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Rare, metal micrometeorites from the Indian Ocean

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ABSTRACT

Metal in various forms is common in almost all meteorites but considerably rare among micrometeorites. We report here the discovery of two metal micrometeorites : 1. An awaruite grain similar to those found in the metal nodules of CV chondrites. 2. Metal micrometeorite of kamacite composition enclosing inclusions of chromite and merrillite. This micrometeorite appears to be a fragment of H5/L5 chondrite.

These metal micrometeorites add to the inventory of solar system materials that are accreted by the earth in the microscopic form. They also strengthen the argument that a large proportion of material accreted by the earth that survives atmospheric entry is from asteroidal sources.

INTRODUCTION

Fe-Ni metal is a common constituent of most meteorites and is a sensitive indicator of the metamorphism, thermal history undergone by the respective meteorites, therefore it is a diagnostic tool to understand redox conditions in the nebula and also to distinguish between groups/sub-groups of meteorites (Wood 1967; Afatalab and Wasson, 1980; Rubin, 1990, Kimura et al. 2008; Smith et al. 1993). The metal is present in the form of kamacite (most common), plessite, taenite, Fe-Ni-S, and also as beads of Fe-Ni (Brearley and Jones, 1998). There are rare metallic minerals such as the awaruite, buchwaldite, schreibersite etc., reported exclusively from different meteorites (Rubin, 1997), such minerals are never reported from the micrometeorites although they constitute a predominant fraction of the extraterrestrial flux.

In spite of several collections made in the oceans (Millard and Finkelman 1970; Murrell et al., 1980; Brownlee 1985; Prasad et al., 2013, 2017), from polar regions (Maurette et al., 1987; Taylor et al., 1998) and in the stratosphere as well, the finding of pure metallic particles has been extremely rare : Maurette et al. (1987) described metal beads as non-oxidized Fe/Ni spherules and more importantly, they found unmelted metal which was described as unmelted-unoxidized Fe/Ni of kamacite composition which comprised 2% the unmelted fraction of their collection (I-type spheres =1%; Fe-Ni beads 0.5%; Fe-Ni particles =0.5%). The importance of this finding stems from the fact that these particles were identified as primary, rather than ablation products of larger meteorites. Bonte et al. (1987) suggested that the irregular Fe-Ni metallic particles could be the parent bodies of I-type spherules in view of their similar elemental ratios. However, in essence, they suggested that these are primary particles accreted by the earth. Badjukov et al. (2009) reported two unmelted metallic particles from Antarctica, one of which contained both the kamacite and taenite phases. They suggested iron meteorites cannot be the precursors for these particles. Genge et al. (2017) carried out detailed investigations on a large number of I-type spherules. They suggested that these spherules are the ablation products of kamacites and also taenites released from H-type ordinary chondrites, CM, CR chondrites and iron meteorites.

Metal in melted micrometeorites is mostly reported to have formed due to the process of carbothermic reaction of carbonaceous chondritic materials resulting in the formation of the I-type and the G-type spherules (Blanchard et al., 1980; Brownlee et al., 1983; Genge et al., 2008). The metal thus formed is not a true representative of the conditions in the parent bodies. There are alternative explanations which suggest the derivation of melted micrometeorites from metallic minerals in meteorites (Herzog et al., 1999; Genge et al., 2017) . reports of primary metal are rare.

More recently, Prasad et al. (2017) presented metal micrometeorites for the first time. They presented a wide range of unmelted materials such as Fe-Ni beads, kamacites, plessites, taenites etc., released due to asteroidal collisions and entered the earth as primary particles. These particles were identified to be sourced from a variety of meteorite groups such as the carbonaceous chondrites and the ordinary chondrites as well. Rudraswami et al.(2014) analyzed Fe-Ni beads from all the three basic types of cosmic spherules (S-type, I-type and the G-type) and confirmed that these beads have formed during atmospheric entry due to reduction of carbonaceous chondritic precursors.

We present here the discovery of two metal micrometeorites : an awaruite and a metal micrometeorite of kamacite composition enclosing merrillite and chromite. These features have not been reported so far among micrometeorites and form an addition to the inventory of metal from cosmic sources in the microscopic form.

METHODS

The samples have been collected from the deepsea sediments of the Indian ocean using magnetic collection methods. The magnets were placed inside a metal dredge which was dragged along the deep seafloor several times. The material attracted by the magnets were examined in the lab. They were mounted in epoxy, ground and polished and were analyzed using the EPMA. A CAMECA SX-5 EPMA was used for this study. The details of sampling, sample processing, analytical procedures, standards used etc are as described in Prasad et al., (2017). In addition, a JEOL T-300 was used for SEM-EDS and for imaging of the particles in the present study.

