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The Sitathali meteorite

T. V. VISWANATHAN, N. R. SEN GUPTA, D. R. DAS GUPTA, AND S. BANERJEE

Geological Survey of India,[1] Calcutta-13

SUMMARY. Sitathali is an olivine-bronzite chondrite, consisting largely of olivine (Fa_{18}) and orthopyroxene (Fs_{19}) with minor amounts of a clinopyroxene ($Ca_{36}Fe_{12}Mg_{52}$), plagioclase (An_{12}), nickel-iron, troilite, chromite, and a phosphate (apatite or merrillite). The chemical analysis of a 4 gm sample gave SiO_2 39·85, TiO_2 0·10, Al_2O_3 2·84, Cr_2O_3 0·35, FeO 13·27, MnO 0·28, MgO 23·01, CaO 1·84, Na_2O 0·65, K_2O 0·15, H_2O+ 0·23, H_2O- 0·05, P_2O_5 0·25, FeS 5·09, Fe 10·22, Ni 1·58, Co tr. total 99·76. The metal displays Neumann bands, some deformed, as well as areas of apparent flowage. Troilite locally exhibits twin lamellae and in places replaces kamacite in the plessite fields. Elsewhere it is in braided veinlets and globules, both reflecting former melting. The varied textures suggest a complex post-formational history encompassing several deformational events presumably due to breakups and possible extraterrestrial impacts.

EXCEPT for a short description of fall by Medlicott (1876, p. 115–16) and of morphological characters by Murthy *et al.* (1967), the Sitathali meteorite has not been studied in detail; the results of detailed microscopic, X-ray, and chemical studies are reported below. The most interesting features, however, are the textural characteristics, as they throw light on the complex history of this apparently ordinary stony chondrite. The observations are, by their nature, interpretative and therefore to some extent speculative.

General description and crust morphology. The fragment, 11 cm × 5·5 cm × 3·5 cm, in the Indian Museum (no. 171, registered collections of the Geological Survey of India) has the appearance of a segment of a cylinder with three groups of faces, convex, wavy, and rough. Shallow irregular regmaglypts noted on the wavy face are characteristically absent on the other faces. Fusion crust (0·4–1·0 mm wide) varies in colour and texture on the three groups of faces. The crust on the convex face is greyish black, slightly shining and close textured with a few small fused chondri; the crust on the wavy face is more greyish, dull, ribbed to netted also with a few fused chondri. The crust on the rough face is greyish black and sooty with brownish patches due to alteration of nickel-iron; it is slightly dull with imperfectly developed shining knobs and in places porous. Fused crust has flown across the edges of the convex face towards the wavy and the rough faces. This suggests that during the final stages of the atmospheric flight the convex face probably formed the front.

The meteorite consists of numerous light and dark grey crystalline vitreous fragments and chondri in an earthy white crystalline matrix. Specks of nickel-iron and troilite

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are scattered throughout the meteorite, in places aggregates are also noted. Troilite veins traverse the crust forming long continuous ribs. Alteration of the metallic minerals gives a rusty appearance to the fractured faces.

The density of the meteorite was determined as 3·65 by hydrostatic weighing in carbon tetrachloride after evacuation to remove air from the pores.

