

**FIRST NEW MINERALS FROM MARS: DISCOVERY OF AHRENSITE  $\gamma\text{-Fe}_2\text{SiO}_4$  AND TISSINTITE  $(\text{Ca},\text{Na},\square)\text{AlSi}_2\text{O}_6$ , TWO HIGH PRESSURE PHASES FROM THE TISSINT MARTIAN METEORITE.**

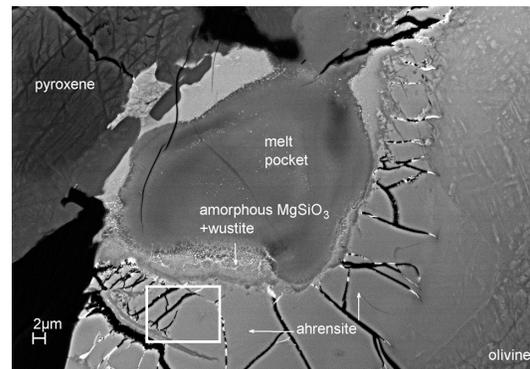
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**Introduction:** Tissint, the recent meteorite fall in 2011, is a fresh heavily-shocked olivine-phyric shergottite from Mars [1]. During a nanomineralogy investigation of this meteorite by high-resolution analytical scanning electron microscope, electron probe, micro-Raman, and synchrotron diffraction, we discovered two new shock-induced minerals ahrensite  $\gamma\text{-Fe}_2\text{SiO}_4$  and tissintite  $(\text{Ca},\text{Na},\square)\text{AlSi}_2\text{O}_6$  [2]. These phases provide new insights into shock conditions and impact processes on Mars. In this presentation, we describe these new minerals in greater detail than in [2] and demonstrate how nanomineralogy works and plays a unique role in meteorite and Mars rock research.

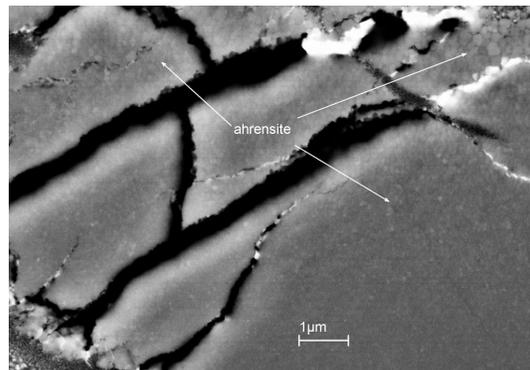
**Ahrensite (IMA 2013-028):** Ahrensite ( $\gamma\text{-Fe}_2\text{SiO}_4$ ) is the polymorph of fayalite with a cubic spinel structure and the Fe-analog of ringwoodite ( $\gamma\text{-Mg}_2\text{SiO}_4$ ) and a well known high-pressure phase [3]. The name honors Thomas J. Ahrens, a geophysicist at Caltech, for his many fundamental contributions to high-pressure mineral physics.

Both ahrensite and ringwoodite are found in Tissint as fine-grained polycrystalline aggregates in the rims of olivines adjacent to shock-melt pockets (Figs. 1-2) but they preserve the Mg-Fe gradient of the original olivine crystal. They are often separated from the melt pocket by a thin layer of amorphous (Mg,Fe)SiO<sub>3</sub> and wüstite (Fe,Mg)O. Ahrensite occurs as translucent, bluish-green, 5–20  $\mu\text{m}$  polycrystalline aggregates consisting of submicron-sized crystals of 50–400 nm in diameter with grain size generally increasing towards the melt pocket (Fig. 2). The mean chemical composition of the type region is (wt%) SiO<sub>2</sub> 34.95, FeO 43.76, MgO 21.15, MnO 0.75, sum 100.61 with an empirical formula of  $(\text{Fe}_{1.06}\text{Mg}_{0.91}\text{Mn}_{0.02})\text{Si}_{1.01}\text{O}_4$ . Synchrotron micro-diffraction reveals that ahrensite has a cubic spinel structure with space group  $Fd\bar{3}m$ . The cell parameters are  $a = 8.163(1) \text{ \AA}$ ,  $V = 543.96(7) \text{ \AA}^3$ ,  $Z = 8$ , which leads to a calculated density of 4.135  $\text{g/cm}^3$ .

