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Experimental shock metamorphism of terrestrial basalts: Agglutinate-like particle formation, petrology, and magnetism

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Abstract

© The Meteoritical Society, 2017. Hypervelocity impacts occur on bodies throughout our solar system, and play an important role in altering the mineralogy, texture, and magnetic properties in target rocks at nanometer to planetary scales. Here we present the results of hypervelocity impact experiments conducted using a two-stage light-gas gun with 5 mm spherical copper projectiles accelerated toward basalt targets with ~6 km s−1 impact velocities. Four different types of magnetite- and titanomagnetite-bearing basalts were used as targets for seven independent experiments. These laboratory impacts resulted in the formation of agglutinate-like particles similar in texture to lunar agglutinates, which are an important fraction of lunar soil. Materials recovered from the impacts were examined using a suite of complementary techniques, including optical and scanning electron microscopy, micro-Raman spectroscopy, and high- and low-temperature magnetometry, to investigate the texture, chemistry, and magnetic properties of newly formed agglutinate-like particles and were compared to unshocked basaltic parent materials. The use of Cu-projectiles, rather than Fe- and Ni-projectiles, avoids magnetic contamination in the final shock products and enables a clearer view of the magnetic properties of impact-generated agglutinates. Agglutinate-like particles show shock features, such as melting and planar deformation features, and demonstrate shock-induced magnetic hardening (two- to seven-fold increases in the coercivity of remanence Bcr compared to the initial target materials) and decreases in low-field magnetic susceptibility and saturation magnetization.

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References

[1] Ahrens T. J. 1993. Equation of state. In High-pressure shock compression of solids, edited by Asay J. R. and Shahinpoor M. New York: Springer-Verlag. pp. 75–114.

[2] Ahrens T. J. and Johnson M. L. 1995a. Shock wave data for minerals. In Mineral physics and crystallography: A handbook of physical constants, edited by Ahrens T. J. Washington, D.C.: American Geophysical Union. pp. 143–175.

[3] Ahrens T. J. and Johnson M. L. 1995b. Shock wave data for rocks. In Rock physics and phase relations: A handbook of physical constants, edited by Ahrens T. J. Washington, D.C.: American Geophysical Union. pp. 35–44.

[4] Ahrens T. J. and O'Keefe J. D. 1977. Equation of state and impact-induced shock-wave attenuation on the moon. In Impact and explosion cratering, edited by Roddy D. J., Pepin R. O., and Merril R. B. New York: Pergamon Press. pp. 639–656.

[5] Badjukov D. D., Kozlov E. A., Kolesnikov E. M., Lebedeva L. M., and Nazarov M. A. 2000. Behavior of Ar in obsidian subjected to strong shock-wave compression. Doklady RAS, Earth Sciences 373:905–908. (in Russian)

[6] Basu A., Wentworth S. J., and McKay D. S. 2002. Heterogeneous agglutinitic glass and the fusion of the finest fraction (F) model. Meteoritics & Planetary Science 37:1835–1842.

[7] Bezaeva N. S., Rochette P., Gattacceca J., Sadykov R. A., and Trukhin V. I. 2007. Pressure demagnetization of the Martian crust: Ground truth from SNC meteorites. Geophysical Research Letters 34:L23202.

[8] Bezaeva N. S., Badjukov D. D., Rochette P., Gattacceca J., Trukhin V. I., Kozlov E. A., and Uehara M. 2010. Experimental shock metamorphism of the L4 ordinary chondrite Saratov induced by spherical shock waves up to 400 GPa. Meteoritics & Planetary Science 45:1007–1020.

[9] Bezaeva N. S., Swanson-Hysell N. L., Tikoo S. M., Badyukov D. D., Kars M., Egli R., Chareev D. A., Fairchild L. M., Khakhalova E., Strauss B. E., and Lindquist A. K. 2016. The effect of 10 to >160 GPa shock on the magnetic properties of basalt and diabase. Geochemistry, Geophysics, Geosystems 17:4753–4771.

