CONCERNING THE ORIGIN OF THE METAL IN METEORITES

By George P. Merrill
Head Curator of Geology, United States National Museum

The peculiar relationship existing between the metallic and silicate portions of a stony meteorite has been noted by several, and particularly the earlier workers. The present writer has on more than one occasion (noted later) made reference to it and also to the work of others. In discussing the matter among his contemporaries he finds, however, a considerable difference of opinion such as has led to the preparation of this paper in which he reviews these opinions and gives the results of his own observations.

In his discussion of the composition of the Lodran meteoric stone, Tschermak wrote [1] as long ago as 1870:

> Das Nicheleisen und der Magnetkies müssen später fest geworden sein als die übrigen Mineralien, und ihre Bildung dürfte zu gleicher Zeit mit jenen Veränderungen vor sich gegangen sein, welche der Olivin erlitten zu haben scheint.

With reference to the metallic constituent of the Homestead meteorite, Gumbel wrote, five years later:

> Noch häufinger erscheinen die aus Meteoreisen bestehenden körnchen der Gesteinmasse in meist zackigen, winkelig gebogenen, oft in feine Spitzen auslaufenden Klumpchen beigemengt, welche so innig an die nicht metalischen Theile sich ausschmiegen als ob das Eisen erst zuletzt etwa durch Reduction an der Stelle ausgeschieden worden wäre, wo es sich vorfindet.[2]

So far as I am aware these are the first suggestions of their kind, though they seem to have attracted little attention from other workers.

Before entering upon the discussion of these and other views yet to be noted, the following illustrations of actual conditions are given.

Figure 1, Plate 1, is from a photomicrograph of the chondritic stone from Anthony, Kans., recently described.[3] The dark center (1) is troilite; the lighter border (2) metal, which forms, as it were, a

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[1] Sitzbericht d. k. Akad. der Wiss. II Abtheil., 1870.

[2] Sitzbericht München Akad. der Wiss., vol. 5, 1875, p. 325.

[3] Proc. Nat. Acad. of Sciences, vol. 10, p. 306.

binding or cementing constituent holding the fragments together. The manner in which the metal projects into the interstices of the silicates is to be noted. Instances of this nature are common in many chondritic meteorites, both crystalline and otherwise.

Figure 2 of the same plate is that of a fragment of a dark chondritic stone embedded with others of a quite different nature, as described in my paper entitled "The Cumberland Falls, Kentucky, Meteorite," published in 1920.[4]

Attention was there particularly called to the fine threadlike forms sometimes assumed by the metal, (1) white in the figure. These veinlets or stringers vary from 1 or 2 millimeters in thickness to mere films of only microscopic dimensions, and divide and subdivide repeatedly, their ramifications reaching out and completely surrounding or penetrating into the silicates along cleavage or fracture lines.

A noticeable layer of metal, too, lies along the boundary line of the fragment, a condition which it was thought might indicate a deposition of the material since the consolidation of the stone in its present brecciated form.

Figure 3 is that of a slice of a pallasite belonging to the Rökicky group, found at Admire, Kans., and described in 1902.[5]

The dark areas are olivine, the white (1), nickel-iron with scattered particles of schreibersite (2), and troilite (3). The feature of importance in the present instance, is the angular character of the olivines. It is to be noted that they are not products of crystallization, in situ. They are rather fragments, in some cases mere splinters, as sharply angular as so much shattered glass. These are firmly embedded in the metal with no signs of corrosion or alteration indicative of heat or moisture. The same is true of the Eagle station meteorite and others of its class.

Figure 4 is from the Four Corners meteorite. This consists largely of a coarsely granular aggregate of metal inclosing fragments of disintegration from a fine granular pyroxenic rock, now in some cases reduced to mere sand. The metal, as shown at (1) completely incloses these silicate particles (2) and in places penetrates slightly into their interiors. The stony fragments are all unchanged, with no sign of corrosion by heat or otherwise, even when in the condition of finest sand, no slag nor glass; the contact is as sharp and free from signs of alteration as though the admixture had taken place when cold.

