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Mechanical transport of metallogenic materials in endogenic hydrothermal solutions: evidence from the microspherules in micro-disseminated gold deposits, northwestern Sichuan, China

Jiajun Liu[a,b,*], Minghua Zheng[c], Jianming Liu[d], Xuexiang Gu[a], Yufeng Zhou[b], Caixia Feng[a]

[a]Open Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China
[b]China University of Geosciences, Beijing 100081, China
[c]Institute of Mineral Deposits, Chengdu University of Technology, Chengdu 610059, China
[d]The Research Center of Mineral Resources Exploration, Chinese Academy of Sciences, Beijing 100101, China

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Abstract

Numerous steel-gray microspherules were recently unexpectedly discovered in ore and rock samples from several disseminated gold deposits hosted in Middle–Upper Triassic turbidites in northwestern Sichuan Province, China. Both nature surfaces and part sections of 227 microspherules have been observed by reflected light microscope, scanning electron microscope (SEM), electron microprobe analyses, X-ray energy spectra, X-ray powder patterns, the results reveal them to be cosmic dust. It is the first discovery of cosmic dust in this kind of deposits in China.

The size of the microspherules ranges from 25 to 185 μm and generally is less than 100 μm. According to their composition, they belong to chromium-rich iron cosmic dust. The microspherules have complex, diverse and diagnostic microscope structures and textures, and such as very distinct airprint structure that are compatible with extraterrestrial material. Variation of geochemical content of the microspherules in the gold deposits in generally positively correlates with both the Ir content of the enclosing strata and the intensity of mineralization and hydrothermal alteration. The abnormally high content of Ir is important evidence for an extraterrestrial source for the microspherules. The fact that a geological body with strong alteration and mineralization is rich in microspherules may raise a new concept: Under endogenic conditions, it is not only possible but also realistic for mineralized material to be transported mechanically, in addition to the generally accepted chemical transport of ore constituents in hydrothermal solution because it is obviously impossible for cosmic spherules to fall directly from space into cemented hydrothermal ore veins more than 1 km deep in the earth.

Keywords: Microspherule; Cosmic dust; Gold deposit; Mechanical transport; Northwestern Sichuan, China

* Corresponding author. Open Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China.

E-mail addresses: jiajunl@public.gz.cn, jiajun_liu@hotmail.com (J. Liu).

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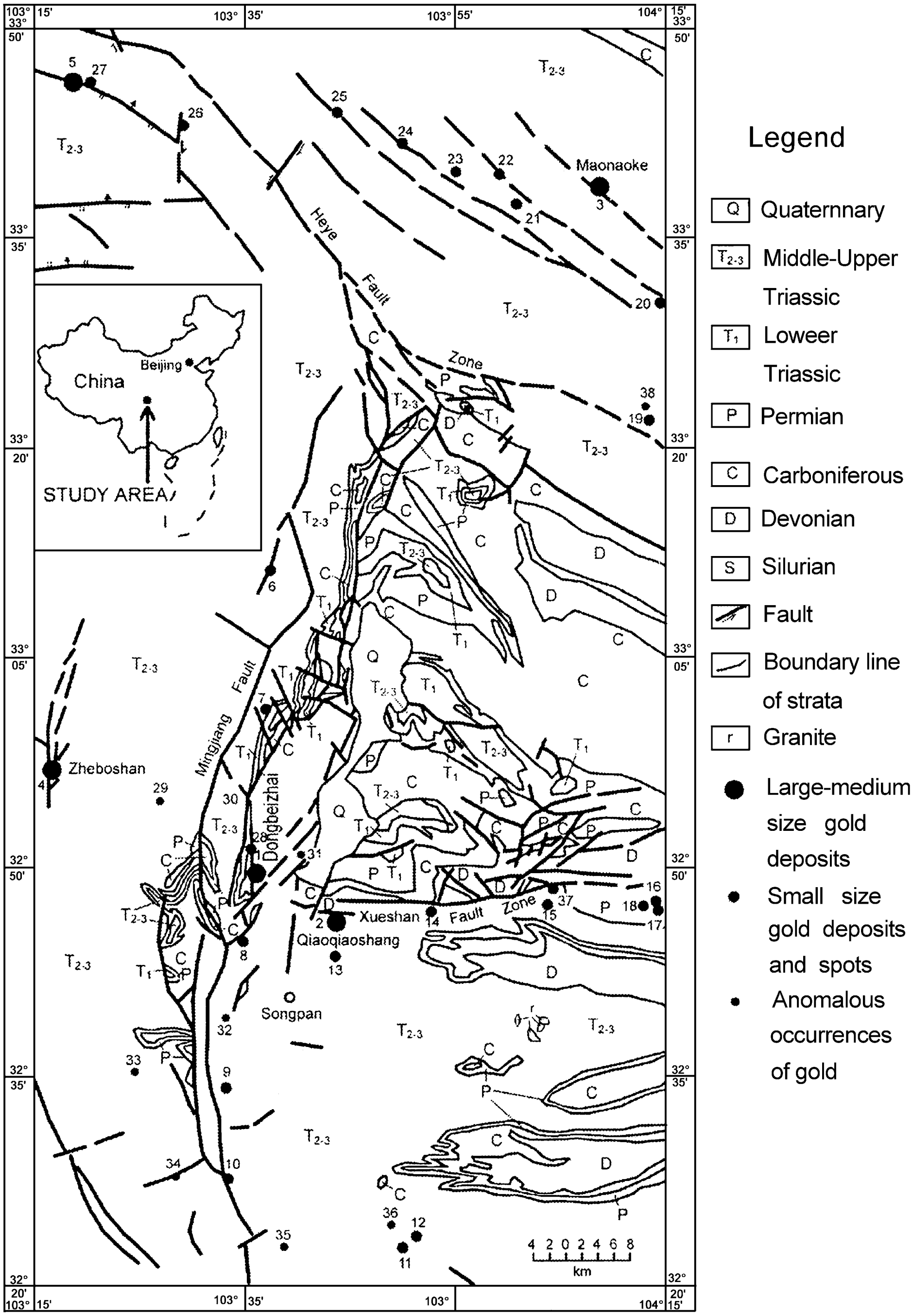

Fig. 1. Generalized geological map of the study area in NW-Sichuan, China (after Zheng et al., 1994). (1) Dongbeizhai, (2) Qiaoqiaoshang, (3) Manaoke, (4) Zheboshan, (5) Baxi, (6) Tatama, (7) Xianglatai, (8) Dagou, (9) Rongbagou, (10) Nanggai, (11) D86, (12) D76, (13) Jingou, (14) Huanglong, (15) Dawan, (16) Longdishui, (17) D42, (18) D39, (19) D119, (20) Heihexiang, (21) Raolagou, (22) Shuishengou, (23) Dalugou, (24) Xiangzhagou, (25) Badun, (26) Xiabaozuo, (27) Tuanjie, (28) Yanshuigou, (29) Shaigagou, (30) Yayigou, (31) Heisigou, (32) Ganhaizi, (33) Segong, (34) Rewugou, (35) Rebeigou, (36) Beidinguan, (37) D47, (38) D116.