DESCRIPTION OF METAL MICROMETEORITES

AAS26-D6-M6-P4 : Awaruite

This grain has dimensions of 47 x 99 μm and is enveloped by an oxidized rim developed during entry. The awaruite (Ni_3Fe) particle has a nickel content of ~63% and Co content of 2.56% (Fig. 1; Table 1). The magnetite rim enveloping the particle has a thickness of a few μm (Fig.1;Table 1) and forms the outer layer. Such a rim is found typically on all unmelted/partially melted micrometeorites, it forms due to the skin melting during entry. In silicate materials the rim comprises of magnetite with the formation of olivines in the proximity of the rim (Genge et al.2006). The melt rim is an excellent evidence for the cosmic origin of micrometeorites and has been produced during experimental ablation studies on carbonaceous chondrites (Toppani et al., 2001) and on iron meteorites (Blanchard and Davis, 1978). Such melt rims have been commonly observed on unmelted cosmic particles (Kurat et al. 1994; van Ginneken et al. 2012; Genge et al. 2008). In

particles that comprise totally of metal, the rim is continuous and sometimes it also contains two microlayers comprising of an outer magnetite and an inner wustite (Prasad et al., 2017). Since the awaruite is a metal particle, the rim is continuous here however there are no microlayers in the rim in the exposed section. If the particle were grounded further, it is possible that wustite may be observed, however that would also entail in the risk of losing the particle altogether.

Prasad et al. (2017) presented Fe-Ni beads having similar cobalt contents as in the present study. Rudraswami et al. (2014) also presented Fe-Ni beads enclosed in I-type and G-type cosmic spherules having similar compositions as shown by the awaruite in the present investigation. It therefore appears that different forms of metal contained in meteorites enters the earth in melted and unmelted forms. The precursor assignment however, is possible if the particles are in an unmelted state.

AAS26-D9-M3-P20 : Kamacite enclosing merrillite and chromite

A kamacite grain having an irregular shape and of size 112x140 μm with Fe, Ni and Co contents of 91.76%, 7.10%, 0.62% respectively, is found to be having two inclusions : merrillite and chromite (Table 2; Fig. 2). The grain does not have an oxidized rim as seen in other kamacite micrometeorites (Prasad et al., 2017). Therefore this particle is apparently a part of a larger micrometeorite/meteorite body which got separated during the entry and subsequently decelerated. This could be the reason for the absence of a rim.

Chromite inclusion

When compared with chromites from different meteorites (Table 4) it is seen that the Cr_2O_3 contents of the particle here (58.24%) are much lower than the chromites in iron meteorites Campo del Cielo (ISWI 74%) and Kendall (ISWI 68.4%) and marginally lower than that of pallasite (Vernon) having 61.3%. Iron meteorite chromites have high MnO contents (2-4%) which is not detected here..

With respect to achondrite chromites The Cr contents in our sample are higher, Al contents are marginally lower, There is a similarity in the Ti and possibly the Fe contents (Table 3). The achondrites have very high MgO contents(35.5%) when compared with the present specimen (26.33%). The carbonaceous chondrites chromites have far too high Al_2O_3 (~22%) when compared with the present specimen (5.16%),

The chromites presented from the Ordovician fossil meteorites from the Finekulle ~~kinekulle~~ site (Sweden) derived from the L chondrite parent body have almost identical composition as the present particle except for MgO which is much higher here (6.74%) as compared with the Thorsberg quarry

(~2.5%) (Schmitz and Haggstrom, 2006). It is also seen that the MgO contents of this quarry have been analyzed in large numbers, however, they show variations in very small percentages (2.57 ± 0.83 : Schmitz et al., 2001).

Merrillite inclusion

The merrillite inclusion has an oval shape measuring $\sim 16 \times 12 \mu\text{m}$ (Fig. 2). Merrillite is reported as inclusions in Lunar rocks, Martian meteorites, in basalt mesostasis in case of achondrites (Joliff et al., 2006), pallasites (David and Olsen, 1991) and also in ordinary chondrites (Jones et al., 2014). The merrillite inclusion in the kamacite particle here appears to be chemically similar to those found in H5/L5 chondrites (Table 2). In comparison with merrillite in different meteorites, it is seen that the FeO content is higher and the CaO content is marginally lower (44.59%) when compared with those from springwater Pallasite (47.30%) (Table 4). The merrillite in the present case is Na-rich therefore it appears to be closer in comparison with those from pallasites. However, in total comparison with merrillites from ordinary chondrites, especially those from H5 and L5 chondrites (Reed and Smith, 1985; Table 4), with respect to all major oxides.

