

High-Mg andesites from Mount Baker and Glacier Peak, Washington: Understanding slab, mantle, and crustal contributions to magma petrogenesis in the northern Cascade arc

May Sas¹, Susan M. DeBari¹, Michael A. Clynne², Brian G. Rusk¹

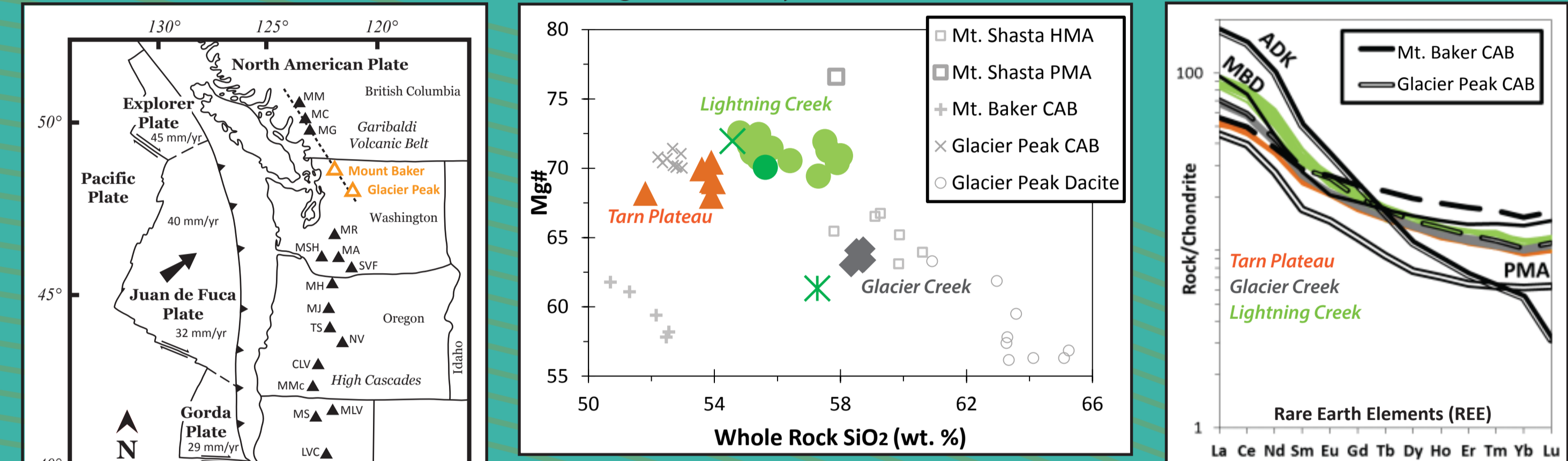
¹ Department of Geology, Western Washington University, Bellingham, WA 98225, USA (*correspondence: msas.geo@gmail.com)
² U.S. Geological Survey, Volcano Science Center, Menlo Park, CA 94025, USA



Introduction

High-Mg andesites and basaltic andesites (HMA and HMBA) are rocks that have an unusually high Mg# (molar Mg/(Mg+Fe)) relative to their SiO₂, as well as Ni and Cr enrichment. They also exhibit a steep Rare Earth Element (REE) pattern, generally with notable depletion in heavy REE. Proposals for their origin vary and provide numerous testable hypotheses, all of which include an important role for garnet since this steep REE pattern is acquired through separation of melt from garnet. The debate centers on where the garnet came from (subducting slab? mantle? basaltic crystallization? thick lower crust?) and how the high-Mg signature is acquired.

To better understand the generation of these magmas in the northern Cascade Arc, this study focuses on mineral geochemical analyses of HMA and HMBA from the two northernmost active volcanoes in Washington. These flows are **Tarn Plateau** and **Glacier Peak** from Mount Baker and **Lightning Creek** from Glacier Peak, which have been previously studied in a broader context and have whole rock geochemistry data available.



Map of Cascade volcanic arc and Pacific Northwest subduction zone. Dashed line represents Garibaldi Volcanic Belt segmentation scheme (7). Subduction rates are from (2). Abbreviations represent major volcanic centers (north to south): MM, Mount Meager; MC, Mount Cayley; MG, Mount Garibaldi; MR, Mount Rainier; MA, Mount Adams; MS, Mount St. Helens; SVS, Simcoe Volcano; FLD, Mt. Hood; Mt. Jefferson; TS, Three Sisters; NW, Newberry Volcano; CV, Crater Lake Volcano; MMC, Mt. McLoughlin; MLV, Medicine Lake Volcano; MS, Mount Shasta; LVC, Lassen Volcano Center. Modified from (2).
 Whole rock* Mg# (molar Mg/(Mg+Fe))*100, with Fe* calculated as 0.85 versus SiO₂ wt. %, HMA: high-Mg andesite, PMA: primitive magnesian andesite, CAB: calcalkaline basalt. Mount Shasta data from (5, 6), Mount Baker data from (10), Lake Shanon, Glacier Peak data from (14), Indian Pass and Glacier Peak dacite.
 Chondrite-normalized whole rock* rare earth element (REE) concentrations. Chondrite REE abundances from (13). ADK: low SiO₂ adakite (8); PMA: Mount Shasta primitive magnesian andesite (5); MB2: Mount Baker dacite (4; Mazama Lake); CAB: calcalkaline basalt; Mount Baker CAB from (10), Lake Shanon, Glacier Peak CAB from (14), Indian Pass.

Petrography

Mineral populations and textures in all three lavas indicate open system mechanisms such as mixing between basaltic and andesitic magmas. These include multiple populations of clinopyroxene and plagioclase, resorption textures in olivine and orthopyroxene, and recrystallization and reverse zoning in clinopyroxene.

