



Mineralogy, petrology, and thermal evolution of the Benton LL6 chondrite

Erin L. WALTON* and John G. SPRAY

Planetary and Space Science Centre, Department of Geology, University of New Brunswick, 2 Bailey Drive, Fredericton, New Brunswick
E3B 5A3, Canada

*Corresponding author. E-mail: j5rng@unb.ca

(Received 5 March 2002; revision accepted 23 May 2003)

Abstract—The Benton LL6 chondrite is a brecciated meteorite that was observed to fall on January 16, 1949 in Benton, New Brunswick, Canada. Internally, the meteorite comprises light-colored, subangular to subrounded clasts embedded in a dark grey-colored matrix. Clasts comprise the same mineral phases as the matrix, as well as chondrules and larger (50–100 μm) single mineral grains (mainly olivine and orthopyroxene). Composite (polyphase) clasts can be several millimeters in length. Numerous examples of post-brecciation and post-annealing shearing and displacement at the micron to millimeter scale occur in the form of shock veins. Benton is a shock stage S3 chondrite, which experienced shock pressures on the order of 15–20 GPa, with an estimated post-shock temperature increase of 100–150°C. Benton's history comprises a sequence of events as follows: 1) chondrule formation and initial assembly; 2) brecciation; 3) thermal metamorphism; and 4) shock veining. Events (2) and (4) can be equated with distinct impact events, the former representing bombardment of target material that remained in situ or collisionally fragmented during metamorphism, and then gravitationally reassembled, the latter probably with release from the source body to yield a meteorite. Thermal metamorphism post-dates brecciation. The mean equilibration temperature recorded in the Benton LL6 chondrite is 890°C, obtained using the two pyroxene geothermometer.

INTRODUCTION

Some workers regard inherent features such as brecciated textures, shock metamorphism, and thermal or aqueous metamorphism as non-fundamental, secondary, or tertiary effects of alteration that can obliterate genetically relevant primordial characteristics. However, these features provide insight into the geological evolution of asteroids and can be regarded as fundamental processes that occurred in the very early history of meteorite parent bodies. Early meteorite research recognized that impact processes, in general, are prime factors affecting the fundamental properties of meteorites, such as the abundance and distribution of noble gases and trace elements (particularly volatile elements), their radiometric ages, and other physical properties (e.g., Clayton 1993; Bogard 1995; Bischoff and Stöffler 1992). One of the greatest challenges in chondrite research is to disentangle the effects of primary and secondary (and even tertiary) processes in order to gain a better understanding of these distinct events (e.g., Keil 1964; Heymann 1967).

The Benton LL6 chondrite is a relatively unweathered, brecciated meteorite that was witnessed as a fall near Benton, New Brunswick on January 16th, 1949 at approximately 4:00

P. M. EST (Millman 1953). Two stones were recovered from the fall, weighing 1.50 kg and 1.34 kg, from which we were loaned 272 grams by the Ottawa National Collection. In hand specimen Benton has a light-dark appearance, owing to the development of subangular to subrounded clasts embedded in a finer-grained matrix. The petrography of the Benton meteorite, as well as the chemical composition of its constituent minerals, have been investigated as a part of this study. Previous work (Millman 1953) classified Benton as an LL6 chondrite, but its brecciated textures and shock metamorphic state have not been investigated.

ANALYTICAL PROCEDURES

The mineralogy of Benton, (clasts, matrix, and shock veins) was characterized by optical microscopy, using both reflected and transmitted light, and by analytical scanning electron microscopy. Shock veins and their host minerals were investigated using a JEOL 6400 digital scanning electron microscope equipped with a Link Analytical eXL energy dispersive spectrometer (EDS) fitted with a Si (Li) LZ-4 Pentafet detector. SEM backscattered electron (BSE) imagery was used to investigate the microtextures and