In view of the Ni content being lower than those of pallasites and the slight departure of chromite and merrillite compositions, pallasite origin for this particle can be tentatively ruled out. There are stronger similarities with respect to the chromite and merrillite inclusions with those from ordinary chondrites, especially from the H5/L5 sub-groups. This particle therefore appears to be metal dislodged from H5/L5 chondrites.

DISCUSSION

AAS26-D6-M6-P4 : Awaruite

Awaruites have been described from oxidized CV chondrites, especially as parts of the metal nodules of CV chondrites such as the Allende (McSween, 1977; Haggerty and McMahon 1979; McMahon and Haggerty 1980). It is also observed in CK3 chondrites (Rubin et al., 1988) and also rarely in ordinary chondrites (Danon et al. 1981; Semenko et al. 2004 in the UOC Krymka LL3.1). It comprises of 65-68% Ni and 1.7-2.6% Co, corresponding to a formula of Ni_3Fe (Brearley and Jones, 2012). Euhedral, zoned awaruites were described in Allende (CV3) by Rubin (1991), he suggested that they are zoned with the central portions being more enriched in Cobalt. The present particle has a homogeneous composition (Table 1), it could also be possible that the central portion of the particle has not been exposed as seen in the polished section (Fig1). The Fe-Ni-Co contents seem to be close to those found in CV chondrites (Table 1).

In carbonaceous chondrites, it has been suggested to form due to subsolidus oxidation of magnetite, where the unoxidised, residual nickel accumulates and forms either as tetrataenite or awaruite (Haggerty and McMahon, 1979). However, Rubin (1991) discovered euhedral awaruites in metallic chondrules of Allende which having higher nickel contents which appear to have solidified from melt, rather than due to subsolidus oxidation.

Awaruite has been observed in terrestrial formations associated with the serpentinization of peridotites forming at temperatures $\leq 750^{\circ}\text{C}$ (Frost 1985). Terrestrially, awaruite is found in hydrothermally altered peridotites, formed due to the serpentinization process (Foustakos et al. 2015; Rajendran and Nosir, 2014). There is an overlap in the awaruite compositions of hydrothermal alteration products and those found in meteorites. However, copper contents appear to be higher among the hydrothermal awaruites (Table 1). The present grain contains a magnetite rim which is indicative of ablation during entry and we did not detect the presence of copper in this grain. Further, the location of this sample is in the Central Indian Ocean which is a few thousand km removed from any known hydrothermal site, and samples from near this site were examined for Australasian microtektites (Prasad et al., 2007) and no evidence of hydrothermal activity was noticed in these sediment cores. Therefore in view of its possessing an oxidized rim and also in view of its chemical composition, the present particle appears to be cosmic. Similar sized metal micrometeorites were reported recently by Prasad et al. (2017). They suggested that these particles were released during asteroidal collisions and entered the earth as independent entities especially in view of their possessing magnetite rims.

AAS26-D9-M3-P20 : (kamacite with chromite and merrillite inclusions)

Based on their nickel contents (and mole Fa contents) pallasites are broadly classified into two groups : the Main Group Pallasites (Ni= 7.8-11.7%; Fa 11-13mole%) and the Eagle Station Group (Ni= 14-16% and Fa 19-20 mole%) (Scott, 1977). In the present case, the particle size is very small and we did not find any olivine associated with the particle and the nickel content is marginally below that of the lower limit of Main Group Pallasites. The nickel percentage of 7% falls marginally within that of the hexahedrites. However, the presence of a chromite grain and merrillite provide better clarity regarding the origin of this particle.

While Chromites are common occurrences in most iron meteorites (Bunch and Kyte, 1970), the combination of the presence of a chromite, merrillite encased in metal of kamacite composition is seen to occur in H5/L5 chondrites and also in pallasites.

Chromite composition in meteorites is related to oxygen fugacities and is therefore a sensitive indicator of physico-chemical conditions of its formation (Bunch and Keil, 1971). Cr, Mn and Zn are highest in the reduced meteorites and Al, Ti are highest in the oxidized meteorites (Bunch and Olsen, 1975). Therefore it is seen that the Cr₂O₃ contents of chromites in iron meteorites are highest among all meteorites and there is a corresponding and systematic decrease in Cr contents from Iron meteorites > pallasites > mesosiderites > ordinary chondrites.

The chromite composition basically shows proximity to that of chromites from ordinary chondrites, especially to that from the H group of ordinary chondrites (Bunch et al., 1967) except for MgO contents which are higher in the present particle. The compositions of H4-H6 chromites show a greater closeness to that of the present sample. The chromites in the L chondrites show higher FeO and much lower MgO contents.

