Influence of Metals' Redox States on Lunar Evolution

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Objectives and Motivations

Objectives: The purpose of this research is to determine the activity of NiO and FeO in liquid at various temperatures, and by doing so, generate a phase diagram. This diagram will be used to elucidate information about the formation and evolution of the moon.

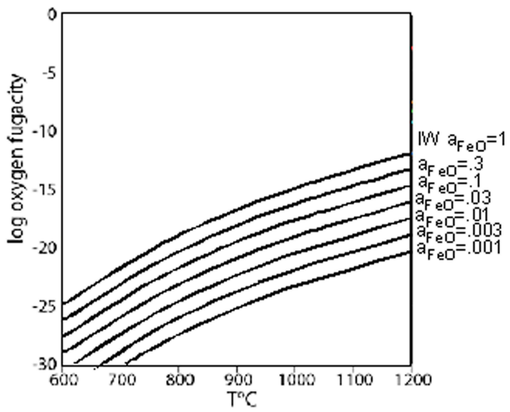
Motivations: This study takes an experimental approach to determining the activities of FeO and NiO in silicate liquids.

Theoretical Background and Hypothesis

It has been found that if a pressure O_2' is exerted and a second pressure O_2" is emulated, then the activity of the liquid may be determined by the relation below.

$$\log(a_{FeO}) = \frac{1}{2}\log\left[\frac{P(O_2)''}{P(O_2)'}\right]$$

Figure 1.



This may give implications to the formation of the moon.

The fundamental difference between the earth and the moon is in the PO_2 of their near surface rocks.

Hypothesis: The original lunar magmatic ocean condensed from the synestia with a range in PO_2. In some parts, nickel dissolved in the magma as Ni^{2+}; in other parts, an immiscible iron liquid formed. As iron is vastly more abundant than nickel, the silicate nickel budget was relatively depleted while enhancement of the iron was relatively small.

Figure 2 from Lock[5].

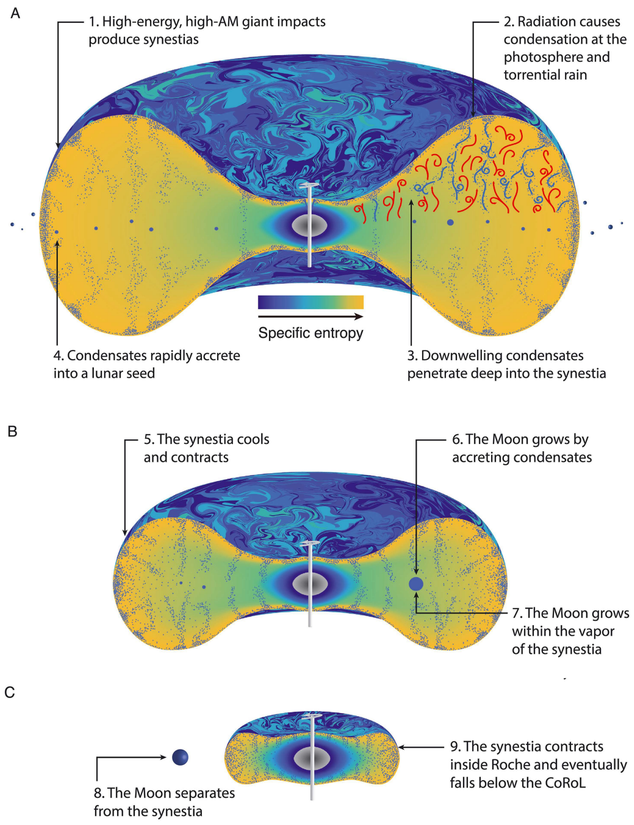
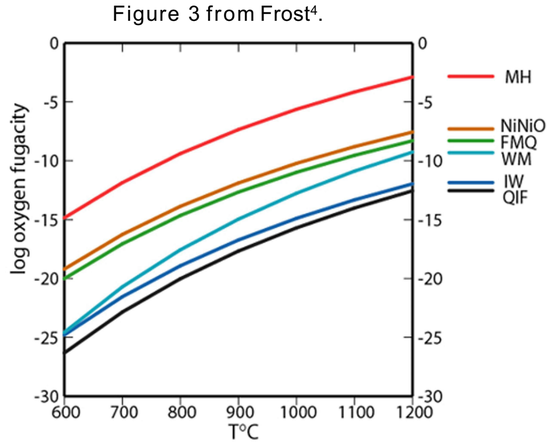


Figure 3 from Frost[4].



MH is magnetite-hematite ($2Fe_3O_4 + 0.5O_2 = 3Fe_2O_3$)
NiNiO is nickel-nickel oxide ($Ni + 0.5O2 = NiO$)
FMQ is fayalite-quartz-magnetite ($3Fe_2SiO_4 + O_2 = 3SiO_2 + 2Fe_3O_4$)
WM is wustite-magnetite ($3FeO + 0.5O_2 = Fe_3O_4$)
IW is iron-wustite ($Fe + O_2 = FeO$)
QIF is quartz-iron-fayalite ($2Fe + SiO_2 + O_2 = Fe_2SiO_4$).
These cover conditions expected in the Earth from near the core to the near surface where Fe^{3+} is common, expressed at 1 bar total pressure.

Experimental

A haplobasalt composition was synthesized from SiO_2, Al_2O_3, $CaCO_3$, $MgCO_3$, Na_2CO_3. Ni metal was placed above a haplobasalt bead and heated at 1300 °C for 4 hours at IW. NiO was placed onto another aliquot of haplobasalt and heated at NNO. Then, half of the NiO-haplobasalt sample was again heated at 1300 °C and at IW for 4 hours. Once the three types of samples were produced, they were polished, carbon coated, and prepared for electron microbeam analysis.