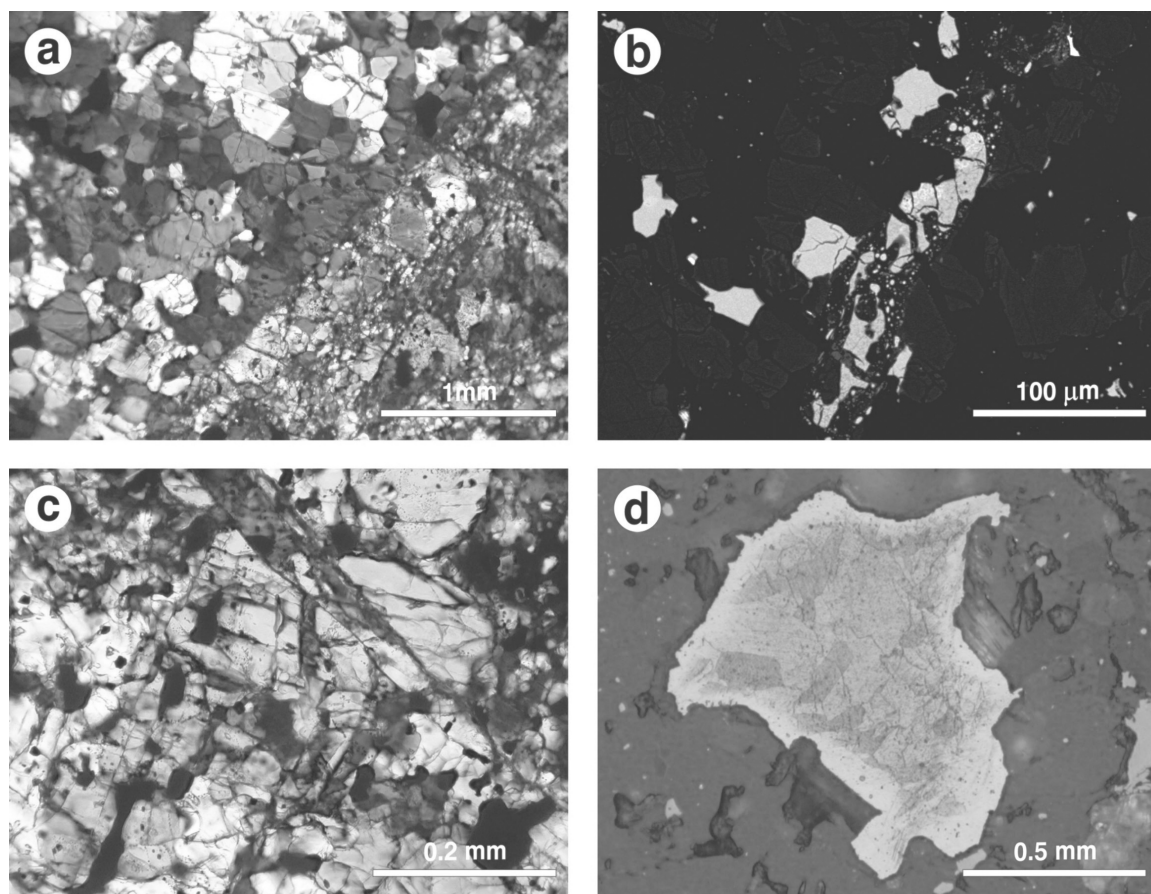


Fig. 1. a) Crossed-polars view of the clast + matrix boundary (bottom left to top right of the photograph); b) SEM image of a shock vein containing blebs of immiscible troilite; taenite is also present as <0.5 mm-sized veinlets in the large central troilite grain; c) Crossed-polars image of a proxene grain offset by a shock vein with a dextral sense of displacement; d) Reflected light photograph of an etched thin section revealing the relationship between cloudy taenite (inner brown island phase) and tetraetaenite (clear outer rim).

mineralogy of the chondrite. Raster scanning was deployed to determine approximate bulk chemistry. Clasts plus matrix minerals were rastered in 100 separate areas of 600 μm by 800 μm (total area of 48 mm^2) using a magnification of 150 \times . A polished section was etched in a standard 2% nital solution (2% HNO_3 in ethanol) to reveal the internal structure of the metal grains (Heide and Wlotzka 1995).

PETROGRAPHY

Texturally, Benton is dominated by the effects of thermal annealing and brecciation attributed to thermal metamorphism experienced early in the history of the parent body and subsequent impact bombardment. Granoblastic textures, observed in both fragmental clasts and the host matrix, indicate that brecciation took place before or during metamorphism. Otherwise, the matrix textures would be dominantly clastic. Later shock metamorphic features (opaque shock veins being the most obvious) crosscut the clasts, enabling a sequence of impact events to be recognized.

The Chondritic Matrix + Metamorphosed Clasts

The meteorite consists predominantly of subangular to subrounded clasts (50–100 μm , $n = 100$), comprising 65% of the meteorite by volume, embedded in a dark grey matrix. The mean matrix grain size is 23 μm ($n = 100$) and it can be considered a fine-grained derivative of the clast material. The light-dark colored texture of the chondrite is attributed to this bimodal grain size distribution between clast and matrix minerals. There is a distinct boundary between clasts and their host matrix based on grain size variation (Fig. 1a). Lithic fragments in Benton commonly have poikilitic textures. “Poikilitic” is used here as a textural description and is not intended to imply an igneous versus a metamorphic origin of the clasts.

