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ORIGINAL ARTICLE

Formation of FeNi metal nodules in the Jilin H5 chondrite, the largest stone meteorite in the world

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Abstract The Jilin H5 chondrite, the largest known stony meteorite in the world, with its No.1 fragment weighing 1770 kg. It contains submillimeter- to centimeter-sized FeNi metal particles/nodules. Our optical microscopic and electron microprobe analyses revealed that the formation of metal nodules in this meteorite is a complex and long-term process, The early stage is the thermal diffusion-caused migration and concentration of dispersed metallic material along fractures to form root-hair shaped metal grains during thermal metamorphism of this meteorite. The later two collision events experienced by this meteorite led to the further migration and aggregation of metallic material into the shock-produced cracks and openings to form larger-sized metal grains. The shock-produced shear movement and frictional heating occurred in this meteorite greatly enhanced the migration and aggregation of metallic material to form the large-sized nodules. It was revealed that the metal nodule formation process in the Jilin H5 chondrite might perform in the solid or subsolidus state, and neither melting of chondritic metal grains nor shock-induced vaporization of bulk chondrite material are related with this process.

Keywords Jilin chondrite · Metal nodules · Thermal diffusion · Shock metamorphism · Shear movement · Frictional heating

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1 Introduction

The FeNi metal and troilite (FeS) are main constituent metallic minerals in ordinary chondrites. Most of FeNi metal grains in ordinary chondrites are < 0.1 mm^2 when viewed two-dimensionally, but occasionally large FeNi metal grains are encountered (Kong et al. 1998). When > 3 mm in length, the FeNi metal grains are called nodules (Scott 1973; Widom et al. 1986).

Fortunately, in a crushed Jilin chondrite fragment weighing 1500 g we could separated 305.8 g FeNi metal grains of different sizes, from < 0.11 mm to > 10 mm in size (Fig. 1). Among them 37 grains (nodules) are larger than 5 mm, and the largest one is 30 mm in length (Xie and Wang 1992). The chemical composition of FeNi metal grains/nodules of different sizes are listed in Table 1. From this table it can be seen that the Fe content for the large- and very large-sized nodules is a litter higher than that in small-sized grains, but the Ni content is a litter enriched in small-sized particles.

The FeNi metal grains in ordinary meteorites are relatively movable during thermal metamorphism (Wood 1967; Xie and Wang 1979, 1992; Xie and Chen 2020), and the small meal particles could accumulate gradually by thermal diffusion into larger grains (Xie end Wang 1992), and they are easily experienced melting together with iron sulfide (troilite) to form euthectic FeNi–FeS mixtures during shock metamorphism (Ohno 1987; Xie et al. 2001; Chen et al. 2002; Moreau and Schwinger 2021). In the latter case, the melt composition is dominated by iron sulfide. Melting of metals as isolated grains is rarely observed (Bennett and McSween 1996).

Our previous investigation has revealed that during thermal metamorphism of the Jilin H5 chondrite the fine

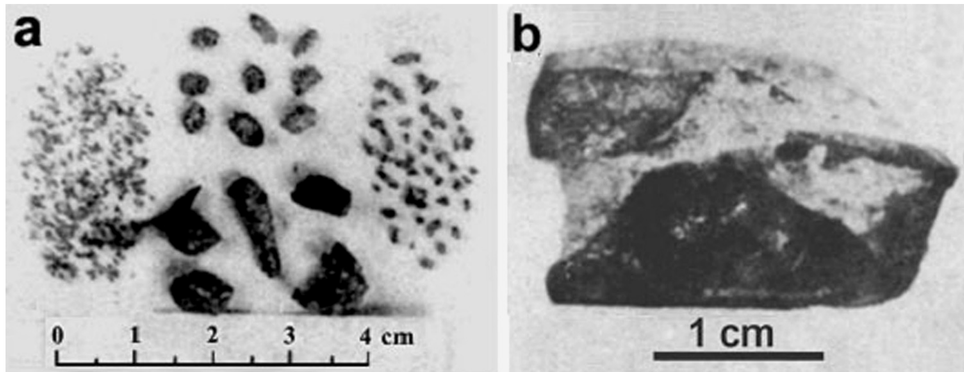

Fig. 1 **a** FeNi metal grains of different sizes. **b** A largest FeNi metal grain of 30 mm in length found in the Jilin H5 chondrite (Xie and Wang 1992)

Table 1 Chemical composition of metal grains of different sizes (%)

	Size (mm)	Fe	Ni	Co	Cr	Total
Small-sized	0.11	90.79	7.83	0.73	0.03	99.38
Small-sized	0.14	90.89	8.31	0.76	0.02	99.98
Middle-sized	0.78	90.36	8.70	0.76	0.01	99.83
Middle-sized	1.08	90.75	8.31	0.75	0.03	99.84
Middle-sized	1.21	91.39	7.84	0.67	0.02	99.92
Large-sized	10.2	92.39	6.58	0.77	0.07	99.81
Very large sized	30.4	92.28	7.48	0.72	0.04	100.52

FeNi metal particles did show some moving ability along some fractures (Xie end Wang 1992). We also investigated the Yanzhuang H6 chondrite and found numerous rounded, elliptic, and elongated FeNi–FeS eutectic nodules/blebs of different sizes (0.1 $\sim$ 11 mm) in its shock-produced melt veins and melt pockets. In these nodules/blebs the FeNi metals in the form of dendrites or round cells are embedded in FeS matrix (Kong and Xie 2003; Xie and Chen 2020). Melted metals as isolated grains were very rarely observed in the Yanzhuang melt regions (Xie and Chen 2020).

