A new meteoric iron from Piedade do Bagre, Minas Geraes, Brazil.

(With Plates XI and XII.)

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A MASS of iron weighing 130 lb., stated to have been found in 1922 near the village of Piedade do Bagre in Minas Geraes, Brazil, and believed to be meteoric, was submitted by Mr. N. Medawar in January 1929 to the Mineral Department of the British Museum for examination. The following description of the mass fully confirms the supposition of its meteoric origin. Unfortunately, only scanty details are available of the circumstances of the finding of the mass. All the information that Mr. Medawar was able to supply is given in the following short note written by Mr. R. J. Bohrer, with a rough sketch-map of the locality.

Meteorito encontrado no ponto marcado +. Vendido por intermedio do Snr. Padre José Alves de Curvello a Rodolpho J. Bohrer. Encontrado em 1922 por um situante cujo nome não se conhece. Vendido a Snr. Medawar em Março de 1927.

Mr. Medawar's translation of this is :

Meteorite found at the point marked +. Sold by the intermediary of Mr. Padre José Alves of Curvello to Rodolpho J. Bohrer. Found in 1922 by a local native whose name not known. Sold to Mr. Medawar in March of 1927.

The spot marked is about 16 km. (10 miles) SW. of the village of Piedade do Bagre in Minas Geraes. This village is situated between the Rio São Francisco and the Rio das Velhas, and is about 155 km. NW. of Bello Horizonte, the capital of Minas Geraes, and about 155 km. WSW. of Diamantina. It is about 50 km. west by south of the railway station of Curvello and about 33 km. east of the railway station of Paraopéba.[1] The district of Piedade do Bagre is in the municipio of Curvello, but it is probable that the meteorite was found just over the boundary in the adjoining municipio of Pitanguy. As near as can be determined, the position of the find is given by lat. 18° 56½′ S., long. 44° 59′ W. The position is indicated by a cross on the accompanying sketch-map (fig. 1), which is a tracing from the Brazilian sheets dated 1922 of the International Map of the World on a scale of 1 : 1,000,000.

When received at the Museum the mass was first weighed and measured. The weight was 130 lb. (= 59 kg.) and the maximum dimensions in three directions at right angles were 39·7 × 32·1 × 17·2 cm. (= 15⅝ × 12⅝ × 6¾ inches). It was then photographed by the Museum photographer, Mr. H. G. Herring, and coloured plaster casts were made by Mr. P. Stammwitz, preparator in the Department of Zoology. With Mr. Medawar's approval an end-piece was then sawn off, and from this a corner weighing 19 grams was cut off for chemical analysis. After smoothing and polishing the two cut surfaces, the end-piece weighed 2127½ grams. This piece (pl. XII, fig. 7) was generously presented to the Museum by Mr. Medawar. Sawdust and filings weighed about 100 grams, leaving the main mass at 125 lb.

The general shape of the mass, which is represented from three points of view in figs. 2 and 3, and fig. 5 of pl. XI, calls for no special remark. There are broad concave surfaces, but no smaller well-marked pits. The surface is weathered and a small amount of scale was detached in the process of cleaning. Portions of this scale are magnetic and attract the filings from the mass. The complex of broad and shallow concave surfaces shown by most iron meteorites would appear to be the result of atmospheric weathering.[2]

[1] Another place called Paraopéba, the chief town of the municipio of the same name, is situated 62 km. south of Curvello.

[2] The same character of surface is shown by the gigantic meteoric iron at *Hoba* in South-West Africa, on the Hoba West farm, 12 miles west of Grootfontein [Min. Abstr., vol. 4, p. 261]. Here the mass is surrounded by a thick layer of scale, which has obviously been formed by the weathering of the iron. This 'iron shale' is well exposed in the sides of the pit that has been dug partly round the mass. It has a thickness of one foot and shows a lamination parallel to the adjacent surface of the unaltered iron from which it is sharply separated. The scale is dark-brown to black with a dark-brown streak and it is slightly magnetic. It shows green nickel stains and is seamed with calcium carbonate from the surrounding surface limestone (Kalahari Kalk) in which the mass is embedded. The meteorite has the form of a roughly rectangular block with its large upper surface level with the surrounding ground. A dozen people can