1. Introduction

Transport mechanisms of metallogenic materials during endogenic hydrothermal mineralization is an issue that ore geologists pay close attention to (Sorokin, 1973; Hodder and Briggs, 1993; Zheng, 1993). Forms of sulfide and halide materials, dissoluble complexes and colloidal materials have been studied in order to explain the transport of metallogenic materials in endogenic hydrothermal solutions (Liu et al., 1994; Liu, 1997). All of these transport forms are based on the solubilities of the metallogenic materials, that is, they are based on the assumption that transport of metallogenic materials is by chemical solution. While researching the Carlin-type (micro-disseminated) gold deposits in northwestern Sichuan, China (Fig. 1), the authors unexpectedly found numerous microscopic grains of cosmic dust, in country rocks, hydrothermal gold ores and/or in the Au-bearing hydrothermal veins such as stibnite–realgar–quartz vein and realgar–calcite vein. This paper describes evidence for extraterrestrial origin of the microspherules and for their mechanical transport in hydrothermal solution.

2. Methods

Most microspherules have been identified in selected mineral separates of heavy mineral concentrates from country rock and various hydrothermal ore types, such as gold–realgar–quartz ore, gold–realgar–stibnite–quartz ore and gold–realgar–pyrite–quartz–calcite ore (Fig. 2) in the Dongbeizhai, Manaoke and Qiaoqiaoshang gold deposits, northwestern Sichuan Province, China (see Fig. 1).

The microspherules were first picked out manually under a binocular microscope and petrographic microscopes and were cleaned ultrasonically and washed with acetone, and then photographed with a scanning electron microscope (SEM) to examine morphology (Figs. 3 and 4). An energy dispersive X-ray analyzer (EDX) equipped with SEM provided qualitative or semiquantitative element compositions of the microspherules. Selected microspherules were mounted in epoxy and sectioned and polished to expose a flat surface. Polished sections were analyzed with an electron microprobe to obtain quantitative chemical compositions. Pure metals were used as standards for Ni, Co, Cr and Mn; magnetite and quartz were used as standard for Fe and SiO_2; pyrite, arsenopyrite, edisonite and SbIn were used as standards for S, As, Ti, Sb, respectively. A 10-μm beam diameter was used when probing the spherules. All analyses were carried out at 20–25 kV accelerating voltage with 20 s counting. The results were corrected using $\Phi-\rho-\zeta$ program. The homogeneity of the spherules was investigated by analyzing at least four random spots on the microspherules. Once homogeneity (<1 wt.%) was confirmed, two domains were analyzed on each microspherule, one at the rim, and the other near the center. The experimental conditions of X-ray analysis were: camera Φ57.3 mm; iron target; light-filter-free; voltage 35 kV; electric current 10 mA; exposure time 6 h.

Data on microstructural features, chemical composition, mineral composition, and other features of the microspherules, described below, leave no doubt that the microspherules originated as cosmic dust because their morphology and surface textures are similar to cosmic Fe spherules and contain wüstite but have a low Ni content.

3. Geological features of the gold deposits

In the 1980s and 1990s, northwestern Sichuan Province has been acknowledged as one of the most important and potential gold producers in China and has attracted world-wide attention, largely because of the discovery of a series of sedimentary rock hosted micro-disseminated gold deposits in Middle–Upper Triassic strata (Zheng et al., 1994; Gu, 1996). The gold deposits are stratabound in specific host strata horizons. Because of the micro-disseminated form of gold in ores and other mineralogical and geochemical characteristics, the deposits are considered to be comparable with the so-called "Carlin type" deposits in the USA (Zheng et al., 1994; Gu, 1996; Liu and Liu, 1997; Liu et al., 1997, 1998). The fundamental mineral compositions of ores are the same: major compositions are realgar and pyrite; minor compositions are stibnite, arsenopyrite and arsenic. Scheelite is common associated with a few deposits, such as the Manaoke deposit (Zheng et al., 1993a, 1994). Essentially two types of ore mineralization are recognized in the gold deposits. The sedimentary stratiform ores are composed of

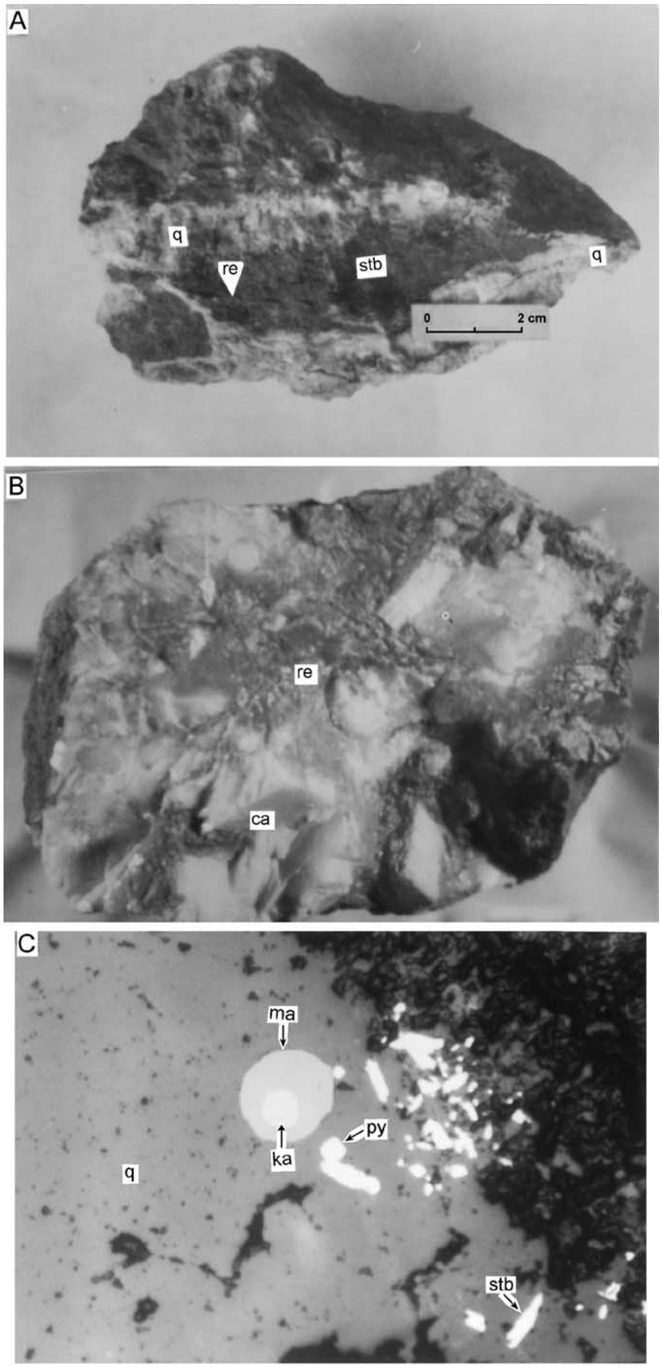

Fig. 2. The Au-bearing hydrothermal ores in which several microspherules were found. Abbreviations: stb = stibnite, re = realgar, q = qurtz, ca = calcite, py = pyrite, ma = magmetite, ka = kamacite. (A) Stibinite–realgar–quartz vein from Manaoke PD5 tunnel. (B) Realgar–calcite vein from Dongbeizhai PD78 tunnel. (C) Microspherule-bearing stibnite–pyrite–quartz vein from Manaoke prospecting line 8, polished, (–). The sight diagonal linear measure is 0.38 mm.