The formation mechanism of FeNi–FeS eutectic nodules/blebs in many shock-produced melt veins and melt pockets of ordinary chondrites can be easily understood because the melt regions in ordinary chondrites were heated to peak temperature similar to the melt point of olivine (2049 K). The FeNi metal, sulfide and silicates were melted. During cooling silicates crystallized first from the melt, then the FeNi–FeS mixed melt finally solidified in the form of eutectic nodules and blebs at about 1000 °C (Kong et al. 1998; Xie and Chen 2020).

As for the formation of FeNi metal nodules in the Jilin H5 chondrite, we had proposed a mechanism of diffusion-caused migration + concentration in solid state during thermal metamorphism (Xie and Wang 1992) and then Kong and the author of this paper proposed a mechanism by subsolidus diffusion along grain boundaries in parent body during metamorphism (Kong et al. 1998). But our recent microscopic observations, electron microprobe (EPMA) analyses on the Jilin metals have revealed that the metal particles can only be aggregated into grains smaller then 1–2 mm in size by the diffusion-caused migration and concentration during thermal metamorphism. The shock-induced fractures/cracks, shear movement and friction heating in chondrite could facilitate the migration and aggregation of metallic material and formation of metal nodules in the Jilin chondrite, but no shock melting and vaporization is concerned in this aspect. In this paper we report our new summary on the formation mechanism of FeNi metal nodules in the Jilin H5 chondrite.

2 Samples and methods

The Jilin meteorite is the largest stone meteorite in the world. Its main body (No. 1 meteorite) is 1770 kg in weight, and the other fragments weigh more than 600 kg (Xie and Wang 1992). Photographs of Jilin meteorite hand specimens were obtained by using Huawei Mate 30 Pro 5G cell phone. Polished thin sections of this meteorite were prepared from its fragments. The mineral occurrences in thin sections were investigated by optical microscopy using a Leica DM2500p microscope. A Shimadzu 1720 electron microprobe (EPMA) was used to study the chemical composition of metals of different sizes using the wave length dispersive technique at 15 kV accelerating voltage and beam current of 10 nA. Natural and synthetic phases of well-known compositions were used as standards, and the data were corrected using a ZAF program.

We also manually crushed a specimen weighing 1.5 kg from Jilin No. 2 meteorite. The separation of metal grains and nodules from the specimen was effected by hand sorting, sieve and magnet separation. The results show that the metal grains in the Jilin meteorite generally within the range of 0.2–0.8 mm in size, and there also exist small metal particles of 0.01–0.1 mm and some large grains up to 8–10 mm across. Three types of samples, small-sized

(< 0.2 mm), medium-sized (0.5–2 mm) and large-sized (> 3 mm) metal grains mounted in epoxy resin were chosen for EPMA analysis.

3 Results

3.1 Occurrence of the small-sized chondritic metal particles

The FeNi metal in the Jilin meteorite occur mostly as irregular fine particles dispersed in the chondritic matrix, packing interstitially in the grains of olivine and pyroxene or distributed on the rims of silicate chondrules. Additionally, fine metallic particles occurred in the manner of dissemination may be seen in a variety of meteoritic chondrules. It is believed that the small-sized metal particles in ordinary chondrites were formed in the stage of condensation of solar nebula (Ouyang et al. 1978).

The chemical composition of FeNi metal grains of different sizes are listed in Table 1. From this table it can be seen that the Fe contents for the small- and medium-sized metals are a litter lower than that in large- and very large-sized nodules, but the Ni contents are slightly higher in small- and medium-sized grains.

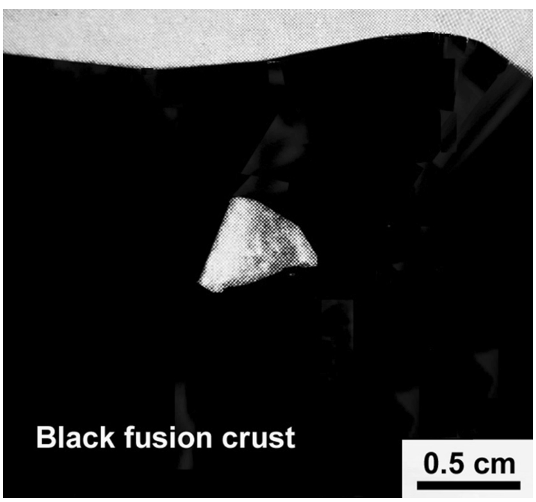

Fig. 2 A large-sized metal nodule exposed on the surface of a Jilin meteorite fragment

3.2 Formation mechanism of the large-sized metal nodules

The large-sized metal nodules of > 3 mm across can be observed inside some fragments of the Jilin meteorite (Fig. 1). Some large metal nodules even exposed on the surface of individual fragments (Fig. 2). It is believed that the formation of large- sized metal nodules in the Jilin meteorite is not by a simple mechanism but through a combination of several factors related to thermal metamorphism and shock metamorphic events. In the following sections we shall discuss them in more detail.

