MINERALOGICAL MAGAZINE, JUNE 1972, VOL. 38, PP. 736–55

A metallographic study of some iron meteorites of high nickel content

H. J. AXON *and* P. L. SMITH
Metallurgy Department, University of Manchester, Manchester M13 9PL

SUMMARY. A metallographic investigation of macro- and microstructure, supported in some instances by microprobe examination, has been made on a number of nickel-rich iron meteorites from the British Museum Collection. Monahans, Wiley, Cowra, and Deep Springs are considered together as plessitic irons rather than ataxites, whilst Morradal shows an unusual and coarse plessitic structure that has been altered by pre-terrestrial shock and reheating. Cape of Good Hope, Hoba, Tlacotepec, and Chinga show chemical and structural similarities and are discussed together, as are Weaver Mountains, Klondike, and Warburton Range. Meteorites considered separately include Kokomo, Piñon, Shingle Springs, South Byron, San Cristobal, Lime Creek, and Santa Catharina. Particular attention is paid to the presence of sulphides and of phosphorus-containing phases and their influence on the formation of the macro- and microstructure of these meteorites. Patches of oriented sheen form a macroscopic feature of the Cape of Good Hope group of irons and this effect is considered in relation to details of the microstructure. Attention is drawn to the fact that in Cowra, Piñon, Weaver Mountains, South Byron, and Morradal the troilite appears to have been remelted and dispersed by a shock event that operated at a temperature sufficiently high to allow obvious shock damage to anneal out of the metal phases.

THROUGH the courtesy of Dr. Max Hey and The Keeper of Minerals at the British Museum (Natural History) we have been able to make a metallographic examination of a number of nickel-rich irons in the British Museum Collection of Meteorites. In addition a sample of South Byron from the Field Museum, Chicago, was kindly placed at our disposal by Dr. E. Olsen. In Table I we have collected for each meteorite under study a selection of the analytical data that is available, together with the museum catalogue number, the weight in g of the specimen that was studied in the present work and an indication of the approximate number of square centimetres of surface that we examined metallographically. Table I also includes a brief description of the macrostructure of each specimen as it appeared to the unaided eye after etching for microscopic examination in 2 % Nital. In a number of cases it was possible to make microprobe investigations, using an A.E.I. S.E.M.2. instrument.

It is necessary to give a brief explanation of the composition data used in Table I. Most of the meteorites in the present study have been analysed for nickel by several reliable analysts and the values in Table I are weighted averages of a number of determinations that agree quite closely. Where only a single determination is used the result is placed in brackets and corresponds to the value quoted in Hey's (1966) Catalogue of Meteorites. Discussion with Dr. Hey leads us to believe that these values are likely to be reliable and the presence of brackets must not be taken as suggesting otherwise. The older literature on the meteorites of North America was collected by

TABLE I. *Analytical and descriptive information for the meteorites in the present study (in the final column coarse and fine structures refer to centimetre and millimetre scales respectively)*

	Chemical analysis			Material studied			Macrostructure as seen by unaided eye	
	% Ni	ppm Ga	ppm Ge	B.M. Catalogue number	wt. g.	Approx Area cm²	Spindles of kamacite	Over-all macrostructure O–S indicates oriented sheen
Monahans	10·6	9	127	1959, 910	19	5	rare	frosty pattern of interlaced needles
Wiley	11·5	39	114	1959, 914	31	10	profuse	mottled in blotches on a coarse scale
Cowra	~13	74	12	68205	78	30	v. profuse	mottled on a very coarse scale
Deep Springs	13·7	0·42	0·108	84437	10	4	v. rare	structureless—matt
Kokomo	(15·7)			47240	7½	3		O–S in parallel bands: matt
Piñon	~16	2·32	1·15	1959, 911	37	16	profuse	O–S in streaks and patches:
Cape of Good Hope	16·2	0·19	0·04	46975	18	4		O–S in parallel bands: structureless—matt
Hoba	16·3	0·20	0·032	1930, 976	5	3		O–S Spencer (1930, 1932): structureless—matt
Tlacotepec	16·5	0·18	0·03	1959, 913	112	9		O–S visible on larger sections: structureless—matt
Chinga	16·7	0·18	<0·18	1956, 317	154	5		shear zone: structureless—matt
Shingle Springs	(16·7)			51634	75	15	profuse	O–S in irregular patches: dull—finely mottled
Weaver Mountains	18·1	0·21	0·06	86946	155	10	profuse	dull—finely mottled
Klondike	18·2	0·3	0·054	1919, 43	23	3½	present	Thermally diffused—finely mottled
Warburton Range	18·2	0·3	0·05	1966, 483	29	5	profuse	dull—finely mottled
South Byron	~18·2	19·6	45	(Me 2552)	12	3	(microscopic)	O–S in patches: iridescent
Morradal	19·5	46·3	119	1924, 146	92½	18	profuse	massive sulphides: dull—finely mottled
San Cristobal	(25·6)	11·9	25·8	86763	58½	4½	occasional	massive sulphide: bright—polycrystalline
Lime Creek	(29·9)	15·8	29	35964	15½	4½		bright but corroded
Santa Catharina	33·6	5·28	9·07	52283	36	5½		bright but cracked

Farrington (1915) and re-analyses have recently been made by either Moore, Lewis, and Nava (1969) or by Wasson (1967), Wasson and Kimberlin (1967), or Wasson and Schaudy (1971). For Warburton Range the nickel value is taken from the paper by McCall and Wiik (1966) and the gallium and germanium values were reported to us privately by Dr. Max Hey. Excellent photomicrographs, usually with a Picral etch, have been given by Perry (1944) for all of the meteorites in the present study except Piñon, Chinga, Weaver Mountains, Warburton Range, and South Byron. In general Perry's study was restricted to microscopic examination of metallic areas that were free of massive non-metallic inclusions and in general, when allowance is made for the different etching response to Picral and to Nital, our own observations agree with his. Perry's sample of San Cristobal shows a variety of lamellar and acicular structures that were not encountered in B.M. 86763 and it appears that in addition to being polycrystalline San Cristobal has a variety of structures at different locations.

The classification of iron meteorites has been discussed in detail by Goldstein (1969) in terms of nickel content, cooling rate, and trace element chemistry, particularly with reference to gallium and germanium content.

In the present work an attempt is made to extend Perry's (1944) observations to include macrostructure and the content of non-metallic inclusions such as sulphides, phosphides, phosphates, and carbides.

General macrostructures. In Table I the column marked 'Spindles of kamacite' records the presence of such spindles when they can be easily seen with the unaided eye. However, they are also present in minute quantities, typically of the order ten to the square centimetre, in Chinga, Tlacotepec, Hoba, Cape of Good Hope, and Kokomo and in these meteorites may be detected by careful microscopic examination. By contrast there is a profusion of microscopically visible spindles in South Byron that are not visible to the unaided eye. The dimensions of kamacite spindles in the different meteorites are recorded in Tables II and III.

The last column of Table I gives a description of the over-all macrostructure. Tlacotepec and a number of other meteorites that have essentially no macroscopically visible kamacite spindles show a structureless matt surface when etched. By contrast most of the meteorites with 18 % nickel show a finely mottled appearance with visible spindles of kamacite in profusion. The pattern of mottling in Wiley and Cowra is very much more coarse than in the 18 % nickel ataxites and these two meteorites should be discussed separately from the true nickel-rich ataxites.