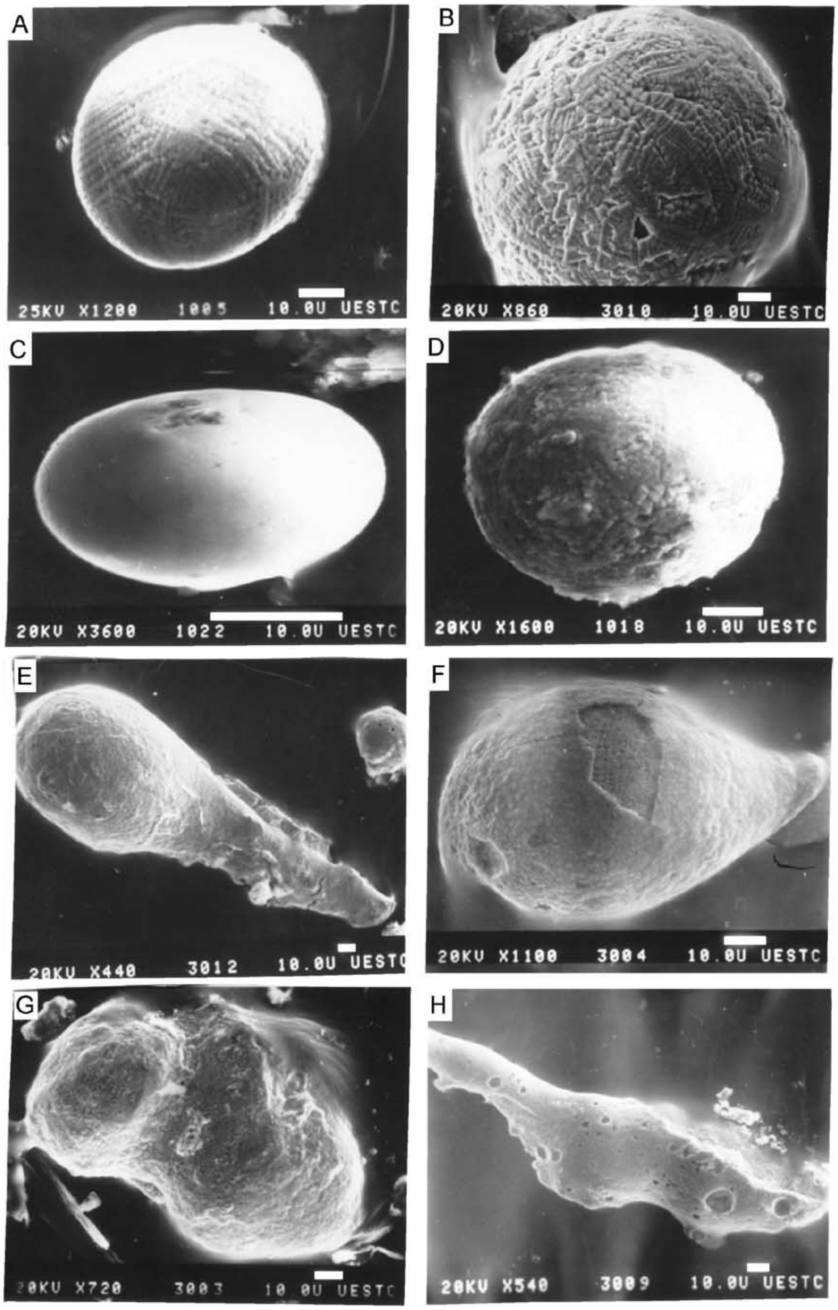

Fig. 3. Scanning electron micrographs of black, magnetic Fe spherules recovered from the micro-disseminated gold deposits, NW-Sichuan, China. (A) Iron cosmic dust, spheroid, mymekitic or sheet-grain-like structure on surface; × 1200; (B) iron cosmic dust, spheroid, mymekitic or sheet-grain-like structure, arrangement of somewhat disorderly crystallites; × 860; (C) iron cosmic dust, ellipsoid, smooth surface, small pits on some parts; × 3600; (D) iron cosmic dust, ellipsoid, spherule structure on surface; × 1600; (E) iron cosmic dust, tadpole-like, spherule structure on surface; × 440; (F) iron cosmic dust, tadpole-like, crust-layer structure, part of outer crust is lost; × 1100; (G) iron cosmic dust, linking-sphere-like, slight rise on the surface, looks coarsely; × 720; (H) iron cosmic dust, immature-fish-like, vesicular structure; × 540.

