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Limitations on the Estimation of Parental Magma Temperature Using Olivine-melt Equilibria: Hotspots Not So Hot

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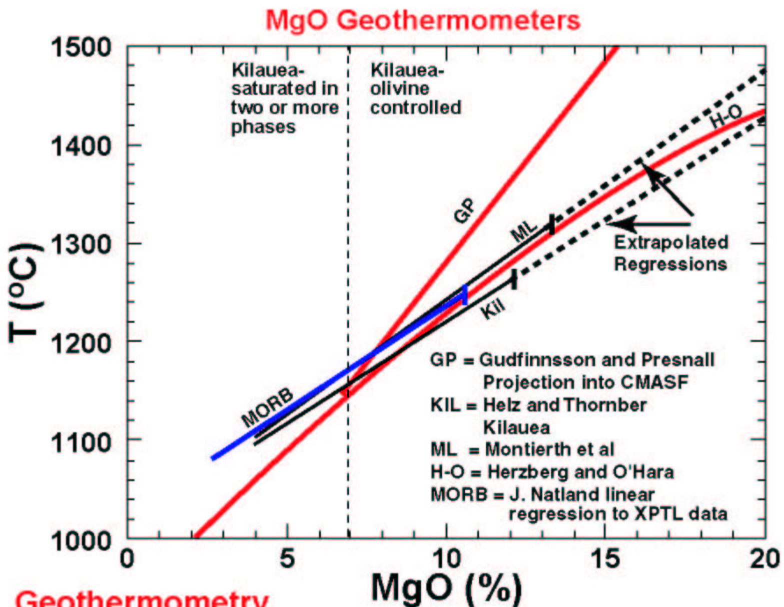
Abstract

Estimates of temperatures of magmas parental to picritic tholeiites using olivine-melt equilibria and FeO-MgO relationships depend strongly on the assumption that a liquid composition, usually a glass, is related to the most magnesian olivine in the rock, or to an olivine composition in equilibrium with mantle peridotite, along an olivine-controlled liquid line of descent. The liquid Fe^{2+}/Fe^{3+} also has to be known; where data exist, average values from wet chemical determinations are used. Crystallization histories of tholeiitic picrites from islands, spreading ridges, and large igneous provinces, however, usually reveal them to be hybrid rocks that are assembled by two types of magma mixing: 1) between a) differentiated magmas that are on olivine-plagioclase or olivine-plagioclase-clinopyroxene cotectics and b) crystal sludges with abundant olivine that *may* have accumulated from liquids crystallizing olivine alone; and 2) between primitive magma strains in which olivine crystallized either alone or with other silicate minerals at elevated pressure on separate liquid lines of descent. Many picrites give evidence that both types of mixing have occurred. If either type has occurred, the assumption of olivine-control linking a glass and an olivine composition can only circumstantially be correct. Oxidation state can also be underestimated and therefore FeO contents overestimated if basalts have degassed S, as at Hawaii.

In Case 1, hybrid host glass compositions often have higher FeO at given MgO content than liquids which produced many olivine crystals in the rock. In Case 2, the separate parental melt strains are revealed by diversity of compositions of both melt inclusions and Cr-spinel and are most often interpreted to mean local heterogeneity of the mantle source. The inclusions do not always affirm an olivine-controlled liquid line of descent. Instead, inclusions with <13% Al2O3 are increasingly interpreted from both major oxides and trace elements to be derived from melt strains produced by partial melting of both depleted and enriched pyroxenite or recycled ocean-crust (eclogite) (e.g., refs.1 and 2). Some Icelandic picrites also contain large phenocrysts of plagioclase and clinopyroxene; their abundant olivine evidently resulted from mechanical processes of concentration of olivine such as flowage differentiation. Using compositions of low-Al_2O_3 melt inclusions and host liquids to estimate spinel compositions (ref. 3) reveals many instances of crystallization at higher oxidation states than occur during MORB crystallization, and successfully predicts presence of spinel with Cr/(Cr+Al) = 60-75 actually found in picrites from Hawaii, Iceland, elsewhere in the North Atlantic Igneous Province, and the komatiites of Gorgona, but not in MORB. Where fresh glass is lacking (e.g., Gorgona), bulk-rock compositions have been used to reconstruct conditions of crystallization of parental liquids; but this is greatly complicated by the type and extent of alteration of the rocks. The consequence of all of these factors is that FeO in presumed olivine-controlled liquids is often overestimated, thus many estimated temperatures of crystallization of primitive magnesian liquids are too high by as much as 50-100^{o} absolute, and derived potential temperatures consequently are too high by more than this.

1) **Hansteen, T., 1991. Contrib. Mineral. Petrol. 109, 225.**
2) **Sobolev, A., Hofmann, A., and Nikogosian, I., 2000. Nature, 404, 986.**
3) **Poustovetov, A., and Roeder, P., 2001, Canad. Mineral. 39, 309.**



Geothermometry

Most empirical MgO geothermometers calibrated to measurements in natural systems (lava lakes) and experimental data on rocks give consistent results out to about 10-11% MgO. Only the ML geothermometer is calibrated to olivine-controlled liquids out to 13% MgO.

MORB liquids are mostly multiply saturated in plag, ol, and in some cases cpx out to MgO = 10%, whereas Hawaiian tholeiite is multiply saturated only to about 7% MgO. Above that only olivine and Cr-spinel are on the liquidus.

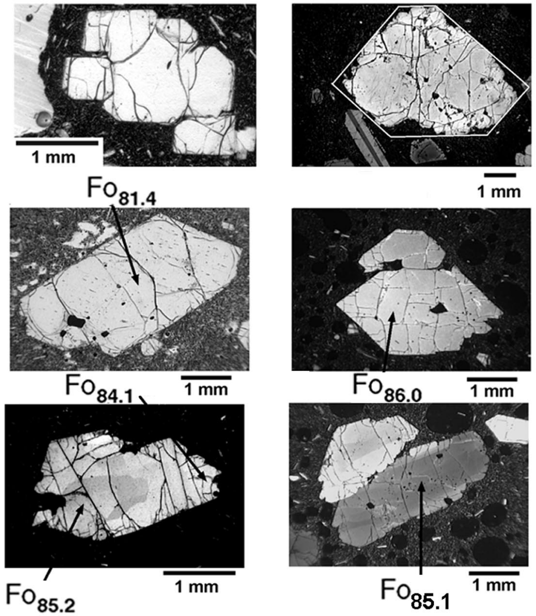
Geothermometers based on the procedures of Beattie and Ford et al give similar results, but T is not a simple function of MgO content.