Chondrules

Chondrules within Benton are uncommon, constituting <5% of the meteorite by volume. The majority have become

integrated with the matrix as a result of thermal annealing, rendering few chondrules as easily recognizable. One unique metal-rich chondrule has been observed with an assemblage of troilite + taenite + chromite.

Shock Effects

The most obvious manifestation of impact bombardment in Benton is the lithic fragments, discernable in hand specimen by their light colour with respect to the matrix. Later shock veins, which crosscut the clasts, form an interlocking network in thin section. The veins range from 3 to 100 μm apparent thickness and are largely defined by the remobilization of opaques, mainly troilite, that are sheared and intruded along the veins. The shock veins form planar to curvilinear surfaces that have sharp contacts with the host chondrite, enlarging at triple point junctions into melt pockets. With increasing volume of the melt zones, the internal texture of the shock veins changes from one dominated by troilite to exsolved opaque phases embedded in a microcrystalline matrix of silicates, predominantly olivine. Spheres of immiscible troilite and metals grade in size with increasing vein thickness from μm -sized spheres of troilite and metal to larger ($>5\text{ mm}$) spheres or globules with specific eutectic textures of sulfide and metal (Fig. 1b).

Numerous examples of post-brecciation and post-annealing shearing and displacement at the micron to millimeter scale can be discerned in the form of shock veins (Fig. 1c). Offsets along the shock veins indicate that there may have been a frictional component to melting (Spray 1999). Undulose extinction grades into slight mosaicism approaching the shock veins. Both irregular and parallel planar fractures have been observed in olivine. Irregular and parallel planar fractures, both within and adjacent to shock veins, are coated with troilite, which has been injected from the melt region into these preexisting fractures. Plagioclase has not been transformed to maskelynite.

Tetrataenite

Tetrataenite occurs most commonly as rims (10–20 μm apparent width) on normally zoned taenite grains, but is also present as isolated grains in contact with troilite, cloudy taenite, and more rarely, kamacite (Fig. 1d). Both massive and rim tetrataenite are composed of irregular crystals 1–15 μm in size, which are only visible under crossed (or slightly uncrossed) polars and are orientated in three different directions.

MINERALOGY

Modal abundances of major phases include olivine (55), orthopyroxene (23), opaques (15), plagioclase (5), and clinopyroxene (2). Representative microprobe analyses of

mineral phases are presented in Table 1. Low standard deviations of mineral analyses (Table 1) indicate chemical equilibrium, which in turn corresponds to the high degree of thermal metamorphism characteristic of petrologic type 6 chondrites. Table 1 also gives analyses of tetrataenite, taenite, kamacite, and troilite.

GEOOTHERMOMETRY

Geothermometry, based on the compositions of clinopyroxenes in the Benton LL6 chondrite, yields coherent results, but the estimated temperatures obtained from coexisting orthopyroxenes are lower than for clinopyroxenes. Coexisting orthopyroxenes give apparent equilibration temperatures that are approximately 60–90°C lower and are suspect due to compositional effects of polymorphic inversions and/or kinetic factors of Ca diffusion (McSween and Patchen 1989). The calibrations of Kretz (1982) and Lindsley (1983) for geothermometry based on the compositions of clinopyroxenes and orthopyroxenes were applied to Benton (Table 3). Both thermometers are based on Ca-Mg partitioning between coexisting pyroxenes, which is strongly dependent on temperature, but largely independent of pressure (Carlson 1989). Temperatures obtained using the Kretz geothermometer seem unreasonably high, based on the absence of eutectic melting, which should occur by 950–1000°C (McSween and Patchen 1989), thus, the Lindsley thermometric data is taken as the most viable. The reported uncertainty in temperatures derived from the Lindsley thermometer is $\pm 50^\circ\text{C}$ and that for the Kretz thermometer is $\pm 60^\circ\text{C}$.

