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Meteoric iron and silica-glass from the meteorite craters of Henbury (Central Australia) and Wabar (Arabia).

(With Plates XIII–XX.)

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THE study of the materials from these two recently discovered occurrences has added much to the knowledge of meteorite craters.[1] The two present many points in common and they supplement one another. At Henbury there is a much better development of the meteoric iron, while at Wabar the silica-glass predominates.

The Henbury craters were visited and investigated by Mr. A. R. Alderman[2] in May 1931; and since then they have been twice visited by Mr. R. Bedford, of the Kyancutta Museum, South Australia, who has sent a large amount of material and much detailed

[1] L. J. Spencer, Meteorite craters. Nature, London, 1932, vol. 129, pp. 781–784, 5 figs. Meteorite craters as topographical features on the earth's surface. Geogr. Journ. London, 1933, vol. 81, pp. 227–248, 4 pls., 3 text-figs. [Min. Abstr., vol. 5, p. 301.]

[2] A. R. Alderman, The meteorite craters at Henbury, Central Australia. Min. Mag., 1932, vol. 23, pp. 19–30, 3 pls., 3 text-figs. With addendum by L. J. Spencer, pp. 30–32.

information to the British Museum. The Wabar craters were discovered by Mr. H. St. J. B. Philby in February 1932,[1] and the whole of the material collected by him has been presented to the British Museum by His Majesty ʻAbdul ʻAziz ibn Saʻud, King of the Hejaz and Nejd and its Dependencies.

The meteoric irons from these two localities are strikingly similar in structure and in chemical composition—both are medium octahedrites containing 7·3 % of nickel. The larger pieces when sectioned, polished, and etched show the normal lamellar octahedral structure with very narrow bands of taenite and only a few small nodules of troilite. Neumann lines are well developed in the kamacite, indicating strain. On the other hand, the smaller pieces of both irons show a partial destruction of this structure with granulation of the kamacite, indicating that they had been heated to at least 850° C. —the transformation temperature of α-iron to γ-iron (body-centred to face-centred lattice).

At Wabar one mass of 25 lb. (11·4 kg.)[2] and six small pieces (totalling 114 grams) of iron were collected around the craters. Mr. Philby had heard rumours of a mass of iron ʻ as big as a camel ʼ, but no such mass was found. The pieces collected are much rusted, being in part coated with laminated iron-shale in which sand grains are cemented. The rusting and flaking away has continued since the material was received at the Museum. The largest piece, with an irregular triangular cross-section, measures $26 \times 15 \times 13$ cm.; it is evidently only a weathered remnant of a larger mass. One end was sawn off (476 grams) and the cut surface polished for etching. The etched surface (plate XIV, figs. 5 and 6) shows kamacite bands, 1–1½ mm. in width, with an oriented sheen and well-marked Neumann lines. In small patches the kamacite is granulated and the Neumann lines obliterated. A section of a smaller piece (23 grams) of the iron shows the complete granulation of the kamacite and plessite, and the structure as a whole is less clear, but the narrow bands of taenite are still bright (fig. 7).

[1] H. St. J. B. Philby, Rubʻ al Khali: an account of exploration in the Great South Desert of Arabia . . . Geogr. Journ. London, 1933, vol. 81, pp. 1–26 (Meteorite craters mentioned, pp. 12–14, 24–25, plates at pp. 7 and 10); and Journ. Roy. Central Asian Soc. London, 1932, vol. 19, pp. 569–586. See also his book ʻThe Empty Quarterʼ, London (Constable & Co.), 1933, pp. 157–180, 6 pls., with appendix ʻMeteorites and fulguritesʼ by L. J. Spencer, pp. 365–370.

[2] A photograph of the 25 lb. mass is reproduced in Mr. Philby's book ʻThe Empty Quarterʼ, fig. 14*a*.

At Henbury the meteoric iron is abundant. Mr. Alderman [1] mentions that he collected in 1931 more than 800 pieces with a total weight of about 500 lb., the largest piece weighing 52½ lb. Mr. R. Bedford has sent to the British Museum 647 pieces of the iron with a total weight of 935 lb. (424 kg.). The largest of these pieces weigh 292, 170½, and 120 lb., others 40¼, 33½, 26½ lb., &c., and the smallest 0·9 gram. These two lots do not account for all the material that has been collected at the locality. With the exception of two pieces found by Mr. Alderman just inside the rim of crater no. 3 and the masses excavated by Mr. Bedford from crater no. 13, mentioned below (p. 391), all these pieces have been found outside the craters. The majority of them are small, curiously twisted fragments. The larger pieces with the normal concave surface and pittings of meteoric irons are seen in etched sections each to consist of a single crystal, and the normal lamellar octahedral structure extends up to the very edges of the mass, without any granulation of the kamacite. This clearly proves that these masses are merely weathered remnants of still larger masses, the cores of which had not been raised to a temperature of 850° C. by the conduction of heat from outside.

In only two instances [2] was any indication of the internal crystalline structure shown by the outward form of the masses. In order to determine the crystallographic orientation of one of the irregular masses, a sphere (4·5 cm. diameter) was turned, polished, and etched.[3] Plane surfaces were then cut parallel to the faces of the cube, octahedron, and rhombic-dodecahedron. This work was very efficiently performed in the metal workshop of the Science Museum in London, by kind permission of the Director. The mass was reduced in weight from 2285 grams (5 lb.) to 1544 grams, and the result is represented in pl. XIII, fig. 1. Figs. 2–4 show the etching figures on these same three planes, which were correctly orientated by Mr. Bedford on one piece of the iron without the aid of first cutting a sphere.

[1] A. R. Alderman, The Henbury (Central Australia) meteoric iron. Rec. South Australian Museum, 1932, vol. 4, pp. 555–563, 9 figs. [Min. Abstr., vol. 5, p. 159.]

[2] See fig. 11; on another specimen there are poor indications of an octahedral fracture.

[3] An etched sphere of meteoric iron has been described and figured by V. Goldschmidt, Zeits. Kryst. Min., 1909, vol. 46, p. 193, where he mentioned that the same had been previously done, but not published, by K. Vrba in Praha.

Many of the masses of iron collected around the Henbury craters are small pieces curiously twisted and bent (fig. 14). Etched sections of these show the bands of the lamellar structure to be bent and crumpled (figs. 8 and 9). The kamacite and plessite are granulated but the taenite still persists. These pieces were no doubt torn in a plastic condition from larger masses by the force of the explosions which made the meteorite craters. But it is evident that they have been further broken up and reduced in size by oxidation proceeding along cracks, as seen at the top in fig. 8.

The surface markings of the Henbury irons show a great diversity in character. In all cases they appear to be the result of sculpturing by weathering processes. No clear evidence was detected that the original surface on any of the masses had been preserved. All the surfaces are coated with a thin skin of iron rust, which varies in character depending on whether the masses were found buried in the ground or on the surface exposed to the air. On buried masses the scale is usually thicker, softer, and lighter in colour, while on exposed surfaces it is thinner, harder, and darker in colour. The scale gives a dark brown streak and is strongly magnetic.

The small nodules of troilite scattered sporadically through the iron must act as centres for the attack of weathering processes. Free sulphuric acid from the decomposition of the troilite will act directly on the iron and will probably also give rise to electrolytic action. In the case of buried masses this acid will be retained by the surrounding soil and the action will be continuous, giving rise to the larger broad concavities up to 10 cm. across (fig. 13, left of fig. 10, and right of fig. 15). But on exposed surfaces the acid will not be held, and the pittings will be smaller (2–3 cm.).

In desert regions the exposed surfaces will undoubtedly be corroded by the action of sand-blasts, and possibly the sculpturing from this cause may be of different types. One Henbury iron with a smooth upper surface has much the appearance of a faceted pebble (' dreikanter'). The scoop-shaped pittings on the exposed portion shown to the right in fig. 10 are probably the result of wind-action, being quite different from the broad concavities shown on the buried portion to the left. The prominently pock-marked upper surface shown in fig. 11 was also no doubt produced by wind-action. Here the sculpturing has faintly developed the octahedral structure of the iron (lower left-hand corner). These pock-marks measure 1–3 mm. across. The under side of this iron, where it rested on the ground, shows no pock-marks. Similar pock-marks are shown on the exposed surfaces of some meteoric irons from the deserts in Chile. C. Palache [1] asserts that pock-marks showing a triangular pattern on the Baquedano iron are due to sand-blast action; but F. Heide [2] thinks that those on the Buey Muerto [not Buen Huerto] iron are due to the action of dew-drops condensed on the surface.