Further, Merrillite is found as inclusions within metal grains in ordinary chondrites (L L) 3.9 – 6 studied by Jones et al. (2014). The metal in such cases is usually kamacite, kamacite/taenite or taenite. Jones et al. (2014) further suggested that the phosphatic mineral formed during mild metamorphism (grade 4) resulting in oxidation and growth of P which was originally incorporated in metal. It is also found as rounded inclusions in metal, similar to the occurrence in the present study. In addition, some of the phosphate minerals are also associated with chromite-plagioclase assemblages.

Therefore, considering the nickel content of the particle, the chromite and merrillite composition showing similarities with those of H5/L5 chondrites, it is suggested here that this particle is part of a metal inclusion in H5/L5 chondrites which was dislodged during asteroidal collisions and entered the earth. Furthermore, this particle does not have an oxidized rim reported from unmelted kamacites from the same collection (Prasad et al., 2017). Because of its small size this particle could have escaped frictional heating altogether during atmospheric entry. However, the density of Fe-Ni being high even a low entry angle, low velocity entry would have left some marks of atmospheric entry in the form of a thin rim around the particle because this particle would traverse deeper into the atmosphere before decelerating (Rudraswami et.al., 2017). Due to lack of evidence of atmospheric entry, the alternative explanation could be that this was part of a larger particle which fragmented

upon interaction with the Earth's atmosphere and got separated after the initial entry velocity was checked.

The total flux of primary metal on the earth is low.. Iron meteorites (4.7%) and stony irons (0.7%) constitute low percentages of total meteorite flux (Krot et al., 2003). Among micrometeorites the metal-rich micrometeorites are the I-type and the G-type spherules where the metal has been segregated during atmospheric entry, these constitute ~5% of the total flux (Taylor et al., 2000 ; Prasad et al., 2013). Primary metal among micrometeorites is rare, among unmelted particles Maurette et al. (1987) reported 0.5% of the particles observed by them comprising of metal micrometeorites. Therefore, in order to study the range of metals from extraterrestrial sources that the earth receives, one needs to collect them using a method that would be concentrate them, recently, Prasad et al. (2017) presented a collection that showcased metal minerals commonly observed in chondrites such as kamacites, plessite, taenites, metal-beads in the microscopic forms. While such minerals are common in meteorites they were never reported from micrometeorites.. Although they are released due to asteroidal collisions they can only be collected in areas where large spatial and temporal domains need to be scanned as in the deepsea regions with very low sedimentation rates (Prasad et al., 2018). The metal micrometeorites described here occur only in specific meteorites sub-groups and are not common, for example awaruites are described among the metal nodules of oxidized CV chondrites (Rubin, 1991; Haggerty and McMahon, 1979), LL chondrites (Afialab and Wasson, 1980; Rubin, 1990) and also as an alteration product in iron meteorites (Pedersen, 2009). The case is similar with respect to merrillite as well – it is seen in H5/L5 chondrites or in pallasites.

While melted micrometeorites have been attributed precursor sources dominantly from either CI or CM carbonaceous chondrites (Brownlee et al., 1997), it is well known that these micrometeorites have lost most of their primary characteristics due to melting during entry. Recent investigations on unmelted micrometeorites have revealed a wide range of sources for micrometeorites that includes carbonaceous chondrites (CI, CM, CV etc. : Kurat et al., 1994), most groups and sub-groups of ordinary chondrites (Rochette et al., 2008; van Ginneken et al., 2012; Imae et al., 2013), achondrites (Badjukov et al., 2010), metals segregated from different groups, sub-groups of carbonaceous chondrites and ordinary chondrites (Prasad et al., 2017). Many of these investigations also present the minor components observed in meteorites. Most if not all the investigators believe that these particles have been released by asteroidal collisions into the inner solar system (Prasad et al. 2017). Therefore, all these investigations point towards the fact that the unmelted micrometeorites comprise

of fragments of components of the known range of meteorites and the difference between the melted and unmelted ones apparently seems to be the entry parameters. Slightly different angles, velocities, physical properties and chemical compositions of the incoming particles would make the transition between melted and unmelted particles (Rudraswami et al.,2016). The more evolved meteorites such as the high metamorphic grade ordinary chondrites find lesser representation among the micrometeorites because they have greater tensile strengths because of which they do not fragment into smaller sized pieces during asteroidal collisions (Rudraswami et al.,2018). This is also the probable reason why no evidence is found for pallasites or iron meteorites among the unmelted micrometeorites. This is in contrast to the carbonaceous chondrites which dominate the sub-millimetre size classes in view of their hydrous, friable nature because their fragile nature facilitates fragmentation into sub-mm particles (Flynn and Durda, 2004).

