

PENTLANDITE IN CHONDRITES: A COMPOSITIONAL INDICATOR OF OXYGEN FUGACITY.

D. L. Schrader¹, T. J. Zega², J. Davidson¹, T. J. McCoy³, and K. J. Domanik², ¹Buseck Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, AZ 85287, USA (devin.schrader@asu.edu), ²Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. ³Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119, USA.

Introduction: Fe-sulfides are ubiquitous in chondrites and are sensitive indicators of formation and alteration conditions in the protoplanetary disk and small Solar System bodies [e.g., 1–14]. We previously constrained a minimum oxygen fugacity (fO_2) needed to form pentlandite, $(Fe,Ni)_9S_8$, [6,7] and identified trends with pentlandite compositions between distinct meteorite groups [6,7]. We also identified a relationship between the at.% Fe/S ratio of pyrrhotite group sulfides and the fO_2 of formation, either in the protoplanetary disk or the parent body during aqueous alteration or thermal alteration [13]. Since pentlandite formed with pyrrhotite (they are typically intergrown in these chondrite groups [1–14]), fO_2 may have influenced pentlandite compositions. To increase the information gained from individual mineral systems, here we report the chemical compositions of pentlandite in chondrites that experienced a wide range of formation and parent body alteration conditions (including fO_2 [13]). This will allow us to investigate a potential trend(s) with the pyrrhotite at.% Fe/S ratio, and by extension fO_2 .

Samples and Analytical Procedures: We determined the major and minor element compositions of pentlandite in each of the following 54 chondrites: CI (Alais), a C1-ungrouped (Miller Range [MIL] 090292), C2-ungrouped (Tarda and Tagish Lake), CY (Belgica [B]-7904), CM1/2 (Allan Hills [ALH] 83100 and Kolang [two lithologies]), unheated CM2s (Aguas Zarcas [multiple lithologies], Mighei, Queen Alexandra Range [QUE] 97990, Theil Mountains [TIL] 91722, and D'Angelo Bluff [DNG] 06004), stage I heated CM2 (Asuka [A]-881458), stage II heated CM2 (Yamato [Y]-793321), CM-like (Sutter's Mill), CO3.00 (Dominion Range [DOM] 08006), CR1 (Grosvenor Mountains [GRO] 95577), CR-an (Al Rais), CR2 (Elephant Moraine [EET] 87770, EET 92048, EET 96259, Gao-Guenie (b), Graves Nunatak [GRA] 95229, LaPaz Ice Field [LAP] 02342, LAP 04720, MIL 090657, Northwest Africa [NWA] 801, Pecora Escarpment [PCA] 91082, QUE 99177, Shişr 033, and Y-793495), shock-heated CR2 (GRO 03116), CV3_{OxA} (Allende), CV3_{OxB} (Bali), and CV3_{Red} (Vigarano), CK4 (ALH 85002 and Karoonda), CK5 (Larkman Nunatak [LAR] 06868), CK6 (Lewis Cliff [LEW] 87009), L3.05 (EET 90161 and QUE 97008), LL3 (Semarkona and Vicencia), LL4 (Hamlet and Soko-Banja), LL5 (Chelyabinsk and Siena), LL6 (Appley Bridge and Saint-Séverin), R3 (MET 01149), R3.6 (LAP 031275), R5 (LAP 03639), and R6 (LAP 04840 and MIL 11207) chondrites. We acquired high-resolution backscatter electron images and quantitative chemical compositions with the JEOL-8530F Hyperprobe electron microprobe analyzer (EPMA) at Arizona State University (ASU) and the Cameca SX-100 EPMA at the University of Arizona (UA) following [13]. Some pentlandite compositions were previously reported [6,7,10,11].

Results and Discussion: Our data show that there is a relationship between the at.% Fe/S of pyrrhotite (data from [13]) and pentlandite compositions. Since the at.% Fe/S ratio of pyrrhotite is a proxy for fO_2 [13], this demonstrates that there is a relationship between fO_2 and pentlandite composition. Therefore, pentlandite compositions were influenced by the fO_2 of formation. This is true whether pentlandite formed: (1) during chondrule formation in the protoplanetary disk (i.e., during chondrule cooling, as previously noted by [6,8,10,11] for CR2, CO3.00, and LL3.00 chondrites), (2) during thermal alteration on the parent asteroid under relatively reducing (i.e., LL4–6 chondrites) or oxidizing (i.e., R4–6 and CK chondrites) conditions, or (3) during oxidizing aqueous alteration (i.e., as in CI, CM1, C1-ung, and C2-ung chondrites). Therefore, in addition to the at.% Fe/S ratio of pyrrhotite, the chemical compositions of pentlandite can also be used as a proxy for the fO_2 of formation. This discovery has implications for the interpretation of pentlandite compositions in meteorites and in asteroid returned samples from Ryugu and Bennu.

References: [1] Zolensky M. E. et al. (2002) *Meteorit. Planet. Sci.* 37:737–761. [2] Bullock E. S. et al. (2005) *Geochim. Cosmochim. Acta* 69:2687–2700. [3] Schrader D. L. et al. (2008) *Geochim. Cosmochim. Acta* 72:6124–6140. [4] Berger E. L. et al. (2011) *Geochim. Cosmochim. Acta* 75:3501–3513. [5] Harries D. and Langenhorst F. (2013) *Meteorit. Planet. Sci.* 48:879–903. [6] Schrader D. L. et al. (2015) *Meteorit. Planet. Sci.* 50:15–50. [7] Schrader D. L. et al. (2016) *Geochim. Cosmochim. Acta* 189:359–376. [8] Schrader D. L. et al. (2018) *Earth Planet. Sci. Lett.* 504:30–37. [9] Singerling S. A. and Brearley A. J. (2018) *Meteorit. Planet. Sci.* 53:2078–2106. [10] Davidson J. et al. (2019) *Geochim. Cosmochim. Acta* 265:259–278. [11] Davidson J. et al. (2019) *Geochim. Cosmochim. Acta* 267:240–256. [12] Singerling S. A. and Brearley A. J. (2020) *Meteorit. Planet. Sci.* 55:496–523. [13] Schrader D. L. et al. (2021) *Geochim. Cosmochim. Acta* 303:66–91. [14] Holt M. C. and Herd C. D. K. (2022) *Meteorit. Planet. Sci.*: In Press, doi: 10.1111/maps.13819.

Acknowledgements: We thank the Smithsonian Institution, NASA/NSF, the ASU Buseck Center for Meteorite Studies (BCMS), and the National Institute of Polar Research (NiPR) for the loan of the meteorites used in this study, and NASA grant NNX17AE53G (DLS PI, TJZ Co-I) and the BCMS for funding this research.