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Natural CaTi_2O_4 -structured FeCr_2O_4 polymorph in the Suizhou meteorite and its significance in mantle mineralogy

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Abstract—The first natural occurrence of a high-pressure polymorph of chromite has been discovered in the shock-metamorphosed Suizhou meteorite. The composition of this high-pressure polymorph is identical to that of the precursor chromite. The Raman spectrum of this polymorph is distinct from that of chromite. Synchrotron X-ray diffraction analysis revealed that this polymorph has an orthorhombic CaTi_2O_4 -type structure. The cell parameters are: $a = 9.462(6)$ Å, $b = 9.562(9)$ Å, $c = 2.916(1)$ Å, $V = 263.8(4)$ Å³ ($Z=4$), space group = $Bbmm$, and the density = 5.63 g/cm³ (the numbers in parentheses are standard deviations on the last significant digits). This polymorph is 11.5% denser than chromite. The P-T conditions for the phase transformation from chromite to the CaTi_2O_4 -structured polymorph are estimated at 20–23 GPa and 1800 to 2000 °C, respectively. This dense CaTi_2O_4 -structured FeCr_2O_4 phase could be a host phase for Cr, Al, Fe, Mg and Mn and other metallic elements in the deep Earth. Copyright © 2003 Elsevier Ltd

1. INTRODUCTION

Spinel-type AB_2O_4 compounds occur in many geological settings of the Earth's crust and mantle, as well as in lunar rocks and meteorites. High-pressure AB_2O_4 compounds are of great importance for the understanding of the constituents of the deep Earth. High-pressure experiments revealed that AB_2O_4 compounds at high-pressure may adopt CaFe_2O_4 -, CaMn_2O_4 - and CaTi_2O_4 -type structures, whereby their structures attain atomic arrangements such that these structures become denser than spinel (Reid and Ringwood, 1970). Experimental investigations have also indicated that the spinel compounds Mn_3O_4 and Fe_3O_4 , and MgFe_2O_4 transform to CaMn_2O_4 -type structure at pressure above 25 GPa, that the CaAl_2O_4 and MgAl_2O_4 transform to a CaFe_2O_4 structure at pressure above 26.5 GP, and that the MgAl_2O_4 structure changes to a CaTi_2O_4 structure at pressure above 40 GP (Reid and Ringwood, 1969; Mao et al., 1974; Irifune et al., 1991; Funamori et al., 1998; Akaogi et al., 1999; Fei et al., 1999; Andrault and Bolfan-Casanova, 2001). In addition, CaFe_2O_4 -type $\text{NaAlSi}_3\text{O}_8$ was experimentally shown to be stable at lower mantle conditions (Liu, 1978; Irifune et al., 1994; Yagi et al., 1994; Tutti et al., 2000). Dense CaFe_2O_4 -, CaMn_2O_4 - and CaTi_2O_4 -structured high-pressure phases have so far not found in nature.

Chromite is an important member of the spinel group. In this paper, we report the discovery of a shock-produced high-pressure polymorph of chromite in a chondritic meteorite. This finding is important for the understanding of the structural characteristics of natural AB_2O_4 compounds under high-pressure and temperature.

2. THE SUIZHOU METEORITE

The Suizhou meteorite is a fall that was recovered in Dayanpo in the southeast of Suizhou in Hubei, China, on April 15, 1986. This meteorite was classified as an L6 chondrite, and its shock classification stage as S3 to S4 (Xie et al., 2001, 2002). The meteorite is moderately shock-metamorphosed as expressed by weak mosaicism, planar fractures in olivine and partial isotropism of plagioclase (i.e., presence of maskelynite). The meteorite also contains thin shock-produced veins ranging from 20 to 90 μm in width (Fig. 1). The host meteorite consists mainly of olivine, pyroxene, and plagioclase (partially maskelynite), and iron-nickel metal and troilite, in addition to accessory chromite, ilmenite, whitlockite (merrillite) and chlorapatite. As observed for many other shock vein-bearing meteorites (Putnis and Price, 1979; Rubin, 1985; Langenhorst et al., 1995; Chen et al., 1996; Tomioka and Fujino, 1997; Gillet et al., 2000; Langenhorst and Poirier, 2000), the shock veins of the Suizhou meteorite contain abundant high-pressure minerals thought to also occur in the Earth's mantle. The high-pressure mineral assemblages in the shock veins of Suizhou meteorite were previously investigated in detail by Xie et al. (2001, 2002). The high-pressure minerals identified are: (1) coarse-grained polycrystalline aggregates of ringwoodite, majorite, $\text{NaAlSi}_3\text{O}_8$ -hollandite and a high-pressure polymorph of whitlockite formed from the precursor minerals olivine, pyroxene, plagioclase, and whitlockite, respectively; and (2) fine-grained majorite-pyroxene garnet and ringwoodite crystallized from shock-induced dense melt. Metal and troilite in the shock veins were molten and occur as eutectic FeNi-FeS grains.

