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The Barwell meteorite

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Summary. Part of a meteorite was seen to fall on a road (52° 33′ 55″ N., 1° 20′ 23″ W.) in the village of Barwell, Leicestershire, at about 16.20 hrs G.M.T. on 24 December 1965. Fragments have been found over an area some ¾ mile long by ½ mile across, and appear to have been part of a single stone, of which 44 Kg (97 lb) have been recovered. The distribution, impact effects, and crustal morphology of the recovered fragments are described. Barwell is a moderately metamorphosed white olivine–hypersthene chondrite; a chemical analysis, with the derived Wahl norm, and a modal analysis are given, together with optical data and electron-probe analyses of the principal constituent minerals.

AT approximately 16·20 hrs G.M.T. on Christmas Eve, 24 December 1965, Mr. A. E. Crow of 18 The Common (a road leading to the centre of Barwell, Leicestershire) was walking home from work 'when he saw a flash in the sky and heard a bang. A few moments later he heard something "swish" down out of the sky and land somewhere in the vicinity with a thud. He then heard four or five other objects come down in quick succession but separately. He felt that they all landed quite nearby and the last one landed in the road with a thud and shattered, one piece breaking Mr. Grewcock's window. He said the impact made a shallow hole in the road and the area was covered with a white dust and

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particles of rock.' The latitude and longitude of this, the first recorded point of fall, are 52° 33′ 55″ N., 1° 20′ 23″ W. Mr. Crow's neighbour, Mr. J. Grewcock of 14 The Common, 'later went outside to see what had broken his window . . . he went to pick up the piece . . . but it was too hot to handle'.

On 27 December Mr. Grewcock reported the incident to the local policeman, P.C. Scott, and it is from his official report (recorded immediately after the interview with the observers) that the above quotations are taken. The report mentions also that about 4.15 p.m. Scott himself saw 'a white flash like lightning but of brief duration, which seemed to be from the direction of Hinckley [some 2 miles SSW. of Barwell] and which was followed some two seconds later by what sounded to be an explosion some considerable distance away'. Several reports of the phenomena were received by the police at Coventry (some 12 miles to the SSW.). Miles and Meadows (1966) have collected and collated the reports of many observers over a wide area who saw similar phenomena. They have been able to plot the track of the meteorite along a line bearing approximately 23° east of true north over southern England and the Midlands to its extinction point over Coventry.

The material was sent by the police to Leicester Museum and pieces were passed to the Geological Survey and Museum, to the British Museum (Natural History), and to Leicester University for confirmation of identification. Preliminary examinations showed that the material was a chondritic meteorite. On 6 January 1966, representatives from the institutions mentioned met at Barwell to inspect material found elsewhere in the village that had been handed to the police and to carry out a search for further fragments. During that day's search a crater *c.* 23 cm diameter was discovered by Dr. T. D. Ford of Leicester University and on investigation yielded two large fragments and smaller pieces weighing over 4·85 Kg (no. 7, see list and map); in the afternoon Dr. Ford also found a fragment of 2·3 Kg (no. 8) lying on the surface of a well-trodden field in use for horse grazing; the ground surface was frozen but at the time of the fall the ground was soft and muddy as a result of rain. Further search on 7 and 9 January yielded additional fragments and the total weight recovered by then was approximately 20 Kg.

Subsequently systematic traverses of fields around Barwell using several observers walking a few feet apart produced a fragment of 0·71 Kg (no. 15) on 30 January and many smaller fragments in the southern part of the area shown on the map. During some sweeps a mine detector and a magnetic rake were used but with limited success. During the period

9 to 30 January school children were known to have recovered many small fragments in the area south of Barwell Recreation Ground; on one Saturday afternoon Mr. H. F. Miles of Lanchester College of Technology, Coventry, saw in the possession of schoolboys at least fifty fragments and a conservative estimate of their total weight was obtained by weighing a dozen typical examples and multiplying the 'average' weight by fifty. Careful search of the area south of the dotted line shown on the map failed to reveal any small fragments and no recoveries have been reported from there. The possibility of the presence of fragments of 'sand' size cannot, however, be excluded.

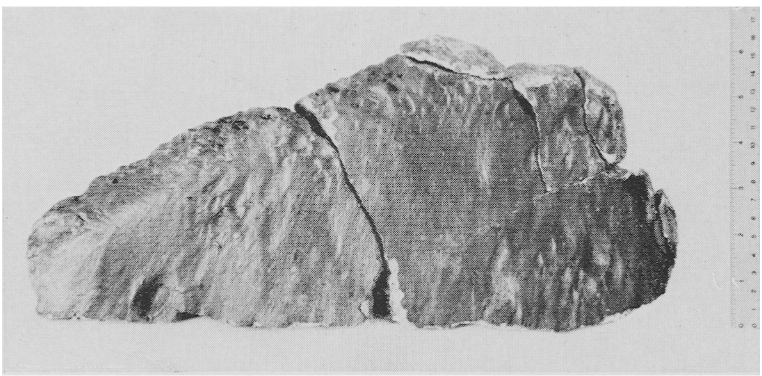

FIG. 1. Fragments (nos. 4 and 5) of the Barwell meteorite that fit exactly, but which fell $\frac{3}{8}$ mile apart. Scale in cm and inches.

Dark brownish-black fusion crust was present on part of the surfaces of several of the fragments recovered up to 30 January, and early in February an attempt was made to fit the fragments together in an endeavour to establish the form of the original stone. Only two large fragments, nos. 4 and 5, which fell $\frac{3}{8}$ mile apart, fitted exactly (see fig. 1). From the nature and extent of the crust on the fragments it was apparent that a considerable proportion of the meteorite had yet to be recovered. Since no significant recoveries had taken place during the first three weeks of February it was decided to offer to purchase any additional fragments found. The local newspapers publicized this offer on 26 February. On 28 February a fragment of 2·3 Kg (no. 17) was found, followed on 2 March by one of 7·7 Kg (no. 18). The latter is the largest so far recovered, and was found at a depth of about 75 cm in an apparently vertical hole about 16 to 17 cm diameter near the Pavilion on the