A feature of special interest is the natural octahedral fracture shown on the prominent corner of the mass (upper right-hand corner in fig. 2, and to the right in fig. 5). The crack shown on the shoulder in fig. 2 is parallel to this fractured surface. On this surface there are lines of fissure in three directions at 60° bringing out the octahedral structure of the iron (fig. 6). The elongated triangular surface to the left in fig. 6 appears to be an old saw cut. Beneath

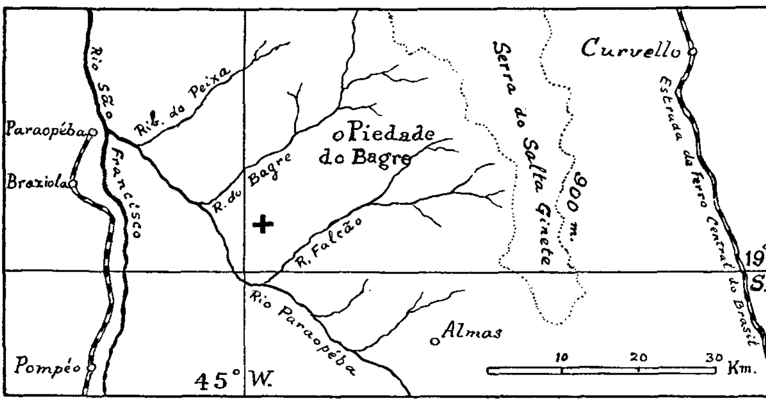


FIG. 1. Sketch-map of locality of the Piedade do Bagre meteorite, Minas Geraes, Brazil. Scale 1 : 1,000,000.

this is a thin ($\frac{1}{2}$–1 mm.) pliable plate of metal (kamacite) standing out from the surface. Indications of an octahedral structure are also shown on two flattish surfaces on the mass, one of them showing on the right in the lower right-hand corner of fig. 3.

The plane of section of the end-piece that was cut off the mass was taken more or less parallel (but unfortunately at about 20°) to this octahedral fracture. The polished surface (fig. 7) shows a more or less regular system of cracks parallel to the kamacite bands, again bringing out the octahedral fracture of the iron. This 'cleavage' is a separation along the kamacite lamellae, and not a true crystal

walk about on the level surface of the meteorite. Measurements taken by me in September, 1929, are 295 × 284 cm. (about 10 × 9 feet) on the large flat surface, with a thickness at one end of 111–122 cm. and at the other end of 55–75 cm. From these measurements I calculated the weight of the mass to be about 60 metric tons. This considerably exceeds the largest mass (Ahnighito or 'The Tent', 36½ tons) of the Cape York (Greenland) meteoric iron, now in the American Museum of Natural History in New York City, which has hitherto been the record size for a meteorite.

cleavage.[1] This fracturing of the mass was no doubt brought about by the fall of the meteorite on this end on hard rock. The unusually fine development of Neumann lines shown on the etched surface (fig. 8) is also no doubt due to the shock of the impact on this corner of the mass.

Etching with dilute nitric acid gave unsatisfactory results. After

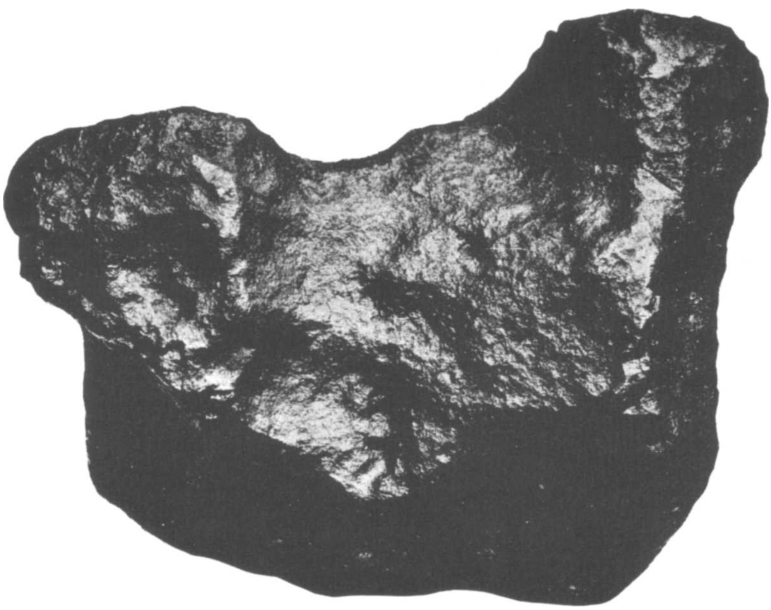


FIG. 2. Photograph of one side of the Piedade do Bagre meteorite, Minas Geraes, Brazil. $\times \frac{1}{4}$.

