

Extraterrestrial matter in the oceans

M. Shyam Prasad

National institute of Oceanography, Dona Paula, Goa-403 004
shyam@nio.org

Extraterrestrial matter in the oceans could be of several types :

- 1) Cosmic dust : ubiquitous
- 2) Tektites/Microtektites : restricted to geographic domains
- 3) Meteorite impact craters/meteoritic material : Rare

I. Cosmic dust

Cosmic dust can be defined as the material produced by the fragmentation of asteroids and comets, they form into solidified droplets during their hypervelocity into the earth's atmosphere and are recoverable as cosmic spherules and also as micrometeorites. Cosmic spherules from the deep sea sediments were retrieved for the first time during the HMS Challenger expedition (Murray and Renard, 1886). Both stony and iron types were found and their origin was assigned to ablating meteoroids.

About 40,000 ± 20,000 tons of dust of all sizes rains on the earth annually (Love and Brownlee, 1993). Materials raining into the earth's atmosphere have two origins : particles released from comets during their perihelional passage and debris generated by collisions of asteroids (Brownlee, 1981), and dust collection is the only earth based technique for obtaining typical cometary solids. While sample returns are very rare and expensive, to date only lunar samples are present as sample returns, although this scene has changed marginally with the important collection made by the Stardust Mission. In effect, cosmic dust due its large flux is available in plenty in the earth's materials and more importantly, is a unique way of actually studying asteroidal as well as cometary material. Further, the dust accreted by the earth offers the widest spectrum of solar system material than represented by conventional meteorites. It is expected that all the spherules > 50 um are asteroidal and these results provide information on composition of what may be the most common main belt in asteroid type. The information provided by these cosmic spherules is better and less biased than those provided by conventional meteorites of centimeter and larger size for investigation of asteroid composition.

The majority of the particles entering the earth become ferromagnetic because of magnetic formation due to friction during atmospheric entry and therefore can easily be attracted by simple hand held magnets.

This aspect has been utilized in almost all deepsea collections so far.

Many large collections of cosmic dust have been made in a variety of environments (including deep sea, beach sands, paleosediments, polar regions, and in the stratosphere etc.), with a recent, larger concentration of efforts in the polar regions. These collections have enhanced our understanding of the types of materials that comprise the asteroids and comets manifold. However, it is also acknowledged that cosmic dust, more so large collections, provide greater insights into the types of materials that asteroids or comets comprise of, and in turn have the potential to provide clues to the early solar system processes.

Cosmic dust has been isolated from beach sands (Marvin and Einaudi, 1966), Antarctic ice (Maurette et al., 1991; 1992; Koeberl and Hagen 1989), from Greenland ice melt water lakes (Maurette et al., 1986; 1987; Robin et al., 1990) and from old, lithified sedimentary formations on land (Tailor and Brownlee, 1991). Most initial efforts were concentrated in recovering the dust from deep sea sediments (Millard and Finkelman, 1970; Brownlee et al., 1979; Murrell, 1980) – in view of the low sedimentation rates in these regions and the relatively easier accessibility as compared with the polar regions.

Importance of cosmic dust

Cosmic dust is a valuable resource of meteoritic material. There are two fundamental reasons for its study. First, the most friable extraterrestrial materials can only be collected in the form of dust, as these materials cannot survive the hypervelocity entry in to the atmosphere. Second, the cosmic dust is very abundant whereas, meteorites are exceedingly rare. The dust accreted by the earth offers the widest spectrum of solar system material than represented by conventional meteorites, therefore by studying dust we get to sample material of a wider spectrum than presented to us by conventional meteorites. This cosmic dust reaching in to earth's atmosphere have two sources-

(1) Asteroids generate particles as a byproduct of collisions.

(2) The ice in a comet sublimates and releases dust from the nucleus during its perihelional passage around the sun.

