Chemical compositions and cassfication of Grove Mountains (GRV) 98003 and other Chinese iron meteorites

Wang Daode[1] (王道德) and Lin Yanting[1,2] (林杨挺)

1 Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640

2 Institute of geology and Geophysics, Chinese Academy of Sciences, Beijing 100029

Abstract Concentrations of Cr, Co, Ni, Cu, Ga, Ge, As, Sb, W, Re, Ir, Pt and Au of two ungrouped iron meteorites, Grove Mountains (GRV) 98003 from Antarctica and Ujimqin, were measured using instrumental neutron activation analysis. According to the bulk chemistry, GRV 98003 is classified as a member of IAB group, and Ujimqin as a unique one of IAB iron meteorite complex. The elemental abundance pattern and correlation between elements (e. g. Ni-Au, Co-Au, As-Au, W-Au, Cu-Au, Sb-Au) of GRV 98003 are similar with those of NAW 468 (IAB), but significantly depleted in refractory siderophile elements (Re, It) and moderate volatile elements (Ga, Ge) relative to the latter. In addition, we reclassify Nantan (II-ICD) as a member of IAB main group (MG) and Yongning (IA) as a unique iron meteorite related with IAB iron meteorite complex.

Key words Antarctica, Grove Mountains, classification, iron meteorite, trace elements, INAA.

1 Introduction

Iron meteorite groups are divided into magmatic types, including I C, II AB, II C, II D, II F, III AB, III E, III F, IV A and IV B chemical groups, and non-magmatic types including I AB, III CD and II E chemical groups. The magmatic types show large variation in concentrations of Ir and other refractory siderophile elements, e. g. a factor of 5000 for Ir in II AB and 2000 in III AB (Rubin *et al.* 2002). Such wide ranges can be produced only by fractional crystallization during slow cooling of liquid of metal. In contrast, nonmagmatic groups have a narrow range of Ir concentration (a factor of < 5), and they were not produced by fractional crystallization. There is no compositional hiatus between IAB and III CD on the Ga-Ni, Ge-Ni, Ir-Ni, or other element-Ni diagrams, and Wasson *et al.* (1980) and Choi *et al.* (1995) suggested to treat them as a single group. Recently, Wasson and Kallemeyn (2002) reexamined more than 160 iron meteorites, including early-classified I AB and III CD and a large numbers of ungrouped iron meteorites that have compositions similar to I AB-III CD. The new data show moderate clustering when plotted with Au against Ni, Co, As, Ga, Ge, W, Cu and Sb. Hence, these iron meteorites are referred to as a main group of I AB (I AB-MG). Other meteorites are classified as three low-Au subgroups

closely related with I AB-MG, two high-Au subgroups less related with IAB-MG and some solo iron meteorites. All these iron meteorites are referred to as IAB iron meteorite complex. Most of I AB complex contain accessory silicates and C (graphite and carbides) commonly coexisting with troilite (FeS). The silicate inclusions consist of olivine, low-Ca-pyroxene, plagioclase, metal and troilite, typical mineral assemblages of chondrites. Bulk chemical compositions of the silicate inclusions are approximately chondritic too. Wasson *et al.* (1980) and Choi *et al.* (1995) proposed that IAB complex crystallized from impact-induced melts within mega regoliths of chondritic asteroids. Benedix *et al.* (2000) modeled I AB iron meteorites as products of a complex process involving partial melting, incomplete differentiation, and metamorphism, followed by impact mixing. Wasson and Kallemeyn (2002) assumed that the high-temperature history of I AB complex, involved rapid heating and cooling, is more consistent with impact heating than with radiogenic heating. In this paper, we summarize the chemical classification of I AB iron meteorite complex, and examine the classification of GRV 98003, an iron meteorite from Antarctica, and several Chinese iron meteorites (Ujimqin, Nantan and Yongning), based on the results of instrumental neutron-activation analysis (INAA).

2   Samples and Analytical techniques

The GRV 98003 iron meteorite was collected from Grove Mountains, Antarctica, by the 15th team of Chinese Antarctic Research Expedition (CHINRE), weighting 282.2 g (Ju and Liu 2000). The Ujimqin (Wu-Chu-Mu-Chin) iron meteorite was found in Ujimqin county, inner-Mongolia, in September, 1920. It is a Ni-rich ataxite and weights 68.86 kg. The Nantan iron meteorite was found in Nantan county, Guangxi, in 1958, with a total mass of about 9500 kg. It was classified as IIICD (Wang *et al.* 1983). The Yongning iron meteorite was found in Yongning county, Guangxi, in April, 1971, with mass of 60 kg. It is a coarse octahedrite with kamacite bandwidth of 1.3 – 3 mm. This iron meteorite has been heavily weathered, but Widmanstatten pattern can be noticed. Yongning was classified as an IA iron meteorite (Wang *et al.* 1983; 1985).