repolishing the surface it was etched with very dilute bromine water for $1\frac{1}{2}$ hours, which brought out to perfection the Neumann lines. The second small surface was etched for three minutes with a solution of cupric chloride containing an excess of ammonium chloride. On immersion there was immediately a deposition of copper on the surface. This can be readily wiped off the kamacite, but it adheres firmly to the taenite.

The etched surface (fig. 7) shows well-marked Widmanstätten figures, but owing to the low degree of etching they are somewhat

[1] These 'cleavages' in meteoric iron were first observed by W. H. Wollaston in 1816, and have been called 'Wollaston planes' by O. A. Derby, Archivos do Museu Nacional, Rio de Janeiro, 1896, vol. 9, p. 114.

faint. The etching was stopped to preserve the fine series of Neumann lines; if it had been carried further to give sharp Widmanstätten figures the Neumann lines may have been obliterated. Possibly this is one reason why Neumann lines have been so rarely observed in octahedrites. In addition to a well-marked triangular arrangement

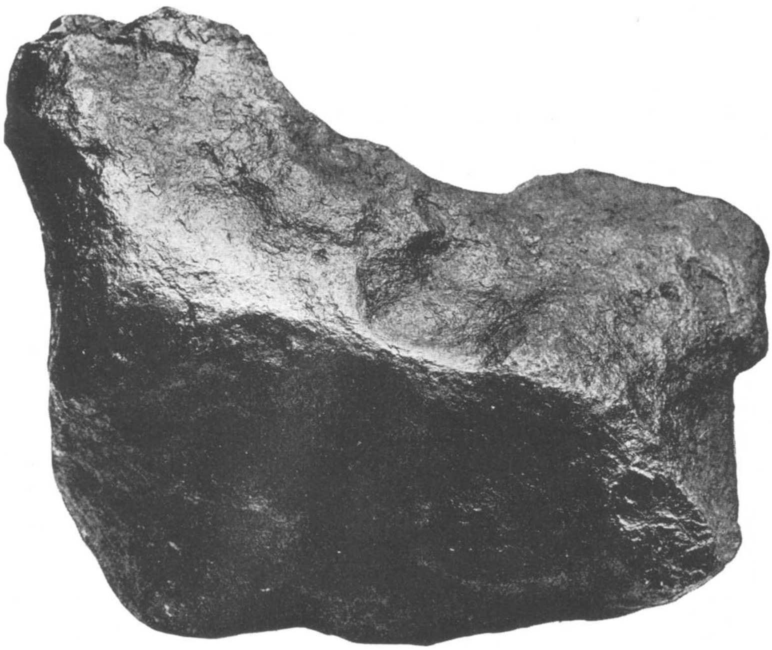


FIG. 3. Photograph of the opposite side of the Piedade do Bagre meteorite. $\times \frac{1}{4}$.

of the kamacite bands, there is a fourth set of broader bands. These broader bands represent the kamacite layers parallel to that face of the octahedron which is inclined at a smaller angle to the section-plane. Measurement of the angles between the kamacite bands could not be made owing to the awkward shape of the specimen. Measurements made on the photographs gave: from fig. 8, 68°, 68°, 44°; and from fig. 7, 71°, 64°, 45°, and for the fourth set 28° + 43° = 71°. These are, however, not the true angles, as the surface was not parallel to the photographic plate.[1]

[1] N. T. Belaiew, Crystallisation of metals. London, 1923, p. 76 [Min. Abstr., vol. 2, p. 87], gives a table of angles showing the relation between the angles of Widmanstätten figures and the orientation of the section-plane. See also J.