Therefore in sufficiently large collections chances are that one samples the asteroidal as well as cometary materials, in addition possibly material from the Moon and the Mars as well. Much of these materials may or

may not have been recovered as conventional meteorite types. Because of the large number of micrometeorites arriving on earth, rare or unusual extraterrestrial materials are more likely to be found in micrometeorite rather than in meteorite collections.

Cosmic spherules are of particular scientific interest because:

1. They provide information about the composition of comets and asteroids including the icy, carbon-rich bodies in the outer asteroid belt.
2. They can be used as tracers to identify debris resulting from the impact of large extraterrestrial objects.
3. Information on the materials and processes that occurred in the solar system 4.6 billion years ago could survive in these primitive small bodies that are mostly destroyed in conventional meteorites by parent body processes.
4. In sufficiently constrained collections, an estimate of the fluxes of dust for a given time can also be calculated.

Deep Sea collections and their contribution to the knowledge

One of the first reports of cosmic dust has been from the HMS Challenger expedition more than a century ago where, 'cosmic spherules' were identified by Murray and Renard (1891). They identified two types (iron and stony) and attributed their origin to ablating meteoroids. Using simple magnetic techniques cosmic spherules were isolated from deep sea sediments.

Several large scale collections were made, each of these collections has provided an important window to the understanding the earth crossing meteoroid complex and the processes that these particles undergo during their atmospheric entry, and the important information that they provide regarding compositions of asteroidal/cometary materials from the various types of particles.

Millard and Finkelman (1970) extracted cosmic dust from a massive 750 kg of Pacific red clay. They could isolate ~1200 spherules from this sediment. By using XRD and neutron activation techniques established reasonably definitive criteria for identifying I-type or iron type of cosmic spherules. Murrell et al. (1980) isolated 72 mg of cosmic spherules from 411 kg of Pacific red clay. They gave estimates of the total abundance of cosmic dust and also quantitative estimates of the flux of stony spherules on earth.

Brownlee et al. (1975) and Blanchard and Davis (1978) simulated atmospheric entry conditions on natural and artificial analogs and devised criteria by which both the iron and the stony spherules could be identified using a scanning electron microscope. Brownlee et al. (1975) revealed that the brickwork structure exhibited by the

stony spherules comprises of euhedral olivine and magnetite grains, and these spherules have major element compositions close to that of the average chondrite. Ganapathy et al. (1978) provided the proof of the extraterrestrial origin of the stony spherules by the abundances of nonvolatile trace elements, which had a close match to those of primitive solar system material. Blanchard et al. (1980), identified g-type spherules in addition to the S-type and I-type ones which also form a part of the meteoroid complex that crosses the earth. Brownlee et al. (1984) also discovered platinum group nuggets in cosmic spherules, especially of the I-type and suggested their interpretation due to heating and oxidation of small meteoritic metal particles during hypervelocity entry into the atmosphere. Bonte et al. (1987) subsequently found similar nuggets in stony spherules also. Brownlee (1981) suggested that the cosmic material that is stored in abyssal sediments will be more representative of the earth-crossing meteoroid complex than the conventional meteorites and can therefore provide uniquely valuable information.

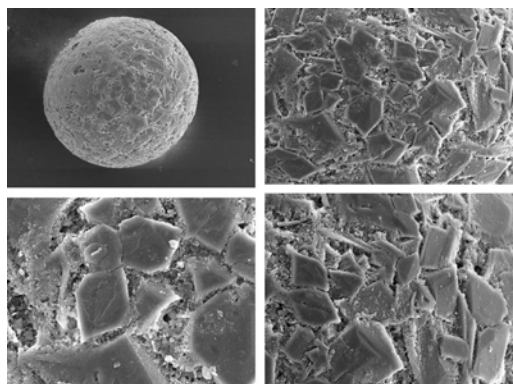


Fig. 1. SEM images of a porphyritic olivine spherule recovered from the MACDUC. This spherule seems to comprise almost entirely of zoned, euhedral olivines and interstitial glass.(width of photographs : a=287 μ m; b=101 μ m; c=38 μ m; d=66 μ m).