3. EXPERIMENTAL TECHNIQUES

Polished thin sections of the Suizhou meteorite, containing shock veins, were prepared for analysis of texture, mineral phases and their crystal structure, and their chemical compositions.

The mineral assemblages and textures in thin sections were investigated with a petrographic microscope and a Hitachi S-3500N scanning electron microscope in back-scattered electron (BSE) mode. Compo-

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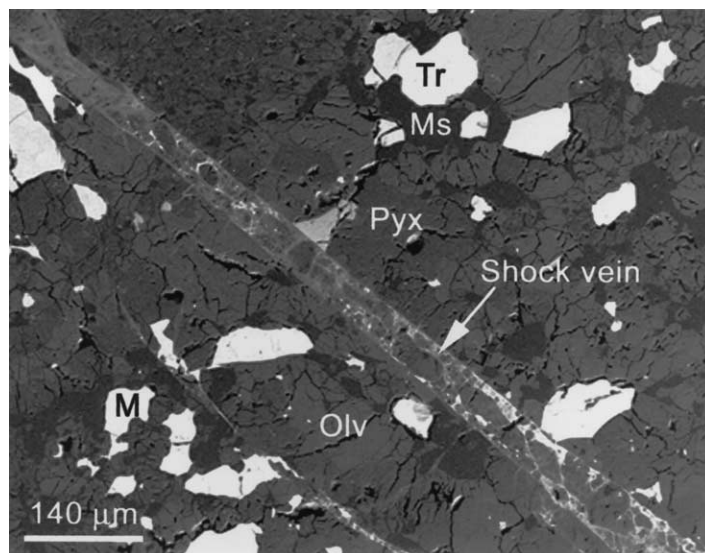


Fig. 1. Back-scattered electron (BSE) image showing a shock vein in the Suizhou meteorite. Olv = olivine; Pyx = pyroxene; Ms = maskelynite; Tr = troilite; M = FeNi-metal.

sitions of minerals were quantitatively determined by a Cameca SX-51 electron microprobe using wave-length dispersive analysis at 15 kV accelerating voltage and 10 nA sample current at the Institute of Geology, Chinese Academy of Sciences.

Raman spectra of minerals in the polished thin section were recorded with a Renishaw RM-1000 instrument at the China University of Geology. A microscope was used to focus the excitation beam (Ar^+ laser, 514 nm line) to 2- μm -wide spots and to collect the Raman signal. Accumulations of the signal lasted from 120 to 150 s. The laser power was 26.8 mW.

For determining the crystal structure of micro-phases in a polished thin section, synchrotron X-ray diffraction analyses were conducted at the beamline X17C of the National Synchrotron Light Source of the Brookhaven National Laboratory, New York. The X-ray beam was collimated to a size of 8 μm by 18 μm . The thin section was rotated to collect diffraction lines. Analysis of diffracted X-rays was carried out with

an intrinsic germanium detector. The X-ray diffraction data were acquired at fixed 2θ (the 2θ is the angle between the incident X-ray beam and the diffracted X-ray beam) settings of 8, 10, 13 and 15 degree, respectively.

4. RESULTS

The chromite grains in the less shocked portions of the meteorite usually contain abundant cracks and fractures (Fig. 2). In the regions adjacent to the shock veins and within the veins, we observed a new phase with only few fractures that has an identical composition to chromite (Figs. 3, 4). This new phase usually occurs as polycrystalline aggregates of 5 to 40 μm size. In particular, many intergrowths between chromite crys-