3.2.1 Thermal diffusion-caused migration and concentration of metal

Our previous studies revealed that the Jilin meteorite had experienced thermal metamorphism (Xie and Wang 1979; Xie and Huang 1991). From fluid inclusion studies we found that the Jilin meteorite may have been thermally altered at temperature close to 800 ± 150 °C (Xie and Wang 1992). Under such circumstances the small metal particles dispersed in the Jilin meteorite become relatively movable and may gradually aggregate by diffusion to form larger metal grains after a short-distance migration and concentration. It was found that some medium-sized metal grains are irregular in shape, some are situated in between two almost perpendicularly intersected fractures (Fig. 3a),

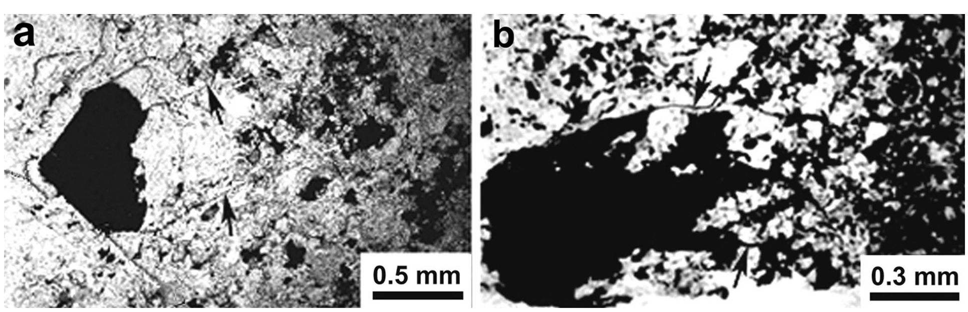

Fig. 3 **a** A medium-sized metal grain No. 1 observed on the polished section prepared from the sample of Jilin No. 1 meteorite. Note the fine metal particles are remarkably decreasing around it and jointing with fractures of different directions. **b** A medium-sized metal grain No. 2 from sample G-62. Note its root-hair shape and jointing with fractures (parallel polarized light)

and some of them being root-hair-shaped, jointing with the fractures developed in the meteorite (Fig. 3b).

It can be seen from Fig. 3a that the medium-sized metal grain No 1 is about 1 mm in length and there almost no small metal particles exist around this grain, but in some distance away abundant small metal particles of 0.01–0.05 mm in size are increasingly distributed in the silicate groundmass. Furthermore, well developed irregular fractures of different directions are connected with this metal grain. It is not hard to image that this metal grain most probably resulted from the clustering of the surrounding fine metal particles by thermal diffusion and concentration during the thermal metamorphism of this meteorite, because the temperature at this period can reach to 800 ± 150 °C (Xie and Wang 1992) or 1100–1000 K (Ouyang et al. 1978).

The Fig. 3b shows another medium-sized metal grain No. 2 which is root-hair shaped and about 1 mm in length and 0.6 mm in width. This metal grain is also jointing with fractures. The width of fractures in direct contact with the metal grain is greatly increased. Some small inclusions of silicate minerals can be observed inside this metal grain. These specific features and the root-hair shape indicate that the metal grain No. 2 is still at the stage of growing and the metallic material has not completely migrated and concentrated to form an intact metal grain.

On the basis of above described points it is suggested that the medium-sized metal grains in the Jilin meteorite could be formed by thermal diffusion-caused migration and concentration of metallic material along preexisted and well developed fractures during the period of the thermal metamorphism of the meteorite. However, it is easily to imagine that the centimeter-sized metal nodules could not be formed simply through thermal diffusion-caused migration and concentration alone. For formation of large-sized metal nodules there should be additional factors that could increase the mobility of metallic material and create necessary openings to accommodate this material.

3.2.2 Migration and aggregation of metal particles to the shock-produced openings

It has been revealed that the Jilin meteorite had been experienced collision events before it fell to the earth (Xie and Huang 1991). Based on the $^{40}Ar/^{39}Ar$ determinations of three Jilin meteorite fragments, Wang et al. (1980) proposed that the Jilin meteorite had experienced at least two significant collisions: one at 2.2 Ga and the other at 0.5 Ga. The temperatures attained in meteorite samples during these two events were estimated to be 300 °C and between 495 and 500 °C, respectively.

In the thin sections of Jilin meteorite we observed some shock-induced fractures/cracks filled with black iron materials in their widened parts (Fig. 4a). We also found some conjugate fractures in two groups and disorderly distributed fractures in the heavily fragmented silicate matrix (Fig. 4b).

Interestingly, the late Prof. Shuyuan Zhang of the Peking University also observed the above mentioned shock-induced fractures/cracks in the Jilin meteorite (Personal communication). She called them shear fissures and tension fissures. The flash tension fissures and conjugate shear fissures are widely spread in the Jilin meteorite. Both they are filled with black metallic materials. She introduced that besides filling along the fissures the black iron materials are concentrated mainly near some of the complex spots of the structure, such as the conjugate spots of the fissures (Fig. 5a), the space in the joint of plumose and fissure staircase form (Fig. 5b), the position of the rhombic knot (Fig. 5c), and the space in the joint of curved and irregular fissures (Fig. 5d).

