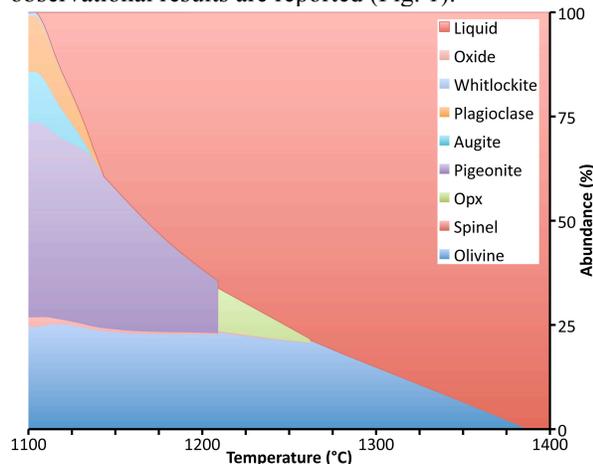


**Observational and Experimental Results for Tissint Magma Formation: The Story Thus Far.** Nicholas Castle and Christopher DK Herd, Department of Earth and Atmospheric Sciences, 1-26 Earth Sciences Building, University of Alberta, Edmonton, Alberta, Canada, T6G 2E3 ([castle@ualberta.ca](mailto:castle@ualberta.ca)).

**Introduction:** Tissint is a recent Martian meteorite fall, one of only five ever observed, providing a fresh look at part of Mars' igneous history. As an olivine-phyric shergottite with an intermediate Fe/Mg ratio and a near-liquidus composition [1,2], Tissint promises to provide new insights into olivine-phyric shergottites and their relationship to other Martian meteorites. This work aims to evaluate the crystallization and redox history of Tissint using oxybarometry and experimental petrology.

**MELTS Reference Model:** The MELTS thermodynamic model was used as a reference to help guide experimental work [3-5]. The composition used is not the bulk composition of Tissint, but rather a parental composition calculated to correct for approximately 5% olivine accumulation [2]. Initial MELTS calculations covered a wide range of likely redox conditions for crystallization, but only the results from the set of conditions that most closely match the observational results are reported (Fig. 1).



**Figure 1:** MELTS reference model. Minerals are listed from the bottom up in crystallization order. The calculation was performed from 1400°C at 1bar with a buffered redox state of QFM-3.

**Observations:** A JEOL 8900 electron microprobe was used. Conditions included: beam diameters between focused and 20 $\mu$ m; 20keV accelerating voltage; 20nA current. Quantitative analysis included all elements present in the simulant powder: Si, Ti, Al, Cr, Fe, Mn, Mg, Na, K, and P. In Tissint, Ni and V were also analyzed.

As previously reported, Tissint contains large olivine phenocrysts, and a groundmass composed of

olivine, pyroxene, plagioclase, ferrichromite, ilmenite, and titanomagnetite [1]. Olivine phenocrysts are zoned and have melt inclusions. Ferrichromite grains are typically excluded from the olivine-cores, indicating that they are not a liquidus phase. A minority subset of ilmenite and titanomagnetite grains are intergrown, but these phases are typically not in contact.

**Olivine-Pyroxene-Spinel Oxybarometry.** The olivine-pyroxene-spinel geothermometry and oxybarometry is regarded as the most robust redox estimate of the primitive magma at the start of crystallization. To make the estimate, we assume that olivine, pyroxene, and ferrichromite (spinel) precipitate concurrently, which is supported by petrographic observations. We utilize the most magnesian composition of pyroxene cores reported in the literature [1] and calculate the Fe/Mg composition of olivine in equilibrium based on an Fe-Mg  $K_D = 1.2$  [6]. A matching olivine composition from microprobe observation was used along with observed ferrichromite compositions to calculate the temperature and redox state using the CT server [7-12].

**Ilmenite-Titanomagnetite Oxybarometry.** The ilmenite-titanomagnetite estimate is not a measurement of the redox state of the primitive melt, but rather of the near solidus melt, as both minerals form very late in the crystallization sequence. This provides an opportunity to examine if and how the redox state may have changed during crystallization. The rarity of ilmenite-titanomagnetite mineral contact makes this method prone to compositional mismatch errors leading to erroneous temperature estimates (and therefore questionable redox estimates). The fine scale of intergrowth, when present, leads to potential errors from beam overlap. The reported values attempt to minimize both of these known issues by using average ilmenite compositions with the most Ti-rich and Cr-poor titanomagnetite compositions. This approach is justified by the lack of variation in ilmenite composition, and the assumption that the latest crystallizing spinel (the titanomagnetite grains with the highest Ti concentrations) would have precipitated concurrently with ilmenite. The calculation was performed on the CT server [13].

**Table 1:** Tissint redox estimates

	$\log f_{O_2}$ (QFM)	Temp. (°C)	n
Ol-Px-Sp	-3.6 $\pm$ 0.1	1090 $\pm$ 20	36
Ilm-Tmt	-1.35 $\pm$ 0.04	830 $\pm$ 10	11

**Experimental Method:** A synthetic mixture of the calculated Tissint parental melt composition was prepared for experimental work. Pressed pellets of simulant powder were suspended in a high-temperature furnace using a CO-CO<sub>2</sub> atmospheric mixture to hold experiments at QFM-3.2 as per oxybarometry for the highest-temperature (nearest liquidus) results. Re-wire was used to minimize Fe loss [14]. Samples were held at their target temperatures for over 24 hrs, or alternatively, soaked above the liquidus for over 1hr, then rapidly cooled to the target temperature and held. Samples were either quenched in air or distilled water.