Inferences that parental liquids have 15-20% or more MgO contents provide liquidus temperature estimates of 1300-1450°C

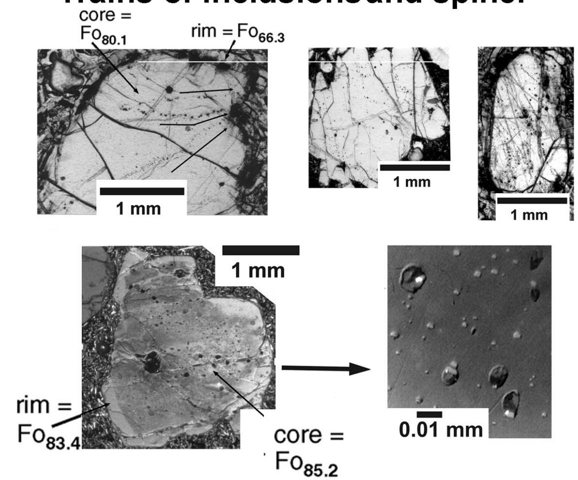
Picrites are complex magma hybrids!

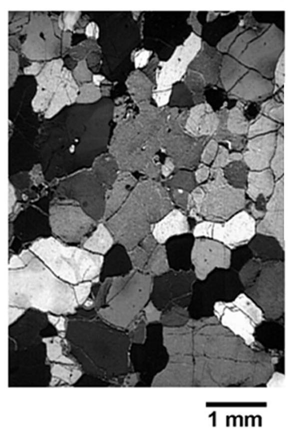
Mixing means that olivine and host liquids do not lie along a common liquid line of descent