The overview from the investigations on collected cosmic dust that survived atmospheric entry, especially from the unmelted micrometeorites is that these particles are derived from the asteroid belt, especially because they can be easily identified with the components of known classes of meteorites. There are some models which suggest a major contribution from the Jupiter family comets (Nesvorný et al. 2010) especially for the particles that are less than 200 μm size. The entry velocities of asteroidal particles are estimated much lower than those from cometary sources (Flynn et al. 1989), therefore it is difficult for cometary particles to survive atmospheric entry without undergoing melting or vaporization (Duprat et al. 2010). More recent investigations provide greater clarity in the identification of cometary particles, this is true especially in the case of the ultracarbonaceous particles found in polar regions which show greater similarities with the chondritic porous-IDPs identified to be cometary (Noguchi et al., 2015; Engrand et al. 2015). While these particles have unique high carbon compositions they are also particularly small in sizes of up to $\sim 10 \mu\text{m}$.

The two metal micrometeorites presented in this study while contributing to the expansion of the inventory of the solar system particles accreted by the earth in the microscopic form also conform to the larger picture strengthening the concept that a large fraction of the cosmic dust that survives atmospheric entry is from asteroidal sources.

CONCLUSIONS

Two metal micrometeorites are reported in this study. One of them is an awaruite which has magnetite rim developed during entry and its composition is suggestive of an origin from the CV chondrites. The other metal micrometeorite is a kamacite particle that has inclusions of chromite and

merrillite. The Fe-Ni composition, and more importantly, the similarities in the compositions of the chromite and merrillite inclusions with those from metal nodules in H5/L5 chondrites implies that this particle is a metal nodule removed from a H5/L5 chondrite during asteroidal collisions.

The above two particles add to the inventory of the meteoritic metal that is accreted by the earth and provide impetus to the concept that asteroids contribute substantially to the unmelted particulate flux on the earth.

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FIGURE LEGENDS

FIGURE 1:

a) Backscattered SEM image of the awaruite particle. A thin magnetite rim envelops the particle.

b) Ni distribution map of the awaruite particle. Ni is strongly depleted in the rim portions of the particle which has developed the composition of a magnetite during atmospheric entry.

FIGURE 2 : Backscattered SEM images of the kamacite particle with inclusions

a) AAS26-D9-M3-P20 : irregular-shaped kamacite particle, there is no magnetite rim on this particle. Two inclusions are seen on the particle : chromite (c) and merrillite (b).

b) Merrillite inclusion shown in (a) under higher magnification.