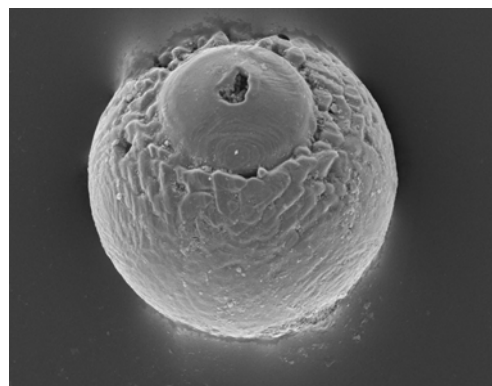


Fig. 2. SEM image of an I-type spherule from the Indian Ocean. Eccentric Fe-Ni core is in the process of being ejected. Magnetite crystals surround the core.(width of photograph : 139 μ m).

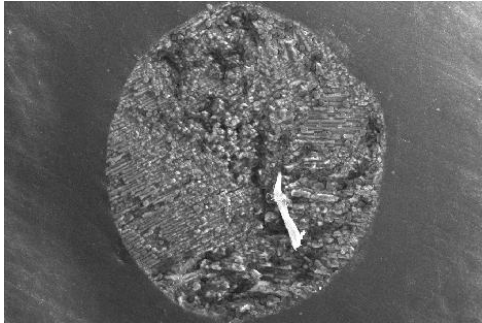


Fig. 3. SEM image of polished section of a barred olivine type spherule. (width of photograph 330 μm)

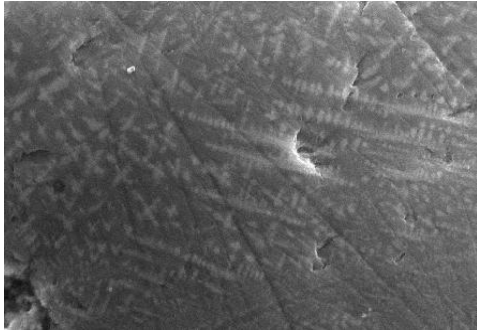


Fig. 4. SEM image of a polished section of a spherule showing bulk Si/Mg ratio close to enstatite chondrites. The bright, skeletal, dendritic crystals have Fe-rich olivine compositions. (width of photograph 49 μm).

Space borne collections and their contribution

Space borne collections have been few, and the material recovered is also orders of magnitude lesser than that from the deep sea regions, however, its importance and contribution to our understanding cannot be undermined. The most primary characteristic of these collections is the pristine character of the material collected – this ensures the preservation of many important clues to the solar system materials/processes. Among the more pioneering works was that of Brownlee (Brownlee et al., 1977; Brownlee, 1985) where interplanetary dust particles (IDP) were collected in the stratosphere using space craft based techniques leading to the discovery of the bunch of grapes structured ‘brownlee particles’ which were chondritic porous IDPs recovered in a pristine condition. In addition, several other unique particle types were recovered such as the metal mound silicate particles and other micrometeorites that make up the earth – crossing meteoroid complex. For example, Mackinnon and Rietmeijer (1987) examined several micrometeorites collected in the stratosphere and concluded that these particles represent a unique group of extraterrestrial materials because they contain some mineral assemblages which do not occur in any meteorite class.

Polar collections and their contribution

More recently, large collections of cosmic dust have been made from the polar ice regions (Maurette et

al. 1986; Taylor et al. 2000; Maurette et al., 1991, 1994, Terada et al., 2001). The largest among these collections are by the EUROMET (Maurette et al., 1992) where, in two different collection efforts, a massive quantity (~40,000 particles) were collected by melting several tens of tons of polar ice. In the polar icy regions the cryogenic conditions offer perfect environment for the preservation of the spherules.