[10] Bischoff A., Scott E. R. D., Metzler K., and Goodrich C. A. 2006. Nature and origin of meteoritic breccias. In Meteorites and the early solar system II, 2nd ed., edited by Lauretta D. S. and McSween H. Y. Jr. Tucson, Arizona: The University of Arizona Press. pp. 679–712.

[11] Bleil U. and Petersen N. 1982. Magnetic properties of natural minerals. In Numerical data and functional relationships in science and technology, group V: Geophysics and space research, edited by Angenheister G. New York: Springer. pp. 308–365.

[12] Bouhifd M. A., Besson P., Courtial P., Gérardin C., Navrotsky A., and Richet P. 2007. Thermochemistry and melting properties of basalt. Contributions to Mineralogy and Petrology 153:689–698.

[13] Bowles J., Jackson M., Chen A., and Solheid P. 2009. Interpretation of low-temperature data part 1: Superparamagnetism and paramagnetism. The IRM Quarterly 19:1, 7–11.

[14] Carter-Stiglitz B., Moskowitz B., Solheid P. Berquo T. S., Jackson M., and Kosterov A. 2006. Low-temperature magnetic behavior of multidomain titanomagnetites: TM0, TM16, and TM35. Journal of Geophysical Research 111:B12S05.

[15] Church N., Feinberg J. M., and Harrison R. 2011. Low-temperature domain wall pinning in titanomagnetite: Quantitative modeling of multidomain first-order reversal curve diagrams and AC susceptibility. Geochemistry, Geophysics, Geosystems 12:Q07Z27.

[16] Cintala M. J., Hörz F., See T. H., Cardenas F., and Thompson T. D. 1984. Regolith evolution experiments I: Grain-size evolution (abstract). 15th Lunar and Planetary Science Conference. p. 160.

[17] Cisowski S. M. and Fuller M. 1983. The role of impact magnetization in the solar system. Advances in Space Research 2:35–39.

[18] Cremonese G., Borin P., Lucchetti A., Marzari F., and Bruno M. 2013. Micrometeoroids flux on the Moon. Astronomy & Astrophysics 551:A27.

[19] Day R., Fuller M. D., and Schmidt V. A. 1977. Hysteresis properties of titanomagnetites: Grain size and composition dependence. Physics of the Earth and Planetary Interiors 13:260–266.

[20] Dunlop D. J. 2002. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc) 1. Theoretical curves and tests using titanomagnetite data. Journal of Geophysical Research 107:EPM 4-1–EPM 4-22.

[21] Dunlop D. J. and Özdemir Ö. 1997. Rock magnetism, fundamentals and frontiers. Cambridge: Cambridge University Press. 573 p.

[22] Ebert M., Hecht L., Deutsch A., Kenkmann T., Wirth R., and Berndt J. 2014. Geochemical processes between steel projectiles and silica-rich targets in hypervelocity impact experiments. Geochimica et Cosmochimica Acta 133:257–279.

[23] Egli R. 2013. VARIFORC: An optimized protocol for the calculation of non-regular first-order reversal curve (FORC) diagrams. Global and Planetary Change 110:302–320.

[24] Frondel J. W. 1975. Lunar mineralogy. New York: Wiley-Interscience. 332 p.

[25] Garcia R. F., Murdoch N., and Mimoun D. 2015. Micro-meteoroid seismic uplift and regolith concentration on kilometric scale asteroids. Icarus 253:159–168.

[26] Gattacceca J., Lamali A., Rochette P., Boustie M., and Berthe L. 2007. The effects of explosive-driven shocks on the natural remanent magnetization and the magnetic properties of rocks. Physics of the Earth and Planetary Interiors 162:85–98.

[27] Gattacceca J., Rochette P., Scorzelli R. B., Munayco P., Agee C., Quesnel Y., Cournede C., and Geissman J. 2014. Martian meteorites and Martian magnetic anomalies: A new perspective from NWA 7034. Geophysical Research Letters 41:4859–4864.