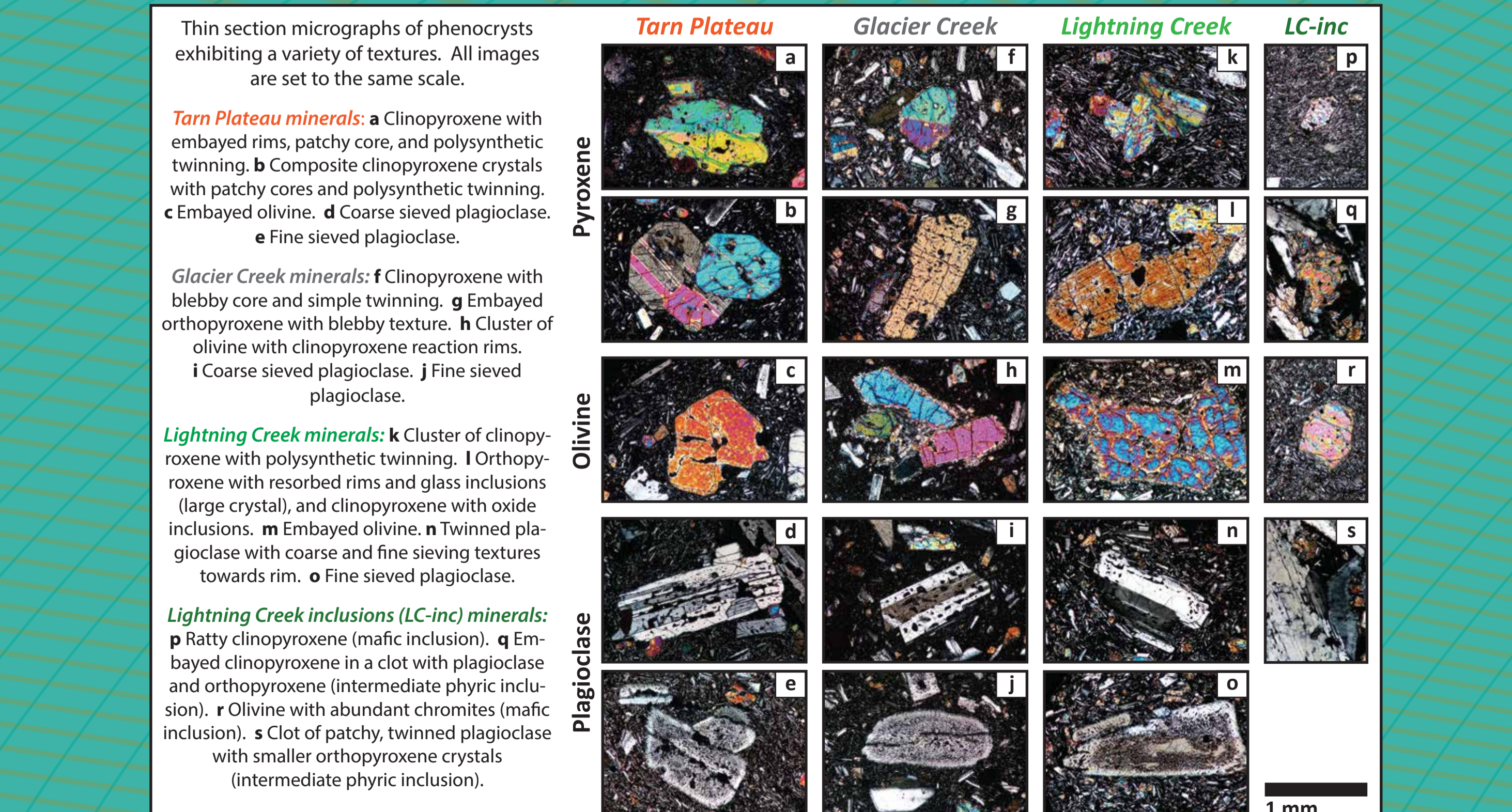
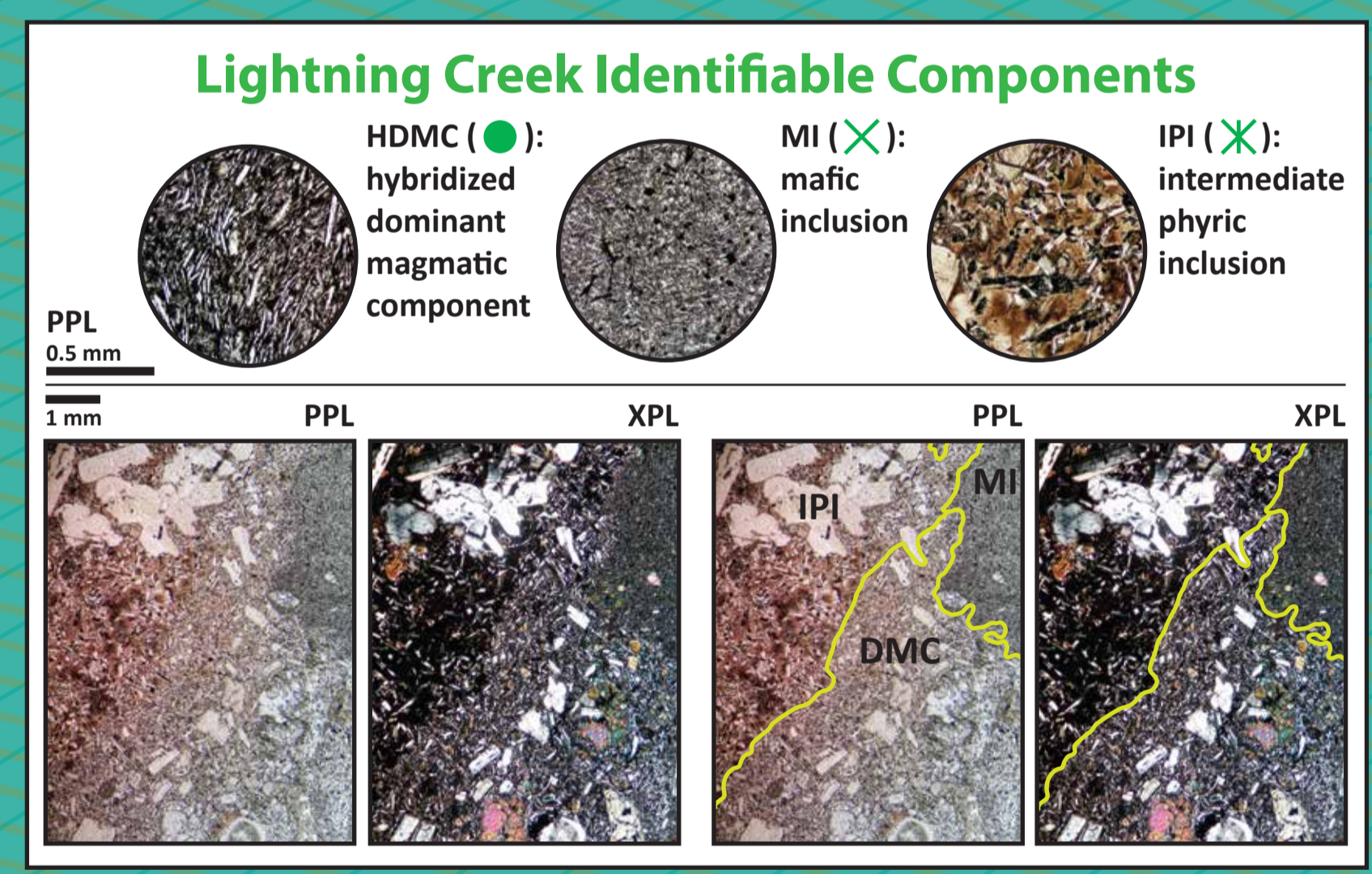
Mount Baker