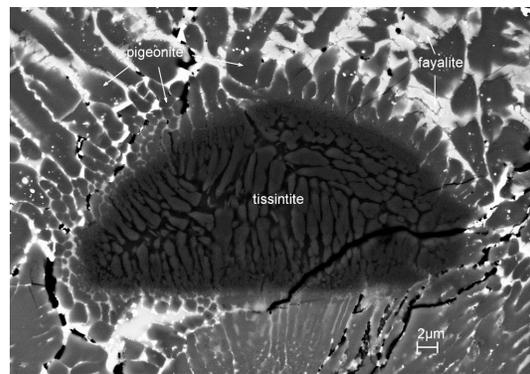
**Tissintite (IMA 2013-027):** Tissintite,  $(\text{Ca},\text{Na},\square_{1/2})\text{AlSi}_2\text{O}_6$ , is a new extraordinarily vacancy-rich high pressure clinopyroxene with a plagioclase composition. It can be thought of as the Ca-analog of jadeite with  $\sim 1/4$  of the M2 sites being vacant. The phase exhibits considerable solid solution towards the



**Fig. 1.** Back-scatter electron (BSE) image showing ahrensite domains with surrounding phases. Box marks location of Fig. 2.



**Fig. 2.** Enlarged BSE image revealing submicrometer- to nanometer-sized polycrystalline ahrensite.



**Fig. 3.** BSE image of fine-grained "wormy" tissintite with surrounding pigeonite and fayalite.

Ca-Eskola pyroxene component  $(\text{Ca}_{0.5}\square_{0.5})\text{AlSi}_2\text{O}_6$ . Tissintite has, to our knowledge, never been synthe-

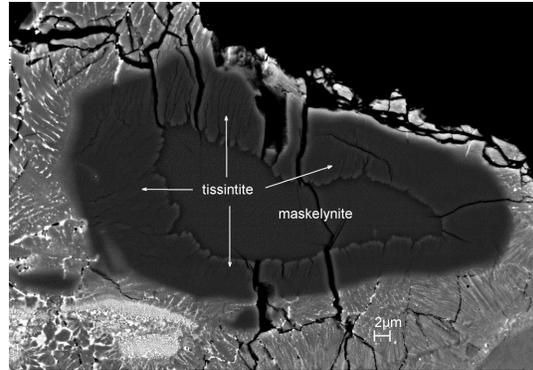
sized. Reported here is its first natural occurrence. The mineral name is after the locality, Tissint, Morocco, where the Tissint meteorite fell.

Tissintite occurs as fine-grained aggregates of 0.5–3  $\mu\text{m}$  single crystals in plagioclase glass that is surrounded by or adjacent to the pigeonite and fayalite of shock-melt pockets (Figs. 3-4). The mean chemical composition of is (wt%)  $\text{SiO}_2$  52.52,  $\text{Al}_2\text{O}_3$  29.61,  $\text{CaO}$  13.14,  $\text{Na}_2\text{O}$  3.89,  $\text{FeO}$  0.93,  $\text{MgO}$  0.18, sum 100.27, with an empirical formula of  $(\text{Ca}_{0.48}\text{Na}_{0.26}\square_{0.26})(\text{Al}_{0.98}\text{Fe}_{0.03}\text{Mg}_{0.01}) (\text{Si}_{1.79}\text{Al}_{0.21})\text{O}_6$ . Type tissintite =  $\frac{1}{2}$  CaEskola +  $\frac{1}{4}$  Jadeite +  $\frac{1}{4}$  Kushi-roite. Synchrotron and electron back-scatter diffraction reveal that tissintite is a  $C2/c$  clinopyroxene (cpx). Its cell parameters are  $a = 9.21(17)$   $\text{\AA}$ ,  $b = 9.09(4)$   $\text{\AA}$ ,  $c = 5.20(2)$   $\text{\AA}$ ,  $\beta = 109.6(9)^\circ$ , and  $Z = 4$ , leading to a cell volume of  $410(8)$   $\text{\AA}^3$  which is very low for a clinopyroxene. Tissintite is the most vacancy-rich natural cpx known with 24-28% vacancies on M2, more than double known cpx from the Earth's mantle (e.g., [4-5]). It also has more M2 vacancies than synthetic cpx based on a literature compilation (Fig. 5).