Bulk compositions of GRV 98003 and Ujimqin were determined using INAA in the Institute of Geophysics and Planetary Physics, University of California, Los Angeles. The experimental procedures followed the description by Wasson *et al.* (1989), except that mean thickness of the sample sections in this work (3.0 mm) is slightly thinner than previous analyses (3.2 mm). The concentration of Ge was measured using radiochemical neutron activation analysis (RNAA).

3   Classification of IAB iron meteorite complex

There are many ungrouped iron meteorites that show compositional and structural links to IAB iron meteorite group. These iron meteorites were referred to as IAB iron meteorite complex (Wasson and Kallemeyn 2002). It was, therefore, necessary to establish criteria for the IAB complex. Wasson and Kallemeyn (2002) proposed the following compositional ranges for possible relationship of IAB iron meteorite complex: Au > 1.3 $\mu g/g$, As > 10 $\mu g/g$, Co > 3.9 mg/g, Sb > 180 ng/g, $0.4 \leqslant Ge/Ga \leqslant 7$. On element-Au diagrams (Fig. 1), new
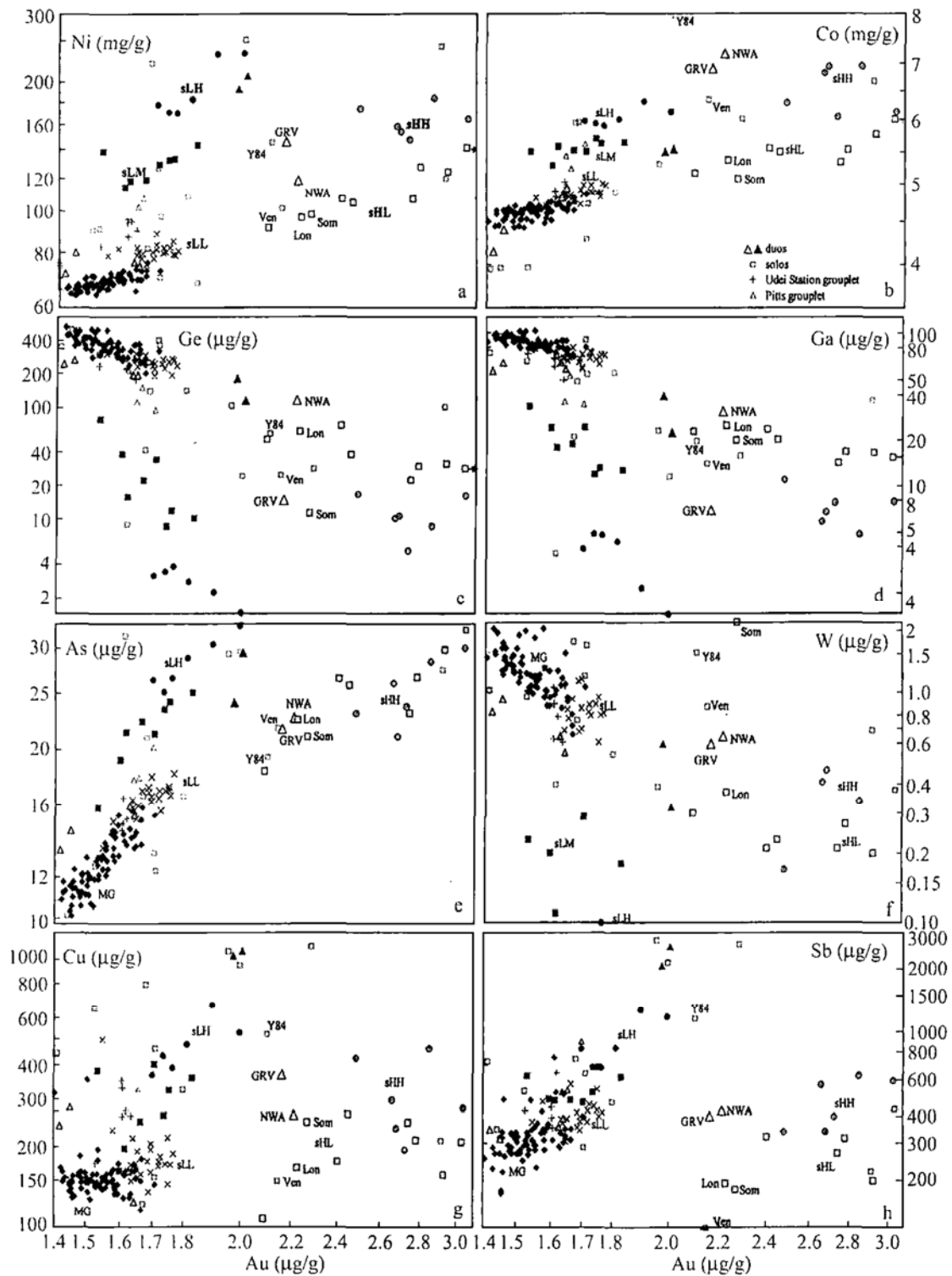
Fig. 1   Elemens - Au plots of IAB iron meteorite complex. Abbreviation: MG: IAB main group; sLL, sLM, sLH, sHL, sHH: subgroups of IAB complex; NWA: NWA 468; GRV: GRV 98003; Lon: Lonaconing (sHL); Ven: Ventura (sHL); Som: Sombrerete (ungrouped); Y84: Yamato 8451 (ungrouped); Ver: Vermillion (ungrouped). Literature: Rubin *et al.* (2002).