DISCUSSION

Geothermometric studies of the types 4 and 5 chondrites show that they are highly unequilibrated. Type 5 chondrite orthopyroxenes exhibit marked clustering at 675–750°C (McSween and Patchen 1989), indicative that this most likely represents an equilibration point. Thus, orthopyroxenes, like clinopyroxenes, appear to record a metamorphic overprint that has completely reset “igneous” crystallization temperatures in type 4 and 5 chondrites. Type 6 chondrites show narrow compositional ranges at higher temperatures, and it is, therefore, interpreted that they have equilibrated during metamorphism (McSween and Patchen 1989). Geothermometric results from clinopyroxenes in the Benton LL6 chondrite are thus interpreted in terms of metamorphic equilibration temperatures. The mean equilibration temperature recorded in the Benton LL6 chondrite is 890°C. Equilibration temperatures for Benton determined in this study are slightly lower than those determined for LL6 chondrites by McSween and Patchen (1989) using the same geothermometers. Their mean value based on the Lindsley calibration was 927°C. In addition, they are slightly higher

Table 1. Representative electron microprobe analyses of mineral phases in Benton LL6 chondrite.

	1a ^a (n = 30)	1b (n = 20)	2a (n = 15)	2b (n = 15)	3a (n = 15)	3b (n = 10)	4a (n = 15)	4b (n = 15)	5a (n = 5)	5b (n = 5)	6a (n = 10)	6b (n = 10)	7a (n = 5)	7b (n = 5)
Wt%														
SiO ₂	37.8	37.9	55.6	55.2	53.7	53.8	64.9	65.1	0.8	0.7	n.d.	n.d.	0.2	0.2
Al ₂ O ₃	n.d.	n.d.	0.2	0.2	0.5	0.4	21.5	21.5	n.d.	n.d.	3.7	3.1	n.d.	n.d.
TiO ₂	n.d.	0.1	0.2	0.2	0.4	0.4	0.1	0.1	n.d.	n.d.	5.5	5.5	41.3	46.2
Cr ₂ O ₃	0.1	0.1	0.1	0.2	0.8	0.8	0.1	n.d.	n.d.	n.d.	55.7	55.8	0.5	0.5
FeO	26.6	26.7	15.4	15.8	6.5	6.5	0.6	0.4	2.0	1.8	31.8	32.2	52.0	47.4
MnO	0.4	0.4	0.4	0.5	0.2	0.2	0.1	n.d.	n.d.	n.d.	0.6	0.7	1.2	1.3
MgO	34.9	35.0	27.0	27.1	16.2	6.3	n.d.	n.d.	3.4	3.3	1.9	1.6	1.7	1.9
CaO	n.d.	n.d.	1.1	1.1	21.2	21.1	2.3	2.2	44.2	44.2	n.d.	n.d.	n.d.	n.d.
Na ₂ O	n.d.	n.d.	n.d.	n.d.	0.6	0.6	10.2	10.2	2.7	2.7	n.d.	n.d.	n.d.	n.d.
K ₂ O	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.1	0.9	0.1	0.2	n.d.	n.d.	n.d.	n.d.
P ₂ O ₅	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	45.2	45.2	n.d.	n.d.	n.d.	n.d.
V ₂ O ₃	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.0	1.0	2.4	2.2
Total	99.3	100.2	100	100.3	100.1	100.1	100.9	100.4	98.4	98.1	100.2	99.9	99.3	99.7

^aMinerals: (1) olivine, $\sigma = 0.3$; (2) orthopyroxene, $\sigma = 0.5$; (3) clinopyroxene, $\sigma = 0.6$; (4) plagioclase, $\sigma = 0.7$; (5) whitlockite (merrillite), $\sigma = 0.7$; (6) chromite, $\sigma = 0.8$; (7) ilmenite, $\sigma = 1$; a: clast minerals, b: matrix minerals, n: number of analyses averaged, n.d.: not detected.

Table 2. Representative electron microprobe analyses of metallic mineral phases in the Benton LL6 chondrite.

	1a ^a	1b	2a	2b	3a	3b
Wt%						
Fe	51.5	51.8	47.4	49.0	85.6	85.7
Ni	45.9	46.5	50.6	48.4	6.2	6.2
S	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co	2.1	2.4	2.5	2.2	8.1	8.3
Cu	0.2	0.4	0.1	0.2	n.d.	n.d.
Total	99.7	99.8	100.1	99.90	99.9	100.2

^aMinerals: (1) taenite, (2) tetraenaite, (3) kamacite; a: clast minerals, b: matrix minerals.

Table 3. Two-pyroxene geothermometry using Kretz and Lindsley calibrations.