The discovery of a concentration process of cosmic particles in the Greenland ice lakes by Maurette et al. (1986) was a pioneering effort which was followed by the same group at the south pole (Maurette et al. 1991) involving even greater efforts. These efforts lead to hitherto unknown types of cosmic material such as the glass spherules. These types of spherules were found in the Antarctica as well by Taylor et al. (1998, 2000). In this unique collection, they also found bubbly glass spherules, spherules with glass caps, and ones with sulfide coatings which have not been reported elsewhere. In addition, this collection also presents valuable constraints on atmospheric entry heating of micrometeorites and also terrestrial weathering effects on these particles because the experiment could constrain the time of fall of the particles and therefore the absolute flux of particles that survive atmospheric entry. Further, Taylor et al. (2000) presented a classification of the s-type spherules based on their structures which were reflective of the degree of intensity (heating and melting) experienced by each of the spherules during atmospheric entry.

Robin et al. (1988) used EDS and INAA and discovered three new families of grains that have never been reported before and provided a new type of origin for the G- (or glassy) type of spherules. Kurat et al. (1994) summarized the important new insights provided by the initial studies of extraterrestrial matter from the polar regions which contained unmelted micrometeorites.

Oxygen Isotopes

Several recent investigations have been undertaken on the oxygen isotopes of cosmic dust/micrometeorites (Taylor et al. 2005; Yada et al. 2005; Engrand et al. 2005). The study aimed at identifying the relationship between microparticle texture and its degree of heating and also the possibility of deriving information for the identification of possible parent bodies.

Taylor et al. (2005) investigated 95 cosmic spherules by electron microprobe techniques from Antarctica and analysed eight of them for oxygen isotopes using ion microprobe. Selection of particles was carried out based on an earlier classification silicate spherule texture by Taylor et al. (2000). Out of the eight spherules analysed for oxygen isotopes, three were mass fractionated with $^{18}\text{O} > 30 \text{ ‰}$, interestingly two out

of the three enrichments were attributed to evaporative losses of oxygen during entry heating, however, the third particle had enrichments which could be due to the presence in its parent material of an exotic phase.

While the above two groups (Taylor et al., 2005 and Yada et al., 2005) analysed silicate type spherules, Engrand et al., (2005) carried out major element and oxygen isotope investigations on almost equal numbers of I-type and S-type spherules. They found mass-dependent enrichments in the isotopes of oxygen (in addition to those of Cr, Fe and Ni as well) in the I-type spherules, whereas the interparticle variability in this type of spherules was found to be less as compared with those of the silicate types indicating either a short duration of pulse heating, lower evaporation temperatures, or longer duration of heating for the iron type spherules. Their studies further suggested that these isotopic analyses would permit estimates of mass loss from cosmic spherules, which in turn would help in fine tuning the estimates of particle flux to Earth.

Finally, given that the micrometeorites/cosmic dust forms a large majority of the influx of extraterrestrial material that rains on the earth ($\sim 40,000 \pm 20,000$ tons/year : Love and Brownlee, 1993), when compared with that of meteorites which are a few orders of magnitude less (2.9 to 7.3 tons/year : Bland et al., 1996). This particulate matter has the potential to provide important clues concerning the origin of materials, and also give us insights concerning the early solar system processes. It is pertinent to note that each particle carries its unique history (different origin, variations in composition and atmospheric entry heating) and therefore it is imperative to examine and analyse large numbers and carry out major element analysis, textural studies and oxygen isotope studies to arrive at their range of precursors, and origins.

Cosmogenic isotopes in marine sediments

Because the $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ ratios in meteorites are drastically different from continental crust values (Dalai et al., 2006), the Re-Os system may provide a sensitive tracer for the presence and quantification of an extraterrestrial component in sediments. These studies not only demonstrate that it appears possible to detect small amounts of the extraterrestrial material incorporated in the sediments but may also permit quantification of mixing of terrestrial/extraterrestrial material in the sediments. In addition, high concentrations of ^3He in marine sediments are also indicative of enhanced influx of interplanetary dust particles (Ozima et al., 1984).

