Trace elements in Cr-Pyrope from the Navajo Field of the Colorado Plateau: Evidence for mixing in the mantle wedge during low-angle subduction

Douglas Smith (doug@jsg.utexas.edu) Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin

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Jackson School of Geosciences

PURPOSE: USE GARNETS TO INVESTIGATE MANTLE AFFECTED BY LOW-ANGLE SUBDUCTION

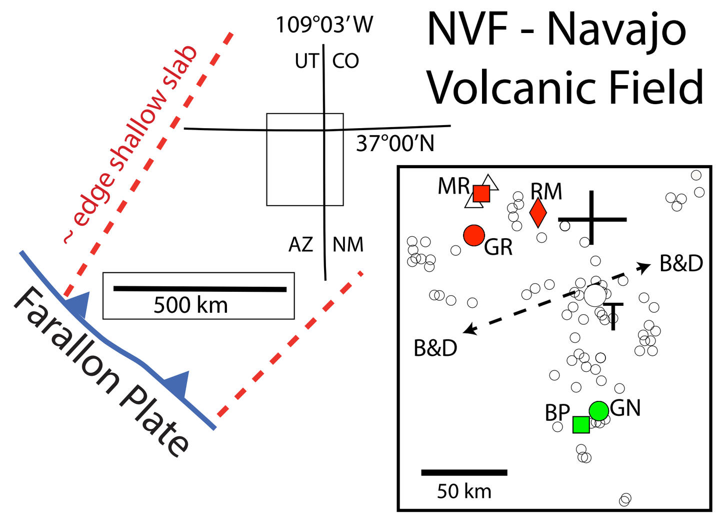
(1) What processes are recorded in Cr-pyrope from unusually cool mantle?
(2) During low-angle subduction of the Farallon Plate, how did the mantle lithosphere of the Colorado Plateau evolve? Were Farallon slab fragments incorporated in the Plateau lithosphere? Were fore-arc mantle fragments translated from the southwest above the Farallon slab and emplaced below the Navajo Volcanic Field?

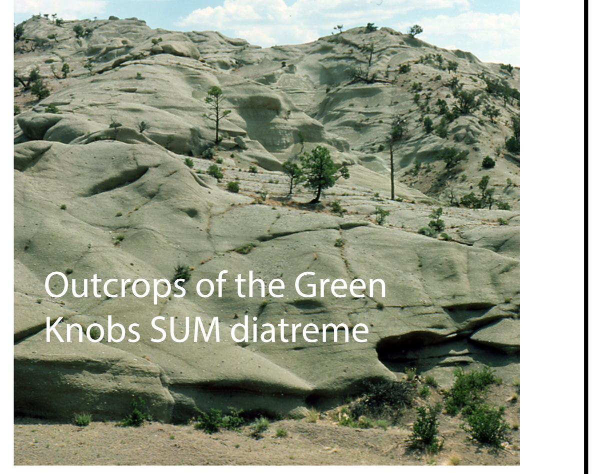
PROCEDURE: ANALYZE TRACE ELEMENTS IN PYROPE, WITH ATTENTION BOTH TO COMPOSITIONAL ZONING AND TO ELEMENTS SUCH AS Nb AND Li

GEOLOGIC CONTEXT

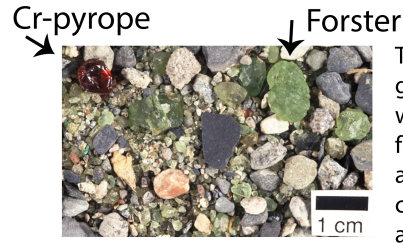
The pyrope grains are from two very different host rocks, each part of the Navajo Volcanic Field (NVF) on the Colorado Plateau, and each emplaced in the crust within the interval 30 to 24 Ma. Deformation associated with low-angle Farallon subduction continued in the area until about 35 Ma (e.g., Copeland et al., 2017)

