

## **New sites of Australasian microtektites in the Central Indian Ocean : Implications for the location and size of source crater**

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### **ABSTRACT**

We have identified 15 new Australasian microtektite sites along a transect roughly N-S in the Central Indian Ocean. These locations, in addition to the existing 46 sites, total to 61 microtektite sites in the oceans. We carried out regression analysis of a selected area between  $12^{\circ}$  -  $26^{\circ}$  N and  $98^{\circ}$  -  $112^{\circ}$  E, at  $0.5^{\circ}$  interval using three microtektite data sets separately : 41 sites, 46 sites (number of sites known up to the years 1994 and 2006 respectively) and, the entire data of 61 sites. This area was chosen because, based on various lines of evidence, several investigators suggested impact craters for the strewn field within this broad area. The 41 site data set defines an impact site at about  $12^{\circ}$  N and  $106^{\circ}$  E. Whereas, the contours joining the highest values of square of the correlation coefficient by using 46 site and 61site datasets, define an area located in NE Thailand – Central Laos, the center of this site is at  $18^{\circ}$  N and  $104^{\circ}$  E. Therefore, with progressive increase in microtektite data, the location of the impact site seems to get defined more rigorously. Based on the equations for the concentration of the ejecta, and the distance from the source region, the calculated crater size has a diameter range between 33-120 km. Interestingly, the lower size limit of 33 km has been found closer to ground truth by verification from the microtektite data of the Ivory coast strewn field.

## INTRODUCTION

Among the four known tektite strewn fields, the Australasian tektite strewn field is perhaps the largest, covering an area 1/10 of the earth's surface (Glass et al., 1979) and, at 0.77 Ma is also the youngest strewn field (Kunz et al., 1995; Izett and Obradovich, 1982) however, the impact crater is still unknown. Tektite research spans over a hundred years, during the initial years the origin of this field was hotly debated. Over the last few decades, several lines of evidence have been important to provide increasingly strong evidence of an impact origin of this strewn field. Some of the strongest evidences for impact have been derived from geochemical studies. The fact that tektites are the impact melt products of continental upper crustal rocks has been established by systematic and detailed geochemistry (Taylor, 1962; Taylor and Kaye, 1969; Koeberl, 1986 and Koeberl, 1994). Subsequently, the presence of an iridium anomaly (Schmidt et al., 1993; Koeberl, 1993), discovery of shocked minerals associated with the Australasian microtektite layer (Glass and Wu, 1993), and more recently, finding of shock lithified rock fragments associated with the Australasian microtektite layer (Glass and Koeberl, 2006), have demonstrated the impact origin of this strewn field beyond doubt.

The search for an impact crater, which generated the Australasian tektite strewn field has a long history. Several approaches have been made in order to identify the crater that generated the Australasian tektite strewn field. Although most investigators agree for a crater in the Indochina region, none has been pinpointed yet. Among the initial proponents, Cohen (1962) suggested a crater in eastern Thailand based on analysis of Ni-content, which followed a two lobed pattern from Thailand.

Recognizing the high concentration of the massive Muong Nong-type tektites in the Indochina region, subsequent investigators focused their efforts in this region. Using remote techniques, such as airborne surveys, and landsat imagery, Hartung and Rivolo (1979), and Ford (1988) suggested an oval ring of hills in NE Cambodia to be the source, whereas based on negative gravity anomaly, Schnetzler et al. (1988) indicated the continental slope off Vietnam to be a possibility. Using satellite imagery and field investigations, Schnetzler and McHone (1996) proposed that the impact site could be

subdued and hidden in eastern Indochina. Stauffer (1978) analysed the radial and concentric pattern of the tektites and suggested that the crater was buried beneath the alluvial deposits in the lower Mekong valley, in Vietnam. Hartung (1990) and Hartung and Koeberl (1994) subsequently favored the 100 X 35 km lake Tonle Sap in Cambodia because of its inferred age and also, the long axis of the location of the lake agrees well with an extremely oblique incidence of the projectile which explains the geographical distribution of tektites.

Based on the distribution of Muong Nong-type tektites, Barnes (1964, 1989) and Wasson (1991) suspected a cometary projectile, while the former suggested in situ melting of soil by a diffuse comet over the whole region of Muong Nong-type tektites, the latter felt that there could have been multiple local sites of impact, which generated the entire stewn field. However, the multiple impact origin has been disputed by the uniform composition of Muong Nong type tektites (e.g., Blum et al., 1992) and the target stratigraphy inferred from the  $^{10}\text{Be}$  isotope data (Ma et al., 2004). Again based on the geographical variation in composition and the distribution of Muong Nong-type and splash form tektites, backed up by intensive field study Schnetzler (1992) proposed a site which was located in the southern part of Thailand-Laos border ( $16^{\circ}\text{N}$ ;  $105^{\circ}\text{E}$ ).

Based on evidence derived from chemical composition and isotope analysis, Chaussidon and Koeberl (1995) narrowed down to a location off the Vietnam coast, near the mouth of the Mekong River in the South China Sea ( $9^{\circ}\text{N}$ ;  $107^{\circ}\text{E}$ ). Ma et al. (2004) analysed  $^{10}\text{Be}$  concentrations in tektites and based on the isotope distribution pattern felt that a location in the Song Hong Basin (off Vietnam, South of Gulf of Tonkin ( $17^{\circ}\text{N}$ ;  $107^{\circ}\text{E}$ ) could be a possible impact site. Further, geochemical and Rb-Sr isotopic investigations by Lee et al. (2004) indicated the provenance of these tektites to be non-marine Jurassic sediments, which are found to occur in the southern part of Thailand-Laos.