In addition, siderophile enrichment, especially enhanced Ir contents have been identified as definitive markers for extraterrestrial event markers in the ocean sediments (Kyte, 1988)

II. Tektites/Microtektites

There are about 160 impacts known on the earth, of which only 4 have been tektite producing. Tektites are natural, dark-colored, rounded silicate glass particles several cm in size and often aerodynamically shaped and are found in various areas referred to as strewn fields around the world. Four tektite strewn fields are known in the Cenozoic: Australasian at ~ 0.77 Ma, Ivory Coast at ~ 1 Ma, Central European at ~ 14.7 Ma and North American at ~ 34 Ma. Three major types of tektites are found: 1) the centimetric elongated, tear drop shaped or rounded splash form tektites, 2) the ablated tektites which are re-melted splash form characterized by a flange, and 3) the more massive Muong-Nong or layered tektites weighting up to several kilos.

The origin of tektites was controversial for many years. Ample geochemical and petrological data now demonstrate that tektites are formed by the melting of terrestrial surficial sediments by hypervelocity impact. The Ivory Coast and Central European tektites are associated respectively with the Bosumtwi crater in Ghana and with the Ries crater in Germany. Whereas the oldest North American strewn field has been recently found to be associated with the Chesapeake Bay structure (Koeberl et al., 1996).

Microtektites are submillimeter-size tektites found in deep-sea sediments within the Australasian, Ivory Coast and North American strewn fields. The Central European strewn field is not known to contain microtektites, due to the simple fact that these are small objects and would get destroyed within no time under the erosional conditions on land.

While tektite findings are rare in the oceans – only at three instances tektites have been found, all three belong to the youngest Australasian tektite strewn field (eg. Saurin and Millie – Lacroix, 1961; Prasad and Rao, 1990; and Prasad et al., 1996). Microtektites have been instrumental in providing important evidences for impact over the years. The finding of shocked minerals (Glass and Wu, 1993) and more recently, shock lithified rock fragments associated with the Australasian microtektite layer (Glass and Koeberl, 2006), in addition with the presence of an iridium anomaly (Schmidt et al., 1993; Koeberl, 1992) have demonstrated the impact origin of this strewn field beyond doubt.

The impact craters for three out of the four strewn fields have been identified, mysteriously, the crater responsible for the Australasian tektite strewn field is still unknown. This strewn field is the youngest having an age of 0.77 Ma and is spread over 1/10 of the earth's surface (Fig.) (Glass et al., 1979). Investigations from different approaches have been made to identify the impact crater – remote sensing using airborne surveys and landsat imagery (Hartung and Rivolo, 1979). Field

investigations in the Indochina region where the largest sized tektites (the Muong Nong-type tektites) have been found (Barnes, 1989; Schnetzler 1992); chemical composition and isotope analysis (Chaussidon and Koeberl, 1995; Ma et al. 2004) and by calculating the variation in the abundance of microtektites in the oceans and using regression analysis (Glass and Pizzuto, 1994; Lee and Wei, 2000; Prasad et al., 2007). All these investigations point out the impact site : Indochina, however the exact impact crater has not yet been pinpointed for this strewn field.



Locations of Tektite strewn fields

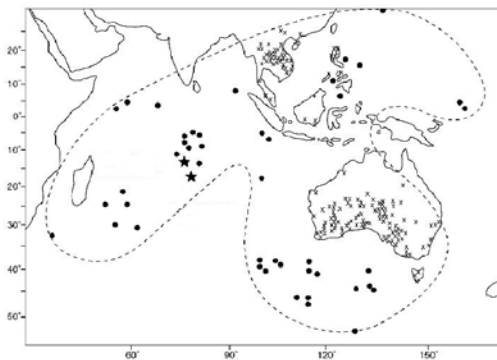


Fig.1

Map showing the Australasian tektite strewn field



Aerodynamically ablated tektites from Australia (Photo from: An Article In Meteorite-Times Magazine by Paul Harris)

Tektite source rocks

Tektite are impact melt products of continental upper crustal rocks has been established by systematic and detailed geochemistry (Taylor, 1962; Taylor and Kaye, 1969; Koeberl, 1986; Koeberl, 1994). This has been further confirmed with the help of ¹⁰Be isotope study (Ma et al., 2004) which also showed a sedimentary origin for tektites.