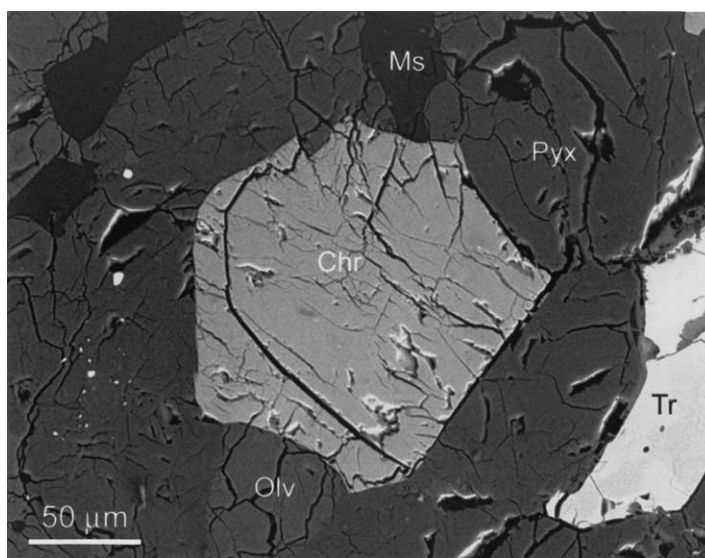


Fig. 2. A chromite grain (Chr) in a, in comparison to the shock veins, less shock metamorphosed area of this meteorite contains abundant fractures that also penetrate the neighboring silicates, in which sets of fractures can be recognized. BSE image. Ms = maskelynite; Olv = olivine; Pyx = pyroxene.

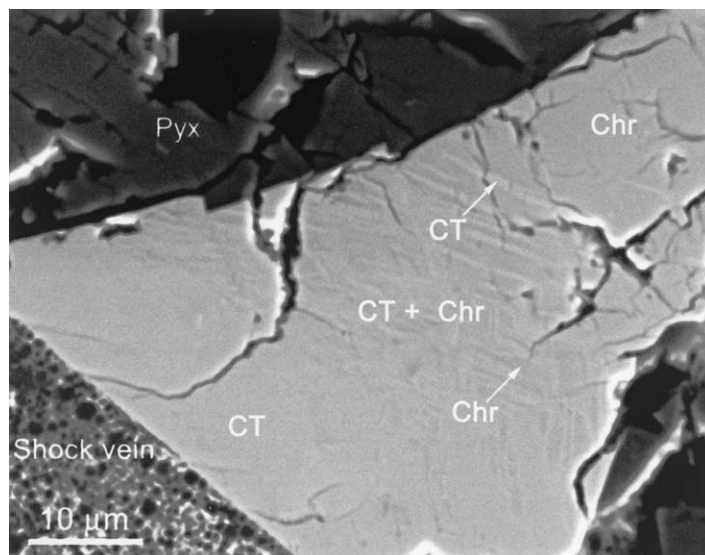


Fig. 3. A BSE image showing an intergrowth of the new phase (CaTi₂O₄-structured FeCr₂O₄, CT) and relic of chromite (Chr). On the image, the new phase is brighter than chromite. The intergrowth area (CT + Chr) occurs between a pure area of chromite (Chr) and a pure area of new phase (CT). This grain was irradiated by the synchrotron beam in an area composed of the new phase (CT) and the intergrowth of two phases (CT + Chr).

tals and the new, relatively electron-brighter phase have been observed in a zone up to 40 μm wide adjacent to shock veins.

Figure 3 shows an intergrowth consisting of the new phase and chromite in the matrix directly in contact with the shock vein. One can see on this back-scattered electron image that the new phase is electron-brighter than chromite (Fig. 3). Such intergrowth grains usually show that the amount of the new phase increases closer to the shock vein, whereby the intermediate zone contains both phases. In comparison with cracked chromite grains, the new phase has few fractures. As the shock veins are thought to have been formed due to shock-induced high-pressure and tem-

perature excursions (Putnis and Price, 1979; Rubin, 1985; Stöffler et al., 1991; Langenhorst et al., 1995; Chen et al., 1996; Tomioka and Fujino, 1997; Langenhorst and Poirier, 2000; Xie et al., 2001, 2002), the formation of the new phase appears to be pressure-dependent. It, thus, appears that this new phase formed due to shock transformation from precursor chromite.

Inside the shock vein, the grain sizes of the new phase are relatively small (less than 20 μm) (Fig. 4). This could mean that the precursor chromite was fragmented first, and then transformed into the new phase. These small grains consist of the new phase only. Neither intergrowths of the new phase and

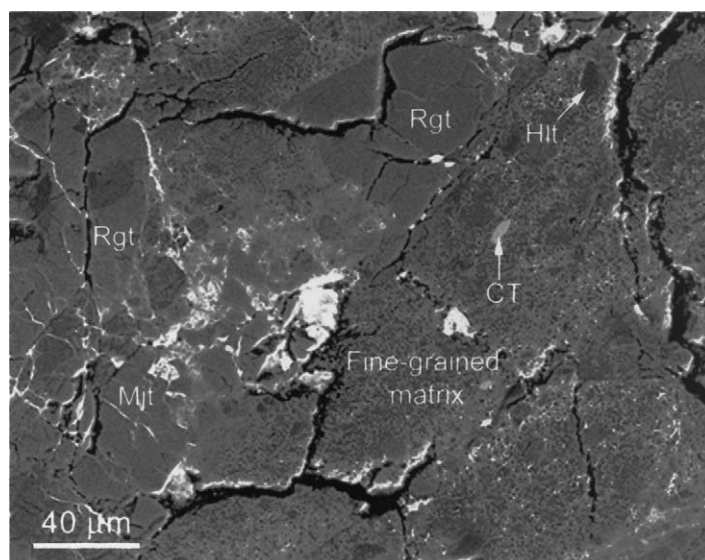


Fig. 4. A BSE image showing that the shock vein consists of ringwoodite (Rgt), majorite (Mjt), NaAlSi₃O₈-hollandite (Hlt), the new phase (CT) and a fine-grained matrix composed of majorite-pyroxene, ringwoodite, molten and solidified metal, and troilite.