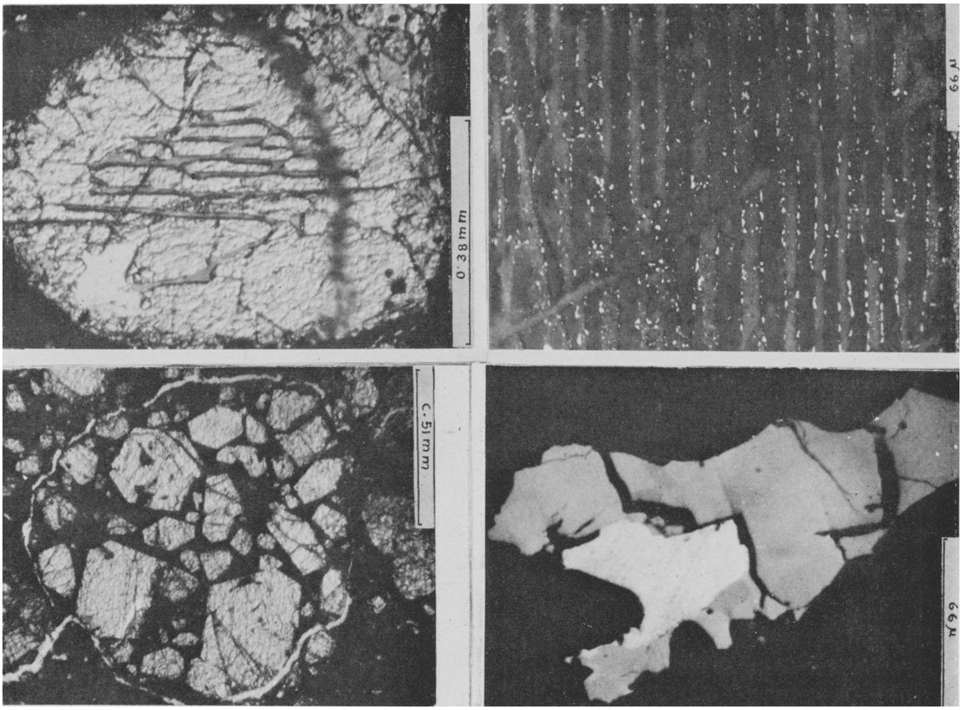
Microscopic characteristics. In thin section the meteorite is composed essentially of well-defined, barred, radiating, and some excentro-radial chondrules, ranging in diameter from 0·45 to 2·05 mm, embedded in a matrix of anhedral olivine, granular bronzite, irregular patches of interstitial metallic minerals, minor clinopyroxene, plagioclase, and some glass. The chondrules form about 28 % by volume in an area of 13 mm × 18 mm, and there are thirty-two chondrules per sq cm. The monosomatic olivine chondrules are more in number than the orthopyroxene chondrules. There appears to be no relationship between the size and structure or composition of the chondrules. Most of the well-defined chondrules have a thin outer rim of dark opaque minerals and glass. Generally irregular patches of nickel-iron and troilite occur marginally around the periphery of the chondrules. When the chondri are composed of orthopyroxene the mineral forms finely fibrous and radiating fan-shaped lamellar chondrules. Circular polarization and optical strain phenomena are frequently observed in these types of chondrules; it is now agreed that this is produced by dynamic metamorphism.

Monosomatic chondrules of olivine are mostly barred, granular, platy, and to a lesser extent lamellar. In one example an irregularly barred chondrule of olivine shows bars of the mineral alternating with glass. These bars give place abruptly to a granular aggregate of olivine, which might have been derived by breaking up of the bars. In a few olivine chondrules (fig. 1) the core is formed of a very fine straight bars of olivine alternating with interstitial glass, and this is surrounded by a thin outer rim of dark opaque minerals. In one chondrule the core consists of a crystal of olivine surrounded by a granular aggregate of olivine. In another chondrule the crystal of olivine in the core is traversed all along its length by fine lines of glass; in plane polarized light the crystal resembles a barred olivine because of its partition by lines of glass into different parts resembling bars; however, under crossed nicols the glass lines are not visible because of the strong interference colour of olivine. The structure appears to be the first stage in the formation of a barred chondrule, in which case all the bars, though separated by interstitial glass, remain in perfect optical continuity. Minute specks of magnesiochromite occur along the interfaces of the interstitial glass and the olivine bars (fig. 2). Faults are evident in a few barred olivine chondrules.

Most of the orthopyroxene chondrules show lamellar, fibrous, frequently radiating, fan-shaped structures characteristic of orthopyroxene chondrules in meteorites. In one chondrule fine laths of orthopyroxene radiate in opposite directions from a central row of small prismatic crystals of orthopyroxene. Only one composite chondrule consisting of a granular aggregate of olivine and orthopyroxene has been noted in the thin section studied. There is only one polysomatic chondrule of olivine (fig. 3) with a number of euhedral crystals of olivine embedded in a glassy matrix.

Mineralogy

By treating a sample of the crushed meteorite with 1 : 1 HCl olivine, nickel-iron, and troilite were dissolved, leaving a residue of orthopyroxene along with minor plagioclase, clinopyroxene, and chromite. The silica released by the decomposition of the olivine was removed by dissolving in Na_2CO_3 solution. In this way pure grains of orthopyroxene, plagioclase, and clinopyroxene were isolated for determinations of refractive index.