In the triangular set the kamacite bands are about 1 mm. wide, so that the iron can be classed as a 'medium octahedrite'. But, as noted above, the width of the bands depends on the direction of the section. Very thin strings of brilliant tin-white taenite border the kamacite bands (fig. 8), and there are well-marked areas of plessite. Troilite is present in small amount as scattered nodules, quite small in size and elongated in shape. Some of them show parallel bands of an included tin-white material, possibly schreibersite. The parallelism of these bands and their abrupt ending at the surface of the troilite suggest that the nodules are corrosion remnants, rather than, say, fused drops. A group of very minute specks of troilite (surrounded by a white stain on the iron) is shown in the upper central part of fig. 7. The minute white spots in some of the kamacite bands (e. g. lower band in fig. 8) are perhaps cohenite.

The smaller etched surface (3 × 2 cm. shown dark on the left in fig. 7) is nearly parallel to a cube face. On this a rectangular arrangement of the Widmanstätten figures is shown. The copper etching brings the taenite into prominence and minute rods and specks of it are seen throughout the plessite areas. Copper-coloured specks seen under the microscope in the kamacite bands perhaps represent cohenite. Neumann lines were not developed by this etching.

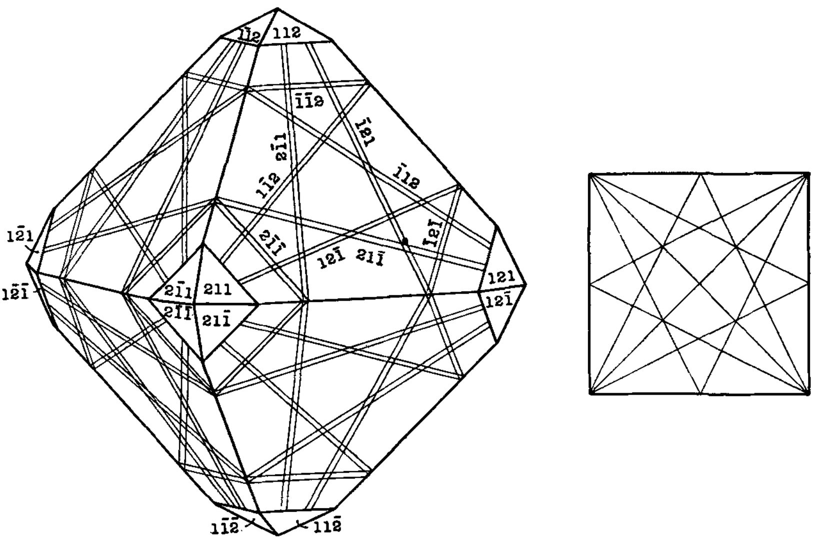
A special feature of the Piedade do Bagre meteorite is the abundance and distinctness of the Neumann lines in the bands of kamacite. In the literature I have not been able to find anything to compare with fig. 8. The lines are readily visible to the unaided eye and are still evident in the slightly reduced photograph (fig. 7), while under a magnification of ten diameters (fig. 8) they are very marked. It will be seen that the lines are confined to the kamacite bands, and that they end abruptly at the narrow strings of taenite.

In parallel bands of the kamacite there is a parallelism of the Neumann lines, but the lines do not always continue in the same straight line across a taenite strip. Further, lines with some directions present in one band may be absent in the next. Under the microscope the lines are seen to be grooves with somewhat jagged edges and a depressed granular surface. An oriented sheen on the etched surface is only slightly evident when the specimen is turned about in reflected light.

Neumann lines are now known to be twin-lamellae produced by

Leonhardt, Neues Jahrb. Min., Abt. A, 1928, vol. 58, p. 179 [Min. Abstr., vol. 4, p. 122].

gliding on planes of the icositetrahedron {211}. The traces of these on the faces of the octahedron are represented in fig. 4*a*, where in each case a plane of {211} passes through a corner of the octahedron. On each octahedral face there are nine directions of these lines, making angles of 0°, 20° 10′, 39° 50′, 60°, and 80° 10′ with an edge of the octahedron. The twelve faces of the icositetrahedron which



a. *b.*

FIG. 4*a*. Neumann lines. Traces of intersection of planes of the icositetrahedron {211} on the faces of the octahedron {111}. Each face of {211} passes through a corner of the octahedron.

FIG. 4*b*. Intersection of planes of {211} on a cube face, giving ten directions for the Neumann lines.

lie in the three zones [111,211], [111,121], and [111,112] account for only three directions of striation on the octahedral face (111); the remaining twelve faces giving rise to the six other directions. Making allowance for the lack of parallelism of the plane of the section with a face of the octahedron, all the directions are represented in fig. 8, though not more than four or five at the same time in any one band of kamacite.