Table 1. Average compositions of chromite and the new phase. All data in weight %; the number in parentheses is the number of analyses (n.d., not detected; STDEV, standard deviation).

	New phase		Chromite	
	(5)	STDEV	(5)	STDEV
MgO	2.62	0.12	2.62	0.11
FeO	29.70	0.28	29.53	0.25
MnO	0.81	0.08	0.85	0.14
CaO	n.d.		n.d.	
TiO ₂	2.59	0.16	2.95	0.16
Cr ₂ O ₃	57.30	0.18	56.81	0.25
Al ₂ O ₃	5.94	0.07	6.29	0.17
V ₂ O ₃	0.97	0.06	0.91	0.04
	99.93		99.96	

chromite, nor single grains of chromite have been observed inside the shock veins.

Electron microprobe analyses of chromite and the new phase indicate that their chemical compositions are identical. The compositions are: 56–57 wt.% Cr₂O₃, 29 wt.% FeO, and small amounts of Al₂O₃, MgO, TiO₂, MnO and V₂O₃ (Table 1).

Raman spectroscopic analysis indicates that the spectrum of the new phase is distinct from that of chromite. We observed three Raman bands at wave numbers 601, 637 and 664 cm⁻¹ in comparison to four characteristic bands of chromite at 500,

595, 631 and 677 cm⁻¹ (Fig. 5). The strong band at 677 cm⁻¹ in chromite can be assigned the A_{1g} mode of the spinel structure (Gupta et al., 1993). The strong peak at 601 cm⁻¹ for the new phase in the Suizhou meteorite is suggestive of a phase with a crystal structure that is different from that of chromite.

We determined the structure of the new phase by synchrotron X-ray diffraction on the same intergrowth shown in Figure 3. The X-ray patterns obtained with the sample in fixed orientation indicate a polycrystalline nature. We collected 21 X-ray reflections from the new phase in addition to several reflections from chromite (Fig. 6 and Table 2), because the target area of the sample irradiated by the X-ray beam contains both the new phase and a small amount of chromite. The crystal structure of the new phase is stable during X-ray irradiation, although the sample was exposed to X-ray irradiation for over 60 h in total. The *d* spacings of 21 X-ray reflections from the new phase were indexed in the framework of an orthorhombic lattice with the cell parameters: *a* = 9.462(6) Å, *b* = 9.562(9) Å, *c* = 2.916(1) Å (numbers in parentheses are standard deviations for the last significant digits). The space group of this orthorhombic lattice is *Bbmm*. The *d*-spacings of the X-ray diffraction lines can be indexed in terms of the CaTi₂O₄ structure (Bright et al., 1958). The calculated density of the new phase is 5.63 g/cm³, which is 11.5% denser than the chromite structure. This is the first observation of a dense postspinel polymorph for AB₂O₄ compounds.