Tarn Plateau Basaltic Andesite
 (cpx>plag>olvn>opx)
 Highly primitive, hybridized

Glacier Peak Andesite
 (plag>cpx>opx>olvn)
 More differentiated, hybridized

Glacier Peak

Lightning Creek Basaltic-Andesite
 (plag>cpx>olvn>opx)
 Incredibly complex, partially hybridized
 Three identifiable magmatic components



Mineral Geochemistry

Mineral major and minor element data was collected using a JEOL 733 Superprobe electron microprobe (EMP) at the University of Washington. Clinopyroxene trace element data collected using an Agilent 7500C Quadrupole inductively-coupled plasma-mass spectrometer (ICP-MS) equipped with a NewWave UP213nm laser (laser ablation-ICP-MS), located at Western Washington University.

Olivine: major elements and Ni

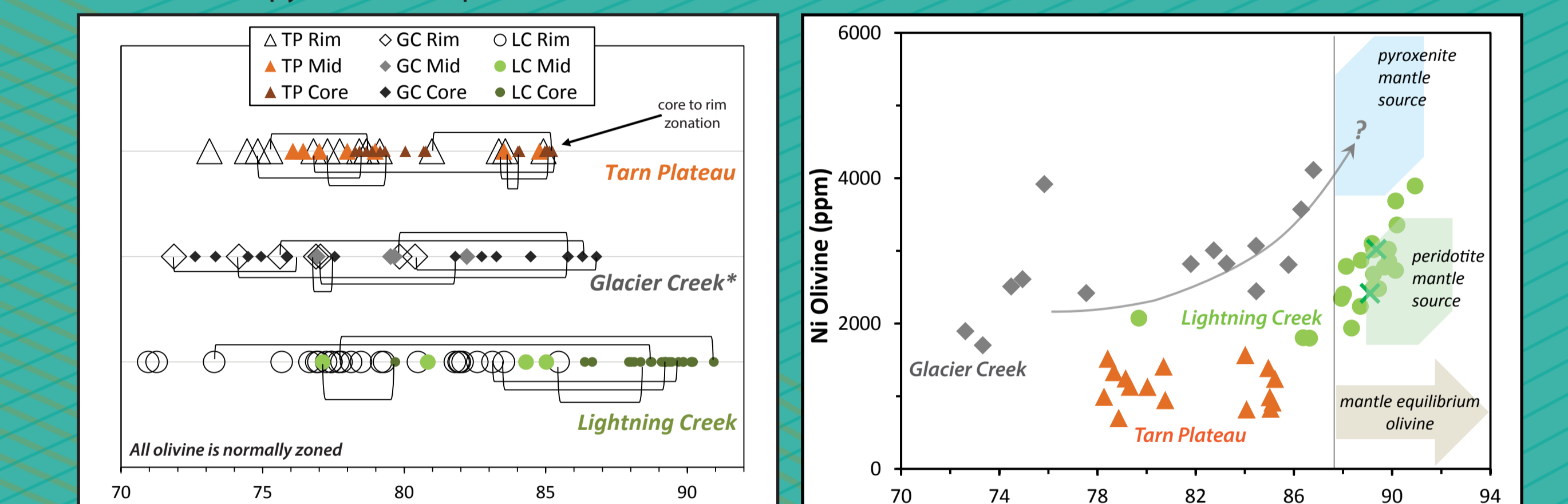
Fo contents ((Mg/(Mg+Fe))*100), Ni contents, and oxide inclusions (see Cr-spinel) provide information regarding the olivine's parental magmas, and the mantle sources their parental magmas were derived from.
 • Higher Fo and Ni contents in phenocrysts indicate that their parental magmas were in equilibrium with mantle olivine, and can be associated with a specific mantle source (e.g. peridotite, pyroxenite).

Previous work:

Straub et al. (2008, 2011) proposed that HMA with high La/Yb in the Mexican Volcanic Belt are generated by melting of mantle that has been metasomatized to pyroxenite through interaction with silicic slab melt. The authors used high-Ni olivines as supportive evidence, as Ni is much more compatible in olivine than pyroxene.

This work: olivine parental magma sources

• **Lightning Creek** data suggest olivine crystallization from a magma that is derived from a peridotite mantle source.
 • **Tarn Plateau** olivine data indicate a fractionated basaltic andesite or andesite parent magma. The parent magma fractionated from a peridotite-derived basalt.
 • **Glacier Peak** olivine is xenocrystic (highly reacted and not in equilibrium with host rock), and data are inconclusive. Derivation must be from a more primitive end member that came either from pyroxenite or peridotite mantle source.