c) Small chromite inclusion shown in (a) under higher magnification

Figure 1

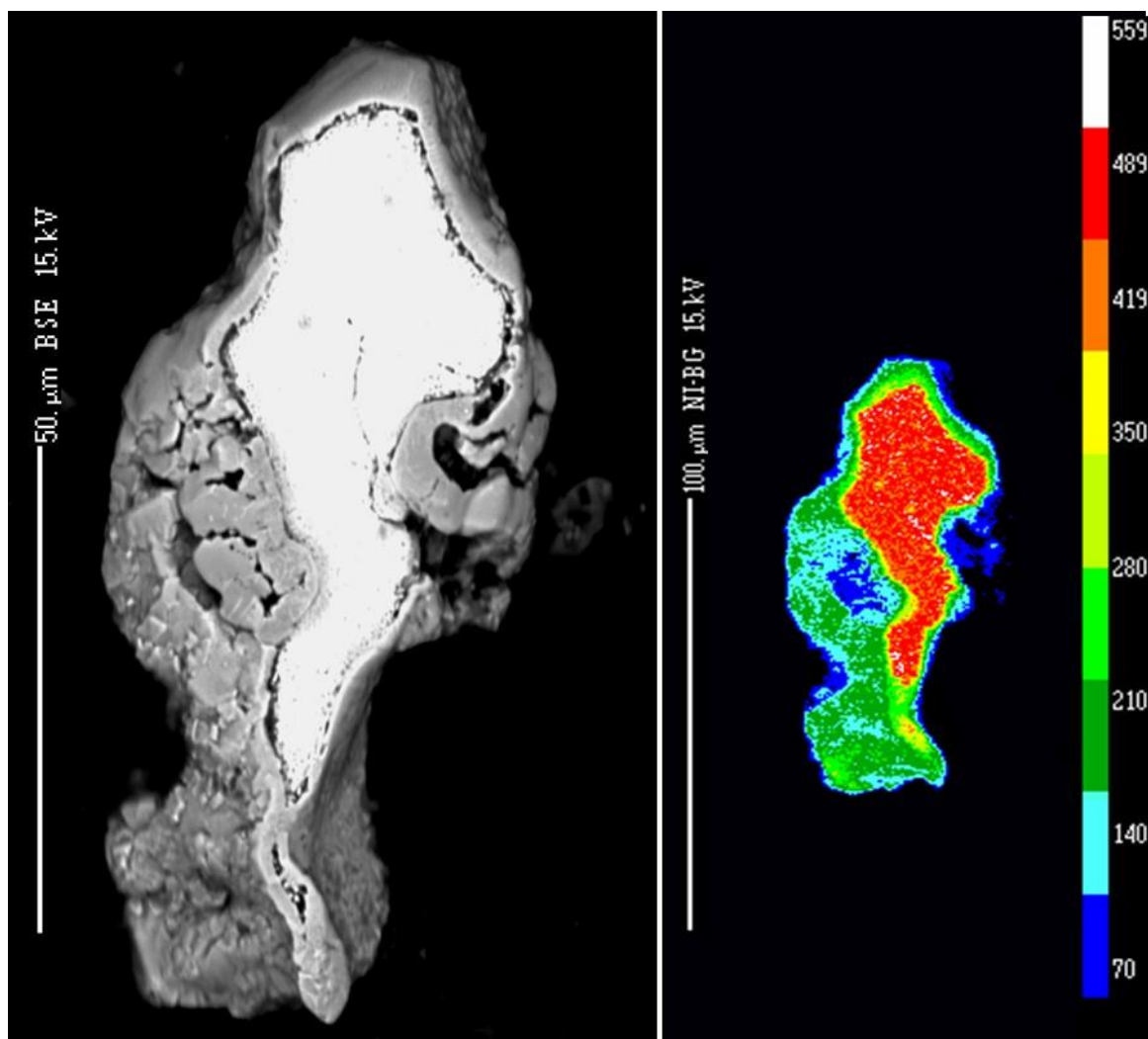


Figure 2

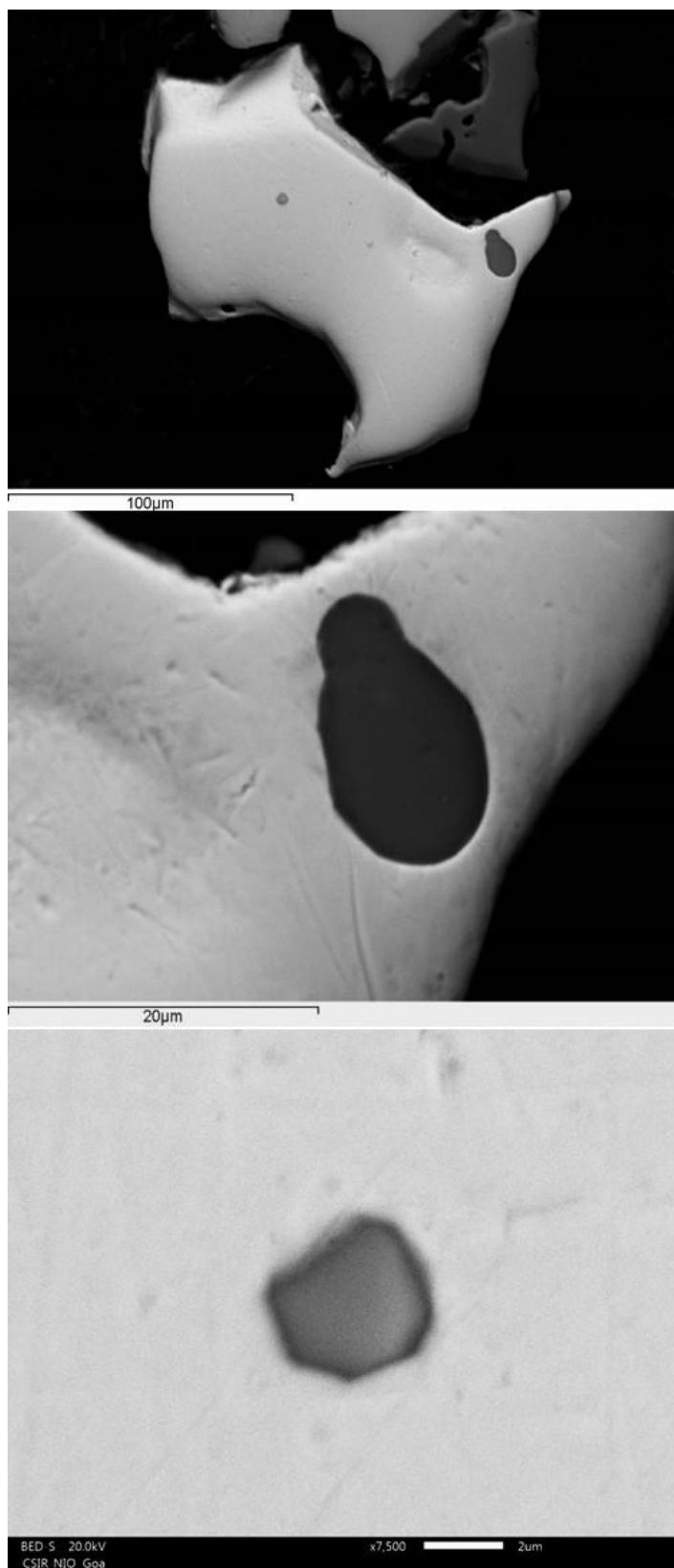


TABLE 1 : Comparison of chemical composition of awaruites from various sources

| Source | Fe | Co | Ni | Cu | P | Reference |
|--|---|--------------------|-------------------------|--------------|--------------|-----------------------------|
| Allende CV3 Opaque Nodules | 27.3 – 32.8 | 1.7- 2.6 | 65.3 -71.2 | N.D | N.D. | Rubin (1991) |
| Ningqiang Carbonaceous Chondrite (CV) | 25.6 – 32.7 | 1.76 – 2.42 | 63.7 – 68.2 | N.D. | Up to 0.36 | Hua et al. 1995 |
| Allende CV3 | 29-30% | 2.5 | 67-68 | 0.1 0.3 | 0.1 | Haggerty and McMahon (1979) |
| Hydrothermal Alteration (Wadi Hibi, Northern Oman) | 28.92 | 0.07 | 70.67 | 0.62 | N.D. | Rajendran and Nosir (2014) |
| Hydrothermal : Hess deep | Stoichiometric Fe Ni ₃ | Up to 2.3% | | Up to 1.2% | N.D. | Alt and Shanks (1998) |
| Coolac Ultramafic belt, Australia | 22.65-28.54 25.13 av (6) | 0.4-2.45 1.34av | 68.76 –74.63 73.09av | Not reported | Not reported | Ashley (1974) |
| AAS26-D6-M6-P4 :Awaruite CORE composition | 34.2 | 2.9 | 63.0 | N.D. | N.D. | PRESENT STUDY |
| AAS26-D6-M6-P4 :Awaruite RIM composition (all oxides) | Fe ₂ O ₃ 67.01 | CoO 1.79 | NiO 25.73 | | | PRESENT STUDY |
| N.D. = Not detected | | | | | | |

TABLE 2 : CHEMICAL COMPOSITION OF KAMACITE

| (ii)Kamacite with chromite and merrillite inclusions | | | | | | | |
|---|-------------|---|-----------|-----------|-----------|--------------|--------------|
