HIGHLY-REDUCED, HSE-RICH METALLIC-Fe DEPOSITS IN THE SIBERIAN TRAP BASALTS: AN ANALOG OF EXTRATERRESTRIAL CONDITIONS?
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Introduction: Metallic native-Fe is a common feature in some silicate-dominated extraterrestrial crustal rocks, including lunar basalts [1-2], certain basaltic meteorites (e.g., mesosiderites), as well as chondritic and iron meteorites [3], because of highly-reducing conditions during their formation. However, occurrences of metallic-Fe in terrestrial crustal rocks are extremely rare, due to more oxidizing conditions (e.g., Fig. 1). For example, terrestrial igneous rocks commonly record crystallization at oxygen fugacities (fO_2) slightly above the quartz-fayalite-magnetite (QFM) redox curve and below the magnetite-hematite (MH) curve (Fig. 1). In comparison, extraterrestrial rocks typically plot considerably below the QFM redox curve. For example, martian meteorites normally plot intermediate between the QFM and iron-wüstite (IW) curves. Lunar basalts and meteorites typically form under considerably more reducing conditions, and plot below the IW curve.

Evolutionary magmatic processes on terrestrial bodies can also be constrained using trace-element contents of certain minerals (e.g., the highly siderophile elements (HSEs): Ru, Rh, Pd, Os, Ir, Pt, Re, and Au). The HSEs are typically compatible in Fe-alloy phases, yet most magmatic (e.g., lunar) occurrences of metallic-Fe are HSE-poor. This is the result of planetary differentiation, which partitions HSEs into a metallic core and results in a HSE-poor residual (mantle) reservoir. Terrestrial magmatic metallic-Fe occurrences are unique in that they contain some of the highest known abundances of HSEs in metallic-Fe, and are the direct result of an additional enrichment process.

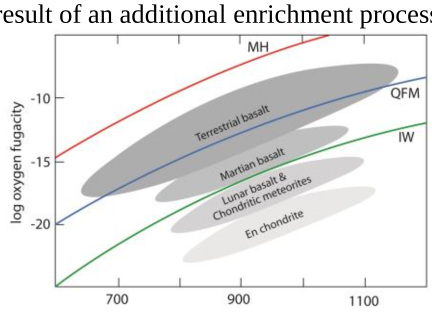

Figure 1. *Comparison of fO_2 conditions from various terrestrial and extraterrestrial environments.*

Here, we report new major- and trace-element data for metallic-Fe samples from one such terrestrial locality, the Siberian flood basalt traps, in order to illustrate the unique nature of HSE enrichment in terrestrial systems.

Terrestrial Occurrences of Native-Fe: There are three known terrestrial, primary metallic-Fe-rich localities: Disko Island (West Greenland), Bühl (Germany), and Siberian flood basalt extrusions (Russia). We focus on two occurrences from the Siberian locality (i.e., Khungtukun and Dzhaltul) that possess abundant metallic-Fe and anomalously high HSEs [4].

Khungtukun basalts are composed of silicates, including two populations of rounded-olivine, plagioclase, and interstitial clinopyroxene oikocrysts. Coarse-grained olivines are typically zoned, displaying Mg-rich cores (Fo_{68}) to Fe-rich rims (Fo_{55}), whereas fine-grained olivine chadacrysts are homogenous and display a Fo range from 53-56. Plagioclase laths are zoned, with calcic cores (An_{75}) and predominantly sodic rims (An_{57}). Clinopyroxene oikocrysts are homogenous in composition ($Wo_{40}En_{42}Fs_{17}$).

The Fe-metal portion is predominantly kamacite, with 2-5 wt.% Ni. Microlitic crystals of cohenite (Fe_3C) are observed at the rims of kamacite grains and metallic-Cu is also completely absent. Metallic-Fe grains, which are included within olivine phenocrysts, contain significantly-higher Ni- (10-25 wt.%; taenite) and Cu-contents, relative to the interstitial kamacite.

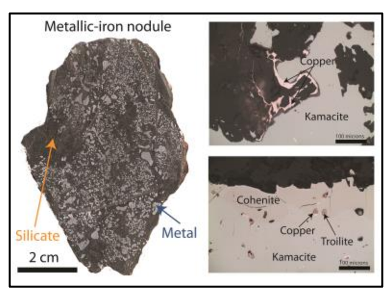

Figure 2. *Representative images of a polished slab of a Dzhaltul native-Fe nodule. Colors are modified to emphasis contrast between minerals.*

The Dzhaltul metallic-Fe basalts consist of similar silicate phases, with Fe-rich olivine (Fo_{30-40}), zoned plagioclase (core-rim; An_{70}-An_{50}), and clinopyroxene. Native-Fe bearing nodules occur within the main ore layer at the Dzhaltul Complex and are composed of (in order of decreasing abundance): kamacite, cohenite, native-Cu, ilmenite, and troilite (Fig. 2). Kamacite contains minor proportions of Ni (1-3 wt.%) and Co (0.2 wt.%), together with trace abundances of Ge (~120 ppm), Sn (~15 ppm), and Sb (~12 ppm). Cohenite is extremely pure, with only minor Ni (<1 wt.%), Co (~150 ppm), and Ge (<1 ppm). Native-Cu contains minor proportions of Ni and Fe (<1 wt. %), in addition to trace abundances of Au (~20 ppm), Ag (30 ppm), and Sn (~50 ppm).