Fo contents in analyzed olivine from all three flows. Fo = molar (Mg/(Mg+Fe))*100. TP: Tarn Plateau, GC: Glacier Peak, LC: Lightning Creek (dominant magmatic component only). Dashed brackets illustrate core-to-rim zonation in phenocrysts (all normal). *Glacier Peak olivine has a single population. Low Fo olivine core analyses seen above are associated with more reacted olivine crystals, which are correlated with samples collected further away from the speculated vent (see image above).
 Olivine core Fo versus Ni contents (ppm). Pyroxenite and peridotite mantle source fields, and mantle equilibrium boundary line, are from (11). Tarn Plateau olivine is not in equilibrium with a mantle source, while Lightning Creek olivine is in equilibrium with a peridotite mantle. Glacier Peak olivine shows a similar trend (dashed line) to olivine found in high-Mg andesites from the Mexican Volcanic Belt (11 and 12), but no mantle equilibrium olivine has been preserved. LC: Lightning Creek, MI: mafic inclusion.

Synthetic: major and trace elements

Uses for clinopyroxene (cpx):

• Mg#, [Mg/(Mg+Fe)]*100, of cpx can provide information about how primitive the host magma is, and non-gradual changes or reversals in Mg# can serve as evidence for magma mixing.
 • Most trace elements are more compatible in cpx than olivine, and can be correlated with Mg# to provide insight about the host magma's trace element chemistry and source (e.g. mantle, crust, slab).

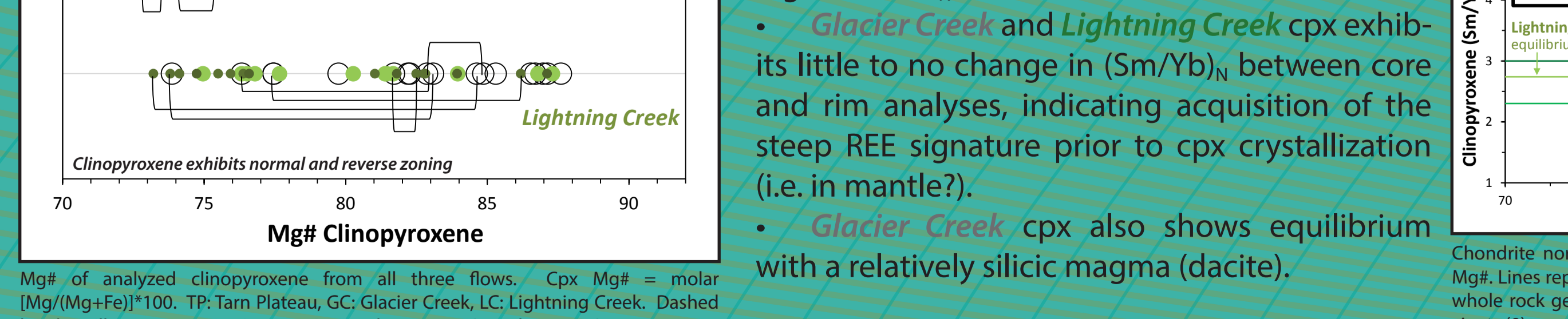
Previous work:

Yogodzinski and Kelemen (1998) asserted that silicic, high La/Yb slab melts become more Mg-rich as they rise through, and interact with, the overlying mantle wedge. In their model, when these hybrid slab melts reach the base of the crust, they mix with clinopyroxene-bearing, differentiated, mantle-derived basalts. The resultant cpx will have positive correlation between high Mg# and high Sr and Nd/Yb (or (Sm/Yb)_N). Negative correlation will occur if primitive basalts mixed with silicic crustal melts.

This work: trace element concentrations in cpx and REE signatures of cpx parental magmas
 (Sm/Yb)_N is a light/heavy REE ratio that represents the steepness of a REE signature; the higher the number, the steeper the signature. Calculated cpx (Sm/Yb)_N were correlated with cpx Mg#, and compared to (Sm/Yb)_N of an equilibrium cpx. An **equilibrium cpx** is in geochemical equilibrium with its host magma (see plots on right). In addition, cpx equilibrium liquids were calculated. **Cpx equilibrium liquids** use the REE concentrations of an analyzed cpx to calculate the REE composition of the liquid it was in equilibrium with. This is done using cpx-liquid partition coefficients (K_ds).

Tarn Plateau has 3 cpx populations that show evidence for mixing between mantle-derived, differentiated basaltic andesite (cpx cores with low Mg# and low (Sm/Yb)_N) and a hydrous slab component that interacted with the overlying mantle (cpx cores with high Mg# and high (Sm/Yb)_N).

• **Glacier Peak and Lightning Creek** cpx exhibits little to no change in (Sm/Yb)_N between core and rim analyses, indicating acquisition of the steep REE signature prior to cpx crystallization (i.e. in mantle).
 • **Glacier Peak** cpx also shows equilibrium with a relatively silicic magma (dacite).



Mg# of analyzed clinopyroxene from all three flows. Cpx Mg# = molar [Mg/(Mg+Fe)]*100. TP: Tarn Plateau, GC: Glacier Peak, LC: Lightning Creek. Dashed brackets illustrate core-to-rim zonation in phenocrysts (mostly reverse).