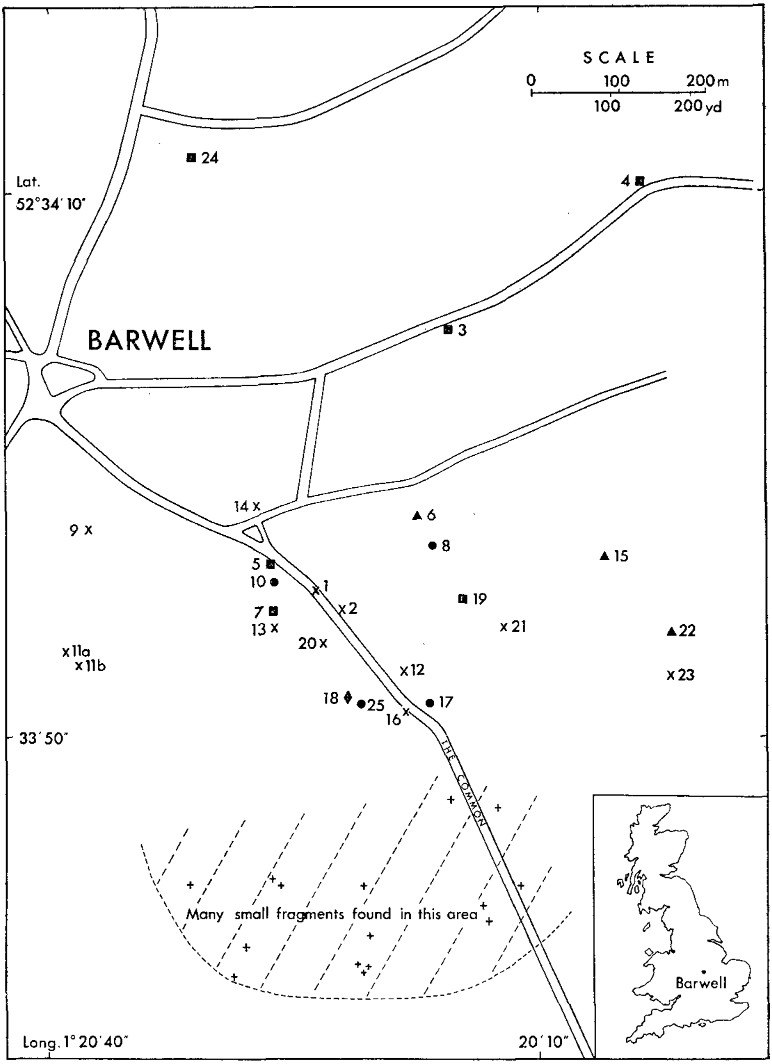

FIG. 2. Plan showing the distribution of recovered fragments of the Barwell meteorite. Weights are indicated: + 0 to 50 g, × 50 to 500 g, ▲ 500 to 1000 g, ● 1000 to 2500 g, ■ 2500 to 5000 g, ◆ over 5000 g. In the 0 to 50 g group only well-localized fragments are shown.

Recreation Ground—an area in very heavy use. At the time of writing we have no knowledge of the recovery of any fragments since 12 March 1966. Barwell is an industrial village with many gardens and allotments and is surrounded by arable land. It is possible that further specimens may appear during gardening and farming operations.

Topographically the area is rather flat. It rises gently to the north, where it is covered by glacial sands and gravels; glacial Boulder Clay occurs to the south. The glacial deposits are underlain by marls and sandstones of the Keuper Marl (Trias).

Details of fragments recovered[1]

1. Recovered 24 December 1965. G.R. SP 44759664. Fell on metalled road forming crater 2 cm deep, *c.* 12 cm long, fragmented and scattered over road. Windows of 14 The Common broken, one piece entered room and lodged in vase of plastic flowers where it was found in unweathered condition about 19 days after fall. Much material was reduced to powder by vehicular traffic and some removed by road-sweeper and lost. Crust, porous. Total weight 469·6 g: pieces 203·4 g, 148·0 g, 50·8 g, 26·7 g, 25·2g, 15·5 g. B.M. (N.H.), registered number B.M. 1966, 58.

2. Recovered 24 December 1965. G.R. SP 44779662. Fell on bonnet of car standing in drive, deeply denting the metal, but a supporting strut beneath bonnet prevented penetration. Original weight estimated at 6 to 7 pounds (*c.* 3 Kg) by car-owner who disposed of fragment on waste land thinking that hooligans had thrown a lump of concrete. He was unable subsequently to find complete fragment but 246 g was recovered later. Crust, porous. Weight 246 g. Griffith Observatory, Los Angeles.

3. Recovered 25 December 1965. G.R. SP 44909694. Fell on tarmac drive, shattered, forming crater 20 cm across and 20 cm deep. Crust striated, with regmaglyptic relief. Total weight 4479·8 g: pieces 1148·2 g, 568·8 g, 442·6 g, 300·0 g, 275·0 g, 264·3 g, 216·6 g, 144·3 g, 134·2 g, 102·7 g, 99·5 g, 95·2 g*, 91·1 g, 82·0 g, 63·5 g, 59·7 g, 52·8 g, 34·4 g, 34·3 g, 33·0 g, 32·0 g, 28·3 g, 25·1 g, 15·5 g, 13·7 g, 13·5 g, smaller pieces totalling 89·5 g. B.M. (N.H.), reg. no. B.M. 1966, 59. *Mus. d'Hist. Nat., Paris.

4. Recovered 25 December 1965. G.R. SP 45129711. Fell on tarmac drive, shattered, forming crater 23 cm long and 9 cm deep elongated in direction 120° to true North, fig. 3*a*. Crust striated, with regmaglyptic relief. Total weight 4143·3 g: pieces 3345 g, 286·0 g, 128·0 g, 85·8 g, 73·4 g, 48·0 g, 35·1 g, 23·0 g, 19·4 g, 15·8 g, 12·0 g, smaller pieces totalling 71·5 g. G.S.M., reg. no. MI 32871.

5. Recovered 28 December 1965. G.R. SP 44699667. Fell on rough grass penetrating to depth of 23 cm in clay. Crater between house and 5 foot high railings whose juxtaposition indicates a very steep descent and confirms general direction of track. Crust striated, with regmaglypts. Weight 2845 g. B.M. (N.H.), reg. no. B.M. 1966, 60.

6. Recovered 3 January 1966. G.R. SP 44869673. Fell on factory roof, penetrating outer asbestos sheet (1 cm thick) and plaster-board lining (*c.* 1·5 cm), fell 90 cm through loft and then penetrated wood floor (2·2 cm) and came to rest on plaster-board ceiling 15 cm below. Pieces fresh and unweathered. Crust striated, with regmaglyptic relief. Total weight 519·9 g: pieces 393·5 g, 105·4 g, smaller pieces totalling 21·0 g.

7. Recovered 6 January 1966. G.R. SP 44709661. Fell on rough grassland form-

[1] Details are given in the following order: number as on Fig. 2; date of recovery; National Grid Reference (G.R.) of point of recovery; impact effects; crustal morphology; weight of fragments; where deposited: G.S.M., Geological Survey and Museum, London; B.M. (N.H.), British Museum (Natural History), London.

ing essentially vertical crater in soil and clay, 23 cm diameter, total depth 32 cm, in which two pieces lay side by side. Top of one piece visible at depth 23 cm. Finder reported grass slightly scorched. Crust smooth, finely dimpled. Total weight 4855·6 g: pieces 3021·0 g, 1690·0 g, 65·2 g, 28·6 g, 16·2 g, smaller pieces totalling 34·6 g. B.M. (N.H.), reg. no. B.M. 1966, 56.

8. Recovered 6 January 1966. G.R. SP 44879670. Found on surface of well-trodden, rather bare grassland, no crater observed. Crust, not examined. Weight 2396·0 g. B.M. (N.H.), reg. no. B.M. 1966, 57.

9. Recovered 6 and 7 January 1966. G.R. SP 44519669. Found just embedded in short turf. Fig. 3*b*. Crust, porous. Total weight 113·6 g: pieces 100·5 g, 12·1 g, smaller pieces totalling 1·0 g. G.S.M., reg. no. MI 32885.