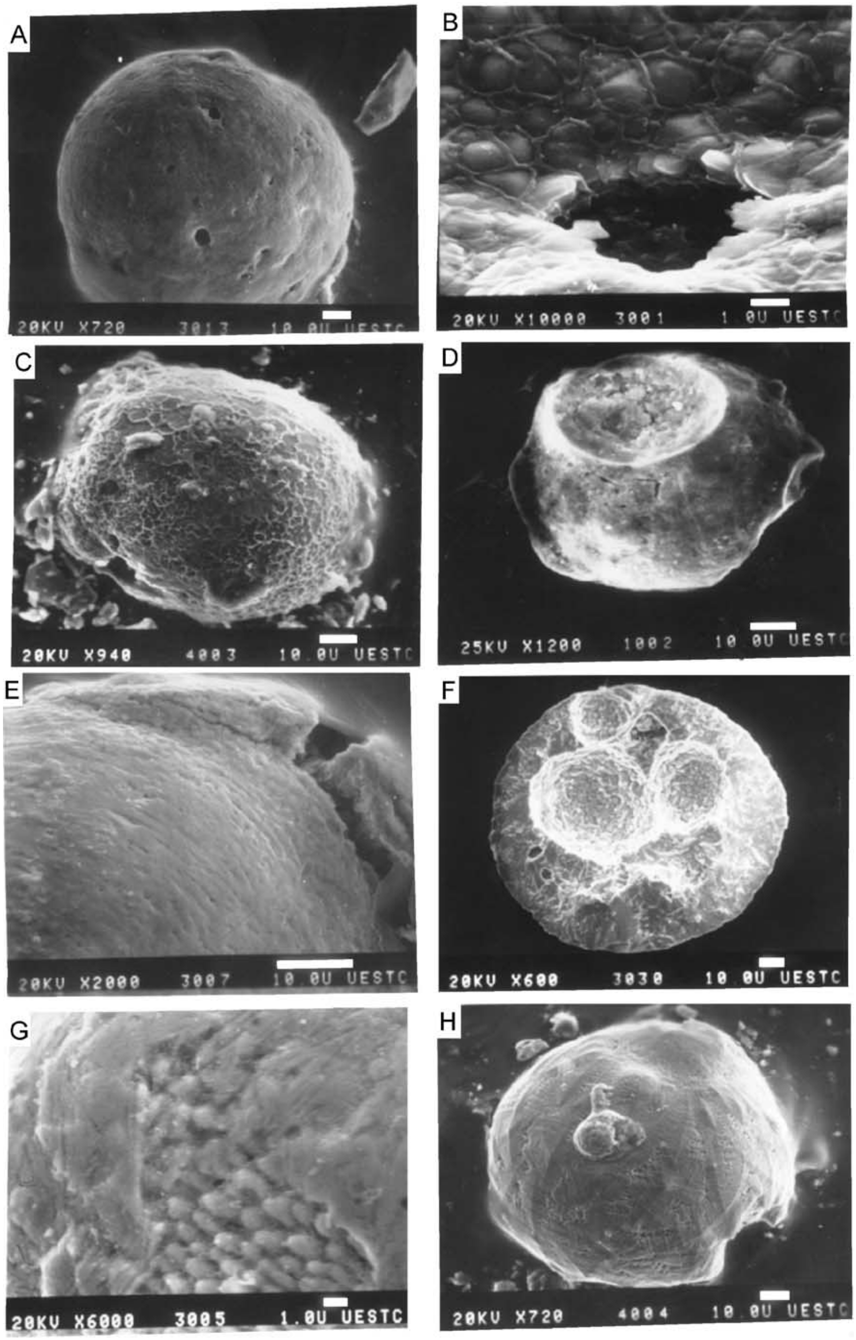

Fig. 4. Scanning electron micrographs of many black, magnetic Fe spherules recovered from the micro-disseminated gold deposits, NW-Sichuan, China. (A) Iron cosmic dust, spheroid, vesicular structure; × 720; (B) welded structure and vesicular structure; × 10000; (C) airprint structure, fish-scale-like pits on surface, flat pit bottoms; × 940; (D) impact pit structure, round and smooth pit, impact cracks on pit bottoms; × 1200; (E) folded ring structure; × 2000; (F) cauliflower-like structure; × 600; (G) cryptocrystalline structure; secondary electron image, × 6000; (H) gas-cut structure; × 720.

rhythmic interbeds of authigenic sulfides and allothigenic detrital quartz, quartzite, sericite and graphite. Relict fabrics of sedimentary origin are still identifiable, although subsequent diagenesis, metamorphism, tectonism and hydrothermal activity have remoulded the primary fabrics. The hydrothermal network ores are characterized by numerous gold-bearing veins and veinlets of quartz–calcite–sulfide. On the basis of characteristic mineral and element paragenesis, the network ores may be subdivided into six types: (1) Au-pyrite–quartz; (2) Au-realgar–quartz; (3) Au-realgar–calcite; (4) Au-realgar–stibnite–quartz; (5) Au-pyrite–realgar–quartz–calcite; (6) Au-stibnite–scheelite–quartz. Wall rock near the mines has been altered strongly. The chief hydrothermal alteration types are the introduction of silica and calce. The intensity of hydrothermal alteration is positively correlates with the concentration of gold and associated ore minerals. Gold mainly is present as invisible gold, but very fine-grained native gold can be occasionally seen under a microscope.

The Middle–Upper Triassic series consists chiefly of interbedded gray, moderately thick-bedded, fine-grained, feldspar-quartz graywacke and dark-gray silty slate with lesser intercalated phyllite. At the base of the series, there often occurs minor amount of gray thin-bedded micritic limestone. The Triassic sedimentary series accommodating the ore belongs to turbidite series (Zheng et al., 1994; Gu, 1996). The turbidite series has a markedly rhythmical characteristic and a thickness of more than 4000 m. Most of the cyclothem can be divided into three textural units:

(1) The sandy unit. This unit occupies the lower coarse-grained part of the cyclothem. At its base is a small quantity of argillaceous sandstone and/or bouldery clay; its top includes fine-grained sandstone and siltstone.
(2) The silty unit. Most of this unit consists of siltstone. The bottom part includes small-scale cross bedding and wavy bedding; the top commonly consists of pelitic siltstone.
(3) The muddy unit. Most of this unit is made up of carbonaceous slate and phyllite, and is generally separated from the sand unit by a washed surface.

The gold ore bodies are generally lens- or layer-like in shape and typically occur in carbonaceous slates, phyllites, siltstones and more rarely, sandstone. Most samples containing microspherules were also collected from the muddy unit.

The gold deposits are on the eastern margin of the Arb massif that includes part of the Chinese Bayankela-Ganzi fold belt, western Qinling fold system, and Motianling fold belt. Because of this complex tectonic environment, structural features formed during Indosinian–Yanshanian orogeny are diverse and of several orientations. Three structure trends are important in controlling ores (see Fig. 1).

(1) South–north-trending structures represented by the Kuashiya fault zone that controls deposits directly, including the well-know Dongbeizhai gold deposit.
(2) East–west-trending structures represented by the Xueshan fault, Qiaoqiaoshang, Longdishui and related deposits lie along this fault belt.
(3) Northwest–southeast-trending structures represented by the main Maqin-Maqu-Nanping fault, which is associated with the Manaoke gold deposit.

These features indicate that the occurrence of micro-disseminated gold deposits in northwestern Sichuan is controlled not only by stratigraphic horizons but also by three main intersecting tectonic belts. Although the deposits lie in structural belts of different orientations, the features of mineralization, ore formation, and ore fabric are similar (Gu, 1996; Zheng et al., 1993a, 1994).

According to Zheng et al. (1994) and Gu (1996), the gold deposits were formed during two ore-building periods including a sedimentary period and a hydrothermal mineralization period, in which gold mineralization took place under considerably different conditions. Stratiform ores were formed simultaneously with their host Middle–Upper Triassic sedimentary rocks by nonvolcanic exhalation on the sea floor. The main mineralized horizons correspond to periods of hemipelagic to pelagic deposition during stagnating stages of turbidite sedimentation. The stratabound network mineralization, on the other hand, was formed as the result of remobilization or reworking of preexisting stratiform ores by epigenetic hydrothermal solutions of meteoric origin during the Late Mesozoic to Cenozoic times. The gold was remobilized and transported as bisulfide complex $Au(HS)_2^-$. The precipitation of hydrothermal gold was mainly due to the change in physicochemical conditions, especially due to decrease of reduced sulfur activity caused by the deposition of sulfides from the solution, under the conditions of temperature from 250 to 120 °C pressure from 400 to 200 bars, and depth less than 2 km. (Zheng et al., 1989, 1990, 1991, 1993a,b,c, 1994; Gu, 1996; Liu and Liu, 1997; Wang and Zhang, 1999, 2001; Liu et al., 2000a,b).