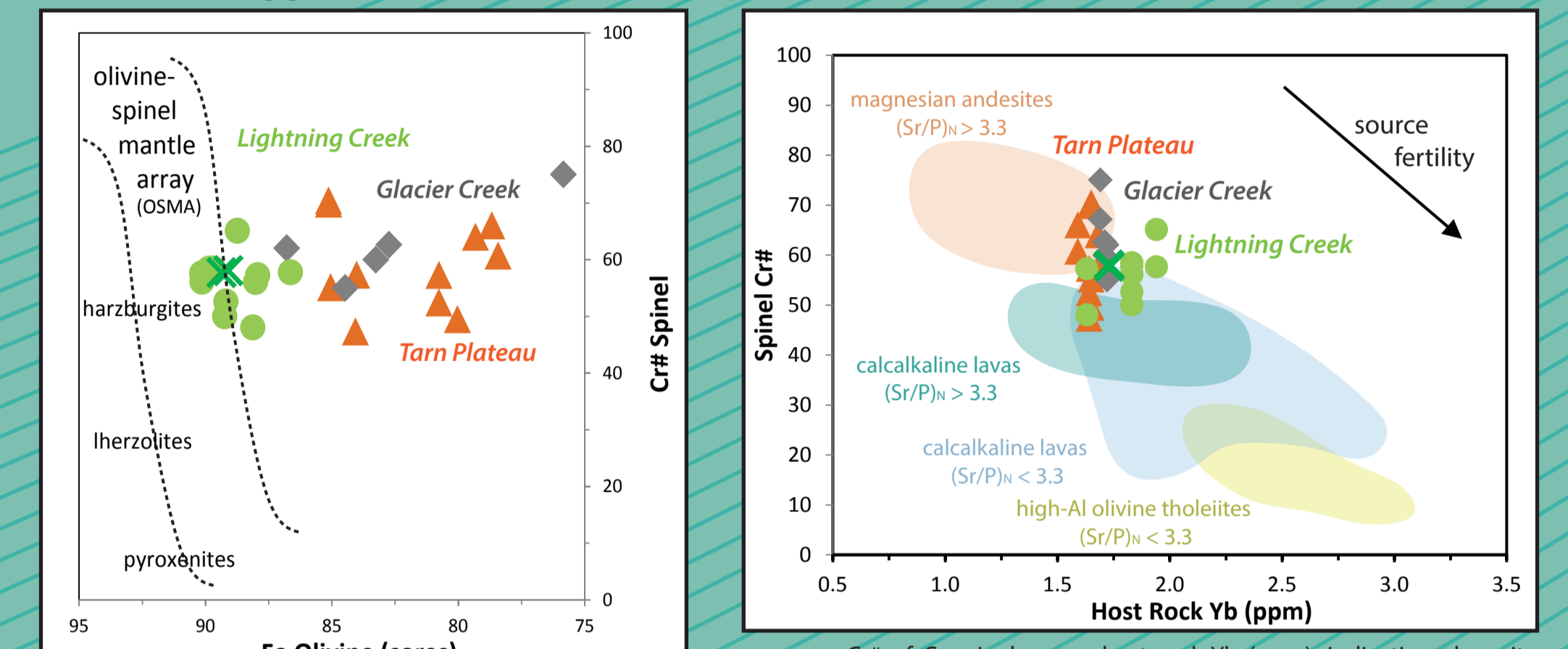
Cr-Spinel (Chromite): major elements

Uses for chromite and previous work:

• Cr# (molar Cr/(Cr+Al))*100 in Cr-spinel has been correlated with the source fertility of the chromite's source peridotite in the south Cascades (2 and 3).
 • High spinel Cr# and high host olivine Fo imply a refractory mantle source.

This work: chromite parental magma sources

The Cr-spinel from **Tarn Plateau**, **Glacier Peak**, and **Lightning Creek** have Cr# between 47-70, and suggest derivation from a depleted mantle source.

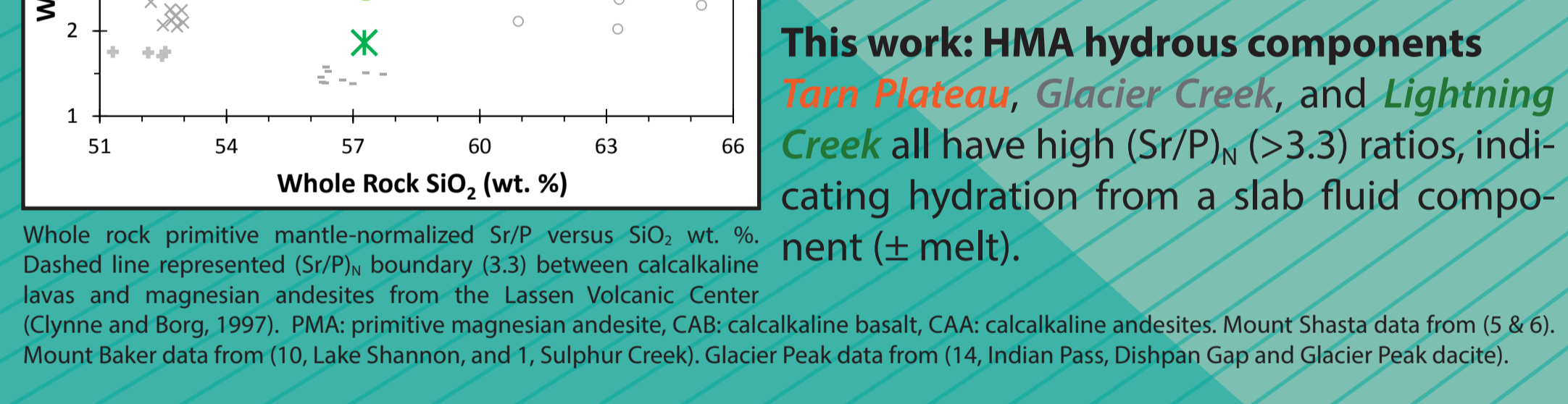


Cr# of chromites versus their host olivine Fo contents (D and S). OSMA from (90). To establish source fertility of these chromites, the Cr# of each chromite crystal needs to be correlated with Fo contents of its respective host olivine. Also, the host olivine must be in equilibrium with the mantle (>67 Mg#). Otherwise, Cr# may not be representative of equilibrium crystallization conditions. Only Lightning Creek olivine exhibits equilibrium with the mantle.

