INTRODUCTION

We welcome the comments on our paper by M. Genge and M. van Ginneken and their attempt at providing an alternative explanation for our discovery of metal micrometeorites in the Indian Ocean. However, their hypotheses throughout the comment paper are based on erroneous assumptions and lack of understanding of magnetic methods of cosmic dust collections from the deepsea sediments.

Cosmic dust has been collected from the deep seafloor using two different techniques: Magnetic (biased) and non-magnetic (unbiased). The magnetic method of collection involved dragging magnet impregnated sampling materials across the deep seafloor (e.g. Bruun et al., 1955; Brownlee et al., 1979; Parashar et al., 2010). The recovered materials comprised of strongly magnetic materials such as rust-like metallic particles, volcanic particles and dominance of metal-rich spherules etc (Fig.1). Cosmic spherules were handpicked from this magnetic material and were investigated (Fig.1b). In view of the magnetic methods employed, such collections showed large percentages the I-type and G-type particles. More importantly, after picking of the spherules from the magnetic materials, no investigator ever examined the rest of the magnetic particles (Fig. 1a). We examined the magnetic materials from four different samples and discovered metal micrometeorites, Fe-Ni beads etc. which were presented in Prasad et al. (2017). Separation,
mounting and analyses of magnetic materials is a cumbersome process because all the particles are strongly magnetic and they tend to adhere to each strongly and form “bunches” and it is akin to literally picking the proverbial needle in a hay stack. For example, we examined over 10,000 such magnetic particles to recover 800 melted micrometeorites (~50% of which comprise of I-type and g-type). In addition, 129 unmelted metal and also 120 unmelted silicate particles were recovered. It is to be noted, however, that we have not come across any investigation on the examination of the magnetic materials recovered from the deepsea sediments, this is the reason why no one ever reported metal micrometeorites from any of the magnetically biased collections. This in a nutshell answers the question raised by Genge and van Ginneken regarding why no one else from any of the collections have ever reported such material.

Now, we will explain how the magnetic method of collection facilitates preferential accumulation and retention of only strongly magnetic particles (eg. metals or metal-rich particles). As mentioned in our paper (Prasad et al., 2017), we fixed 6 strong magnets to a plate which was in turn fastened to a dredge. The dredge is a steel cage (for dimensions, description of operations etc. please refer to our paper Prasad et al. 2017 and for images of the collection please see Parashar et al. 2010) which is dragged across the seafloor for several kilometres during each sampling operation. During this process of ploughing, due to the friction offered by the sediments and the sediment plume only strongly magnetic particles are preferentially retained on the magnetic plate. Subsequently, the dredge is hauled up through a >5 km water column onto the research vessel. During this process, seawater would be gushing through the dredge which is being hauled up at a speed of 90 metres/minute and would be dislodging the not so strongly magnetic materials (e.g. the silicate particles) from the magnetic plate. Upon arrival at the sea surface, the dredge would be brought back onto the deck of the research vessel. During this process it would be enduring a few hits due to the roll and pitch of the vessel, the last thud being when it finally comes to rest on the deck. This method of sampling therefore permits retention of only the most strongly magnetic materials such as the metals and the metal-rich particles, and the more weakly magnetic particles are dislodged at various stages of sampling and recovery. Each operation takes 12 hours to complete. We carried out
several such operations in many parts of the Central Indian Ocean and we find metallic minerals ubiquitously in all the sampling operations, we presented results from 4 such operations in Prasad et al. 2017. Also, the sampler (the dredge in the present case) would penetrate the seafloor in an area which has extremely low sedimentation rates. Which means that the strata sampled by the dredge would have an age range of anywhere from 0 - 200,000 years depending upon the depth of the seafloor sediments penetrated. In view of the age range of the strata sampled and the distance dragged along the seafloor, the percentages of materials cannot be interpreted in quantitative terms with respect to the area sampled because of the inherent bias in the sampling method and lack of control over the volumes of deepsea sediments sampled. Such methods of collection are logistically extremely difficult/impossible to carry out in the polar terrains because if one goes by the ice formation rates in the polar regions, an equivalent sampling operation would involve penetration up to several tens of metres/kilometres deep into the ice and ploughing through for several kilometres. This is the reason why no investigator (except for Maurette et al. 1987) ever reported metal micrometeorites from any of the known polar collections.