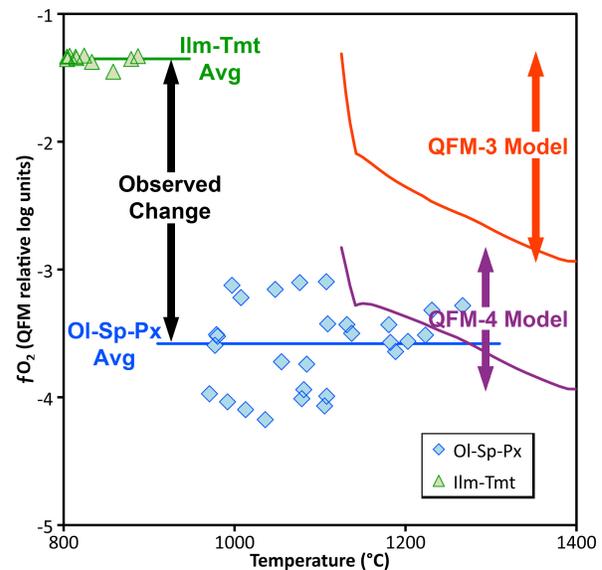
**Experimental Results:** The liquidus for the Tissint parental melt is between 1362-1375°C. At 1362°C minor amounts of olivine are present. At 1250°C the system is still dominated by glass but olivine has become a major phase. Minor amounts of pyroxene (likely orthopyroxene) are also present, but there are no apparent oxides. By 1200°C the system is primarily solid. The solids are dominated by olivine and pyroxene (likely pigeonite) with minor oxides (likely ferrichromite). At 1140°C there is still liquid present (~10%). Mineral compositions and modes will be determined by electron microprobe and mass balance, respectively.

**Discussion:** The observed crystallization roughly parallels the MELTS reference model, but with differences in temperature and mineral modes during the crystallization sequence. MELTS overestimates the abundance of ferrichromite, which is attributable to either the model underestimating Cr-compatibility in pyroxene or under representation of ferrichromite in experiments due to nucleation difficulties.

A potential issue is that temperature estimates from the ilmenite-titanomagnetite geothermometer are often unphysical, either being unrealistically high or low. The high temperature estimates are typically for poorly chosen titanomagnetite grains, which would have formed from a magma with a low activity of Ti. These grains would have formed before ilmenite was stabilized, leading to spurious temperature estimates. The low temperature estimates are physical, as ilmenite and titanomagnetite grains in contact may continue exchanging Ti and Fe (the basis for the geothermometer) below the solidus, and recording the 'lock in' temperature, rather than the crystallization temperature.

Results from oxybarometry suggest that as the magma cooled it experienced an oxidizing event (Fig. 2). The magnitude of oxidation is greater than the effect calculated using MELTS for a closed, unbuffered, magmatic system, suggesting that the

Tissint melt may have crystallized in an open system. Oxidation may have occurred by fractionation of ferric iron, degassing, or a combination of both.



**Figure 2:** Redox conditions computed for Tissint from the Ol-Sp-Px and Ilm-Tmt oxybarometers compared with model results from unbuffered MELTS simulations. The sharp inflection in the MELTS models correlates with plagioclase nucleation. The arrows show the magnitude of the modeled or observed  $fO_2$  change.

**References:** [1] Chennaoui Aoudjehane H. et al. (2012) *Science*, 338, 785-788. [2] Herd C.D.K. et al. (2013) *LPI Contrib.*, 1719, 2683. [3] Asimow P.D. and M.S. Ghiorso (1998) *American Mineralogist*, 83, 1127-1132. [4] Ghiorso M.S. and R.O. Sack (1995) *Contrib. to Min. Pet.*, 119, 197-212. [5] Gualda G.A.R. et al. (2012) *Journal of Petrology*. [6] Longhi J. et al. (1989) *LPSC Proc.*, p. 451-464. [7] Sack R. and M. Ghiorso (1989) *Contrib. to Min. Pet.*, 102, 41-68. [8] Sack R. and M. Ghiorso (1991) *Contrib. to Min. Pet.*, 106, 474-505. [9] Sack R. and M. Ghiorso (1994) *Contrib. to Min. Pet.*, 118, 271-296. [10] Sack R. and M. Ghiorso (1994) *Contrib. to Min. Pet.*, 116, 287-300. [11] Sack R. and M. Ghiorso (1994) *Contrib. to Min. Pet.*, 116, 277-286. [12] Sack R.O. and M.S. Ghiorso (1991) *American Mineralogist*, 76, 827-847. [13] Ghiorso M.S. and B.W. Evans (2008) *American Journal of Science*, 308, 957-1039. [14] Borisov A. and J.H. Jones (1999) *American Mineralogist*, 84, 1528-1534.