[28] Grommé C. S., Wright T. L., and Peck D. L. 1969. Magnetic properties and oxidation of iron-titanium oxide minerals in Alae and Makaopuhi lava lakes, Hawaii. Journal of Geophysical Research 74:5277–5293.

[29] Harrison R. J. and Feinberg J. M. 2008. FORCinel: An improved algorithm for calculating first-order reversal curve (FORC) distributions using locally-weighted regression smoothing. Geochemistry, Geophysics, Geosystems 9:Q05016.

[30] Heiken G. H., Vaniman D. T., and French B. M., eds. 1991. Lunar sourcebook: A user's guide to the moon. Cambridge: Cambridge University Press. 736 p.

[31] Hörz F. and Cintala M. 1997. Impact experiments related to the evolution of planetary regoliths. Meteoritics & Planetary Science 32:179–209.

[32] Hörz F. and Schaal R. B. 1981. Asteroidal agglutinate formation and implications for asteroidal surfaces. Icarus 46:337–353.

[33] Hörz F., Brownlee D. E., Fechtig H., Hartung J. B., Morrison D. A., Neukum G., Schneider E., Vedder J. F., and Gault D. E. 1975. Lunar microcraters: Implications for the Micrometeoroid complex. Planetary and Space Science 23:151–172.

[34] Jackson M., Moskowitz B., and Bowles J. 2011. Interpretation of low-temperature data part III: The magnetite Verwey transition (Part A). The IRM Quarterly 20:1, 7–11.

[35] Kohout T., Pesonen L. J., Deutsch A., Wunnemann K., Nowka D., Hornemann U., and Heikinheimo E. 2012. Shock experiments in range of 10–45 GPa with small multidomain magnetite in porous targets. Meteoritics & Planetary Science 47:1671–1680.

[36] Korotev R. L., Zeigler R. A., and Floss C. 2010. On the origin of impact glass in the Apollo 16 regolith. Geochimica et Cosmochimica Acta 74:7362–7388.

[37] Kramar U., Stüben D., Berner Z., Stinnesbeck W., Philipp H., and Keller G. 2001. Are Ir anomalies sufficient and unique indicators for cosmic events. Planetary and Space Science 49:831–837.

[38] Kurat G., Koeberl C., Presper T., Brandstätter F., and Maurette M. 1994. Petrology and geochemistry of Antarctic micrometeorites. Geochimica et Cosmochimica Acta 58:3879–3904.

[39] Kyte F. T. and Wasson J. T. 1986. Accretion rate of extraterrestrial matter: Iridium deposited 33 to 67 million years ago. Science 232:1225–1229.

[40] Langenhorst F., Pesonen L. J., Deutsch A., and Hernemann U. 1999. Shock experiments on diabase: Microstructural and magnetic properties (abstract #1241). 30th Lunar and Planetary Science Conference. CD-ROM.

[41] Lindquist A. K., Feinberg J. M., Harrison R. J., Loudon J. C., and Newell A. J. 2015. Domain wall pinning and dislocations: Investigating magnetite deformed under conditions analogous to nature using transmission electron microscopy. Journal of Geophysical Research: Solid Earth 120:1415–1430.

[42] Linford N., Jackson M., and Marvin J. 2002. Seahenge, susceptibility and more ways to be wrong. The IRM Quarterly 12:1, 10–11.

[43] Louzada K. L., Weiss B. P., Maloof A. C., Stewart S. T., Swanson-Hysell N. L., and Soule A. 2008. Paleomagnetism of Lonar impact crater, India. Earth and Planetary Science Letters 275:308–319.

[44] Love S. G. and Brownlee D. E. 1993. A direct measurement of the terrestrial mass accretion rate of cosmic dust. Science 262:550–553.

[45] McQueen R. G. and Marsh S. P. 1960. Equation of state for nineteen metallic elements from shockwave measurements to two megabars. Journal of Applied Physics 31:1253–1269.