| PARTICLE NUMBER | TYPE | SIZE IN μm | Fe | Co | Ni | Total | SHAPE |
| AAS 26 D9 M3-P20 | KAMACITE | 112x140 μm | 91.76 | 0.62 | 7.10 | 99.48 | irregular |

TABLE 3 : Comparison of chromites in meteorites with the inclusions found in the kamacite particle in the present stud

| (A)CHROMITE SOURCE | Cr2O3 | Al2O3 | V2O5 | TiO2 | FeO | MgO | MnO | ZnO | Total |
|--|--------------|-------------|-------------|-------------|--------------|-------------|----------|-------------|--------------|
| Campo del Cielo (I AB) ¹ | 74 | 0.79 | 0.24 | 0.42 | 12.3 | 9.2 | 2.32 | 1.44 | 100.71 |
| Kendall Co. Mt. (Ungrouped stony-iron) ¹ | 68.4 | 10.9 | 0.68 | <0.02 | 2.5 | 14.2 | 4.2 | <0.02 | 100.88 |
| Vernon (Pallasite) ¹ | 61.3 | 7.8 | 0.59 | 0.27 | 23.1 | 6.2 | 0.75 | <0.02 | 100.01 |
| Pultusk (H) ¹ | 55.9 | 6 | 0.65 | 2.72 | 30.1 | 2.72 | 1.03 | <0.02 | 99.12 |
| Hainholz (Mesosederite) ¹ | 53.3 | 11.8 | 0.68 | 1.59 | 27.8 | 3.2 | 1.12 | <0.02 | 99.49 |
| Sioux Co. (Basaltic achondrite) ¹ | 51.6 | 7.2 | 0.93 | 3.4 | 35.5 | 0.28 | 0.62 | <0.02 | 99.53 |
| Murchison (CM) ¹ | 41.9 | 22.3 | 0.6 | 0.9 | 27.7 | 6.9 | 0.2 | - | 100.5 |
| H 5/6 ² | 56.7 | 6.45 | 0.88 | 2.17 | 29.12 | 3.03 | 1.02 | 0.33 | 99.7 |
| L 5/6 ² | 56 | 5.86 | 0.91 | 2.73 | 30.16 | 2.73 | 0.84 | 0.31 | 99.54 |
| All fossil meteorites (ordinary chondrites) ² | 57.6 | 5.53 | 0.89 | 2.73 | 26.94 | 2.57 | 1.01 | 1.86 | 99.13 |
| AAS26-D9-M3-P20 Present Study | 58.26 | 5.16 | 0.88 | 2.14 | 26.33 | 6.74 | - | 0.21 | 99.72 |

¹ Data source : Bunch and Olsen (1975).