Neumann lines[1] were first distinguished from Widmanstätten

[1] Also called 'Neumann bands' and 'Neumann figures'. The earliest use of the term that I have been able to find is by A. Brezina ('Neumann'schen Figuren) in Jahrb. Geol. Reichsanst. Wien, 1885, vol. 35, p. 199.

figures by J. G. Neumann[1] in 1848, during his examination of the Braunau (Bohemia) hexahedral iron. They have been studied by G. Rose (1864), G. Tschermak (1875), A. Sadebeck (1875), O. W. Huntington (1886), O. Mügge (1899), and others, and have been generally thought to be due to a lamellar twinning of the cube on a face of the octahedron or triakisoctahedron {221}. The structure came to be regarded as typical of hexahedrites, which are composed wholly of kamacite without any lamellar intergrowth of taenite to mark out the octahedral structure. Neumann lines have, however, been observed also in the kamacite of octahedral irons. For example, they were described by O. A. Derby[2] under the name 'Bendigó lines' in the iron of Bendigó (Brazil). Dr. G. T. Prior[3] mentioned them in the iron of Vaalbult (South Africa), and recently Sir Harold Carpenter and Dr. S. Tamura[4] have studied them in the octahedrite of Cañon Diablo (Arizona).

W. Haidinger[5] in 1855 and G. Linck[6] in 1892 observed the same structure in artificial iron, and Linck was the first to interpret correctly the several directions of the lines as due to lamellar twinning with gliding on planes of the icositetrahedron (211). Similar lines representing slip-planes due to strain are well known in other metals and have been much studied by metallographers.

An elaborate study of Neumann lines has recently been made by Prof. S. W. J. Smith and his assistants.[7] They prove that lamellar twinning by shearing is possible on the planes of (211) in a body-centred cubic lattice, which as shown by X-ray analysis is the structure of kamacite and α-iron (taenite and γ-iron having a face-centred cubic lattice). Under high magnification ($\times$ 1680) they show many beautiful photographs of Neumann lines and etch-figures on polished surfaces of the Coahuila (Mexico) hexahedrite. The etch-

[1] J. G. Neumann, Ber. Mitt. Freunden Naturwiss. Wien, 1848, vol. 4, p. 86. The detailed account appeared later in Naturwiss. Abhandl. Wien, 1850, vol. 3, pt. 2, p. 45.

[2] O. A. Derby, Archivos do Museu Nacional, Rio de Janeiro, 1896, vol. 9, p. 153.

[3] G. T. Prior, Min. Mag., 1926, vol. 21, p. 189.

[4] H. C. H. Carpenter and S. Tamura, Trans. Inst. Mining & Metall. London, 1928, vol. 37, p. 381, figs. 87–93. [Min. Abstr., vol. 4, p. 239.]

[5] W. Haidinger, Sitzungsber. Math.-naturwiss. Cl. Akad. Wiss. Wien, 1855, vol. 15, p. 354.

[6] G. Linck, Zeits. Kryst. Min., 1892, vol. 20, p. 209.

[7] S. W. J. Smith, A. A. Dee, and J. Young, Proc. Roy. Soc. London, Ser. A., 1928, vol. 121, pp. 477–514, 6 pls. [Min. Abstr., vol. 4, p. 121.]

figures inside a band are in reversed orientation to those outside, and when one band crosses another there is a shift (faulting) of the earlier band. These observations prove conclusively that Neumann lines are due to làmellar twinning along glide-planes and that they are of secondary origin and due to strain. They are, in fact, strictly analogous to the secondary twin-lamellae in the grains of calcite in a crystalline limestone that has been subjected to pressure.

The suggestion has already been made by Sir Harold Carpenter (loc. cit.) and others that Neumann lines have been developed in the kamacite of meteoric irons by the shock of impact when the meteorite fell on the earth's surface. The prominent octahedral fracture and the distinct Neumann lines shown by the Piedade do Bagre meteorite give strong support to this view.

The following notes on the chemical analysis of the Piedade do Bagre meteoric iron have been supplied by Mr. M. H. Hey.