This method of collection contrasts strongly with the unbiased collections. During unbiased collections sampling takes place in a given spot of known dimensions. All the cosmic particles in a given volume of sediment/ice/water/snow are extracted, in such cases quantification of different types of cosmic materials from different sources and applying the same to the surface of the earth would be a meaningful and valid exercise. The constitution of metals/metal-rich particles in unbiased collections is generally in single digit percentages (1-5%). This represents the true measure of metal-rich particles that survive atmospheric entry. Unbiased collections have been made by several investigators in the past: Millard and Finkelman (1970); Murrell et al. (1980); Maurette et al. (1986; 1987; 1991); Maurette et al., 1992; Taylor et al. (2000); Yada et al., (1994); Terada et al., 2001, Prasad et al. (2013). In all these collections, it is seen that the metal-rich components are less than 5%. Incidentally, the sampling operations shown in Prasad et al. (2013) are also from the same areas where the magnetic operations are carried out and as expected there is a dramatic difference in the materials recovered from the two different methods of sampling employed (Tables in Prasad et al. 2013).
al. 2013 and 2017). We had operated the dredge with a magnetic panel in other parts of the Central Indian Ocean as well (Parashar et al. 2010) and we found that the I-type and G-type spherules together in these locations also constitute close to 40%. Therefore, basically metallic minerals can be recovered from any part of the deepsea regions of the world if one ploughs through the seafloor using magnets. Since the samplers collect samples from the seafloor to depths of several tens of centimeters, they would be encountering metal particles that have been continuously accumulated over a large span of time which in the present case is 1.5 - ~200,000 years. And these, therefore cannot be interpreted as belonging to a “single large bolide”. We will elaborate on this and the other aspects in a later section of our reply.

**ENTRY HEATING OF METALLIC MICROMETEORITES AND ABUNDANCES :**

Based on the Genge (2016) atmospheric entry model, Genge and van Ginneken suggest that the maximum proportion of metal grains surviving atmospheric entry at diameters of 100 and 150 µm (as shown by us in Prasad et al. 2017) is 10% and 2% respectively. This proportion is sufficient to justify the quantities found by us. The metal micrometeorites or metallic particles are never at high percentage levels in any unbiased collection. They are preferentially concentrated in the present case which is the reason for their high abundance here and their non-occurrence in unbiased samples. Therefore, we wish to dispel the assumption that the percentages presented by us (i.e., 800 melted micrometeorites out of which 50% are I-type and G-type; Unmelted : 129 are unmelted Fe-Ni metal particles and 120 unmelted silicate particles) are not absolute percentages of such particles in a given volume of the seafloor. Genge and van Ginneken also mention our sampling effort in Prasad et al. (2013) where we reported ~5% of the total spherules to be either I-type or G-type and compare these with the abundances of the I-type and the G-type spherules which are close to 50% of the total collection thus implying that in the present area a metal bolide has disrupted in the atmosphere to account for such large abundances of metals in the present study. We wish to clarify
here that the samples used in Prasad et al. (2013) and in Prasad et al. (2017) are from the same geographic domains. The differences in the quantities of metallic particles between both the above methods of collection are because of the differences in the sampling methods employed in both these cases. In the samples presented in Prasad et al. (2013) were spot samples, there was a control in the total volume of sediment sampled and ALL the melted cosmic particles in these samples were recovered. Whereas, the samples presented in Prasad et al. (2017) although are from the same area, they were collected by dragging the dredge that contained magnets across the seafloor for several kilometres and recovered metal micrometeorites and other metal-enriched particles. The metallic particles were preferentially retained because of the process we described in the previous section of this reply.