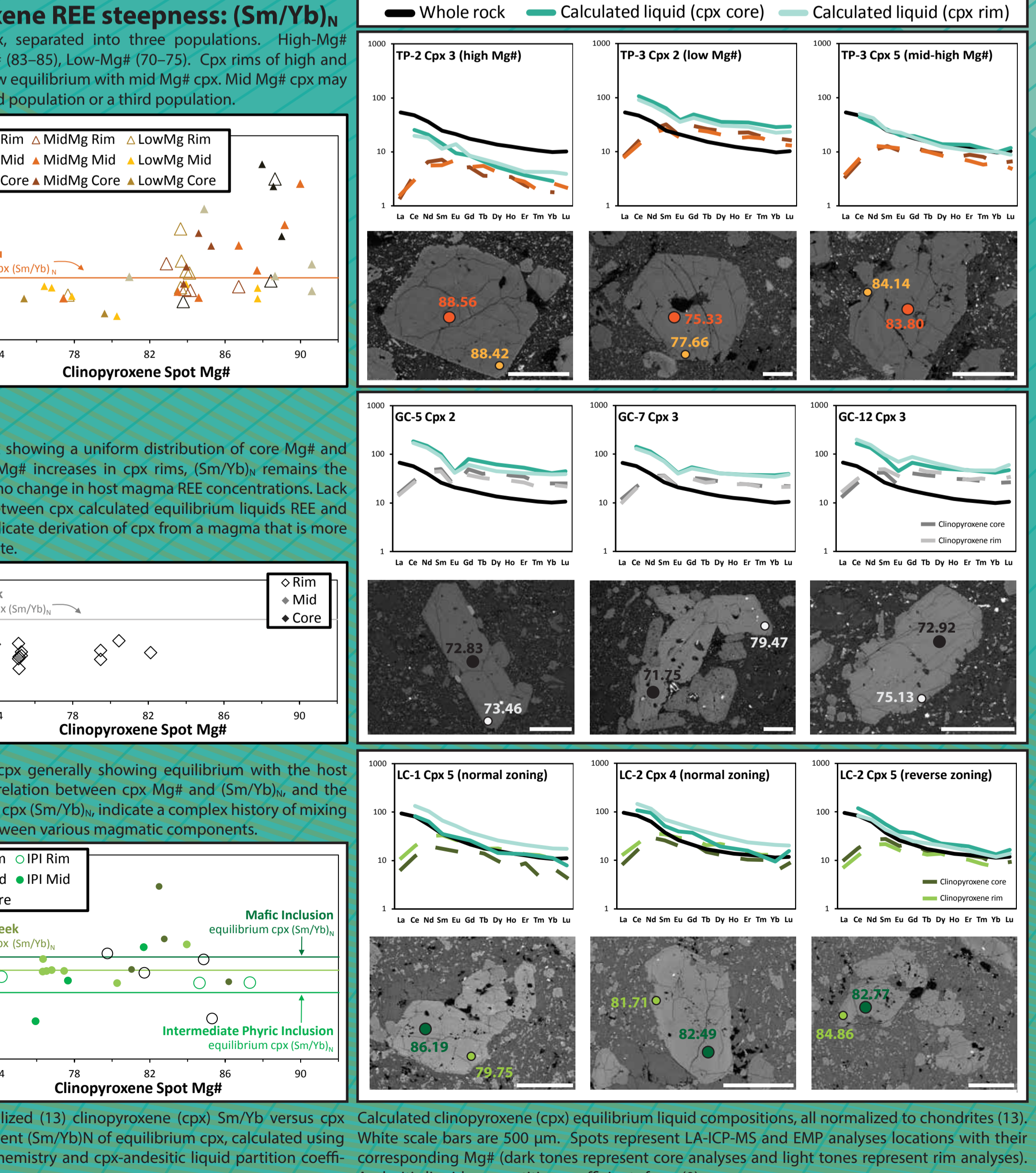
Subduction Fluid Contribution, (Sr/P)_N

Uses for (Sr/P)_N:
 • Since Sr is relatively fluid-mobile and P is fluid-immobile, this ratio makes it possible to assess the relative amount of fluid contribution from a subduction component.
 • Specifically, using primitive mantle-normalized whole rock Sr/P values, (Sr/P)_N

This work: HMA hydrous components
Tarn Plateau, **Glacier Peak**, and **Lightning Creek** all have high (Sr/P)_N (>3.3) ratios, indicating hydration from a slab fluid component (± melt).



Equilibrium liquids calculated from clinopyroxene REE



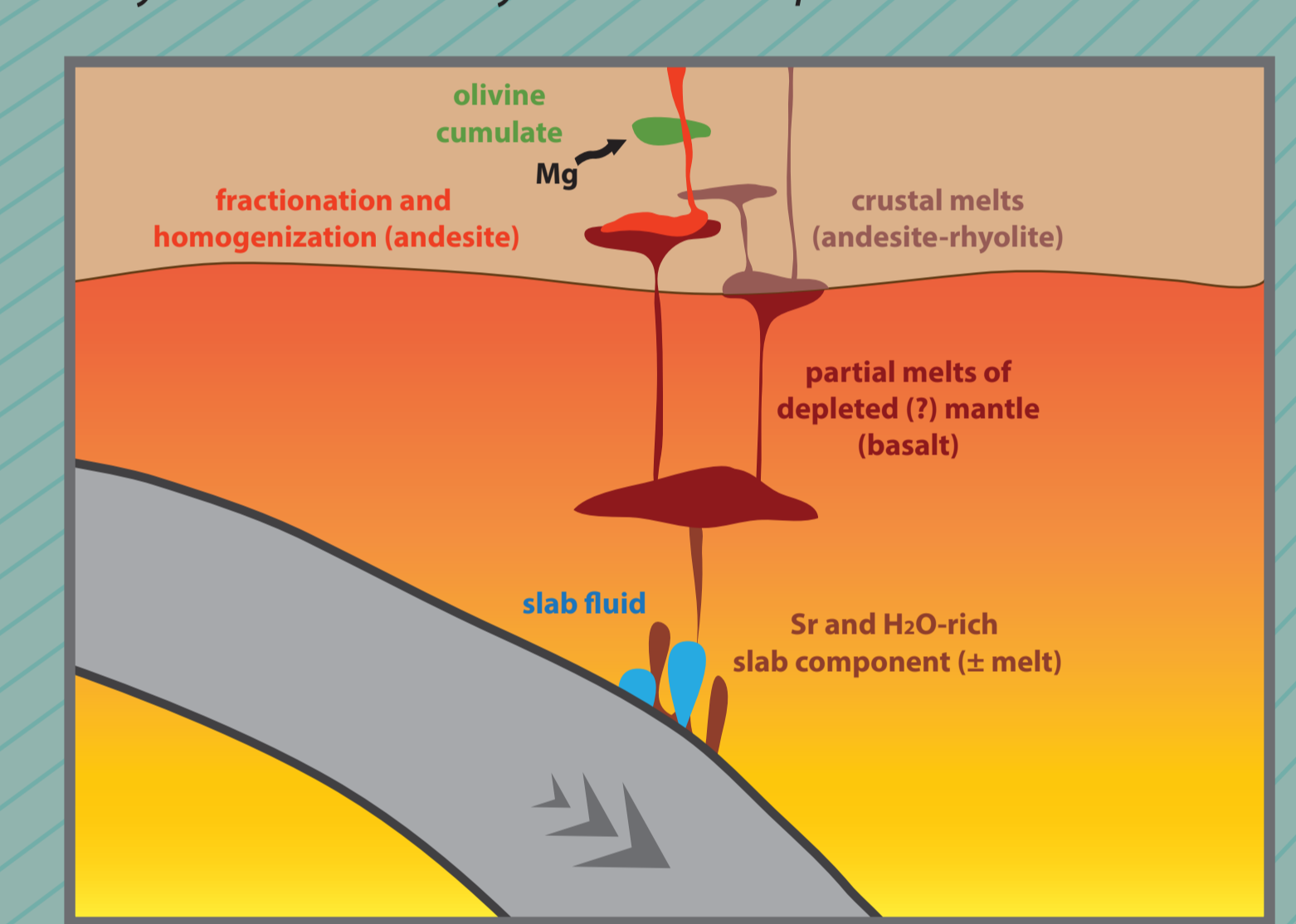
Chondrite-normalized (13) clinopyroxene (cpx) (Sm/Yb)_N versus calculated clinopyroxene (cpx) equilibrium liquid compositions, all normalized to chondrites (13). White scale bars are 500 ppm. Spots represent LA-ICP-MS and EMP analyses localized to their corresponding Mg# (dark tones represent core analyses and light tones represent rim analyses). Andesite-liquid-cpx partition coefficients from (9).