FIGS. 1 to 4: FIG. 1 (top left). An olivine chondrule with a crystal of olivine in the core traversed by lines of glass; this is surrounded by a thin rim of granular olivine which in turn is surrounded by a thin outer rim of dark opaque minerals. FIG. 2 (top right). Barred olivine chondrule with specks of chromite (light grey) along the interface of olivine bars and glass. Oil immersion. FIG. 3 (bottom left). A number of euhedral crystals of olivine in a polysomatic chondrule of olivine. FIG. 4 (bottom right). Troilite surrounds the metal. Black area is silicate; nicols partly crossed. Oil immersion.

Olivine: The refractive indices, α 1·673 and γ 1·710, indicate a content of 18 mol % Fa according to the determinative curve of Poldervaart (1950). This was confirmed by the X-ray method of Yoder and Sahama (1957); the olivine lines in the diffraction photos are sharp and prominent indicating an olivine (a 4·79, b 10·23, c 6·03 Å) of uniform composition; the $d_{130} = 2{\cdot}777$.

Orthopyroxene: The refractive indices are α 1·676 and γ 1·687 with a $2V_\alpha = 79°$ indicating a composition of 19 mol % $FeSiO_3$ (Kuno, 1954) corresponding to meteoritic bronzite.

Clinopyroxene: The clinopyroxene, very much subordinate to the orthopyroxene in the meteorite, is a low-calcic variety. The optical properties of this clinopyroxene are α 1·680, γ 1·702, and $2V_\gamma$ 45°, indicating a composition of $Ca_{36}Mg_{52}Fe_{12}$ according to the determinative curve of Hess (1949). The composition is considerably less calcic than that of diopside from other chondrites (Mason, 1967).

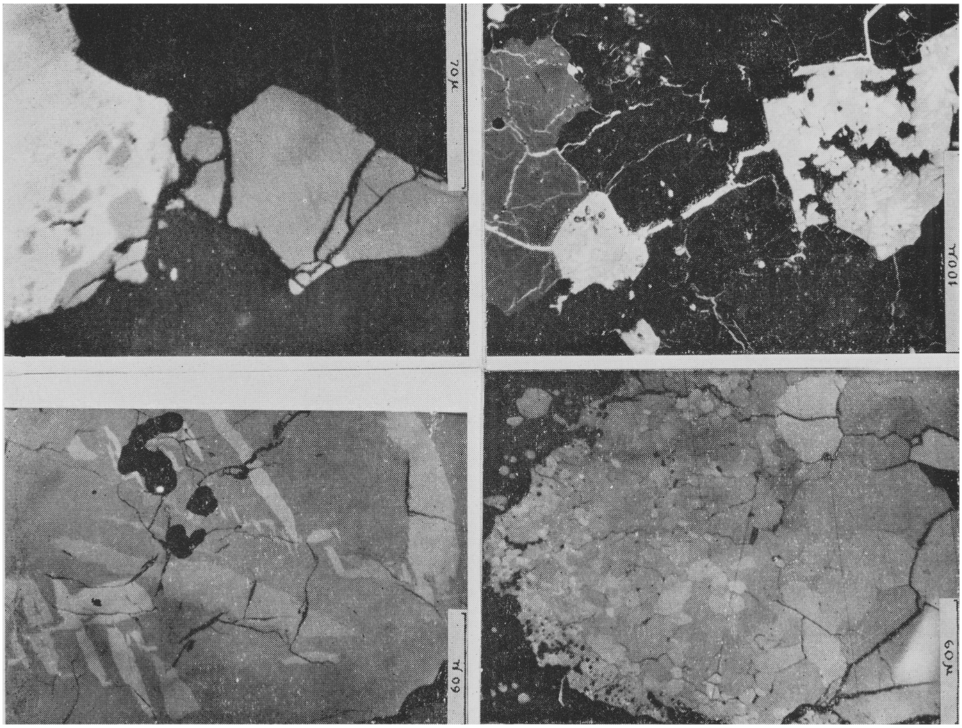
Plagioclase: Plagioclase is in minor amounts. The mean refractive index is approximately 1·538 indicating a composition of An_{12}.

Minute grains of a mineral with low interference colours and an approximate refractive index of 1·625 were noted in Sitathali. They are probably identifiable as apatite or merrillite.