Euhedra, some with subgrains



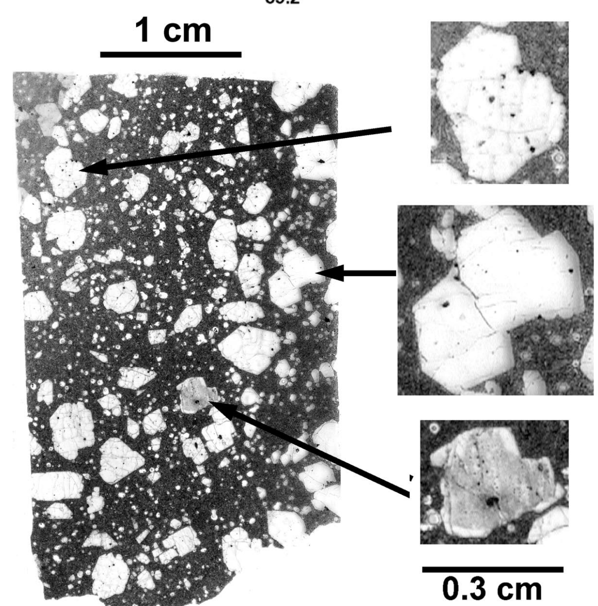
Trains of inclusions and spinel





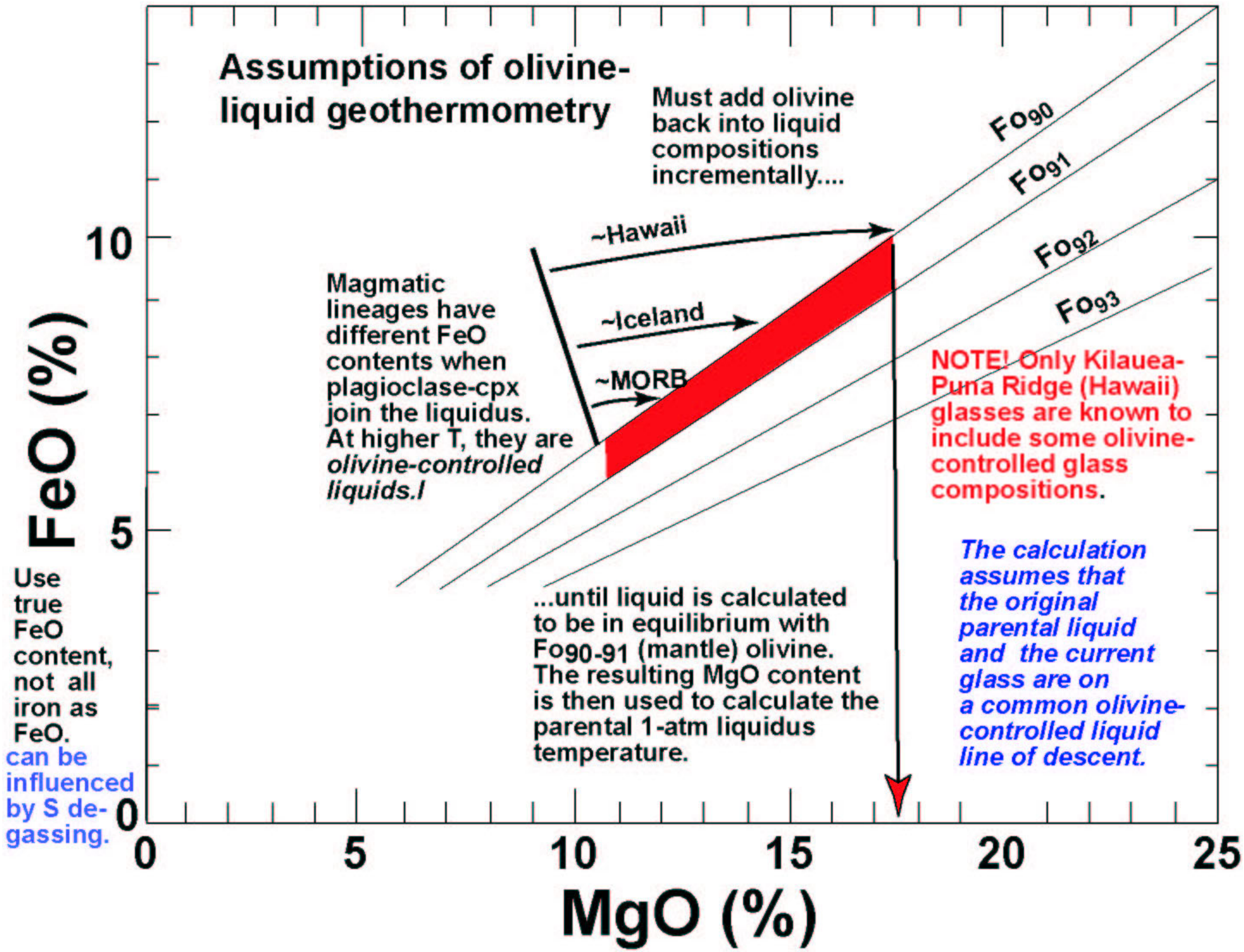
Many Contain Clots of Dunite

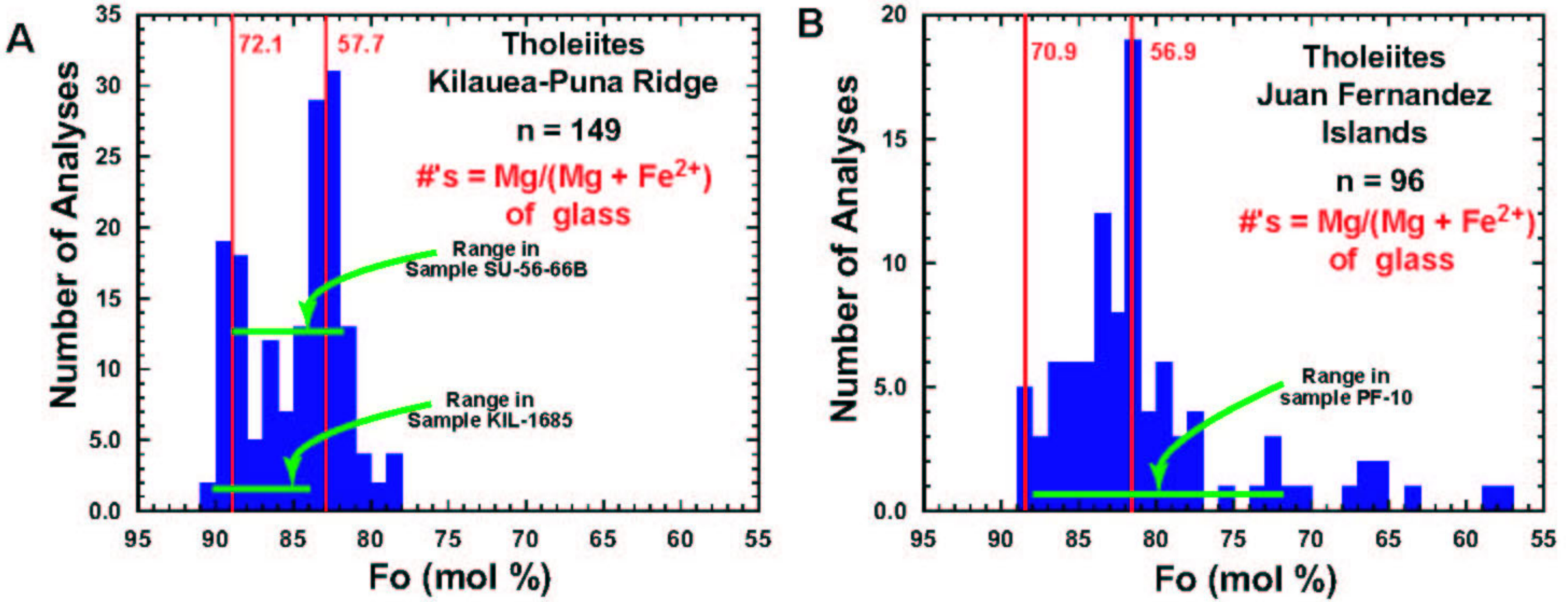
Olivine and slpinel in picrites from the Juan Fernandez Islands