Clinopyroxenes				Orthopyroxenes		
Wo (mole fractions)	Fs	T(Lindsley) °C	T(Kretz) °C	Wo (mole fractions)	Fs	T(Lindsley) °C
0.435	0.876	880	1219	0.024	0.241	820
0.433	0.999	900	1247	0.016	0.238	810
0.431	0.104	890	1232	0.019	0.251	800

than the mean temperature of Olsen and Bunch (1984), who obtained a value of 860°C. Mean values for calibration depend critically on the choice of meteorite analyzed because not all type 6 chondrites equilibrated at the same temperature (McSween and Patchen 1989). Also, the range of type 6 orthopyroxene (and clinopyroxene) equilibration temperatures does not necessarily indicate a lack of equilibration within individual meteorites, because the Van Schmus and Wood (1967) classification scheme assigns chondrites with gradational properties into discrete groups. Therefore, it is expected that meteorites of the same petrologic type may have experienced slightly different peak temperatures (McSween and Patchen 1989).

Based on data presented by Stöffler et al. (1991), Benton is classified as S3, experiencing weak shock effects with shock pressures on the order of 15–20 GPa, with an estimated post-shock temperature increase of 100–150°C.

The bimodal grain size distribution between clast and matrix minerals can be considered a primary feature reflecting comminution by impact bombardment. The high Ni content of FeNi phases in Benton and the rarity of kamacite are consistent with a high degree of overall oxidation. The relative coarseness of plagioclase grains, as well as the degree of chemical equilibration (represented as low standard deviations in mineral analyses) and textural features, are consistent with a petrologic type 6 classification for both clast and matrix minerals.

CONCLUSION

This breccia is monomict: there is neither petrological nor mineralogical evidence that it contains materials of more than one chemical group or petrologic type. It is, thus, concluded that Benton had a relatively simple history (relative to regolith breccias), the components of which formed in situ. The mean equilibration temperature recorded in Benton is 890°C. In addition, Benton is classified as an S3 weakly shocked chondrite, experiencing shock pressures on the order of 15–20 GPa, with an estimated post-shock temperature increase of 100–150°C.

Acknowledgments—This work was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) through research grants to J. G. S. The authors

thank Richard Herd, Curator of the Ottawa National Meteorite Collection in Ottawa, for loan of the Benton meteorite fall, Calvin Nash and Ancel Murphy for preparation of superb ultrathins, Nick Susak for providing the nital etch, and Douglas Hall for EM support. Alan Rubin and Ed Scott are thanked for reviewing an earlier draft of the work, Planetary and Space Science Centre contribution 29.

Editorial handling—Dr. Edward Scott

REFERENCES

- Bischoff A. and Stöffler D. 1992. Shock metamorphism as a fundamental process in the evolution of planetary bodies: Information from meteorites. *European Journal of Mineralogy* 4: 707–755.
- Bogard D. D. 1995. Impact ages of meteorites: A synthesis. *Meteoritics* 30:244–268.
- Carlson W. D. 1989. Subsolidus phase equilibria near the enstatite-diopside join in CaO-MgO-Al₂O₃-SiO₂ at atmospheric pressure. *American Mineralogist* 74:325–332.
- Clayton R. N. 1993. Oxygen isotopes in meteorites. *Annual Review of Earth and Planetary Science* 21:115–149.
- Heymann D. 1967. On the origin of hypersthene chondrites: Ages and shock effects of black chondrites. *Icarus* 6:189–221.
- Heide F. and Wlotzka F. 1995. In *Meteorites—Messengers from space*, edited by Clarke R. S. and Wlotzka F. Berlin: Springer-Verlag, 210 p.
- Keil K. 1964. Possible correlation between classifications and potassium-argon ages of chondrites. *Nature* 203:511.
- Kretz R. 1982. Transfer and exchange equilibria in a portion of the pyroxene quadrilateral as deduced from natural and experimental data. *Geochimica et Cosmochimica Acta* 46:411–421.
- Lindsley D. H. 1983. Pyroxene thermometry. *American Mineralogist* 68:477–493.
- McSween H. Y. Jr. and Patchen A. D. 1989. Pyroxene thermobarometry in LL-group chondrites and implications for parent body metamorphism. *Meteoritics* 24:219–226.
- Millman P. M. 1953. A catalogue of Canadian meteorites. *Royal Astronomical Association of Canada* 47:29–133.
- Olsen E. J. and Bunch T. E. 1984. Equilibration temperatures of the ordinary chondrites: A new evaluation. *Geochimica et Cosmochimica Acta* 48:1363–1365.
- Spray J. G. 1999. Shocking rocks by cavitation and bubble implosion. *Geology* 27:695–698.
- Stöffler D., Keil K., and Scott E. R. D. 1991. Shock metamorphism of ordinary chondrites. *Geochimica et Cosmochimica Acta* 5: 3845–3867.
- Vanschmus N. R. and Wood J. A. 1967. A chemical-petrological classification for the chondritic meteorites. *Geochimica et Cosmochimica Acta* 31:747–765.