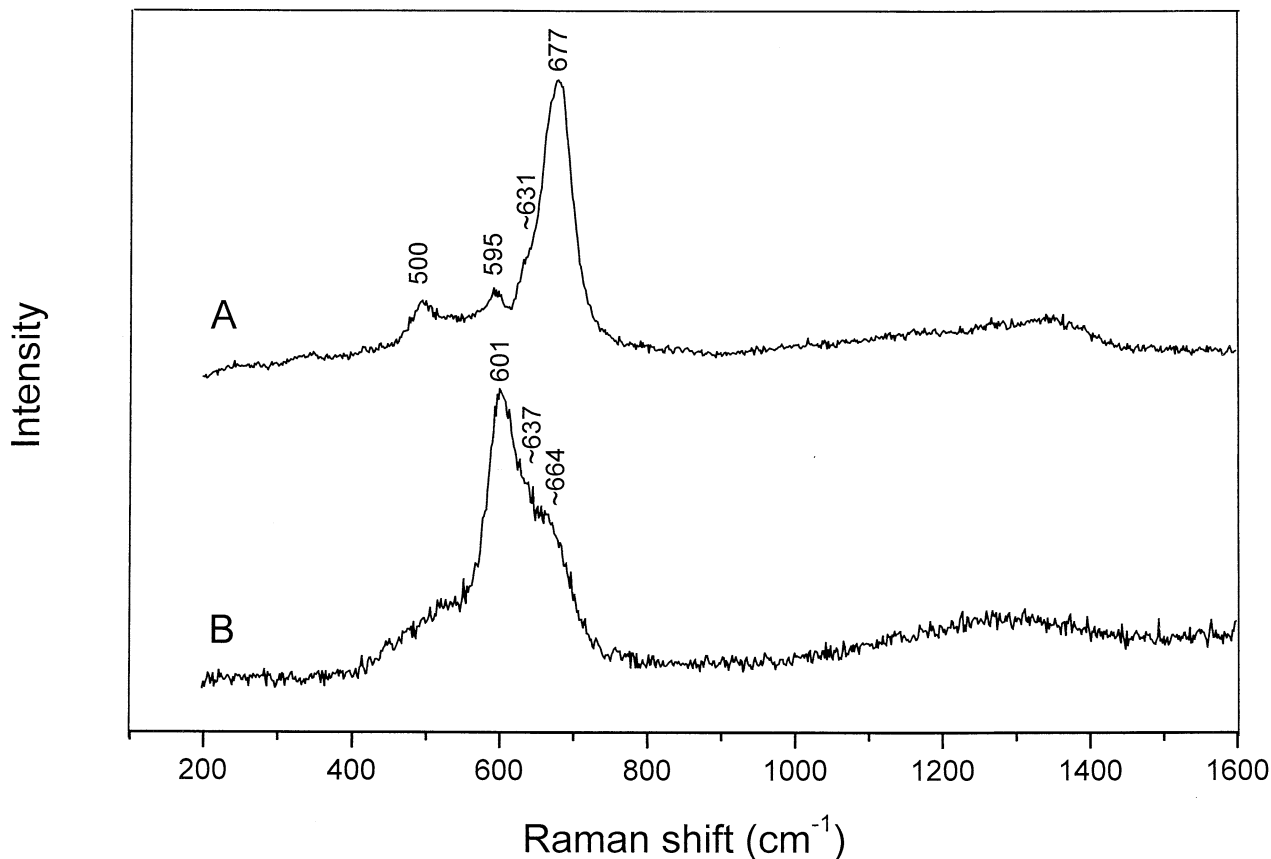


Fig. 5. (A) Raman spectrum of chromite. (B) Raman spectrum of the CaTi₂O₄-structured polymorph of chromite (FeCr₂O₄).