The above illustrations are sufficient, it is thought, to show that, so far as chondritic meteorites and those of the Rökicky and Four Corners type are concerned, the metal is the last constituent to congeal, and that it is probably wholly of secondary origin. The ques-

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[4] Proc. U. S. Nat. Mus., vol. 57, 1920, pp. 97–105.

[5] Idem, vol. 24, 1902, pp. 907–913.

tions for consideration are, then, (1) what is the source of the material and its manner of deposition and (2) will the same explanation apply to the pallasites, particularly those of the Rökicky group which seems applicable to the stony forms.

Nordenskiold in his description in 1879 [6] of the Stalldalen meteorite expressed himself in agreement with the writers above quoted in the view that the metal is the latest formed of the constituents and suggested the possibility of its preterrestrial origin through the reduction of some ferruginous silicate. To quote his own words:

> I afseende a den nu ifrägavarande gruppen är det af dessa meteoriters mikroskopiska struktur tydligt, att det metalliska jernet utgör dessa meteorstenars yngsta beståndsdel och att det saledes uppkommit genom reduktion af de jernhaltiga silikaterna.

This would seem to be essentially in agreement with Daubree [7] who as a result of experimental work inclined to the view that the metal was due to the reduction of a highly ferriferous olivine in an atmosphere of hydrogen, with the simultaneous production of an iron magnesium silicate (enstatite). An exception was taken to this view by Fletcher,[8] who pointed out the existence of pallasites like that of Krasnojarsk, rich in both iron and olivine but quite lacking in enstatite.

Meunier in his article on Meteorites [9] has discussed the matter in considerable detail. He wrote:

> Les manipulations auxquelles les fers météoriques out été sourmis par divers experimentateurs n'ont par tardé à montrer que ces roches cosmiques sont profondement desorgansees par le fait d'une fusion pure et simple, * * *. Il etait donc necessaire de rechercher une méthode propre a fournir, autrement que par fusion, des alliages de fer et de nickel semblables a ceux des météorites.

And further:

> Le protochlorine de fer étant decomposé au rouge par l'hydrogene, on peut admettre que ce qu'on en trouve a simplement échappé à le décomposition et represénte la combination même d'on la fer a été tiré pour prendre l'état métallique.

The suggestion of Jetrofeioff and Latschinoff [10] in 1888 to the effect that the meteorite consists of an isomorphous mixture of the

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[6] Geol. Froeningen Stockholm Forhandlinger, 1878–79, p. 60.

[7] Geol. Experimentale, 1879, pp. 517, 520.

[8] Introduction to the Study of Meteorites, 1908, p. 33.

[9] Encyclopedie Chimique, 1884, p. 322.

[10] Es ergeibt sich auch, dass der Meteorit einem isomorphen Gemenge der Silicate Mg_2 SiO_4 und Fe_2 SiO_4 naher steht, als selbst der Olivin von Fogo. Man gelangt hiernach unwillkührlich zur Voraussetzung, dass der Meteorit ursprünglich ein Olivinmagma darstellte, welches später unter Einwirkung reducirender Körper, wie Wasserstoff der Kohlenoxyd oder Kohlenwasserstoffen unter Abschiedung von metallischen Eisen aus dem Magma und gleichzeitiger Abscheidung von Kohlenstoff aus der reducirenden Verbindung, sich differenzirte. Die freigewordene Kieselsäure ging auf Bildung von Augit. Diese differenz wird zugleich mit der Erhärtung der Hauptmasse des Olivin stattgefunden haben und haben sich daher kohlige Substanz und Nickeleisen hauptsächlich an den Umrandungen der Körner abgesetzt. Es dürfte so auch ras Vorhandensein der Eingangs erwähnten ebenen Aussenflächen des Steines erklärlich werden. (Der Meteorit von Nowo-Urei, M. Jerofeieff und P. Latschinoff in St. Petersburg, 1888.)

silicates Mg_2SiO_4 and Fe_2SiO_4 which under the reducing action of hydrogen, carbon[11] monoxide, or hydrocarbons have been reduced and differentiated with the separation of the metal and silicate minerals, however applicable in cases of direct crystallization from a molten magma, are scarcely so in the cases of the clastic rocks here under discussion and may be passed over. Moreover the suggestion of Fletcher already quoted, still holds good.