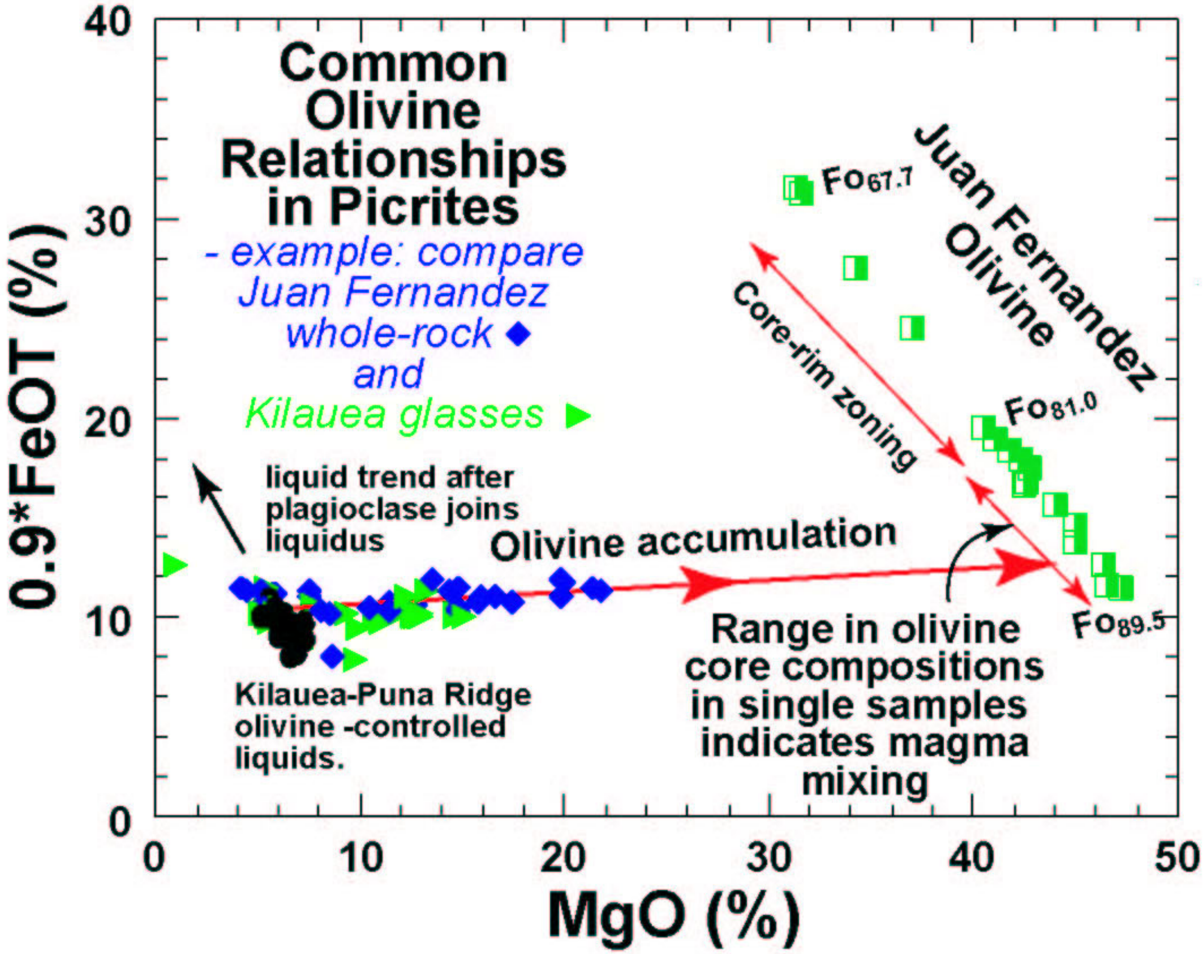
Juan Fernandez MF-S-1

Variable Inclusion Densities

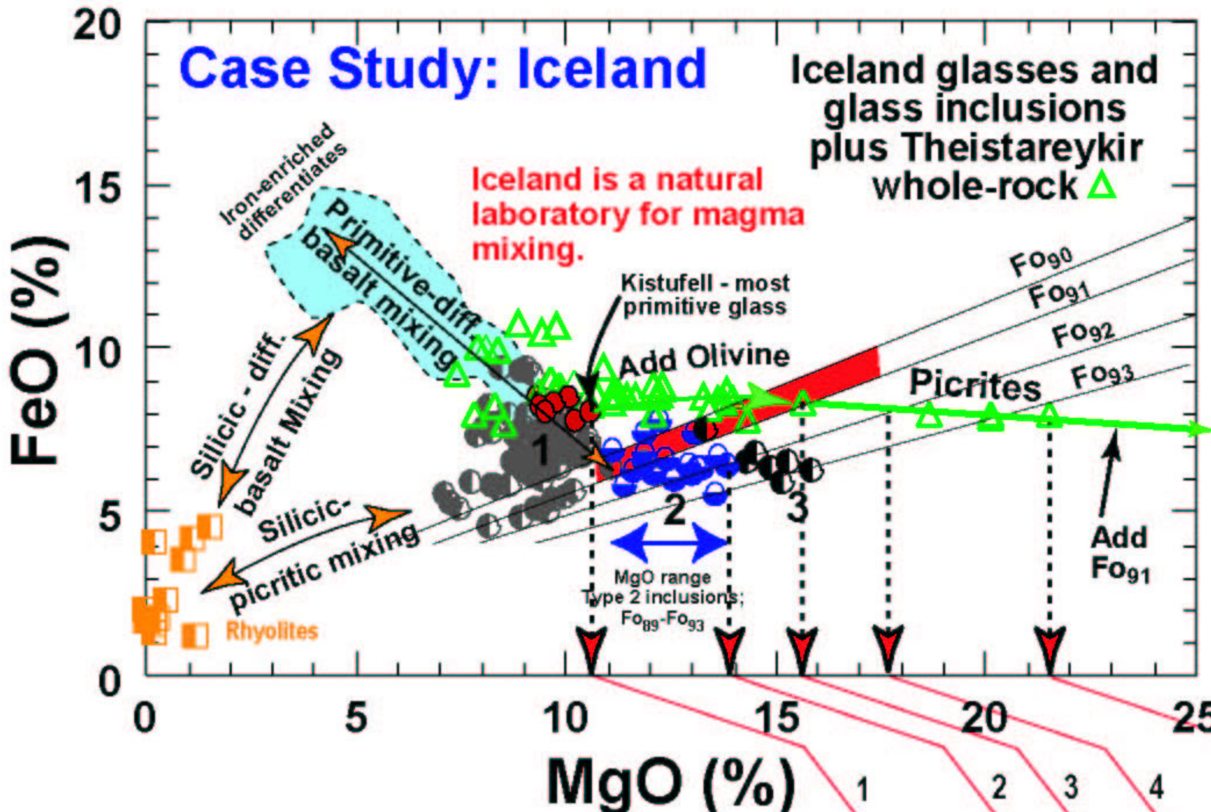

Assumptions of olivine-liquid geothermometry
Must add olivine back into liquid compositions incrementally....
Fo90
Fo91
Fo92
Fo93
~Hawaii
~Iceland
~MORB
Magmatic lineages have different FeO contents when plagioclase-cpx join the liquidus. At higher T, they are olivine-controlled liquids.!
NOTE! Only Kilauea-Puna Ridge (Hawaii) glasses are known to include some olivine-controlled glass compositions.
...until liquid is calculated to be in equilibrium with Fo90-91 (mantle) olivine. The resulting MgO content is then used to calculate the parental 1-atm liquidus temperature.
The calculation assumes that the original parental liquid and the current glass are on a common olivine-controlled liquid line of descent.
Use true FeO content, not all iron as FeO.
can be influenced by S de-gassing.
FeO (%)
MgO (%)
0
5
10
15
20
25
0
5
10



