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Report

Addendum to “Stöffler, D., Hamann, C., and Metzler, K., Shock metamorphism of planetary silicate rocks and sediments: Proposal for an updated classification system. Meteoritics & Planetary Science 53, 5–49, 2018”

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Abstract—With this addendum we provide some correction and additional information regarding the above cited publication. It addresses the following two topics. (1) Clarification for a correct application of the criteria for certain shock stages of chondrites, in particular stage C-S6. (2) Correction of a printing error in the table that contains the shock classification system of chondrites.

Discussions between the authors and with colleagues using the shock classification of chondrites revealed some uncertainty regarding the correct application of the classification system proposed for chondrites in the above cited paper (table 8, page 33). The uncertainty applies for the shock stage C-S6 representing the second highest degree of shock metamorphism before whole-rock melting occurs (shock stage C-S7, which can be identified by texture, mineral and bulk chemistry, and in-situ oxygen-isotopic signatures in olivine; e.g., Lunning et al. 2016). In the Manual for the Classification of a Shock Metamorphosed Rock or Sediment section of Stöffler et al. (2018), the text concerning the correct use of table 8 remains somewhat unclear. Moreover, table 8 also contains errors regarding shock effects in olivine of shock stages C-S4 and C-S5. Therefore, we corrected table 8 and added some additional explanation in the subscript, which is shown here in a corrected and improved version (Table 1) replacing table 8 of Stöffler et al. (2018).

The essential points in defining shock stage C-S6 by thin section microscopy are the following:

1. The thin section must show regions with “pervasive formation of melt pockets, veins, and dikes as well as opaque shock veins.”

2. Within and directly adjacent to these melt zones **olivine** has to be affected by “melting and (re) crystallization and yellow-brown staining” and **plagioclase** should be “melted and appear as normal, flow-textured glass.”
3. Thin section areas adjacent to the regions displaying the above-described maximum shock effects in olivine should display olivine with strong mosaicism, planar fractures (pf) and planar deformation features (pdf), and diaplectic plagioclase glass (maskelynite). It has been defined (Stöffler et al. 1991, 2018) that at least 75% of the plagioclase grains in a thin section should be transformed to diaplectic glass. Consequently, this means that in a thin section of shock stage S6 up to 25% of the grains may still be birefringent or rarely partially isotropic.
4. We want to point out that the mode of definition of shock stage S6 is somewhat different from the one of stages S1–S5 because the shock effects defining S6, as described above in item (2), occur only in *restricted local regions of the thin section*, i.e., inside or directly adjacent to melt veins and melt pockets. Thus, if a thin section of a given specimen contains material that is petrographically consistent with the S6 material properties proposed here, it is of shock

Table 1. Definition of progressive stages of shock metamorphism for classification system C (chondrites, tables 3 and 12 of Stöffler et al. 2018) modified after Stöffler et al. (1991, 2018); shock pressure corresponds to the final equilibration peak shock pressure for polycrystalline rocks (in GPa) derived from shock experiments referenced in table 2 of Stöffler et al. (2018); pf = planar fractures; pdf = planar deformation features; note that high-pressure phases of olivine, pyroxene, and plagioclase may be present, preferably in or near melt veins/pockets of shock stages S5–S6 (ringwoodite, wadsleyite, ahrensite, majorite, akimotoite, bridgmanite, shenzzhuangite, and lingunite; Binns et al. 1969; Smith and Mason 1970; Price et al. 1983; Stöffler et al. 1991; Tomioka and Fujino 1999; Liu and El Goresy 2007; Ozawa et al. 2009; Tschauner et al. 2009, 2014; Ma et al. 2016; Bindi and Xie 2017; Tomioka and Miyahara 2017); see also figs. S2, S4 and S8 of Stöffler et al. (2018). This table is a revised version of table 8 from Stöffler et al. (2018). The revision concerns shock effects in olivine of stages S4 and S5 as well as the subscript and the layout.