It must be at once admitted that no explanation can be offered for some of the peculiar external forms shown by the Henbury irons. On one specimen (B.M. 1932,1431) a sharp spine of metal, $1\frac{3}{4}$ cm. long and $\frac{1}{4}$–$\frac{1}{2}$ cm. thick, projects from the nearly flat pitted surface of the iron. On another (fig. 15) a large curved flake projects with only a small point of attachment from a solid mass of iron. This may be due to weathering along a curved crack with possibly the help of insolation. The large mass of $170\frac{1}{2}$ lb. ($77\frac{1}{2}$ kg.) (this vol., p. 30) shows normal pitting over most of the surface, but along one edge it is scooped out transversely by a series of wide parallel grooves. This mass was found in 1931 at about 30 yards south of the Water Crater (no. 6), and has been very generously presented to the British Museum by the Kyancutta Museum. The flat S-shaped piece (*D* in fig. 12) and the thin arc-shaped piece (fig. 13) clearly owe their shape to weathering, being weathered remnants.

Of special interest is the group of large irons excavated by Mr. Bedford in 1932 from crater no. 13 at Henbury.[3] This is the first record of any considerable mass of meteoric iron having been found buried inside a crater. The four masses (292, 120, 24, and 5 lb.) with a total weight of 441 lb. (200 kg.) are shown in fig. 12 in the relative positions as found. Surrounding and between them with a thickness of $\frac{1}{4}$–2 inches there was about 45 lb. of flaky iron-shale. When received at the Museum some loose scale was scraped from the surface of the iron, and further rusting has since taken place. The four pieces are clearly weathered remnants of a single larger mass. Crater no. 13 is 10 yards (9 metres) in diameter and 3 feet (1 metre) in depth. The irons were found at a depth of 7 feet from the bottom of the crater, i.e. 10 feet below the level of the surrounding ground. Immediately around and beneath the irons were broken blocks of

[1] C. Palache and F. A. Gonyer, Amer. Min., 1932, vol. 17, p. 357. [M.A. 5–158.]

[2] F. Heide, E. Herschkowitsch, and E. Preuss, Chemie der Erde, 1932, vol. 7, pp. 484–485. [M.A. 5–300.]

[3] No. 13 on A. R. Alderman's plan, this vol., p. 21.

sandstone, while the overlying material was fine-grained and free from big stones. Above and near the meteorite about 5½ lb. of 'shale-balls' and fragments of iron-shale were collected. Around the crater sixty small twisted pieces of iron (9·5–850 grams) were collected, but no silica-glass. The partial excavations made by Mr. Bedford in crater no. 11, of diameter 15 yards, yielded no meteorite iron.

The results of Mr. Hey's analyses made on filings of the Henbury and Wabar irons are given below under I and III. The specific gravity (D_4^{19}) 7·73 of the Henbury iron was determined by hydrostatic weighing of a separate piece, clean and free from scale, weighing 508·2 grams. A determination made in the pyknometer on the filings used for analysis gave the value 7·69, which is probably too low. The value (D_4^{19}) 7·66 for the Wabar iron was determined by hydrostatic weighing of the end-piece of 476 grams.

Chemical analyses of meteoric irons.

	Henbury.		Wabar.	Nejed.
	I.	II.	III.	IV.
Fe	93·04	91·54	92·00	91·04
Ni	7·26	7·54	7·30	7·40
Co	0·22	0·37	0·22	0·66
Cu	0·044	—	0·037	trace
Cr	nil	—	nil	—
Pt	trace	—	trace	—
S	0·06	0·01	0·11	trace
P	nil	0·08	nil	0·10
Cl	trace	—	trace	—
C	trace	0·013	trace	—
Insol.	0·06	0·03	0·20	0·59
Total	100·68	99·58	99·87	99·79
Fe : Ni	12·8	12·1	12·6	12·3
Sp. gr.	7·69	7·53	7·64	7·89

I. Henbury, Central Australia. M. H. Hey. (B.M. 1932,1433.)
II. Henbury. A. R. Alderman, Rec. South Australian Museum, 1932, vol. 4, p. 561. [M.A. 5–159.]
III. Wabar, Rub' al Khali, Arabia. M. H. Hey. (B.M. 1932,1136.)
IV. Nejed, Arabia. L. Fletcher, Min. Mag., 1887, vol. 7, p. 182.

Iron-shale is abundant, indicating that the masses of meteoric iron have been considerably reduced in size or completely destroyed by weathering. At Wabar only small pieces (up to 5 cm.) were collected. This material is rather loose and scaly, and yellowishbrown in colour, but still magnetic. Sand grains are cemented in the limonitic material.

At Henbury Mr. Bedford collected a large amount of iron-shale of various types. Some is flaky, cellular, and friable; about 45 lb. of such material was found around and between the group of large irons buried in crater no. 13. Other material, found loose on the surface, especially around the main crater, has the form of large slabby and laminated masses, several pounds in weight and up to 5½ cm. in thickness. This is very hard and compact, blackish-brown in colour, and strongly magnetic. Mr. Hey's analysis (I below) of such material suggests a mixture of limonite, haematite, magnetite, trevorite, and chalybite; but the material is very fine-grained and on a polished surface these constituents would not be distinguished. The section shows lamination and veining of brown limonite in an iron-black groundmass. A few minute specks show a bright metallic lustre,

Chemical analyses of iron-shale.

	I.	II.	III.	IV.
Fe_2O_3	78·45	83·31	74·63	79·50
FeO	8·32	(as Fe_2O_3)	3·91	3·68
NiO	5·28	5·76	9·79	6·44
CoO	0·32	—	0·49	—
H_2O	5·08	9·15	8·02	8·19
CO_2	[2·55]	—	0·35	—
SiO_2 (insol.) ...	trace	0·53	1·09	0·36
Total	100·00	98·75	99·93	98·17
Fe : Ni	14·8	12·9	7·2	11·6
Sp. gr.	4·24	—	3·73	—

	Limonite.	Haematite.	Magnetite.	Trevorite.	Chalybite.
I.	35·10	27·23	13·38	17·58	6·71
II.	63·22	?	?	18·07	—
III.	52·63	—	12·59	30·72	—
IV.	56·58	9·18	11·85	20·20	—

I. Henbury, Central Australia. M. H. Hey. Ca and Mg absent. (B.M. 1932, 1549.)

II. Henbury. A. R. Alderman, loc. cit., p. 562.

III. Cañon Diablo, Arizona. O. C. Farrington, Amer. Journ. Sci., 1906, ser. 4, vol. 22, p. 306 (analyst, H. W. Nichols). Also Al_2O_3 0·05, CaO 1·27, P 0·10, Cl 0·08, S trace, C 0·15.

IV. Cañon Diablo. E. V. Shannon, U.S. Nat. Mus., 1927, vol. 72, art. 21, p. 7. [M.A. 3–534.] Two other analyses of iron-shale from Cañon Diablo are given by W. Tassin, Smithsonian Miscell. Coll., 1927, vol. 50, p. 213. The iron-shale from the Hoba meteorite (nickel-rich ataxite) is much richer in nickel (this vol., p. 15).

but these do not reduce copper from a solution of copper sulphate. A thin section is quite opaque.

'Shale-balls', similar to those found around the meteorite crater near Cañon Diablo in Arizona, are also found at Henbury. These consist of a cluster of curved and cracked plates of the iron-shale, thus presenting a rugose surface. Green nickel stains are sometimes shown on the broken surfaces of a nodule. Only one 'shale-ball' still containing a core of metallic nickel-iron was received; this continued to rust, and unfortunately has since broken up. It was found buried in crater no. 13 above the group of large irons. 'Shale-balls' evidently represent small masses of iron that have completely rusted away, probably while buried in the ground. Some small (1 cm.) balls, resembling crinkled peas, perhaps represent globules of molten iron shot out from the craters.