Picrites are usually NOT primitive (with high MgO and MgNo in glass). They are usually hybrids between primitive and differentiated liquids and have a range in olivine Fo contents reflecting magma mixing (green bars). Tholeiitic picrites from Kilauea and Puna Ridge, Hawaii, and the Juan Fernandez Islands are similar in this respect. The bimodal distribution of olivine compositions at Kilauea and Puna Ridge indicates the general pattern of mixing between primitive and differentiated magmas discerned by Clague et al (1995).



Picrite magma mixing is usually between moderately differentiated liquid that is enriched in iron because ofcrystallization of some plagioclase, and primitive magmas with lots of accumulated olivine having a range ofcompositions. Whole-rock olivine accumulation trends cannot be used for geothermometry. Whole-rock trends based on textural inference that the rocks were quenched liquids (e.g. komatiites) have to be used with great caution.

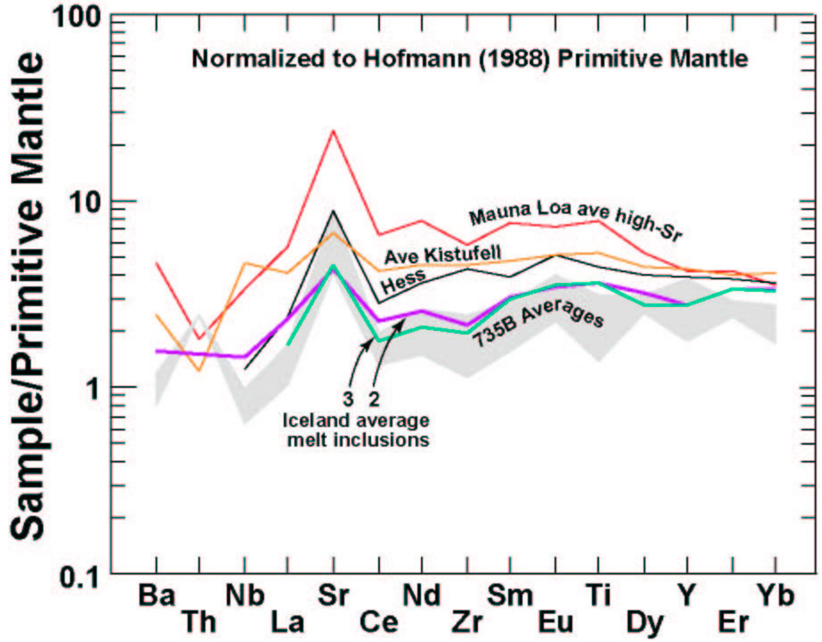


Melt inclusions from Iceland are not olivine-controlled, and are thought to be partial melts of pyroxenite or eclogite sources in the upper mantle. Kistufell and Theystareykir liquids MUST HAVE some iron-enriched liquids in them to provide a net liquid with higher FeO contents than the melt inclusions

1240° ~1300° ~1350° ~1400° 1470° Too Hot!

Best range for Iceland

Besides olivine, Icelandic picrites often contain phenocrysts, megacrysts, and crystal clots of calcic plagioclase and chromian clinopyroxene. Olivine is probably concentrated mechanically (e.g., by flowage differentiation) because it is dense. The minerals contain melt inclusions that, when re-equilibrated using a heating stage, have significantly lower FeO contents than host basalts (Groups 1-3 above). The minerals likely crystallized from glasses resembling Group 2 inclusions shown above with maximum MgO content of about 13%. Geothermometry gives ~1300°C, in agreement with mineral-melt estimates of ~1280°C.



Trace-element concentrations in Types 1 and 2 Icelandic mlt inclusions are similar to those in primitive abyssal gabbro drilled from ODP Hole 735B, Southwest Indian Ridge. This supports contentions that recycled ocean crust is an important component in the Icelandic melt source, and particularly that abyssal gabbro cumulates are immediate sources of the depleted Iceland melt-source component (not the same as depleted MORB mantle). Such gabbros have 10-16% MgO and excess Sr relative to rare-earth elements, that are preserved during eclogite melting to produce Type 1 and 2 melt-inclusion compositions. The liquids were never in equilibrium with mantle peridotite mineral phases, and do not follow olivine-controlled liquid lines of descent during subsequent crystallization in the Icelandic crust. They did crystallize magnesian olivine (Fo_{92-91}) together with calcic plagioclase and chromian clinopyroxene during the early crystallization history of Icelandic picrites. The maximum reasonably inferred temperature of those liquids was ~1300°C, about 60° hotter than primitive MORB.

