Chenmingite, FeCr$_2$O$_4$ in the CaFe$_2$O$_4$-type structure, a shock-induced, high-pressure mineral in the Tissint Martian meteorite

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ABSTRACT

Chenmingite (FeCr$_2$O$_4$; IMA 2017-036), is a high-pressure mineral, occurring as micrometer to submicrometer-sized lamellae within precursor chromite grains along with xieite and Fe,Cr-rich ulvöspinel next to shock-induced melt pockets, from the Tissint Martian meteorite. The composition of type chenmingite by electron probe analysis shows an empirical formula of (Fe$^{2+}$$_{0.75}$Mg$_{0.23}$Mn$_{0.02}$)(Cr$_{1.60}$Al$_{0.29}$Fe$^{3+}_{0.06}$Fe$^{2+}_{0.04}$Ti$_{0.02}$)$_{2.01}$O$_4$. The general and end-member formulas are (Fe,Mg)(Cr,Al)$_2$O$_4$ and FeCr$_2$O$_4$. Synchrotron X-ray diffraction reveals that chenmingite has an orthorhombic $Pnma$ CaFe$_2$O$_4$-type (CF) structure with unit cell dimensions: $a = 9.715(6)$ Å, $b = 2.87 (1)$ Å, $c = 9.49 (7)$ Å, $V = 264.6 (4)$ Å, and $Z = 4$. Both chenmingite and xieite formed by solid state transformation of precursor chromite under high pressure and high temperature during the Tissint impact event on Mars. The xieite regions are always in contact with melt pockets, whereas chenmingite lamellae only occur within chromite, a few micrometers away from the melt pockets. This arrangement suggests that chenmingite formed under similar pressures as xieite but at lower temperatures, in agreement with experimental studies.
Keywords: Chenmingite, FeCr$_2$O$_4$, high-pressure mineral, shock-induced phase, Tissint Martian meteorite, shergottite.

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INTRODUCTION

The Tissint Martian meteorite is a fresh, highly-shocked, olivine-phyric shergottite (e.g., Baziotis et al. 2013; Ma et al. 2015, 2016). Around shock-generated melt pockets and veins in this meteorite, olivine is often transformed to ringwoodite or ahrensite and, in the immediate vicinity of the melt veins or pockets, to bridgmanite plus wüsite (Ma et al. 2016). Plagioclase is transformed to maskelynite, locally melted and partially crystallized to tissintite (Ma et al. 2015) and zagamiite-stishovite assemblages. These responses to shock conditions on Mars provide clues to the nature of the ejection events for Martian meteorites and to local shock conditions. Novel high-pressure minerals can narrow constraints on shock metamorphism in meteorites and the scale of impact events on their parent bodies. As natural phases, they contain minor chemical components which can guide experimental research about deep mantle mineralogy and provide constraints in assessing chemical or textural signatures that survive retrograde transformation in ultrahigh pressure terrains.

Here, we describe a new high-pressure mineral chenmingite, FeCr$_2$O$_4$ with a $Pnma$ orthorhombic CaFe$_2$O$_4$-type (CF) structure. It occurs in Tissint within chromite grains in contact with shock melt pockets (Fig. 1). Chen et al. (2003a) first reported FeCr$_2$O$_4$-CF in the Suizhou meteorite along with xieite but did not name this phase. It has also been synthesized at high pressures and moderate temperatures (e.g., Chen et al. 2003a; Ishii et al. 2014). Preliminary results of this work were given by Ma et al. (2018).

The mineral chenmingite (FeCr$_2$O$_4$; IMA 2017-036) has been approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (Ma and Tschauner 2017). It is one of thirteen newly-approved high-pressure minerals discovered in shocked meteorites since 2013 (Ma 2018). The name is in honor of Ming Chen, a cosmochemist and mineralogist at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, for his outstanding contributions to research on high-pressure mineralogy of meteorites, shock metamorphism and terrestrial impact craters. Among his contributions is the discovery of natural FeCr$_2$O$_4$ with a CF structure and
Xieite (the natural CaTi$_2$O$_4$-type polymorph of chromite) in the Suizhou meteorite, a highly shocked L6 chondrite (Chen et al. 2003a, b; 2008).