Importance of tektite study in planetary geology

It is seen that only 4 out of the 160 known impacts are tektite producing. While glassy ejecta of different impacts have been given the name 'tektite', such as that produced at the K/T boundary and at other impact sites. Tektites contain characteristics which are typical : reasonably homogeneous composition, distribution in large strewn fields, absence of water. Furthermore, tektites have been found to be distributed to one side of the impact craters in all the four strewn fields which is strongly suggestive of a projectile having an inclined incidence. Experiments and models have shown that an incident angle of ~30°- 50° of the incoming projectile could have led to tektite production. However, this is only one of the conditions. Tektites therefore provide importance inputs in understanding oblique impacts on planetary bodies – while they also provide important samples in the form of ground truth, which could be invaluable in understanding similar processes on other planetary bodies.

Further, microtektites contain microimpact features which are similar to those found on the Lunar surface materials (Prasad and Khedekar, 2003). While, these features throw important light on the possibility of interpretation of the microimpacts on lunar features, more importantly, these microimpacts provide inputs in understanding impacts that most 'fundamental process in the formation of planets' (Shoemaker, 1977).

III. Meteorite craters in the oceans

About 160 impact craters have been found on the earth so far (Grieve and Pesonen, 1996). While, the oceans cover >70% of the earth's surface, only one such crater has been found in the oceans (Jansa and Pe-Piper, 1987) – the ~55 million year old Montagnais crater off New Jersey. Therefore, the effects of impacts of meteoritic bodies in the oceans have been poorly understood. There are inherent difficulties in finding meteorite craters in the oceans – the simplest of them being their burial underwater and beneath the sediments. The present day techniques are perhaps inadequate to detect meteorite impact craters in the oceans. While the lunar surface contains more than 7000 craters, both large and small, it is logical that the number of craters on the earth should be a few times this number. However, incessant erosion, continental drift and burial underwater have obliterated/masked these important events in the earth's history.