Opaque minerals: The non-silicate opaque minerals are troilite, kamacite, and taenite with minor proportion of chromite. Troilite occurs as veins, large grains surrounding the metal (fig. 4), globules, lamellae, and irregular shard-shaped (fig. 5) inclusions in kamacite. The shard-shaped grains are scattered throughout a few kamacite grains and have their *c*-crystallographic axes aligned parallel to one another. They have commonly selectively replaced kamacite in kamacite–taenite intergrowths (plessite). The replacement is greatest near the edges of the plessite suggesting that sulphur was introduced or mobilized after plessite development. Further, as the plessite intergrowths are still intact the meteorite could not have been appreciably reheated subsequently. Vein fillings, globules, and droplets are presumably due to local heating.

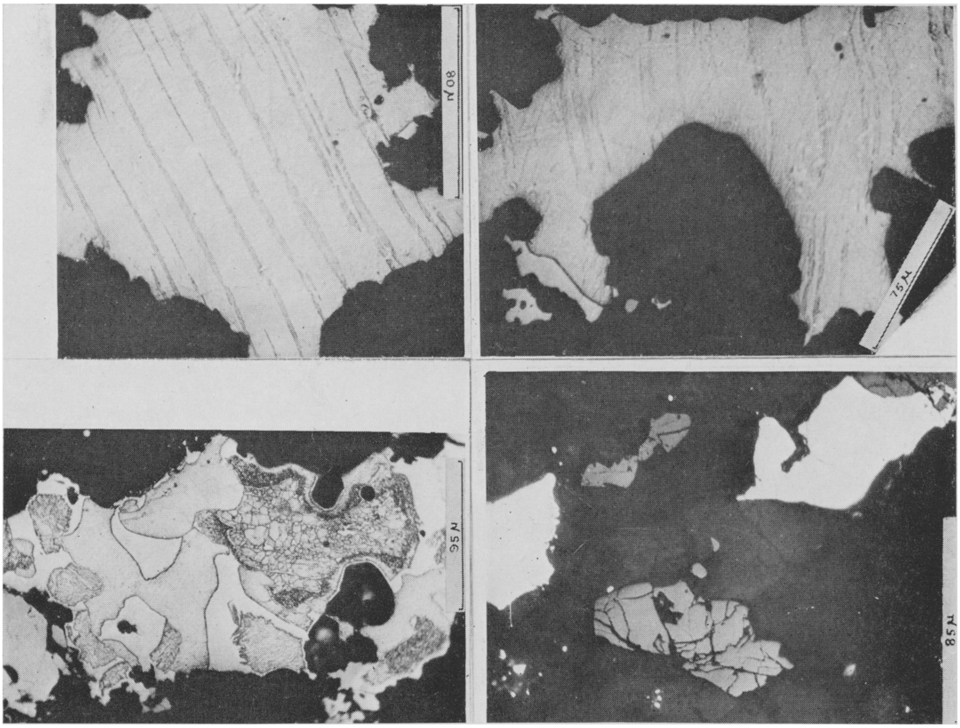
Braided veinlets containing troilite occur near the fusion crust (fig. 6) and presumably formed during passage through the atmosphere. Surficial heating produced local expansion and fracturing; molten troilite flowed into and filled these fractures, thereby forming this braided structure. A few troilite crystals contain lens-shaped lamellae (fig. 7) similar to synthetic deformation lamellae produced by twinning. Granulation (fig. 8) and veins of granular troilite are common in large grains of troilite. Similar features have been noted in the Beenham meteorite described by Buseck (1967). Zukas and Taylor (1965) demonstrated that such structures could be produced in copper by shock. Exsolution lamellae of sulphur-rich phases like pyrrhotine look similar, but would not be expected in the presence of free iron. Further, only troilite was noted in the powder diffraction patterns. Globules of troilite with minor intergrown kamacite occur interstitial to the silicate chondrules in places. Similar globules have been produced experimentally by Fredriksson, De Carli, and Aaramae (1963) with shock pressures ranging from 150 to 800 kb. Such impulses and consequent rarefactions produced instantaneous melting of troilite.

Most of the metal is an intergrowth of the α and the γ phases into plessite, containing Neumann twin bands (fig. 9). Earlier these were described from chondrites by Urey and Mayeda (1959) and Buseck (1967). When initially formed these bands are almost straight. In the Sitathali meteorite later plastic deformation has produced many curved bands (fig. 10). Some of the kamacite veins intersect and offset the Neumann bands and do not contain them, indicating that these veins were formed after the original shock. These veins are also curved, indicating local flowage of kamacite presumably the result of sufficiently strong pressures. A few grains (fig. 11) show two distinct areas of different structures: the greater part consists of macroscopic grains with diversely oriented sheen within which is a finer granulation; the remainder resembles a nickel-poor ataxite, though occasionally enclosing small spots of granulation.