Ideas expressed by Dr. W. Wahl with reference to brecciated structures such as are shown by the Deesa and some other irons are of interest. He says:

> Wie aus der vorhergehenden Beschreibung ersichtlich ist, hat der Silikatanteil unbehindert von dem Metallteile des Gesteins krystallisiert; er hat sich wie innerhalb der Hohlräume eines Schwammes, dessen Gerüst der metallische Anteil war, verfestigt. Aber zur Zeit der Verfestigung der zwischenliegenden Silikatmasse muss das Metallgerüst noch selbst flüssig gewesen sein, denn die Silikate sind dem Metall gegenüber scharf idiomorph ausgebildet und hierdurch erhielten die Eisenteile ihre zackige Begrenzung. Es hat folglich das Magma, aus dem der Siderolith hervorging, vor dem Erstarren aus einem inhomogenen Gemische zweir Flüssigkeiten bestanden, die sich noch nicht entmischt hatten und von denen die eine aus den Plagioklas- und Pyroxensilikaten, die andere aus flüssigem Metall und Metallverbindungen (gediegen Eisen mit Cohenit und etwas Schreibersit? Magnetkies und etwas Magnetit?) zusammengesetzt waren. Die verschiedenen Proportionen zwischen dem metallischen Anteil und silikatanteil erklären sich dann durch eine teilweise Entmischung und durch ein Zerbrechen von schon auskrystallisierten Silikat-partien sowie Hineingeraten derselben in den noch flüssigen metallischen Anteil. In dieser Weise entstand möglicherweise das von Daubrée beschriebene Stück. [i. e., the Deesa Iron.]

The inference here is that the metal is in a condition of fluidity such as could be imparted only by heat. If so the matter is certainly open for further discussion. That it is possible the meteorites of the pallasite group may result from the direct cooling of two immiscible liquids, the metal, owing to its higher fusibility, cooling first and inclosing the gradually solidifying silicate drops, need not here be argued. That, however, the brecciated structure shown in Figures 3 and 4, or the deposits of metal in the interstices of the silicates as in 1 and 2 could thus originate is doubtful.

There is in this connection a view relative to these metal-silicate breccias, belonging to the Rökicky group, that may be worthy of consideration, and in which the question of the origin of the metal itself is not necessarily involved. Is it not possible that this brecciation may be due to pressure acting upon the mass of a normal pallasite after solidification rather than when the metal is in a fluid condition, as Doctor Wahl's paper implies? The metal, being the more plastic, would flow, while the silicates would be crushed. In this

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[11] The possible instrumentality of carbon as a reducing agent was also considered by Nordenskiold in the paper already noted and the idea dismissed as improbable.

way the slight amount of displacement sometimes shown by the silicate particles (fig. 3, plate 1, and upper plate 2) could be accounted for. It may be questionable, however, if under such conditions the original tripartite character of the metallic alloys would not be destroyed or disarranged. In the case of the Admire meteorite the metal gives no visible indications of any such movement.