Petrogenesis of Magmatic Components

Tarn Plateau Components:

- Basaltic andesite (differentiated of mantle basalt)
- Clinopyroxene cores: low Mg#, low (Sm/Yb)_N rims: high Mg#, high (Sm/Yb)_N
- Olivine: low Fo, low Ni
- Chromites: high Cr# (hosted in olivine)
- Plagioclase: high An, finely sieved, overgrowth rims
- Dacite (slab melt that interacted with mantle)
- Clinopyroxene cores: high Mg#, high (Sm/Yb)_N rims: mid Mg#, mid (Sm/Yb)_N
- Hybrid (mixed andesite and dacite)*
- Clinopyroxene cores: mid Mg#, mid (Sm/Yb)_N rims: mid Mg#, mid (Sm/Yb)_N
- Olivine: mid Fo, low Ni
- Chromites: high Cr# (hosted in olivine)

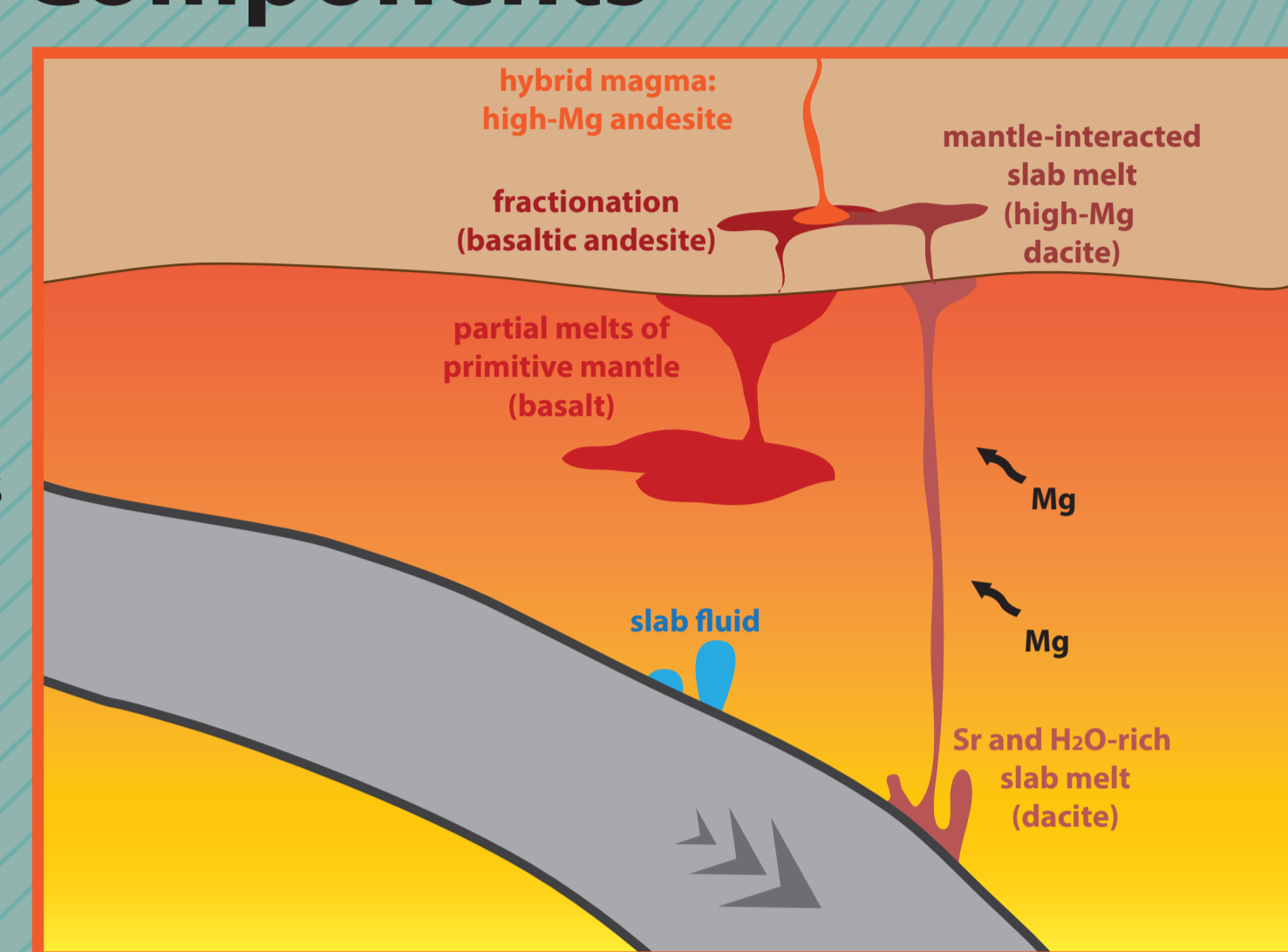
*Potentially a third (basaltic) component that geochemically resembles the hybridized component