² Data source : Schmitz et al. (2001)

TABLE 4 : Comparison of merrillites in meteorites with the inclusion in the kamacite particle in the present study

| MERRILLITE SOURCE | | P2O5 | FeO | MgO | CaO | Na2O | Total | |
|---------------------------------|---------------------------|---------|-------|------|-------|-------|--------|-------|
| Lunar Rocks ¹ | 14161, 7350 | 42.90 | 0.13 | 3.55 | 39.60 | 0.19 | 86.37 | |
| | 14161, 7373 | 42.70 | 1.96 | 2.55 | 41.10 | 0.53 | 88.84 | |
| | 14161, 7044 | 42.70 | 0.86 | 3.18 | 40.50 | 0.58 | 87.82 | |
| | 14161, 7264 | 43.30 | 1.00 | 3.18 | 40.00 | 0.36 | 87.84 | |
| | 14161, 7233 | 42.30 | 0.47 | 3.35 | 40.60 | 0.53 | 87.25 | |
| | 14161, 7069 | 41.90 | 3.47 | 1.57 | 38.80 | 0.18 | 85.92 | |
| | 10085 LR No. 1 | 43.90 | 0.95 | 3.26 | 40.60 | 0.77 | 89.48 | |
| | 12036, 9 | 42.50 | 2.13 | 3.80 | 42.30 | 0.33 | 91.06 | |
| | 12039, 3 | 42.60 | 1.23 | 3.20 | 41.90 | 0.37 | 89.30 | |
| | 12013, 14 | 43.00 | 1.30 | 2.91 | 39.00 | 0.12 | 86.33 | |
| | 15475, 125 | 41.70 | 5.85 | 0.55 | 39.20 | 0.06 | 87.36 | |
| | 65903, 17 -10 | 42.40 | 1.10 | 3.01 | 40.50 | 0.46 | 87.47 | |
| | 73216, 38 | 43.90 | 0.72 | 3.25 | 41.30 | 0.44 | 89.61 | |
| | 76503, 7025 | 42.40 | 1.54 | 2.69 | 38.80 | 0.03 | 85.46 | |
| | LAP022xx | Group 1 | 43.70 | 6.65 | 0.20 | 42.80 | 0.17 | 93.52 |
| | Lunar Meteorite | Group 2 | 42.60 | 6.41 | 0.20 | 39.70 | 0.04 | 88.95 |
| | | Group 3 | 38.00 | 6.62 | 0.05 | 34.20 | 0.00 | 78.87 |
| Martian Meteorites ¹ | ALH 84001 | 46.00 | 0.78 | 3.53 | 46.50 | 2.45 | 99.26 | |
| | Los Angeles | 44.90 | 4.96 | 0.91 | 46.90 | 1.20 | 98.87 | |
| | EETA 79001 | 45.60 | 4.97 | 1.25 | 46.20 | 0.72 | 98.74 | |
| | Shergotty | 44.40 | 4.21 | 1.44 | 46.20 | 1.27 | 97.52 | |
| Pallasite ¹ | Spring-water | 46.90 | 0.91 | 3.61 | 47.30 | 2.50 | 101.22 | |
| Ordinary chondrites | Barbotan H5 ² | 44.92 | 1.29 | 3.98 | 45.61 | 2.70 | 98.50 | |
| | Knyahinya L5 ² | 44.92 | 1.13 | 4.48 | 45.89 | 2.70 | 99.12 | |

| | | | | | | |
|--------------------------------------|--------------|-------------|-------------|--------------|-------------|--------------|
| Menow H4 ² | 46.06 | 0.80 | 3.98 | 46.73 | 2.83 | 100.40 |
| Salles H6 ² | 45.14 | 0.89 | 3.98 | 45.75 | 2.56 | 98.32 |
| Bo Xian LL ³ | 45.40 | 0.79 | 3.45 | 46.20 | 2.70 | 98.54 |
| Bjurbole LL ³ | 45.60 | 0.63 | 3.53 | 46.40 | 2.74 | 98.90 |
| Tuxtuac LL ³ | 45.60 | 0.54 | 3.42 | 47.00 | 2.79 | 99.35 |
| St. Se´verin LL ³ | 45.70 | 0.48 | 3.48 | 47.30 | 2.82 | 99.78 |
| AAS26-D9-M3-P20 Present Study | 47.26 | 1.98 | 3.32 | 44.59 | 2.35 | 99.50 |

¹ Data from Joliff et al. (2006)

² Data from Reed and Smith (1985).

³ Data from Jones et al. (2014).