In Table I the abbreviation O–S is used to indicate the presence of an oriented sheen in geometrically outlined areas on the otherwise structureless matt surface of section. Spencer (1932) drew attention to the effect in Hoba, where an apparently sharp line of demarcation between two areas of different sheen produced the impression of a twin in the parent taenite crystal. Seemingly parallel bands that have the appearance of twin bands are to be found well developed on Cape of Good Hope and less obviously on Kokomo. No areas of differently oriented sheen were visible on the small sample of Tlacotepec that was used in the present study but larger macroetched surfaces do display occasional patches that are bounded by straight rather than curved lines of demarcation and this again produces the impression of annealing twins in the parent taenite. In Piñon there is a profusion of small geometrical patches and at least three, differently oriented, interwoven and less sharply bounded systems of streaks. The origin of the oriented sheen effect in ataxites will be considered later in relation to studies of the microstructure.

Meteorites containing less than 14 % nickel. In Table II we have collected data concerning Monahans, Wiley, Cowra, and Deep Springs. Goldstein (1969) has classed Monahans and Wiley as plessitic octahedrites on the classification of Buchwald and Munck (1965) according to which plessitic octahedrites have an octahedral development of thin kamacite *spindles*, in contrast to the finest octahedrites where the kamacite is of approximately the same thickness but forms continuous bands.

In Wiley and Cowra there is a profusion of macroscopically visible spindles of kamacite all of which are associated with easily visible inclusions of schreibersite, troilite, and phosphate in Wiley and of schreibersite and, very occasionally, minute patches of remelted troilite in Cowra. By contrast Monahans and Deep Springs are exceptionally free of non-metallic inclusions and in these meteorites kamacite spindles are rare and free from inclusions.

In many respects the microstructure of Cowra is most closely similar to that encountered in the finest octahedrites of the Carlton type. The primary spindles of kamacite all contain schreibersite inclusions and the fields of residual taenite that lie between the kamacite spindles have bordering rims of undecomposed nickel-rich taenite with a range of martensitic, tempered martensite, and $\alpha\gamma$ bainitic structures in their central regions. The over-all appearance of the martensitic products in Cowra is suggestive of a significant carbon content and there is the occasional suggestion of a carbide phase within some areas of fine plessite. The macrostructure of Cowra is mottled on a coarse scale. The matt areas occur as patches, at the centres of which are found massive (2·5 × 0·4 mm) phosphide bodies swathed by kamacite to a thickness of about 0·5 mm. Within the matt areas the microstructure shows fine martensitic plessite with only a few small spindles of kamacite. The bright areas form a continuous background to the patches of matt structure and within the bright areas the microstructure is a micro-octahedral array of distinct kamacite spindles, each of which has an inclusion of schreibersite, together with an infilling of martensitic–bainitic cored plessite. Thus in Cowra the mottled effect in the macrostructure arises from an uneven distribution of kamacite spindles and this distribution, in turn, appears to follow the distribution of phosphides in the parent taenite. The suggestion that the phosphides that reside at the centres of matt patches were already present in the parent taenite is supported by the observation within the plessite of a single, large, straight-edged crystal of schreibersite without any swathing kamacite. This suggests that large phosphides exist within the parent taenite as well-shaped crystals that grow and change shape when swathing kamacite is formed around them.

The macrostructure of Cowra is dominated by a huge finger of schreibersite 20 mm long by 2 mm wide and surrounded by swathing kamacite. This massive schreibersite is badly cracked and is associated with small remelted nodules of troilite–daubréelite eutectic, which are not visible to the unaided eye but may be detected at ×100 magnification. In the area immediately surrounding the finger of swathing kamacite there is a matt structure, entirely analogous to the situation that arises in the matt patches of the blotch-mottled structure. So far as can be determined the micro-octahedral spindles are similarly oriented on either side of this finger. Hence it appears that this very massive schreibersite is *not* located at a twin or grain boundary of the parent taenite.

Microscopic examination reveals a zone of heat alteration below the outer surface of Cowra and occasional signs of mechanical deformation may be detected at one location near the outer surface. Unfortunately it is not possible to be certain that this deformation was produced pre-terrestrially but the presence of remelted troilite in association with the heavily cracked schreibersite suggests a history of pre-terrestrial shock at some stage of the meteorite's history.

In the present work it was not possible to make microprobe investigations, and there may be local variations of nickel content. Wasson and Schaudy (1971) reported a nickel content of 12·94 % as against the value of 13·72 % that was obtained earlier by Lovering, Nichiporuk, Chodos, and Brown (1957). In view of this uncertainty in the bulk analysis a value of approximately 13 % has been recorded in Table I. Attention should be drawn to the fact that the holding of Cowra in the American Museum of Natural History, New York, consists of a slice that is essentially similar to B.M. 68205 and, in addition, a nodule of 480 g that appears to have a completely remelted, dendritic, structure.

In Wiley one macroscopic lath of troilite was encountered with dimensions 1·5 ×0·2 mm but it had been so badly chipped in earlier stages of preparation that it was not possible to determine whether daubréelite was present or whether the troilite was in a granular or twinned condition. However, it did not appear to be extensively remelted. The macrostructure has a mottled appearance, similar to Cowra but on a less coarse scale and microscopic examination reveals that the mottling in both meteorites arises from essentially the same cause, except that the total content and size of the phosphides is less in Wiley, but by contrast there are large numbers of phosphate and troilite inclusions. Of the 191 macroscopically visible areas of kamacite, which, in the present specimen, lie at the centres of fine-grained, dull mottled areas, 84 were found to have phosphate and 12 to have troilite inclusions with or without phosphide and a further 57 had phosphide only. When it is remembered that an arbitrary plane of section will not necessarily reveal all the inclusions in a given piece of kamacite it appears that the macrostructure of Wiley is dominated by the precipitation of kamacite (and perhaps phosphide) at nucleii of phosphate and troilite that existed in the parent taenite. The matrix immediately adjacent to this primary kamacite decomposed to a fine grained duplex structure of kamacite and taenite, whereas at locations well away from phosphate and troilite inclusions the parent taenite decomposed on a larger scale. However in Wiley, as in the other two meteorites in Table II, the mode of taenite decomposition is by the nucleation and growth of kamacite platelets on a microscopic scale, giving rise to a plessite with a microscopic Widmanstätten morphology rather than the martensitic form of Cowra.