Fortunately, we observed an FeNi metal nodule of 6 mm in size in a hand specimen of the Jilin meteorite. This nodule is tightly connected with several radiating and irregular fractures and net-shaped cracks (Fig. 6). It is self evidence that the formation of this metal nodule is

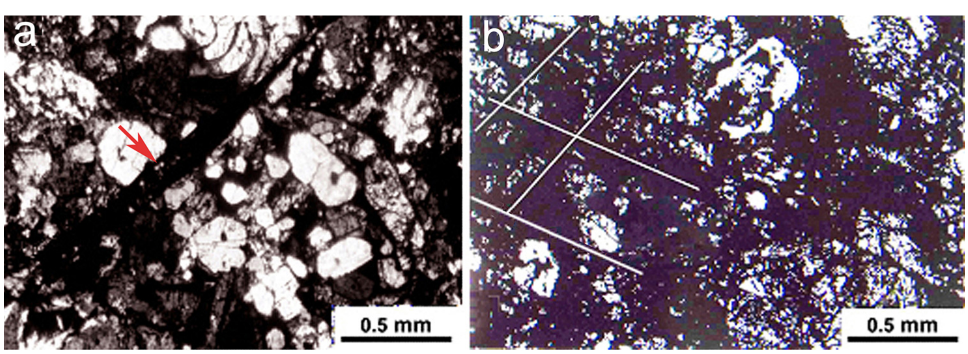

Fig. 4 Optical microscopic photographs of Jilin meteorite under parallel polarized light. **a** A shock-induced fracture filled with black iron material in its widened part (arrow). Note the black disorganized fractures at the lower left area. **b** Conjugate fractures in two groups (left part) and disorderly distributed fractures (right part). Note the silicate minerals are heavily fragmented

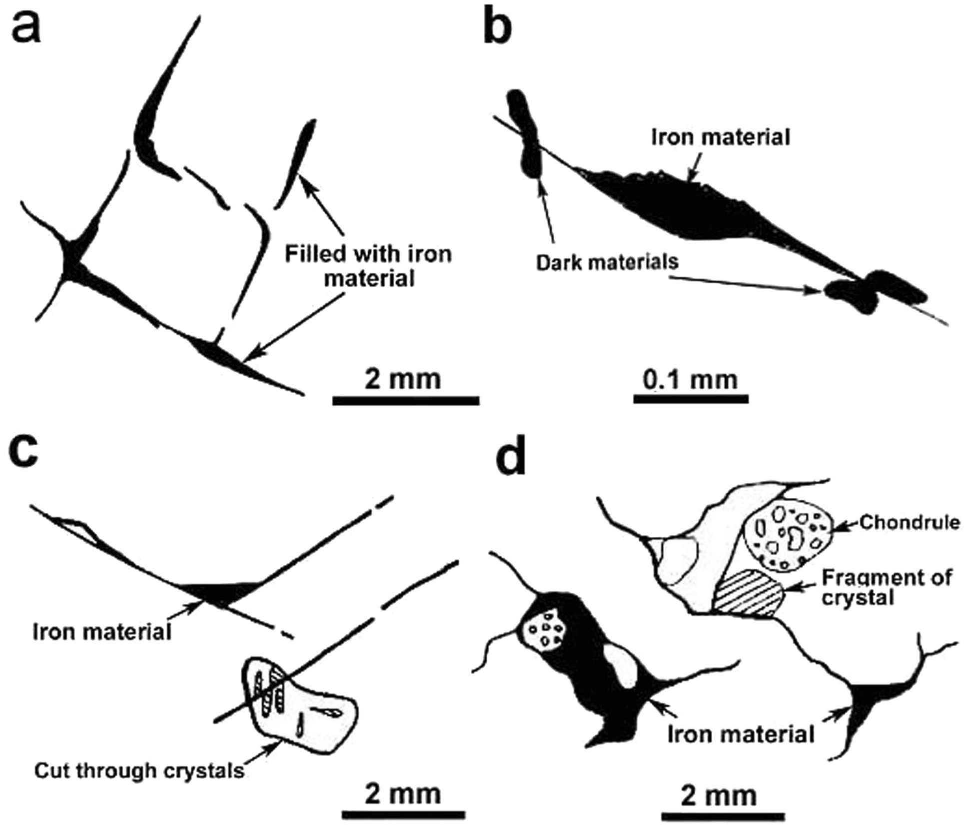

Fig. 5 Tension fractures and cracks filled with iron material observed in the Jilin meteorite. **a** Conjugate phenomena of shear fissures. **b** Staircase-formed plumose of shear fissures. **c** Conjugate fissures in two groups. **d** Net characteristics of shear fissures. Note the medium-sized irregular-shaped metal grain in its left part, and small silicate fragments are enclosed in this metal grain.

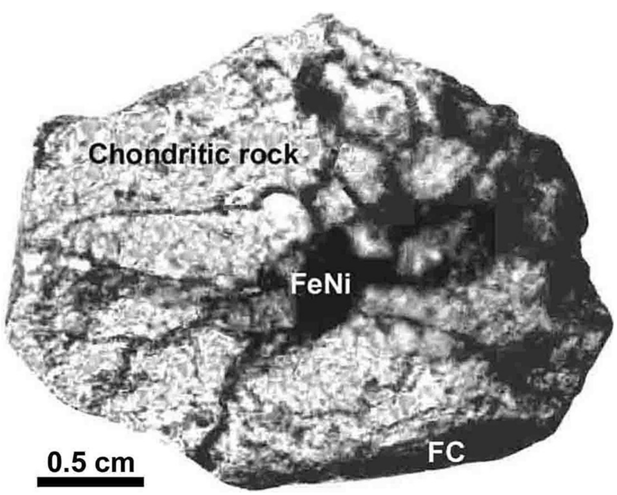

Fig. 6 Photograph of a hand specimen of the Jilin meteorite showing an FeNi metal nodule connected with radiating and irregular fractures and net-shaped cracks. FC = fusion crust

undoubtedly related with the presence of these shock-produced two-dimensional destructive structures in meteorite.