One host rock is serpentinized ultramafic microbreccia (SUM), an inclusion-rich mix emplaced in diatremes as gas-solid mixes. Discrete fragments of Cr-pyrope grains are common in SUM diatremes, although peridotite inclusions with preserved garnet are extremely rare. The other host rock is minette, a potassic mafic igneous rock. Analyzed samples include 27 discrete pyrope grains from SUM diatremes and garnets in 4 peridotite xenoliths from the minette neck at The Thumb. Many analyses of trace elements in NVF pyrope have been published, including average analyses of some grains analyzed here (e.g., Roden and Shimizu, 2000; Griffin et al., 2004). The new data include additional elements and are the first to document TE zoning in SUM-hosted Cr-pyrope. Data were acquired by LA-ICP-MS.

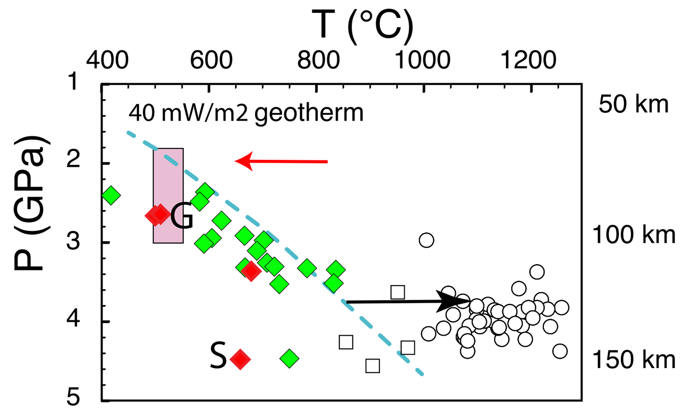




SUM diatremes: Green Knobs, GN ●; Buell Park, BP ■;
Garnet Ridge, GR ●; Red Mesa, RM ♦; Moses Rock, MR ■; Others, △
Minette (T is The Thumb) ○
B&D: possible location of suture between Yavapai and Mazatzal crustal provinces (Selverstone et al., 1999);
lawsonite eclogite and garnetite do not occur in SUM south of B&D



The SUM-hosted garnets are mixed with other rock fragments and are conveniently collected from anthills.



SUM host: Discrete diopside ◆, discrete garnet ■,
typical garnetite G , eclogite ◆ (S - Schulze et al., 2015)
Minette host: The Thumb ○, elsewhere □
T Ni for a Thumb garnet, interior to rim
T Ni for a discrete garnet, interior to edge
T for discrete forsterite, not shown here, are ~ 550°C
Adapted from Smith (2013)

1

Constraints from lawsonite eclogites and garnetites in SUM

Both record recrystallization at ~600°C in the mantle in the presence of hydrous fluids

Both rock types contain inherited Proterozoic zircon*
Both contain zircon formed in range 85 to 60 Ma
Eclogites also have zircons concordant in range 60 to 33 Ma and monazite formed from 28 to 30 Ma (Smith and Griffin, 2005; Usui et al., 2007; Schulze et al., 2015, and references therein)

* Post-meeting addition: The presence of inherited Proterozoic zircon in the eclogites (Smith et al., 2004) is well-supported by Malik et al. (2017) (see added note with references).

Constraints from peridotite inclusions in SUM

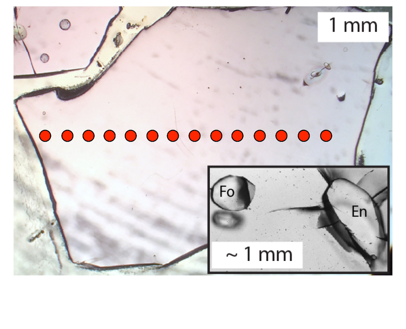
Behr and Smith (2016) described peridotite inclusions from the Green Knobs diatreme that were deformed in the mantle shortly before diatreme emplacement. Mineral assemblages and chemistries constrain deformation to hydrous conditions in the temperature range ~550° to 750°C. None of the inclusions contain garnet.