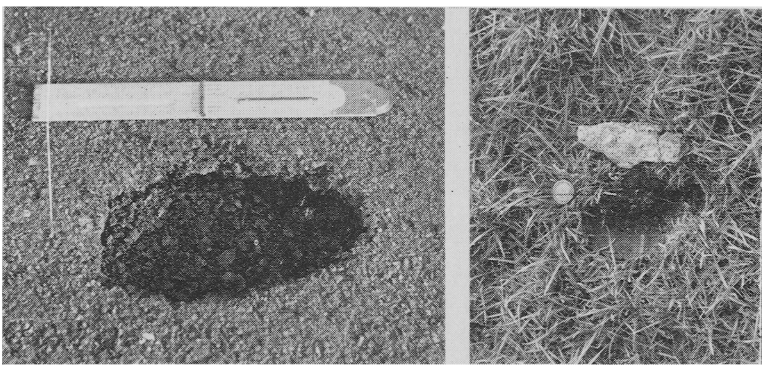

FIG. 3. Impact craters formed by the Barwell meteorite: *a* (left), in a tarmacadam drive, crater 23 cm long and 9 cm deep; *b* (right) in soft turf, crater about 10 cm long and 2·5 cm deep. Both illustrations to same scale; length of ruler 1 foot.

10. Recovered 8 January 1966. G.R. SP 44709665. Fell in well-dug soil; found *c.* 30 cm down, below shallow crater resembling imprint of bullock's hoof. Crust, none. Weight 1554·0 g. B.M. (N.H.), reg. no. B.M. 1966, 61.

11. Recovered 8 January 1966. G.R. SP 44549657(a) and SP 44539654(b). Found lying on grassland. Crust, not examined. Weights 201·6 g (a), 123·8 g (b).

12. Recovered 8 January 1966. G.R. SP 44859655. Found in small hole in soil. Crust smooth, finely dimpled. Total weight 494·0 g: pieces 226·0 g, 117·0 g, 91·0 g, 43·0 g, 9·0 g, 8·0 g.

13. Recovered 9 January 1966. G.R. SP 44709659. Pieces collected over area *c.* 3 square metres in hedgerow beneath tree which had been hit. A branch *c.* 1·5 cm diameter was broken and another branch *c.* 4 cm diameter had been broken in two places. Crust, not examined. Total weight 189·4 g: pieces 99·0 g, 28·0 g, 22·9 g, smaller pieces totalling 39·5 g.

14. Recovered 24 January 1966. G.R. SP 44689673. Fell on rough grass in area with much scattered rubble. Found *c.* 15 cm north of a *c.* 60 cm high wall parallel to lane, thus indicating steep descent. Crust, none. Weight 95·5 g. City of Leicester Museums and Art Gallery, Leicester.

15. Recovered 30 January 1966. G.R. SP 45089668. Fell on soft turf making vertical-sided crater 10 cm deep and lay with its large flat surface parallel to ground surface. Crust, many elongated fused droplets on smooth surface. Weight 701 g.

16. Recovered 7 February 1966. G.R. SP 44859650. Found lying on surface near rubbish bin used by roadsweeper. May be part of the original find (No. 1, this list) swept up by roadsweeper, but exact locality is uncertain. Crust striated, with regmaglyptic relief. Total weight 613 g: pieces 535 g, 65 g*, 13·0 g. B.M. (N.H.), reg. no. B.M. 1966, 62. *Royal Scottish Museum, Edinburgh.

17. Recovered 28 February 1966. G.R. SP 44889651. Fell in cultivated land forming crater *c.* 45 cm deep. When found was covered with *c.* 10 cm soil. Hit pebble which was shattered into 3 pieces, and apparently jinked since crater indicated entry from NE. Crust smooth, finely dimpled. Total weight 2301 g: piece 2216 g, smaller pieces totalling 85 g. City of Leicester Museums and Art Gallery, Leicester.

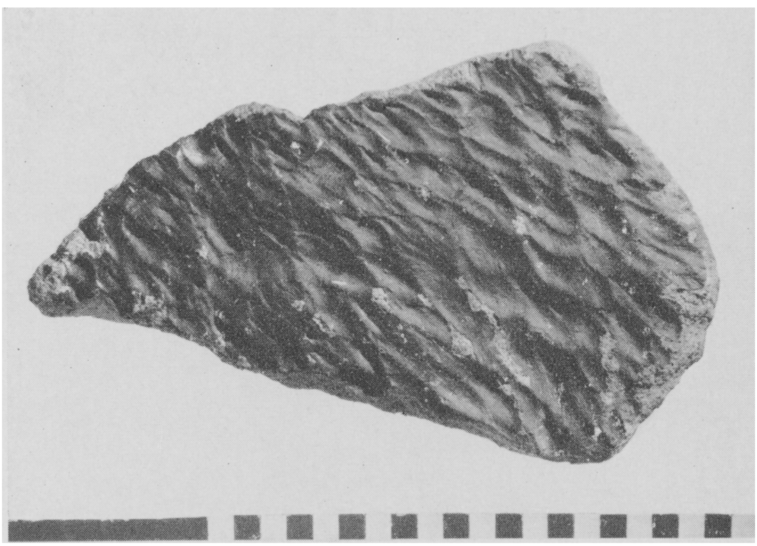

FIG. 4. The largest fragment of the Barwell meteorite recovered (no. 18; B.M. 1966, 63; 7739 g.). Scale in cm.

18. Recovered 2 March 1966. G.R. SP 44789652. Fell on turf underlain by soil and stiff clay. Penetrated *c.* 75 cm in apparently vertical hole *c.* 16–17 cm diameter. (Described by finder, Mr. G. Potterton, as 'long as my arm and as wide as a saucer. You would never have thought the piece had gone in that hole.') Crust on two surfaces intersecting at *c.* 70° (*a*) smooth, finely dimpled, (*b*) pronounced regmaglyptic relief with flowing on ridges (fig. 4). Has one large, flat fracture surface. Weight 7739 g. B.M. (N.H.), reg. no. B.M. 1966, 63.

19. Recovered 5 March 1966. G.R. SP 44929663. Fell on disused allotments penetrating rough grassland forming crater depth 45 cm, diameter *c.* 30 cm. Crust on two separated surfaces (*a*) smooth, finely dimpled, (*b*) regmaglyptic relief with fused drops and small scoriaceous areas. Weight 3438 g. B.M. (N.H.), reg. no. B.M. 1966, 64.

20. Recovered 5 March 1966. G.R. SP 44749657. Found in collapsed crater *c.* 10–12 cm deep *c.* 30 cm diameter in well-dug soil. Crust, none. Total weight *c.* 282 g: pieces 256 g, *c.* 28 g. U.S. Nat. Mus., Washington.

21. Recovered 5 March 1966. G.R. SP 44969660. Fell on rough grass in overgrown allotment penetrating *c.* 30 cm soil. Hole had been reduced to *c.* 2 cm diameter (described by finder as 'size of sixpenny piece') by action of weather. Crust, none. Total weight *c.* 497 g: pieces 412 g, *c.* 85 g. Herbert Art Gallery and Museum, Coventry.

22. Recovered 5 March 1966. G.R. SP 45169659. Penetrated *c.* 10 cm in turf. Very shallow lip to crater. Crust with regmaglyptic relief. Weight 679·5 g. Planetarium, Armagh, Northern Ireland.