Microtektites belonging to the Australasian tektite strewn field enjoy a unique position, because they reveal the geographic extent of the strewn field, they conform stratigraphically to the radiometrically determined ages and, unlike tektites on land, they

are not transported from their places of deposition, therefore provide an opportunity for quantitative estimates. Schmidt et al. (1993), based on the microtektite fluence from data on Australasian tektite generated by Glass and coworkers over the years suggested a location ( $14^{\circ} 46' \text{N}$ ;  $105^{\circ} 25' \text{E}$ ) in the Buntharik area, Thailand to be probable impact site. Based on the microtektite fluence variation from the northern part of the strewn field down to the edge of the strewn field in the south, Glass and Pizzuto (1994) carried out regression analysis of decay in microtektite concentration from a hypothetical source crater and suggested Central Cambodia to be a candidate site. This was further refined with the addition of data by Burns and Glass (1989), Lee and Wei (2000), Glass (2003). Glass and Koeberl (2006) in addition to the microtektite fluence also considered the concentration of unmelted ejecta in the cores especially in the South China Sea, which is in the close proximity of Indochina and further refined the site to  $22^{\circ} \text{N}$  and  $104^{\circ} \text{E}$  in Northern Vietnam.

We have been collecting Australasian microtektites between 1990-2003 from the Central Indian Ocean basin and have so far identified 23 locations of microtektites and two tektites (Prasad and Rao, 1990; Prasad 1994a, 1994b; Prasad and Sudhakar 1996 a; 1996b; Prasad et al., 1998; Prasad and Sudhakar 1998, 1999; Prasad et al., 2003; and Prasad and Khedekar, 2003). Out of the 23 locations identified during our studies, 15 sediment cores contain an identifiable peak abundance of the Australasian microtektite occurrence. We have carried out regression analysis of the total available data on Australasian microtektite abundance (including these 15 cores) in order to further evaluate the possible impact site location in the light of the new data and also calculate the size of the source crater for the Australasian tektite strewn field.

## **MATERIALS AND METHODS**

The sediment cores have been collected during several cruises which were undertaken between 1982 – 2003 in the Central Indian Ocean (Table 1). We collected 18 sediment cores along a near N-S transect in the Central Indian Ocean stretching from  $\sim 5^{\circ} \text{S}$  –  $18^{\circ} 20' \text{S}$  mostly along the  $78^{\circ} \text{E}$  longitude. Out of these, 15 cores have an identifiable peak

of microtektite abundance. While all the cores used in this study fall within this latitudinal range, some of the samples are located up to 4 degrees west of 78<sup>0</sup>E longitude (e.g., SK16/176 Table 1, Fig. 1). All the cores fall well within the geographic limits of the strewn field and all of them contain Australasian microtektites. These cores therefore represent a transect of ~1300 km within the strewn field, although at distances of >3000 km from the source region in Indochina. The abundance varies from 2.20 to ~97 microtektites of >125  $\mu\text{m}$  diameter/cm<sup>2</sup> in these cores (Table 1). Most of these cores also fall in the zone having microtektite abundance values between 20-200 microtektite/cm<sup>2</sup> (Glass and Koeberl, 2006).

All the cores were sub-sampled at 5 cm interval, except for AAS 62/55 and AAS 62/56 which were sub-sampled at 2 cm interval. Blocks of 3.5 X 3.5 X 5 cm from the core top to bottom were wet sieved in mesh size of 63  $\mu\text{m}$ . The coarse fractions (>63  $\mu\text{m}$  material) from each of the sub-sections were separated into two different size fractions by sieving : 125 – 250 and > 250  $\mu\text{m}$ . Using a binocular microscope, microtektites from the >250  $\mu\text{m}$  fraction were directly isolated. For the 125-250  $\mu\text{m}$  material, heavy liquid separation was used to concentrate microtektites, which were later picked using a binocular microscope. The Australasian impact event is an instantaneous event in geologic time, and it is anticipated that the entire ejecta would have been deposited as a single layer in the sediments. The ejecta has been subsequently dispersed within the length of the cores due to bioturbation. Therefore, the total quantity of microtektites recovered from both these size fractions from the entire length of each sediment core, represents the number of microtektites that have been deposited in an area of the seafloor measuring 3.5 X 3.5 cm (12.25 cm<sup>2</sup>). Microtektite abundances were derived in the same manner for all the cores. Larger quantities of sediment (blocks of 15 X 15 X 15 cm) were searched earlier for tektite material in one of the cores (Prasad and Sudhakar, 1999). For the southernmost cores (AAS 62/56 and AAS62/55), a box corer was used to collect large quantities of material (50 X 50 cm area) from this low sedimentation, red clay region. In both the cases, the sampler did not penetrate the peak microtektite layer, however, large numbers of Australasian microtektites have been recovered, especially from AAS62/56 and we suspect the sampler was quite close to the peak abundance stratum in this core.

These two cores have therefore been excluded from the calculations involving crater location. Similarly, AAS4/12, located much north of these cores is also excluded since we suspect that the corer had not penetrated the peak abundance horizon.

