization are rarely given. Recent acquisition of elemental EPMA maps of individual crystals (Millman-Barris et al, 2008; Welsch et al., 2014) also shows that even euhedral olivine is commonly zoned with oscillatory bands of enrichment in P, Cr and Al that parallel crystal faces, with some of these zones intersecting occluded Cr-spinel. The zoning represents a type of dendritic crystal growth at some undercooling (Welsch et al., 2014). The correlation of Cr with P demonstrates that both are excluded from olivine even though they have strongly opposed distributions during fractional crystallization of olivine plus spinel.

Natland (2016) noted the high concentration of Cr-spinel in phenocrysts in tholeiitic picrites from the Juan Fernandez Islands. Indeed, most Cr-spinel in the rocks occurred *only* in olivine. Almost the entire inventory of Cr in the rocks, often 1500-2500 ppm, is tied up in spinel in olivine. Typically, the spinel occurrs in inclusions that also have some devitrified glass, some of which also contain highly skeletal or dendritic clinopyroxene, and a myriad of small Fe-Cu-Ni sulfides. The latter especially indicate that the spinel, abundant in the olivine, likely grew in a boundary layer in which elements excluded from olivine became strongly concentrated, eventually forcing crystallization of spinel and immiscible segregation of sulfides. Bits and pieces of the boundary are incorporated into the olivine to form the oscillatory zones. In the context of OSM, this is decidedly a disequilibrium arrangement. Therefore, standard partitioning theory cannot be applied to Al, P, or Cr distributions between olivine and spinel. Indeed, the zones show up as tiny but densely crowded specks on elemental maps, perhaps indicating that the specks represent very tiny melt/vapor/spinel inclusions that are too small to be seen with a microscope.

**Why Are Picrites Abundant in Greenland and Baffin Bay?**

In a point-counterpoint discussion that began with Natland (2008), Larsen and Pedersen (2009) began by asking in their title, “West Greenland was hot – How else can you make 22,000 km3 of picrite?” My follow-up discussion (Natland, 2009) emphasized the difficulties with magma mixing, as outlined above, and used spinel to estimate lower temperatures than those obtained with olivine-glass FeO-MgO backtracking. Thus, the rocks, whatever they are, are what they are, even if they are picrites.

This, I realize now (duh!), does not answer the question about picrite volumes. I shall now attempt to correct.

In an earlier section, I briefly described the magma supply, recharge, and differentiation mechanism operating at Kilauea volcano, Hawaii. Differentiation occurs primarily in lateral-rift dike swarms that are fed from a central source beneath the crater of Halemaumau. A magma reservoir several kilometers in width and height directly underlies Halemaumau, at a depth of 2-5 km. Magma inflation of this summit reservoir precipitates eruptions on the along the eastern and southwest rifts of Kilauea, and these are often followed by summit eruptions. Much of the magma at first is laterally pushed into the rift systems, which are the main places where magma mixing occurs. Lateral injection is controlled by the existence of a superficial crust of lava flows that overall have low formation density. This is determined by the abundance of fractures, soil horizons, and both inter- and intra-flow voids, which altogether contribute significant open porosity in the upper 2-3 kilometers of the crust. Ascending magma, with a density of about 2600 kg/m3 (or 2.6 gm/cm3) rises buoyantly through mantle and compacted rock until it reaches a level with a similar density, termed the neutral buoyancy region, whereupon it ceases to rise and creates its own free space, ponds and pushes laterally into the flanking dike system.

Eruption of picrite in large volume and both directly and repeatedly on the land surface as in West Greenland and the coast of Baffin Island suggests that in those places a region of neutral buoyancy does not exist in the crust. The geology of both regions is essentially that of Archaean mantle cratons and later Proterozoic granitic intrusions with associated metamorphic rocks. But the most crucial feature of the geology of this part of the world is that it has been and is still in part heavily glaciated. Any low-density rocks in the crust – the superficial zones of high formation porosity – that may once have been there have been scalped and removed by glaciers. The material now is in distant glacial moraines.

The effect of this on magma transport must be significant. At Hawaii, extended low-pressure differentiation occurs in magmas largely trapped within a neutral buoyancy horizon; these trapped magmas prevent most high-temperature, olivine-laden magmas from reaching the surface. At Kilauea, this structure was only rarely ever bypassed or flooded with primitive magma so that picrite could erupt. On the other hand, glacial stripping away of all rock with significant formation porosity means that primitive magma was able to ascend from mantle depths without significantly stagnating in crustal staging areas, for which the appropriate porosity structure does not exist, and formation densities remain high all the way to the land surface. Even a presumably low-density rock like granite still has a density of 2.75 gm/cm3, greater than that of pure molten basalt. Perhaps even more important, granite and granulites tend to be massively coherent, with extremely low formation porosity. They would behave like a smooth well bore (to borrow from the parlance of drilling) with respect to injected and ascending magma, whatever its composition. Magma ponding in them cannot occur. Basalt dikes penetrating cold Archaean granite are therefore not likely to react significantly with fganitic materials if passage through them is quick and the volume of transiting basalt is large.