23. Recovered 5 March 1966. G.R. SP 45169654. Just embedded in turf. Crust, none. Weight 333 g.

24. Recovered 11 March 1966. G.R. SP 44619714. Crater 12 cm deep in cinders which overlay broken bricks. Position of crater in relation to buildings indicates very steep descent. Crust, three relatively flat contiguous surfaces resembling three sides of a prism at *c.* 120° to each other (*a*) finely striated, (*b*) striated with many elongated fused droplets, (*c*) scoriaceous. Total weight 2587 g: pieces 2206 g, 380 g. B.M. (N.H.), reg. no. B.M. 1966, 65.

25. Recovered 12 March 1966. G.R. SP 44799651. Penetrated *c.* 20 cm in well-trodden turf. Crust, two surfaces intersecting at *c.* 100° (*a*) regmaglyptic relief with flowing on ridges, (*b*) smooth faces with some elongated fused droplets. Weight 1262 g. U.S. Nat. Mus., Washington.

26. Miscellaneous small fragments recovered on various dates mostly from the 'small fragments area': G.R. SP 44659619, 25·1 g; G.R. SP 44673623, 7·6 g; G.R. SP 44989630, 2·4 g; G.R. SP 44959639, 4·4 g; G.R. SP 44959627, 12·7 g; G.R. SP 44819625, 34·0 g; G.R. SP 44040628, 23·9 g; G.R. SP 446963, 36·0 g; G.R. SP SP 448962, 9·2 g (total of several small fragments); G.R. SP 448962, 11·6 g (total of several small fragments); other fragments known to have been collected 457·1 g; at least 50 pieces seen in the possession of schoolboys in 'small fragments area', conservatively estimated weight 225 g. Total weight of known small fragments: *c.* 849 g.

The total weight of all the fragments the authors have seen and which have been verified amounts to 43·672 Kg (96 lb. 4½ oz.). The total of estimated weights of other fragments that have been seen in the possession of various people, but have not been deposited with any institution is 338 g. Thus the total recovered weight is at least 44·0106 Kg (97 lb. 0½ oz.). This compares with the heaviest known fall in the British Isles, Limerick County in 1813, which weighed at least 106 lb., but which was of several individual stones.

A second attempt was made in April to fit together the meteorite fragments; nos. 3, 4, 5, 10, 18, 19 (added weights 24·199 Kg) fitted as did nos. 8 and 24 (added weights 4·983 Kg). It was not possible, however, to fit together the two assemblies, although they are probably parts of one large stone; several large fragments with crust did not fit either assembly. It was apparent that much material has yet to be recovered. Nevertheless, the Barwell meteorite appears to be the largest single stone known to have fallen on the British Isles.

The broken surfaces of all Barwell fragments studied in the British Museum (Natural History) are light grey in colour and are studded with abundant darker grey chondrules. Apart from several flat surfaces shown on some of the larger fragments, governing the overall shape of the meteorite before fragmentation, fractures are uneven and cut directly across most chondrules. Some larger chondrules, however, have plucked unbroken from fracture surfaces.

Metal is readily distinguished on sawn surfaces, but is less conspicuous on natural breaks. It is surrounded by reddish-brown stains on surfaces that have been exposed to the weather.

Most of the roughly spherical chondrules are between 1 and 2 mm in diameter, but some range up to 7 mm. Even larger chondrules, up to 1·2 cm across and somewhat polyhedral in shape, are comparatively rare. No veins, brecciation structures, or macroscopic xenoliths occur in any of the Barwell fragments, which are all very similar in overall appearance apart from variation in the nature of fusion crust.

In the Rose–Tschermak–Brezina classification, as outlined by Mason (1962, p. 48) and Krinov (1960, p. 401), Barwell belongs to the Crystalline Globular Chondrites (class Cck).

The following notes on mineralogy and structure are based on a study of six thin sections (one polished for reflected light and electron probe investigations) cut from two separate fragments, and on about one gram of powdered meteorite. Part of the powder was treated with hydrochloric acid (1:1) to remove metal, troilite, and olivine, then leached with boiling sodium carbonate solution and separated with heavy liquids into impure pyroxene and plagioclase concentrates.

Mineralogy

The modal proportions of the main constituent minerals of Barwell, determined by point counter on a thin section (3 cm^2 area) and a polished section (2 cm^2 area) of a fragment lacking exceptionally large chondrules, are listed in table I beside a norm computed from the chemical analysis of a different fragment. An average density of 3·0 was assumed for the fine-grained unresolved silicate portion when calculating the mode into weight per cent. form. Taking into account errors possibly introduced by this assumption, and also the small area covered by the point counter, the norm and mode show good agreement. The sectioned fragment apparently contains a little more metal than that used for chemical analysis, for the accuracy of the analysis is attested by close correspondence between the normative iron:magnesium ratio of the mafic silicates and their compositions determined by optical, X-ray, and electron-probe methods.

Olivine, by far the most abundant constituent of the meteorite, occurs in both chondrules and matrix as variously sized grains essentially free of inclusions. Its optical properties (α 1·683±0·002, β 1·703±0·001, γ 1·721±0·002, $2V_\gamma$ 96°±2°; Na–light) indicate a content of 25 mol. % fayalite, using the charts of Poldervaart, 1950, or of Deer, Howie, and

TABLE I. Chemical and mineralogical composition of the Barwell meteorite

					Wahl norm		Mode wt. %	Mode vol. %
Fe	5·49 %							
Ni	0·70	6·23	Metal		6·2		10·1	4·8
Co	0·043		Troilite		6·6		6·0	4·5
Fe	4·20		Chromite		0·5		0·9	0·7
Ti	0·0025	6·62	Ilmenite		0·2		—	—
Mn	0·0055		Apatite		0·6		tr.	tr.
S	2·41			Or	0·7			
SiO_2	40·0		Feldspar	Ab	10·5	12·4	4·9	6·7
TiO_2	0·09			An	1·2			
Al_2O_3	2·60		Olivine	Fa	16·3	50·0	44·0	45·0
Cr_2O_3	0·37			Fo	33·7			
FeO	15·13		Diopside		4·9		—	—
MgO	24·86		(ferroan)					
MnO	0·29		Hypersthene	Fs	5·5	18·1	18·4	19·6
CaO	1·80			En	12·6			
Na_2O	1·24		Others		0·1*		15·7†	18·7†
K_2O	0·12		Sum		99·6		100·0	100·0
P_2O_5	0·26							
H_2O	0·10							
Sum	99·71							

* H_2O.
† Fine unresolved silicates; assumed density 3·0.
Normative ratios:
100 An/(An+Ab+Or) 9·0±1·0
100 Ni/(Fe+Ni+Co) 11·2±0·4
100 Fe/(Fe+Mn+Mg) 25·0±0·8

Analyst: A. J. Easton

Zussman, 1962, fig. 11; the X-ray diffractometer method of Yoder and Sahama (1957) gives 26 mol. % fayalite (d_{130} 2·783 Å), with sharp reflections indicating uniformity of composition; electron-probe measurements give 23·7±0·7 mol. % fayalite, also with no significant variations.