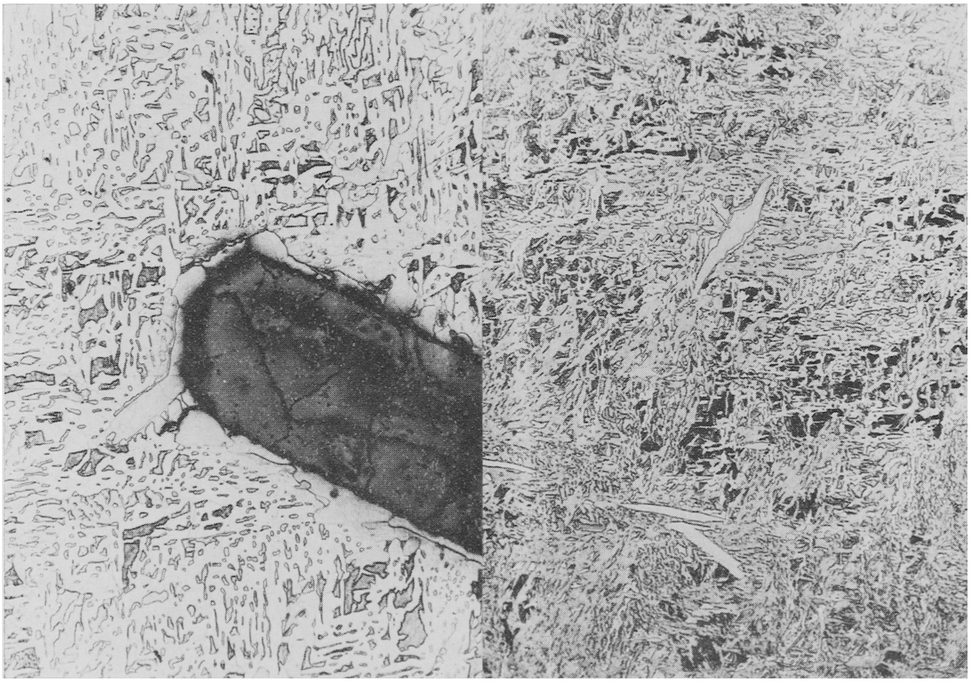
Thus the mottled macrostructure in Cowra and Wiley appears to be induced respectively by phosphide and by troilite–phosphate nucleii, which were present in the parent taenite. In both meteorites there is an octahedral array of kamacite spindles with phosphide inclusions and there is little doubt that in these meteorites the presence of phosphorus significantly influences the exsolution of kamacite.

For Monahans, Nininger and Nininger (1950) have given a photograph of the external form of the meteorite as it was discovered and have drawn attention to a fracture that divided the mass. Perry (1944) has observed macroscopic inclusions of troilite. In the present specimen a troilite crystal was observed but there was no macroscopically visible schreibersite. The macrostructure has occasional to rare spindles of kamacite, either isolated or in small clusters. On microscopic examination these rare kamacite spindles prove to be remarkably free from all forms of inclusion. The matrix between the spindles appears, on macroscopic viewing, to consist of an irregular basket-weave, or pattern of interlaced needles. The unaided eye cannot resolve any structure within the interlaced needles and the macrostructure of the matrix thus appears frosty. When this frosty matrix is examined at ×200 it reveals a microscopic pattern of kamacite bands that are either interleaved with ribbons of taenite or intermeshed with fields of fine plessite accordingly as the fine kamacite bands have either all grown parallel or have intergrown in more than one direction. The fine microscopic fields of plessite usually have borders of clear nickel-rich taenite with martensite or a fine α–γ aggregate as the interior structure. A small amount of microscopic schreibersite is associated with the kamacite. Thus, as is shown in figs. 1 and 2, the structure of the matrix in Monahans is a small-scale version of the Widmanstätten structure that characterizes the normal octahedrites but differs in that the scale of the kamacite–taenite aggregate is microscopic instead of being visible to the unaided eye.

In the macrostructure of conventional octahedrites the pattern of the Widmanstätten structure is usually continuous throughout the plane of section and is formed by the precipitation of kamacite equally on all the differently oriented octahedral planes of the parent taenite. By contrast the microscopic Widmanstätten structure that constitutes the matrix of Monahans does not show a uniform pattern over the whole plane of section. Instead it is broken up into differently patterned colonies, which manifest themselves in the macrostructure as the basket-weave of interlaced needles. Within each colony the orientation of the microscopic Widmanstätten pattern is uniform. Early formed colonies usually have an elongated or lenticular shape and within such elongated colonies the kamacite is usually precipitated on a single set of octahedral planes. Later formed colonies have a more equiaxed shape and show kamacite precipitation on two or more octahedral planes.

Deep Springs is one of the meteorites that undergo extensive corrosion. In the uncorroded metal of the present specimen a troilite–daubréelite inclusion was observed but no schreibersite was encountered. The macrostructure has rare spindles of kamacite, which prove to be remarkably free from all forms of inclusions. In these respects Deep Springs is very similar to Monahans despite the marked difference of trace element chemistry.

On macroscopic viewing the matrix of Deep Springs appears matt and structureless but when it is examined at ×400 it is revealed as a microscopic version of the conventional octahedrite structure with octahedrally oriented bands of kamacite and intermeshed fields of cored and partly decomposed residual taenite. No phosphide was encountered. When compared with Monahans the structure of Deep Springs is somewhat finer and the Widmanstätten pattern extends more continuously over the surface of section instead of being broken up into colonies.



FIGS. 1 and 2: FIG. 1 (left). Monahans. ×90. Nital etched. Cracked crystal of troilite with a thin swathing layer of kamacite. The metallic matrix is a microscopic version of the Widmanstätten structure consisting of kamacite and fields of cored or decomposed residual taenite. FIG. 2 (right). Monahans. ×60. Nital etched. Spindles of kamacite set in a background of fine Widmanstätten-type plessite which has grown in a series of interwoven colonies to produce in the macrostructure the impression of a basket-weave pattern.

Thus, by contrast with Wiley and Cowra, which are characterized by an abundance of sulphur- and phosphorus-rich inclusions at the centres of kamacite spindles, Monahans and Deep Springs are marked by an absence of all forms of inclusion and a great scarcity of macroscopically visible kamacite spindles. Although the structure is finer and more uniform in Deep Springs than in Monahans, in both meteorites the matrix has decomposed by a diffusion-controlled process to produce microscopically scaled versions of the Widmanstätten structure that is found macroscopically developed in conventional octahedrites.

TABLE II. *The plessitic irons. S, schreibersite; T, troilite; D, daubréelite; t, twinned; m, melted; C?, possible carbide*

Name	Macroscopic inclusions			Kamacite spindles		Microscopic inclusions in		Type of plessite (not including kamacite spindles)
	Sulphide		Phosphide Size mm	Major	Minor	Kamacite	Matrix	
	Type	Size mm						
Monahans	T	1·0×0·3	none	1·5×0·02 (isolated)	0·5×0·05 (clustered)	none	S	Microscopic Widmanstätten colonies of α plates with cored and martensitically decomposed fields of residual γ and small phosphide bodies†
Wiley	T	1·5×0·2	1·0×0·1	2·0×0·25	0·2×0·02	TS phosphate	none	Microscopic Widmanstätten α+phosphides. The residual γ is cored, giving microscopic fields of picture-frame, sorbitic, martensitic, γ decomposition product.
Cowra	none	—	20×2 2·5×0·4 0·2×0·1	2·6×0·7	0·8×0·1 0·3×0·01	S (Tm)	C?	γ fields with cored martensitic interiors similar to plessite in finest octahedrites.
Deep Springs	DT_t	0·8×0·1	none	—	0·5×0·1	none	none	Very fine version of Monahans structure without macroscopic colony structure.

† The pattern of the microscopic Widmanstätten structure is not of uniform orientation over the whole section, but varies from one macroscopic colony of interlaced needles to another. See Table 1, macrostructure.