## **MICROTEKTITE SIZES AND ABUNDANCES**

For determination of average microtektite size, we measured diameters of representative numbers of mostly unetched, spherical microtektites using a binocular microscope, from both the size fractions (125-250 and >250  $\mu\text{m}$ ). The weighted mean average microtektite size for each core was determined. The weighted mean average size for the entire data (16 cores) was determined by averaging the weighted mean average diameters of all the cores. In all, diameters of 1889 microtektites from 16 cores were measured and the average sizes were determined for each of the cores which varied from 232 to 353  $\mu\text{m}$  and the average microtektite size for all 16 cores is 269  $\mu\text{m}$  (Table 1). This is quite close to the average microtektite size of 267  $\mu\text{m}$  determined for the entire strewn field by Glass and Pizzuto (1994), whereas they found a larger average size range of 130-467  $\mu\text{m}$  from 39 sites. There is a general decrease in abundance N-S as anticipated, from  $\sim 90$  microtektites of  $>125 \mu\text{m}/\text{cm}^2$  in the northernmost cores to 8.16 in AAS38/5 which is the southernmost location (Table 1). In all these cores, we find that the cores with higher abundances have lower average microtektite sizes. The southernmost cores have the least abundance and highest average size.

On an average, the size class 125-250  $\mu\text{m}$  contains twice the number of microtektites than >250  $\mu\text{m}$  size class (Table 1). The average ratio of abundance between 125-250 and >250  $\mu\text{m}$  size classes for 18 cores in this study is 2.19. This ratio varies from 1.24 (AAS4/6) to 3.6 in AAS4/2 which is located along almost the same latitude, but is  $\sim 3$  degrees west of AAS4/6. While it is anticipated that at locations where the 125-250  $\mu\text{m}$  microtektites are larger in number, the average size would be skewed towards the lower size class – however, this does not seem to happen in this data set. In all the stations, the average size seems to be dictated by overall abundance, which appears to have an inverse

relation with average size. It has been observed that the microtektite abundance increases with decreasing size down to at least 40 $\mu\text{m}$  (Glass and Pizzuto, 1994), although the bulk of the mass was suggested to be residing in the >125  $\mu\text{m}$  size category (Glass, 1968).

## **LOCATION OF SOURCE CRATER**

Including the 15 locations in this study, we find that there are 61 microtektite locations that contain the Australasian microtektite peak of abundance along with quantifiable estimates of microtektites (Table 2). In addition, there are 14 other locations where microtektite abundance estimates are not possible (Table 3). Thus, today we know 75 locations containing Australasian microtektites, which define the boundaries of this strewn field and the quantity of ejecta generated.

Based on the method devised by Burns and Glass (1989), Glass and Pizzuto (1994) carried out regression analysis using microtektite data from 42 locations for determining the location of the crater. The crater location was determined by first assuming a location for the crater and then performing the regression analysis of the microtektite number density at each site versus the distance from the postulated crater location. Then the log-log plot of microtektite abundance versus distance from postulated location was plotted which is fitted with a least square fit straight line and then the square of the correlation coefficient ( $R^2$  value) between the regression line and the actual data is computed for the postulated crater location. The site with the highest  $R^2$  value represents the crater that best explains the spatial variation in microtektite concentrations. In order to find the location having the highest  $R^2$  value, initially the spatial distance of each of the core locations from the predicted crater location was calculated (Glass and Pizzuto, 1994). Similar method was followed by Lee and Wei (2000) by adding two more locations located closer to the source area, and confirmed the crater location determined by Glass and Pizzuto (1994).

A majority of the locations postulated by various authors (Table 4) are seen to be falling close to each other demarcating an area roughly defined by the coordinates  $12 - 26^{\circ}\text{N}$  and  $98 - 112^{\circ}\text{E}$  (Fig. 2). We have chosen twelve such locations given by several investigators (Table 4). We carried out a detailed correlation analysis in this area by first considering each point within the above specified area as being the postulated crater location. These points are in the form of nodes in a mesh with  $0.5^{\circ}$  spacing. Once such a node from the specified area is assumed to be the crater location its distance with respect to each one of the microtektite core sites in the Australasian strewn field is computed. The relation between the distance from the crater location and the microtektite concentration is such that it indicates the decay in abundance as the distance increases. To find out the reliability of the postulated crater location a regression analysis is carried out over the plot of  $\log_{10}$  (thickness of the microtektite layer) versus  $\log_{10}$  (distance from the hypothetical source). By regressing these data points a linear, best fit line is obtained whose correlation with the entire data gives an indication of how well the crater location has been postulated.

On carrying out this activity over the entire specified area, the square of correlation coefficients or  $R^2$  values were computed at each of these nodes. A total of 841  $R^2$  values were contoured within the co-ordinates mentioned above ( $12 - 26^{\circ}\text{N}$  and  $98 - 112^{\circ}\text{E}$ ). Contouring these values joins all the nodes having similar  $R^2$  values wherein the innermost contour has the highest  $R^2$  value. This offers a rigorous way to estimate the most probable locations of the crater with respect to the coordinate system. Also, the shapes of the contours delineate the probable shape of the crater.