Hypersthene occurs as large prismatic grains in chondrules and as smaller granules in both chondrules and matrix. Electron-probe measurements indicate a content of 19·1±0·6 mol. % ferrosilite, with no significant variation. The refractive indices (α 1·678±0·002, β 1·685±0·001, γ 1·689±0·001, $2V_\gamma$ 84°±5°, Na–light, with no detectable variation in γ), when compared with the charts of Poldervaart (1950), Kuno (1954), and Deer, Howie, and Zussman (1963, fig. 10), lead to compositions with 17, 22, and 20 mol. % ferrosilite respectively. The data for coexisting olivine and pyroxene[1] in meteorites obtained by Keil and Fredriksson (1964) fit closely to a line Fa = 1·34 Fs−3·9 (mol. %); for an olivine with 23·7 % Fa this would predict a hypersthene with 20·6 % Fs. X-ray diffractometer patterns of the pyroxene concentrate from Barwell resemble those of orthorhombic hypersthene from the olivine-hypersthene chondrite *Appley Bridge*. However, between crossed nicols on a universal stage, most of the larger hypersthenes show a striated or twinned structure not unlike that of clinohypersthene. The maximum extinction angle of this pyroxene is only 10°, and the boundaries separating individual lamellae are not as sharp as those in true clinohypersthenes found in, e.g. the chondrites *Parnallee, Barratta,* and *Mező–Madaras*. There are no clinohypersthene peaks on diffractometer traces, and the maximum and minimum refractive indices of striated grains are indistinguishable from γ and α of apparently untwinned hypersthene grains. The Barwell hypersthenes give poor interference figures, and their anomalous positive optic axial angle is probably related to the striated structure.

Diopside occurs as thin platelets and equant granules, up to 0·05 mm across, between crystals of hypersthene in certain radiating pyroxene chondrules. It is rarely found in other kinds of hypersthene-bearing chondrule, and is not nearly as abundant as is suggested by the norm unless it occurs also as a constituent of fine-grained silicate aggregates in chondrule and interchondrule matrices. Some diopside is probably contained in solid solution in hypersthene. The larger diopside grains show extremely fine (100) and (001) exsolution lamellae. Electron-probe analyses showed some variation in calcium content, presumably arising from the presence of exsolution lamellae; the average composition obtained, when recalculated to 100 mol. %, was $CaSiO_3$ 47·5±1·4, $MgSiO_3$ 42·5±1·3, $FeSiO_3$ 10·0±0·3.

Plagioclase forms tiny equant grains, up to 0·1 mm across, in the fine-grained silicate matrix between and within chondrules. The relative abundances of plagioclase listed in the norm and mode (table I) suggest that this mineral is also a major constituent of the very fine unresolved silicate aggregates. Universal-stage examination reveals that most plagioclase grains are finely twinned on the albite law with low maximum extinction angles (2 to 3°). This twinning precludes accurate measurement of optic axial angles, and the observed values of 70 to 100° for $2V_\gamma$, based on conoscopic universal stage measurements and on

[1] Keil and Fredriksson claim an absolute accuracy of ±0·3 % in their Fe and Mg determinations, which would imply an accuracy of about ±0·5 in the Fe/(Fe+Mg) ratio when this is around 20 to 25 %.

curvature of isogyres in interference figures, result largely from composite optical effects. The refractive indices of Barwell plagioclase (α 1·534, β 1·539, γ 1·542, all $\pm$0·001, for Na-light) indicate an unzoned sodic oligoclase composition with about 12 mol. % anorthite (data of Smith, 1957). Optic axial angles and the following angular separation of peaks on X-ray diffractometer traces of the plagioclase concentrate reveal a low structural state, possibly slightly more disordered than most terrestrial plutonic plagioclases of comparable composition: $2\theta\,(131)-2\theta\,(1\bar{3}1) = 1{\cdot}58\pm0{\cdot}05^\circ$ (Cu-$K\alpha$ radiation, cf. Smith, 1956) $\Gamma = 2\theta\,(131)+2\theta\,(220)-4\theta\,(1\bar{3}1) = 0{\cdot}12\pm0{\cdot}05^\circ$ (Cu-$K\alpha$ radiation, cf. Smith and Gay, 1958).

A few grains of a near-isotropic, polysynthetically twinned mineral with refractive index 1·510$\pm$0·002 were noted in the plagioclase concentrate from Barwell. Despite precautions taken to avoid contamination, these are thought to be leucite impurities introduced from other mineral separations being prepared at the time in the same laboratory. Any meteorite leucite should have dissolved during the HCl treatment to which the crushed meteorite was subjected before separation.

Apatite. Minute grains of a mineral rich in calcium and phosphorus, probably apatite or merrilite, were encountered in Barwell during electron probe investigations, but despite the quantity of apatite in the norm, neither mineral occurred in grains large enough to be recognized optically. All near-isotropic uncleaved grains examined conoscopically proved to be olivine.

Kamacite occurs as large grains up to 1 mm across, and as tiny granules in certain chondrules and in the interchondrule matrix. The larger grains have irregular cuspate margins, contain no inclusions of silicate or other opaque phases apart from occasional marginal granules or strips of taenite, and prove on etching with 2 % nital to be single crystals lacking any detailed structure (fig. 5*a*). Certain smaller kamacites, however, including many tiny grains in chondrules, etch in a complex fashion resembling ϵ-iron structures (fig. 5*c*). Electron-probe traverses across larger kamacite grains show homogeneous compositional profiles, averaging 6 to 7$\pm$0·1 wt. % nickel and 1·0 % cobalt (mean of 12 analyses with negligible variation); totals were all near 100 %, and the mean values are as recalculated to 100 %.

Taenite is present in roughly equal proportion to kamacite, but tends to form slightly smaller grains, ranging up to 0·25 mm across, usually independent of other opaque constituents but in places associated with troilite or more rarely with large kamacites. Some grains adjacent to troilite contain small irregular or wedge-shaped inclusions of that mineral (fig. 5*d*). Small kamacite inclusions within taenite are rare (see fig. 5*e*). When etched with 2 % nital, taenite grains show a distinctly zoned structure, confirmed by electron probe study of four grains as a compositional zoning with nickel-rich rims (48 % Ni) and nickel-poor cores (30 % Ni); the average cobalt content of the taenite is 0·25 %. The zone pattern faithfully follows grain outlines (fig. 5*b*), but is disturbed by projections or inclusions of troilite or by inclusions of kamacite. Nickel-rich zones that surround inclusions are more sharply delineated than the normal nickel-rich margins (fig. 5*e* and *f*), suggesting that the two types of nickel-rich zone formed at different stages or by different processes during the cooling history of the meteorite.

Troilite forms ragged individual grains up to 0·5 mm across, slightly larger aggregates of two or more different grains, small inclusions within taenite, and tiny dust-like grains in chondrules and the interchondrule matrix. It is distinctly anisotropic in reflected light, changing colour between crossed nicols from grey to brown. Where adjacent to kamacite, troilite possesses smooth convex surfaces, but boundaries against taenite tend to be less regular.

Chromite also occurs as larger ragged grains up to 0·1 mm across, either independently of other opaques or at the margins of metal or troilite, and as fine granules in certain chondrules and in the interchondrule matrix. It is grey in polished section, much darker than the metal phase, and is isotropic. It tends to form convex surfaces against silicates and other opaque minerals. Because of the ilmenite content in the norm, a careful search was made to ensure that some grains identified as chromite were not indeed ilmenite, but no grains of the latter were found.