To sum up, the shock-induced fractures/cracks or fissures and the space they created in the Jilin meteorite provided the passageway for increased migration of iron material and the openings for its continuous aggregation in them.

3.2.3 Enhanced migration and growth of metal grains by shock-produced shear movement and frictional heating

As we have mentioned in the previous section that the Jilin meteorite had experienced at least two significant collisions. One of the consequence of these events is the production of shock-induced shearing movement and frictional heating as well as the formation of very thin shock melt veinlets inside the Jilin chondritic rock. Hence, we could observe plenty of scratch surfaces with slickenside lines by naked eye in the hand specimens of this meteorite. Figure 7 shows four Jilin hand specimens containing such well developed shock-induced structures. Based on the presence of skickenside lines on the scratch suface and the coexisting shock melt veinlets, the shearing- and friction-caused temperature might reach 1000 °C.

The shock-produced shear force and frictional heating would certainly enhance the movement and aggregation of iron material to form the metal nodules in the Jilin meteorite. We actually found a metal nodule of more than 1 cm across on a scratch surface with clear slickenside lins in one direction in a Jilin hand specimen (Fig. 8a). Electron microprobe analysis of this nodule gave the following results (in wt %): Fe-92.41, Ni-6.47,

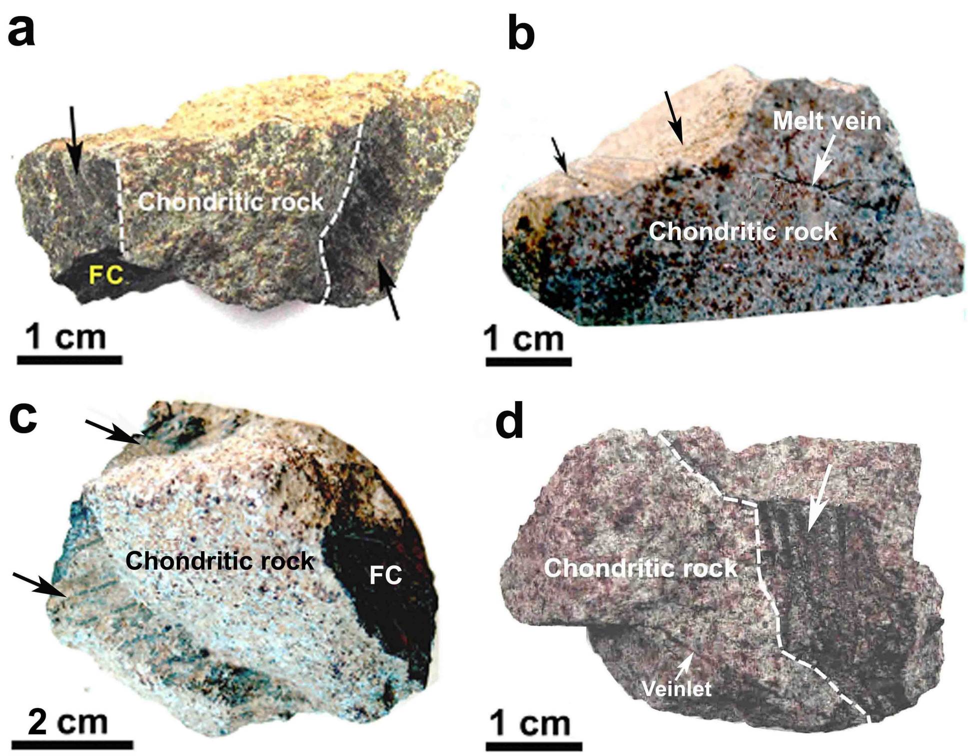

Fig. 7 Photographs of hand specimens of the Jilin meteorite showing the well developed scratch surfaces with clear slickenside lines (arrows). Note the black fusion crust (FC) in (**a**) and (**c**), and shock melt veins in (**b**) and (**d**)

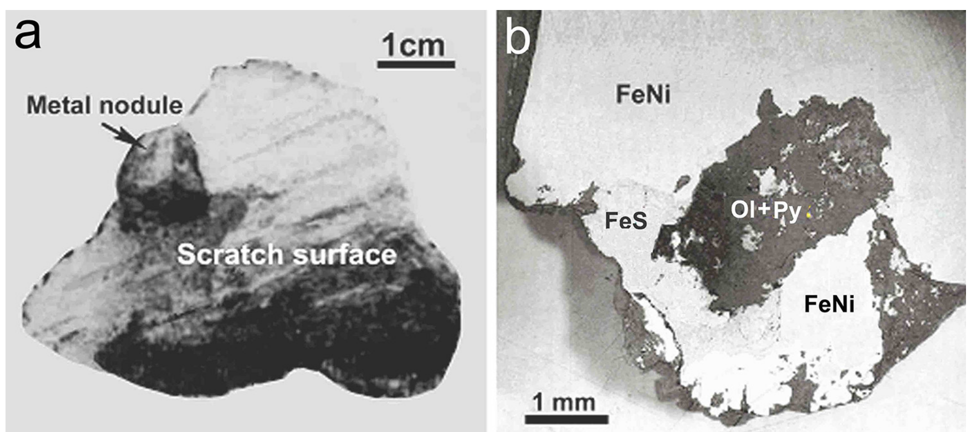

Fig. 8 **a** Photograph of a hand specimen of Jilin meteorite showing a metal nodule occurring on the scratch surface with slickenside lines. **b** Part of the polished section of the metal nodule shown in (**a**). Note the dark minerals enclosed by metal are olivine (Ol) and pyroxene (Py), and sulfide (FeS) is pare grey in this picture (Kong et al. 1998)