and revised data plot within six clustered regions. The major cluster consists of about 70 i-ron meteorites that were previously designated as IAB group with Ga > 50 μg/g. These

meteorites are referred to as IAB main group (IAB-MG). The other clusters are referred to as various subgroups of IAB iron meteorite complex, assigned with letters based on contents of Au (L = low: ≤2.0 μg/g; H = high: ≥2.1 μg/g) and Ni (L = low: ~75 to 90 mg/g; M = medium: ~110 to 145 mg/g; H = high: ≥170 mg/g) (Rubin *et al.* 2002). These subgroups are IAB- sLL (low Au, low Ni,), IAB- sLM (low Au, medium Ni; originally IIIC), IAB- sLH (low Au, high Ni; originally IIID), IAB- sHL (high Au, low Ni) and IAB-sHH (high Au, high Ni). In addition, there are other two grouplets: Udei-Station grouplet with six low-Ni members, and Pitts grouplet with four high-Ni members. Both grouplets are closely related to the low-Au subgroups, and plot in regions between sLL and sLM on the Ni-Au diagram. All low-Au subgroups tend to be related to one another, and some of them may come from same parent bodies. In contrast, there is no significant relationship between the main group (MG) and the high-Au subgroups.

Besides the main group and other 5 subgroups, there are five duos (pairs of more-or-less related iron meteorites) and17 solos that appear to be members of IAB complex (Table 1). Iron meteorites of the main group, the low-Au subgroups and the related grouplets commonly contain fine-grained silicates. El Goresy (1965) reported silicates in all graphite-troilite nodules in IAB Canyon Diablo, Odessa and Toluca, but no silicates in graphite-free FeS inclusions. A large number of the iron meteorites contain coarse-grained silicates. Buchwald (1975) divided these silicate assemblages into various types, including angular chondritic, non-chondritic, sulfide-rich, round, graphite-rich, and phosphate bearing. The chondritic type of silicate assemblages is the most abundant. Most IAB iron meteorites contain large (1 ~ 5 cm) ellipsoidal troilite nodules with variable amount of graphite. These troilite nodules are usually surrounded by cohenite and schreibersite layers with thickness of >1 mm.