Small granules, golden yellow in colour and softer than the metal, were observed within several taenite grains containing inclusions of troilite. Although these showed no definite anisotropism between crossed nicols, possibly due to their orientation, they are tentatively identified as *chalcopyrite*.

Chemical analyses and electron-probe studies

A chemical analysis of Barwell, made by the classical magnetic separation technique as developed by Prior (1913, 1914) gave the results included in table I; a further partial analysis, made by a modification of the chlorination technique (Hey, in Smith, 1932; Moss, Hey, and Bothwell, 1961) at present under development, shows that there is no appreciable amount of schreibersite present, that a small fraction of the titanium and of the manganese present are in the sulphide phase (the

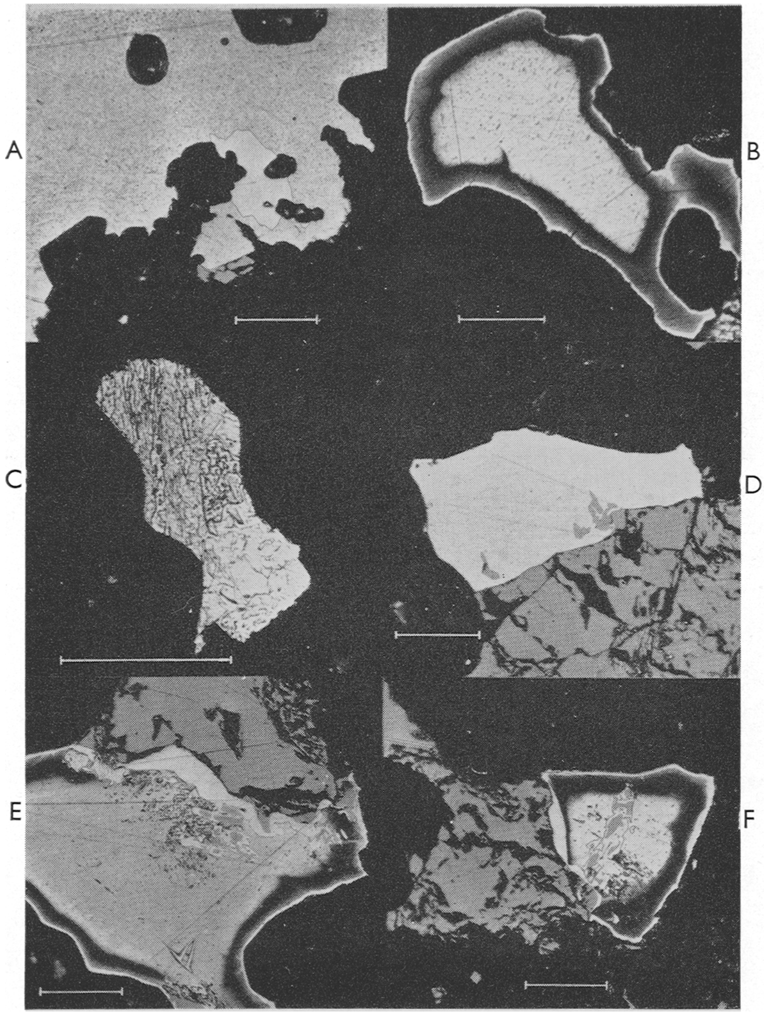

FIG. 5. Opaque constituents of the Barwell meteorite, photographed in reflected light. All scale bars 0·05 mm long. A, Portion of a large kamacite grain (light grey) lightly etched to show lack of detailed structure. A small unetched (and practically unzoned) marginal taenite inclusion (white) lies just right of centre on the photograph, and a small chromite grain (dark grey) abuts against kamacite at the left. B, Large isolated taenite grain, lightly etched to show zoned structure. The white unattacked fringe is nickel-rich taenite and the slightly etched core (light grey) nickel-poor taenite. Intermediate zones appear dark on the photograph, but in reality show red and blue interference colours in polarized light (uncrossed nicols). C, Small kamacite grain, etched to show martensite-like structure. D, Taenite grain

metal does not contain any detectable amount of either), and that all the chromium is present as chromite or in the silicates.

The agreement between the normative composition and the modal analysis is good except for the percentage of metal. This discrepancy is probably due to inhomogeneity of the meteorite; none of the sources of error suggested by Keil and Fredriksson (1964) appears to be relevant; for the present the chemical value (6·3 %) appears more reliable, since it was derived from a larger sample, but it is hoped to make an areal analysis of a much larger polished surface shortly.

The atomic ratio 100 Fe/(Fe+Mg+Mn) in the silicates, derived from the chemical analysis, is $25{\cdot}0 \pm 0{\cdot}8$ (assuming probable errors of 0·4 in the FeO and 0·3 in the MgO), in reasonable agreement with that derived from the modal analysis together with the micro-probe analyses of the olivine and pyroxene, which is 23 ± 1. The normative feldspar contains 9 mol. % anorthite, in reasonable agreement with the value of 12 % derived from the refractive indices.

The 'Prior parameters' for Barwell are: *f* 6·2, *n* 7·8, *t* 6·6, *m* 3·0, and the atomic ratio Mg/Si is 0·926.

Electron-probe studies were made of several of the minerals present and the results are included in the descriptions above. Corrections for background, dead-time, fluorescence, and absorption, and an estimated correction for atomic-number effect were made by methods to be described in a forthcoming paper.

Structure

Barwell contains most of the common kinds of chondrule found in olivine-hypersthene chondrites. They are generally between 1 and 2 mm in diameter and spherical or ovoid in shape, but some have been broken, and certain microporphyritic varieties are somewhat polyhedral or angular and have dimensions greater than the typical size range.

Microporphyritic olivine chondrules are the most common type. These contain euhedral to subhedral tabular olivine crystals up to 0·7 by 1·0 mm in cross section, dispersed in a partly unresolvable groundmass of fine-grained granoblastic silicate minerals including hypersthene, olivine, plagioclase, and possibly either apatite or merrillite, together

(white) adjacent to troilite (dark grey), showing small inclusions and projections of troilite in the taenite. Unetched. E and F, Taenite grains adjacent to troilite and with inclusions of troilite, etched to show zoned structure of taenite and sharply bounded nickel-rich zones around the troilite inclusions. Small inclusions of kamacite (high etch relief), surrounded by nickel-rich taenite, occur in the upper left and lower centre of the taenite grain in E.