References

- Barnes V.E. (1989), Origin of tektites, *Texas J. of Sci.*, 41, 5-33.
- Blanchard M.B. and Cunningham G. (1974) Artificial meteor ablation studies - olivine. *J. Geophys. Res.* 79, 3973-3980.
- Blanchard M.B. and Davis A. (1978) Analysis of ablation debris from natural and artificial iron meteorites. *J. Geophys. Res.* 83, 1793-1808.
- Blanchard M.B., Brownlee D.E., Bunch T.E., Hodge P. and Kyte F.T. (1980) Meteoroid ablation spheres from deep sea sediments. *Earth Planet. Sci. Lett.* 46, 178-190.
- Blanchard M.B. (1972) Artificial meteor ablation studies : iron oxides. *J. Geophys. Res.* 77, 2442-2455.
- Brownlee D.E. (1985) Cosmic dust : collection and research. *Ann. Rev. Earth Planet. Sci.* 13, 147-173.
- Brownlee D.E., Bates B., and Schramm L. (1997) The elemental composition of stony cosmic spherules. *Meteoritics and Planetary Science*, 32 : 157-175
- Brownlee D.E. (1981) Extraterrestrial components in deep sea sediments. In *The Sea V. 7*, E. Emiliani (editor). Wiley, New York, pp. 733-762.
- Brownlee D.E., Blanchard M.B., Cunningham G., Beauchamp R. and Fruland R. (1975) Criteria for identification of ablation debris from primitive meteoric bodies. *J. Geophys. Res.* 80, 4917-4924.
- Brownlee D.E. and Hodge P.W. (1973) Ablation debris and primary micrometeoroids in the stratosphere. *Space Res.* 13, 1139.
- Brownlee D.E., Hodge P.W. and Bucher W. (1973) The physical nature of the interplanetary dust particles as inferred by particles collected at 35 km. In *Evolutionary and Physical Properties of Meteoroids*, IAU Colloq. No. 13. C.C. Hemenway, P.M. Milliman and A.F. Cook (editors), pp. 291-295.
- Dalai T.K. and Ravizza G. (2006) Evaluation of osmium isotopes and iridium as paleoflux tracers in pelagic carbonates. *Geochimica et Cosmochimica Acta*, 70: 3928-3942
- Engrand C. et al. (2005) Isotopic compositions of oxygen, iron, chromium, and nickel in cosmic spherules : toward a better comprehension of atmospheric entry heating effects. *Geochimica et Cosmochimica Acta* 69 : 5365 – 5385.
- Glass B.P., Swincki M.B., and Zwart P.A. 1979. Australasian, Ivory Coast and North American tektite strewn fields: Size, mass, and correlation with geomagnetic reversals and other earth events. *Proceedings, 10th Lunar Science Conference*. pp. 2535-2545.
- Glass B.P., and Pizzuto J.E. 1994. Geographic variation in Australasian microtektite concentrations : Implications concerning the location and size of the source crater. *Journal of Geophysical Research* 99: 19075-19081.
- Glass B.P. and J. Wu (1993), Coesite and shocked quartz discovered in the Australasian and North American microtektite layers, *Geology*, 21, 435-438.
- Glass B.P. and C.Koeberl (2006), Australasian microtektites and associated impact ejecta in the South China Sea and the Middle Pleistocene supereruption of Toba, *Meteorit. Planet. Sci.*, 41, 305-326.
- Grieve R.A.F. and Pesonen L.J. (1996) Terrestrial impact craters : their spatial and temporal distribution and impacting bodies. *Earth, Moon & Planets* 72, 357-376.
- Hartung J.B. and Rivolo A.R. (1979) A possible source in Cambodia for Australasian tektites. *Meteoritics* 14, 153-160.
- Jansa F. L. and Pe-Piper G. (1987) Identification of an underwater extraterrestrial impact crater. *Nature* 327 : 612-614.
- Koeberl C. 1994. Tektite origin by hypervelocity asteroidal or cometary impact : Target rocks, source craters, and mechanisms. In *Large meteorite impacts and planetary evolution*, edited by Dressler B.O., Grieve R.A.F., and Sharpton V.L. Boulder, The Geological Society of America. pp133-152.
- Koeberl C. (1993), Extraterrestrial component associated with Australasian microtektites in a core from ODP Site 758B, *Earth Planet. Sci. Lett.*, 119, 4530458.
- Kyte F.T. and Wasson J.T. (1986) Accretion rate of extraterrestrial matter : iridium deposited 33 to 67 million years ago. *Science* 232, 1225-1229.
- Kyte F.T. (1988) The extraterrestrial component in marine sediments : description and interpretation. *Paleoceanography* 3 : 235-247.
- Koeberl, C. (1986), Geochemistry of tektites and impact glasses, *Ann. Rev. Earth Planet. Sci.*, 14, 323-350.
- Koeberl C., and Hagen E.H. (1989) Extraterrestrial spherules in glacial sediment from the Transantarctic Mountains, Antarctica : Structure, mineralogy, and chemical composition. *Geochimica et Cosmochimica Acta*, 53 : 937-944.
- Lee Meng-Yang, and Wei Kuo-Yen 2000. Australasian microtektites in the South China Sea and the West Philippine Sea : Implications for age, size, and location of the impact crater. *Meteoritics and Planetary Science* 35: 1151-1155.
- Love SG and Brownlee DE (1993) A direct measurement of the terrestrial mass accretion rate of cosmic dust. *Science*, 256 : 550-553

