

## DISCOVERY OF NEW HIGH-PRESSURE MINERAL TSCHAUNERITE, $(\text{Fe}^{2+})(\text{Fe}^{2+}\text{Ti}^{4+})\text{O}_4$ , A SHOCK-INDUCED, POST-SPINEL PHASE IN THE MARTIAN METEORITE SHERGOTTY.

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**Introduction:** Shergottites are highly shocked martian meteorites and their study provides insight, not only into shock conditions and impact processes associated with their ejection from Mars, but also into the nature of materials at high pressures and temperatures within the Earth. Recent advances in electron-beam and synchrotron techniques, particularly high-resolution analytical scanning electron microscopy, have led to the characterization of numerous shock-induced phase assemblages in highly shocked meteorites, including the discovery of new high-pressure minerals and phases [e.g., 1-3].

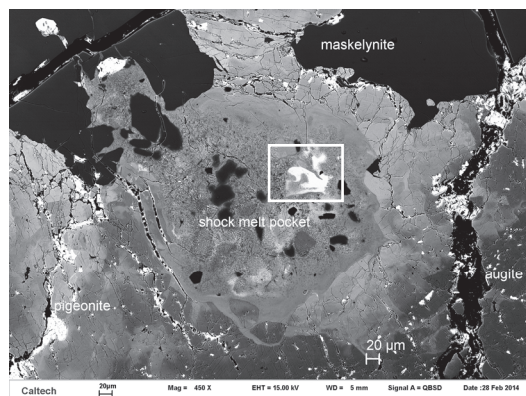
During a nanomineralogy investigation of the Shergotty martian meteorite, we discovered the three new shock-induced, high-pressure minerals tschaunerite,  $(\text{Fe}^{2+})(\text{Fe}^{2+}\text{Ti}^{4+})\text{O}_4$  (simply  $\text{Fe}_2\text{TiO}_4$ ) [4], feiite,  $\text{Fe}^{2+}_2(\text{Fe}^{2+}\text{Ti}^{4+})\text{O}_5$  (simply  $\text{Fe}_3\text{TiO}_5$ ) [5], and liuite,  $\text{FeTiO}_3$  [6], in an Fe-, Ti-rich clast within a shock melt pocket. In a companion abstract [7], we consider feiite and liuite. Here, we describe the new mineral tschaunerite and discuss its origin and significance.

Tschaunerite is a polymorph of ulvöspinel with an orthorhombic  $\text{CaTi}_2\text{O}_4$ -type (CT) post-spinel structure. It is well-known from high-pressure experiments [e.g., 8-9], which show that it is the stable  $\text{Fe}_2\text{TiO}_4$  phase over a broad range of conditions at high pressures. The mineral tschaunerite has been approved by the IMA-CNMNC (IMA 2017-032a) [4] and the name honors Oliver Tschauner, a geophysicist at the University of Nevada, Las Vegas, for his significant contributions to mineral physics and to the discovery and characterization of high-pressure minerals.

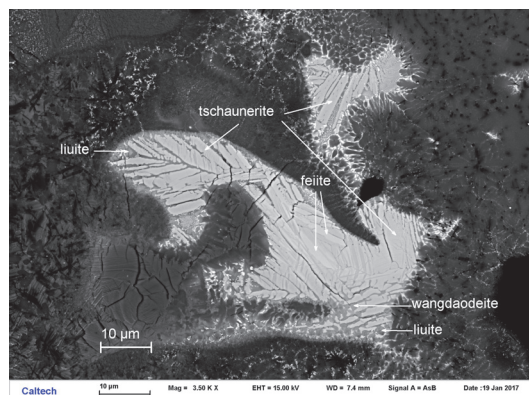
### Occurrence, chemistry, and crystallography:

Tschaunerite occurs as micrometer-sized, lath-shaped crystals, 1 – 5  $\mu\text{m}$  in size, together with ulvöspinel, feiite, liuite and wangdaodeite in an Fe-, Ti-rich clast within a shock-induced melt pocket (Figs. 1-3). The host melt pocket is ~ 400  $\mu\text{m}$  in diameter, and contains stishovite, wüstite, magnetite, clinopyroxene, stöflerite and zagamiite. The melt pocket is surrounded by augite, pigeonite and maskelynite of the host rock.