It would seem scarcely necessary to consider the possibility of the iron as having been introduced or injected in the ordinary condition of molten fluidity. The melting point of pure iron is, as given, 1,530° C.; that of nickel 1,452° C. The pyroxenes, on the other hand, fuse at approximately 1,400° C., and olivines at 1310°–1430° C. (according to Doelter). Apparently it could not then be a question of simple dry fusion as the silicates would be reduced to the condition of slag—"profondement désorganées," as Meunier expressed it. Existing conditions can be explained, moreover, without assuming that the metal has at any time been in a condition of fusion. Direct reduction of an ore as practiced in the early days of iron smelting, or as still practiced in the well-known Catalan process, results in the production at temperatures not above 700° or 800° C. of a spongy or pasty mass of metal. It is easy to conceive that such material, commingled with rock fragments and subjected for sufficient time to a moderate pressure, might give rise to the structures described, particularly such as shown by the Four Corners iron.[12]

Another feature which may have a bearing upon the subject is this. Meteoric irons almost invariably partake of the nature of the so-called "wrought iron," in that they are soft and malleable. Reports to the contrary can be accounted for only on the supposition that the material selected was a mixture. Some irons, like that of New Baltimore, Pennsylvania, can be hammered down when cold; others are more brittle but still malleable.[13] Fused in an ordinary gas furnace in the laboratory these soft irons yield a bead no longer malleable but hard and brittle like ordinary cast iron and with an entirely different microscopic structure.[14] (See pl. 3.)

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[12] I am indebted to Prof. Albert Sauveur, of the Harvard Engineering School, to whom I sent a photograph of the slice shown in fig. 4, pl. 1, for the following suggestion:

"The structure to which you call my attention recalls somewhat that of wrought iron, in which we also find particles of silicates embedded in an iron matrix. This results from the fact, as you undoubtedly know, that in the manufacture of wrought iron the reduced metal is not melted, but remains pasty, retaining some of the liquid silicates or slag very much as a sponge retains water. Also, just as further cooling of the sponge results in particles of ice within the sponge, so further cooling of the wrought iron results in particles of silicates within the iron matrix. I wonder whether such a process might have been at work in this case? It would, of course, imply reduction of an iron oxide or of an iron salt at such low temperature that the reduced iron remains below its melting point."

[13] The United States National Museum collections contain two knife blades 7 and 14 inches long hammered out of the Coahuila and Nejed irons, respectively, by our local blacksmith in a small charcoal forge. Though easily shaped they could not be tempered.

[14] These experiments have not been carried far enough nor with sufficient refinement to allow the drawing of safe conclusions other than those mentioned.

All the evidence at present available, as I interpret it, points to the origin of the metal as introduced at a temperature lower than that of the melting point of the silicates. As above noted, a reduction of a ferriferous silicate either through the aid of carbon or hydrogen is ruled out of consideration by the complete absence of any secondary or residual products. Of all other known meteoric constituents the ferrous chloride, lawrencite, would seem to best meet the apparent necessities of the case. It is found in varying though small proportions an almost universal constituent, and it is permissible to imagine its one-time presence in vastly greater quantities. It is reduced according to Meunier and, as already noted, at a temperature not exceeding 400° C. (750° F.) in an atmosphere of hydrogen. It would seem, then, not too much to assume that this mineral was, as Meunier conceived, the original source, and the fractional amount of chlorine found in nearly all meteorites, stony as well as metallic, but an unreduced residue. And further, it is possible to conceive of a hot mass of commingled rock fragments and ferrous chloride, in which the latter is being reduced to the condition of a metallic paste in which the fragments become engulfed as in Figures 3 and 4, Plate 1, or simply cemented as in Figure 1. It must not be forgotten that H. C. Sorby as long ago as 1864 suggested that the metallic constituents of meteorites were introduced into the interstices of the silicates in a state of vapor.

Such a conception would seem to be particularly applicable to the metal in a stone like that of Estherville, Iowa, in which the iron is in slag or spongelike masses not always closely compacted in all its parts with the silicates.[15] (Fig. 2, lower.) Tschermak's observation on this is of interest. He wrote:[16]

> Das Eisen verhält sich oft so, als ob es die letze Bildung wäre eine impregnation welche die zum Theil krystallinische, zum Theil Tuffartige masse durchdrungen hat.