We considered three microtektite data sets in determining the correlation coefficient for all the crater locations postulated by various authors within the grid shown in Fig. 2. 1. Data from Glass and Pizzuto, (1994) from which we used only 41 locations (discarding core E48-6, as it had an abundance of only 1 microtektite). (2) Microtektite abundance data from Glass and Koeberl (2006), representing microtektite sites which total to 46 locations. In addition to the 41 sites of Glass and Pizzuto (1994), this data set also contains 5 additional sites in the South China Sea (including two sites reported by Lee



and Wei (2000). (3) Complete data of 61 microtektite sites, which includes additional 15 locations from the Central Indian Ocean from the present study, added to the 46 locations from Glass and Koeberl (2006).

Using these three data sets, we have tried to predict the crater location based on the highest correlation coefficient or the  $R^2$  value. Table 4 gives the correlation coefficients obtained by using these three data sets for 12 predicted crater locations within the square shown in Figure 2. Figure 3 shows the various correlation coefficients obtained by using these three data sets. It is observed that the effect of adding the 15 new core sites to the 46 core site locations, is that the overall correlation coefficient decreases by only 5%, confirming the validity of the method. The reason for such decrease could be attributed to the large distance at which the new core sites are located. However, the pattern of variation in  $R^2$  value is retained, and is identical to that generated by using microtektite data of Glass and Koeberl (2006) (Fig. 3). It is observable that there are marked differences in the correlations for these locations when compared to the data of Glass and Pizzuto (1994). Within this large area ( $12 - 26^{\circ}\text{N}$  and  $98 - 112^{\circ}\text{E}$ ), considering the Glass and Koeberl (2006) microtektite data and the 61 location total data set, the location having the least correlation is the Qui Nhon continental slope off Vietnam, followed by the location off the Vietnam coast proposed by Chaussidon and Koeberl (1995). Whereas, the location proposed by Glass and Koeberl (2006) ( $22^{\circ}\text{N}$  and  $104^{\circ}\text{E}$ ), shows less correlation coefficient when we consider exclusively the microtektite data from 41 sites, 46 sites and 61 sites (Fig. 3). However, Glass and Koeberl (2006) defined a large, oval area in this region by using unmelted ejecta from 13 cores located in the South China Sea, Philippines Sea, Sulu and Celebes Seas. They then calculated the regression values for all microtektite locations having microtektite abundances of  $>50$  and derived  $R^2$  values of 0.73 for  $22^{\circ}\text{N}$  and  $104^{\circ}\text{E}$ , however, when they evaluated the same site using unmelted ejecta they obtained  $R^2$  value of 0.83.

When we use the 46 microtektite location data (Glass and Koeberl, 2006) and construct a contour plot for the area between  $12 - 26^{\circ}\text{N}$  and  $98 - 112^{\circ}\text{E}$ , we find that the highest  $R^2$  value corresponds to the inner most oval contour shown in Fig 4a, the crater location

falls within this innermost contour, located in NE Thailand – Central Laos. We now added the 15 locations from this study to the 46 presented by Glass and Koeberl (2006), and followed the same procedure with the result that the center of the location showing maximum correlation coefficient is seen at  $18^{\circ}\text{N}; 104^{\circ}\text{E}$  (Table 3, Fig.4b) located in the central part of Laos. Hence, on a finer scale  $18^{\circ}\text{N}; 104^{\circ}\text{E}$  may be a more appropriate crater location using microtektite data. This location is in the same broad area as that shown by the 46 site data of Glass and Koeberl (2006), however, there is a very slight eastward shift into the Gulf of Tonkin. The oval shape of this crater with a N-S south elongation is apparently in agreement with the ejecta distribution in the strewn field. The impact site derived from unmelted ejecta (Glass and Koeberl, 2006) and the innermost contour of the area having highest  $R^2$  using microtektite data in this study, have ~40 % overlap.

It could be seen that evidence derived from varying sources, i.e., the distribution of Muong Nong-type tektites, isotopic and chemical data, Landsat imagery data, as well as evaluations derived from microtektite abundance data, all point towards a location broadly within the geographic confines shown in Fig. 2 ( $12 - 26^{\circ}\text{N}$  and  $98-112^{\circ}\text{E}$ ). This general location seems to be reasonably rigorously defined. From the data presented here, the center of the crater location that best explains the spatial variation of the entire data of microtektite core sites is  $18^{\circ}\text{N}; 104^{\circ}\text{E}$ .

Majority of investigators using different methods converged on a source crater with a diameter range of 32-125 km (Glass and Pizzuto, 1994; Burns and Glass, 1989; Schnetzler et al., 1988; Hartung and Koeberl, 1994; Schnetzler, 1992; Lee and Wei, 2000; and Glass, 2003), the exceptions being Schmidt et al. (1993) and Ma et al. (2004) whose proposed crater sizes are in the range 15-19 km and 4.4-18 km respectively. Therefore, considering the crater sizes of the other three tektite strewn fields, and by the estimations given by several investigators it is reasonable to assume that the crater diameter of the Australasian tektite strewn field should be at least  $\geq 30$  km. It has been a frustrating aspect of this strewn field that none has been identified as yet. Crater location based on microtektite data has been refined with the addition of new data (e.g., Lee and

Wei, 2000; Glass, 2003; Glass and Koeberl, 2006) since the technique has been first applied by Glass and Pizzuto (1994). Finally, in this study, using all available microtektite data the crater location shows highest regression value at  $18^{\circ}$  and  $104^{\circ}$  E. Offshore sampling has not been systematic and radially away from the Indochina region, because the primary purpose of all samples used in these studies has not been to investigate Australasian impact ejecta distribution. Whereas, onland in Indochina, more focused sampling was carried out (e.g., Izokh, 1988), with the result that a large region of  $\sim 200 \times 350$  km in NE Thailand, S. Laos and Vietnam of Muong Nong-type only tektites has been identified (Schnetzler, 1992; Wasson et al., 1995; Schnetzler and McHone, 1996; Fiske et al., 1999). The above region is very close ( $\sim 125$  km due S-SE) to the crater site identified in this study.