FIGS. 5 to 8: FIG. 5 (top left). Kamacite replaced by troilite; troilite fragments within the metal. All the troilite crystals have the same optic orientation. Nicols partly crossed; oil immersion. FIG. 6 (top right). Troilite (white) showing intergrowth with metal; molten troilite flowed and filled the fractures in silicates and a subhedral crystal of chromite (dark grey) to the left. Oil immersion. FIG. 7 (bottom left). Twin lamellae within troilite; nicols partly crossed. The black areas are silicate. Oil immersion. FIG. 8 (bottom right). Troilite granulation and development of droplets; nicols partly crossed. Oil immersion.

Chromite (reflectivity: 15 % in air; 530 $m\mu$ green light) occurs as minor inclusions in the silicate chondrules; intergrowths with silicates are not uncommon. It also occurs as fairly dense but discontinuous strings (fig. 12) bordering the rounded to sub-angular troilite grains, sometimes accompanied by traces of kamacite. According to their form, size, and mineralogical composition, they cannot be classed as chondrules. One silicate chondrule contains idiomorphic chromite crystals 'frozen to the walls'. The chondrule is devoid of chromite in the outer parts, except for fine chromite dust. Instead, it contains fairly substantial amounts of pyroxene (?) as well as minor troilite and kamacite; the chromite crystals in the inner parts of the chondrule are large and euhedral. In one chromite–plagioclase chondrule both primary and pseudomorphic chromite in typical laths occur side by side.



FIGS. 9 to 12: FIG. 9 (top left). Straight Neumann bands in kamacite. Oil immersion; picral etch. FIG. 10 (top right). Curved and contorted Neumann bands in kamacite. Clear grains are troilite. Oil immersion; picral etch. FIG. 11 (bottom left). Two distinct areas of different structures in metal; the greater part consists of macroscopic grains with diversely oriented sheen within which is a finer granulation, the remainder resembles a nickel-poor ataxite. Oil immersion; picral etch. FIG. 12 (bottom right). Discontinuous string of chromite in association with troilite. Oil immersion.

Chemical analysis

A 4-g portion of the meteorite was powdered and used for chemical analysis. One portion was dissolved by extraction with 1:1 HCl, followed by alkali fusion of the insolubles, and the principal constituents determined by standard rock-analysis methods. Alkalis were determined by flame photometry after solution of the sample in $HF+H_2SO_4$, and sulphur as $BaSO_4$ after a sodium peroxide fusion. Iron present as metal was determined by extraction of a portion of the meteorite with $HgCl_2$ and titration of the Fe^{2+} with dichromate, and a determination of FeO was made on the material insoluble in $HgCl_2$, following Kondo and Fuke (1958). Water was determined by the modified Penfield method.

A spectrochemical analysis of a portion of the powder for minor constituents gave (all in p.p.m.): Pb 8, Cu 15, Co 720, V 30, Ga 8, Zr 10, Ba 10, and Sr 8; the following were not detected (detection limits in p.p.m. in parentheses): Sn (10), Zn (50), In (2), Ag (1), Mo (2), Ge (2), B (1), La (50), Yt (30), Yb (3), Nb (30), Ta (500), W (200), Li (10), Rb (30).

TABLE I. *Chemical analysis* (A), *Wahl norm* (B), *and modal composition* (C) *of the Sitathali meteorite*

A		B		C	
SiO_2	39·85	Olivine	33·6	Olivine	32·8
TiO_2	0·10	Orthopyroxene	34·5	Orthopyroxene	39·3
		Clinopyroxene	2·5	Clinopyroxene	3·8
Al_2O_3	2·84	Albite	5·5		
		Anorthite	4·7	Plagioclase	5·2
Cr_2O_3	0·35	Orthoclase	0·8		
FeO	13·27	Troilite	5·1	Troilite	4·9
MnO	0·28	Nickel-iron	11·8	Nickel-iron	13·2
MgO	23·01	Chromite	0·5	Chromite	0·3
CaO	1·84	Ilmenite	0·2		
Na_2O	0·65	Apatite	0·6		
K_2O	0·15			*Composition of the phases*:	
H_2O+	0·23			Olivine $Fa_{18}Fo_{82}$	
H_2O-	0·05			Orthopyroxene $En_{81}Fs_{19}$	
P_2O_5	0·25			Plagioclase An_{15}	
FeS*	5·09			Clinopyroxene $Ca_{36}Mg_{52}Fe_{12}$	
Fe	10·22			(observed)	
Ni	1·58			Clinopyroxene $Ca_{33}Mg_{52}Fe_{15}$	
Co	tr.			(calculated)	
Total	99·76				

* Calculated on the basis of S, which is 1·85.