Meteorites are unmistakably volcanic products.

It is fair then to consider the original chloride itself a product of volcanic emanations as in terrestrial volcanoes. There would, in result, be this difference, however: The chloride of terrestrial volcanoes exposed to an oxygen-rich atmosphere manifests itself almost at once as an oxide. In a heated atmosphere of hydrogen or other reducing gases such as it is possible to imagine exists at the fountain source of meteorites a contrary result would be effected and the iron appear in metallic form.

This source would then be comparable to that of the metal in the basalt of Bühl bei Cassel, Germany, as described by Eitel in his re-

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[15] See Notes on the Meteorite of Estherville, etc., Proc. U. S. Nat. Museum, vol. 58, 1920, pp. 22–24.

[16] Sitz. Kais. Akad. Wien, vol. 88, 1883, p. 253.

view of the Researches of F. Flade.[17] The metal in this case, it will be remembered, is shown to have been reduced from magnetic pyrites. That, however, in the meteorite it was not derived from the sulphide is shown apparently by the fact that the latter is the later formed mineral of the two.

Objection to such a possible source might be raised on account of the large amount of chloride demanded to produce the 10 per cent and upward of metal contained by the average stone. (Lawrencite, $FeCl_2$=Fe 40.1 per cent, Cl 55.9 per cent.) Could it be allowed, however, it would be an aid in accounting for the enormous quantities of sodium chloride in seawater and locked up in the rocks of the earth's crust.

EXPLANATION OF PLATES

PLATE 1

FIG. 1. Anthony (Kans.) stone. (1) Troilite; (2) nickel-iron. Dark, nearly black areas, silicates.

2. Dark inclosure in Cumberland Falls stone. Small white dots and stringers (1) are metal. Dark areas, silicates.

3. Admire (Kans.), pallasite. (1) Nickel-iron, (2) schreibersite, (3) troilite. Dark areas, olivine.

4. Four Corners (N. Mex.), iron. (1) Nickel-iron, (2) granular admixture of silicates and metal.

PLATE 2

UPPER. Polished slice of Admire pallasite, showing clastic structure and shattered condition of olivines. Natural size.

LOWER. Polished slice of Estherville mesosiderite, showing shrinkage cavities black, metal white, silicates dark gray. Enlarged about four diameters. 1 Silicate; 2 metal; 3 cavities.

PLATE 3

UPPER. Structure of Mount Joy meteroric iron—a coarse kamacite octahedrite—after fusion.

LOWER. Structure of Canon Diablo iron—a coarse octahedrite—after fusion.

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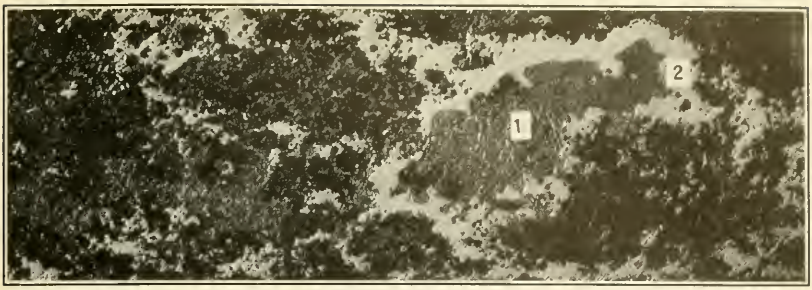
[17] Das Bühleisen hat alle Eigenschaften eines extrem niedrig gekohlten Schmiedeeisen, is infolge dessen ausserordentlich zähe und dehnbar, aber nur schwer mit der Gesteinschneidemaschine oder mit der Säge zuzerkleinern. (Senkenbergia, vol. 2, Heft 5, Aug. 15, 1920.)