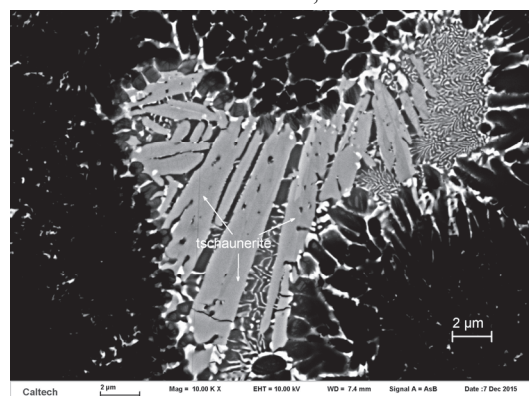
Tschaunerite is black and opaque with a metallic luster. The mean chemical composition, as determined by low-voltage electron probe (Table 1), gives rise to an empirical formula (based on 4 O atoms *pfu*) of  $(\text{Fe}^{2+}_{0.91}\text{Mg}_{0.06}\text{Mn}_{0.02}\text{Ca}_{0.01})(\text{Fe}^{2+}_{0.83}\text{Ti}_{0.78}\text{Fe}^{3+}_{0.22}\text{Al}_{0.09}\text{Si}_{0.05}\text{Cr}_{0.02})\text{O}_4$ , where  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  are partitioned,



**Fig. 1.** Back-scatter electron (BSE) image showing the tschaunerite-bearing shock melt pocket. Box marks location of Fig. 2.



**Fig. 2.** Enlarged BSE image revealing micrometer-sized tschaunerite within an Fe-, Ti-rich clast.



**Fig. 3.** Further enlarged BSE image (from upper portion of clast) showing tschaunerite.

based on stoichiometry; in terms of components, Shergotty tschaunerite consists mostly of  $\text{Fe}^{2+}(\text{Fe}^{2+}\text{Ti}^{4+})\text{O}_4$

(78%) with minor  $\text{Fe}^{2+}\text{Fe}^{3+}_2\text{O}_4$  (i.e.,  $\text{Fe}_3\text{O}_4$ ; 11%) and  $\text{Fe}^{2+}\text{Al}_2\text{O}_4$  (3%). The general formula is  $(\text{Fe}^{2+}, \text{Mg})(\text{Fe}^{2+}, \text{Ti}^{4+}, \text{Fe}^{3+}, \text{Al})_2\text{O}_4$  with an end-member  $(\text{Fe}^{2+})(\text{Fe}^{2+}\text{Ti}^{4+})\text{O}_4$ , or more simply,  $\text{Fe}_2\text{TiO}_4$ .

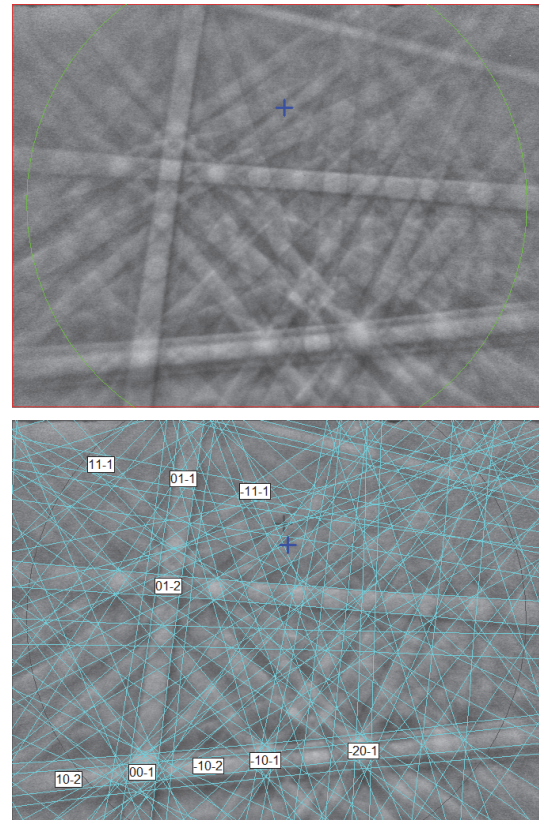
Electron back-scatter diffraction revealed that tschaunerite has a  $Cmcm$   $\text{CaTi}_2\text{O}_4$ -type post-spinel structure (Fig. 4). Its unit cell parameters via synchrotron diffraction are:  $a = 2.708(16)$  Å,  $b = 9.216(8)$  Å,  $c = 9.103(4)$  Å,  $V = 227.2(1.8)$  Å<sup>3</sup>, and  $Z = 4$ , which together with the composition (Table 1), leads to a calculated density of 6.41 g/cm<sup>3</sup>.