TABLE III. *Structural details of the nickel-rich ataxites*

Name of meteorite	Macroscopic inclusions		Kamacite spindles			Plessite structure (not including α spindles when present)
	Sulphides	Phosphide	Amt.	Size mm	Inclusions	
Kokomo	no	no	vr	0·5×0·01	no	Unidirectional coarse lamella $\alpha\gamma$ 'pearlite' γ uniform. No phosphides
Piñon	Tm	yes	P	1×0·04 & 0·1×0·1	S	Interwoven fine $\alpha\gamma$ needles+'pearlite'+phosphide laths
Cape of Good Hope	DTgt	no	r	0·3×0·02	vrDTS	fine $\alpha\gamma$ needles (reheated: reticulated residual γ)
Hoba	no	no	r	0·4×0·03	½DT(S)	Interwoven fine $\alpha\gamma$ needles. Interior of residual γ decomposed to sorbite
Tlacotepec	no	no	r	0·4×0·05	½DT(S)	Interwoven fine $\alpha\gamma$ needles. Interior of residual γ decomposed to sorbite
Chinga	DTt	no	vr	0·5×0·03	vrD(S)	Interwoven fine $\alpha\gamma$+retained γ+some acicular product
Shingle Springs	T(?)	no	P	0·6×0·05	S	Martensite with occasional fine interwoven $\alpha\gamma$ needles +phosphide laths
Weaver Mountains	Tm	yes	P	0·3×0·04	OS	Interwoven fine $\alpha\gamma$ needles+acicular transformation product
Klondike	no	yes	P	0·2×0·01	S	reheated: reticulated
Warburton Range	no	yes	P	0·2×0·01	S(rDT)	Colonies of very fine $\alpha\gamma$ needles with acicular product
South Byron	Tm	no	P	0·1×0·005	S	Interwoven fine $\alpha\gamma$ needles+fine lamella 'pearlite'
Morradal	DTm	yes	O	1×0·02 & 0·2×0·01	OS	Large globules of uniform γ (Isothermal taenite—reheated)
San Cristobal	T	Swathing	O	0·1×0·01	SC	Polycrystal parent γ. Martensitic γ

gt, granulated; r, rare; vr, very rare; P, profuse; O, occasional; ½, signifies that approx. half the spindles show this effect.

Meteorites containing 14–20 % nickel. In Table I Cape of Good Hope, Hoba, Tlacotepec, and Chinga have very similar chemical compositions both as regards nickel content and also as regards gallium and germanium. Cape of Good Hope has a history of reheating by man (Hey, 1966) and the specimen B.M. 1956, 317 of Chinga shows well developed macroscopic zones of shear deformation, fig. 3. However, subject to these special effects the macro- and microstructures of all four meteorites appear very similar and it is reasonable to discuss them as a group. In Table I the macrostructure of these meteorites is recorded as structureless and matt with no significant macroscopically visible spindles of primary kamacite but with bands of oriented sheen. In Table III the plessite microstructure is recorded as a finely interwoven arrangement of α and γ needles, although in the case of Chinga some small areas of untransformed γ and some acicular transformation product also contribute to the over-all structure. The bands or fields of oriented sheen in these meteorites arise from variations in the direction of the oriented pattern of the needles of α and γ transformation product that constitutes the metallic matrix. In some areas the transformation product is essentially unidirectional whereas in other areas it is interwoven, as is shown in fig. 4. At higher powers, under oil immersion the $\alpha\gamma$ transformation product appears to have the general form that is sketched in fig. 5, where subsequent to the very small and rare macroscopic spindles of kamacite that appear to have been nucleated on minute sulphide particles, the early stage of decomposition of the taenite matrix takes the form of long, slender, fascicular needles of kamacite in which the subordinate needles are marked out by thin elongated ribbons of residual γ. The structure of these bundles of needles is analogous to the structure of upper bainite in the iron–carbon system and they may well have been produced by a bainitic process. Certainly the diffusion of nickel is an important effect during the production of the fascicular needles, since there is a rim of undecomposed nickel-enriched taenite around their outer edges. The unenriched residual taenite located at some distance from the needles of α, has undergone secondary decomposition to

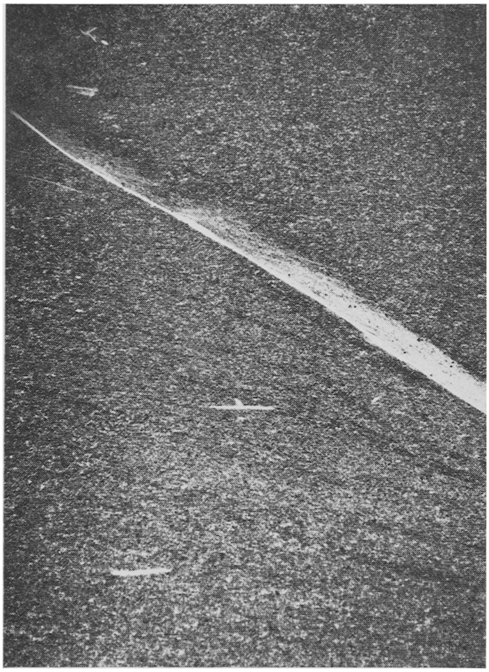
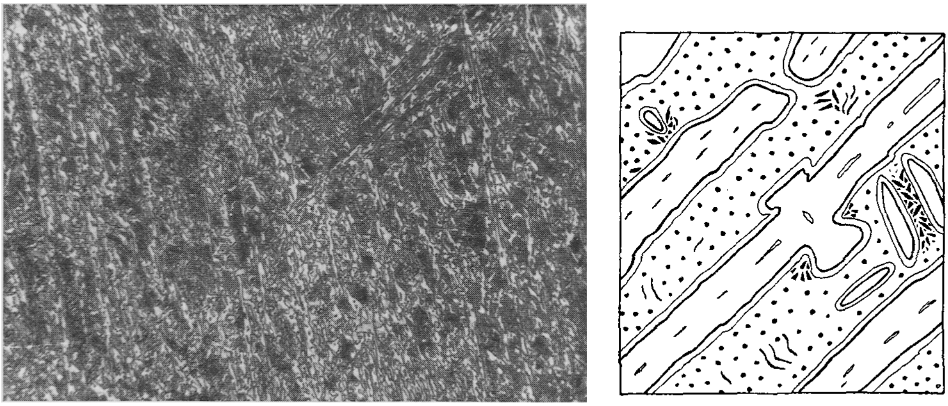


FIG. 3. Chinga. Nital etched. Macrostructure ×8. Showing deformation in the metal and a pronounced white band of intense shear deformation within which the original microstructure has been completely destroyed. This photograph is near to the edge of the prepared surface of section and the dark area in one corner arises because of the bevel at the edge of the specimen. The two small white streaks are kamacite spindles.

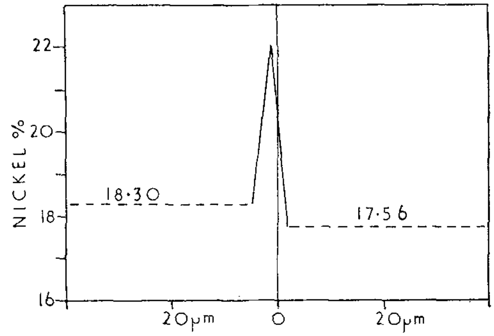
produce a fine globular (sorbitic) arrangement of α and γ with some lamellar and a small amount of acicular transformation product. The structure in Cape of Good Hope is similar except that it is diffused by terrestrial reheating. In Chinga the transformation product is somewhat finer than in Hoba and there are indications of patches of retained γ and larger quantities of acicular transformation product. The Chinga meteorite also shows well-developed macroscopic shear deformation and shock-induced polymorphism in the kamacite spindles, such as is consistent with a crater-forming event when Chinga hit the surface of the earth. The troilite in Chinga is twinned but not shock melted. Troilite is also twinned and granulated in Cape of Good Hope, which has been subject to terrestrial reheating, but appears unaltered in Hoba and Tlacotepec.