Considering all the different types of investigations carried out so far in the Indochina region, if a crater was on land the possibility is that such a large structure should have been discovered by now, or at least strong possibility of its location would have been identified. The offshore regions, especially the Gulf of Tonkin have not been investigated in any detail as yet, these areas should hold some concrete evidence. Glass and Koeberl (2006) suggested the Gulf of Tonkin to be a promising candidate site in view of the indication shown by low  $^{10}\text{Be}$  contents of the tektites surrounding this area which indicate proximity to the impact site (Ma et al., 2004).

## **CRATER SIZE ESTIMATION**

Once the location of the source crater is determined, the slope obtained from the regression can help us define the radial decay constant and use it to estimate the diameter of the source crater (Glass and Pizzuto, 1994). Based on the earlier equations given by Stöffler et al. (1975) and McGetchin et al. (1973), Glass and Pizzuto (1994) refined the equation to estimate the size of source crater, based on estimated thickness of the microtektite layer at each site.

For the total microtektite data set with 61 locations, the postulated crater location obtained from the algorithm developed to carry out rigorous analysis is 18° N and 104° E. The regression analysis done assuming this as the crater location gives:

$$\text{Slope} = -4.3 \pm 0.3 \text{ and intercept} = 23.7 \pm 0.9$$

The equation as per Glass and Pizzuto, (1994), describing the decrease in thickness of the ejecta blanket away from the source crater is :

$$t = cR(r/R)^{-b} \quad (1.1)$$

Where

t is thickness, R is radius, r is distance, c is constant,

b is the exponent that describes the decrease in thickness with distance

c = 0.02 for Australasian crater

b is determined from the regression analysis i.e. the slope of  $\log_{10}$  (thickness of the microtektite layer) versus  $\log_{10}$  (distance from the hypothetical source).

$$b \cong -4.3 \pm 0.3 \quad (1.2)$$

Simplifying the equation:

$$t = 0.02 \times R(r/R)^{-(-4.3 \pm 0.3)} \quad (1.3)$$

Taking log on either side:

$$\log_{10} t = (-4.3 \pm 0.3) \log_{10} r + (23.7 \pm 0.9) \quad (1.4)$$

$$t = 10^{(23.7 \pm 0.9)} r^{(-4.3 \pm 0.3)} \quad (1.5)$$

Applying boundary equation for the crater where r=R equation 1 becomes

$$t = 0.02 \times R \quad (1.6)$$

Substituting we get

$$0.02 \times R = 10^{(23.7 \pm 0.9)} \times R^{(-4.3 \pm 0.3)} \quad (1.7)$$

$$R^{(5.3 \pm 0.3)} = 10^{(23.7 \pm 0.9)} / 0.02 \quad (1.8)$$

$$R \cong 60 \text{ km} \quad (1.9)$$

Therefore the estimated diameter of the crater is approximately 120 km.

We see that there may occur some uncertainty in determination of the crater diameter based on the error present in the estimates of regression analysis. Thus the uncertainty in the diameter lies between 50 km to 360 km. If we consider the 46 location data from Glass and Koeberl (2006), having slope =  $-4.3 \pm 0.27$  and intercept =  $24 \pm 0.9$ , following the same procedure we get a diameter equal to 124 km. And the uncertainty in the diameter estimate lies between 50 km to 350 km. However, by using Stöffler et al's (1975) equation using the concentration of ejecta and the distance from the source, the crater size considering the entire microtektite data is  $33 \pm 8$  km. This is quite close to the crater diameter of  $\sim 32 (\pm 14)$  km proposed by Glass and Pizzuto (1994) using the same equation. However, Glass and Koeberl (2006) considered solely the unmelted ejecta associated with the Australasian microtektite layer for which they obtained a higher  $R^2$  value, and defined a crater diameter of  $43 \pm 9$  km by using the equations given by Stöffler et al. (1975). While the least square method shows much higher levels of uncertainty, calculation according to Stöffler et al's (1975) equation gives a crater size much closer to reality as ascertained by Glass and Pizzuto (1994) by testing with the data on the Ivory coast tektite strewn field and the Bosumtwi crater. However, it is pertinent to note that Stöffler et al's (1975) equations apply mainly to the lunar craters where the gravitational field is different.

## **CONCLUSIONS**

In all, 75 locations containing Australasian microtektites have been identified so far. Based on various sources of evidence, most investigators agree that the source crater for the Australasian tektite strewn field is located in Indochina. Glass and Pizzuto (1994), Lee and Wei (2000) and Glass and Koeberl (2006) carried out regression analysis using microtektite abundance data to arrive at the location of the possible impact site.

We identified 15 new Australasian microtektite bearing locations, added this data to the existing database and carried out regression analysis of the microtektite number density at each site for three data sets starting from that presented by Glass and Pizzuto (1994) for

42 sites, Glass and Koeberl (2006) for 46 sites and the total microtektite data set (including 15 from this study) comprising of 61 locations.