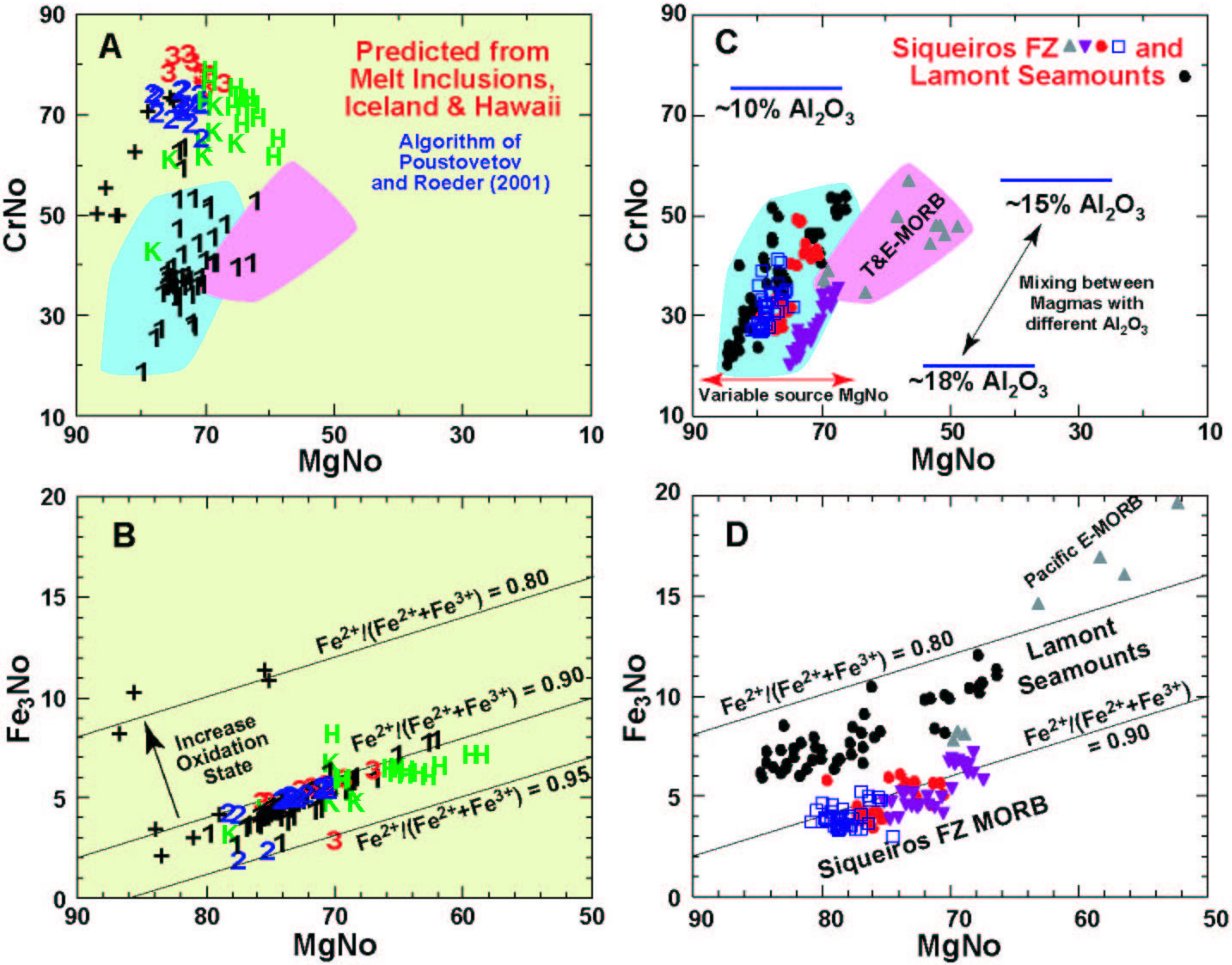
Iceland is not hot.

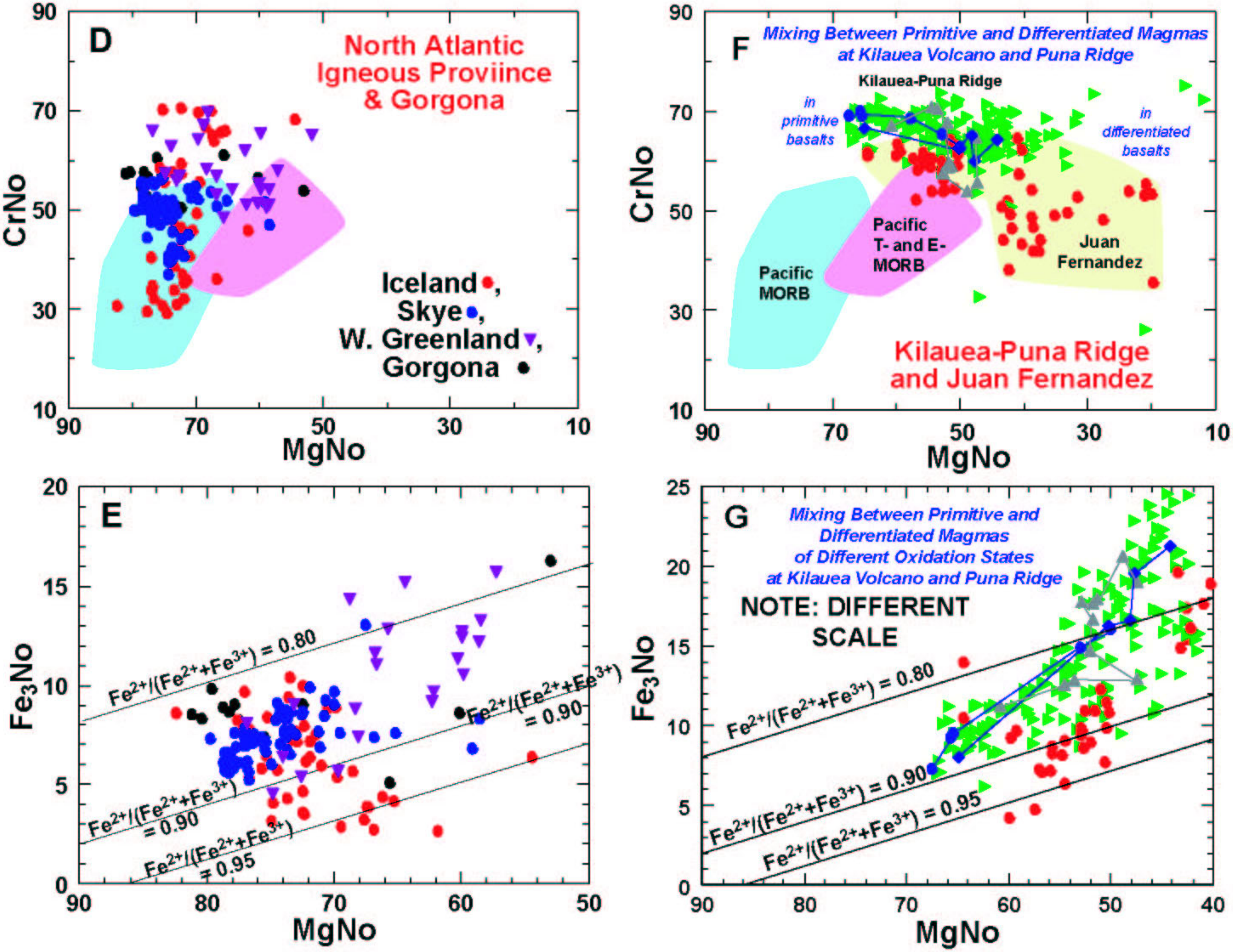
Model Compositions of Cr-spinel Compared to Natural Spinel compositions (next two figures)