FIGS. 4 and 5: FIG. 4 (left). Hoba. Nital etched. ×225. Plessite typical of the Cape of Good Hope type of meteorites. Unidirectional and also interwoven needles of fascicular kamacite with a form suggestive of upper bainite in steels. The background to the kamacite needles is finely sorbitic, unresolvable at this magnification but illustrated in the sketch of fig. 5. FIG. 5 (right). Sketch of the microstructure of Hoba as it appears under high magnification, oil immersion, after etching with Nital. Primary needles of kamacite appear to be composed of two or more subordinate needles, incompletely welded together. Around this kamacite there is a boundary of clear nickel-rich taenite. The regions of parent taenite more distant from the kamacite have decomposed predominantly to a fine globular (sorbitic) arrangement of kamacite and taenite with some lamella and some acicular transformation product.

In Table I a second group of chemically similar bodies is provided by Weaver Mountains, Klondike, and Warburton Range, and these meteorites also show similar structures. They differ from the Hoba group in having a profusion of macroscopic kamacite spindles, most of which contain phosphide inclusions. The macrostructure is dull and mottled on a fine scale. There are no obvious patches of oriented sheen. The structure of Klondike has become diffused through reheating but enough of the original structure remains to suggest that it was originally similar to Weaver Mountains.

Although kamacite spindles are a profuse feature of these three meteorites there is considerably more spindle kamacite in Warburton Range than in Weaver Mountains. This influences the detailed microstructure of the background transformation product



FIGS. 6 and 7: FIG. 6 (top). Microprobe trace of nickel content across the boundary between two colonies of acicular decomposition product (lower bainite) in Warburton Range. The peak nickel value of 22 % lies at the boundary between two colonies of differently oriented product. The average nickel content differs slightly between the two colonies. FIG. 7 (bottom). Warburton Range. Nital etched. ×280. Chunky areas of kamacite, sometimes associated with phosphide, surrounded by thin rims of bright, unetched, high-nickel taenite. The bulk of the taenite has decomposed to form differently oriented colonies of acicular product. The microprobe trace of fig. 6 is taken across such a colony boundary.

in the two cases. In Weaver Mountains, where there is less spindle kamacite, the plessite background has a very fine interwoven structure that is continuous in orientation over the whole plane of section. By contrast, in Warburton Range the fine plessite forms small, differently oriented colonies that lie between the profuse kamacite spindles. In Weaver Mountains the plessite is predominantly a finely interlaced basket weave of fascicular needles of kamacite but with some more acicular transformation product in the nickel-enriched regions of the structure. By contrast in the small colonies of plessite in Warburton Range the acicular lower bainite structure predominates but there is a skeleton of upper bainite in fascicular needle form. Microprobe investigation reveals an increase of about 5 % in the nickel content at the boundary between adjacent colonies of transformation product (fig. 6), and this build-up of nickel indicates a diffusion-controlled process rather than a strictly martensitic one without diffusion. A view of the colony structure in Warburton Range plessite is given in fig. 7. Massive nodules of troilite were not encountered in the samples of Klondike and Warburton Range in the present study but in Weaver Mountains the troilite was extensively remelted, presumably by shock since there were no signs of reheating in the metal.

In Table I Kokomo, Piñon, Shingle Springs, and South Byron do not appear to demonstrate shared chemical compositions and, indeed, they each show individual if not entirely unique structures. However, Piñon shows macroscopic kamacite spindles superimposed on a macrostructure that shows oriented sheen effects in streaks and patches whereas South Byron shows microscopic kamacite spindles superimposed on an oriented sheen, and in both instances we obtain significant hints as to the origin of the oriented sheen, not only in these particular bodies, but also in the Hoba type meteorites where spindles of primary kamacite are rare.

Kokomo has not been analysed for trace elements and there is no recent redetermination of its nickel content. The microstructure of Kokomo is particularly free of sulphide and phosphide inclusions. On microscopic examination a few small inclusion-free spindles of primary kamacite are encountered as a rare feature and the plessitic background is found to consist of alternating lamellae of kamacite and taenite. The lamellae are of approximately equal thickness and, although convoluted and bent, are oriented in an approximately parallel manner in one predominating direction. On close examination a small amount of lamellar structure is encountered interwoven at an angle with the predominant direction. The taenite in Kokomo is free from microscopically detectable decomposition, although the examination of replicas in the electron microscope suggests a trace of martensitic decomposition at the centres of the lamellae, which, therefore, are not truly homogeneous. Buchwald (1966) has published a characteristic microstructure of the lamellar plessite in Kokomo. By analogy with the iron–carbon system it is tempting to refer to the plessite in Kokomo as a coarse unidirectional 'pearlitic' arrangement of α and γ lamellae.

The macrostructure of Kokomo shows bands of oriented sheen, similar to those encountered in Cape of Good Hope and, as in that case, the sheen arises from variations in the orientations of adjacent colonies of the directional transformation product.

Piñon, by contrast, is abundantly endowed with both sulphide and phosphide phases and shows a profusion of macroscopically visible kamacite spindles. On macroscopic examination the matrix appears frosty, but with a pattern of regular patches and of interwoven streaks of differently oriented sheen. The patches have geometrical outlines and, as in the case of Kokomo and Cape of Good Hope, appear to be suggestive of γ twins. That the geometrical patches are not γ twins is revealed by the fact that the kamacite spindles within the patches have a similar orientation to those outside. Microscopic examination reveals that in Piñon also the sheen is due to a lamellar $\alpha\gamma$ transformation product—'pearlite'—that is differently oriented, in patches and streaks, within the same original crystal of parent taenite. In general terms the 'pearlitic' $\alpha\gamma$ transformation structures are similar in Kokomo and in Piñon, although in Kokomo the lamellae are essentially unidirectional and about four times as coarse as in Piñon, where the pearlitic lamellae degenerate in some areas into a fine globular or sorbitic structure. Moreover, in Piñon the lamellar pearlite is predated by small quantities of fascicular needles of $\alpha\gamma$ transformation product analogous to upper bainite in steel. These needles of 'upper bainite' are lacking in Kokomo but in Piñon, where they are present in small amounts, they are aligned in directions approximately parallel to the primary spindles of α and are interwoven to form a spine-like structure about which the fine pearlitic product is formed.

Macroscopically visible nodules of about 1 mm diameter and laths about $1{\cdot}5 \times 0{\cdot}3$ mm are common in Piñon and on microscopic examination these prove to be composed of troilite that has been remelted and allowed to resolidify as a fine metal–troilite eutectic, similar to that reported in the Gibeon octahedrites by Axon and Smith (1970). However, no daubréelite has been detected in Piñon, although in some of the nodules schreibersite was obviously present as a swathing layer about the troilite before it suffered remelting. The remelting event was most probably induced by shock, since the metal and phosphide phases show no signs of bulk reheating to the melting point of the metal–troilite eutectic. Also the troilite was molten for only a short interval of time as is indicated by the incomplete dissolution of swathing schreibersite in the melt and limited penetration of the melt into the surrounding metal. Where this penetration has taken place the sulphide eutectic cuts into and is obviously formed later than the 'pearlitic' α–γ transformation structure of the matrix. On the other hand there are no obvious signs of shock effects in the metallic phases and it is thus probable that the shock event that remelted the troilite took place subsequent to the formation of the pearlitic transformation structure but at a stage when the bulk temperature of the meteorite was sufficiently high to allow the effects of shock damage to anneal out of the metal phases. In addition to the swathing schreibersite already noted a few of the smallest of the macroscopically visible inclusions consist of schreibersite crystals, with typical dimensions 0·6×0·6 and 0·6×0·1 mm, surrounded by swathing kamacite. These schreibersite crystals are usually fractured and displaced and many have small veins of molten troilite intruded at their boundaries. The final location of phosphide in Piñon is as microscopic particles, about 0·05×0·05 mm, at the centres of kamacite spindles and as laths within the 'pearlitic' $\alpha\gamma$ transformation structure. In many instances the phosphide inclusions in Piñon could have been present in the parent taenite before the onset of kamacite precipitation. Thus, the sequence of events in the formation of the microstructure of Piñon from its original parent taenite appears to have been: first the formation of swathing kamacite and kamacite spindles at the sites of pre-existing schreibersite, followed by the formation of a spine-like growth of fascicular needles of 'upper bainite', which in turn was followed by the formation of fine lamellar 'pearlite' or sorbite with minute laths of schreibersite entangled in the lamella $\alpha\gamma$ structure. The nickel analyses reported for Piñon range from 16·58 (Lovering *et al.*, 1957) to 15·54 (Wasson and Schaudy, 1971) and the value of approximately 16 % recorded in Table I is selected to avoid the intrusion of the anomalous Piñon among the Cape of Good Hope group of meteorites.