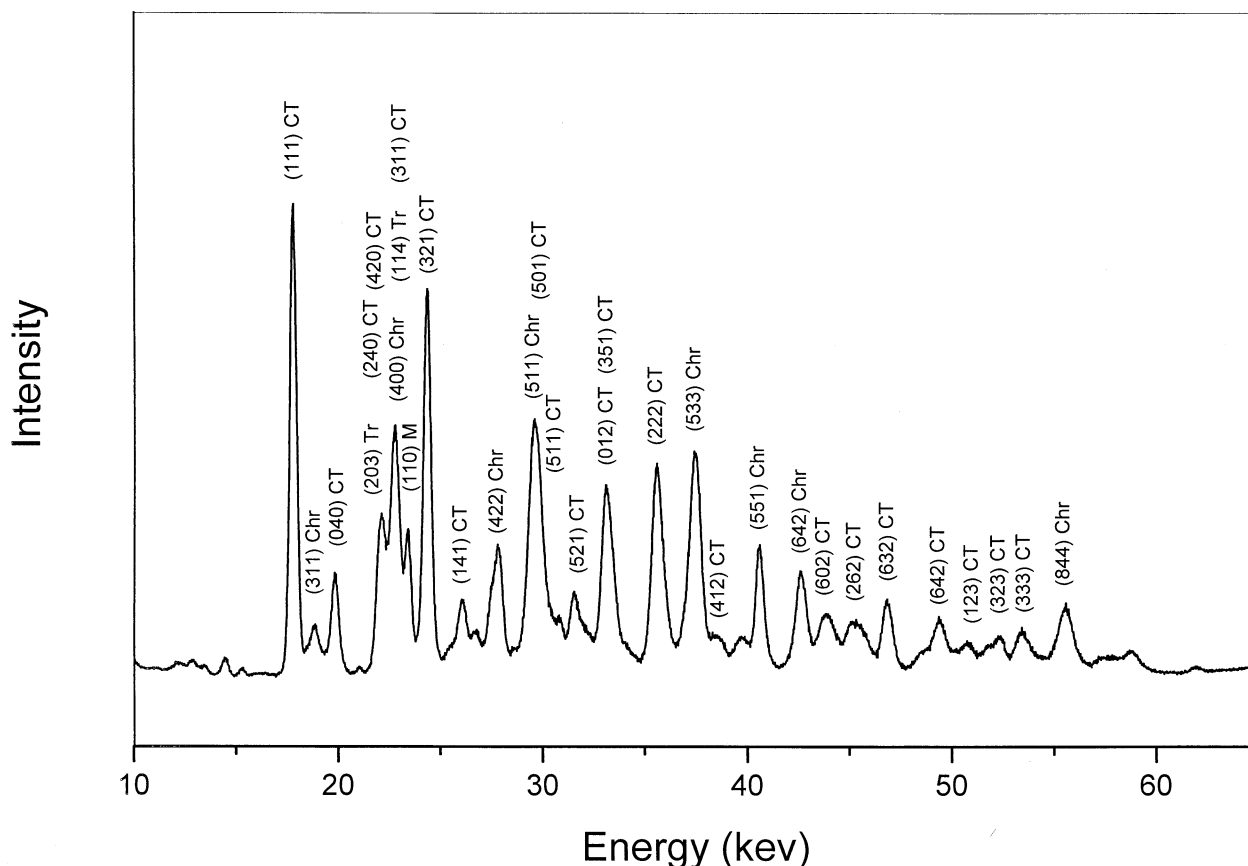


Fig. 6. (A) X-ray diffraction pattern obtained on an intergrowth grain consisting of the new phase (CaTi₂O₄-structured FeCr₂O₄) and a relic of chromite, collected at fixed $2\theta=14.9977$. In total, 21 diffraction lines could be indexed for the CaTi₂O₄ structure (CT). The remaining lines belong to chromite (Chr) and FeNi-metal (M).

5. DISCUSSION

The CaTi₂O₄-structure is intimately related to the CaFe₂O₄- and CaMn₂O₄-structures. The orthorhombic CaTi₂O₄-, CaFe₂O₄-, and CaMn₂O₄ type structures are composed of dodecahedral (AO₈) and octahedral sites (BO₆), in which the differences among these structures lie in slight modifications of the polyhedral linkage (Reid and Ringwood, 1970; Andraut and Bolfan-Casanova, 2001). The only natural occurrence of minerals of any these three structural types is marokite (CaMn₂O₄) that has been found in two terrestrial rocks formed at low pressure (Gaudefroy et al., 1963; Villiers and Herbstein, 1968). A CaTi₂O₄ crystal with space group *Bbmm* was synthesized experimentally (Bertaut and Blum, 1956; Bright et al., 1958). No natural occurrence of CaTi₂O₄ and CaFe₂O₄-structured minerals has been reported to date.

The occurrence of the CaTi₂O₄-structured FeCr₂O₄-phase is related to a shock vein in the Suizhou meteorite, where peak shock pressure and temperature experienced by this meteorite were located. The P-T conditions for the formation of this CaTi₂O₄-structured FeCr₂O₄ phase can be constrained according to the high-pressure mineral assemblage within the shock vein. The occurrence of ringwoodite, majorite, NaAlSi₃O₈-hollandite and majorite-pyrope garnet in the shock vein constrains the peak pressure and temperature to 20–23 GPa and 1800–2000 °C, respectively (Agee et al., 1995; Chen et al.,

Table 2. Indexed peaks of the X-ray diffraction pattern and Miller indices for the natural CaTi₂O₄-structured FeCr₂O₄ phase. d_{obs} and d_{cal} are observed and calculated d values, respectively. The cell parameters calculated from these data are: $a = 9.462(6)$ Å, $b = 9.562(9)$ Å, $c = 2.916(1)$ Å, $V = 263.8(4)$ Å³ ($Z = 4$), space group = *Bbmm*, calculated density = 5.63 g/cm³.

hkl	d_{obs} , Å	d_{cal} , Å
111	2.6747	2.6754
040	2.3890	2.3905
240	2.1306	2.1336
420	2.1220	2.1203
311	2.0887	2.0895
321	1.9526	1.9542
141	1.8138	1.8144
501	1.5881	1.5875
511	1.5661	1.5661
521	1.5060	1.5066
012	1.4394	1.4414
351	1.4247	1.4263
222	1.3373	1.3377
412	1.2292	1.2309
602	1.0717	1.0706
262	1.0502	1.0490
632	1.0140	1.0149
642	0.9775	0.9771
123	0.9479	0.9477
323	0.9138	0.9119
333	0.8900	0.8918

1996; Gillet et al., 2000; Xie et al., 2002). There must be a sharp gradient of temperature from the shock veins to the surrounding less shocked material, as the new phase is not observed beyond 40 μm from the edge of a shock vein. It indicates that the high-pressure phase transitions are not kinetically obstructed in hot regions, especially inside and close to the shock veins. In comparison to experimentally unquenchable CaMn_2O_4 -structured Fe_3O_4 (Fei et al., 1999) and CaFe_2O_4 (or CaTi_2O_4)-structured ZnCr_2O_4 polymorphs (Wang et al., 2002), this natural CaTi_2O_4 -structured FeCr_2O_4 phase is quenchable during decompression.