4. Characteristics of the microspherules

Cosmic dust has importance to basic theoretical research and solution of some important theoretical problems. Since cosmic spherules were first recovered from ocean-floor sediments during the voyage of the HMS Challenger in the late 19th century (Murray and Renard, 1891), they have been found in the Antarctic and in Greenland ice (Thiel and Schmidt, 1961; Wright et al., 1963) or glacial sediment (Hagen et al., 1990), deep-sea sediments (Bruun et al., 1955; Millard and Finkelman, 1970; Parkin et al., 1980), manganese nodules (Finkelman, 1970) or sediments (Bi et al., 1993), rock salts (Mutch, 1964), desert sands (Fredriksson and Gowdy, 1963; Dai et al., 1994), beach sands (Marvin and Einaudi, 1967), sedimentary rocks (Crozier, 1960; Fechtig and Utech, 1964; Li, 1986; Li et al., 1990; Wang, 1992; Wang and Chatterton, 1993; Wang et al., 1998), migmatitic granite (Wang et al., 1993, 1995), and soils around meteor craters (Krinov, 1964; Brett, 1968; Zhao et al., 1995). However, the discovery reported here, in micro-disseminated gold deposits, is to our knowledge the first such occurrence at least in China.

4.1. Basic features

Most of the microspherules discovered in this region are black or brown-black, a few are copper-yellow. They are fragile, generally of strong magnetism (a few are weakly magnetic), and have conchoidal fracture. The surface of some microspherules is covered by a thin oxidized film (hematite?). The microspherules appears steel gray (a few are bright yellow) after being soaking in dilute hydrochloric acid, and they dissolve slowly in acid-dissolving experiments. Under the microscope in reflected light, they show steel-gray or less commonly light-yellow reflection color, and are isotropic, having no internal reflection.

According to the current internal and external terminology on extraterrestrial objects, the term "cosmic dust" refers to microspherules less than 2 mm in diameter (Brownlee, 1985; Ouyang, 1988). The microspherules discovered in northwestern Sichuan Province are far smaller than this. We measured 227 grains at random and found sizes range from 25 to 183 μm. The distribution of microspherules in different size fractions is shown in Fig. 5 and shows that the overwhelming majority of microspherules are smaller than 100 μm, finer than that of the cosmic dust found in other areas of China (Li et al., 1990).

Observed under a binocular microscope and scanning electron microscope, the outer shapes of the microspherules are largely spherical (Figs. 3A–B and 4). In addition, there are less-abundant irregular shapes, including tadpole-like, linking-ball-like, and immature-fish-like (Fig. 3C–H). In polished sections, the monocyclic and double-deck textures of microspherules are manifested (Fig. 6).

4.2. Surface microstructures

As revealed by meteorites, surface microstructure is an important basis on which to interpret the origin

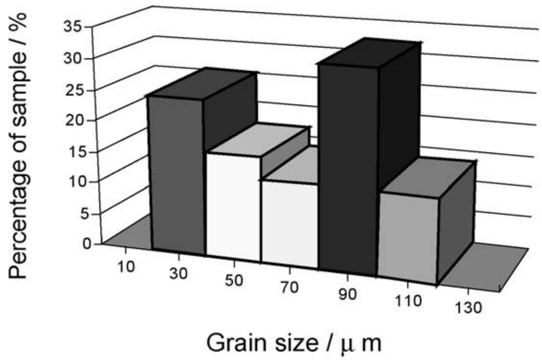

Fig. 5. Distribution of size of the microspherules (obtained by measuring the maximum dimensions of 227 grains selected at random).

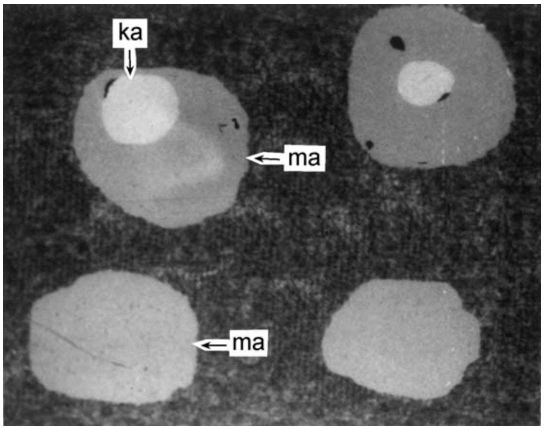

Fig. 6. Monocyclic and double-deck textures of the microspherules from the gold deposits, polished surface, 0.144 mm of sight diagonal linear measure. Abbreviations: ma = magmetite; ka = kamacite.

and mechanism of formation of microspherules (Ouyang, 1988; Wang, 1991). The authors therefore used an SEM to observe and photograph secondary images (Figs. 3 and 4). The principal microstructures of the microspherules are myrmekitic, crust-layer, vesicular, welded, airprint, impact-pit, folded-ring, cauliflower-shape, cryptocrystalline, gas-cut and spherulitic structures all common to most extraterrestrial dust.

Myrmekitic or sheet-grain-like microstructures take the format of the surface arranged myrmekitically or in sheet-grain shape, as shown in Fig. 3A–B. It is a characteristic microstructure of cosmic dust (Ouyang, 1988, 1991), displayed by numerous crystallites adhering to one another (Fig. 3D). This structure might be produced by abrupt transformation constituents from a high-temperature molten state to a low-temperature solidified state.

Crust-layer structure is made up of an outer crust and inner core (Fig. 3F). The outer crust is likely a melting crust (generally caused by remelting, Ouyang, 1988); it is thin, black and coarse, and easily falls off. In some cases, numerous round particles appear to be linked together on the coarse surface; this characteristic appears to result from the process of fused liquid drops cooling gradually with numerous crystallocentres. Under the crust, crystallites or the inner core may be assembled in orderly fashion-like lattice or sheet-grain structure (Fig. 3F).

Vesicular structure on the surfaces of some microspherules is present as holes of various sizes and shapes. The magnitude and inward extension of holes vary (Figs. 3H and 4A–B). Such holes appear to result from the escape of volatiles contained within the spherules during the course melting.

Welded structure is not common in most world-wide occurrence of cosmic dust, but it is common on the surface of microspherules in gold deposits in northwestern Sichuan. Welded structure appears to have formed when micrograins remelted, during which melted or remelted liquid dropped solidified along the crevices between crystallites (Fig. 4B).

Fish-scale-pits-like airprint structure is a common and characteristic structure on the surface of meteorites and also is present on the surfaces of cosmic dust (Ouyang, 1988), consisting of an array of small sunken pits, like fish scales (Fig. 4C). The size of pits varies, and pits may be ordered or disordered. Opinions on the genesis of this structure are varied. Liang et al. (1982) suggested that it is caused by extraterrestrial substances being bombarded by cosmos ray; Peng et al. (1982) have hypothesized that the circular pits are caused by corrosion of streaming, burning gases that were generated when the uncemented or incompletely cemented microspherules enter the earth's atmosphere at high speed; Zheng et al. (1995) considered the structures as the result of burning corrosion when extraterrestrial substances drop into the atmosphere.

Airprint structure is prevalent on the surface of meteorites and cosmic dust discovery in many areas of the world (Ouyang, 1988, 1991; Li et al., 1990; Wang et al., 1993, 1995, 1998). This structure results from a process burn-corrosion of the microspherule surfaces. The pits or grooves (which sometimes are wedge-shape, so-called ablation wedges) on the burnt-corrosion surface are a burn-corrosion phenomenon in a transition area of the boundary layer. It is similar to experimental phenomenon that the wedges orderly arranged on ball beads of beeswax and some high-temperatures materials, forming a regular pattern related to the increase of turbulent spots (Lin, 1981).