Co-0.48, Cr-0.09, total-99.45. This composition indicates that this metal nodule is consisted of common kamacite, an alloy of Fe and Ni, and the Ni content is in the range of 5–7%. The polished section prepared from this metal nodule shows that the surface of this nodule is smoosh and it occurs in close contact with a troilite grain and an irregular–shaped silicate fragment consisted of olivine and pyroxene (Fig. 8b). There is no eutectic FeNi–FeS blobs and molten silicate minerals ware observed. This indicates that this large enough metal nodule was formed neither via melting nor from vaporization of metallic material.

4 Discussion

Metallic nodules are common in metamorphosed ordinary chondrites. Since such nodules are not found in unequilibrated ordinary chondrites, the nebular origins proposed for FeNi metal nodules were not very compelling. Hence, the mechanism of the formation of metal nodules has been debated for rather long time (Pekeroglu 2012). Several proposed scenarios, e.g., the metal nodules could be shock melted products of chondritic metal grains (Widom et al. 1986; Rubin 1999), and/or could be formed by shock-induced vaporization of bulk chondrite material consisting of small metal grains, silicates, and troilite (Widom et al. 1986), or formed by diffusion and aggregation in solid state

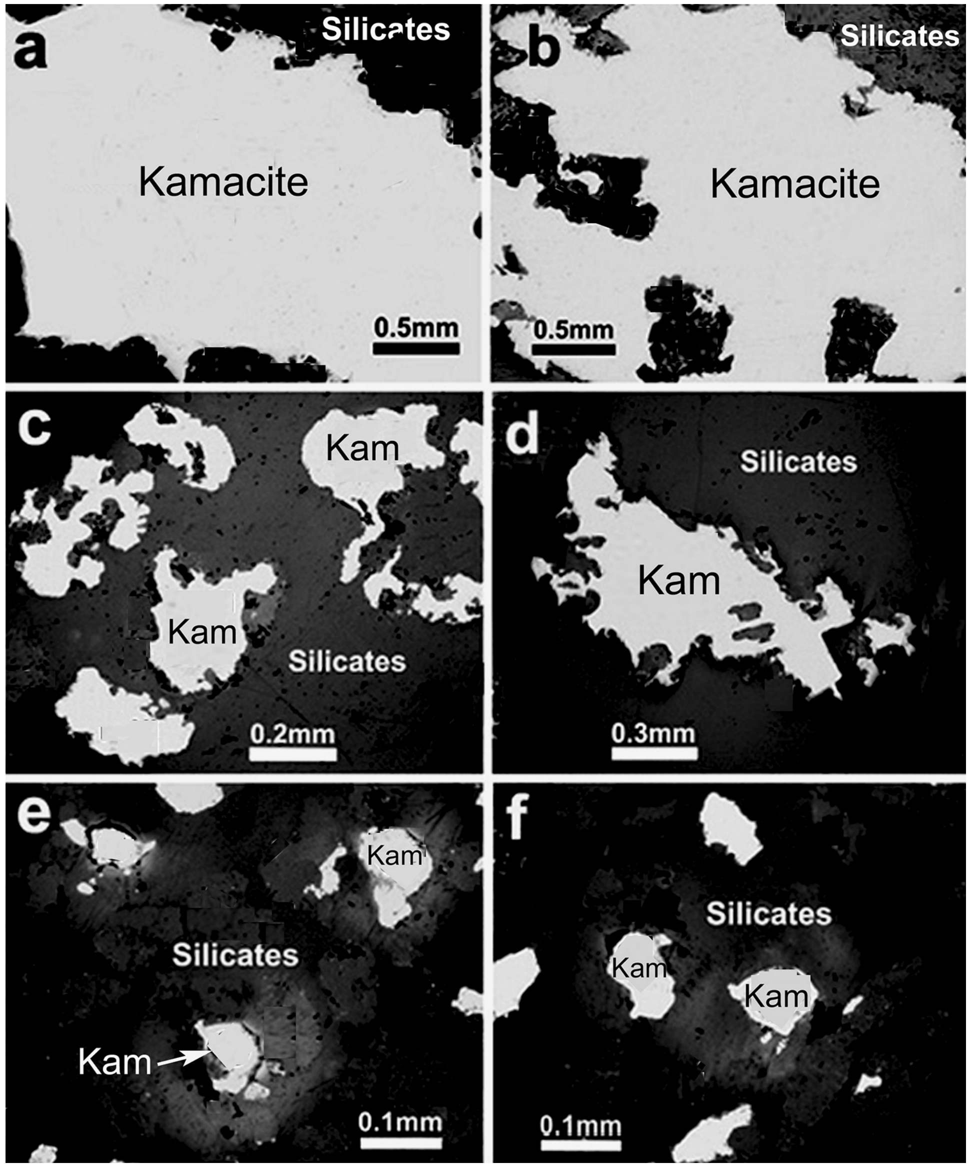

Fig. 9 Reflect light microphotographs of pure kamacite (Kam) grains of different sizes in the Jilin meteorite. **a**, **b** the large-sized nodules; **c**, **d** the medium-sized grains; and. **e**, **f** small-sized particles

during thermal and shock metamorphisms (Xie and Wang 1992), or by subsolidus diffusion along grains boundaries during metamorphism in the parent body (Kong et al. 1998).