A piece of the meteorite free from rust and weighing 9·3032 grams was dissolved in hydrochloric acid. The residue (0·0034 gram) was boiled with aqua regia and left 0·0013 gram silica insoluble, which left no residue on evaporation with hydrofluoric and sulphuric acids. The aqua regia extract was evaporated to dryness, taken up with dilute hydrochloric acid, and added to the main bulk.

A little macerated filter paper was added and copper precipitated with hydrogen sulphide. The precipitate was dissolved in dilute nitric acid, the solution evaporated to dryness, taken up in water and a drop of nitric acid, and the copper determined colorimetrically with ammonia. The filtrate and washings were bulked to 1,000 c.c. after boiling off the hydrogen sulphide. The nickel was determined in two portions, one of 100 c.c. and one of 25 c.c., the iron being kept in solution by tartaric acid; to each portion was added an excess of sulphurous and tartaric acids, then the alcoholic solution of dimethylglyoxime, and finally excess of ammonia; found 7·44 and 7·56 %. Cobalt was determined on 50 c.c. as potassium cobàltinitrite.

It was found impossible to determine the iron accurately by double precipitation with ammonia and ammonium chloride, nickel being co-precipitated, but four precipitations, using a considerable excess of ammonia, gave a nickel-free ferric hydroxide. Satisfactory results were also obtained by a triple basic acetate precipitation. The first method gave 91·81 %, the second 92·35 %, using 25 c.c. of solution in each case. The first attempts at the iron estimation, by double ammonia precipitation, which gave high results owing to co-precipitation of nickel, were corrected by determining the nickel in the filtrate and then allowing a correction for that precipitated with the iron. Taking the total nickel at 7·44 %, the results were: Iron with some nickel, 94·20, 94·38, and 95·62 %; nickel in filtrate, 5·08, 4·54, and 3·15 %; hence iron (corrected), 92·10, 91·80, and 91·80 %. The first two determinations were carried out on 25 c.c. each of the solution, the third on a separate solution of 0·6305 gram of the meteorite dissolved in aqua regia.

Sulphur was determined on a third portion of 0·7034 gram of the meteorite, which was dissolved in strong nitric acid saturated with bromine in a flask, any sulphur in the reaction gases being trapped in a wash-bottle filled with nitric acid and bromine, the solution in which was added to the main bulk after solution was complete. The bromine was then boiled off, and the sulphur (now present as sulphuric acid) precipitated as barium sulphate.

In taking the means, the first value for the nickel has been included twice, as more accurate, being found with 100 c.c. of solution; and the first two values for the iron also twice, the other three being found indirectly. The final results so obtained are:

Fe.	Ni.	Co.	Cu.	S.	P.	SiO_2.	Pt.	Total.
92·03	7·48	0·39	0·0097	0·22	trace[1]	0·01	trace[1]	100·14

[1] P less than 0·001 %; Pt less than 0·005 %.

The ratio of the percentage weight of Fe : Ni is 12·3 (and of Ni : Co, 19), which is in agreement with G. T. Prior's grouping for a medium octahedrite.[1]

The specific gravity was determined by weighing the end-piece (2127·5 grams) in air and water to be $7{\cdot}71 \pm 0{\cdot}02$, corrected $D_4^{18} = 7{\cdot}69 \pm 0{\cdot}02$.

List of Brazilian Meteorites.

A list of seven Brazilian meteorites was given by Orville A. Derby in 1888,[2] when he described four as new from the National Museum at Rio de Janeiro, and he mentioned some others that proved to be pseudo-meteorites or doubtful. The following list has been compiled from the British Museum Catalogue of Meteorites,[3] with, of course, the addition of the new meteorite now described. Of the eighteen listed, ten are stones and seven irons, and one doubtful. Five are from Minas Geraes.

Angra dos Reis, Rio de Janeiro. Stone of 1½ kg., fell January 30, 1869.
Bendegó, Bahia. Iron of 5360 kg., found 1784.
Bezerros, Pernambuco. Iron about 20 tons, fell May 9, 1915 [? no confirmation].
Cratheus, Espirito Santo. Iron, found 1909 (?).
Itapicuru-Mirim, Maranhão. Stone of 2 kg., fell March, 1879.
Macao, Rio Grande do Norte. Shower of stones, fell November 11, 1879.
Minas Geraes. Stone of 1·2 kg., known in 1888.
Monte Alto, Bahia. Iron, known in 1888 [? no confirmation].
Morro do Rocio, Santa Catharina. Stone, known before 1927.
Piedade do Bagre, Minas Geraes. Iron, 59 kg., found 1922.
Ponta Grossa, Paraná. Stone of 667 grams, fell April, 1846.