Impact-pit structures on the surfaces of some microspherules show one or two sunken pits like small basins or bowls appear on the surface of microspherules (Fig. 4D). The boundaries of this kind of pit are smooth and round, and appear to be formed by microspherules colliding with each other in a plastic state or by earlier solidified microspherules impacting the surface of uncemented or incompletely cemented particles. Impact cracks on the bottom of some pits result from particularly strong impact.

Folded-ring structure is present on the surface substance of the microspherules and is distributed directionally, assuming the form of circular flow (Fig. 4E). The genesis is probably from rotation of cosmic dust particles against each other in a high-temperature melting state (Li et al., 1990).

Cauliflower-shape structure take the format crystallite cauliflower-shaped heads, separated by cracks or gaps can been seen on the surface of microspherules (Fig. 4F). It might be formed by flow of interior molten constituents into the external spherules during rapid condensation and shrink of the microspherules (Li et al., 1990; Zheng et al., 1995).

Cryptocrystalline structure is present as many approximately parallel noncrystalline small cylinders in the microspherules that contain generally rounded outer ends (Fig. 4G). This structure appears to be the result of melting drops flowing and cementing quickly (Li et al., 1990; Zheng et al., 1995).

Gas-cut structure results from a gas stream cutting the outer crust of microspherules during rapid descent of cemented or semi-cemented particles (Fig. 4H) (Li et al., 1990; Zheng et al., 1995).

Spherulitic structure is displayed by numerous crystallites adhering to on another (Fig. 3D). Like myrmekitic structure, it appears to be the result of numerous crystocenters adhering to crystal sprouts at the same or almost the same time during the cooling of melted drops. However, the possibility of many microspherules in a plastic state, adhering to one another in a directional pattern, cannot be discarded.

In addition to above textures, some microspherules have polygonal and dendritic surface textures (Fig. 7A,B), which are similar to the ablation surface texture of some typical cosmic Fe spherules (Czajkowski, 1987; Jehanno et al., 1988; Hagen et al., 1990).

The morphology and surface textures of the microspherules being similar to cosmic Fe spherules show that they underwent ablation, ejection, explosion, mutual impact and rapid cooling when they passed through the atmosphere. So we regard the microspherules only as cosmic spherules at this time. When these microspherules fell down, they were preserved in Middle–Upper Triassic series in northwestern Sichuan, China.

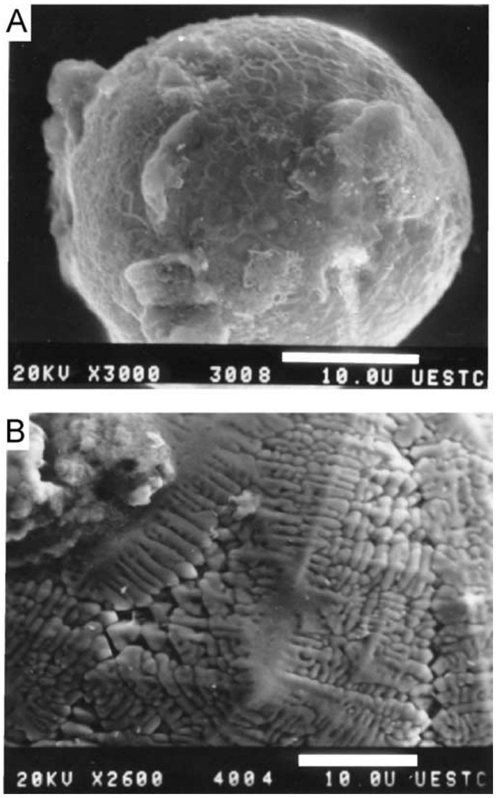

Fig. 7. Scanning electron micrographs of two microspherules from the gold deposits. (A) Polygonal surface pattern. (B) Magnified surface texture of the microspherule showing dendritic pattern and iron oxide (magnetite) crystals.

5. Composition

The mineral composition of the microspherules from electron microprobe and energy spectrum analysis are shown in Table 1, where it is apparent that the microspherules are made essentially of Fe. The steel-gray microspherules generally contain Cr and Ni in trace amounts; the bright-yellow microspherules generally lack Cr and Ni but contain As. Trace Si is contained in both kinds of the microspherules, but its content in steel-gray microspherules in slightly higher. A systematic geochemical study of the distribution of nobel metals in host rocks and ores rich in micro-

Table 1
Chemical composition of microspherules

Sample No.	Surface features	FeO	SiO_2	Cr	Ni	As	Sb	Ti	Mn	S
s-1005	Black, spheroid	97.32	T	2.68	T	ND	ND	ND	ND	T
s-1007	Steel gray, semi-spheroid	98.64	T	1.36	T	ND	ND	ND	ND	ND
s-1015	Steel gray, spheroid	96.84	T	3.16	T	ND	T	ND	ND	ND
s-1011	Steel gray, spheroid	96.32	0.76	2.83	T	ND	ND	ND	ND	ND
s-1018	Steel gray, spheroid	96.56	1.50	1.94	T	ND	ND	ND	ND	ND
s-3001	Steel gray, ellipsoid	97.35	2.01	0.64	T	ND	ND	ND	ND	ND
s-3002	Steel gray, tadpole-like	95.82	2.74	1.64	T	ND	ND	0.07	ND	ND
s-3003-1	Bright yellow, bi-spheroid	99.68	T	0.32	T	ND	ND	ND	ND	ND
s-3004-1	Steel gray, tadpole-like	99.26	T	0.01	T	0.73	ND	ND	ND	T
s-3004-2	Steel gray, tadpole-like	97.83	0.65	1.52	T	ND	ND	ND	ND	ND
s-3005-1	Bright yellow, spheroid	97.02	0.07	ND	ND	1.91	ND	ND	ND	ND
s-3005-2	Bright yellow, spheroid	99.09	ND	ND	ND	0.91	ND	ND	T	ND
s-3007-1	Bright yellow, semi-spheroid	99.36	T	T	ND	0.64	ND	ND	ND	ND
s-3007-2	Bright yellow, semi-spheroid	96.76	T	ND	ND	3.24	ND	ND	ND	T
s-3009	Steel gray, tadpole-like	91.83	T	8.17	ND	T	ND	ND	ND	ND

Unit of measure of chemical components: wt.%; all Fe expressed as FeO.
T: Trace; ND: not detected.
Analyzed by Microprobe Section of Multiple Utilization of Mineral Resources (Chengdu), Ministry of Geology and Mineral Resource.

spherules (Zheng et al., 1994) indicates that Ir anomalies occur markedly in the ore-bearing strata and the ore deposits therein. The contents of Ir in this set of strata are commonly higher than that in other strata; typical contents are 2.0×10^{-9}–3.5×10^{-9}, and one or two samples have reached 20×10^{-9}. It is thought conventionally that abnormally high content of Ir is a result of extraterrestrial objects (after Ouyang, 1988).