We presented a break-up of the metal-rich particles collected by the magnetic methods (Prasad et al. 2017). Genge and van Ginneken have incorrectly assumed that the break up presented by us is representative of the absolute concentrations of these particles in this part of the Indian Ocean. The problem here is with quantification of this collection. The numbers calculated by Genge and van Ginneken are based on an erroneous assumption. For a collection of this type using strong magnets dragged along the deep seafloor and traversing through an estimated maximum sediment thickness of 70 cm implies at the rates of sedimentation here to be up to 200,000 years. The magnets retain only those particles that are strongly magnetic, the others have been washed away during the collection and during the ascent of the dredge in >5 km of seawater as explained above.

The numbers and percentages of particles presented by us are relative percentages between the most strongly magnetic materials that have adhered to the magnetic plate fixed to the dredge. These particles have been continuously falling throughout the time span represented by our collection (i.e., ~1.5 – 200,000 years).
M. Genge as a reviewer of our paper (Prasad et al. 2017) suggested that detonations at the top of the atmosphere could be one of the reasons for the survival of the metal micrometeorites shown in our paper. This we agreed to be a possibility (Fig. 2) because in order to release such large particles (maximum size observed here is ~400 µm) and facilitate their entry they should have entered the earth at a low angle and low velocity. Several large unmelted composite silicate particles have been reported in the literature that contain chondrules accompanied with meteorite matrix (e.g. Rochette et al., 2008; van Ginneken et al., 2012). These have been suggested to be fragmented parts of meteorites arriving on the earth. Further, many of such particles did not have continuous magnetite rims implying that they may be fragments of larger particles that broke up during entry (Rochette et al., 2008; van Ginneken et al., 2012). Meteorite matrices also commonly contain kamacite and taenite grains, we suggested that they have been dislodged from their parent bodies in a similar mechanism due to collisions and during entry they have further fragmented before arriving on the earth. Further, if the particles are accompanied by meteorite matrix, as is common among unmelted silicate materials, the heating during entry of the more volatile components of the matrices can be sufficient to volatilize these components releasing the metal micrometeorites. This is similar to the phenomenon suggested by Genge (2006) that facilitates the delivery of chondrules in the form of coarse-grained micrometeorites in unmelted forms.

Genge and van Ginneken compare the break up metal micrometeorites in the present paper with that of presence of the metal-rich spherules presented in our paper (Prasad et al., 2013) and that of Taylor et al. (2000) where the I-type and G-type together constitute 5% and 1% respectively. And further suggest that in order to account for the almost total dominance of metals in the present collection: "The significant enhancement in I-types in the reported collection, therefore, would require the removal of 99% of S-types but the survival of unmelted metal grains". This is exactly what has taken place in the present method of sampling. We have described how only materials that are strongly magnetic are preferentially concentrated and how the weakly magnetic silicate particles are dislodged during our collection methods in an earlier section of this reply. Genge and van Ginneken are in effect comparing two totally different methods of sampling which would recover different types of materials. Therefore materials collected during such a strongly biased collection cannot be
used to quantify in absolute terms. Further, Genge and van Ginneken advocate that all these metal micrometeorites are part of a "single large bolide event". The particles presented in our study have an estimated age range of ~1.5 year to 50,000 or if we consider that the sampler has submerged entirely into the seafloor then the oldest particle here can be even 200,000 years. This is reflected in the different grades of aqueous alteration undergone while on the seafloor, wide range of particles, vast differences in chemical compositions etc.. We observe that the particles range from completely unaltered, euhedral-shaped crystalline entities or even Fe-Ni beads to particles that have undergone almost complete aqueous alteration into serpentine clays due to large residence times on the seafloor. We have also mentioned in our paper (Prasad et al. 2017) that the amounts of aqueous alterations observed on different grains suggest that these particles have a vast range of terrestrial residence times and these particles have been raining on the earth continuously over a large time interval. Therefore, it is clear from the morphologies and their altered chemical compositions, the particles presented in our study have had a vast range in their terrestrial ages and could not have been deposited in a "single large bolide event".