[1] G. T. Prior, Min. Mag., 1920, vol. 19, p. 55.

[2] O. A. Derby, Notas sobre meteoritos Brasileiros. Revista do Observatorio, Rio de Janeiro, 1888, vol. 3, pp. 3–6, 17–20, 33–37. An abstract of this paper was given in Amer. Journ. Sci., 1888, ser. 3, vol. 36, p. 157.

[3] G. T. Prior, 1923; Appendix, 1927.

Santa Barbara, Rio Grande do Sul. Stone of 400 grams, fell September 26, 1873.
Santa Catharina. Iron, several masses, about 25 tons, found 1875.
Santa Luzia, Goyaz. Iron of 4½ kg., found in 1921.
São Sébastião da Boa Vista,[1] Minas Geraes. An enormous meteorite, fell 1914 [? no confirmation].
Serra de Magé, Pernambuco. Shower of small stones, fell October 1, 1923.
Sete Lagôas, Minas Geraes. Six small stones, fell December 15, 1908.
Uberaba, Minas Geraes. Stone of 1½ kg., fell June 29, 1903.

Others listed by O. A. Derby as pseudo-meteorites or as doubtful are:

Areado, Minas Geraes.
Curitiba, Paraná.
Curvello, Minas Geraes.
Morro do Chapéo, Bahia.
Pernambuco.

A circumstantial account of the fall of a meteorite near Curvello in Minas Geraes on 11 April 1833 has been given by P. Claussen.[2] At 6.45 in the evening of that day in Curvello he saw for the period of half a second a luminous meteor with an apparent diameter equal to that of the moon moving rather quickly in a direction from SSW. to NNE. and leaving a long luminous trail. When almost overhead it burst into three large pieces and several smaller ones and then disappeared. After the disappearance he counted 123 pulsations and then there were violent detonations followed by loud roarings lasting for three minutes. The meteor was also seen and heard at Diamantina (110 km. distant) and at Sabará (140 km.). At the same time a large 'stone' fell in a deep swamp on the Matto Grosso estate, 15 km. ESE. of Curvello, and a branch of a tree near the house was broken off. The proprietor caused a search to be made by his negroes, but nothing was found. However, a few days later a negro brought to Claussen a piece of metal, thought to be silver, which weighed about three ounces [i. e. 85 grams, if the ounces were English avoirdupois]. This Claussen acquired and placed in the National Museum at Rio de Janeiro. He further remarks that on 15 August 1834 he heard at Curvello similar detonations, but on this occasion a fall was not observed.

[1] Incorrectly listed as 'San Sebastiano da Boa Vista'.

[2] P. Claussen, Notes géologiques sur la province de Minas Geraes au Brésil. Bull. Acad. Sci. Bruxelles, 1841, vol. 8, pt. 1, pp. 322–343. (Fer météorique, pp. 341–343.)

Curvello came to be listed as a definite meteorite fall by Otto Buchner[1] in 1863; he gave the weight as 170 grams [i. e. just double 85 grams], and he thought that the meteorite was more probably a stone than an iron. Later, Orville A. Derby[2] found in the Rio de Janeiro Museum a piece of iron weighing 218 grams without any information, but which was presumed to be the piece deposited by Claussen. A fragment of this was sent for examination to A. Brezina[3] in Vienna, who previously had cast doubts on the authenticity of the meteorite; and it was afterwards in 1888 stated by Derby to be artificial iron. E. A. Wülfing[4] in 1897 says that it was possibly a pseudo-meteorite and presumably lost.

The above has been given in some detail because it may perhaps have some bearing on the meteorite now described. The name Piedade do Bagre has here been decided upon, rather than Curvello (which had indeed been used provisionally before the above account was found in the literature), in order to avoid any possible confusion. It is, however, quite possible that this is part of the meteor so graphically described by Claussen.

Explanation of Plates XI and XII.

Meteoric iron of Piedade do Bagre, Minas Geraes, Brazil.

Fig. 5. Third view of the mass, with the ridge in fig. 3 on top and the projecting corner showing the natural octahedral fracture to the right. $\times \frac{1}{4}$.