Experimental investigations indicate that, with increasing pressure, the MgAl_2O_4 spinel dissociates first to Al_2O_3 plus MgO above 25 GPa, then both oxides recombine to a CaFe_2O_4 -type phase above 34 GPa, and finally to a CaTi_2O_4 -structured phase above 40 GPa (Funamori et al., 1998). We did not find any evidence indicating that chromite was decomposed into Cr_2O_3 plus FeO or recombined to a CaTi_2O_4 -structured phase. Direct phase transition from FeCr_2O_4 to CaTi_2O_4 -structure phase is, therefore, inferred.

In the spinel group (AB_2O_4), the cationic substitutions between Al^{3+} and Cr^{3+} , and between Mg^{2+} and Fe^{2+} are extensive. Chromspinel $(\text{Mg,Fe})(\text{Al,Cr})_2\text{O}_4$ is an important accessory mineral in the Earth's mantle, as for example seen in ilmenite from the upper mantle (Scarfe et al., 1979). If the compound $(\text{Mg,Fe})(\text{Al,Cr})_2\text{O}_4$ or its analogues exist in the transition zone and the lower mantle, they might take the structure of CaTi_2O_4 - or CaFe_2O_4 -type compounds. Experiments have indeed demonstrated the existence of CaTi_2O_4 - and CaFe_2O_4 -structured MgAl_2O_4 phases at P-T conditions of the lower mantle (Irifune et al., 1991; Funamori et al., 1998). The natural CaTi_2O_4 -structured FeCr_2O_4 phase in the Suizhou meteorite contains about 6 wt.% of Al_2O_3 and 2.6 wt.% of MgO , whereby the cations Al^{3+} and Cr^{3+} occupy octahedral sites (BO_6) and the Mg^{2+} and Fe^{2+} occupy the dodecahedral sites (AO_8). Therefore, the natural occurrence of the CaTi_2O_4 -structured FeCr_2O_4 phase in the Suizhou meteorite indicates that the CaTi_2O_4 structure could be an important host phase for Cr^{3+} , Al^{3+} and other metal elements (Mg^{2+} , Fe^{2+} , Ni^{2+} , Mn^{2+} , Zn^{2+} and Mn^{3+} etc) in the deep Earth.