Silica-glass is very abundant at Wabar. Mr. Philby's photographs of the craters show the cindery masses thickly strewn over the surface of the ground; and the walls of the meteorite craters here appear to be built entirely of this material. The occurrence is unique, and, unfortunately, is not readily accessible for study on the spot, but a good selection of material was brought back by Mr. Philby. Most of it is highly vesicular, and has much the appearance of cinders or of iron-furnace slag. It is not the cinders of the legendary 'city destroyed by fire from heaven' nor a volcanic lava. The low density and refractive index at once suggested a silica-glass (for pure silica-glass, d 2·20, n 1·46), and this is confirmed by the chemical analyses given below. Each specimen appears to be an individual bomb, which had no doubt been ejected from the craters by the explosions. These bombs are of two main types:

(*a*) The larger bombs have a rough and cavernous surface, often showing ropy forms (fig. 16) much like the surface flow of a basaltic lava. The surface is dull and dark grey or black in colour. The largest piece brought back by Mr. Philby measures $21 \times 15 \times 10$ cm. and weighs 928 grams. They consist mainly of a bluish-grey or brownish glass full of bubbles of all sizes up to 6 cm. across. The interior surface of the bubbles is highly glazed, and blue, green, and brown in colour. Embedded in this material are often fragments of a snow-white glass (fig. 17) in which the bubbles are smaller, and also flaky fragments of sintered white sandstone. The white glass is welded into the grey glass, while the fragments of sintered sandstone are only partly enclosed.

(*b*) Smaller bombs (figs. 18, 19, 20) consist inside of a very cellular snow-white glass, resembling pumice (seen on the broken portion at the top of figs. 18, 19). Outside they consist of black glass with a highly glazed surface and almost free from bubbles. This black glass is often only a thin skin on the surface of the bomb, but in some cases it forms the larger part. On some specimens there is an open network of black globules, or only one or two small isolated patches on the surface of the white glass. The surface of the black glass is often beset with minute pimples (figs. 18, 19, 20). Small and very light pellets consisting of cellular white glass with a thin, glazed skin of black glass, were collected in large numbers by the Arabs accompanying Mr. Philby's expedition. Unfortunately, his collection of these 'black pearls' was lost in transit, and only one larger specimen (2 cm. in diameter) came to the British Museum.

In micro-sections the Wabar silica-glass shows colourless and brown portions, both of which are optically isotropic. Fig. 24 of a fragment from a larger bomb shows an area of white glass surrounded by brown glass; in the white glass is a grain of shattered quartz. Fig. 23 shows a section of one of the smaller (1 cm.) bombs, with the brown glass of the exterior streaking into the cellular white glass of the interior. In addition to the many bubbles of all sizes, numerous small black spots are shown, ranging from 0·14 down to 0·003 mm. in diameter, and further to mere dust.

These black spots show a metallic lustre by reflected light, but the idea that they could be metal appeared at first to be so improbable that they were thought to represent small bubbles filled with the grinding powder used in the preparation of the section. When, however, a fragment of the glass was crushed in oil on a microscope slide, it was seen that these small spots became isolated. A small piece of the glass was crushed (not ground) in an agate mortar, and spheres were then picked out from the powder with a magnetic needle, to which they adhere in long strings and clusters by the thousand (fig. 22). The spheres readily break away from the glass, but minute fragments of glass still enclosing a sphere are also attracted. They are perfectly spherical with a highly polished steel-grey surface. In a solution of copper sulphate, copper is deposited on their surface. A count of the conspicuous black spots in an area of 4×4 cm. in the dark glass in fig. 24, i.e. in one square millimetre of the micro-section, gave about 120, corresponding to about 1330 per cubic millimetre, or one and a third million per cubic centimetre;

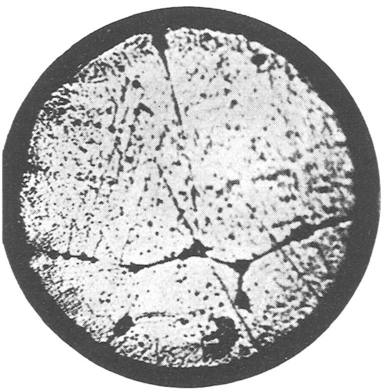
while a similar count in an area of the white glass in fig. 23 gave two million per c.c.

Analysis of these metallic spheres made by Mr. M. H. Hey (on 0·03 gram, after deducting silica-glass) gave Fe 91·2, Ni 8·8 %, corresponding to the ratio Fe : Ni = 10·4. Rotation and Laue X-ray photographs taken by Mr. F. A. Bannister of single spheres show that the material is body-centred cubic with a cell-side a 2·856 ± 0·005 Å., proving it to be α-iron. Each sphere consists of a sub-parallel grouping of smaller individual crystals.

With the kind permission of Professor Sir Harold Carpenter, these spheres of nickel-iron in a section of the silica-glass have been examined by Dr. J. M. Robertson in the Metallurgical Laboratory of the Royal School of Mines. He reports that the smaller sections (from 0·025 down to 0·0005 mm. in diameter) are usually of a single crystal, while larger ones (up to 0·07 mm.) generally consist of several grains. The individual grains have not smooth polyhedral outlines, and numerous inclusions are situated at their boundaries. In each grain there is an indistinct type of martensitic structure, which seems to be more pronounced in the smaller than in the larger spheres (but this is not brought out in the photomicrographs, figs. 27 and 28). These observations correspond with what would be obtained by the rapid cooling of an iron-nickel alloy containing Ni 4–9 %.

At Henbury the silica-glass is much less abundant and is less obvious. It also is of two main types. (*a*) Dark dull-brown to black cellular masses with much the appearance of cellular limonite, and sometimes showing an indistinct ropy surface. The vesicles are small, rarely exceeding 1–2 mm. across. Some pieces are sintered fragments of sandstone with the bedding planes of the rock curved and crumpled, and free from bubbles. The largest piece sent by Mr. Bedford measures 10 × 10 cm. (*b*) Small bombs with a black glazed surface often beset with pimples (fig. 21) and with a brown cellular interior. In some of these the black glass is splashed on portions only of the brown glass. Some of them show a certain resemblance to tektites and are exactly like some of the smaller bombs and drops from Wabar (cf. fig. 20). Material of type (*a*) was collected by Mr. Bedford in 1931 close to the rim on the west side of the main crater (no. 7); that of type (*b*) was collected by him in 1932 along a narrow strip of ground extending eastwards for a distance of a mile from the same crater.

In micro-sections the Henbury glass is dark-brown and in part opaque with impregnated limonite, being colourless only in portions. It is optically isotropic and in places encloses a residue of small grains of quartz. Fig. 25 shows a section of a small bomb with the surface layer of black glass almost free from bubbles. Here only few black spots are seen, and very few metallic spheres were extracted by a magnetic needle from the powdered material. A micro-section of one pale-brown glazed fragment showed in ordinary light the structure



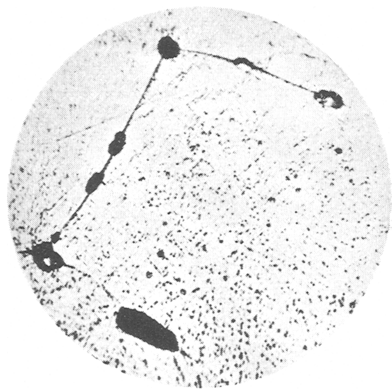


FIG. 27. FIG. 28.

Photomicrographs (by Dr. J. M. Robertson) of etched sections of spheres of nickel-iron in the silica-glass from the meteorite craters at Wabar, Arabia. ×820.

of a sandstone with a dark material surrounding each grain; but between crossed nicols all the grains are isotropic. This is a silica-glass (fused sandstone) free from bubbles.

Chemical analyses of the white and black glass selected from bombs of type *b* from Wabar are given below under I and II respectively. Deducting the amount of iron present in the white glass,[1] the ratio of Fe : Ni in the black glass is 15. This is near to the ratio of Fe : Ni in the meteoric iron. The much higher ratio in the Henbury black glass (analysis III) can only partly be accounted for by the iron in the original sandstone.

The abundance of nearly pure silica-glass at Wabar is clearly due to the fusion of the clean desert sand. Immediately south of the

[1] A micro-section of the piece of white glass analysed showed none of the metallic spheres.

Chemical analyses of silica-glass and sandstone from Wabar and Henbury.
(By M. H. Hey.)