**SAMPLE AND ANALYTICAL METHODS**

The Tissint meteorite, which fell at Tata, Morocco on 18 July 2011, is a Martian meteorite (olivine-phyric shergottite). The type material is in Tissint section UT2 deposited in the Meteorite Collection of the Frank H. McClung Museum at the University of Tennessee, Knoxville, Tennessee 37996, USA. Section UT2 also hosts type ahrensite (IMA 2013-028; Ma et al. 2016) and type tissintite (IMA 2013-027; Ma et al. 2015). Tissint consists mostly of olivine (microphenocrysts and magnesian macrocrysts with thin ferroan rims), pyroxene (mostly pigeonite with some subcalcic augites), maskelynite (An58-69), with minor chromite and ilmenite, and accessory pyrrhotite, merrillite and magnetite. The meteorite contains scattered shock melt pockets and rare melt veins, and associated high pressure phases.

High-resolution scanning electron microscope (SEM), electron back-scatter diffraction (EBSD), electron probe microanalysis (EPMA), and synchrotron X-ray diffraction (SXRD) were used to characterize the composition, structure and petrography of chenmingite and associated phases. Back-scatter electron (BSE) imaging was performed using a ZEISS 1550VP field emission SEM. EBSD analyses were attempted using an HKL EBSD system on a ZEISS 1550VP SEM, operated at 20 kV and 6 nA in focused-beam mode with a 70° tilted stage and variable pressure mode (25 Pa). However, no meaningful EBSD pattern was obtained from chenmingite. Chemical analyses of chenmingite and associated phases were carried out using a JEOL 8200 electron microprobe interfaced with the Probe for EPMA program from Probe Software, Inc. and operated in focused beam mode at 15 kV and 15 nA with a probe diameter of ~150 nm. Standards were chromite (CrK$_\alpha$, FeK$_\alpha$), spinel (AlK$_\alpha$, MgK$_\alpha$), TiO$_2$ (TiK$_\alpha$), and Mn$_2$SiO$_4$ (MnK$_\alpha$). Quantitative elemental microanalyses were processed with the CITZAF correction procedure (Armstrong 1995) and analytical results are given in Table 1.

Synchrotron diffraction data were collected at the undulator beamline 13-IDD (GSECARS, APS, Argonne National Laboratory) using a primary beam of wavelength 0.495936 Å, monochromatized by a double-crystal Si monochromator. The X-ray beam was focused to 2×3 μm$^2$ by vertical and horizontal Kirkpatrick-Baez mirrors of 200 mm focal length. A MAR165 CCD area detector was used for collecting diffraction data, which were
obtained in forward scattering geometry. Calibration was conducted with GSE-ADA (Dera et al. 2013) and DIOPTAS (Prescher and Prakapenka 2015). Integration and correction for geometric distortion were conducted with DIOPTAS (Prescher and Prakapenka 2015).

Diffraction from chenmingite is prominent in some locations but generally overlaps with xieite, host chromite, and ulvöspinel. A pattern from the border of a melt pocket (Fig. 2) that contains no signal from xieite and comparatively weak diffraction from chromite was used for structure modeling.

RESULTS

Occurrence, appearance, physical and optical properties

In Tissint, type chenmingite occurs in the interior of two chromite grains exposed to melt pockets (Fig. 1). Xieite (FeCr$_2$O$_4$ in a CaTi$_2$O$_4$-type (CT) structure; e.g., Chen et al. 2008) and Fe,Cr-rich ulvöspinel occur in the same precursor chromite grains but these phases are in direct contact with shock melt pockets (Fig. 1), whereas chenmingite lamellae only occur within the precursor chromite, a few micrometers away from the melt pockets. The shock melt pockets, surrounded by olivine (Fo42-73), pyroxene and ‘maskelynite’ (An64-66), contain abundant ringwoodite-ahrensite, bridgmanite and wüstite transformed from olivine, and tissintite in maskelynite, and clinopyroxene from relict pyroxene or the melt.

Chenmingite occurs as lamellae, < 1 µm in width and up to 4 µm in length, set in arrays within the host chromite (Fig. 1c). It is optically not distinguishable from chromite. Higher scratching hardness than chromite is evidenced by disruption of polishing streaks as they cross chenmingite lamellae. Streak, tenacity, cleavage, fracture and reflection pleochroism could not be determined empirically because of the small grain size. The density, calculated from its crystal structure and the empirical formula, as described below, is 5.27 ±0.02 g/cm$^3$.