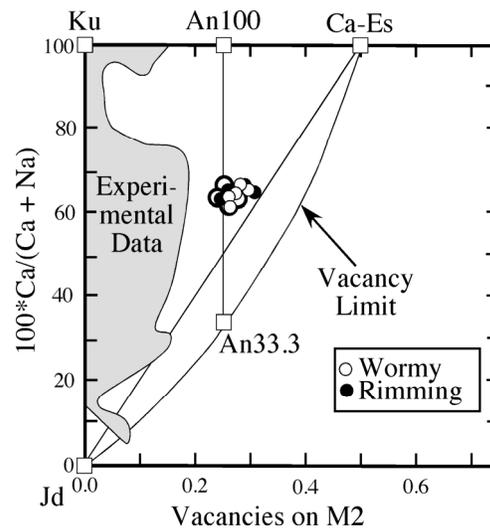
**Origin and significance:** Both ahrensite and tissintite are high-pressure shock-induced minerals formed during the impact event(s) on Mars that led to the excavation and ejection of Tissint off the planet.

Ahrensite (and ringwoodite) in Tissint is high-P phases apparently formed by solid-state transformation of olivine without significant diffusion, given preservation of Mg-Fe zoning from the original olivine. Crystal size increases towards the melt pocket (Fig. 3), reflecting higher temperatures as the interface is approached. The sequence of phase assemblages across a melt pocket into olivine is: quenched melt  $\rightarrow$  wüstite/periclase + vitreous magnesium metasilicate  $\rightarrow$  ahrensite or ringwoodite  $\rightarrow$  amorphous orthosilicate (or highly-deformed olivine)  $\rightarrow$  olivine. This sequence is mainly the result of T rather than P differences across the hot spot and it suggests rather narrow constraints on P, 19 to 22 GPa in the “wall rock” of the melt pocket and not more than 10–15 GPa in the melt zone.

Conditions of tissintite formation are rather narrowly constrained in P-T-time (t) between maskelynite toward lower T and shorter t and toward stishovite + garnet at higher T and longer t. It formed as a metastable phase during a shock event that was just severe enough to allow nucleation and growth of cpx in plagioclase composition amorphous materials heated by shock melt pockets but not so severe that other more stable phases, which would have destroyed the tissintite, could nucleate and grow as demonstrated by the kinetic experiments of [6] on amorphization and crystallization in plagioclase. The kinetics for nucleation and growth of tissintite is probably slower for more sodic plagioclase precursors, so tissintite is most



**Fig. 4.** BSE image showing “rimming” tissintite with maskelynite in a melt pocket.



**Fig. 5.** Ca #, molar  $\text{Ca}/(\text{Ca}+\text{Na})$  expressed as %, in tissintite as a function of the concentration of vacancies on the M2 site. “Vacancy limit” defines the locus of points for which the M1 site is fully occupied with 3+ cations and the tetrahedral site by 4+ cations. Compositions for Ca-Na plagioclase defined in terms of a clinopyroxene formula unit, plot along a vertical line at an M2 vacancy concentration of 0.25; this line extends from end-member anorthite (Ca# of 100), labeled An100, to a Ca# of 33.3, below which clinopyroxene formulas based on M2 vacancies cannot be constructed from plagioclase. Compositions of jadeite (Jd), kushi-roite (Ku), and the Ca-Eskola component (Ca-Es) are also shown.

likely to be found in the depleted olivine phryic shergottites like Tissint that consistently contain plagioclase precursors in the appropriate composition range.

**References:** [1] Baziotis I. et al. (2013) *Nature Comm.* 4:1404. [2] Ma C. et al. (2014) *LPSC* 45, A1222. [3] Ringwood A. (1958) *GCA* 15:18. [4] Ober-ti R. and Caporuscio F.A. (1991) *Am. Mineral.*, 76:1141. [5] Smyth J.R. (1980) *Am. Mineral.* 65: 1185. [6] Kubo T. et al. 2010. *Nature Geosci.* 3:41.