**Textural and Mineralogical Evidence for an Unmelted Origin**

We mentioned that "The presence of wustite implies that the particle has passed through a region of very low oxygen fugacity and has attained a temperature of 550°C." This does not in any way disagree with the calculations presented by Genge and van Ginneken in their Fig. 2.

Genge and van Ginneken express reservation on the fact that the oxide rims present on the metal micrometeorites particles have been suggested by us to be due to melt origin. They suggest that solid state oxidation as seen in high temperature corrosion of steels (Chen and Yuen, 2003) could be the process responsible for the generation of oxide rims. We thank them for this suggestion; this could definitely be a possibility. We had indeed suggested exactly the same possibility of high
temperature oxidation of Fe-Ni which facilitates formation of a continuous layer of magnetite/wustite reflecting the attainment of respective oxidation states attained by Fe during the entry (Kosakevich and Disnar, 1997). In addition, we also cited the experimental results of Blanchard and Davis (1978) who simulated Fe-Ni metal of different compositions and also iron meteorites under the conditions of an entry velocity of 12 km/s and an altitude of 70 km above the earth. These results clearly showed skin melting of the Fe-Ni metal, a "melted rind" comprising of magnetite and wustite have been observed.

Genge and van Ginneken have not presented accurately our arguments regarding the origin of the Fe-Ni beads. Genge and van Ginneken further explain that the metal beads shown by us are the cores of I-type spherules and are not unmelted grains. We had not emphasised that these beads are primary or unmelted. We had suggested that they could have originated due to several well documented processes: the Fe-Ni beads could have been generated by metal segregation taking place during their atmospheric entry, for example see Fig. 2 (Blanchard et al., 1980; Brownlee et al., 1983; Genge and Grady, 1998). They are found in all the three basic types of cosmic spherules and have been suggested to be due to pyrolysis of carbon during entry facilitating metal segregation, followed by inertial separation and release during entry (Rudraswami et al., 2014). Some of the beads have well developed magnetite/wustite rims (Fig. 1g, Prasad et al. 2017), this is proof that they have entered the atmosphere as primary Fe-Ni beads therefore giving rise to the possibility that the beads could also be primary asteroidal material. Herzog et al. (1999) suggested that heating and oxidation of kamacites/taenites in meteorites to be a possible origin of the I-type spherules.

We have not emphasised on the possibility of a particular mode of origin for these particles – there are strong evidences for several mechanisms. Considering their compositions and the present forms in which they occur, it would be extremely difficult to identify their process of formation.

Chemical Evidence for formation as Metal Micrometeorites
The range of Co/Ni shown by us in Fig. 6 (Prasad et al. 2017) cannot be reconciled to belong to a single source. The particles have originated from a variety of meteorites over a period of time and have been deposited in the Indian Ocean, this diversity is demonstrated by their range in compositions as is depicted in our Fig. 6. This diversity is also demonstrated by the vast range of particles presented in Prasad et al. (2017). While Genge and van Ginneken agree with the difficulty in assigning the compositional ranges to a single source, they suggest that the alteration undergone by the particles could be a reason for the deviations in the ratios. The different alterations undergone by the particles clearly attune to the fact that these particles have had different resident times on the seafloor thus negating the “single large bolide event” hypothesis. Further in order to justify such particles over a large span of time several iron meteorites repeatedly disrupting in the atmosphere in the same spot should have been responsible – this is a statistically impossible event.

Regarding the M-shaped patterns of nickel diffusion in the taenite grains: these are an excellent evidence for slow cooling in the parent body preserved in few grains. We do not have access to the Chen and Yuen (2003) cited by the authors. But these patterns are found in only the best preserved taenites which show only very thin rims. This indicates that the melting has not reached the interiors to destroy the nickel diffusion patterns. Blanchard and Davis (1978) experiments have shown that beneath the magnetite-wustite rims, the Fe-Ni of the iron meteorites due to heating would undergo a change which would result in disequilibrium phases. The fact that the M-shaped patterns are well preserved attunes to the fact that these particles have not been heated to that extent where the Co/Fe/Ni patterns are altered. Further, it is not coincidental or difficult to understand that 4 out of so many particles still preserve these patterns considering that the collection represents metal particles deposited on the seafloor for over 50,000 years.