Chemical composition and crystallography

The composition (Table 1) of type chenmingite corresponds to an empirical formula based on 3 cations and 4 oxygens apfu of (Fe$^{2+}_{0.75}$Mg$_{0.23}$Mn$_{0.02}$)(Cr$^{1.60}$Al$^{0.29}$Fe$^{3+}_{0.06}$Fe$^{2+}_{0.04}$Ti$_{0.02}$)$_{2.01}$O$_4$, where Fe$^{2+}$/Fe$^{3+}$ was obtained by assuming an M$_3$O$_4$ stoichiometry. Within 1-σ uncertainties, the composition of chenmingite is the same as that of host chromite as well as that of xieite from the same host grain (Table 1). Chenmingite has a general formula of (Fe,Mg)(Cr,Al)$_2$O$_4$ and an end-member formula of FeCr$_2$O$_4$. The Fe,Cr-
rich ulvöspinel, as indicated by EBSD and synchrotron diffraction, has an empirical formula of \( (\text{Fe}^{2+}_{0.86}\text{Mg}_{0.12}\text{Mn}_{0.02})(\text{Cr}_{0.57}\text{Fe}^{3+}_{0.31}\text{Al}_{0.23}\text{Ti}_{0.44}\text{Fe}^{2+}_{0.45})\text{O}_4 \) with ~ 44 mole% ulvöspinel, 29% \( \text{FeCr}_2\text{O}_4 \), 15% \( \text{Fe}_3\text{O}_4 \), and 12% \( \text{MgAl}_2\text{O}_4 \).

In diffraction patterns, the occurrence of chenmingite is marked by disintegration of the chromite grain into a highly textured aggregate of two spinel phases (based on lattice parameters, chromite and an Fe-, Cr-rich ulvöspinel) with a grain size of roughly 50 nm. Chenmingite diffraction implies a similar grain size but it exhibits less broad profiles than nearby chromite and ulvöspinel and marked orientation. For structure refinement, we chose a pattern from the border of the chromite grain near a shock melt pocket (Fig. 2). In this pattern, chenmingite exhibits continuous Debye fringes with intensity variation along the azimuthal angle, which we fitted with both March-Dollase and spherical harmonics. Diffraction from surrounding chromite (around and underneath the lamella) could not be completely avoided and this resulted in spotty broad Bragg reflections, which were initially fitted by modeling a preferred orientation, followed by a Le Bail fit. \(|F(\hkl)|\) of overlapping reflections of chenmingite may have been compromised but this could not be avoided. For chenmingite initially, the xieite structure was initially used as a model because we assumed the diffraction patterns were generated by this phase. After Le Bail extraction of apparent structure factor moduli, a reversed Monte Carlo optimization in space group \( P1 \) was performed. The optimized structure was compatible with space group \( Pnma \) but not \( Cmcm \) (xieite) and exhibited a marked shift of one oxygen atom, consistent with a difference in octahedral linkages relative to the xieite structure. The resulting structure was of the \( \text{CaFe}_2\text{O}_4 \)-type rather than the \( \text{CaTi}_2\text{O}_4 \)-type of xieite (Chen et al. 2003b, 2008). We obtained an \( R_F \) of 28% for the initial xieite model and 11% for an optimized model in the \( \text{CaFe}_2\text{O}_4 \) harmunite-type structure. We also checked the modified CF-type structure (mCF) that had been observed by Ishii et al. (2014) and found that \( R_F \) was nearly as high as that for xieite. We repeated the Le Bail extraction based on a cell in space group \( Pnma \) and conducted a second reversed Monte Carlo optimization using a \( \text{CaFe}_2\text{O}_4 \)-type model structure. This second optimization resulted in an \( R_F \) of 9.1%. Le Bail-extraction converged to \( R_p = 4.3\% \) (Kraus and Nolze 1996). The difference between \( R_F \) and \( R_p \) reflects the noise level of the data and overlap of chenmingite reflections with coexisting chromite. Rietveld refinement (von Drese and Larson 2004; Kraus and Nolze 1996) was then conducted based on the structure model from the rMC optimization, and by either initially refining the preferred orientation
with the March-Dollase approach along 302 and 020 or by modeling texture with spherical
harmonics to 2nd order. Both approaches converged to the same orientation along the same
main directions. Subsequently, atomic positions and isotropic thermal displacement factors
were refined. The final wR$_p$ of the Rietveld-refinement was 5.7% with a $\chi^2 = 43.9$ for 2062
observations. Pseudovoigt peak profiles were used with Gaussian terms U = 858, V = 231, W
= 17.1 and Lorentzian terms L$_x$ = 18.9 and L$_y$ = 16.2 (with GSAS).