	Silica-glass			Sandstone	
	Wabar (white) (B.M. 1932,1165a).	Wabar (black) (1932,1158).	Henbury (black) (1932,1546).	Wabar (1932,1167).	Henbury (1932,156
	I.	II.	III.	IV.	V.
SiO_2 ...	92·88	87·45	68·88	92·06	86·71
TiO_2 ...	0·12	0·15	3·64	0·12	0·32
ZrO_2 ...	nil	—	—	nil	nil
Al_2O_3 ...	2·64	1·77	5·60	2·80	3·84
Cr_2O_3 ...	nil	—	—	nil	nil
Fe_2O_3 ...	0·23	0·28	8·46	0·60	2·84
FeO ...	0·53	5·77	7·92	0·19	0·46
NiO ...	nil	0·35	0·28	nil	nil
CoO ...	—	trace	trace	—	—
CuO ...	—	nil	trace	—	—
MnO ...	0·01	0·01	0·05	0·01	0·005
MgO ...	0·47	0·60	2·03	0·45	0·90
CaO ...	1·46	1·90	2·51	1·19	1·00
SrO ...	0·01	0·01	nil	0·01	nil
BaO ...	nil	—	—	nil	nil
Na_2O ...	0·42 } *	0·39	0·03	1·03	0·13
K_2O ...	1·61 }	0·58	1·43	1·04	1·15
P_2O_5 ...	trace	trace	nil	nil	nil
Cl	nil	—	—	trace	nil
SO_3 ...	nil	—	—	trace	trace
S	nil	—	—	nil	nil
CO_2 ...	nil	—	—	0·58†	nil
H_2O+ ...	0·32	0·04	0·03	0·20	1·85‡
H_2O- ...	0·11	0·08	0·05	0·22	0·82
Total ...	100·81	99·38	100·91	100·50	100·03
Sp. gr. (D_4^{22})	2·10	2·24	2·31	2·50	2·37
Ref. ind. ...	1·468	1·500	1·545	—	—

* Separation of alkalis probably inaccurate.
† CO_2 as difference between loss on ignition and total water.
‡ Loss on ignition; all other determinations of water at +110° C. by the Penfield method.

craters is an outcrop of sandstone, marked on Mr. Philby's plan [1] as 'gypsum'. This is white or cream-coloured and very soft and friable. When crushed in oil on a microscope slide it shows small splinters of quartz, and micro-sections could not be prepared by the ordinary method. Sections of material hardened with red-stained bakelite,

[1] Geogr. Journ. London, 1933, vol. 81, pp. 10, 234, and 'The Empty Quarter', p. 180.

kindly prepared at the Building Research Station at Garston, near Watford, show shattered grains of quartz giving undulose extinction in a groundmass of powdered quartz (fig. 26). Sintered fragments of this sandstone are enclosed in the larger bombs of silica-glass. An analysis is given in column IV above. The country-rock at Henbury is a ferruginous sandstone consisting of small angular grains of quartz. Analysis V is of a small light-coloured fragment early received from Mr. Bedford and is less ferruginous than samples sent later.

Deductions from the observations recorded above.

The facts briefly recorded above provide ample scope for speculation. It is clear that very high temperatures were involved, and the heat must have been developed by the impact of large masses of meteoric iron. A simple calculation from the kinetic energy $\frac{1}{2}mv^2$ of a large mass of iron moving with planetary velocity gives indeed temperatures far in excess of any that we may be called upon to account for.

Very little moisture is present in the desert sand at Wabar and the highly vesicular structure of the silica-glass must have been caused by the boiling of the silica. That silica was actually vaporized is proved by the condensation of black glass on the surface of the bombs of white glass; and the pimples on the surface of the black glass are dew-drops of silica. The presence in this black glass of iron and nickel in about the same ratio as in the meteoric iron proves that a part of the meteorite was also vaporized. The millions of tiny spheres of nickel-iron enclosed in the silica-glass represent a rain, or rather drizzle, of molten metal, condensed from iron and nickel vapours. The fact that these spheres are intimately intermixed with the vesicular silica-glass suggests that this rain fell into a pool of boiling silica. Some of them no doubt also represent drops of molten metal from the meteorite incorporated in the silica-glass (as seen in slags from metal furnaces); but no larger globules of metal were found.

From these considerations we can provisionally fix the following points on a ‘geological thermometer’.

	°C.
Transformation of α-iron to γ-iron (body-centred to face-centred lattice) ...	850
Melting-point of nickel	1452
,, ,, iron	1535
,, ,, silica	1710
Boiling-point of nickel	2900
,, ,, iron	3200
,, ,, silica	3500 ?

These are the boiling-points calculated for the pressure of one atmosphere; at the enormous pressure which must have prevailed at the meteorite craters they were no doubt considerably higher.

The highly polished surface of the tiny spheres of nickel-iron indicates that oxygen was excluded from the surrounding atmosphere. A large meteorite moving through the earth's atmosphere has in front of it a cushion of highly compressed air at a very high temperature, and oxygen will be largely burnt up with the iron. At the impact on the earth's surface there will be a further and sudden development of gas from the vaporization of part of the meteorite and of the materials of the earth's crust. The earth's atmosphere will be blown away in a fiery blast, as was witnessed in the case of the Siberian fall in 1908.

The sudden development of a large volume of gas would give rise to a violent explosion. Generation of steam from water in the surrounding rocks would also have some effect. It seems clear that the few meteorite craters at present known are not merely dents on the earth's surface made by the percussion of meteorites, but that they are explosion craters. Their closest analogy is given by the craters formed by military mines and by high-explosive shells.[1] Everything is 'back-fired' out to form the crater, and bombs of molten silica are sent flying through an atmosphere of silica, iron, and nickel vapours. Smaller pieces of metal torn off in a plastic condition from the surface of the meteorite are scattered around. In such fragments the temperature exceeded 850° C., as proved by the change in their structure. Large masses of iron, also found outside the craters, which still preserve their original structure, were not heated to this temperature. Time is required for the conduction of heat into the interior of a large mass, and these larger pieces must be merely weathered remnants of still larger masses, representing in fact the cores to which the temperature did not reach 850° C. These larger masses were perhaps torn asunder along planes of the octahedral structure by the force of the explosion.

The effects of a violent concussion, due either to the direct impact of the meteorite or to the subsequent gaseous explosion, are seen in the Neumann lines in the kamacite of the unheated meteoric iron, and in the extensive shattering of the quartz grains in the sandstone.

[1] Pictures of such craters are given in the general article on meteorite craters in Geogr. Journ. London, 1933, vol. 81, plates facing pp. 231, 235.

The only record of a large mass of meteoric iron being found buried inside a crater is in the smallest (10-yard) crater at Henbury (p. 391). Here the force of the explosion was evidently not sufficient to 'back-fire' the main mass out of the crater. It seems very unlikely that large meteoric masses will ever be found buried inside larger craters. There must be wide variations in the conditions and in the results at different craters. This is shown by the very different appearance and character of the silica-glass at Wabar and Henbury, and at Meteor Crater in Arizona.[1] Groups of craters, as at Wabar and Henbury, must have been formed by a shower of a corresponding number of large meteorites.

Meteoric irons from other localities in Arabia.

A small piece of iron was picked up by Mr. Philby on March 4, 1932, on the sand-dunes at Naifa. This spot[2] (19° 56′ N., 51° 13′ E.) is about 110 miles (177 km.) south by east of Wabar, and is in the region where fragments of meteoric stones were collected by Mr. Bertram Thomas in 1931 and by Mr. Philby in 1932.[3] The small mass weighs 8 grams and is bean-shaped, measuring $2 \times 1{\cdot}2 \times 0{\cdot}8$ cm. It shows concave depressions and the surface is smooth and free from rust. A small area when levelled, polished, and etched showed the same crystalline structure as the Wabar iron, with kamacite bands 1–1½ mm. in width and narrow bands of bright taenite. The kamacite and the plessite areas show the same granulation as in the smaller piece of the Wabar iron. This piece of metal had no doubt been transported from Wabar by the Arabs; though, of course, there is the possibility that it fell where found as part of the Wabar shower. In the latter case the meteor must have travelled from the south, the larger masses that formed the group of craters at Wabar carrying farther.

The 'Nejed' meteoric irons weighing 131 lb. and 137 lb. were said to have fallen during thunderstorms in 1863 and 1891 in the 'Wadee Banee Khaled'. The first mass was received at the British Museum

[1] A. F. Rogers, A unique occurrence of lechatelierite or silica glass. Amer. Journ. Sci. 1930, ser. 5, vol. 19, pp. 195–202. [Min. Abstr., 5–16.]

[2] See map in this vol., p. 335, copied from Mr. Philby's map in Geogr. Journ. London, January 1933, vol. 81.