Marshall et al. (2017) have reported age constraints on peridotite inclusions in SUM diatremes, many from Green Knobs. They found Re depletion ages in the most-depleted inclusions to be in range 2.1 to 1.7 Ga, about the time of accretion and stabilization of the overlying crustal Yavapai and Mazatzal provinces. Clinopyroxene separates from the unmetasomatized peridotite inclusions plot on a ~1.4 Ga isochron, evidence of a major mantle thermal event after crustal accretion. Implications are further discussed by Marshall at this meeting today (Sunday) at 11:35 am in Skagit 2.

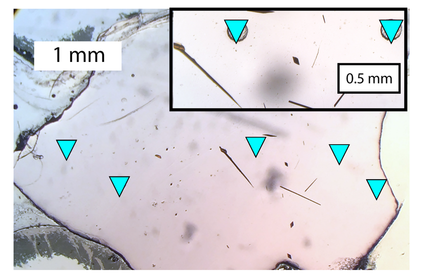
INCLUSION AND P-T CONTEXTS FOR SUM-HOSTED GARNETS

Many of the garnets were chosen for analysis because of the inclusions within them. Olivine and pyroxene are common, as in 3 of the grains shown below. Rutile, crichtonite series minerals, and other oxides rich in Ti and Zr are not uncommon, as in GR1-3 below. Chlorite, magnesite, dolomite, amphibole, Ti-clinohumite, Ba-rich phlogopite, chlorapatite, and spinel are among other inclusion minerals. Temperatures based on electron-probe analyses of inclusion-garnet pairs and of the inclusions themselves (some multi-phase) are mostly in or near the range 500°C to 700°C. Interpretations of recorded pressures have been based on inclusion populations as well as garnet compositions, and most have been in or near the range 1.5 to 3 GPa. Among the discussions of the inclusions and of the inferred P-T histories are those by McGetchin and Silver (1970), Hunter and Smith (1981), Wang et al. (1999), Griffin et al. (2004), and Sakamaki et al. (2016).

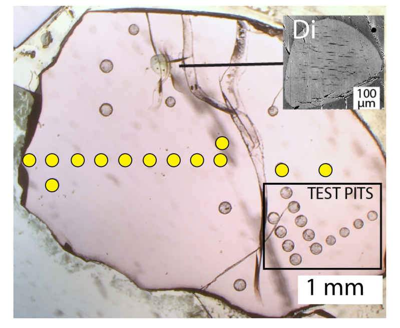
The four grains shown below were chosen to illustrate inclusion-host pairs and a variety of trace-element systematics. In several cases, the inclusions are no longer present due to re-polishing. The calculated temperatures for inclusion-host pairs are based on compositions close to mutual contacts. In contrast, the Ni-in-garnet temperatures are based on the lowest Ni values in the fragments, using the calibration of Ryan et al. (1996).



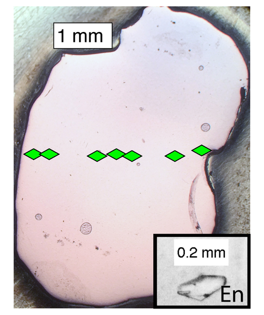
GR1-1 Enstatite and forsterite inclusions
En-garnet T 610°C at 2.6 GPa, Fo-gar T 560°C at 2.6 GPa, Ni-in-garnet T 865°C



GR1-3 Forsterite, rutile, and ? inclusions
Fo-garnet T at 3 GPa: 504°C
Ni-in-garnet T 690°C



GR1-10 Diopside and forsterite inclusions.
Di-garnet T, P: 680°C, 2.6 GPa.
Fo-garnet T 600°C. Ni-in-garnet T 650°C