Shingle Springs is reported by Hey (1966) to have been rescued from a blacksmith's shop and has a nickel content of 16·7%. No recent re-analyses or values for gallium and germanium content appear to be available. The macrostructure shows occasional sulphide inclusions approximately 0·5×0·2 mm although in the section that was available for study these sulphides were badly chipped and it was not possible to make a detailed investigation of their composition and condition. In some, but not all, instances the sulphide areas were swathed with kamacite. No massive phosphide bodies were detected and the macrostructure of the metallic matrix was dull and finely mottled and showed small and irregular patches of oriented sheen. There is a profusion of small octahedrally oriented kamacite spindles, all of which appear to have phosphide particles associated on a microscopic scale but which appear to be very free from other inclusions. Microscopic laths of phosphide also occur within the rather acicular $\alpha\gamma$ transformation structure that lies between the kamacite spindles and in this respect there is a similarity to the structure of the plessite in Piñon. Spines of fascicular $\alpha\gamma$ also feature in the plessite of Shingle Springs but, by contrast, the subsequent mode of decomposition is to an acicular martensitic or lower bainite structure instead of to the pearlitic–sorbitic structure of Piñon. Thus the microstructure of Shingle Springs may have formed in a manner similar to that previously outlined for Piñon, except that the final stage of decomposition of the parent taenite was acicular (martensite to lower bainite) rather than lamellar (pearlite).

In the case of South Byron a nickel content of approximately 18·2 % is recorded in Table I. This takes account of the fact that Wasson and Kimberlin (1967) reported a value of 18·2 whereas Moore, Lewis, and Nava (1969) give values of 17·77 and 18·57 with a phosphorus content of 0·23 %. South Byron differs in both structure and trace element chemistry from the trio of phosphide-containing ataxites (Weaver Mountains, Klondike, Warburton Range) that share structural and chemical features at 18·1–18·2 % nickel. No macroscopically visible phosphides were encountered in the present specimen of South Byron but three small globules of troilite, about 0·2 mm diameter, appeared to have been remelted subsequent to the formation of the fine structural detail in the metallic matrix. Patches of oriented sheen are an important macroscopic feature of South Byron and moderately deep etching produces a pronounced pearlitic iridescence. Spindles of kamacite escape detection by the unaided eye but at moderate magnifications they are revealed in rare instances with dimensions 0·2×0·01 mm and profusely with dimensions 0·1×0·005 mm. All of these kamacite spindles have microscopic phosphide bodies in association and their octahedral orientation does not vary from one patch of oriented sheen to the next. Thus, as in the case of Piñon, the continuity with which the kamacite spindles are oriented reveals that the patches of oriented sheen do not originate from twins in the parent taenite. Examination at high magnifications reveals that the plessitic matrix, which forms a background to the kamacite spindles, consists of interwoven fine lamellae of kamacite and taenite among which occasional small laths of phosphide are encountered but no acicular transformation product is observable. In these respects the fine structure of the matrix of South Byron is similar to that reported for Piñon.

Oriented sheen in ataxites. A number of instances have been noted where bands or patches of oriented sheen form part of the macrostructure of ataxites. The effect is particularly marked in Cape of Good Hope, where, in some instances, it takes the form of bands that on first sight appear sufficiently parallel and sharply defined to suggest the presence of twin orientations in the parent taenite. Near-parallel bands are a feature also of Kokomo. In Shingle Springs to a small extent, in South Byron to a marked extent, and occasionally on sufficiently large sections of Tlacotepec the sheen is found in irregular patches that sometimes appear to be bounded by segments of straight lines. In Piñon it appears both in patches and in interwoven streaks, while in Hoba the line of demarcation between areas of different sheen was sufficiently well defined in one instance to suggest to Spencer (1932) that the effect arose from twin orientations in the parent taenite. The twin hypothesis is not easy to test in Hoba because oriented spindles of primary kamacite are very rare, although close examination of Spencer's actual specimen shows that the line of demarcation is not so well defined as would appear from the published photograph. However both Piñon and Shingle Springs have a profusion of kamacite spindles, all of which are oriented in relation to the parent taenite from which they precipitated. In both Piñon and Shingle Springs the kamacite spindles are uniformly aligned over the whole plane of section, indicating that they precipitated from an untwinned single crystal of parent taenite and thus an explanation that is not related to γ twinning must be sought.

Those ataxites that show patches of oriented sheen also display certain similarities of microstructure. The most simple example is encountered in the case of Kokomo, where the characteristic structure may be described as a unidirectional microscopic arrangement of alternating lamellae of kamacite and residual taenite, or, by analogy with the structure of steels, as a directional pearlitic structure of α and γ. The sheen arises by the reflection of light from the oriented lamellae and in this respect is similar in origin to the mother-of-pearl appearance of deeply etched pearlite in steel. In the Kokomo structure the alternating lamellae are approximately parallel and are composed of the α and γ solid solutions of nickel in iron. In the pearlite of steel the lamellae are metallic iron and the iron–carbon compound cementite, Fe_3C, and in most instances the lamellae are not parallel but tend to form a radiating fan structure. However the Kokomo structure, while being predominantly unidirectional, is not absolutely so, and even in the most nearly unidirectional areas it shows occasional cross-members, while a much greater proportion of interwoven structure is found in the other meteorites.

Features of structure that vary from one meteorite to another include the effective spacing of the diffraction grating, the proportions of α to γ and the nature of the final decomposition product in the residual γ. Kokomo is unusual in having a very coarse interlamellar spacing with approximately equal proportions of α and γ, moreover the γ lamellae are only slightly inhomogeneous with respect to nickel content and are therefore uniform in microstructure. By contrast, in Hoba the microstructure is more complicated, since the α takes the form of bundles of fine needles having the appearance of upper bainite whereas the residual γ is sufficiently inhomogeneous with respect to nickel content to allow it to transform into a mixture of lamellar, globular, and sometimes acicular structures within a boundary zone of nickel-enriched taenite. Moreover, by contrast with the predominantly unidirectional lamellar structure of Kokomo, the meteorites Hoba and Tlacotepec (and probably Cape of Good Hope before it was reheated) show several mutually interwoven families of bundles of α needles, and this is also the situation in Piñon and South Byron. In the two latter meteorites the residual α has decomposed into a pearlitic lamellar structure that is similar in form but is much finer than that of Kokomo.