[3] W. Campbell Smith, A new meteoric stone from Suwahib, Arabia. Min. Mag., 1932, vol. 23, pp. 43–50; Meteoric stones from Suwahib, Arabia. Ibid., 1933, vol. 23, pp. 334–336.

in 1885 and was described by the late Sir Lazarus Fletcher.[1] The second mass was brought to the Museum in 1893, and is now in the Field Museum in Chicago. The accounts given with the two masses did not tally, and the locality 'Wadi Bani Khaled' has not been identified. In the Vienna meteorite catalogues by A. Brezina (1896) and F. Berwerth (1903) the locality is given at latitude 28° 0′ N. and longitude 45° 0′ E.; but in H. A. Ward's Chicago catalogue (1904) it is given at 24° 15′ N., 46° 25′ E., which is close to Riyadh the capital of Nejd. These are only guesses. No place of this name is known to Mr. Philby. In the correspondence relating to the 'Nejed' irons Mr. Philby recognized (allowing for errors of transcription from the Arabic) the name of the Shaikh of the tribe to which belonged the man who had dug the well of Umm al Hadid, 14 miles from Wabar.[2] The 'Nejed' iron is identical in crystalline structure and chemical composition with the Wabar iron (being of the common type of medium octahedrite containing Ni 7·3 %), and it is therefore very probable that these masses had really been transported from Wabar by the Arabs.

Hadid is the Arabic name for iron, and Al Hadida, i.e. place of the iron, is identified by Mr. Philby with the site of the legendary city of Wabar, mentioned in semi-classical Arabian writings as having been 'destroyed by fire from heaven'. The 'ruins' are the meteorite craters and the 'cinders' the abundant silica-glass. This spot is at 21° 29½′ N., 50° 40′ E. From information given to Mr. Bertram Thomas, during his journey across the Rub' al Khali in 1931, he provisionally placed the legendary city of 'Ubar' on his map at about 19° N., 52½° E.[3] Farther north he passed within ten miles of the meteorite craters, but unfortunately missed them, and Mr. Philby is the only European who has visited the spot. The identity and location of 'Wabar' or 'Ubar' or 'Obar' (or 'Ophir') are, in fact, still matters for discussion.[4]

[1] L. Fletcher, On a meteoric iron seen to fall in the district of Nejed, Central Arabia, in the year 1863. Min. Mag., 1887, vol. 7, pp. 179–182.

[2] Details in H. St. J. B. Philby's book 'The Empty Quarter', London, 1933, p. 179.

[3] Bertram Thomas, Geogr. Journ. London, September 1931; 'Arabia Felix', London, 1932.

[4] See H. St. J. B. Philby, Journ. Roy. Central Asian Soc. London, 1932, vol. 19, p. 569; 1933, vol. 20, pp. 488, 495; and Bertram Thomas, ibid., 1933, vol. 20, pp. 259, 441, 491.

EXPLANATION OF PLATES XIII–XX.

Meteoric iron and silica-glass from the meteorite craters at Henbury (Central Australia) and Wabar (Arabia).

(Photographs by H. G. Herring; photomicrographs by F. N. Ashcroft.)

PLATE XIII, FIG. 1. Meteoric iron: Henbury. The sphere was cut and etched to determine the crystallographic orientation of the mass. The black triangles mark the poles of the octahedron and the white squares the poles of the cube. Section planes were then cut parallel to the faces of the cube, octahedron, rhombic-dodecahedron. (B.M. 1932,1529.) Same size.

— FIG. 2. Meteoric iron: Henbury. Etched section approximately parallel to a face of the cube, showing the bars of kamacite making angles of nearly 90°.

— FIG. 3. Ditto. Parallel to a face of the octahedron; angles of 60°.

— FIG. 4. Ditto. Parallel to a face of the rhombic-dodecahedron; angles of 70° 32′ and 54° 44′.

FIGS. 2–4 show sections on the same piece of iron (267·5 grams). (B.M. 1932,1432.) Same size.

PLATE XIV, FIGS. 5 and 6. Meteoric iron: Wabar. Etched end-section of the 25 lb. mass, photographed at two angles of lighting to show the oriented sheen from the kamacite bands. The kamacite is granulated in places. (B.M. 1932,1136*b*.) Same size.

— FIG. 7. Meteoric iron: Wabar. Etched section of small piece weighing 23 grams, showing the granulation of the kamacite between the taenite bands. (B.M. 1932,1137.) ×3.

— FIG. 8. Meteoric iron: Henbury. Etched section of small, twisted piece weighing 511 grams, showing the curved lamellae and granulation of the kamacite. (B.M. 1932,98.) Same size.

— FIG. 9. Meteoric iron: Henbury. Etched section of small, curved piece weighing 65 grams, showing further obliteration of the structure. (B.M. 1932,1486.) ×2.

PLATE XV, FIG. 10. Meteoric iron: Henbury. Mass weighing 33 lb. (15 kg.), showing different types of sculpturing produced by subterranean and subaerial weathering. The mass was found standing up with the half to the left buried in the ground. (B.M. 1932,1424.) $\times\frac{3}{7}$.

— FIG. 11. Meteoric iron: Henbury. Mass weighing 1240 grams, pockmarked by wind-action, bringing out the octahedral structure (shown below on the left). Underneath, where the mass was resting on the ground, pockmarks are not developed. (B.M. 1932,1428.) $\times\frac{6}{7}$.

PLATE XVI, FIG. 12. Meteoric iron: Henbury. Group of four masses, *A* 292 lb., *B* 120 lb., *C* 24 lb., *D* 5 lb. (total weight 441 lb. = 200 kg.), in the relative positions as found at a depth of 7 feet in the 10-yard crater no. 13. (B.M. 1932,1359–1362). $\times\frac{1}{7}$.

— FIG. 13. Meteoric iron: Henbury. Weathered remnant (197 grams), showing the large shallow concavities produced by subterranean weathering, which has given rise to the curved outline. (B.M. 1932,1517.) $\times\frac{9}{11}$.

— FIG. 14. Meteoric iron: Henbury. Weathered remnant (157 grams) of a twisted fragment torn off by the explosion. (B.M. 1932,1518.) $\times\frac{9}{11}$.

— FIG. 15. Meteoric iron: Henbury. Mass weighing 5 lb. (2288 grams) showing a large flake nearly detached. The upper surface is pock-marked and the lower (buried) surface shows broad concavities. (B.M. 1932,1426.) $\times \frac{5}{8}$.

PLATE XVII, FIG. 16. Silica-glass: Wabar. Outer ropy surface of a large bomb. (B.M. 1932,1143.) Slightly reduced.

— FIG. 17. Silica-glass: Wabar. Broken surface of the same bomb, showing brecciated fragments of white glass with small bubbles embedded in grey and blue glass with large bubbles. (B.M. 1932,1143.) Slightly reduced.

PLATE XVIII, FIG. 18. Silica-glass: Wabar. Complete bomb consisting inside of highly vesicular white glass (shown at the top) and a highly glazed exterior of black glass with pimples on the surface. (B.M. 1932,1147.) Same size.

— FIG. 19. Silica-glass: Wabar. Another view of the same bomb, photographed with a film of moisture on the glazed surface to suppress the high lights. (B.M. 1932,1147.) Same size.

— FIG. 20. Silica-glass: Wabar. Small bombs of black glass showing pimples on the highly glazed surface. [The fibres are cotton-wool.] (B.M. 1932,1158.) Same size.

— FIG. 21. Silica-glass: Henbury. Small bombs of black glass showing pimples on the highly glazed surface. Two of these approximate to the button shape and one to the dumb-bell shape of australites.[1] (B.M. 1932, 1542.) Same size.

— FIG. 22. Minute spheres of nickel-iron isolated from the silica-glass of Wabar, attracted to a magnetic needle. $\times 80$.

PLATE XIX, FIG. 23. Silica-glass: Wabar. Micro-section of a small bomb (like fig. 20), showing the black (brown in section) glass of the exterior streaking into the vesicular white glass of the interior. The black dots are spheres of metallic nickel-iron embedded in the glass. (B.M. 1932,1159*b*.) $\times 28\frac{1}{2}$.

— FIG. 24. Silica-glass: Wabar. Micro-section of a fragment from a large bomb (like fig. 17), showing a patch of white glass surrounded by brown glass. Embedded in the white glass (at the right) is a shattered grain of quartz. The black dots are metallic nickel-iron embedded in the glass. (B.M. 1932,1159*c*.) $\times 40$.

PLATE XX, FIG. 25. Silica-glass: Henbury. Micro-section of a small bomb (but larger than those in fig. 21) of black glass, showing the glazed surface free from bubbles and the vesicular interior dark with iron oxide. [The crinkly edge in some of the bubbles is the bakelite used for hardening the section.] (B.M. 1933,11.) $\times 28\frac{1}{2}$.

— FIG. 26. Sandstone: Wabar. Micro-section showing shattered grains of quartz in a groundmass of powdered quartz. The material is very friable and could be sectioned only after being impregnated with bakelite (red-stained): this was kindly done at the Building Research Station at Garston, near Watford. (B.M. 1932,1168.) $\times 70$.

FIGS. 27 and 28 in the text, p. 397.