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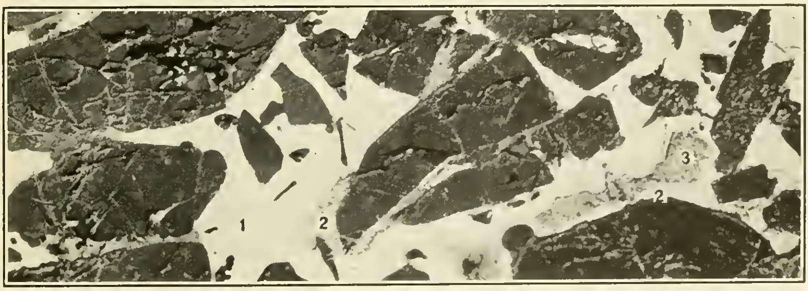

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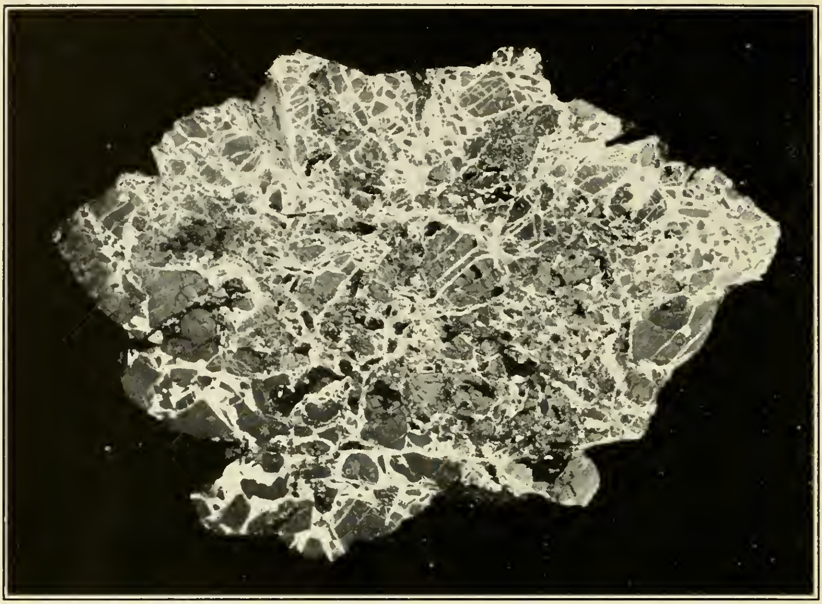
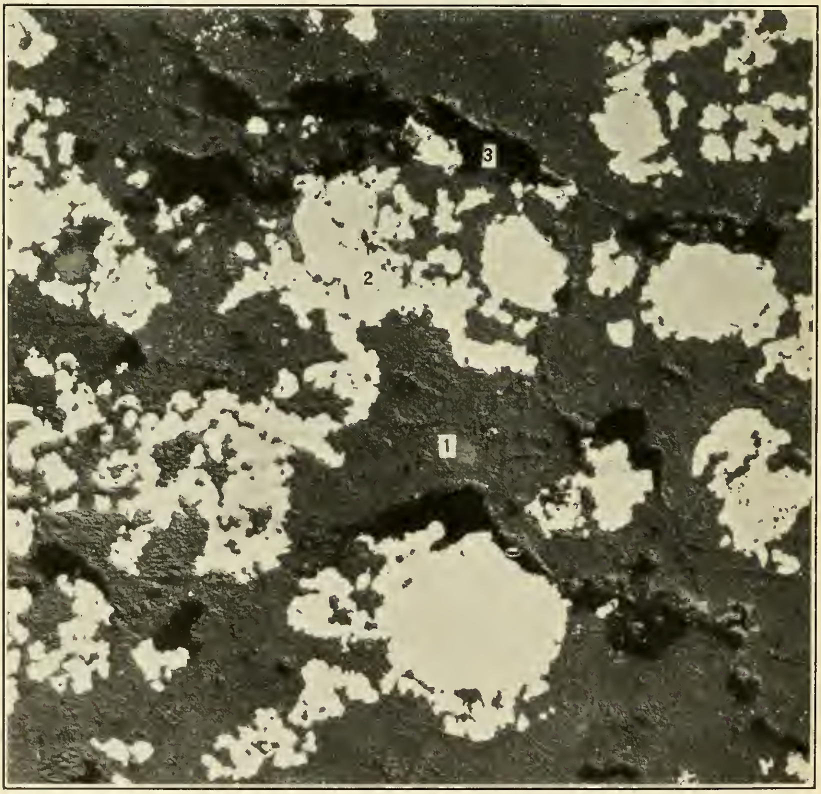
ORIGIN OF METAL IN METEORITES