Crust of this type will allow primitive magma ready access to the Earth’s surface where it couldwell pile up as lava in unusually large volume. Picrite need not be especially hot for this to happen. The average temperature derived from 22 quenched glasses from West Greenland and Padloping Island, Canada, is 1200°C

**The Picritic Minor Intrusions of Skye**

These rocks first attracted attention with the seminal work on olivine crystal morphologies and growth, and the concentration of olivine in them by flowage differentiation (Harker, 1909; Drever and Johnston, 1956; 1957). The latter authors termed them *eucrites* because of their low concentrations of alkalis, especially K2O, and of TiO2. This was a deliberate comparison to meteorites, before the discovery of MORB.

At Skye, the main layered series of the Cuillin intrusion is encased in a cup-like mass of non-layered, varitextured gabbro, called the Outer Gabbro. From thin sections of rocks collected in 1989, it is not at all primitive, carrying abundant large crystals of magnetite and ilmenite. This carapace evidently expanded, or stretched the way a sock goes onto a foot as the main magma chamber inflated. The base of the layered series is layered cumulus peridotite. The picrite dikes intruded the gabbro carapace at about the level of the cumulus peridotite, being exposed particularly to the south and west of the intrusion. On the west, at Glen Brittle, numerous picrite dikes are exposed. Many have large olivine phenocrysts concentrated in the middle of the dikes, and thus, are the type examples of flowage differentiation (e.g., Harker, 1909; Drever and Johnston, 1957). The dike margins are fine grained and without much olivine. The dikes evidently intruded soft and hot gabbro, probably containing some interstitial melt, since some have small fault offsets of a few centimeters, but with small, blade-like spikes projected from the ends of the offset across it to the other side. Similar occurrences are described and illustrated in Harker (1909)

Bedard et al (1988) described the layered peridotites of Rum, the next large intrusion to the south of Skye, as being a series of cross-cutting beds that were produced by intrusion of dense picritic magma, one pulse at a time, into the base of a sequence of ultramafic cumulates. Each layer, then, was described not as a sequence of settled crystals that produced, but as peridotite sills that intruded each other.

Conceptually, the two occurrences can be related by supposing that ascending picritic magma suddenly reached a partially or completely molten igneous mass, the main functioning bodies of the intrusions where layered cumulates were forming and, following the principal of neutral buoyancy, could rise no further. They thus spread laterally, first at the base of the intrusions, and then, in the case of Skye, out into the older, but still rheologically soft gabbro carapace. From there, they penetrated country rock. Density differences controlled the magma supply route, and the focusing of picritic minor intrusions at the bases of the complexes. The “region of neutral buoyancy” was in a narrow zone at the bases of the principal intrusions. Occurrences of cumulus dunite xenoliths in, e.g., picrites from Durban Island, offshore of Baffin Island in Canada (N. Starkey, personal communication of scanned photomicrographs), is evidence for the physical progression of the lava flow through a mat of ultramafic cumulates where mixing of different olivine populations could occur, and probably flowage differentiation in dikes before eruption.

**Accumulation of Olivine in Picrites**

One assumption behind backtracking is that all olivine in picrites crystallized along a single olivine fractionation pathway. This is whether or not some (or all) of the matrix (quenched marginal glass) experienced cotectic differentiation. If no such mixing occurred, then an olivine fractionation pathway still needs to be demonstrated. If, however, the primitive mixing (or non-mixing) component itself is a hybrid, then not even Primelt3 will be able to sort it out.

So, how does so much olivine accumulate in picrite? The two classical mechanisms previously and frequently invoked to explain it are 1) olivine crystal settling; and 2) flowage differentiation. It stands to reason that if all or most olivine phenocrysts have either faceted or skeletal crystal morphologies, that those were attained in a melt. Such crystals cannot have been scavenged from some pre-existing consolidated wall rock. Far more likely, they crystallized during ascent of the magma, they protruded from wall rocks as growing crystals into the magma and were plucked into it, or they were loosely bedded on the floor of a magma chamber. We can probably assume that a rising primitive magma could even have collected the in all of these ways. One or more intervals of flowage differentiation in this sequence may have caused them to become highly concentrated at the points of crustal dike injection and eruption.

At Skye, the geology of almost all dikes was radial, away from principal magma centers. At Hawaii, lateral flank eruptions of picrite more than likely followed the transport pattern of 1) ascent to a shallow staging area or magma chamber; 2) formation of loosely compacted dunite cumulates; 3) injection of magma through the cumulates, thus entraining olivine; and 4) flowage differentiation in lateral rift-flank dikes. We have no information of this sort for West Greenland and Padloping Island. For those rocks, we depend on 1) variable compositions and morphologies of olivine; 2) compositions of coexisting Cr-spinel; and 3) occurrence of glomerocrysts and crystal clots of olivine, and perhaps even occurrences of dunite with cumulus textures. Francis (1985) is the only study that explicitly advocates a mixing model, this on the basis of glass compositions and diverse olivine crystal morphologies and compositions.

This conclusion, of course, depends on careful integration of bulk chemical, mineralogical and petrographic data. Approaches that simply take bulk compositions and use techniques with simplified assumptions to obtain “mantle temperatures” and compositions in equilibrium with a single mantle phase, olivine of composition Fo91, miss most of the story. The mantle may yet be hot beneath the North Atlantic, but this is not the way to prove it.