These observations, especially the orientation of the bainitic kamacite needles parallel to octahedral kamacite spindles, together with the lamellar decomposition of the cored residual taenite, strongly suggest that the structure developed by a diffusion-controlled process whereby kamacite needles were produced from the parent taenite but instead of transformation taking place with equal probability on all of the possible habit planes (as usually happens in the gross macroscopic Widmanstätten structure of the conventional octahedrites) it appears that separate patches of $\alpha\gamma$ transformation nucleated at a number of locations within the parent taenite and inside any one patch the precipitation of kamacite was restricted to a single habit plane or to a limited number of planes. This suggests that at the low temperature at which the structure forms there exist a variety of nucleation sites in the parent taenite but that from each nucleus the growth of kamacite takes place more easily as clusters of parallel needles rather than by simultaneous precipitation on all the possible habit planes.

In those meteorites that have been considered so far the final mode of decomposition of the parent taenite appears to be predominantly by the diffusion controlled growth of pearlite and, with the exception of South Byron, these are the meteorites for which the nickel contents lie in the region of 16–17 % and which show macroscopically visible patches of oriented sheen. However, at 18·2 % nickel and correspondingly low temperatures an alternative mode of growth appears by way of an acicular bainitic or martensitic product and in Shingle Springs, Weaver Mountains, and Warburton Range both fascicular $\alpha\gamma$ and acicular decomposition products have formed to varying extents, although in each case there is a skeleton of fascicular $\alpha\gamma$ structure that appears to have been formed earlier than the acicular product.

Morradal is treated as a unique object in the present study, partly because its chemical analysis and structure are different from the other meteorites under investigation, partly because its structure shows pronounced signs of alteration by shock and reheating and partly because its original (unaltered) structure appears to have been remarkably different from what would be expected by analogy with other meteorites that have slightly greater or slightly smaller contents of nickel.

In sample B.M. 1924, 146 a portion of the heat alteration zone that formed during atmospheric entry is still present at part of the outer surface and the metallographic structure within this zone overlies the bulk structure in such a way as to suggest that the bulk structure was of truly pre-terrestrial origin.

The macrostructure is dominated by massive phosphide bodies (3 × 0·7 mm) that are surrounded by swathing kamacite and by large nodules (1 mm dia.) and laths (10 × 0·5 mm) of remelted sulphides. In addition, in the metallic matrix there are a number of kamacite spindles of approximate size 1 × 0·02 mm and others of size 0·2 × 0·01 mm. These spindles are set in a metallic matrix that is dull and finely mottled with no macroscopic directionality.

On microscopic examination the original form of the sulphide areas appears to have been laths or nodules of a coarse troilite–daubréelite association, swathed by schreibersite and by kamacite. In its present condition the troilite is completely remelted but the more massive crystals of daubréelite are only partly redissolved in the molten troilite. The schreibersite is also partly redissolved and the swathing kamacite is in some areas partly invaded by the molten troilite. Where the swathing kamacite remains uninvaded it is granulated and contains exsolved particles of isothermal taenite, similar to those observed by Axon and Smith (1970a) in Weekeroo Station.

The swathing kamacite around the larger phosphides is also granulated and contains isothermal taenite. The spindles of kamacite usually have microscopic inclusions of schreibersite and the larger ones show exsolutions of isothermal taenite. In their study of Weekeroo Station Axon and Smith (1970a) ascribed the isothermal taenite to a process that reheated the primary kamacite into the $\alpha+\gamma$ field of the iron–nickel equilibrium diagram, followed by a lengthy annealing process that produced final phase equilibrium appropriate to the temperature range 330 to 360 °C. Unfortunately it was not possible to make microprobe determinations on the present specimen of Morradal.

The metallic matrix consists of a coarse microscopic arrangement of rather globular bodies of taenite in a background of kamacite. In the vicinity of the kamacite spindles the $\alpha\gamma$ matrix shows a vague microscopic directionality that parallels the orientation of the kamacite spindles, but more usually the $\alpha\gamma$ matrix shows no directionality. In spite of the high nickel content of Morradal the globular $\alpha\gamma$ structure in the matrix is approximately twice as coarse as the lamellar structure in Kokomo.

The thermal and mechanical history of Morradal must have been quite complex. By comparison with the other ataxites its original structure was very coarse, indeed in many respects Morradal appears like a plessitic octahedrite of unusually high nickel content and having large quantities of phosphide and sulphide phases. Subsequent to the formation of the sulphide, phosphide, and $\alpha\gamma$ metal phases the meteorite was shocked to such an extent that the troilite was remelted, although the duration of remelting was not sufficient to dissolve the more massive of the daubréelite inclusions that were present in the original sulphide assembly. In addition the material must have been uniformly reheated sufficiently to exsolve taenite from previously formed kamacite and to cause an over-all diffusion of the metallic structure.

Remelted troilite structures have now been observed not only in Morradal but also in Cowra as a microscopic feature and in Piñon, Weaver Mountains, and South Byron as macroscopic features. Axon and Smith (1970) have drawn attention to similar structures in the Gibeon octahedrite and the effect has also been observed in a number of hexahedrites, including the Angra dos Reis iron (Axon and Waine, 1971).

San Cristobal, Lime Creek, and Santa Catharina. These three meteorites differ markedly in nickel content, trace elements, and structure. However, it is convenient to consider them together since they display a range of structures quite different from those already encountered. In each case the matrix consists of taenite that has to a greater or less extent decomposed to martensite, although various quantities of sulphide, phosphide, and kamacite also contribute to the total structure.

In San Cristobal the parent taenite is polycrystalline with a grain size of approximately one inch and there is a tendency for phosphide and kamacite to form in the γ grain boundaries. Troilite exists as massive nodules, of which the largest in the present section is about 1 cm diameter. On microscopic examination the troilite usually proves to be swathed first with schreibersite and then with kamacite, although in some regions the troilite comes directly into contact with the taenite matrix. Kamacite also occurs as microscopic spindles in the matrix of bright taenite. The amount of this latter kamacite is small and is fairly evenly distributed except near the swathing kamacite around troilite when the spindles are rare and small in size. In the majority of cases the spindles consist of kamacite with central phosphide inclusions but in some cases the kamacite has been replaced by a late-formed carbide to give a complex phosphide, kamacite, carbide assembly. Microprobe examination reveals the composition of the kamacite at 5–5½ % nickel and the carbide at 4·5–4·7 % nickel. Slight decomposition of the matrix taenite has taken place to produce martensite. This is not visible on optical examination of the etched specimen but shows up in the back-scattered electron image in the way that has previously been reported for Weekeroo Station by Axon and Smith (1970a).

Microprobe examination at the interface between troilite and taenite shows a buildup of nickel in the taenite such as would be produced if at a relatively late stage nickel was rejected from the sulphide into the surrounding taenite. Correspondingly, where swathing schreibersite has formed around the troilite there is a gradient of nickel content within the schreibersite and, when the schreibersite is in turn followed by swathing kamacite, it shows a cored nickel distribution with relatively low (40 %) nickel content at the centre of the swathing band and the nickel enrichment (50 %) at the troilite interface is accompanied by a lesser (45 %) enrichment at the kamacite interface, due to the rejection into the schreibersite of nickel from the growth of the swathing kamacite.

The sample of Lime Creek is badly invaded by terrestrial weathering product, which helps to reveal the detail of the original microstructure. Schreibersite is present both as a macroscopic feature and as small crystals within microscopic regions of kamacite. Occasional microscopic spindles of kamacite are present but the predominant feature in the microstructure of this meteorite is the martensitic product into which the bulk of the taenite matrix has decomposed.