- Ma P., K. Aggrey, C. Tonzola, C. Schnabel, P. de Nicola, G.F. Herzog, J.T. Wasson, B.P. Glass, L. Brown, F. Tera, R. Middleton, and J. Klein (2004), Beryllium-10 in Australasian tektites : Location of the source crater, *Geochim. Cosmochim. Acta*, 68, 3883-3896.
- Maurette M., Hammer C., Brownlee DE, and Reeh N. (1986) Traces of cosmic dust in blue ice lake Greenland. *Science*, 233:869-872.
- Maurette M., Jehanno C., Robin E., and Hammer C. (1987) Characteristics and mass distribution of extraterrestrial dust from the Greenland ice cap. *Nature*, 328 : 699-702.
- Maurette M., Olinger C., Michel-Levy Ch.M., Kurat G., Puchet M., Brandstatter F., and Bourot-Denise M. (1991) A collection of diverse micrometeorites recovered from 100 tonnes of Antarctic blue ice. *Nature*, 351 : 44-47.
- Maurette M., Immel G., Perreau M., Porchet M., Vincent C. and Kurat G. (1992) The 1991 EUROMET collection of micrometeorites at Cap Prudhomme, Antarctica : Dission of possible collection biases. *Proceedings of the Lunar Planetary Science Conference 33rd.*, 859-860.
- Millard H.T. and Finkelman R.B. (1970) Chemical and mineralogical compositions of cosmic and terrestrial spherules from a marine sediment. *J. Geophys. Res.* 75, 2125-2133.
- O'Keefe J.A. (1976) *Tektites and their origin*. Elsevier, New York, 254 p.
- Ozima M., Takayanagi M., Zashu S. and Amari S. (1984) High $^3\text{He}/^4\text{He}$ ratio in ocean sediments. *Nature* 311 : 448 – 450.
- Prasad M.S., and Rao P.S. 1990. Tektites far and wide. *Nature* 347: 340
- Prasad M.S., Mislankar P.G., Charan S.N., and Krishna Prasad 1998. A tektite fragment discovered in the Central Indian Ocean. *Current Science* 74: 405-408.
- Prasad M.S. and V.D. Khedekar (2003) Impact microcrater morphology on Australasian microtektites. *Meteoritics and Planetary Science*, Vol. 38, 1351-1371, (2003).
- Saurin E., and Millies-Lacroix 1961. Tectites par 1270 m de fond au large du Vietnam. *Geological Society of France* 5: 128-129.
- Schmidt G., L.Zhou, and J.T. Wasson (1993), Iridium anomaly associated with the Australasian tektite-producing impact : Masses of the impactor and of the Australasian tektites, *Geochim. Cosmochim. Acta*, 57, 4851-4859.
- Schnetzler C.C., L.S. Walter and J.G. Marsh (1992), Mechanism of Mong Nont-type tektite formation and speculation on the source of Australasian tektites, *Meteoritics*, 27, 154-165.
- Taylor S., Lever J.H. and Harvey R.P. (2000) Numbers, types and compositions of an unbiased collection of cosmic spherules. *Meteoritics and Planetary Science* 35 : 651-666.
- Taylor, S.R. (1962), Fusion of soil during meteorite impact and the chemical composition of tektites, *Nature*, 195, 32-33.
- Taylor, S.R., and M. Kaye (1969), Genetic significance of the chemical composition of tektites : A review, *Geochim. Cosmochim. Acta*, 33, 1083-1100
- Taylor S. and Brownlee DE (1991) Cosmic spherules in the geological record. *Meteoritics*, 26 : 203-211.
- Taylor S., Lever J and Ralph PH (1998) Accretion rate of cosmic spherules measured at south pole. *Nature*, 392 : 899-903.
- Taylor S., Lever J.H. and Harvey R.P. (1998) Accretion rate of cosmic spherules measured at the South Pole. *Nature*, 392 : 899 – 903.
- Yada T. et al. (2005) Oxygen isotopic and chemical compositions of cosmic spherules collected from the Antarctic ice sheet : implications for their precursor materials. *Geochimica et Cosmochimica Acta*, 69 : 5789-5804.