RM1-102 Enstatite inclusion
En-garnet T, P: 580°C, 2.3 GPa
Ni-in-garnet T 722°C

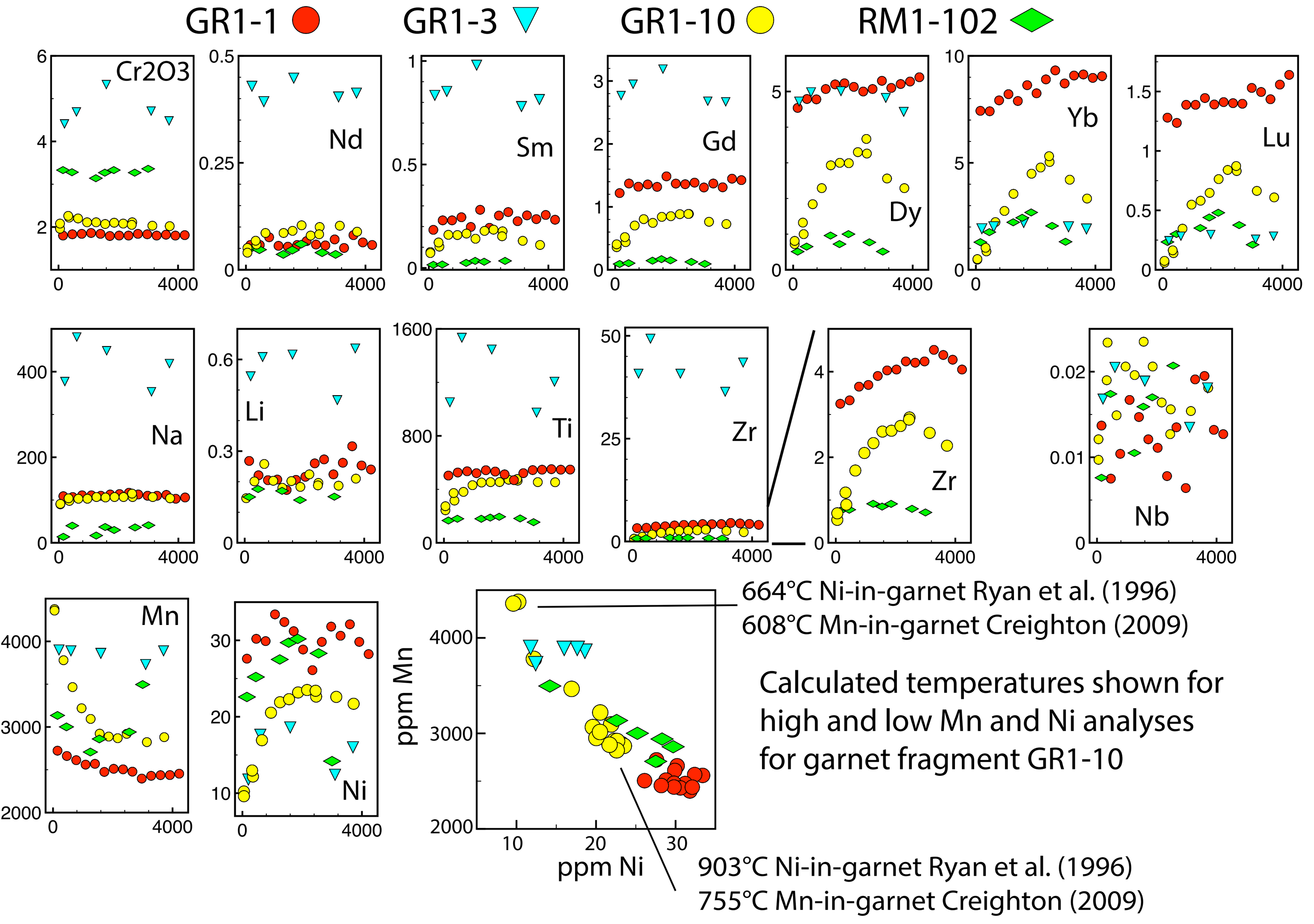
PATTERNS OF INHOMOGENEITIES IN SUM-HOSTED GARNETS

2

Typical patterns are illustrated by traverse data for selected elements in the four grains above. All element scales are ppm, except for Cr2O3 (wt %).