HSE abundances in Native-Fe Deposits: Native-Fe basalts represent some of the most HSE-enriched 'basaltic' rocks found on Earth (>>1 ppm), relative to continental crust and intraplate basaltic lavas (~10 ppb) [5]. Native-Fe HSE enrichments follow the order: Siberia (>10 ppm; up to ~50 ppm) > Disko Island (~2 ppm) > Bühl (<1 ppm; Fig. 3). Variations in the extent of HSE enrichment are likely a function of metal/silicate partitioning of the total-HSE contribution in staging chambers. However, the mechanism for these HSE enrichments remains enigmatic. Hypotheses include: 1) an early stage of HSE enrichment in lower-crustal staging chambers, associated with sulfide-liquid immiscibility [6] and 2) enrichment in upper-crustal ore-hosting intrusions [7]. The former hypotheses is preferred, however both require a period of HSE enrichment in the parent magma, prior to crystallization, in order to produce such rare HSE-rich ore deposits.

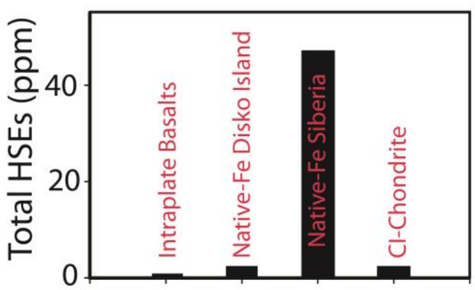

Figure 3. *Total PGE concentrations (ppm) for Siberian metallic-Fe rocks versus other occurrences [4-5,8].*

In comparison, chondritic HSE abundances typically display total HSE concentrations ~3 ppm, and overlap with concentrations measured in Disko Island [8]. This reflects the lack of core formation in the primitive parent bodies of chondritic meteorites. Notably, HSE contents observed in impact-related mesosiderites and ureilites overlap with CI-chondrites. In contrast, lunar basalts are depleted in HSEs by >>4 orders of magnitude relative to chondritic-material.

Terrestrial native-Fe occurrences span a wide range in HSE content and require an important additional PGE-enrichment step as well as assimilation of carbon-rich material. This extraordinary HSE-enrichment stage remains the largest uncertainty associated with the petrogenesis of HSE-rich native-Fe basalts. It is hypothesized that during crustal residence, a HSE-depleted melt is forced into a stage of sulfide-liquid immiscibility, perhaps by direct contact with a felsic layer, whereby this sulfide-rich melt effectively forms a sink for HSEs. Repeated and continued passage of the basaltic melt through such a felsic layer results in further accumulation of the HSEs into this ever-increasing pool of sulfide melt. Lastly, with the depletion of the felsic layer, the intruding basaltic melt scavenges the HSEs from this sulfide melt, thereby becoming a HSE- and sulfur-enriched magma.

Upon emplacement in the upper-crust, highly-reducing conditions are forced upon the HSE-enriched magma by assimilation of carbonaceous material (e.g., coal, bituminous shale, oil) [4]. Once these conditions have been reached, the resultant crystallization sequence is similar to those observed in extraterrestrial samples.

Analogous Formation Conditions?: While chondritic HSE contents and fO_2 conditions overlap with some terrestrial native-Fe occurrences, they have much different petrogenic evolutions. Most importantly, chondrites do not require a pre-eruptive HSE enrichment process, and instead form from HSE-rich parent materials, with metallic-Fe representing one of the many phases in the crystallization process. In contrast, core formation processes result in HSE-rich, metallic-Fe cores and HSE-depleted (mantle) residues, and thus explain the observed depletions in terrestrial intraplate and lunar basalts [9].

Instead, the petrogenesis of terrestrial native-Fe samples may be most closely related to that of some impact-related mesosiderites and ureilites [3,10], whereby chondritic (e.g., HSE-rich) material is assimilated into these rocks during impact, resulting in reduction conditions analogous to the addition of carbon-rich organic material to a terrestrial basaltic magma. As such, Siberian native-Fe occurrences provide a potentially useful analog for these unique and highly-reducing extraterrestrial conditions.

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