Cosmic spherule traditionally is divided by composition into three categories iron cosmic dust, silicate cosmic dust, and glassy cosmic dust (Blanchard et al., 1980). The microspherules in gold deposits of northwestern Sichuan all are iron spherules, similar in chemical composition to cosmic dust in the Middle–Upper Proterozoic Erathem in Bainaimiao, Inner Mongolia (Li, 1986), and to cosmic dust in Archean

Table 2
X-ray material phases analysis data of the microspherules

S-1166		S-1043		S-2002-1		S-2002-5		JCPDS (1993)					
Magnetite		Magnetite		Magnetite and *wüstite		Kamacite		Magnetite (19–629)		Wüstite (6–615)		Kamacite (37–474)	
I/I_0	d (Å)	I/I_0	d (Å)	I/I_0	d (Å)	I/I_0	d (Å)	I/I_0	d (Å)	I/I_0	d (Å)	I/I_0	d (Å)
3	4.79	3	4.80	2	3.011	3	2.238	3	4.852	7	2.49	10	2.028
2	2.97	5	2.96	10	2.530	10	2.035	6	2.967	10	2.153	2	1.434
10	2.54	10	2.53	3	2.471 *	2	1.812	10	2.532	8	1.527	3	1.1708
2	2.11	6	2.095	10	2.150 *	2	1.435	6	2.0993	5	1.299	1	1.0139
2	1.62	4	1.72	4	2.090	1	1.295	4	1.7146	5	1.243	1	0.9070
8	1.49	4	1.61	2	1.721	3	1.171	6	1.6158	4	1.077	1	0.8279
3	1.28	6	1.48	5	1.621	2	1.018	8	1.4845	4	0.988		
6	1.095	2	1.28	9	1.524 *			4	1.2807	1	0.9631		
4	1.05	6	1.092	6	1.482			7	1.0930				
		4	1.049					4	1.0496				

Analyzed by Mineral Section, Chengdu University of Technology.
Joint Committee on Powder Diffraction Standards (JCPDS).

Huoqiu group of Erathem in Anhui Province, China (Yan et al., 1982). Their similarity is that all contain Cr and Si (Yan et al., 1982; Li, 1986). However, the composition of the microspherules in northwestern Sichuan is different from that of cosmic dust found in Zhedang, Tibet (Liang et al., 1982), in Xitieshan, Qinghai Province (Zhang, 1987, 1989), and in modern deep-sea sediment of the west mid-Pacific, which bear Ni but lack Cr (Peng et al., 1982). It may be attributed to different parent meteorite sources (Bi et al., 1993).

Results of X-ray analysis of typical microspherules showing mineral composition are in Table 2. When compared with standard mineral and crystal powder data on cosmic dust in other areas, the data in Table 2 show that the microspherules discovered in this region is composed mainly of magnetite and minor amount of wüstite and kamacite. EDX and SEM analyses of polished section indicate that the microspherules consist of dark- and light-colored iron oxides phase (Fig. 8): the oxygen and iron spectra from the EDX show that the light-colored phase (wüstite) contains less oxygen per iron atom than the dark-colored phase (magnetite). Thus, it is similar in composition to cosmic dust discovered in many other parts of China, which have magnetite as a main mineral component (Yan et al., 1982; Li, 1986; Li et al., 1990; Wang et al., 1993, 1995, 1998).

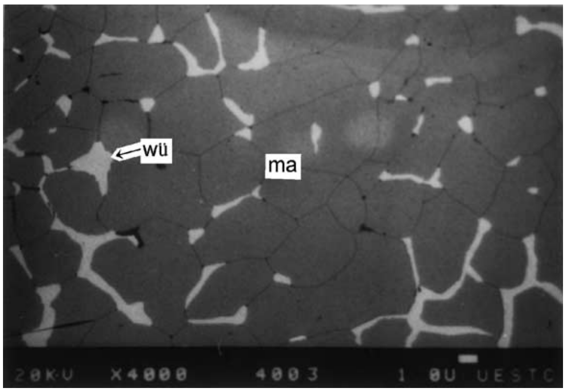

Fig. 8. Scanning electron micrograph in the back-scattered mode of the polished section of microspherule, showing the interlocking growth pattern of magnetite (dark phase, ma) and wüstite (light phase, ka).

6. Discussion

6.1. Origin of the microspherules

Numerous magnetic microspherules in the Middle–Upper Triassic and stratabound disseminated gold deposits on the eastern margin of the Aba massif are in deposits located up to a few dozens of kilometers to a few hundred kilometers apart. Therefore, the microspherules were likely to have been originally scattered in a vast areal extent from an extraterrestrial source. Analyses of the microspherules from the gold deposits of Dongbeizhai, Qiaoqiaoshang, and Maonaoke show that their basic features are largely similar. Abnormally high content of Ir in ore-bearing strata indicates indirectly the extraterrestrial origin material in the Dongbeizhai, Manaoke, and Qiaoqiaoshang gold deposits in which the microspherules were discovered, indicating a large-scale extraterrestrial impact on the surface of the earth in the Middle to Late Triassic.

Although tuffaceous material has been recognized in some lithologic members of the Middle–Upper Triassic strata in the eastern part of Aba massif, no large tracts of volcanic rocks have been found there; particularly, volcanic material is absent in the gold ore horizon of the deposits. Moreover, no magmatic rock of this period has been seen within an area of a few tens of thousands square kilometers. As Ir anomaly is present in the ore horizon, the abundance ratio of Pt-group elements to siderophile elements (see Table 3) is close to that of meteorites, volcanic material is absent and the microspherules have typical airprint structure, the possibility that the microspherules were formed by volcanism can be ruled out.

The authors consider that the microspherules discovered in the gold deposit in the Middle–Upper Triassic of northwestern Sichuan should be the product of the impact of extraterrestrial bodies. This implies that there was an event of large-scale impact and fall of extraterrestrial material on the surface of the earth in this period. This event coincided with the same events that took place in other areas such as Suzhou in China (Hu et al., 1996; Wan et al., 1996).

Observed under the SEM and the reflected light microscope, various microstructures displayed on the surface of this type of microspherules (Figs. 3, 4, 6, 7 and 8) consistently reflect extraterrestrial characteristics. For example, when celestial bodies such as meteorites, meteors, or comets fall, their surface temperature and pressure decrease rapidly and the surface substance vaporized and melts, so that smog tags along after these falling celestial bodies (according to the categories of Ouyang, 1988, the microspherules should belong to the ablation-type). These characteristics result not only in flow phenomena of melted drops, cementing and impacting, but also in evidence of volatile components escaping. It is believed that the spurt of kinetic energy of cosmic dust particles spurt in the top of the atmosphere can reach 5×10^{11}–3×10^{13} erg/g, whereas the energy needed for melting and vaporizing the minerals and metals in meteorites is only 8×10^{10} erg/g (Brownlee, 1981).