Fig. 6. Closer view of the natural octahedral fracture. Actual size.

Fig. 7. Polished and etched surface nearly parallel to an octahedral face. Slightly reduced (size of specimen $12\frac{1}{2} \times 9$ cm.).

Fig. 8. Neumann lines in the kamacite bands. The area magnified is outlined in fig. 7. $\times 10$.

1 O. Buchner, Die Meteoriten in Sammlungen. Leipzig, 1863, p. 56.

2 O. A. Derby, loc. cit., 1888, pp. 35–36.

3 A. Brezina, Die Meteoritensammlung des k.k. mineralogischen Hofkabinetes in Wien am 1. Mai 1885. Jahrb. Geol. Reichsanst. Wien, 1885, vol. 35, pp. 151–276. (Curvello in the Appendix on p. 221.)

4 E. A. Wülfing, Die Meteoriten in Sammlungen. Tübingen, 1897, p. 399.

FIG. 5.

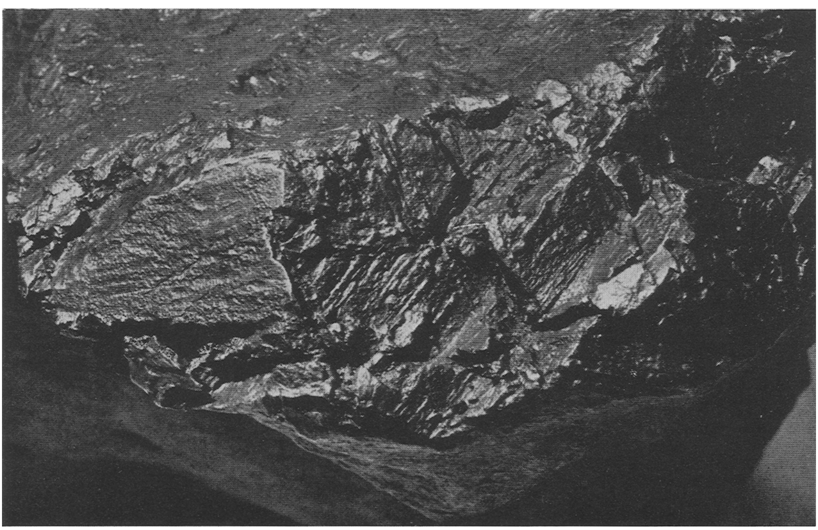


FIG. 6.

L. J. SPENCER: METEORIC IRON OF PIEDADE DO BAGRE MINAS GERAES, BRAZIL.

FIG. 7.

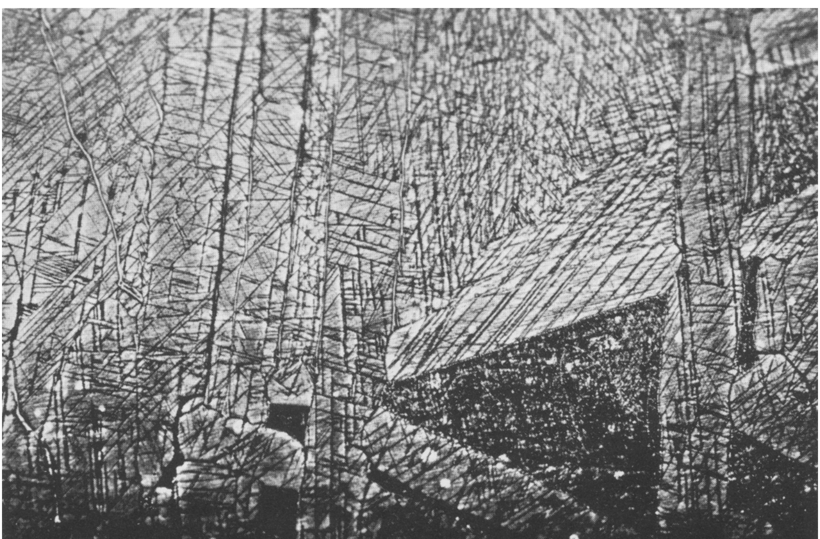


FIG. 8.

L. J. SPENCER: METEORIC IRON OF PIEDADE DO BAGRE
MINAS GERAES, BRAZIL.