[1] See L. J. Spencer, Origin of tektites. Nature, London, 1933, vol. 131, pp. 117–118, 876; Compt. Rend. Acad. Sci. Paris, 1933, vol. 196, pp. 710–712. [Min. Abstr., vol. 5, p. 304.]

Fig. 1

Fig. 2

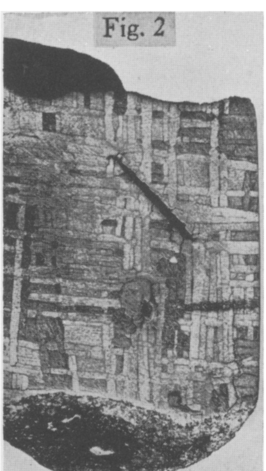


Fig. 3

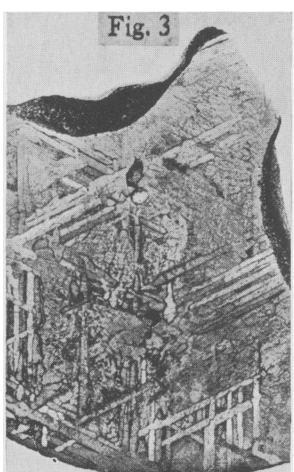
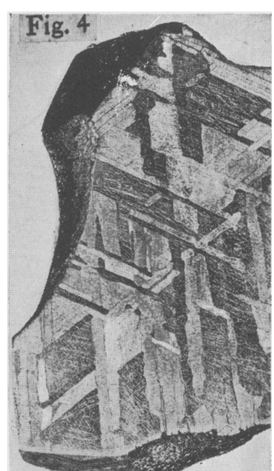