4 GRV 98003 and other Chinese iron meteorites

The major and minor elements of GRV 98003 are (wt%): Fe 82.3, Ni 15.3, Co 0.39, Cu 0.02, Zn 0.09, P 0.18. It was classified as a very fine-grained octahedral iron (Chen *et al.* 2001), and later as an ungrouped iron meteorite according to trace elements (Wang and Lin 2002; 2003). In the elements-Au diagrams, GRV 98003 plots within the range of IAB complex (Fig. 1), and its abundance pattern of Pt, Ni, Co, Au, As and Cu is similar to that of NAW 468, another ungrouped and silicate-rich member of IAB complex (Rubin *et al.* 2002). Although the concentrations of Re, Ir, Ga, Ge and Cr are significantly lower in GRV 98003 than in NAW 468 (Fig. 2), both are referred to as duo iron meteorites (Wasson and Kallemeyn 2002). Like NAW 468, GRV 98003 has a sharply defined octahedral structure of plessite. The plessite consists of sparks and spindles of kamacite, which often have cores of schreibersite (Rubin *et al.* 2002). It is possible that kamacite nucleated on schreibersite. The similar texture and composition of metallic phases suggest that both irons have a similar origin.

In silicate assemblages of NAW 468, low-Ca clinopyroxene is coarse-grained (~300 μm), and shows polysynthetic twinning. The texture of pyroxene suggests of quenching from high temperature. A possible scenario is that the iron meteorite formed by impact melting followed by rapid cooling to ≤660 °C (Rubin *et al.* 2002). The oxygen isotopic com-

Table 1.   Chemical classification of IAB iron meteorite complex

Chemical group, subgroup, grouplet	Compositional features	Resolved on the element-Au diagrams	Brief explain
1. Main group IAB-Main group (IAB-MG)	Main threshold values: Au > 1.3 μg/g, As > 10 μg/g, Co > 3. 9 mg/g, Sb > 180 ng/g. Most of the previous IAB members, Ga > 50 μg/g.	Ni-Au Co-Au As-Au Ga-Au Ge-Au W-Au Cu-Au Sb-Au	The O isotopic compositions (* $\Delta^{17}O$ = ±0.30− −0.62‰) of IAB silicates (Clayton and Mayeda 1996) are in the carbonaceous chondrite range ($\Delta^{17}O$ < −0.30‰).
2. Low Au subgroup, 6 to 15 members low Au, low Ni subgroup(IAB-sLL)	Au (2. 0 μg/gNi = ~ 75 −90 mg/g	sLL is well defined on the Ni − Au diagram, occupying a position between the main group and the sLM but nearer the main group.	
low Au, medium Ni subgroup (IAB-sLM)	Au (2.0 μg /g Ni = ~110 − 145 mg/g	As a satellite of MG on Ni-Au diagram.	Previous ⅢC
low Au, high Ni subgroup (IAB-sLH)	Au≤2.0 μg /g Ni≤170mg/g	As a satellite of MG on Ni-Au diagram	Previous ⅢD
3. High Au subgroup, 6 to 15 members high Au, low Ni subgroup (IAB-sHL)	Au≥2.1 μg g/g Ni = ~75 − 90 mg/g	Ni-Au Ga-Au Co-Au	
High Au, high Ni subgroup (IAB-sHH)	Au≥2.1 μg /g Ni≥170 mg/g	Ni-Au Ga-Au Co-Au	
4. Low Au grouplets Udei Station grouplet (6 members),	Low Ni, closely related with sLL		4 members with silicate inclusions.
Pitts grouplet(3 members)	High Ni, intermediate between sLL and sLM		2 members with silicate inclusions.
5. 5 duo and 17 solo irons related with IAB			Yongning and Ujimqin belong to solo iron meteorites related with IAB.
(1) Algarrabo duo (Livingston, Algarrabo)	Au > 1.3 μg/g, As >10 μg/g, Co > 3.9 mg/g, Sb > 180 ng/ g,	Ni-Au Co-Au As-Au	
(2) Mundrabilla duo (Mundrabilla, Waterville)	0.4 ≤ Ge/Ga ≤7.	Ga-Au Ge-Au W-Au	
(3) Britstown duo (Britstown, EET87506)		Cu-Au Sb-Au	
(4) NWA468 duo (GRV 98003, NWA468)	NWA 468 contains coarse-grained (~ 300 μm) low-Ca clinopyroxene; NWA 468 and GRV 98003 contains similar Pt, Ni, Co, Au, As and Cu, but the latter is much lower in Re, Ir, Ga, Ge and Cr.		NWA 468 is silicate-rich
(5) Twin City duo (Santa Catharina, Twin City)			
6. Other	Lowest Au contents (μg/g): 0.744, 0.862 and 0.879, respectively.		These irons are Zacatecas1792, NWA 176, Bocaiuva