In view of the fact that the Jilin H5 chondrite is the largest stone meteorite in the would, and plenty of millimeter- and centimeter-sized FeNi metal nodules could be easily observed by naked eye inside or even on the surface of it, a detailed investigation into such huge meteorite would undoubtedly provide us with a lot of clues and information valuable in the study of the behavior of FeNi metal during thermal and shock metamorphisms.

The results of our present investigations show that the formation of metal nodules in the Jilin H5 meteorite is a complex and long-term process in the history of this meteorite, that is thermal diffusion-caused migration and concentration of metallic material during thermal metamorphism, and the later collision events experienced by this meteorite led to the further migration and aggregation of metallic material into the shock-produced cracks and openings to form medium-sized metal grains, and the shock-produced shear movement and frictional heating in the chondritic rock greatly enhanced the migration and aggregation of metallic material to form large-sized nodules. The following clear evidences show that all these processes performed in the solid or subsolidus state, and no melting or vaporization is concerned with the formation of metal nodules.

Table 2 Concentration ratios between metal nodule/bulk metal fractions in Jilin chondrite and melted metal grains/bulk metal in Yanzhuang chondrite (concentration in ppm unless otherwise indicated)

Elements	Jilin H5 chomdrite*			Yanzhuang H6 chondrite**		
	Metal nodule	Bulk metal	Nodule/Bulk metal	Melted metal	Bulk metal	Melted/Bulk metal
W	0.991	0.858	1.155	0.984	1.043	0.943
Re (ppb)	8.547	350	0.024	383	276	1388
Os (ppb)	216.3	3540	0.063	4140	2180	1899
Ir (ppb)	22.72	3220	0.007	4103	1913	2145
Mo	4.763	3.96	1.203	4.84	4.19	1.155
Ru	0.295	6.65	0.044	8.012	4.522	1.772
Pt	1.197	9.05	0.133	9.13	7.35	1.242
Rh	0.290	0.75	0.387	1.114	0.911	1.223
Ni (%)	7.512	8.50	0.884	8.63	7.23	1.194
Fe (%)	90.87	90.50	1.004	90.3	91.3	0.989
Co	5288	4940	1.071	4710	4860	0.969
Pd	2.200	2.78	0.884	3.32	3.16	1,051
Au	14.67	14.2	1.033	1.113	1.013	1.099
Cu	132.9	237	0.561	274	104	2.635
Sb	452.5	492	0.920	0.396	0.586	0.676
Ga	12.20	12.8	0.956	26.63	11.93	2.232
Ge	68.50	123	0.557	–	–	–

*Data taken from Kong et al. (1998); **Data taken from Kong and Xie (2003)

(1) Melting of metals as isolated grains is rarely observed in ordinary chondrites (Bennett and McSween 1996), but FeNi metal grains in these meteorites are easily experienced melting together with iron sulfide (troilite) to form euthectic FeNi–FeS mixtures during shock metamorphism (Ohno 1987; Xie et al. 2001; Chen et al. 2002). However, we have not found any euthectic FeNi–FeS mixtures in the Jilin chondritic rock. All the isolated FeNi metal grains of different sizes in this meteorite are of pure kamacite (Fig. 9). Their chemical compositions also show that all these metal grains do not contain any sulphur (Table 1). Furthermore, a large-sized metal nodule we found in a hand specimen of the Jilin chondrite is in close contact with a troilite (FeS) grain but both they did not experienced melting to form eutectic FeNi–FeS mixture (Fig. 8b).

(2) Surprisingly, all the metal grains and nodules we studied are irregular shaped, especially, the configurations of large-sized metal nodules and medium-sized metal grains are extremely complicated and irregular, mostly sawtooth-, baymouth-, root-hair and rhizome-shaped (Fig. 9). This implies that all they formed by diffusion and aggregation of metallic materials in solid or subsolidus state.

(3) The trace element distribution patterns obtained from metal nodules in the Jilin H5 meteorite (Kong et al. 1998) and from melted metal grains in the Yanzhuang H6 chondrite are quite different (Kong and Xie 2003). The concentration ratios of rare earth elements, especially Ir, and chalcophile element Cu for metal nodules of the Jilin meteorite show negative anomaly, while those for shock-melted metals of Yanzhuang chondrite show positive anomaly (Table 2; Fig. 10). This result indicates that the formation of metal nodules in the Jilin meteorite could not be related with shock melting.

(4) The Jilin H5 chondrite did experience thermal and shock metamorphisms, but the temperature at the period of thermal metamorphism only reached to 800 ± 150 °C (Xie and Wang 1992) or 1100–1000 K (Ouyang et al. 1978), and the temperatures attained in the Jilin meteorite samples during the two collision events were estimated to be 300 °C and 450–500 °C, respectively (Wang et al. 1980). These thermal- and shock-metamorphism-produced temperatures are lower than the melting points of pure Fe (1535 °C) and pure Ni (1453 °C), and obviously much lower than the vaporization point of Fe and Ni. This is consistent with the conclusion given by Bennett and McSween (1996): melting of