The microspherules have textural and geochemical characteristics of iron cosmic dust sorted approximately into two series: a Ni-rich type and a Cr-rich type (Ye and Chen, 1964; Peng et al., 1982; Yan et al., 1982; Liang et al., 1982; Ouyang, 1988; Li et al., 1990; Wang et al., 1993, 1995; Dai et al., 1994; Zhao et al., 1995). The microspherules discovered in this region are clearly the Cr-rich type. Generally, the presence of a Ni-rich metallic core or a PGE nugget in Fe-oxide spherules would clearly indicate their extraterrestrial origin (Bi et al., 1993). However, A lower Ni content or the absence of Ni in Fe-oxide spherules does not preclude an extraterrestrial origin because during oxidation of meteoritic metals at high temperature, Ni tends to be concentrated in the metallic phase (Ni-rich core), leaving the oxide phase depleted in Ni (Marvin and Einaudi, 1967). A Ni-rich metallic core can be separated from its host iron oxides through the ejection process proposed by Bi et al. (1993). This core-ejection process could explain a low Ni content in the microspherules in this region.

6.2. *Transport form of metallogenic materials in hydrothermal solutions*

According to traditional concepts of mineralization, endogenic hydrothermal fluids, under endogenic condition of higher temperature and pressure, can only transport metallogenic materials in the form of various complexes and a few colloids; that is to say, transport and precipitation are accomplished in chemical form. According to the same traditional concepts, mechanical transport of metallogenic materials can only occur under epigene conditions. However, in the silicated and calcitized rocks of the micro-disseminated gold deposits in northwestern Sichuan, and especially in such hydrothermal mineral veins as gold-bearing sulfide-quartz vein and gold-bearing sulfide-calcite vein, some microspherules were found. The content of microspherules is highest where the hydrothermal veins or net-veins are most concentrated, demonstrating a close relation between the distribution of microspherules and degree of mineralization. This rare geological phenomenon compels us to reappraise the traditional concepts of mineralization.

The melting temperature of meteorites and cosmic dust is over 1000 °C (Ouyang, 1988), but the temper-

Table 3
Abundance ratios between noble metals and siderophile elements in the gold ores

Ratio	Ir/Fe	Ir/Co	Ir/Ni	Pt/Fe	Pt/Co
The gold ores in NW-Sichuan	4.72×10^{-6}	2.70×10^{-4}	6.00×10^{-5}	1.43×10^{-6}	8.10×10^{-3}
Crust	2.00×10^{-8}	2.50×10^{-5}	1.00×10^{-5}	1.00×10^{-7}	1.25×10^{-4}
Chondrite	1.92×10^{-6}	6.00×10^{-4}	3.56×10^{-5}	8.00×10^{-6}	2.50×10^{-3}
Metal phase of meteorite	4.41×10^{-6}	6.35×10^{-4}	4.66×10^{-5}	2.20×10^{-5}	3.17×10^{-3}

Ratio	Pt/Ni	Pd/Fe	Pd/Co	Pd/Ni	Remarks
The gold ores in NW-Sichuan	1.81×10^{-3}	1.82×10^{-7}	1.03×10^{-3}	2.31×10^{-4}	a
Crust	5.00×10^{-5}	2.00×10^{-7}	2.50×10^{-4}	1.00×10^{-4}	b
Chondrite	1.48×10^{-4}	4.00×10^{-6}	1.25×10^{-3}	7.41×10^{-5}	b
Metal phase of meteorite	2.33×10^{-4}	9.91×10^{-6}	1.43×10^{-3}	1.05×10^{-4}	b

[a] Calculated according to the data obtained in this study.
[b] Calculated according to the data from Mason and Moore (1982).

ature of formation of micro-disseminated gold deposits is not more than 250–300 °C (Zheng et al., 1989, 1993a,b,c, 1994; Gu, 1996), and so hydrothermal solutions of such low temperature cannot melt cosmic dust. Preservation of surface structures on microspherules also demonstrates that the microspherules have not been melted, but the presence of some microspherules in hydrothermal ore veins shows that it has undoubtedly been transported. It is obviously impossible for cosmic spherules to fall directly from space into cemented hydrothermal ore veins more than 1 km deep in the earth. A reasonable explanation is that during the Middle–Late Triassic era, cosmic microspherules fell into the sea and entered the sedimentary strata, then consolidated into rock together with the other sediments. Later, in the period of mineralization, the strata underwent tectonic disruption and deformation. When hydrothermal solutions moved through tectonized zones and porous strata, the solutions physically moved the microspherules from the strata into the hydrothermal solution and transported them in many pores, especially fracture pores, which are big enough for the micron-sized grains to pass through. We are convinced that this is an important phenomenon in endogenic mineralization, which should not be neglected.

The presence of extraterrestrial microspherules in hydrothermal ore leads the authors to propose that under endogenic conditions, metallogenic materials in hydrothermal solution can be transported physically as well as chemically, although the distance of physical transport is probably limited.

Recognition of mechanical transport of metallogenic materials in endogenic hydrothermal solutions permits the explanation of some mineralization phenomena that have puzzled researchers for a long time (Zheng et al., 1994). For instance, some endogenic hydrothermal deposits show a close association of typical hydrothermal minerals, such as scheelite, wolfamite, and cassiterite, with typical epithermal minerals, such as stibnite and realgar. Such association can even be seen in hydrothermal veins of the same mineralization phase (Liu et al., 1994, 2000c; Zheng et al., 1993c, 1994). General knowledge tells us that the two kinds of minerals are not only different in crystallizing temperature, but also much different in physicochemical conditions of transport and precipitation. Many researchers have come up with different opinions (Liu et al., 1994, 2000c; Zheng, 1993; Zheng et al., 1993c, 1994), but because the question has been approached from only the chemical perspective, no satisfactory explanation has been reached.

If chemical and mechanical transports are combined, however, the problem may be readily solved. That is, scheelite and cassiterite, formed under higher temperature and oxygen fugacity in an early stage, may be affected by a hydrothermal solution bearing As, Sb, and so on. Under lower temperature and higher sulfur fugacity in a later stage, these hydrothermal minerals could be transported in particulate form into another tectonic zone to precipitate in the same vein with newly precipitated realgar and stibnite, which were transported in dissolved chemical form. Such association phenomena can be regarded as actual paragenesis as well as pseudomorphic paragenesis.

In summary, if mechanical transport of metallogenic materials by endogenic hydrothermal solution is tenable, fresh answers will be available for problems of mineralization that have been argued for a long time.

7. Conclusion

(1) The microspherules that we have found in the gold deposits in northwestern Sichuan, China, are similar in morphology, surface textures, mineral and chemical composition, and size to typical cosmic Fe spherules. Now it has proven that these microspherules are of extraterrestrial origin and were the ablated production of cosmic material, which underwent ablation, ejection, explosion, mutual impact and rapid cooling when they passed through the atmosphere. When these microspherules fell down, they were preserved in Middle–Upper Triassic series in northwestern Sichuan, China.

(2) The microshperules are concentrated in rich ores more than in poor ores, and in poor ores more than in host rocks. In other words, concentration of microspherules is positively closing correlated to mineralization strength. It is important for us to have discovered a few microspherules in hydrothermal ore veins. This fact indicates that during the hydrothermal mineralization period, microspherules in the sedimentary rocks were trans-

ported and riched to a certain degree, which further suggests that chemical migration was not the only mechanism for the transport of metallogenic materials in endogenic hydrothermal solutions. Migration of metallogenic materials in mechanical (physical) forms is not only possible but also exists.

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