Note: Based on Wasson et al. (2002), Rubin et al. (2002).
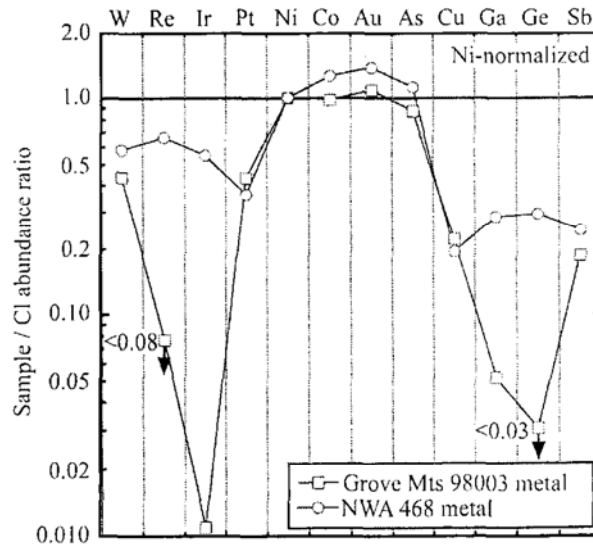   * : $\Delta^{17}O = \delta 17O - 0.52 \times \delta^{18}O$.

Fig. 2 Elemental abundance patterns of GRV 98003 and NWA468, Ni-Cl-normalized. After Rubin *et al.* (2002).

position of NAW 468 ($\Delta^{17}O = -1.39$ ‰) indicates a genetic relationship with metal-rich (e. g. , CR) carbonaceous chondrites (Rubin *et al.* 2002). It plots outside the range of IAB ($\Delta^{17}O = -0.30$ ‰ to -0.62 ‰, Clayton and Mayeda 1996), but close to those of Sombrerete (IAB-sHL, $\Delta^{17}O = -1.39$ ‰), acapulcoites (e. g. , ALH81187, $\Delta^{17}O = -1.03$ ‰), lodranites (e. g. , MAC 88177, $\Delta^{17}O = -1.23$ ‰), CR chondrites (e. g. , EET87770, $\Delta^{17}O = -1.22$ ‰), CH chondrites (e. g. , ALH85085, $\Delta^{17}O = -1.62$ ‰) and a few CV chondrites (e. g. , Mokoia, $\Delta^{17}O = -2.74$ ‰, Clayton and Mayeda 1996). The MAC 88177 lodranite also contains low-Ca clinopyroxene (Clayton and Mayeda 1996), and most unweathered lodranites contain 20 − 38 wt% metallic Fe-Ni. They may have formed by impact melting of metal-rich carbonaceous chondrite precursors, without significantly separating metal-rich melts from silicates (Rubin *et al.* 2002).

Chemical composition of Nantan iron meteorite is consistent with IAB main group, within the compact field on the element-Au diagrams (Fig. 1). Accordingly, we reclassify it as a member of IAB-MG. Ujimqin iron meteorite contains high Au and sLH-like Ni and Co, but it plots in the sLL field on Ga- and As-Au diagrams. The Ujimqin iron meteorite do not related to any of the groups. The Yongning iron meteorite is heavily weathered. Its a-bundance pattern of most elements is similar to that of **AB-MG**. The Co content is 10% lower than the range of **IAB-MG**, probably due to selectively weathering loss of kamacite. Although both Yongning and Ujimqin do not plot within **IAB-MG** or other five subgroups, they can be classified as IAB complex according to their chemical compositions (Au > 1. 3 μg /g, As > 10 μg /g, Co > 3. 9 mg/g, Sb > 180 ng/g, 0. 4 ≤ Ge/Ga ≤ 7). The ratio of Ge/Ga is 5. 22 for Yongning (IA iron meteorite group) and 2. 90 for Ujimqin.

The chemical compositions of the above four iron meteorites are given in Table 2.

5 Discussion

After accretion of planets and asteroids in the early solar system , the evolutionary

Table 2. The chemical compositions of Nantan (IAB-MG) and 4 ungrouped irons related with IAB-MG.