Cr-spinel commonly occurs as isolated phenocrysts or intergrown with olivine and plagioclase in many picrites. Its composition is dependent on melt Mg#, oxidation state, and Al_2O_3 contents of the liquid from which it crystallized. Using exchange equilibria, Poustevotov and Roeder (2001) have produced an algorithm that can be used to predict spinel compositions from compositions of natural glasses. I have applied their algorithm to compositions of picritic glasses and melt inclusions from Iceland and Hawaii. In the green panels, numbers correspond to Iceland melt inclusions, Groups 1-3. Other symbols are K = Kistufell volcano, central Iceland, and H = Hawaiian melt inclusions. Changing the ratio $Fe^{2+}/(Fe^{2+} + Fe^{3+})$ shifts compositions to positions indicated by +'s.

The most important comparison is that Type 1 melt inclusions predict spinel compositions similar to the range in MORB (blue field, from C in Figure). Types 2 and 3 Iceland and Hawaiian melt inclusions predict spinel that, at given MgNo (A in figure) has CrNo (= Cr/[Cr+Al] from structural formulae) $\geq$ 65, higher than in MORB (C in figure). The principal control in producing such chromian spinel is low Al_2O_3 (indicated by blue lines in C). Using $Fe^{2+}/(Fe^{2+} + Fe^{3+}) = 0.9$ (green panel B in Figure) for all melt inclusions predicts spinel Fe^3No (=$Fe^{3+}/[Fe^{3+}+Al+Cr]$) comparable to that in spinel of some MORB picrites (D in Figure), but increasing the oxidation state to $Fe^{2+}/(Fe^{2+} + Fe^{3+}) = 0.8$ brackets the range seen in spinel from depleted MORB from seamounts near the East Pacific Rise (data of Jamie Allan). Crystallization of spinel in primitive N-MORB liquids occurs at different oxidation states.

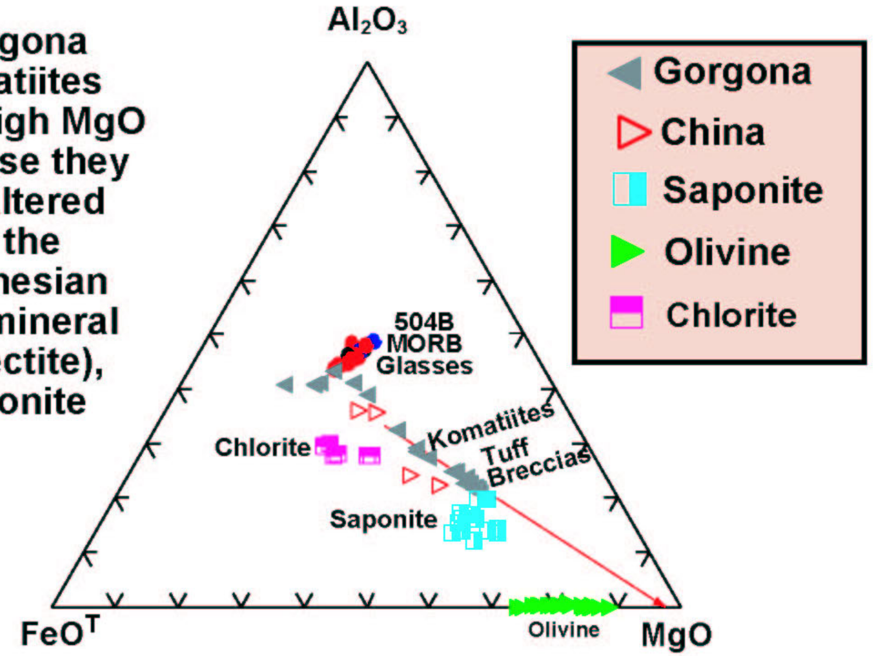
On the next figure, spinel compositions from the North Atlantic Igneous Province (W. Greenland, Skye, and Iceland), Kilauea-Puna Ridge and Gorgona (Tertiary komatiite locality, eastern Pacific), all include spinel with high CrNo and variable oxidation states (ranges in individual samples from Kilauea and Puna Ridge are connected by lines). From Poustovetov and Roeder (2001) these crystallized from melt strains with only ~10-13% Al_2O_3, values too low for MORB. Such liquids at Iceland originated from pyroxenitic/eclogitic liquids rather than liquids derived from partial melting of peridotite. Highly chromian spinel thus is a proxy indicator of the presence of these materials in the mantle source. It is present in all provinces shown, including Gorgona.


