American Mineralogist, Volume 104, page 1, 2019

Highlights and Breakthroughs

Iron carbide in the core

Xiaowan Su[1,2] and Jin Liu[2,3,*]

HPSTAR
686-2019

[1]School of Earth and Space Sciences, Peking University, 100871 Beijing, China
[2]Center for High Pressure Science and Technology Advanced Research, Beijing 100094, China
[3]Department of Geological Sciences, Stanford University, Stanford, California 94305, U.S.A.

Knowledge of the high-pressure behavior of candidate inner-core components is crucial to understanding the formation, evolution, and dynamics of our planet. In the October 2018 issue of *American Mineralogist*, Lai et al. presented an experimental study on the thermoelastic properties of Fe_7C_3, a candidate component in the inner core, by single-crystal X-ray diffraction at high pressure and high temperature. Based on the anisotropic behavior of its compressibility and thermal expansivity along the crystallographic directions, they showed that high temperatures would have a significant influence on the elastic anisotropy of Fe_7C_3 under high pressure.

Iron is the most abundant cation by mass on Earth. Oxygen is the most abundant element by the number of atoms and the second element by mass (30 wt%) on Earth, while iron is the most abundant element by mass 35 wt% and carbon is the fourth most abundant element in the solar system. The most primitive C1 chondrites, which are believed to be the building blocks of our planet, contain 3.5 wt% C. The Fe-C system has been proposed as a candidate component in the Earth's core, largely based on its high cosmochemical abundance, the frequent occurrence of iron carbide phases (e.g., Fe_3C) in meteorites, and the high solubility of carbon in Fe-Ni liquids. Recently, Nakajima et al. (2009) observed that Fe_3C melted incongruently above 5–10 GPa into liquid Fe-C alloy and a more carbon-rich carbide, Fe_7C_3. Therefore, Fe_7C_3 appears to be more stable than Fe_3C under conditions relevant to the Earth's core and could be a more promising deep-carbon carrier in the inner core (Fei and Brosh 2014).

Knowledge of the high-pressure behavior and nature of Fe_7C_3 is indispensable to understanding core composition and inner-core seismic anisotropy as well as the core's role in the global carbon cycle (Hazen and Schiffries 2013; Deuss 2014). In the past few years, the crystal structure, equations of state, sound velocities, melting, spin state, and magnetism of compounds that might inhabit the core have been investigated at extreme conditions (e.g., Nakajima et al. 2011; Chen et al. 2012, 2014; Prescher et al. 2015; Liu et al. 2016a). Lord et al. (2009) determined the melting temperatures of the Fe-C system up to 70 GPa, indicating that Fe_7C_3 could form a eutectic relation with Fe at core pressures. If the solubility of carbon in iron is limited at the core conditions, Fe_7C_3 might crystalize out of the early Earth's molten core and could be a constituent of the innermost inner core due to its melting point being higher than pure iron (Liu et al. 2016b). Most importantly, the high Poisson's ratio and anomalously low-shear velocity of Fe_7C_3 at high pressures match that of the preliminary reference Earth model (PREM) for the inner core, which favors its potential presence in the inner core (Chen et al. 2014; Prescher et al. 2015). The core might thus be the largest reservoir of the Earth's carbon (Chen et al. 2014). See Chen and Li (2016) for excellent reviews of deep-carbon studies.

* E-mail: jinliu1@stanford.edu

Lai et al. (2018) investigated the anisotropic thermoelastic properties of single-crystal Fe_7C_3 at high-pressure and high-temperature conditions by synchrotron X-ray diffraction. The starting material Fe_7C_3 were synthesized in a multi-anvil apparatus at 18 GPa and 1773 K. The run products Fe_7C_3 were further analyzed in an externally heated diamond-anvil cell.