Iron meteorites	Cr (μg/g)	Co (mg/g)	Ni (mg/g)	Cu (μg/g)	Ga (μg/g)	Ge (μg/g)	As (μg/g)	Sb (ng/g)	W (μg/g)	Re (ng/g)	Ir (μg/g)	Pt (μg/g)	Au (μg/g)
Nantan[1,2]	20	4.72	68.8	143	79.8	293	12.8	309	1.01	168	1.79	6.3	1.530
(IAB-MG)		4.7	68	138	77	293	12.9	312	1.14		1.7		1.64
GRV	13	6.94	144.8	375	6.76	<100	21.8	408	0.62	<40	0.070	5.8	2.11
98003[1]	11	6.84	147.8	366	7.16	<100	21.8	400	0.58	<66	0.065	5.9	2.21
mean	12	6.89	146.3	371	6.96	<50	22.0	404	0.60	<40	0.068	5.9	2.158
NWA 468[1]	230	7.19	118.5	263	31.0	117	22.8	431	0.65	281	2.75	4.0	2.214
Yongning	37[1]	3.96	64.4	151	93.9	490	10.3	350	2.08	389	3.97	11.2	1.450
	33[2]	4.4	65	152	98	480	10.3	350	2.15	371	3.7		1.47
Ujimqin[1]	10	5.90	225.1	837	46.6	111	20.3	845	0.64	263	2.68	6.8	1.704
	20	5.97	218.3	764	49.7	245	21.7	750	0.87	260	2.59	6.3	1.658
mean	15	5.94	221.7	801	48.2	140	21.0	750	0.76	262	2.64	6.6	1.681

[1] Wasson and Kallemeyn (2002); [2] Wang DD (1983, 1985).

paths of asteroids diverged. The asteroids nearer the Sun were heated more severely than those farther away, because intensity of several heat sources increases towards the Sun (Rubin 2002). The possible energy sources are below: (1) electrical current generated by solar wind that is stronger close to the Sun; (2) impact heating that tends to be more efficient close to the Sun because of increasing impact velocities; (3) decay of short-lived radioactive nuclei such as aluminum-26. Asteroids close to the Sun accreted faster, hence incorporated more short-lived nuclei (Rubin 2002). A large proportion of asteroids, especially those in the outer regions of the asteroid belt, remain unmelted (hence primitive and chondritic). These chondritic asteroids have never segregated into iron cores and silicate mantles. In contrast, other asteroids, particularly those in the inner regions of the asteroid belt, were probably melted and differentiated. These differentiated asteroids are parent bodies of iron meteorites, pallasites, achondrites and mesosiderites. Iron meteorites are divided into magmatic and nonmagmatic groups. The magmatic group formed through sufficiently fractional crystallization of magma that cooled slowly (Wasson and Richardson 2001), and the nonmagmatic one experienced less solid/liquid partitioning of impact-derived melts (Wasson et al. 1980; Choi et al. 1995). The IAB iron meteorite complex has a nonmagmatic origin. Kelly and Larimer (1977) confirmed that IAB iron meteorites were successive extractions of partial melts from chondritic sources. Wasson and Kallemeyn (2002) suggested that IAB iron-meteorite complex was formed by impact heating and melting on a carbonaceous chondritic asteroid or on a porous chondritic body. Compositional variation can be related to different degree of impact melting.

In summary, IAB iron meteorite complex has below features: (1) limited degree of fractional crystallization (variation with factors of 4 for Ir and 1.3 for Au, except for 4 irons of IAB-MG), and a relatively large number of ungrouped members, different from magmatic groups (Wasson and Kallemey 2002). The abundance ranges of Ni, Au, Ga and Ge of IAB iron meteorite complex are given in Table 3; (2) Most of IAB iron meteorite complex contain silicate inclusions. The silicates in the main group and the low-Au subgroups and grouplets are reduced. The highest Fa content of olivine is 8.0 mol% in Udei Station, and the lowest Fa value is 1.0 mol% in Pine River (Benedix et al. 2000). Graphite and car-

bides occur commonly in these meteorites, and may serve as reducing agents. Occurrence of chondritic silicates and fine-grained (2 – 40 cm) γ-iron (taenite) in melts suggests that cooling through γ-iron stability field is too fast to allow diffusive growth of large crystals; (3) The oxygen isotopic compositions of silicates in IAB-MG, low-Au subgroups fall within a narrow range, with $\Delta^{17}O$ ($= \delta^{17}O - 0.528\delta^{18}O$) varying from – 0.30 ‰ to – 0.68‰ (Benedix *et al.* 2000). The range of $\Delta^{17}O$ values of most silicate-bearing iron meteorites (– 0.30 ‰ – 0.70 ‰) is similar to that of whole-rock carbonaceous chondrites (– 0. 7‰ < $\Delta^{17}O$ < –0.3‰), suggesting that carbonaceous chondrites could be the precursor materials of these iron meteorites. Silicates in a few iron meteorites have more negative Δ^{17} O values (e. g. $\Delta^{17}O$ = – 1. 39 ‰ for the Sombrerete IAB-sHL meteorite); (4) High a-bundance of planetary-type noble gases and gas-retention ages, because limited diffusive loss of noble gases during a short high-temperature period after shock melting. These iron meteorites cooled below the closure temperatures probably within 100 ka (Wasson and Kal-lemeyn 2002).