Sample GR1-10 shows the best-developed zonation for many elements, Cr being an interesting exception. These zonation trends are typical of many other grains. In particular, Ti and Zr and REE are commonly lower at fragment edges. No evidence of metasomatism was recognized in the zonation patterns, although some garnets have "sinusoidal" REE patterns (Roden and Shimizu, 2000) that may record introduction of LREE. Mn is the element most commonly enriched at margins of the garnets.

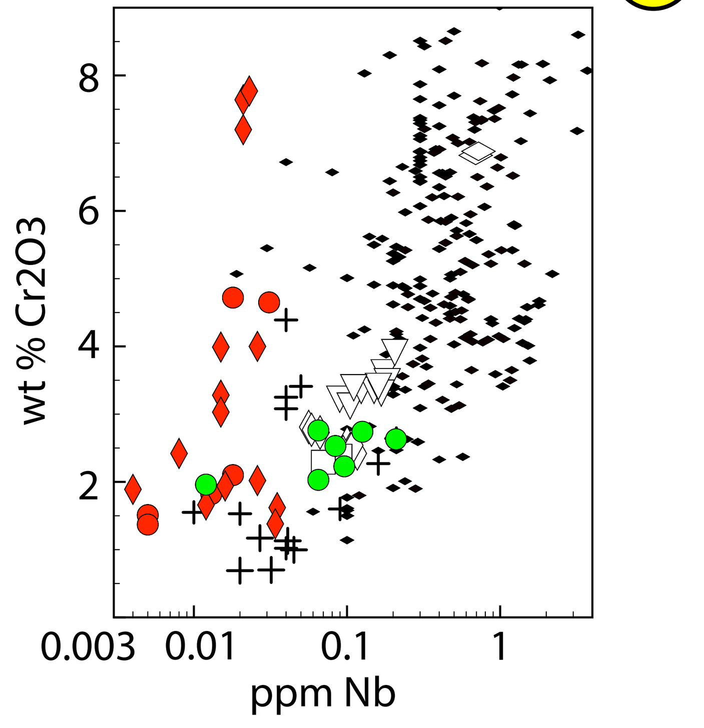
Sample GR1-3 is high in Cr2O3 and low in Lu, evidence of magmatic depletion of the garnet source peridotite: that garnet is also relatively enriched in LREE, Na, Li, Zr, and Ti, but as is typical, those elements are not relatively high at grain edges. Irregularities in the Ti and Zr profiles such as those in grain GR1-3 are representative of those in other grains with inclusions of rutile and unidentified phases (probable Zr-Ti-rich oxides).



DISTINCTIVE LOW Nb

Nb in garnets from northern SUM diatremes is unusually low for mantle pyrope but like that in garnets of many orogenic peridotites. Most garnets hosted by southern SUM diatremes and all 4 from minette have typical mantle values. (Nb analyses were reproducible in multiple sessions; typical detection limits were about 0.004 ppm.)