Most of the impact sites suggested by several investigators fall within the coordinates :  $12 - 26^{\circ}$  N and  $98 - 112^{\circ}$  E We used these three data sets and carried out a systematic regression analysis at 0.50 degree interval grid within these coordinates. The area having the maximum correlation coefficient by using the entire microtektite data is located at  $18^{\circ}$  N and  $104^{\circ}$  E. Systematic investigation of the Gulf of Tonkin, South China Sea should provide better clarity on the Australasian tektite source crater.

Further, using the average microtektite size derived from size measurements from 16 different locations, and using the equations given by Glass and Pizzuto (1994), the estimated diameter of the crater is  $\sim 120$  km, however, the diameter could vary from 50 km to 360 km, given the uncertainties in the data, however by using Stöffler et al.'s (1975) equation the crater has a diameter of  $33 \pm 8$  km.

## **ACKNOWLEDGEMENTS**

We are grateful to the Director, NIO for providing the infrastructure, and encouragement for carrying out this work. Thanks are due to our numerous colleagues who helped in the collection of sediment cores during several cruises spread over a decade. Further, we thank the project assistants who helped immensely in processing the samples. We are extremely grateful to Christian Koeberl and Philippe Claeys for their incisive reviews, which helped in improving the manuscript considerably.

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## LEGENDS TO FIGURES

1) **Figure 1** : Map showing the outlines of the Australasian tektite strewn field, figure based on Glass and Wu (1993). Filled circles show core location data from Glass and Pizzuto (1994) and Glass and Koeberl (2006) – 46 cores used for estimating crater location. Filled squares are 15 cores from the present study. Diamond in the Indochina region is the location of the proposed crater in this study.

2) **Figure 2** : Map showing the seven best correlated sites using 61 microtektite locations (1) This study; (2) Glass and Koeberl (2006) : 46 microtektite location data; (3) Ma et al., (2004); (4) Schmidt et al. (1993); (5) Glass (2003); (6) Schnetzler (1992); (7) Glass and Koeberl (2006) using unmelted ejecta. The stars are high abundance core sites from Glass and Koeberl (2006).

3) **Figure 3** : Plot showing the square of correlation coefficients or  $R^2$  values plotted against the crater location postulated by various authors. Serial numbers 1-12 along the x-axis correspond to the serial numbers in Table 4. Diamond shows  $R^2$  values using 41 core location data from Glass and Pizzuto (1994); filled circle shows 46 location data from Glass and Koeberl (2006), and the line with the square boxes as symbol is computed utilizing the entire core site data (61 locations) including the 15 new core sites from this study.

4) **Figure 4** : (a) The  $R^2$  contour map indicating the crater location based on 46 microtektite sites from Glass and Koeberl (2006). The  $R^2$  values were calculated by performing a systematic regression analysis at every node spaced at an interval of  $0.5^0$ . This indicates that the crater location could anywhere within the innermost contour having the highest  $R^2$  value.

(b) The  $R^2$  contour map indicating the crater location based on all the cores sites (61 sites in all) including the 15 new cores used in this study. The  $R^2$  values were again calculated by performing a systematic regression analysis at every node spaced at an interval of  $0.5^0$ . The crater could be located anywhere within the innermost contour having the highest  $R^2$  value. Note that while the crater defined in this figure falls in the same broad area as (a) above, however, there is a slight eastward shift into the Gulf of Tomkin.

Table 1 : Australasian Microtektite abundance data (this work)

S. No.	Core/site	Cruise dates	Position	Number of microtektites (>125µm) recovered	Ratio of microtektites of 125 - 250µm size	Abundance >125 µm size/cm <sup>2</sup>	Average Microtektite size (µm)	Remarks
1	<u>AAS38/1</u>	May-June, 2001	04°58.564'S 78°01.204'E	1164	1.9	86	250	This work
2	AAS22/8	Oct-Nov, 1999	07° 05.289'S 78° 07.712'E	1107	2.62	91.26	259	This work
3	AAS38/2	May-June, 2001	8° 29.868'S 77° 59.761"E	384	2.52	29.95	257	This work
4	SK69/001	Oct-Nov, 1991	08° 58.885'S 77° 07.021'E	1115	2.80	13	274	Prasad and Sudhakar (1999) This work
5	AAS22/7	Oct-Nov, 1999	10° 00.988'S 78° 08.971'E	637	1.64	50.12	263	This work
6	AAS 4/1	July-Aug, 1994	11° 15.661'S 75° 00.706'E	1275	2.6	96.89	261	This work
7	AAS 4/2	July-Aug, 1994	12° 00.105'S 75° 29.967'E	707	3.6	54.20	232	This work
8	AAS4/5A	July-Aug, 1994	12° 30.500'S 76° 30.990'E	990	2.54	94.50	247	This work
9	AAS4/12 <sup>1</sup>	July-Aug, 1994	12° 30.200'S 74° 29.328'E	127	2.30	8.89*	256	This work
10	AAS38/3	May-June, 2001	12° 34.831'S 75° 15.351'E	283	2.1	20.97	285	This work
11	AAS 4/6	July-Aug, 1994	12° 36.968' S 78° 30.757'E	410	1.24	19.84	304	This work
12	<b>SK16/176</b>	June-July, 1985	14° 00'3"S 74° 04'6"E	306	1.97	62	267	Prasad and Sudhakar (1996b) This work
13	AA S38/4	May-June, 2001	14° 00.254'S 75° 00.070'E	36	2.00	2.20	244	This work