Fig. 4



L. J. SPENCER: METEORIC IRON FROM HENBURY, CENTRAL AUSTRALIA.

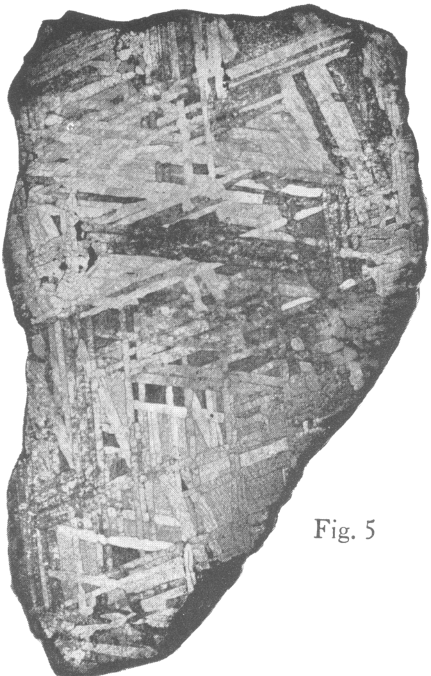


Fig. 5

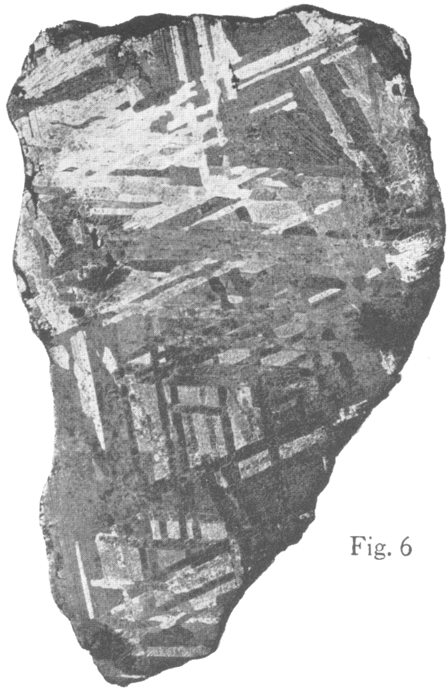


Fig. 6

Fig. 7

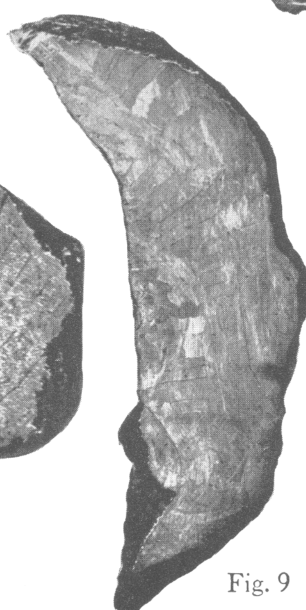


Fig. 9

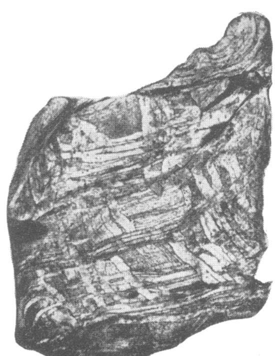


Fig. 8

L. J. SPENCER: METEORIC IRON FROM WABAR AND HENBURY.

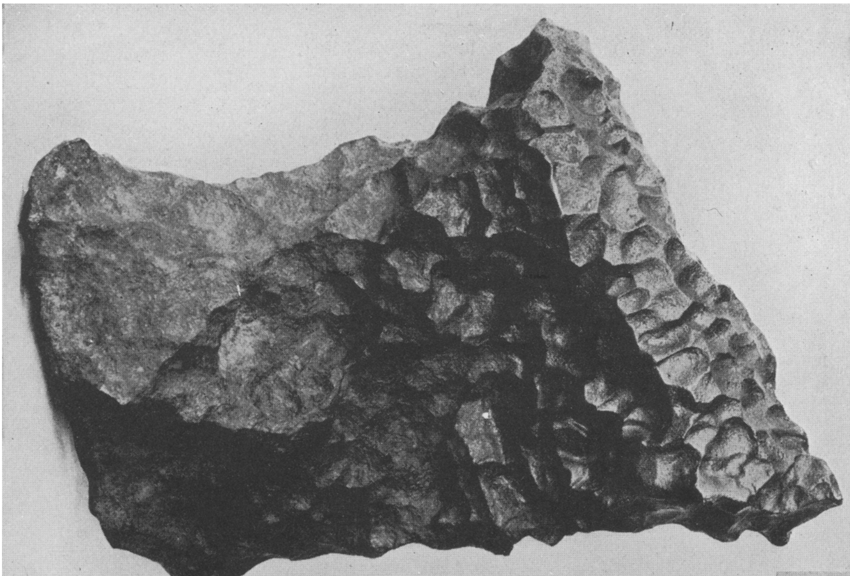


Fig. 10

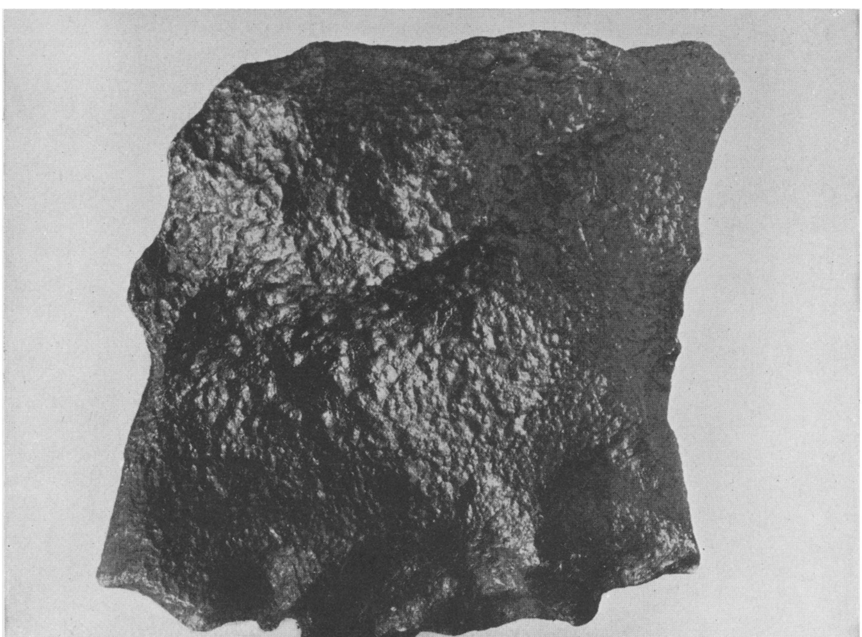


Fig. 11

L. J. SPENCER: METEORIC IRON FROM HENBURY, CENTRAL AUSTRALIA.

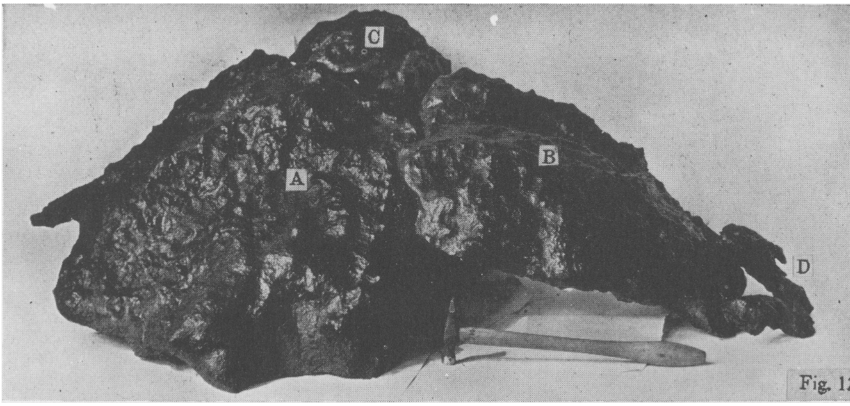


Fig. 12

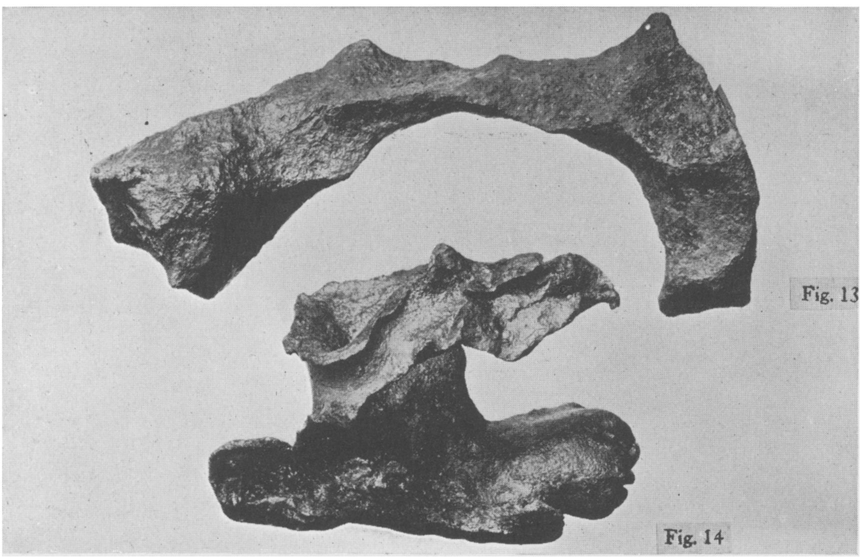


Fig. 13

Fig. 14

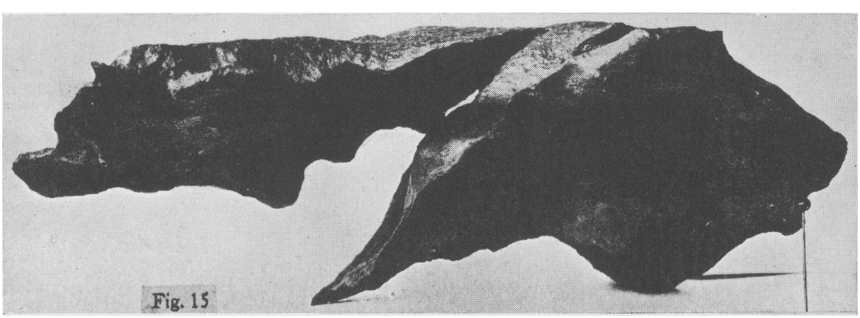


Fig. 15

L. J. SPENCER: METEORIC IRON FROM HENBURY, CENTRAL AUSTRALIA.

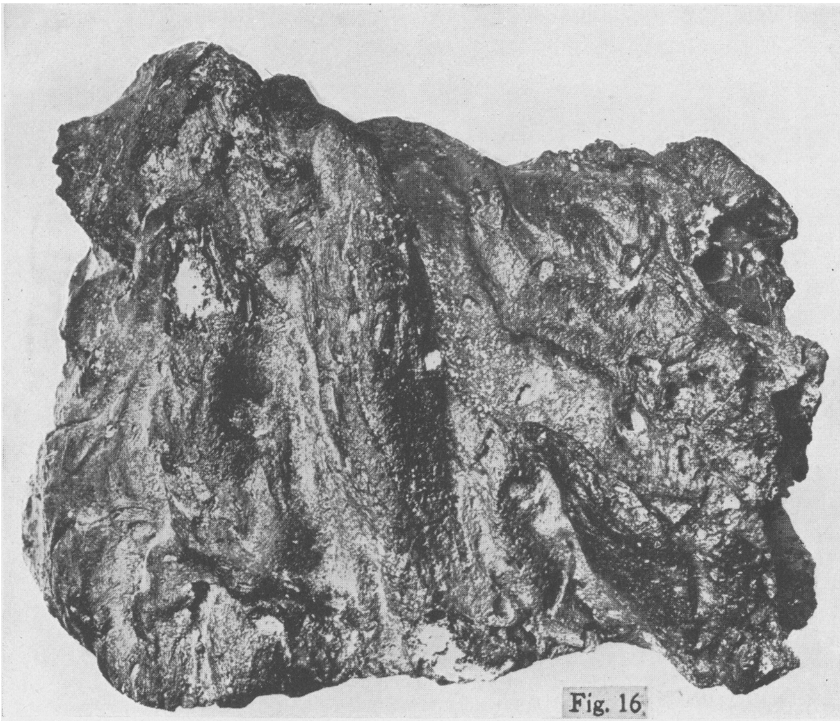