Shock stage	Pressure GPa ^a (293 K)	Pressure GPa ^b (920 K)	Effects resulting from equilibration peak shock pressure			Effects resulting from local <i>P–T</i> -excursions	
			Olivine			Plagioclase	
C – S1			Sharp optical extinction Irregular fractures	Angular variation of extinction position: <2°	Sharp optical extinction Irregular fractures	None	
C – S2	<4–5		Undulatory extinction Irregular fractures	Angular variation of extinction position: > 2°	Undulatory extinction Irregular fractures	None	
C – S3	5–10		Planar fractures (pf) Undulatory extinction Irregular fractures	Low grade: Maximum of 2 sets of pf High grade: 3 or more sets of pf	Undulatory extinction	Opaque shock veins; incipient formation of melt pockets (sometimes interconnected)	
C – S4	15–20	10–15	Mosaicism (weak)	Planar fractures (pf)	Low grade: Undulatory extinction High grade: Partially isotropic, pdf	Melt pockets; interconnected melt veins; opaque shock veins	
C – S5	30–35	25–30	Mosaicism (strong)	Planar fractures (pf) and planar deformation features (pdf)	Diaplectic glass (maskelynite)	Pervasive formation of melt pockets, veins, and dikes; opaque shock veins	
C – S6	45–55	45–60	<i>Restricted to local regions in or near melt zones^c</i> Melting and (re)crystallization and yellow-brown staining of olivine			Shock melted (normal glass)	As in stage S5
C – S7	>70–75	45–60	Whole-rock melting ^d				

^aFrom Stöffler et al. (1991).

^bFrom Schmitt (2000).

^cThin section areas outside the described melt zones display olivine with strong mosaicism, pf, and pdf as well as diaplectic plagioclase glass as in stage S5 (see text).

^dResulting in holocrystalline impact melt rocks (e.g., Lunning et al. 2016) which are extremely rare.

stage S6. A “multiple” classification for a given thin section/sample (e.g., “S4–S6,” or “S5, partly S6”) is not defined by any classification system proposed so far.

5. The assignment of a certain shock stage holds only for the specimen from which the thin section is made. It cannot be concluded with absolute certainty that all samples taken from a large meteorite or from a meteorite strewn field show the same degree of shock metamorphism, although the probability that this is the case is rather high.

It is important to note that the identification of high-pressure phases (hpp) of olivine, pyroxene, and plagioclase inside or adjacent to melt zones (see legend of table 8) is not critical per se for the identification of shock stage C–S6, although this may be concluded from previous shock classification systems of chondrites (Stöffler et al. 1991; Stöffler and Grieve 2007). There are two reasons for excluding hpp’s as sole shock stage indicators. First, with the exception of ringwoodite, they cannot be safely identified by the polarizing microscope, which is the tool on which all shock classification systems are based. Moreover, they are not indicative of the “equilibration peak shock pressure” achieved in the relevant regions of the chondrite sample in question because they crystallize during pressure release but only if the shock pressure pulse is long enough.

One further critical point to be addressed here concerns again the above mentioned Manual for the Classification of a Shock Metamorphosed Rock or Sediment section. We stated in Stöffler et al. (1991) that for all shock stages of chondrites lower than S5, i.e., S2, S3, S4, “we recommend to choose the highest shock stage shown by any significant fraction of grains (at least 25% of grains) to establish the shock level of a chondrite.” We changed this in Stöffler et al. (2018) to 50%. This change is obviously not reasonable, and it was recommended to keep the 25% rule in order to avoid incompatibilities between shock classifications of chondrites made between 1991 and 2018 and those to be made after 2018. We agree to keep the 25% threshold and propose a change of the text on page 35 of Stöffler et al. (2018). However, we emphasize again that in shock stages C–S5 and C–S6 (outside the melt veins and pockets) at least 75% of the plagioclase grains need to be converted to diaplectic glass (maskelynite) as expressed in both papers (Stöffler et al. 1991, 2018).

Finally, we want to add a comment on the contents and applicability of Table 1 (table 8 of Stöffler et al. 2018). The table can be applied to all types of chondrites including ordinary chondrites and C chondrites (see also Stöffler et al. [1991] and Scott et al. [1992]). In the case of enstatite chondrites, shock effects

in pyroxene can also be considered in addition to shock effects in olivine and plagioclase (Rubin et al. 1997). They are, however, less relevant because some of them exist over very large ranges of shock pressure (table 2 of Stöffler et al. 2018). For the shock classification of C chondrites some restrictions have to be considered which relate to the application of the pressure scales (columns 2, 3, and 4 of Table 1) and the post-shock temperature estimates. Because of the elevated porosity and the presence of OH-bearing sheet silicates, the pressure scales given in Table 1 are not applicable. For the same reason a post-shock temperature scale has been omitted in compatibility with table 5 in Stöffler and Grieve (2007). For the classification itself, these *P–T* scales are absolutely irrelevant as they serve only as supporting information. Moreover, shock stages higher than S3 are very rare (Scott et al. 1992).