Lai et al. (2018) revealed the high-temperature effects on the anisotropy of iron carbide Fe_7C_3. Their diffraction data indicated that Fe_7C_3 adopts an orthorhombic structure under experimentally investigated conditions. They reported the linear compressibility anisotropy of Fe_7C_3 along the crystallographic axes, together with the thermal equation of state of Fe_7C_3 up to 80 GPa and 800 K. In particular, high temperatures affect compressibility and the magnitude of anisotropy during thermal expansion.

As our understanding of the role of carbon in the formation and evolution of our planet advances, Lai et al. (2018) elucidated that high temperatures must be considered when explaining the inner-core seismic anisotropy, and further advocated the existence of iron carbide in the inner core.

References cited

Chen, B., and Li, J. (2016) Carbon in the core. Deep Earth: Physics and chemistry of the lower mantle and core, 277–288.

Chen, B., Gao, L., Lavina, B., Dera, P., Alp, E.E., Zhao, J., and Li, J. (2012) Magneto-elastic coupling in compressed Fe_7C_3 supports carbon in Earth's inner core. Geophysical Research Letters, 39(18), L18301.

Chen, B., Li, Z., Zhang, D., Liu, J., Hu, M.Y., Zhao, J., Bi, W., Alp, E.E., Xiao, Y., Chow, P., and Li, J. (2014) Hidden carbon in Earth's inner core revealed by shear softening in dense Fe_7C_3. Proceedings of the National Academy of Sciences, 111(50), 17755–17758.

Deuss, A. (2014) Heterogeneity and anisotropy of Earth's inner core. Annual Review of Earth and Planetary Sciences, 42(1), 103–126.

Fei, Y., and Brosh, E. (2014) Experimental study and thermodynamic calculations of phase relations in the Fe–C system at high pressure. Earth and Planetary Science Letters, 408, 155–162.

Hazen, R.M., and Schiffries, C.M. (2013) Why deep carbon? Reviews in Mineralogy and Geochemistry, 75(1), 1–6.

Lai, X., Zhu, F., Liu, J., Zhang, D., Hu, Y., Finkelstein, G.J., Dera, P., and Chen, B. (2018) Anisotropic thermoelastic properties of Fe_7C_3 at high pressures by single-crystal X-ray diffraction. American Mineralogist, 103(10), 1568–1574.

Liu, J., Li, J., and Ikuta, D. (2016a) Elastic softening in Fe_7C_3 with implications for Earth's deep carbon reservoirs. Journal of Geophysical Research: Solid Earth, 121, 1514–1524.

Liu, J., Lin, J.F., Prakapenka, V.B., Prescher, C., and Yoshino, T. (2016b) Phase relations of Fe_3C and Fe_7C_3 up to 185 GPa and 5200 K: Implication for the stability of iron carbide in the Earth's core. Geophysical Research Letters, 43(24), 12415–12422.

Lord, O.T., Walter, M.J., Dasgupta, R., Walker, D., and Clark, S.M. (2009) Melting in the Fe–C system to 70 GPa. Earth and Planetary Science Letters, 284(1–2), 157–167.

Nakajima, Y., Takahashi, E., Suzuki, T., and Funakoshi, K.-i. (2009) "Carbon in the core" revisited. Physics of the Earth and Planetary Interiors, 174(1-4), 202–211.

Nakajima, Y., Takahashi, E., Sata, N., Nishihara, Y., Hirose, K., Funakoshi, K.-i., and Ohishi, Y. (2011) Thermoelastic property and high-pressure stability of Fe_7C_3: Implication for iron-carbide in the Earth's core. American Mineralogist, 96(7), 1158–1165.

Prescher, C., Dubrovinsky, L., Bykova, E., Kupenko, I., Glazyrin, K., Kantor, A., McCammon, C., Mookherjee, M., Nakajima, Y., Miyajima, N., and others. (2015) High Poisson's ratio of Earth's inner core explained by carbon alloying. Nature Geoscience, 8, 220–223.

Manuscript received October 4, 2018
Manuscript accepted October 13, 2018
Manuscript handled by Keith Putirka

0003-004X/19/0001–001$05.00/DOI: http://dx.doi.org/10.2138/am-2019-6835