Lightning Creek Components:

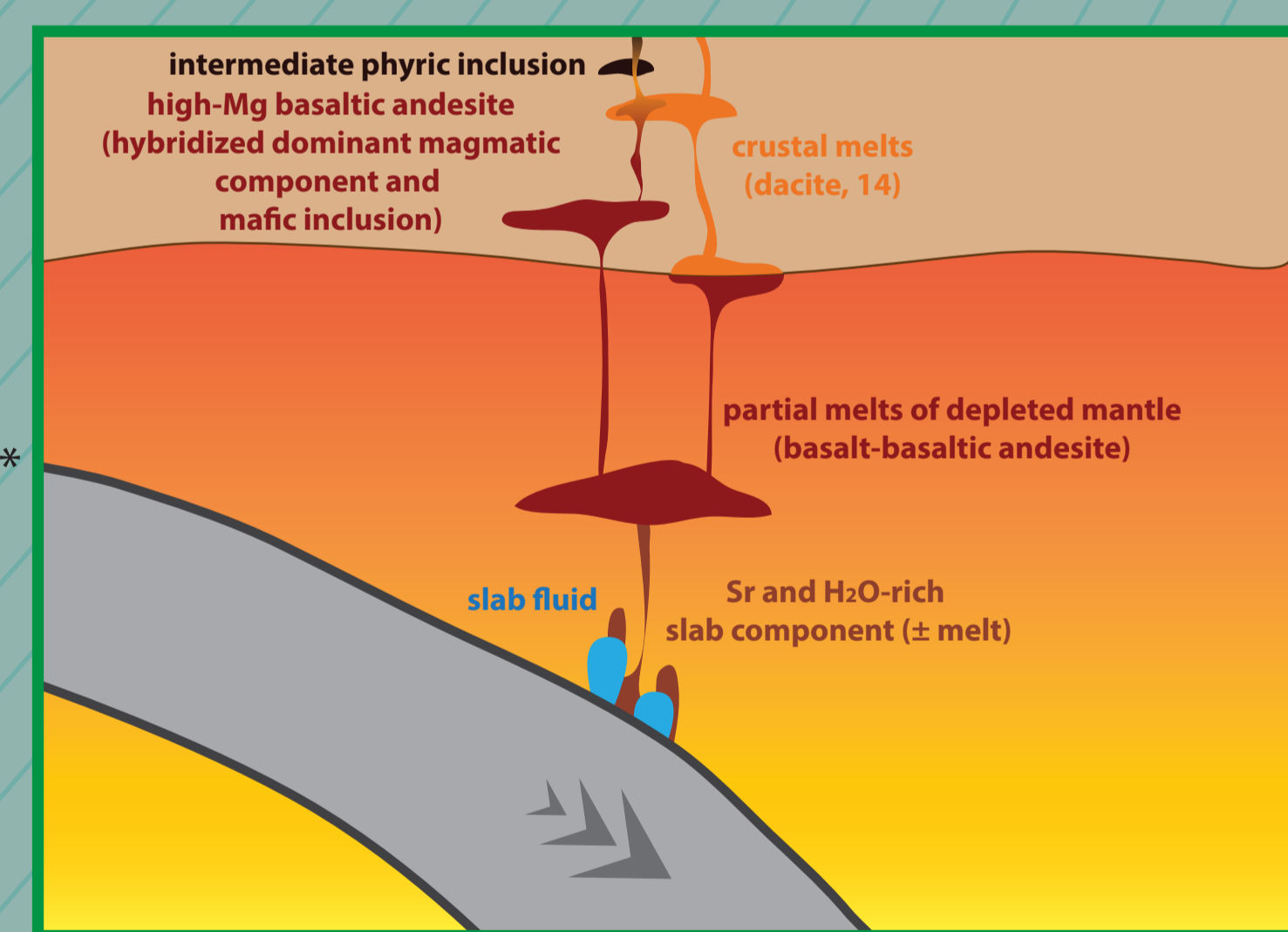
- Hybridized dominant magmatic component (HDMC): hydrated (± melt) depleted mantle basalt*
- Clinopyroxene: high-mid Mg#, mid (Sm/Yb)_N
- Olivine: high Fo, high Ni
- Chromites: high Cr# (hosted in olivine)
- Plagioclase: high and low An, complex populations*
- Whole rock (Sr/P)_N: high (>3.3)
- HDMC is a hybridized product, and likely contains an unidentified andesitic component
- Mafic inclusion (MI): hydrated (± melt) depleted mantle basalt (same mantle source as HDMC)
- Primitive mixing endmember (geochemically identical to most primitive Lightning Creek samples)
- Clinopyroxene: high Mg#**
- Olivine: high Fo
- Chromites: high Cr# (hosted in olivine)
- Large apyric
- Whole rock (Sr/P)_N: high (>3.3)

**Qualitative analyses using energy dispersive X-ray (EDX)



Glacier Peak Components:

- Andesite (mantle-derived, differentiated, mixed)
- Clinopyroxene: low Mg#, low (Sm/Yb)_N
- Plagioclase: mid An, bimodal size distribution, numerous populations, complex textures
- Ultramafic cumulate
- Olivine: mid-high Fo, high Ni, xenocrystic
- Chromites: high Cr# (hosted in olivine)
- Hydrous component (slab fluids ± melt)
- Whole rock (Sr/P)_N: high (>3.3)



- Intermediate phric inclusion (IPI): andesite
- Likely added in crust (geochemically distinct, no identifiable mixing trends, more silicic)
- Clinopyroxene: low Mg#
- Olivine: low Fo**
- Plagioclase and orthopyroxene dominated
- Whole rock (Sr/P)_N: low (<3.3)

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