**Origin and significance:** Tschaunerite is one of at least 20 high-pressure, shock-induced phases [7,10,11] formed during the impact events on Mars that led to the excavation and ejection of Shergotty and other martian meteorites off the planet. The composition is consistent with that of an ulvöspinel precursor transformed to tschaunerite by a solid-state transformation that involved little, if any, diffusive interaction with the surrounding melt pocket. Some bands of ulvöspinel are observed within tschaunerite crystals (see Fig. 2 in [7]). We interpret these lamellae to represent partial retrograde transformation of high-pressure tschaunerite back to ulvöspinel. If this interpretation is correct, none of the original ulvöspinel remains.

Tschaunerite by itself is not a quantitative indicator of shock conditions because it is stable or metastable over a very broad range of conditions. With increasing pressure at ambient conditions [9], the cubic end-member  $\text{Fe}_2\text{TiO}_4$  (ulvöspinel) transforms to a tetragonal phase at 8-12 GPa, although this phase is destabilized by increasing  $\text{Fe}_3\text{O}_4$ , and to the orthorhombic tschaunerite, which is stable from 8-12 GPa to ~50 GPa. At more elevated temperatures under equilibrium conditions [8], high-pressure tschaunerite breaks down to the lower-pressure phase assemblage of liuite ( $\text{FeTiO}_3$  in the perovskite structure) + wüstite (~13-16

**Table 1.** EPMA data for tschaunerite.

| Constituent                    | wt% (n=12) | SD   |
|--------------------------------|------------|------|
| FeO                            | 56.79      | 1.48 |
| Fe <sub>2</sub> O <sub>3</sub> | 7.97       | 0.21 |
| TiO <sub>2</sub>               | 28.47      | 1.29 |
| Al <sub>2</sub> O <sub>3</sub> | 2.07       | 0.49 |
| Cr <sub>2</sub> O <sub>3</sub> | 0.84       | 0.15 |
| SiO <sub>2</sub>               | 1.37       | 0.41 |
| MgO                            | 1.15       | 0.39 |
| MnO                            | 0.65       | 0.22 |
| CaO                            | 0.26       | 0.26 |
| Total                          | 99.57      |      |



**Fig. 4.** (top) EBSD pattern of a tschaunerite crystal; (bottom) the pattern indexed with the  $Cmcm$   $\text{Fe}_2\text{TiO}_4$ ,  $\text{CaTi}_2\text{O}_4$ -type structure.

GPa for 1000-1600 °C). This provides a nominal lower bound for the formation of tschaunerite but, due to nucleation difficulties during shock, it is certainly possible that tschaunerite could form metastably at even lower pressures. Shock pressures for Shergotty of ~24 GPa, derived by [7] from the composition of tetragonal garnet, and ~30 GPa obtained by [12] using refractive indices of diaplectic, plagioclase-composition glasses, are both consistent with the formation of stable tschaunerite from an ulvöspinel precursor.

**References:** [1] Ma C. (2018) *Am. Mineral.*, 103, 1521-1522. [2] Ma C. et al. (2015) *EPSL*, 422, 194-205. [3] Ma C. et al. (2016) *GCA*, 184, 240-256. [4] Ma C. and Prakapenka V. (2018) *Eur. J. Mineral.*, 30, 1188. [5] Ma C. and Tschauner O. (2018) *Eur. J. Mineral.*, 30, 1188. [6] Ma C. and Tschauner O. (2018) *Eur. J. Mineral.*, 30, 1189. [7] Ma C. et al. (2021) *LPS*, 52, Abstract #1681, this volume. [8] Akaogi M. et al. (2019) *Minerals*, 9, 614. [9] Yamanaka T. et al. (2009) *Phys. Rev. B*, 80, 134120. [10] Ma C. et al. (2019) *Am. Mineral.*, 104, 1521-1525. [11] Tomioka N. and Miyamoto M. (2017) *Meteoritics & Planet. Sci.*, 52, 2017-2039. [12] Fritz J. et al. (2005) *Meteoritics & Planet. Sci.*, 40, 1393-1411.