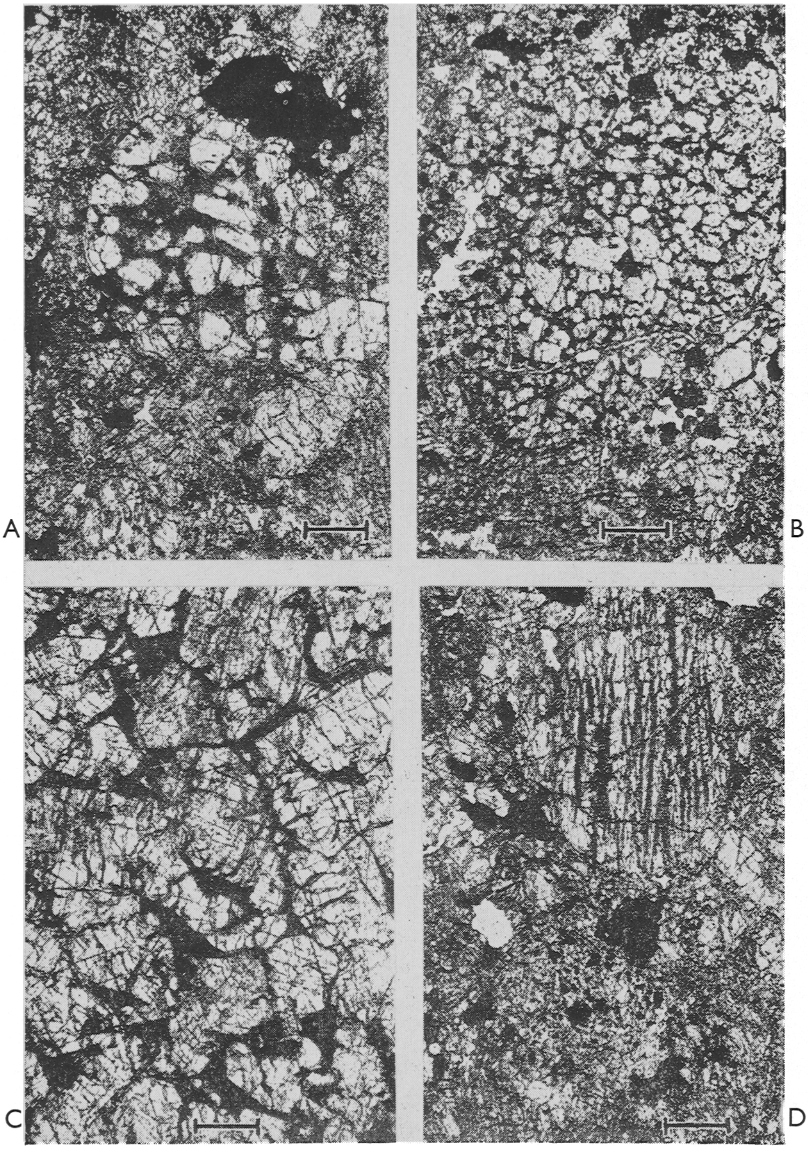

FIG. 6. Chondrules from the Barwell meteorite. A and B, microporphyritic olivine chondrules; C, portion of a large microporphyritic pyroxene chondrule; D, barred olivine chondrule (upper) and granular olivine chondrule (lower). Note diffuse margins and finely granoblastic groundmass of chondrules, also nature of the interchondrule matrix. All photomicrographs taken with ordinary light. Scale bars are 0·2 mm long.

with scattered opaque granules (fig. 6*a*, *b*). In some, slightly smaller olivine phenocrysts are so abundant that they developed only imperfect crystal outlines; these grade into the less common granular olivine chondrules, in which equant olivine crystals are closely packed and anhedral (fig. 6*d*).

Microporphyritic and granular pyroxene chondrules show a similar range of textures, but are less abundant. The pyroxene phenocrysts are orthorhombic hypersthene or the striated variety described above, tend to be prismatic with moderately well-developed terminal faces, may show projections, embayments, or parallel growth structures, and in different chondrules range in size from 0·05 mm to 1 mm long (see fig. 6*c*). Diopsidic pyroxene or opaque minerals are rarely encountered in such chondrules, but some contain large subhedral or ragged grains of olivine and these grade into two relatively uncommon chondrule types, on the one hand into microporphyritic chondrules with phenocrysts of olivine and hypersthene in varying proportion, and on the other into poikilitic chondrules containing rounded or irregular olivine grains enclosed by a single large hypersthene crystal or by a granular arrangement of several large hypersthenes.

Barred olivine chondrules, though conspicuous, are not abundant. Most are constructed of a single large olivine grain, spherical in outline and 1 to 1·5 mm in diameter, with an interior consisting of structurally continuous or slightly distorted plates (erroneously called 'bars' because of their appearance in thin section) between which lies a fine granoblastic or turbid silicate groundmass, commonly rich in plagioclase and lacking opaque granules (fig. 6*d*). Some are broken, and one was observed to consist of three separate olivine grains, each with its own differently oriented barred structure. The interior olivine bars range from 5 to 20 μ in thickness in different chondrules.

Radiating pyroxene chondrules are equally conspicuous but also comparatively scarce. The needles and plates of hypersthene vary in thickness from chondrule to chondrule (fig. 7*a*, *b*), and in some of the finer varieties appear to have recrystallized into tiny equant granules retaining approximately their original orientation, so that the radial structure may still be observed between crossed nicols. Narrow rods or stouter granules of diopside, and tiny opaque granules (usually chromite ?) lie between the hypersthene crystals. Radiating pyroxene chondrules tend to be more perfectly spherical in outline than most other chondrule types, but a few have been broken into hemispheres. Some such chondrules contain more than one marginal point from which the pyroxenes