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REFERENCES

- Agee C. B., Li J., Shannon M. C., and Circone S. (1995) Pressure-temperature phase diagram for the Allende meteorite. *J. Geophys. Res.* **100**, 17725–17740.
- Akaogi M., Hamada Y., Suzuki T., Kobayashi M., and Okada M. (1999) High pressure transitions in the system MgAl_2O_4 - CaAl_2O_4 : A new hexagonal aluminous phase with implication for the lower mantle. *Phys. Earth Planet. Int.* **115**, 67–77.
- Andraut D. and Bolfan-Casanova N. (2001) High-pressure phase transformations in the MgFe_2O_4 and Fe_2O_3 - MgSiO_3 system. *Phys. Chem. Minerals.* **28**, 211–217.
- Bertaut E. F. and Blum P. (1956) Determination de la Structure de Ti_2CaO_4 par la Méthode Self-Consistante d'Approche Directe. *Acta Cryst.* **9**, 121–126.
- Bright N. F. H., Rowland J. F., and Wurm J. G. (1958) The compound $\text{CaO.Ti}_2\text{O}_3$. *Can. J. Chem.* **36**, 492–495.
- Chen M., Sharp T. G., El Goresy A., Wopenka B., and Xie X. (1996) The majorite-pyrope + magnesiowüstite assemblage: Constraints on the history of shock veins in chondrites. *Science* **271**, 1570–1573.
- Fei Y., Frost D. J., Mao H. K., Prewitt C. T., and Häusermann D. (1999) In situ structure determination of the high-pressure phase of Fe_3O_4 . *Am. Mineral.* **84**, 203–206.
- Funamori N., Jeanloz R., Nguyen J. H., Kavner A., and Caldwell W. A. (1998) High-pressure transformations in MgAl_2O_4 . *J. Geophys. Res.* **103**, 20813–20818.
- Gaudefroy C., Jouravsky C., and Permingeat F. (1963) La marokite, CaMn_2O_4 , une nouvelle espèce minérale. *Bull. Soc. Franç. Mineral. Cristallogr.* **86**, 359–367.
- Gillet P., Chen M., Dubrovinsky L., and El Goresy A. (2000) Natural $\text{NaAlSi}_3\text{O}_8$ -hollandite in the shocked Sixiangkou meteorite. *Science* **287**, 1633–1636.
- Gupta H. C., Sinha M. M., Balram B. B., and Tripathi B. B. (1993) Lattice dynamics of oxide-spinel ZnCr_2O_4 . *J. Solid State Chem.* **102**, 315–317.
- Irifune T., Fujino K., and Ohtani E. (1991) A new high-pressure form of MgAl_2O_4 . *Nature* **349**, 409–411.
- Irifune T., Ringwood A. E., and Hibberson W. O. (1994) Subduction of continental crust and terrigenous and pelagic sediments: an experimental study. *Earth Planet. Sci. Lett.* **126**, 351–368.
- Langenhorst F. and Poirier J. P. (2000) Anatomy of black veins in Zagami: Clues to the formation of high-pressure phases. *Earth Planet. Sci. Lett.* **184**, 37–55.
- Langenhorst F., Joreau P., and Doukhan J. C. (1995) Thermal and shock metamorphism of the Tenham chondrite: A TEM examination. *Geochim. Cosmochim. Acta* **59**, 1835–1845.
- Liu L. (1978) High-pressure phase transformation of albite, jadeite and nepheline. *Earth Planet. Sci. Lett.* **37**, 438–444.
- Mao H. K., Takahashi T., Bassett W. A., Kinsland G. L., and Merrill L. (1974) Isothermal composition of magnetite to 320 kbar and pressure-induced phase transformation. *J. Geophys. Res.* **79**, 1165–1170.
- Putnis A. and Price G. D. (1979) High-pressure $(\text{Mg,Fe})_2\text{SiO}_4$ phases in the Tenham chondritic meteorite. *Nature* **280**, 217–218.
- Reid A. F. and Ringwood A. E. (1969) Newly observed high pressure transformations in Mn_3O_4 , CaAl_2O_4 , and ZrSiO_4 . *Earth Planet. Sci. Lett.* **6**, 205–208.
- Reid A. F. and Ringwood A. E. (1970) The crystal chemistry of dense M_3O_4 polymorphs: High pressure Ca_2GeO_4 of K_2NiF_4 structure type. *J. Solid State Chem.* **1**, 557–565.
- Rubin A. E. (1985) Impact melt products of chondritic material. *Rev. Geophys.* **23**, 277–300.
- Scarfe C. M., Mysen B. O., and Rai C. S. (1979) Invariant melting behavior of mantle material: Partial melting of two ilmenite nodules. *Carnegie Inst. Wash. Yearb.* **78**, 498–501.
- Stöffler D., Klaus K., and Scott E. R. D. (1991) Shock metamorphism of ordinary chondrites. *Geochim. Cosmochim. Acta* **55**, 3845–3867.
- Tomioka N. and Fujino K. (1997) Natural $(\text{Mg,Fe})\text{SiO}_3$ -ilmenite and perovskite in the Tenham meteorite. *Science* **277**, 1084–1086.
- Tutti F., Dubrovinsky L. S., and Saxena S. K. (2000) High pressure phase transformation of jadeite and stability of NaAlSiO_4 with calcium-ferrite type structure in the lower mantle conditions. *Geophys. Res. Lett.* **27**, 2025–2028.
- Villiers P. R. and Herbstein F. H. (1968) Second occurrence of marokite. *Am. Mineral.* **53**, 495–496.
- Wang Z., Lazor P., Saxena S. K., and Artioli G. (2002) High-pressure Raman spectroscopic study of spinel (ZnCr_2O_4). *J. Solid State Chem.* **165**, 165–170.
- Xie X., Chen M., and Wang D. (2001) Shock-related mineralogical features and P-T history of the Suizhou L6 chondrite. *Eur. J. Mineral.* **13**, 1177–1190.
- Xie X., Miniti M., Chen M., Mao H. K., Wang D., Shu J., and Fei Y. (2002) Natural high-pressure polymorph of merrillite in the shock melt veins of the Suizhou L6 chondrite. *Geochim. Cosmochim. Acta* **66**, 2439–2444.
- Yagi Y., Suzuki T., and Akaogi M. (1994) High pressure transitions in the system KAlSi_3O_8 - $\text{NaAlSi}_3\text{O}_8$. *Phys. Chem. Minerals* **21**, 12–17.