14	AAS22/5	Oct–Nov, 1999	15° 06.567'S 78° 11.734'E	437	1.51	33.87	353	This work
15	AAS22/3	Oct–Nov, 1999	16° 59.959'S 77° 59.792'E	387	1.79	21.8	314	This work
16	AAS38/5	May–June, 2001	17° 03.194'S 74° 02.669'E	190	1.56	8.16	320	This work
17	AAS62/56 <sup>1</sup>	April–May, 2003	17° 57.223'S 78° 01.711'E	2646	1.57	5*	289	This work
18	AAS62/55 <sup>2</sup>	April–May, 2003	18° 19.480'S 77° 55.737'E	161	0.53	<1*	393	This work
19	SS10/649	June–Aug, 1987	12° 34.105' S 76° 16.456' E	10		Unknown		Prasad (1994a)
20	SS10/655B	June–Aug, 1987	13° 58.773' S 75° 57.990' S	12		Unknown		Prasad (1994a)
21	SS2/89	Sep–Nov, 1982	14° 01.213'S 75° 59.700'E	3		Unknown		Prasad (1994a)
22	SS2/94	Sep–Nov, 1982	19° 00.043'S 76° 00.043'E	8		Unknown		Prasad (1994a)
23	SS7/428D	June–July, 1983	10° 30'S 79° 00'E	105		Unknown		Prasad (1994b)
	TOTAL			12500	2.19 (average ratio)		269 (average diameter)	

1. AAS2/12 and AAS62/56; AAS62/55 : corer not penetrated the peak of microtektite abundance in these cores.

2. AAS62/55 : insufficient numbers of both size classes were recovered, there the ratio between the two size classes and the average size are unreliable here

3. # 20-22 are surficial samples, microtektites are displaced to the surface due to bioturbation or sediment removal by bottom currents therefore the size ratio would not be valid here.

# 19 is from a dredge and possibly a bioturbated sediment, therefore the ratio would not be valid here.

# 23 is from a dredge sample, and the search bias was more towards >250 um size fractions therefore the ratio would not be valid.

Table 2 : Australasian microtektite sites used for postulation of crater location

S. No.	Name of the Core sites	Latitude	Longitude	No. of microtektites >125 $\mu$ m / cm	Distance (km) from center of the hypothetical crater location at 18°N; 104° E
1	ODP 769A	8.79°N	121.22° E	3196	2083
2	ODP 758B	5.38° N	90.36° E	3255	2111
3	ODP 767B	4.79° N	123.50° E	2980	2545
4	RC 14-46	7.82° S	100.00° E	1056	2949
5	V19-153	8.85° S	102.12° e	329	3033
6	V19-158	18.18° S	99.40° E	39	4098
7	V19-171	7.07° S	80.77° E	20	3848
8	RC14-24	6.62° S	79.44° E	39	3913
9	V20-138	28.87° N	135.55° E	49	3355
10	V19-169	10.22° S	81.62° E	56	4054
11	V29-39	7.70° S	77.38° E	50	4159
12	V29-40	10.48° S	78.05° E	106	4330
13	RC14-23	9.18° S	76.76° E	55	4323
14	MSN 48G	15.25° S	81.13° E	52	4539
15	RC12-331	2.50° N	69.87° E	82	4173
16	V29-43	12.33° S	75.08° E	82	4702

17	RC12-328	3.95 <sup>0</sup> N	60.60 <sup>0</sup> E	14	5043
18	RC12-327	1.73 <sup>0</sup> N	57.83 <sup>0</sup> E	13	5422
19	RC8-53	39.38 <sup>0</sup> S	104.37 <sup>0</sup> E	4	6417
20	E50-2	39.96 <sup>0</sup> S	104.93 <sup>0</sup> E	2	6481
21	E45-89	39.52 <sup>0</sup> S	114.47 <sup>0</sup> E	11	6514
22	E49-51	39.93 <sup>0</sup> S	99.94 <sup>0</sup> E	4	6496
23	E49-50	40.61 <sup>0</sup> S	99.91 <sup>0</sup> E	5	6572
24	RC8-52	41.10 <sup>0</sup> S	101.42 <sup>0</sup> E	14	6616
25	V28-239	3.25 <sup>0</sup> N	159.18 <sup>0</sup> E	7	6168
26	RC9-143	41.36 <sup>0</sup> S	114.13 <sup>0</sup> E	18	6709
27	V28-238	1.02 <sup>0</sup> N	160.48 <sup>0</sup> E	3	6391
28	RC9-142	42.72 <sup>0</sup> S	116.89 <sup>0</sup> E	16	6904
29	V16-75	22.22 <sup>0</sup> S	58.38 <sup>0</sup> E	2	6753
30	E49-4	46.99 <sup>0</sup> S	110.13 <sup>0</sup> E	14	7285
31	V16-76	25.15 <sup>0</sup> S	59.90 <sup>0</sup> E	18	6840
32	E45-74	47.55 <sup>0</sup> S	114.44 <sup>0</sup> E	2	7391
33	E45-71	48.02 <sup>0</sup> S	114.49 <sup>0</sup> E	13	7444
34	LSDH 23G	31.23 <sup>0</sup> S	62.97 <sup>0</sup> E	4	7080
35	E35-9	45.05 <sup>0</sup> S	128.02 <sup>0</sup> E	2	7436
36	RC9-137	45.02 <sup>0</sup> S	132.75 <sup>0</sup> E	10	7599