Specimens of Santa Catharina are usually encountered in a badly corroded condition with a pronounced cracking pattern parallel to the cube planes of the parent taenite. Recent investigations of the condition of the metallic matrix have been made by Lovering and Anderson (1965) and by Kvasha, Kolomenskii, and Budko (1969) who have suggested that thin plates of nickel-rich taenite lie parallel to the cube planes of the parent taenite and are particularly susceptible to corrosion.

The specimen used in the present work contained a number of macroscopically visible schreibersite inclusions and the metallic matrix was characterised by the cubically oriented cracking pattern that has been noted by previous investigators. Microscopic examination of a small sample that was relatively free of corrosion revealed two types of phosphide inclusion on the microscopic scale. Rarely small rhabdite-like bodies were embedded directly in the taenite of the matrix and displayed a nickel content that was indistinguishable from that of the surrounding metal, but the more usual situation was for the phosphide to contain variable (~40 %) amounts of nickel in excess of the taenite matrix (~30 %) and to be surrounded by a rim of low nickel (~5 %) kamacite. In these instances no build-up of nickel could be detected in the taenite at the kamacite–taenite interface and, within the limits of experimental uncertainty the accumulation of nickel in the phosphide phase appeared to be balanced by its depletion from the surrounding kamacite. Thus it appears that in Santa Catherina the production of phosphide and kamacite was mutually interrelated. In most cases the kamacite exists as a swathing band around the phosphide but occasionally it is found as octahedrally oriented spindles growing outward from the swathing kamacite. In Santa Catharina kamacite is rare and highly localized and the structure is further complicated by variable amounts of oxidation. However, in areas of taenite that are particularly free of oxidation microscopic examination of the nital-etched surface at high magnification reveals a small amount of martensitic decomposition product.

Accounts of the history of Santa Catharina place emphasis on the large quantity of material that was available and the smelting of Santa Catherina material for nickel. All specimens are extensively oxidized and cracked, but in the sample that was available for examination in the present work there were no signs of thermally induced diffuseness at the phosphide–metal interfaces. Thus it is unlikely that peculiarities of structure in the present specimen could have been introduced by a smelting operation. On the other hand if the original meteoroid was of massive proportions it could have suffered considerable damage when it made its impact on the earth's surface and this possibility must not be overlooked when seeking an explanation of the badly cracked structure of Santa Catharina material.

The effect of phosphorus on ataxite structures. Doan and Goldstein (1970) have drawn attention to the fact that when laboratory-made alloys of iron and nickel contain a sufficient quantity of phosphorus they can be made to develop the body-centred cubic (ferritic) solid solution on slow laboratory cooling, in marked contrast to the behaviour of pure binary iron–nickel alloys. These authors have also determined a series of isothermal sections in the Fe–Ni–P equilibrium diagram.

The influence of phosphorus may also be seen on the structure of the nickel rich ataxites. A particularly interesting case is provided by Santa Catharina in which small well-shaped phosphide bodies are occasionally found embedded in the taenite matrix with no detectable difference of nickel content between the two phases. The more usual situation in Santa Catharina is for the phosphides to be enriched in nickel relative to the bulk of the taenite but to be surrounded by a sheath of kamacite and the nickel lost from this kamacite appears to balance that gained by the phosphide. Very occasionally in Santa Catharina octahedrally oriented spines of kamacite are found growing out from the swathing kamacite and under these circumstances an enrichment of nickel may be detected in the taenite at the interface with the octahedral, but not with the swathing, kamacite. It thus appears that the presence of phosphides in the parent taenite of Santa Catharina may materially assist the formation of kamacite.

Up-to-date analytical values for the phosphorus contents of all the ataxites are not available, but from the older literature it appears likely that meteorites of the Cape of Good Hope type contain less than 0·1 % P whereas Piñon, Shingle Springs, South Byron, and Klondike contain >0·2 % P. When the available analytical data are considered in relation to the Fe–Ni–P equilibrium diagrams of Doan and Goldstein (1970) there appears a very reasonable correlation between the observed structures and those predicted from the equilibrium diagrams. In particular we find that at 650 °C the Cape of Good Hope group of meteorites are situated in the single-phase γ field but at 550 °C have entered the $\alpha+\gamma$ phase field. By contrast the meteorites noted above with $>0{\cdot}2$ % P are in the γ+phosphide field at 650 °C and have moved into the $\alpha+\gamma$+phosphide field at 550 °C. Similarly the meteorites Monahans and Deep Springs (Table II) are reported to have particularly low phosphorus contents and, according to the equilibrium diagrams, inhabit the $\alpha+\gamma$ phase field at both 650 °C and 550 °C. In both of these meteorites the bulk of the kamacite occurs as a component of the fine plessitic matrix but the small amount of kamacite that exists as primary spindles appears to have nucleated at small sulphide bodies in the parent taenite. Thus both laboratory studies and detailed observations on meteorites indicate that phosphorus plays an important part in the development of ataxite structures but when the phosphorus content is low the action of sulphide particles as nucleating sites for primary kamacite may be identified.

REFERENCES

Axon (H. J.) and Smith (P. L.), 1970. *Min. Mag.* **37**, 888.

—— —— 1970a. Ibid. **37**, 670.

—— and Waine (C. V.), 1971. Ibid. **38**, 94.

Buchwald (V. F.), 1966. *Acta Polytechnica Scandinavica*, Ch. 51, 46 pp.

—— and Munck (S.), 1965. Catalogue of Meteorites, *Analecta Geologica I, Copenhagen.*

Doan (A. S.) and Goldstein (J. I.), 1970. *Met. Trans.* **1**, 1759.

Farrington (O. C.), 1915. Catalogue of the Meteorites of North America. *Nat. Acad. Sci., Mem.* **8**, 513 pp.

Goldstein (J. I.), 1969. *Meteorite Research*, ed. Millman (P. M.), pp. 721–37. Dordrecht (D. Reidel).

Hey (M. H.), 1966. *Catalogue of Meteorites.* London (British Museum).

[Kvasha (L. G.), Kolomenskii (V. D.), and Budko (I. A.)] Кваша (Л. Г.), Коломенский (В. Д.) и Будко (И. А.), 1969. Метеоритика (*Meteoritika*), **29**, 68.

Lovering (J. F.), Nichiporuk (W.), Chodos (A. A.), and Brown (H.), 1957. *Geochimica Acta*, **11**, 263.

—— and Anderson (C. A.), 1965. *Science*, **147**, 734.

McCall (G. J. H.) and Wiik (H. B.), 1966. *Journ. Roy. Soc. Western Australia*, **49**, 13.

Moore (C. B.), Lewis (C. F.), and Nava (D.), 1969. *Meteorite Research*, ed. Millman (P. M.), pp. 738–48. Dordrecht (D. Reidel).

Nininger (H. H.) and Nininger (A. D.), 1950. *The Nininger Collection of Meteorites.* Winslow (American Meteorite Museum).

Perry (S. H.), 1944. The Metallography of Meteoric Iron. *U.S. Nat. Mus. Bull.* **184**, p. 206.

Spencer (L. J.), 1932. *Min. Mag.* **23**, 1.

Wasson (J. T.), 1967. *Geochimica Acta*, **31**, 161.

—— and Schaudy (R.), 1970. *Icarus*, **14**, 59.

—— and Kimberlin, 1967. Ibid. **31**, 2065.

[*Manuscript received 15 July 1971*]