3

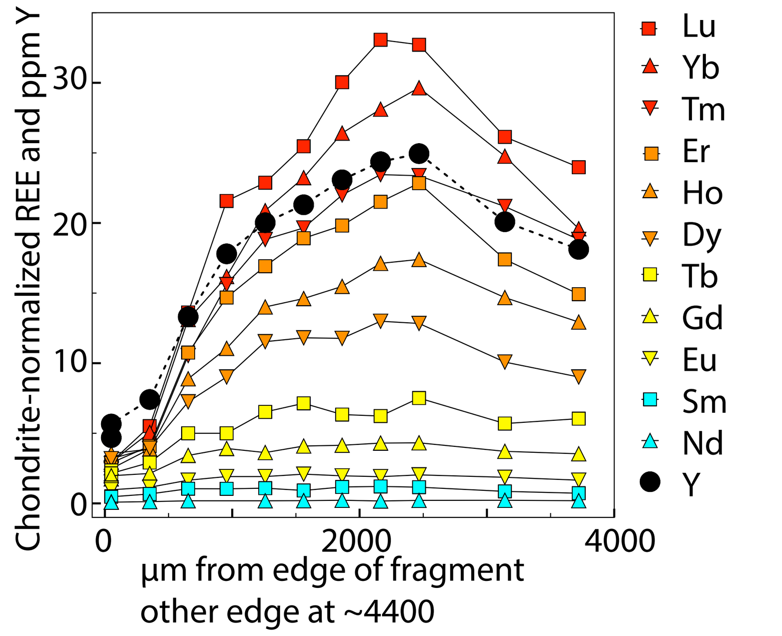


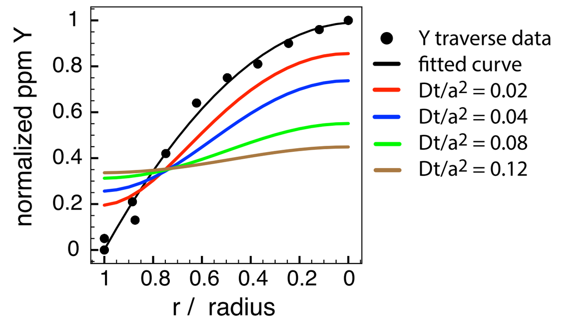
Kimberlite - hosted ◆ Orogenic peridotite +
NVF minette-hosted (individual analyses, 4 rocks) □ ▽ ◇ ◇
Northern SUM diatremes (average analyses, 20 grains) ● ◆
Southern SUM diatremes (average analyses, 7 grains) ●
Kimberlite and Orogenic sources by request

T - t CONSTRAINTS FROM REE PROFILES

Typically HREE are relatively high in interiors of SUM-hosted Cr-pyrope fragments. Grain GR1-10 provides an extreme example. The zonation probably formed during garnet growth and may be little changed. Regardless, the preservation of the zoning constrains possible temperature histories.

4





The graph on the left shows normalized Y data plotted against normalized radius and 4 curves illustrating how the Y concentrations would change by diffiusion for values of Dt/a^2. Below are shown values of time (t in m.y.) for a radius of 2400 µm and D (tracer diffusion coeficient for Y calculated from Carlson, 2012). The model assumes radial diffusion in a sphere with zero flux at the surface. Note that at T at and above 900°C, diffusion would drastically change the Y profile in less than 350 m.y. but would make only a very small change at 800°C.

Dt/a^2	1000°C	900°C	800°C
0.02	5.9	88	2200 m.y.
0.04	12	180	4400 m.y
0.08	23	350 m.y.	
0.12 he	35	530 m.y.	

SUMMARY AND CONCLUSIONS

The garnet compositions span a range of Cr2O3 from 1 to 8 wt% (3), the more Cr-rich compositions being characteristic of depleted continental lithosphere -- one reason that origin from the Farallon slab or asthenosphere is improbable. The distinctive Nb contents of SUM garnets in the northern diatremes (3) are consistent with a history related to that of the lawsonite eclogites and garnetites, rock types absent from the southern localities (1). Selverstone et al. (1999) suggested that the eclogites may record NW-dipping subduction when the younger province was accreted at about 1.7 Ga. However, Marshall et al. (2017) have documented a major heating event in the mantle below the NVF at about 1.4 Ga (1), and the eclogites and garnetites record recrystallization in cool hydrous environments.

The SUM-hosted garnets record growth at low to moderate mantle temperatures, followed by cooling. The apparent growth zoning of REE in garnet GR1-10 and in other grains indicates little or no time at high mantle temperatures (4), consistent with the conclusion of Wang et al. (1999) that the garnets grew in the range from about 600° to 800°C. An additional constraint is available based on REE measured in the clinopyroxene and host garnet GR1-10 by Roden and Shimizu (2000): their REE data yield 880°C with the thermometer of Pickles et al. (2016). Despite the diverse garnet compositions, all record pre-eruption cooling to in or near the range 500° to 700°C, consistent with temperatures of the hydrous environments for recrystallization of the eclogites and garnetites (1). Unless the back-arc Colorado Plateau lithosphere was cold and wet not long before low-angle Farallon subduction began, it is probable that the eclogites, garnetites, and Nb-poor garnets represent fore-arc mantle translated from the SW above the low-angle Farallon slab, consistent with an idea of Helmstaedt and Schulze (1991).