[46] Melosh H. J. 1989. Impact cratering: A geologic process. New York: Oxford University Press. p. 253.

[47] Morris R. V. and Gose W. A. 1976. Ferromagnetic resonance and magnetic studies of cores 60009/60010 and 60003—Compositional and surface-exposure stratigraphy. Proceedings, 7th Lunar Science Conference. pp. 1–11.

[48] Noguchi T., Kimura M., Hashimoto T., Konno M., Nakamura T., Zolensky M. E., Okazaki R., Tanaka M., Tsuchiyama A., Nakato A., Ogami T., Ishida H., Sagae R., Tsujimoto S., Matsumoto T., Matsuno J., Fujimura A., Abe M., Yada T., Mukai T., Ueno M., Okada T., Shirai K., and Ishibashi Y. 2014. Space weathered rims found on the surfaces of the Itokawa dust particles. Meteoritics & Planetary Science 49:188–214.

[49] O'Keefe J. D. and Ahrens T. J. 1982. Cometary and meteorite swarm impact on planetary surfaces. Journal of Geophysical Research 87:6668–6680.

[50] Ostertag R. 1983. Shock experiments on feldspar crystals. Proceedings, 14th Lunar and Planetary Science Conference. pp. B364–B376.

[51] Papike J. J. 1981. The lunar regolith: significance of the chemistry of the <10 μm fraction and a model for agglutinate formation involving fusion of the finest fraction (F). Proceedings, 12th Lunar and Planetary Science Conference. pp. 851–853.

[52] Pesonen L. J., Deutsch A., Hornemann U., and Langenhorst F. 1997. Magnetic properties of diabase samples shocked experimentally in the 4.5 to 35 GPa range (abstract #1370). 28th Lunar and Planetary Science Conference. CD-ROM.

[53] Rochette P., Gattacceca J., Ivanov A. V., Nazarov M. A., and Bezaeva N. S. 2010. Magnetic properties of lunar materials: Meteorites, Luna and Apollo. Earth and Planetary Science Letters 292:383–391.

[54] Rochette P., Gattacceca J., Devouard B., Moustard F., Bezaeva N. S., Cournède C., and Scaillet B. 2015. Magnetic properties of tektites and other related impact glasses. Earth and Planetary Science Letters 432:381–390.

[55] Schaal R. B., Thompson T. D., Hörz F., and Bauer J. F. 1979. Shock metamorphism of granulated lunar basalt. Proceedings, 10th Lunar and Planetary Science Conference. pp. 2547–2571.

[56] See T. and Hörz F. 1988. Formation of agglutinate-like particles in an experimental regolith. Proceedings, 18th Lunar and Planetary Science Conference. pp. 423–433.

[57] Stuart J. S. and Binzel R. P. 2004. Bias-corrected population, size distribution, and impact hazard for the near-Earth objects. Icarus 170:295–311.

[58] Taylor L. A., Pieters C., Keller L. P., Morris R. V., McKay D. S., Patchen A., and Wentworth S. 2001. The effects of space weathering on Apollo 17 mare soils: Petrographic and chemical characterization. Meteoritics & Planetary Science 36:285–299.

[59] Van de Moortèle B., Reynard B., Rochette P., Jackson M., Beck P., Gillet P., and McMillan P. F. 2007. Shock-induced metallic iron nanoparticles in olivine-rich Martian meteorites. Earth and Planetary Science Letters 262:37–49.

[60] Verwey E. J. W. 1939. Electronic conduction of magnetite (FeO) and its transition point at low temperatures. Nature 144:327–328.

[61] Wittmann A., Korotev R. L., Jolliff B. L., Irving A. J., Moser D. E., Barker I., and Rumble D. 2015. Petrography and composition of Martian regolith breccia meteorite Northwest Africa 7475. Meteoritics & Planetary Science 50:326–352.

[62] Worm H.-U., Clark D., and Dekkers M. J. 1993. Magnetic susceptibility of pyrrhotite: Grain size, field and frequency dependence. Geophysical Journal International 114:127–137.