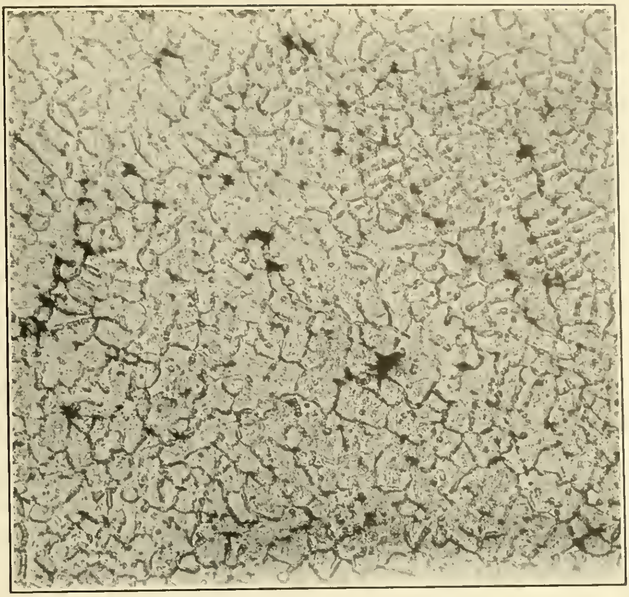
FOR EXPLANATION OF PLATE SEE PAGE 7

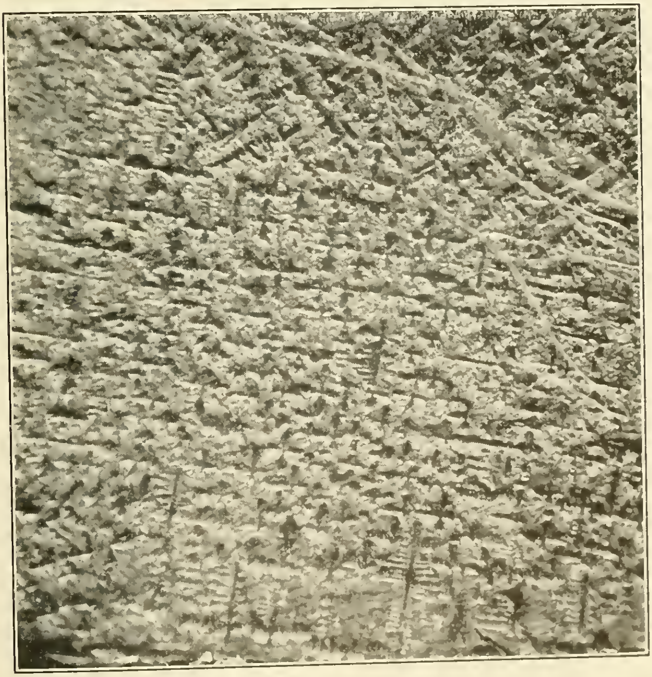




ORIGIN OF METAL IN METEORITES

FOR EXPLANATION OF PLATE SEE PAGE 7





ORIGIN OF METAL IN METEORITES

FOR EXPLANATION OF PLATE SEE PAGE 7