Genge and van Ginneken present a figure (Fig. 3) showing the compositional fields and the compositional trends of the metal micrometeorites, Fe-Ni beads from our study and impact ejecta of
iron meteorites from different impact sites. There are several issues with the Fig.3 presented by Genge and van Ginneken. The metal micrometeorites (MMs) presented in our paper (Fig. 6; Prasad et al. 2017) have been plotted as they occurred. It is found that these MMs occur in different clusters defined by metallic minerals from different types of meteorites as presented by us in our Fig. 6 (Prasad et al. 2017). They all have specific compositions that relate to the metallic minerals seen in many meteorites. We have deliberately not included the Co/Ni values of the Fe-Ni beads from our study in this figure because the mechanism of formation of the beads is totally different. The metallic minerals are primary particles from the asteroid belt, whereas the Fe-Ni beads could have been generated during atmospheric entry. In view of which using the Co/Ni ratios of Fe-Ni beads in this study for identifying the parent source is not tenable. The authors have also plotted Fe-Ni cores from I-types spherules recovered from Antarctica. It is now well established that the Fe-Ni bead formation is a phenomenon that takes place in all types of cosmic spherules during atmospheric entry – the metal thus produced is not primary. The Fe and Ni concentrations in these beads depend upon several variables such as the total metal and carbon present in the precursor meteorite, oxygen fugacity, entry angle, entry velocity, size of the particle and the efficiency of the metal segregation mechanism during entry. Given these variables, it is not surprising that these beads show a vast range in their compositions (eg. Rudraswami et al., 2014). Under these conditions, it is a matter of debate as to how valid their Co:Ni ratios are extending the compositional trends shown by primary metallic minerals occurring in meteorites. Furthermore, the Kamil crater particles are impact melts that comprise of a mixture of the host rock as well as the impactor iron meteorite, therefore the Fe-Ni ratios occur over a vast range that does not confine strictly to the mineral grains of kamacite, plessite or taenite found in meteorites. This is generally the case with all meteorite impact ejecta found near simple, small and young impact craters. Therefore the question arises as to how can trend lines from primary kamacites/plessite/taenites be extended to the Fe-Ni beads or meteorite impact ejecta which have been generated by totally different mechanisms. More appropriate comparison of the metal micrometeorites presented by us would be with those of metallic minerals that occur in different meteorites. They have diagnostic Co/Ni ratios (Wood, 1967).
Meteorite Ablation Origin

Yet again, Genge and van Ginneken have considered the percentages of different metal-rich particles presented in our study (Prasad et al. 2017) to be of absolute abundance in this part of the Indian Ocean. We have described the sampling and concentration methods of strongly magnetic materials in the beginning of our reply therefore we will not further present any argument here to counter this assumption.

Further, any comparisons with the 480 kyr event or a Tunguska-like event (Van Ginneken et al. 2010) or with the H-chondrite event reported by Harvey et al. (1989) are not apt, because the debris from these events are collected from an area after sampling known volumes of samples. In the present case, such control over area and more importantly stratigraphic control are lacking. Furthermore, as described in an earlier section, the concentration method used here negates any such comparison with unbiased materials collected from stratigraphically controlled conditions of Antarctica. To put it quite plainly, we have only attracted the metallic particles and eliminated the silicate particles in a large area of over 3 km (that would equal to 12 km for four samples) that fell within a time span of 1.5 to ~200,000 years. Therefore the recovered particles cannot belong to any single bolide event.