We used the extracted structure factor moduli to obtain the average electron density at
each of the three cation sites. Site occupancies were assigned based on EPMA results and the
assessed relative average electron density of the cation sites. The relative electron density of
the three sites were assessed by rMC, using the Le Bail extracted structure factor moduli (the
multiplicity is taken into account by the rMC method and splitting of $|F(hkl)|$ between strictly
overlapping hkl does not need to be considered here). rMC cannot directly assess partial
occupancies but electron density on distinct sites. Hence, we modeled a site with, for
example, ~ 20 electrons as ‘Ca’ in the rMC optimization (although there is no significant
concentration of Ca in the specimen). In reality, 20 electrons correspond to some occupancy
by the actually present species (e.g., 0.82-Cr + 0.18-Al or 0.69-Fe + 0.16-Al + 0.15-Mg, etc).
Using bulk composition as a constraint, we obtained the range of possible occupancies given
in Table 2. We repeated the procedure using different background- and orientation-fits prior
to Le Bail extraction. Resulting differences are within the given uncertainties. No potentials
were used in the rMC optimizations. We vary electron density at different sites by integers
changing the apparent cation (Ca = 20, Sc = 21 etc.). We interpolated if the best $R_F$ was
obtained for an electron density intermediate between two integers. The sequence of electron
density for the three sites was reproducibly assessed as Site 3 > Site2 ≥ Site1. Form factors in
rMC are spherical. This is a sufficient approximation for the given data (with best $R_F = 9\%$.
Differences between spherical and higher order Bessel-function-based form factors are
generally not significant for $R_F > 2\%$). Isotropic thermal displacement factors of cation sites
were refined individually, and those of O were arbitrarily set equal to each other.

Synchrotron-diffraction data, which were obtained for regions free of xieite, reveal
that chenmingite has an orthorhombic $Pnma$ CF-type structure with unit cell: $a = 9.715$ (6) Å,
$b = 2.87$ (1) Å, $c = 9.49$ (7) Å, $V = 264.6$ (4) Å, and $Z = 4$. Atom coordinates are given in
Table 2 and X-ray powder diffraction data are listed in Tables S1-S2. Chenmingite is isotypic.
with harmunite (CaFe$_2$O$_4$). 50-60 vol% of the selected sample region were from chenmingite and 40 - 50% from chromite and ulvöspinel (Fig. 2).

**DISCUSSION**

Phase relations for FeCr$_2$O$_4$ (Ishii et al. 2014) show that chromite, the stable ambient pressure phase in the spinel structure, breaks down to form ludwigite-type Fe$_2$Cr$_2$O$_5$ plus eskolaite (Cr$_2$O$_3$) with increasing pressure (12-16 GPa, decreasing with increasing temperature; see Fig. 3). At higher pressures (16-18 GPa), this phase assemblage yields to single phase fields of chenmingite (CF-structured FeCr$_2$O$_4$) at lower temperature and xieite (CT-structured FeCr$_2$O$_4$) at higher temperature. CF-type endmember FeCr$_2$O$_4$ undergoes a transition upon release to ambient conditions (mCF; Ishii et al. 2014) whereas xieite can be recovered to ambient conditions. Type chenmingite contains Mg and Al as minor components and the formula may be broken down as approximately 75 mole% chenmingite, 15% MgAl$_2$O$_4$, and 7% MgCr$_2$O$_4$. In the MgCr$_2$O$_4$ system, the CT structure is stable relative to CF to low temperatures (< 1100°C; Ishii et al. 2015). For MgAl$_2$O$_4$, the CF-structure is stable only above 23 GPa and 1600 °C (Kojitani et al. 2007) up to at least 2000°C whereas the CT-structured phase appears only above ~ 40 GPa (Ono et al. 2006; Ishii et al. 2015).

Disregarding real mixing volumes, an increasing FeCr$_2$O$_4$-component is expected to reduce the pressure of the spinel-to-postspinel transformation, whereas the MgAl$_2$O$_4$ component appears to stabilize the CF-over the modified CF-structure in the given (Fe,Mg)(Cr,Al)$_2$O$_4$ solid solution.

Comparing all examined end-member phase diagrams, the CF-structure (i.e., chenmingite) is the low-temperature, high-pressure form and the CT-structure (xieite) is the high-temperature, high-pressure form. This experimental finding is consistent with the observation of chenmingite as dominant over xieite in shocked chromite further away from melt pockets.