Interpretations of the mantle history of the NVF are difficult partly because recorded temperatures in SUM-hosted garnets are so low and partly because of temperature pulses, metasomatism, and deformation that affected only parts of the inclusion population. For instance, temperatures in 5 cool SUM-hosted garnets and a hot minette-hosted peridotite evolved from similar intermediate values (6). Metasomatic enrichment of elements such as Ti and Zr and LREE is documented by some but not all SUM-hosted garnets although it is not recorded by compositional zoning (2, 5). Antigorite and other hydrous minerals formed in the Plateau mantle before deformation (1), but no record of that late hydration was recognized in the garnets: chlorite and other hydrous inclusions in SUM garnets record earlier events.

Li - Na - Ti CORRELATIONS

Li and Na are well-correlated with Ti in SUM-hosted garnets and in garnets of minette-hosted peridotite, although correlations are not the same. On an atom basis, Ti > Na + Li, so the correlation is not an obvious result of a coupled substitution for charge balance.

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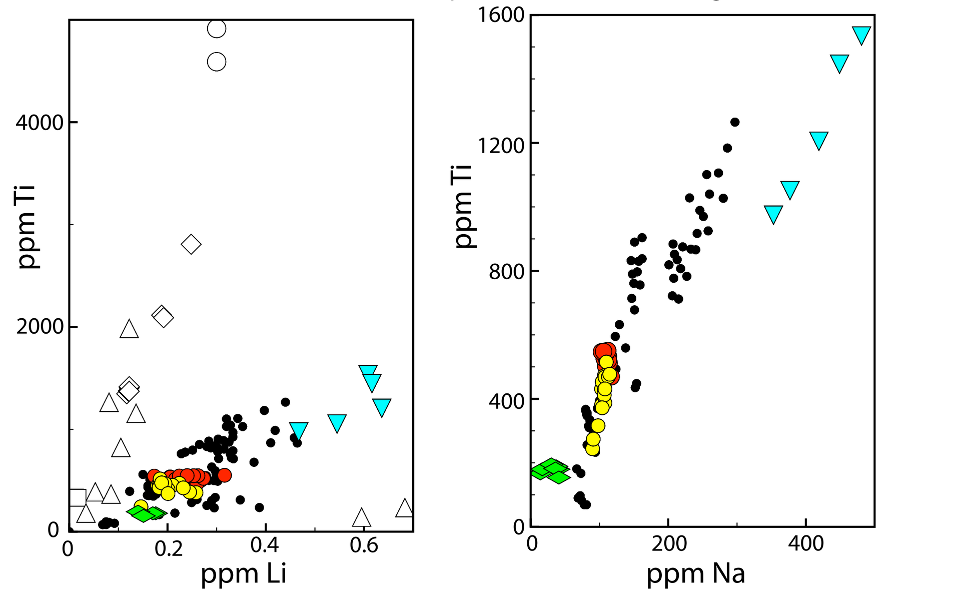

SUM-hosted garnets: GR1-1 ●; GR1-3 ▽; GR1-10 ●; RM1-102 ◆; Other ●
Minette-hosted garnets in peridotite (4 xenoliths): □ △ ◇ ○

A HOT MINETTE-HOSTED GARNET PERIDOTITE AND 5 COLD SUM-HOSTED GARNETS RECORD OVERLAPPING Ni-in-garnet TEMPERATURES

Smith et al. (1991) found that although thermometry for pyroxenes in peridotite A082 records 1080°C, garnets in the rock are zoned to Ni-poor interiors (PIXE analyses): the rock was heated and metasomatized shortly before minette emplacement. One such garnet was re-analyzed by LA-ICP-MS for comparison with SUM-hosted garnets. In parts of five SUM-hosted grains, Ni contents are higher than lowest values in the minette-hosted garnet core.