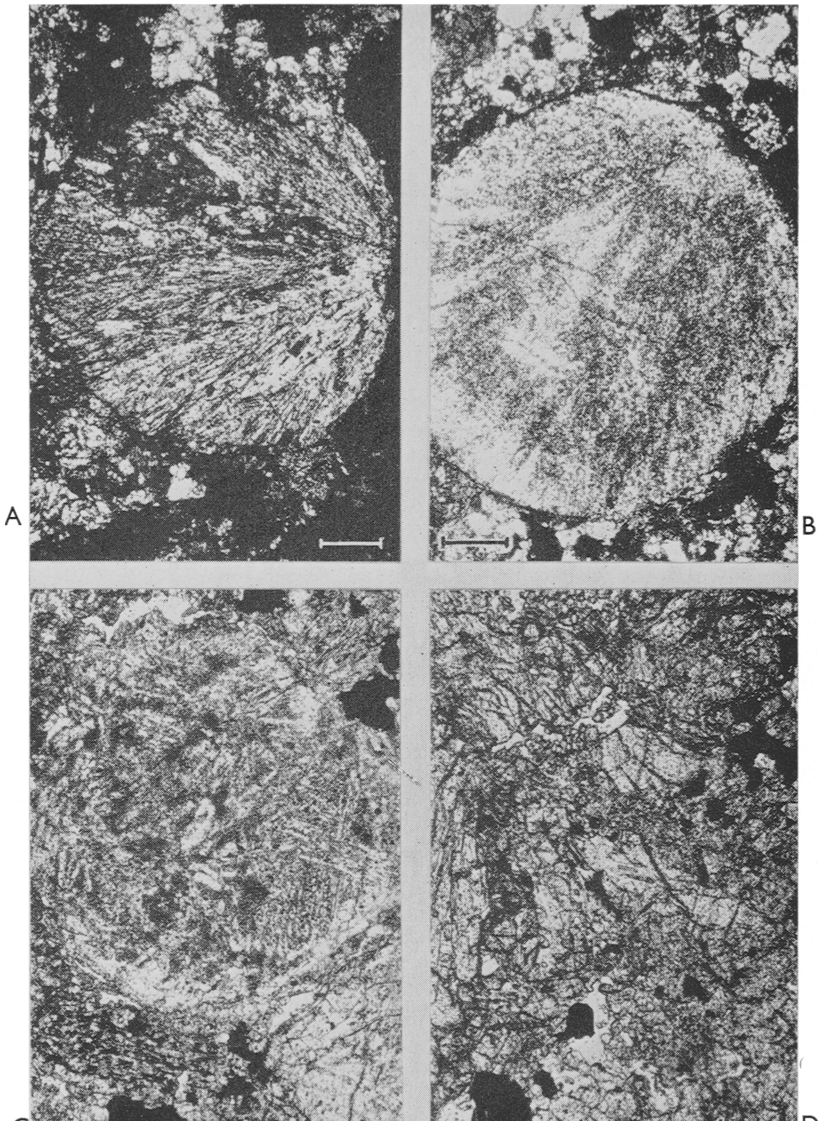

FIG. 7. A, Coarse radiating pyroxene chondrule containing plates of hypersthene with fine platelets and granules of diopside. Crossed nicols. B, Fine-grained radiating pyroxene chondrule, taken with crossed nicols. The hypersthene platelets appear to have recrystallized to granules, but this chondrule may be a recrystallized glassy variety. C, Uncommon variety of chondrule showing olivine microphenocrysts (centre), some fine granoblastic groundmass, and marginal intergrowths of olivine and hypersthene. Note plagioclase (low relief) in surrounding matrix. Ordinary light. D, Portion of the interchondrule matrix, showing larger olivine, hypersthene and opaque grains, and fine granoblastic silicate aggregate. Plagioclase shows low relief. Ordinary light. All scale bars 0·2 mm long.

radiate; these are generally very fine grained and may represent recrystallized glassy chondrules rather than varieties that originally formed with a distinct radial texture, as might also some of the fine granular types described above.

Rare chondrule types include a variety made up of a fine parallel intergrowth between rods or plates of hypersthene and olivine (cf. fig. 7*c*), and one in which thin bars or sheets of olivine lie at right angles to the elongation of the radiating or sub-parallel hypersthene containing them, producing a grid or net-like structure. One chondrule contains numerous tiny opaque rods (chromite or troilite) in a granoblastic aggregate consisting largely of plagioclase. In several microporphyritic chondrules, the olivine phenocrysts are skeletal or hollow.

The interchondrule matrix of Barwell contains some large olivine and hypersthene grains, not clearly belonging to any particular chondrule, but for the most part it is made up of fine granoblastic aggregate of olivine, hypersthene, and plagioclase, with scattered opaque granules (fig. 7*d*), similar to the groundmass of microporphyritic and barred chondrules but tending to be slightly coarser in grain size. The component mineral grains vary considerably in dimension at any one point, and the average grain size varies from one part of the matrix to another, rarely exceeding about 0·02 mm and usually considerably less. The 'unresolved silicates' listed in the mode in table I include all such granoblastic aggregates, either within chondrules or between them, where the identity of the material under the microscope cross-hairs was uncertain because of its fine grain size.

The large opaque mineral grains mostly lie outside the chondrules. The variety of textures they develop has been described above under the individual minerals.

Metamorphism

In unmetamorphosed olivine-hypersthene chondrites such as *Parnallee*, *Barratta*, and portions of *Mező-Madaras*, the matrix of microporphyritic and barred chondrules is a clear brown or turbid, finely devitrified glass known from electron probe investigations to be rich in alumina and alkalis (Fredriksson, 1965; Binns and Reed, unpublished data). The pyroxenes in their microporphyritic and radiating chondrules are almost exclusively clinohypersthenes that appear to have inverted by quenching from a form akin to protoenstatite, and their interchondrule matrix consists of small angular chips of olivine and pyroxene with a proportion of black basic glass (cf. Tschermak, 1885; Wood, 1963; Dodd and Van Schmus, 1965; Binns, in preparation).

By comparison with these unmetamorphosed or primitive chondrites, Barwell shows many indications of having undergone a period of high temperature recrystallization. The effects of this, however, are not so great as in *Appley Bridge* and *Tauq*, two of the most metamorphosed of the olivine-hypersthene chondrites. The chondrules of Barwell are still quite distinct, both macroscopically and microscopically, but their margins are somewhat diffuse as a consequence of reaction with the interchondrule matrix during metamorphism. The groundmass of microporphyritic and barred chondrules has recrystallized to fine-grained granoblastic aggregates of olivine, hypersthene, and plagioclase, as has most of the interchondrule matrix. Calcium-poor pyroxenes have inverted to the orthorhombic polymorph, those in radiating pyroxene chondrules exsolving part of their calcic component as discrete platelets or granules of diopside. However, there remain some twinned or striated grains, possibly a partly inverted type transitional between true monoclinic (i.e. quenched proto-) and orthorhombic pyroxene. In all these respects, the Barwell meteorite belongs to what will be termed the *Transitional Group* in a metamorphic classification of chondrites to be published shortly (Binns, in preparation).

The agency responsible for, and the duration of the metamorphism are not known with certainty, and will not be discussed here apart from mentioning that recrystallization may have occurred during cosmic reheating subsequent to the initial cooling of the meteorite from its original primitive state, or may have taken place during a delay in the cooling period, when temperatures were maintained at some fairly high temperature for a prolonged interval of time. Some estimate of likely temperatures during metamorphism can be derived from the mineralogy of the Barwell meteorite. Recrystallization clearly occurred within the stability field of orthorhombic hypersthene rather than of protohypersthene. The temperature range of this field has not yet been determined accurately, but a maximum limiting temperature in the region of 950° C may be deduced from the proto-ortho inversion of iron-free enstatite, 985° C at 1 atmosphere (Atlas, 1952; Boyd and Schairer, 1964), and from the data of Bowen and Schairer (1935) suggesting the manner in which this inversion temperature is dependent on iron content. That metamorphic temperatures for Barwell lay near this upper limit is suggested by the composition of diopsidic pyroxene exsolved from (?) protohypersthene in radiating pyroxene chondrules during recrystallization.

No mineralogical indications of metamorphic pressures are found in

Barwell, or in other olivine-hypersthene and olivine-bronzite chondrites, but the presence of tridymite as an ubiquitous minor phase in metamorphosed enstatite chondrites (Binns, data in preparation) suggests very low pressures, if indeed it is correct to postulate similar metamorphic conditions for these three major chondrite groups.

Unmetamorphosed chondrites are also characterized by silicate minerals with notably inhomogeneous compositions, whereas uniform equilibrium compositions appear to be rapidly established between the mafic mineral phases in those subjected to metamorphism (Keil and Fredriksson, 1964; Dodd and Van Schmus, 1965). The homogeneous compositions of olivine, hypersthene, and plagioclase in Barwell, as revealed by optical and electron-probe investigations, place it in the latter category. The zoned structure of taenite in chondritic meteorites has been ascribed to diffusion between the two metal phases during cooling (cf. Wood, 1966). The extent to which this might be disturbed or interrupted during metamorphism has not been thoroughly investigated, but it is perhaps significant that the narrow nickel-rich rims around troilite and kamacite inclusions in certain Barwell taenites appear different from the normal marginal nickel-rich zones.

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