The ablation coefficients of stony bolides are far higher than those of iron bolides and they have at least 10X lower tensile strengths therefore they tend to break up far more easily (Bland and Artemieva, 2006), into smaller fragments during atmospheric entry. Flynn et al. (1989) and Flynn and Durda (2004) experiments have shown that the dust production during asteroidal collisions is greater among those meteorites that are more friable in nature such as the carbonaceous chondrites. The meteoritic bodies with higher tensile strengths do not break down to sub-millimetre sizes that frequently during asteroidal collisions. Whereas the fragments of a disrupted iron meteorite such as the Sikhote-Alin strike the earth with much greater velocities and create several small craters (Bland and Artemieva, 2006). This part of the Central Indian Ocean has been mapped using multibeam swath bathymetric system systematically by the CSIR-NIO, we have not come across any crater-like depression in this area. We collected several grab samples and also three sediment cores in this area (Prasad et al. 2013), we did not find any such evidence of a disrupted iron meteorite body and we found normal sedimentation in all the cores (Prasad et al., 2013) – no disruption due to impact was
noticed. Further, large iron meteorite bodies do get disrupted during atmospheric entry but their impact will be concentrated in a smaller coherent area (Bland and Artemieva, 2006), we have carried out several sampling operations using the dredge impregnated with magnets in several parts of the Central Indian Ocean and find that such metallic particles are ubiquitous in all these collections and not just restricted to the four samples reported in this study. Essentially, if one ploughs through the deep seafloor sediments having low sedimentation rates with strong magnets, it is certain that metal micrometeorites and other meteoritic metal can be recovered. They have not been reported from any of the deepsea collections because, as mentioned earlier, only the melted micrometeorites were isolated and examined from these collections by previous investigators, the magnetic fractions were never searched for unmelted particles.

Finally, the abundance of metal micrometeorites is not enhanced as per the assumptions of Genge and van Ginneken but as explained in this reply, these are metal micrometeorites collected by a method of sampling using strong magnets due to which they are preferentially concentrated. All other weakly magnetic materials such as the silicate particles etc. have been dislodged from the magnetic panel during sampling, transit through the water column and during the recovery process on the ship's deck. We thank Genge and van Ginneken for acknowledging that “whether they are the first unmelted MMs or the first iron meteoroid fragmentation products, these particles remain a clearly important discovery”.

REFERENCES


LEGENDS TO FIGURES

Fig. 1. a: magnetic fractions recovered from the magnetic plate fixed to the dredge which was dragged on the seafloor. These fractions were mounted in over 30 epoxy mounts, and metal micrometeorites, Fe-Ni beads and other varieties of metal-rich materials presented in Prasad et al. (2017) were identified from the polished sections.

b: Spherules isolated from the magnetic fraction shown in a, ~50% of the spherules are either I-type or of G-type.

Fig. 2: Ejection features releasing Fe-Ni beads and potential I-type spherules into the atmosphere

a - c: I-type spherules with Fe-Ni beads. Radial stress cracks emanating from the bead to the oxidized areas are discernible, these could cause the outer oxide mantle to be separated from the cores and release the cores as Fe-Ni beads.

d: A silicate, barred olivine spherule that contains a Fe-Ni bead formed to metal segregation process during atmospheric entry. Inertial forces would facilitate release of this bead into the atmosphere. This is one of the origins of the Fe-Ni beads.

e – f: A silicate, barred olivine spherule about to release a Fe-Ni bead from its surface. The bead formed by metal segregation process during atmospheric entry.
Fig. 1. a: magnetic fractions recovered from the magnetic plate fixed to the dredge which was dragged on the seafloor. These fractions were mounted in over 30 epoxy mounts, and metal micrometeorites, Fe-Ni beads and other varieties of metal-rich materials presented in Prasad et al. (2017) were identified from the polished sections.

b: Spherules isolated from the magnetic fraction shown in a, ~50% of the spherules are either I-type or of G-type
Fig. 2. Ejection features releasing Fe-Ni beads and potential atmosphere. a–c) I-type spherules with Fe-Ni beads. Radial cracks in the bead to the oxidized areas are discernible, and these cracks would cause the outer oxide mantle to be separated from the cores and release the core of the barred olivine spherule that contains a Fe-Ni bead formed by metal segregation process during atmospheric entry. Inertial forces would facilitate release of this bead into the atmosphere. This is one of the origins of the Fe-Ni beads.