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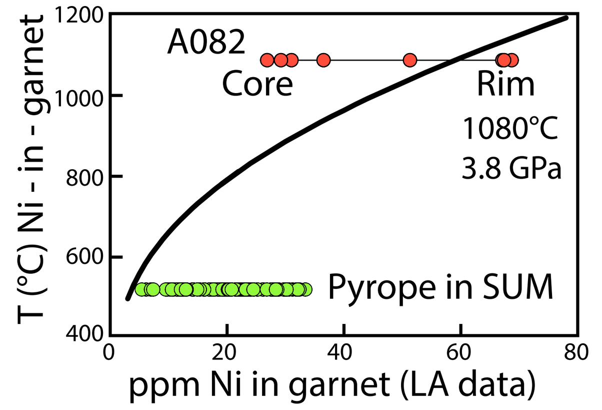
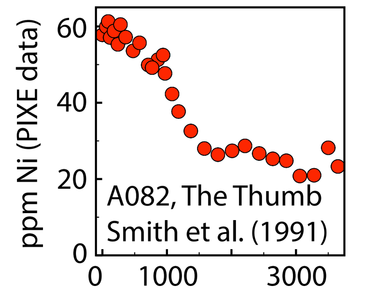
The curved line in the figure below was calculated with the Ni-in-garnet thermometer of Ryan et al. (1996)





Above are shown one of the PIXE (proton-induced x-ray emission) traverses. The new LA-ICP-MS data are in good but not perfect agreement.

Acknowledgements:
The Navajo Nation is thanked for permission to collect these samples. W. C. Hunter collected and sectioned most of these SUM garnets as part of his PhD research. S. N. Ehrenberg provided xenoliths from The Thumb. Nate Miller ably acquired the LA-ICP-MS data.

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Behr and Smith (2016) Geochem. Geophys. Geosys. 17, 2643-2660; Carlson (2012) Amer. Mineral. 97, 1598-1618; Copeland et al. (2017) Geology 45, 223-226; Creighton (2009) Lithos 112S, 177-182; Griffin et al. (2004) Lithos 77, 873-922; Helmstaedt and Schulze (1991) J. Geophys. Res. 96, 13225-13235; Hunter and Smith (1981) Contrib. Mineral. Petrol. 76, 312-320; Marshall et al. (2017) Geology 45, 519-522; McGetchin and Silver (1970) Amer. Mineral. 55, 1738-1771; Pickles et al. (2016) Chem. Geol. 424, 17-31; Roden and Shimizu (2000) Chemical Geology 165, 283-305; Ryan et al. (1996) J. Geophys. Res. 101, 5611-5625; Sakamaki et al. (2016) Progress Earth and Planet. Sci. 3: 20; Schulze et al. (2015) Geology 43, 727-730; Selverstone et al. (1999) Geol. Soc. Amer. Bull. 111, 590-606; Smith et al. (1991) Contrib. Mineral. Petrol. 107, 60-79; Smith and Griffin (2005) J. Petrol. 46, 1901-1924; Smith (2013) Geochem. Geophys. Geosys. 14; Usui et al. (2007) Chem. Geol. 239, 336-351; Wang et al. (1999) Contr. Mineral. Petrol. 135, 164-178;

*Post-meeting note and additions to cited references:

Although Smith et al. (2004) documented the presence of Proterozoic zircon in the Navajo eclogites, those old ages have been challenged. Malik et al. (2017) have confirmed the inheritance of Proterozoic zircon and provided more information about other zircon with concordant or nearly concordant ages in the range 80 to 27 Ma.

Malik, L., Schulze, D. J., Davis, D. W., and Helmstaedt, H. H., 2017, Age and Origin of Eclogite Xenoliths from Navajo Diatremes on the Colorado Plateau. Fall 2017 AGU V13D-0409;
Smith et al. (2004) Geochem. Geophys. Geosys. 5, doi:1029/2003GC000675