Discussion

The normative mineral composition (table I) is in close agreement with the observed mineralogy. However, there is a slight discrepancy in the plagioclase composition; the Ab:An ratio of the normative plagioclase in the analysis is higher than that of the observed composition. This discrepancy can be ascribed to the assumption in the norm calculation that all Al is combined as feldspar, whereas some is present in the chromite and clinopyroxene, which also contains rather more lime than the norm suggests. However, the R.I. and 2V of clinopyroxenes cannot safely be used as a basis for accurate CaO assessment and hence the discrepancy between clinopyroxene composition observed and calculated is not significant (M. H. Hey, personal communication, 1970). Further it is possible that the orthopyroxene and the olivine also contain some CaO as reported elsewhere in other meteorites (cf. Fredriksson and Mason, 1967). As a result the actual amount of the anorthite component is less than the calculated amount. Normative chromite is more than the amount actually present; most of the chromium is contained in the pyroxenes and the olivine. The titanium content is low and this is present in the silicate minerals since ilmenite as a separate mineral phase has not been noted.

The composition of olivine and orthopyroxene places the Sitathali meteorite in the olivine-bronzite chondrite group of Prior's (1920) classification, though the total iron content, 24·27 wt % is much below the average (28·58 wt %) for the high-iron (H) group of Urey and Craig (1953). According to Keil (1962a, b) the L group shows a Fe/Ni ratio (in metallic nickel-iron, on the basis of superior chemical analysis) ranging from 4·40 to 11·65; on this basis also the Sitathali meteorite with a Fe/Ni ratio of 6·47 could be classified as belonging to the L group; the low total iron suggests that the 4-gm sample was too small to be truly representative. The FeO/(FeO+MgO) ratio (molecular) for the bulk analysis is far too high (24·5); it should be near that for the olivine and the pyroxene. This is strong evidence that the FeO is seriously high, and metallic iron correspondingly low. However, the composition of its olivine and orthopyroxene is like that of the H group chondrites, whereas the L group chondrites have olivine and orthopyroxene considerably richer in ferrous iron.

The morphology would suggest that the convex face was formed first, followed by the wavy face and finally the rough face developed. The lack of regular variation in the fusion crust (heat affected zone) indicates that the Sitathali meteorite has been tumbling and breaking up as it fell through the atmosphere.

The occurrence of skeletal crystals of chromite in chondrules 'frozen to the walls' also suggests that they formed at sufficiently high temperatures. At high temperatures the metal and troilite can be expected to form a liquid, which solidified as globules and droplets. Molten troilite flowed and filled the fractures developed due to local expansion during passage through the atmosphere and shock pressures.

From the features described above for the metal, sulphide, oxide, and silicate phases the following sequence of events in the history of the Sitathali meteorite could be evaluated: The earliest identifiable event was the chondrule and chromite (I) formation; most of the chondrules are free of metal and sulphide minerals and thus preceded the crystallization (or possibly introduction) of the denser opaque minerals. Subsequently the metal and chromite (II) formed. Selective replacement by troilite of kamacite within plessite fields indicates that some troilite crystallized after the metal had cooled enough to permit taenite decomposition. After troilite crystallization the meteorite was subjected to shock deformation as evidenced by the presence of Neumann twin bands in kamacite and twin lamellae in troilite. It is possible that there might have been several such deformational events. The Neumann bands are distorted and offset by a few veins of kamacite due to flowage along zones of weakness following the development of these bands. The time gap between these events is indeterminate. The plessite has grains that are rounded and distorted; this could have been produced by one of these shock events. It is also quite possible that the plessite itself formed in response to an early shock reheating of martensite, according to the model of Wood (1967). Likewise, the rounded, molten troilite globules (with or without intergrowths of kamacite) formed at an unidentified time within this sequence.

The final identifiable event, short of limonite formation on earth, was the melting of the fusion crust with consequent troilite vein development. Thus there is evidence of at least six and perhaps more discrete, sequential events in the history of the Sitathali meteorite. It is possible that these disruptions presumably reflect extraterrestrial impacts and breakups.

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