The ratio of the sum of the lengths of the two long axes over that of the short axis (a+c)/b (in standard cell setting) of 6.67 of type chenmingite is within the range of other CF-type phases reported in the literature: 6.64 to 6.70 (Irifune et al.1991; Lazic et al. 2006; Arevalo-Lopez et al. 2010; Ishii et al. 2018) including mCF-type FeCr$_2$O$_4$ (6.66; Ishii et al. 2014). Thus, the relative contraction of the c-axis of chenmingite is compensated by expansion of the a- and b-axis. An apparent relation of the ratio of the effective cation radii...
with this axial ratio is well matched by chenmingite. On the other hand, the apparent bond
valences are low, with values between 4 and 5 rather than 6. This observation suggests a high
degree of disorder of the anion lattice (because the relation between cation radii and cell-
parameters are well within the expected range). Such disorder is not unexpected in a
structure of limited metastability.

The EPMA analyses show no significant difference in chemistry between host
chromite and either xieite or chenmingite, which suggests that both chenmingite and
xieite formed by solid-state transformation from precursor chromite under high pressures
and temperatures during the Tissint impact event on Mars. These features are consistent
with expectations based on phase relations of the FeCr$_2$O$_4$ system (Fig. 3). Upon release
breakdown to eskolaite and Fe-Cr-ludwigite is not observed, consistent with rapid
temperature-release at still high dynamic stresses, which also allow for the conservation
of bridgmanite (Tschauer et al. 2014). Bridgmanite has been observed in shock melt
pockets of Tissint (Ma et al. 2016). It is important to note, in this context, that xieite
regions (aggregates of sub-micrometer-sized crystals) are always in contact with melt
pockets, whereas chenmingite lamellae only occur within the precursor chromite, a few
micrometers away from the melt pockets. This spatial correlation suggests that
chenmingite formed in the same pressure regime as xieite but at lower temperatures. A
similar textural relationship between xieite and chenmingite has been reported for the
Suizhou S6-L6-chondrite (Chen et al. 2003a).

**IMPLICATIONS**

In meteorites and, possibly, in terrestrial impactites, chenmingite and xietite document
the effect of high-pressure, high-temperature shock conditions on precursor chromite. Based
on the FeCr$_2$O$_4$ system, the formation of chenmingite from chromite requires pressures
exceeding 16-18 GPa and temperatures below ~1350°C. The formation of xieite requires
comparable pressures but higher temperatures. Peak shock pressures in Tissint have been
estimated to ~ 30 GPa (Baziotis et al. 2013; Walton et al. 2014; Ma et al. 2016). Generally,
kinetic phase boundaries are shifted relative to the thermodynamic ones to higher pressure at
lower temperature as evidenced by the zoned paragenesis strained olivine $\rightarrow$ ringwoodite or
ahrensite $\rightarrow$ wüsite + bridgmanite around Tissint shock-melt pockets (Ma et al. 2016).
Equivalently, chenmigite represents a cooler regime within a sequence of kinetically shifted
phase boundaries along a temperature gradient of a hotspot: Chromite with deformation
twinning $\rightarrow$ chenmingite $\rightarrow$ xieite. Hence, chenmingite and xieite are potential markers for
S4 to S6 level shock metamorphism depending on the approximate temperature regime of
formation. That is within or at some distance from a shock melt pocket or vein.

Chromite is commonly observed as an exsolution phase from former high-pressure
silicates in diamonds (e.g., Brenker et al. 2002). In the Earth’s transition zone, Cr and Ti are
easily dissolved in majoritic garnet (Kessel et al. 2005) and may not be major constituents of
accessory minerals such as in spinel peridotite. On the other hand, an ilmenite-inclusion at a
remnant pressure of 10-12 GPa has been found in diamond (Tschauner et al. 2018). Hence,
the occurrence of chenmingite and xieite in adamantiferous metasomatized mantle appears
possible. Within such an environment, chenmingite or xieite could operate as carriers of high
field strength elements.

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American Mineralogist, 92, 1112‒1118.


Table 1. EPMA data for type chenmingite and associated phases.

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<tr>
<th>Constituent</th>
<th>Chenmingite</th>
<th>Xieite</th>
<th>Chromite</th>
<th>Fe, Cr-rich ulvöspinel</th>
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<td>n=7</td>
<td>n=12</td>
<td>n=11</td>
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<tr>
<td>Cr$_2$O$_3$</td>
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<td>57.7 (0.4)</td>
<td>20 (2)</td>
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<td>Al$_2$O$_3$</td>
<td>7.1 (0.1)</td>
<td>6.79 (0.05)</td>
<td>7.2 (0.2)</td>
<td>5.3 (0.4)</td>
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<td>TiO$_2$</td>
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<td>0.65 (0.03)</td>
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<td>FeO</td>
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<td>MgO</td>
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<td>MnO</td>
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<td>0.62 (0.01)</td>
<td>0.63 (0.03)</td>
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<td>1.59</td>
<td>1.60</td>
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<td>Mn</td>
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<td>Sum cations</td>
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<td>3.00</td>
<td>3.01</td>
<td>3.00</td>
</tr>
</tbody>
</table>

$^a$n = number of analyses.