A
Predicted from
Melt Inclusions,
Iceland & Hawaii
Algorithm of
Poustovetov
and Roeder (2001)
CrNo
MgNo
B
Fe3No
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.80$
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.90$
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.95$
Increase
Oxidation
State
C
Siqueiros FZ and
Lamont Seamounts
~10% Al_2O_3
~15% Al_2O_3
~18% Al_2O_3
T&E-MORB
Mixing between
Magmas with
different Al_2O_3
Variable source MgNo
D
Pacific E-MORB
Lamont
Seamounts
Siqueiros FZ MORB
$Fe^{2+}/(Fe^{2+}+Fe^{3+})$
= 0.90

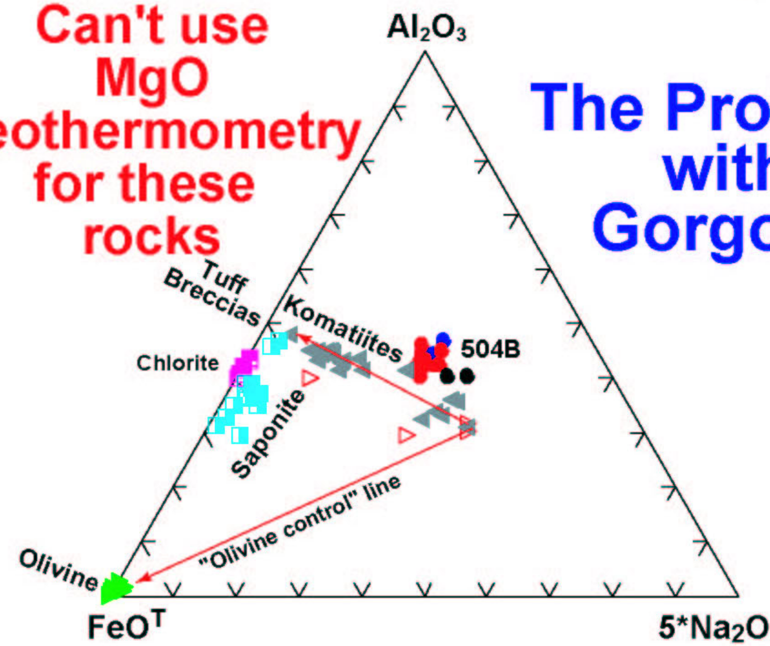

D
North Atlantic
Igneous Proviince
& Gorgona
Iceland,
Skye,
W. Greenland,
Gorgona
CrNo
MgNo
F
Mixing Between Primitive and Differentiated Magmas
at Kilauea Volcano and Puna Ridge
Kilauea-Puna Ridge
in
primitive
basalts
in
differentiated
basalts
Pacific
MORB
Pacific
T- and E-
MORB
Juan
Fernandez
Kilauea-Puna Ridge
and Juan Fernandez
CrNo
MgNo
E
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.80$
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.90$
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.95$
Fe_3No
MgNo
G
Mixing Between Primitive and
Differentiated Magmas
of Different Oxidation States
at Kilauea Volcano and Puna Ridge
NOTE: DIFFERENT
SCALE
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.80$
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.90$
$Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.95$
Fe_3No
MgNo

The Problem with Gorgona

Gorgona komatiites have high MgO because they are altered to the magnesian clay mineral (smectite), saponite



Can't use MgO Geothermometry for these rocks



Conclusion: Potential Temperatures are likely to be overestimated by improper Use of olivine-liquid thermometry

Potential Temperature Curves are those of

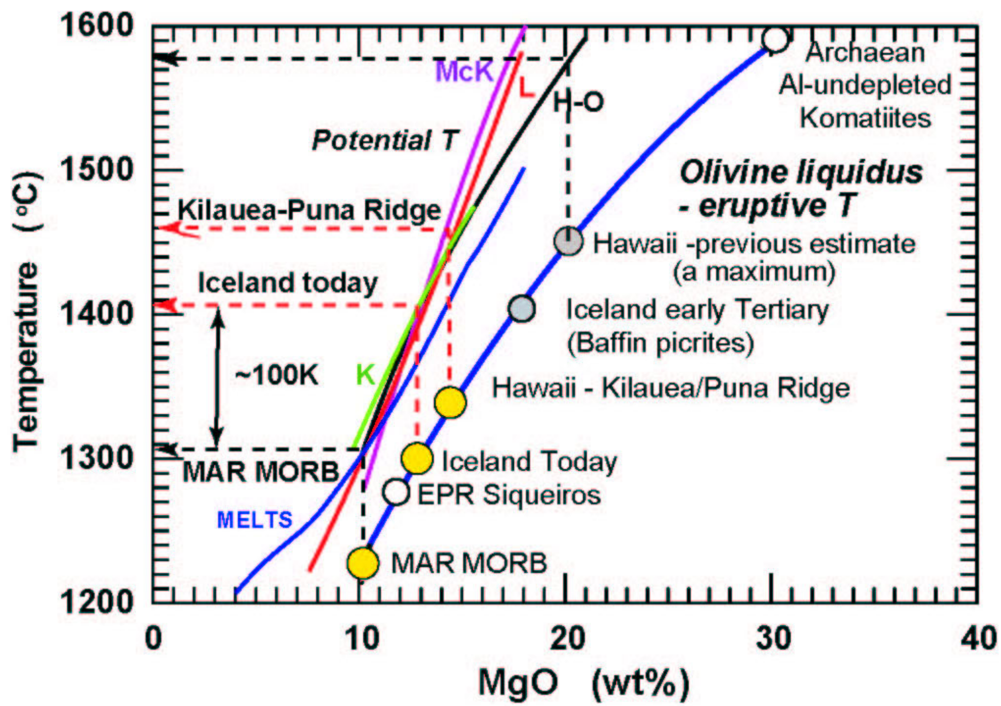
McK –McKenzie

L – Langmuir et al

H-O – Herzberg and O'Hara

Melts

I have used H-O For illustrative Purposes



Potential temperatures can be estimated from olivine-liquidus eruptive temperatures by linear extrapolation at constant MgO content to your favorite potential-temperature curve (dashed lines with arrows). A maximum liquidus T at Iceland results in a potential temperature just above 1400°C. The maximum liquidus T for Hawaiian picritic glass, 1325°C at 15% MgO gives a potential temperature of 1460°C. Inferences of higher MgO for primary Hawaiian tholeiite based on FeO-MgO relationships of existing hybrid glass to oivine are not correct. All that can be said is that they provide a MAXIMUM estimate of potential temperature given by the black dashed line in the Figure. This is 120K higher than the certain lower estimate that can be made using natural glass compositions.