Results and Discussion

Elemental nickel had precipitated. (Rebutes argument of Colson[1].) Coexisting metal grains in the anorthosites were reported by Dickey[2] to have 6-29 %nickel.

Figure 4. Nickel-Haplobasalt Sample on Microprobe.

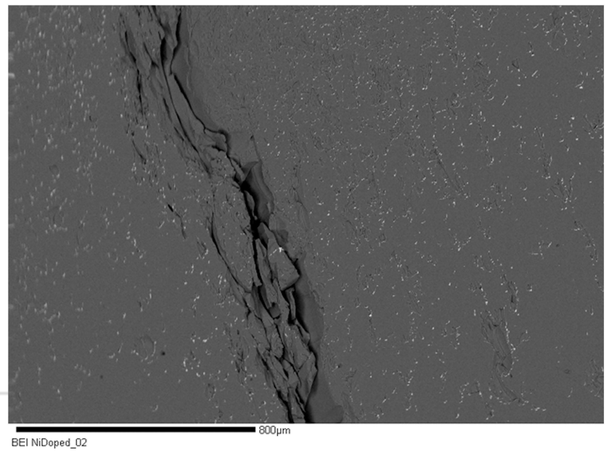
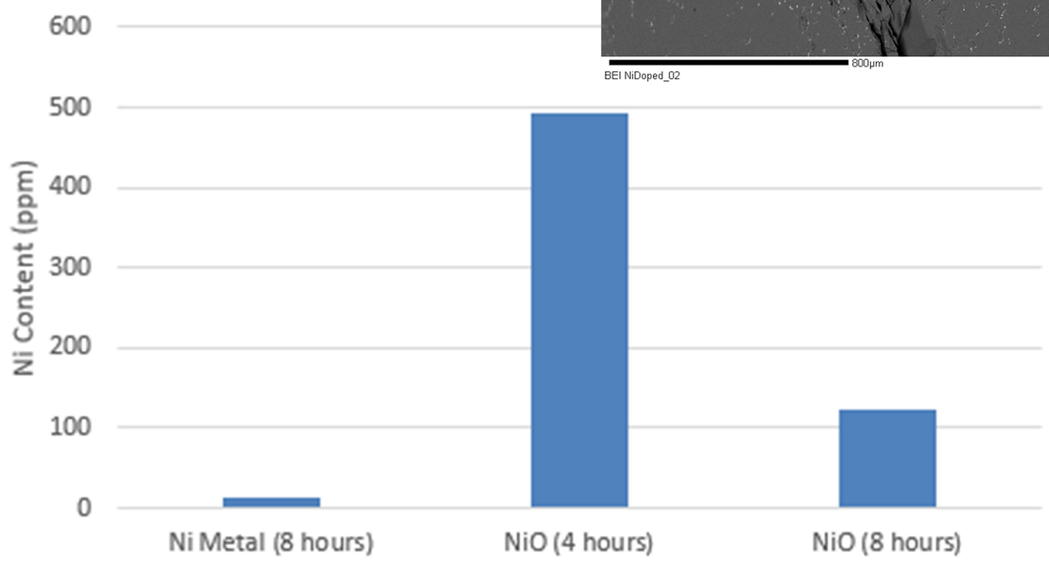


Figure 5. Nickel Content in Glass at 1300 °C at IW.



It is possible that there is no "shortage" of nickel on the moon, because it is all precipitated in the neutral metal in very localized areas.

Conclusion

Many lunar processes involve liquid crystal equilibration. Each has scavenged the nickel out of the Bulk Silicate Moon and incorporated it in metal. The presence of neutral and divalent nickel in primordial rocks suggests inhomogeneity in their sources.

Future Work

1. Does the nickel solubility change linearly from NNO to IW? 2. What does this tell us about the a-X of nickel in basalts?
3. Can similar experiments elucidate the a-X of iron in basalts?
4. What do the a-X relationships tell us about phase relations of lunar basalts?
5. Will accurate phase diagrams be generated from a-X relationship calculations?

References

1. Colson, R.O. Solubility of Neutral Nickel in Silicate Melts and Implications for the Earth's Siderophile Element Budget. Nature 1992, 357 (6373), 65–68.
2. Dickey, John S. "Nickel-Iron in Lunar Anorthosites". Earth and Planetary Science Letters. (8): 387-392. 1970. 3. Dingwell, D. B.; O'Neill, H. S. C.; Ertel, W.; Spettel, B. The Solubility and Oxidation State of Nickel in Silicate Melt at Low Oxygen Fugacities: Results Using a Mechanically Assisted Equilibration Technique. Geochimica et Cosmochimica Acta 1994, 58 (8), 1967–1974.
4. Frost, B.R. "Introduction to Oxygen Fugacity and its Petrologic Importance", in "Oxide Minerals: Petrologic and Magnetic Significance" Reviews in Mineralogy Volume 25, Mineralogical Society of America (D.H. Lindsley, editor), p. 1-10. 1991.
5. Lock, S. J.; Stewart, S. T.; Petaev, M. I.; Leinhardt, Z.; Mace, M. T.; Jacobsen, S. B.; Cuk, M. The Origin of the Moon Within a Terrestrial Synestia. Journal of Geophysical Research: Planets 2018, 123 (4), 910–951.