$^b$Errors given inside parentheses are one standard deviation of the mean based on all of the analyses.

$^c$Fe$^{3+}$ and Fe$^{2+}$ were calculated from total Fe to produce the ideal M$_3$O$_4$ stoichiometry.
Table 2. Fractional atom coordinates, site fractional occupancies, and isotropic thermal displacement factors of chenmingite. Site occupancies of O are fixed. All atoms reside on Wyckoff sites 4c. Isotropic displacement parameters are in Å².

<table>
<thead>
<tr>
<th>Atom</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>SOF</th>
<th>Uiso</th>
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<td>Cr1</td>
<td>0.754(4)</td>
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<td>0.347(2)</td>
<td>0.80(4)</td>
<td>0.040(8)</td>
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<td>0.25</td>
<td>0.347(2)</td>
<td>0.20(4)</td>
<td>0.040(8)</td>
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<td>0.102(9)</td>
<td>0.67(18)</td>
<td>0.011(8)</td>
</tr>
<tr>
<td>Al+Mg</td>
<td>0.933(2)</td>
<td>0.25</td>
<td>0.102(9)</td>
<td>0.29(7)</td>
<td>0.011(8)</td>
</tr>
<tr>
<td>Fe1</td>
<td>0.92(4)</td>
<td>0.25</td>
<td>0.61(2)</td>
<td>0.87(10)</td>
<td>0.048(1)</td>
</tr>
<tr>
<td>Cr3</td>
<td>0.92(4)</td>
<td>0.25</td>
<td>0.61(2)</td>
<td>0.13(10)</td>
<td>0.048(1)</td>
</tr>
<tr>
<td>O1</td>
<td>0.21(1)</td>
<td>0.25</td>
<td>0.84(2)</td>
<td>1</td>
<td>0.03(2)</td>
</tr>
<tr>
<td>O2</td>
<td>0.115(4)</td>
<td>0.25</td>
<td>0.52(1)</td>
<td>1</td>
<td>0.03(2)</td>
</tr>
<tr>
<td>O3</td>
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<td>0.25</td>
<td>0.21(7)</td>
<td>1</td>
<td>0.03(2)</td>
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<tr>
<td>O4</td>
<td>0.42(1)</td>
<td>0.25</td>
<td>0.58(1)</td>
<td>1</td>
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</table>
(a) 
maskelynite

chromite + chenmingite

pyroxene

olivine

melt pocket

olivine

chromite + chenmingite

100 μm

(b) 
Fe,Cr-rich ulvöspinel

chenmingite

chenmingite

xieite

10 μm
Figure 1. (a) Backscatter electron (BSE) image showing the chenmingite-bearing chromite grains next to shock melt pockets in Tissint. (b)(c) Enlarged BSE images of areas in panel a revealing chenmingite in two chromite grains with xieite and Fe,Cr-rich ulvöspinel. (d) Enlarged BSE image of area in panel c showing chenmingite lamellae in chromite.
Figure 2. Polycrystalline diffraction pattern of chenmingite, chromite and ulvöspinel. red line: Rietveld-refined modeled pattern of chenmingite, blue and green lines: Le-Bail fitted patterns of chromite and ulvöspinel, black crosses: observed pattern, bottom green line: residual of fit, red tick marks: allowed reflections of chenmingite. Blue and green tick marks: chromite and ulvöspinel. The chenmingite aggregate is fine grained, powder-like but highly oriented. Preferred orientation along axes 302 and 020 was modeled. Extracted structure factor moduli were corrected for orientation effects. The primary beam wavelength was 0.4959 Å.

Figure 3. Phase diagram of FeCr$_2$O$_4$ based on Ishii et al. (2014). Sp: spinel-FeCr$_2$O$_4$ (chromite); mLd: modified ludwigite type Fe$_2$Cr$_2$O$_5$; Es: eskolaite; CF: CF-structured FeCr$_2$O$_4$ (chenmingite); CT: CT-structured FeCr$_2$O$_4$ (xieite).