Table 3.   Abundance ranges of Ni, Au, Ga and Ge of IAB iron meteorite complex [*]

Group or grouplet[#]	Ni (mg/g)	Au (μg/g)	Ga (μg/g)	Ge (μg/g)
IAB-MG (71)	64.2 – 76.2	1.417 – 1.707	72.3 – 104	204 – 519
IAB-sLL (20)	77.8 – 85.3	1.555 – 1.776	58.6 – 80.0	194 – 355
Grouplets related with IAB-sLL (6)	80.4 – 94.7	1.529 – 1.706	49.4 – 73.6	179 – 273
IAB-sLM (8)	114.0 – 143.0	1.535 – 1.830	11.9 – 33.2	8.59 – 78.3
Grouplets between IAB- sLL and IAB-sLM (3)	100.5 – 128.1	1.640 – 1.700	34.5 – 53.1	95.6 – 153
IAB-sLH (6)	170.6 – 234.0	1.700 – 1.997	1.45 – 4.85	1.47 – 3.78
IAB-sHL (9)	91.7 – 139.9	2.00 – 3.36	14.2 – 24.8	11.3 – 69.6
IAB-sHH (6)	145.7 – 183.9	2.44 – 3.04	4.79 – 10.8	5.26 – 16.6
Duo iron meteorites (10)	72.3 – 358.8 (a) 72.3 – 80.8 (b) 76.3 – 75.0 (c) 190.6 – 208.3 (d) 146.3 – 118.5 (e) 358.8 – 304.8	1.421 – 3.68 (a) 1.421 – 1.459 (b) 1.634 – 1.643 (c) 1.927 – 1.982 (d) 2.16 – 2.21 (e) 3.64 – 3.68	4.53 – 67.3 (a) 59.4 – 64.7 (b) 67.3 – 58.3 (c) 39.0 – 22.6 (d) 6.96 – 31.0 (e) 5.22 – 4.53	<50 – 267 (a) 250 – 267 (b) 196 – 196 (c) 183 – 104 (d) <50 – 117 (e) 9.01 – 7.50
Solo iron meteorites (17)	55.5 – 596.3	1.286 – 2.92	3.61 – 93.9	9.00 – 490

[*] :Data from Wasson and Kallemeyn (2002);
[#]:Meteorite numbers.

It should be pointed out that the element-Au diagrams can well distinguish nonmagmat-ic iron meteorites, especially IAB-MG, subgroups and grouplets. The metallic melts were produced by impact on various chondritic asteroids that show large variation in petrography, mineral chemistry and bulk chemical compositions. In addition, degree and extension of the shock melting are variable. Hence, various groups of iron meteorites and some ungrouped members are expected. It is reasonable to classify these ungrouped iron meteorites as IAB i-ron meteorite complex. It may be unnecessary to preserve the term of duo (pairing) iron meteorites. Although these meteorites share have similar chemical compositions, they are not pared (*i. e.* different pieces of a same meteorite fall). For example, GRV 98003 and NWA 468 iron meteorites were collected in Antarctica and hot desert, respectively. In ad-dition, GRV 98003 has distinctly lower concentrations of Ga, Ge, Ir and Re than NWA

468 as mentioned above, arguing against paring of them. GRV 98003 and NWA 468 probably formed on different precursor asteroids by impact events.

6 Conclusions

Nantan iron meteorite is reclassified as a member of IAB main group based on the taxonomic system of IAB iron meteorite complex proposed by Wasson and Kallemeyn (2002). The similar metal textures and compositions between GRV 98003 and NAW 468 suggest a same origin (Rubin *et al.* 2002). They probably formed on metal-rich carbonaceous chondrite parent bodies by impact melting. The Ujimqin iron meteorite is a unique member of IAB complex, and Yongning is reclassified as a member or solo iron meteorite of IAB iron meteorite complex.

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