Editorial Handling—Dr. Christian Koeberl

REFERENCES

- Bindi L. and Xie X. 2017. Shenzhuangite, IMA 2017-018. CNMNC Newsletter No. 38. *Mineralogical Magazine* 81:1033–1038.
- Binns R. A., Davis R. J., and Reed S. J. B. 1969. Ringwoodite, natural (Mg,Fe)₂SiO₄ spinel group in the Tenham meteorite. *Nature* 221:943–944.
- Liu L.-G. and El Goresy A. 2007. High-pressure phase transitions of the feldspars, and further characterization of lingunite. *International Geology Review* 49:854–860.
- Lunning N. G., Corrigan C. M., McSween H. Y., Tenner T. J., Kita N. T., and Bodnar R. J. 2016. CV and CM chondrite impact melts. *Geochimica et Cosmochimica Acta* 189:338–358.
- Ma C., Tschäuner O., Beckett J. R., Liu Y., Rossman G. R., Sinogeikin S. V., Smith J. S., and Taylor L. A. 2016. Ahrensite, c-Fe₂SiO₄, a new shock-metamorphic mineral from the Tissint meteorite: Implications for the Tissint shock event on Mars. *Geochimica et Cosmochimica Acta* 184:240–256.
- Ozawa S., Ohtani E., Miyahara M., Suzuki A., Kimura M., and Ito Y. 2009. Transformation textures, mechanisms of formation of high-pressure minerals in shock melt veins of L6 chondrites, and pressure-temperature conditions of the shock events. *Meteoritics & Planetary Science* 44:1771–1786.
- Price R. D., Putnis A., Agrell S. O., and Smith D. G. W. 1983. Wadsleyite, natural β-(Mg,Fe)₂SiO₄ from the Peace River meteorite. *Canadian Mineralogist* 21:29–35.
- Rubin A. E., Scott E. R. D., and Keil K. 1997. Shock metamorphism of enstatite chondrites. *Geochimica et Cosmochimica Acta* 61:847–858.
- Schmitt R.-T. 2000. Shock experiments with the H6 chondrite Kernouvé: Pressure calibration of microscopic shock effects. *Meteoritics & Planetary Science* 35:2547–2571.
- Scott E. R. D., Keil K., and Stöffler D. 1992. Shock metamorphism of carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 56:4281–4293.

- Smith J. V. and Mason B. 1970. Pyroxene-garnet transformation in Coorara meteorite. *Science* 168: 832–833.
- Stöffler D. and Grieve R. A. F. 2007. Impactites. In *Metamorphic rocks: A classification and glossary of terms, recommendations of the International Union of Geological Sciences*, edited by Fettes D. and Desmons J. Cambridge: Cambridge University Press. pp. 82–91, 111–125, and 126–242.
- Stöffler D., Keil K., and Scott E. R. D. 1991. Shock metamorphism of ordinary chondrites. *Geochimica et Cosmochimica Acta* 55:3845–3867.
- Stöffler D., Hamann C., and Metzler K. 2018. Shock metamorphism of planetary silicate rocks and sediments: Proposal for an updated classification system. *Meteoritics & Planetary Science* 53:5–49.
- Tomioka N. and Fujino K. 1999. Akimotoite, (Mg,Fe)SiO₃, a new silicate mineral of the ilmenite group in the Tenham chondrite. *American Mineralogist* 84:267–271.
- Tomioka N. and Miyahara M. 2017. High-pressure minerals in shocked meteorites. *Meteoritics & Planetary Science* 52:2017–2039.
- Tschauner O., Asimow P. D., Kostandova N., Ahrens T. J., Ma C., Sinogeikin S., Liu Z., Fakra S., and Tamura N. 2009. Ultrafast growth of wadsleyite in shock-produced melts and its implications for early solar system impact processes. *Proceedings of the National Academy of Sciences of the United States* 106:13,691–13,695.
- Tschauner O., Ma C., Beckett J. R., Prescher C., Prakapenka V. B., and Rossman G. R. 2014. Discovery of bridgmanite, the most abundant mineral in Earth, in a shocked meteorite. *Science* 346:1100–1102.
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