Fig. 16

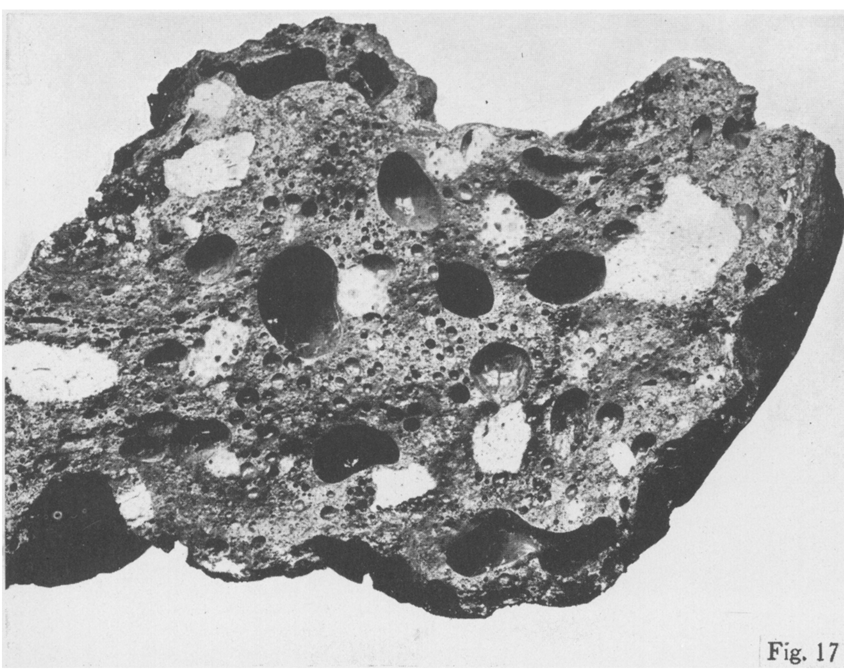


Fig. 17

L. J. SPENCER: SILICA-GLASS FROM WABAR, ARABIA.

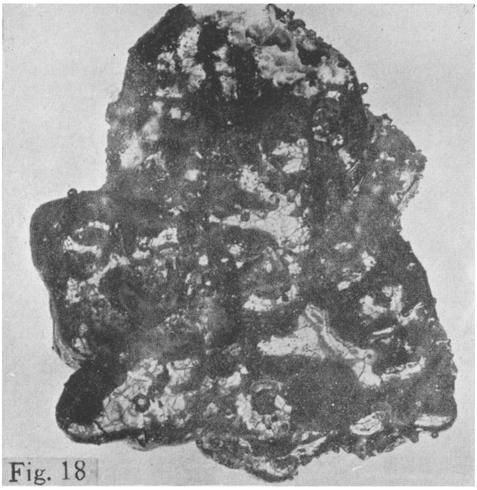


Fig. 18

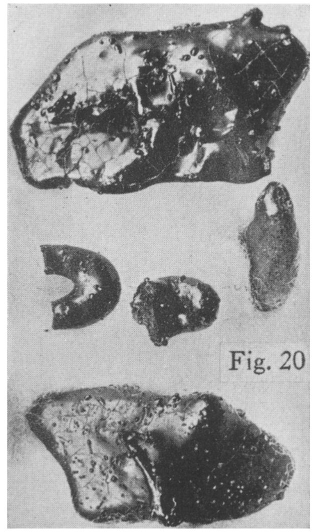


Fig. 20

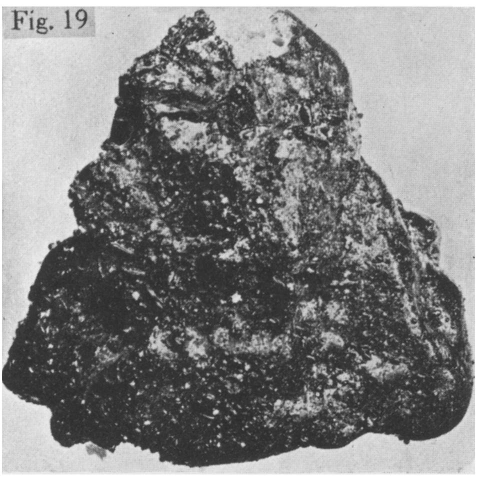


Fig. 19

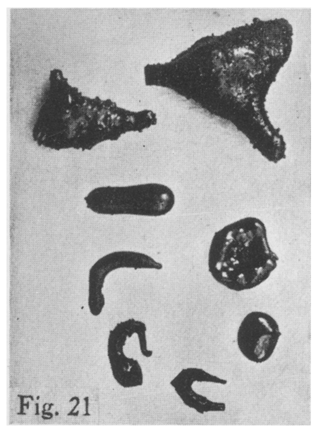


Fig. 21

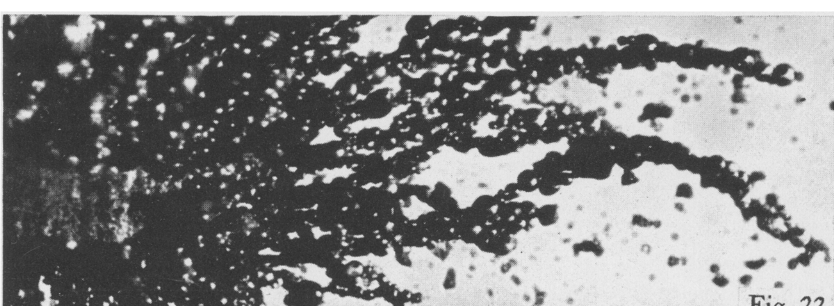
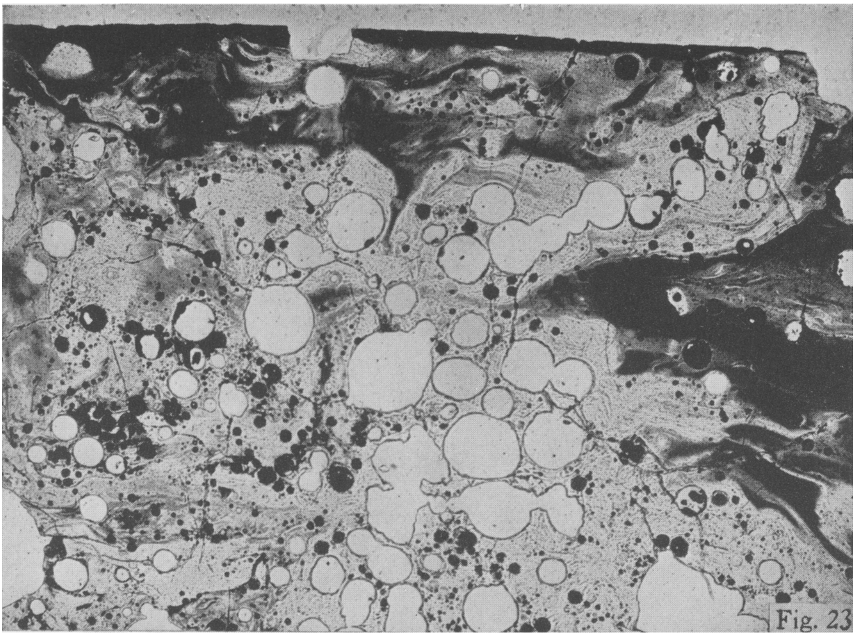
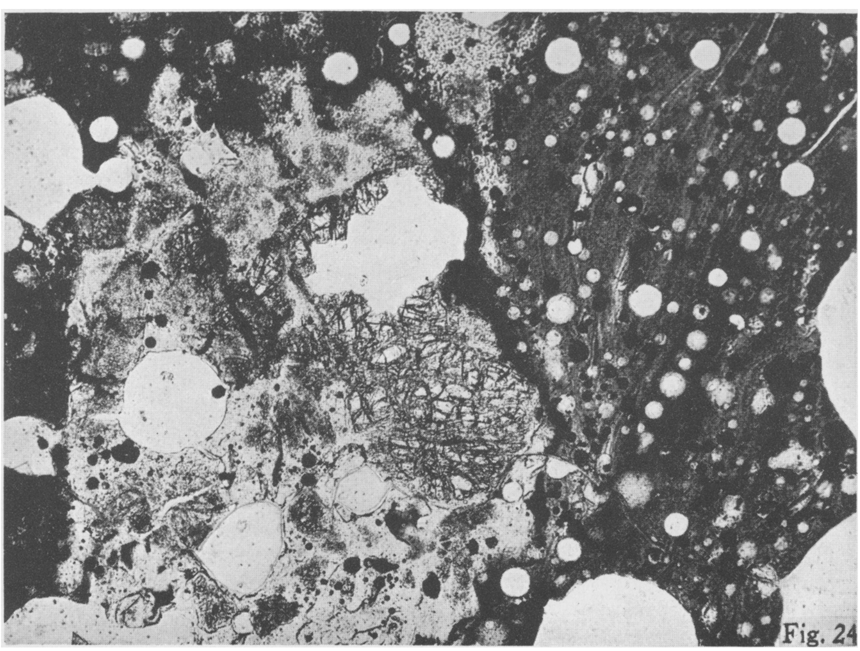


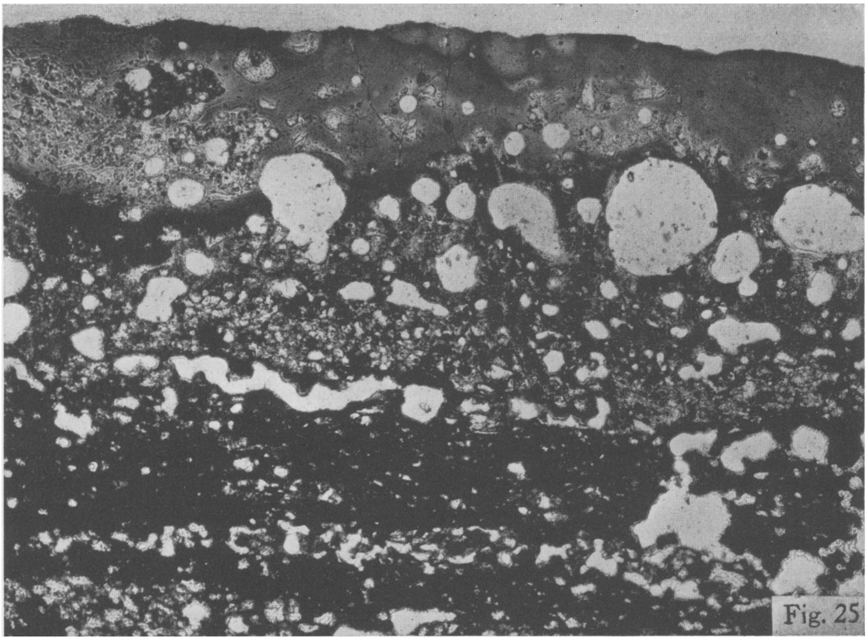
Fig. 22

L. J. SPENCER: SILICA-GLASS FROM WABAR, ARABIA, AND (FIG. 21) FROM HENBURY, CENTRAL AUSTRALIA.
FIG. 22. SPHERES OF NICKEL-IRON ISOLATED FROM SILICA-GLASS.





L. J. SPENCER: SILICA-GLASS FROM WABAR, ARABIA.



L. J. SPENCER: FIG. 25. SILICA-GLASS FROM HENBURY.
FIG. 26. SANDSTONE FROM WABAR.