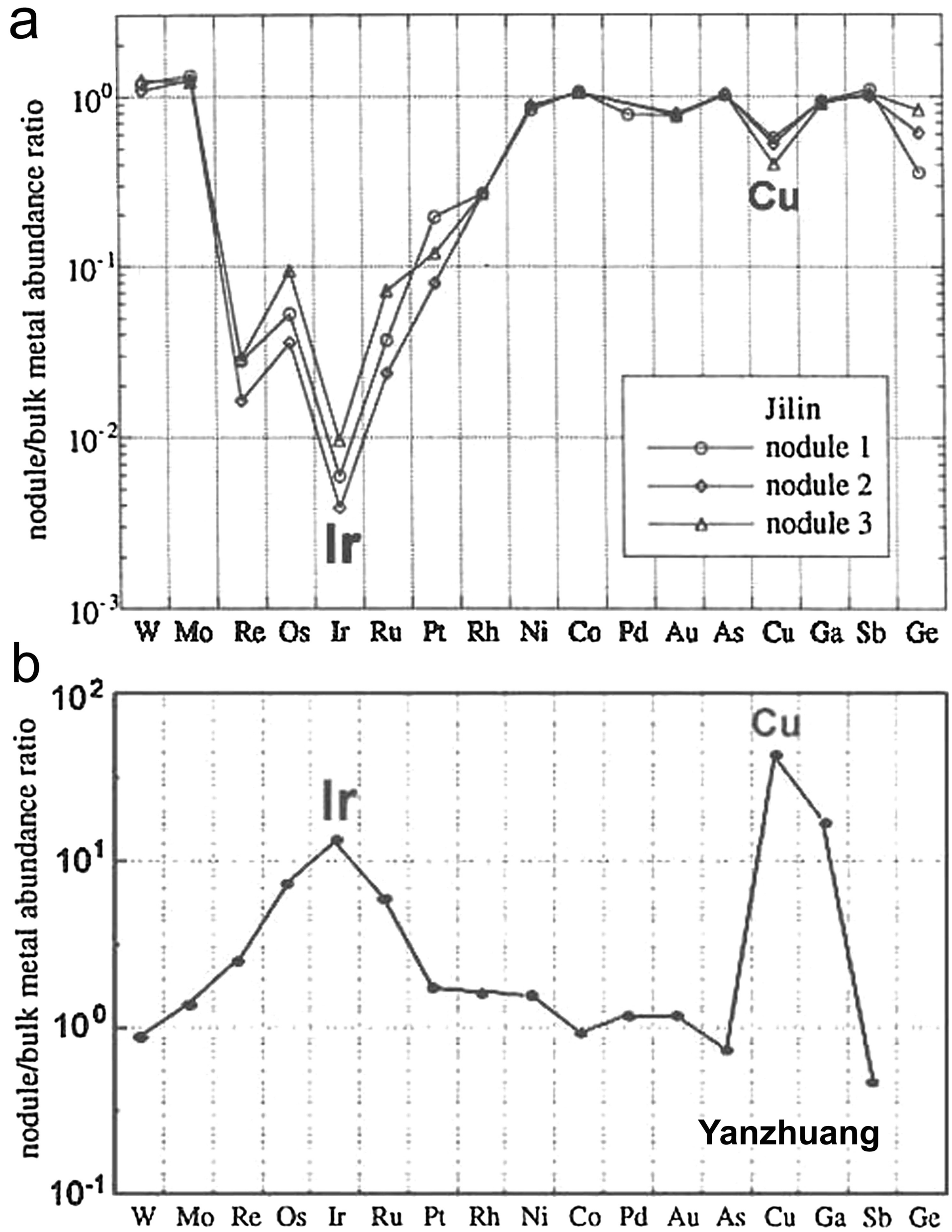

Fig. 10 **a** Concentration ratios between metal nodules and bulk metal fractions in the Jilin H5 meteorite (after Kong et al. 1998). **b** Concentration ratios between melted metal and unmelted metal grains in the Yanzhuang H6 chondrite (Data from Kong and Xie 2003). Note the big difference in concentrations ratios of Ir and Cu between these two chondrites

metals as isolated grains is rarely observed in ordinary chondrites.

(5) Moreau and Schwinger (2021) reported that the metallic iron experienced low degree of shock heating in ordinary chondrites. They indicated that the iron metal does not melt primarily by shock heating but by diffusion of heat from adjacent, strongly shock heated phases. They indicated that localized melting of iron metal in shocked ordinary chondrites is strong depending on the textural context (i.e. type of adjacent phases, eutectic mixtures).

5 Conclusion

1. The Jilin H5 chondrute contains FeNi metal grains of different sizes, from small-sized particles (< 0.2 mm), to medium-sized grains (0.5–2 mm) and large-sized nodules (> 3 mm), and the largest one is 30 mm in length.
2. The formation of metal nodules in the Jilin meteorite is a complex and long-term process in the history of this meteorite. The first stage is the thermal diffusion-caused migration and concentration of small metal particles dispersed in this meteorite along fractures to

form medium-sized root-hair shaped grains during thermal metamorphism of this meteorite.

3. The later two collision events experienced by the Jilin meteorite led to the further migration and aggregation of metallic material into the shock-produced cracks and openings to form larger-sized metal grains. The shock-produced shear movement and frictional heating occurred in this meteorite greatly enhanced the migration and aggregation of FeNi metal to form the large-sized nodules.
4. The metal nodule formation processes were performed in the solid or subsolidus state, and no melting of chondritic metal grains or shock-induced vaporization of bulk chondrite material is related with the formation of metal nodules in the Jilin H5 chondrite.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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