37	E39-45	45.16° S	133.96° E	4	7659
38	V20-84	25.80° S	53.68° E	10	7374
39	V16-70	32.10° S	55.85° E	14	7641
40	E35-6	53.21° S	128.10 E	8	8270
41	17957-2 (SONNE-95)	10.90° N	115.31° E	2918	1416
42	ODP 1144A	20.05° N	117.42° E	9834	1361
43	ODP1143A	9.36° N	113.29° E	663	1720
44	MD972142	12.69° N	119.56° E	3199	2148
45	MD972143	15.87° N	124.65° E	1117	1367
46	ODP 768	8.00° N	121.22° E	2961	2132
47	<u>AAS38/1</u>	4.976° S	78.02° E	86	3899
48	AAS22/8	7.088° S	78.128° E	91.26	4052
49	AAS38/2	8.498° S	77.996° E	29.95	4174
50	AAS22/7	10.016° S	78.149° E	50.12	4284
51	AAS 4/6	12.616° S	78.513° E	19.84	4475
52	AAS22/5	15.109° S	78.195° E	33.87	4711
53	AAS22/3	16.999° S	77.996° E	21.8	4889
54	AAS38/3	12.58° S	75.256° E	20.97	4708
55	AAS 4/1	11.261° S	75.012° E	96.89	4622
56	AAS 4/2	12.002° S	75.499° E	54.20	4644
57	AAS4/5A	12.508° S	76.516° E	94.50	4609

58	SK16/176	14.005 <sup>0</sup> S	74.076 <sup>0</sup> E	62	4911
59	AAS38/4	14.004 <sup>0</sup> S	75.002 <sup>0</sup> E	2.20	4843
60	AAS38/5	17.053 <sup>0</sup> S	74.044 <sup>0</sup> E	8.16	5162
61	SK69/001	8.981 <sup>0</sup> S	77.117 <sup>0</sup> E	13	4280

#1-40 data from Glass and Pizzuto (1994)

#41-46 data from Glass and Koeberl (1994)

#47-61 from the present study

**Table 3 : Australasian microtektite sites, which are not included for calculations on crater location.**

S. No.	Sample No.	Location	No. of microtektites recovered (125 $\mu$ m size)	Abundance of microtektites	Author	Reasons for not using this site
1	E48-6	34.00° S 97.54° E	1	1/cm <sup>2</sup>	Glass and Pizzuto (1994)	Has abundance of only one microtektite/cm <sup>2</sup> , therefore not useful for computation
2	ODP772A	16° 39.00 N 117° 42.00 E	277	unknown	Wang et al. (2000)	Abundance unknown
3	17959 Sonne-95	11° 08.3' N 115° 17.2'E	unknown	33.6 grains/g	Wang et al (2000)	Abundance unknown
4	L1025	6°00.07'S 173° 15.'06" E	unknown	unknown	Peng et al. (1982)	Abundance unknown
5	C2030	5° 00.01'N 165° 00.09'E	unknown	unknown	Peng et al. (1982)	Abundance unknown
6	C2032	2° 59' 05" N 164°55' 5"E	unknown	unknown	Peng et al. (1982)	Abundance unknown
7	SS10/649	12° 34.105' S 76° 16.456' E	10	unknown	Prasad (1994a)	Dredge sample, not possible to compute abundance
8	SS10/655B	13° 58.773' S 75° 57.990' S	12	unknown	Prasad (1994a)	Surficial sample, not possible to compute abundance
9	SS2/89	14° 01.213'S 75° 59.700'E	3	unknown	Prasad (1994a)	Surficial sample, not possible to compute abundance
10	SS2/94	19° .043'S 76° .043'E	8	unknown	Prasad (1994a)	Surficial sample, not possible to compute abundance
11	SS7/428D	10° 30'S 79° 00'E	105	unknown	Prasad (1994b)	Dredge sample, not possible to compute abundance
12	AAS62/56	17° 57.223'S 78° 01.711'E	2646	5/cm <sup>2</sup> *	This work	Core did not penetrate

13	AAS62/55	18 <sup>o</sup> 19.480'S	77 <sup>o</sup> 55.737'E	161	<1/cm <sup>2</sup> *	This work	peak of microtektite abundance Core did not penetrate peak of microtektite abundance
14	AAS4/12	12 <sup>o</sup> 30.200'S	74 <sup>o</sup> 29.328'E	127	8.89/cm <sup>2</sup> *	This work	Core did not penetrate peak of microtektite abundance

**\* Abundance values not reliable**

Table 4 : Suggested craters in Indochina and their correlation coefficients using microtektite data

Sl. no.	Authors	Location	R <sup>2*</sup>	R <sup>2@</sup>	R <sup>2#</sup>
1.	Schnetzler et al. (1988)	13.78 <sup>0</sup> N;110.62 <sup>0</sup> E: Qui Nhon Slope Anomaly	0.78	0.79	0.75
2.	Chaussidon and Koeberl (1995)	9 <sup>0</sup> N ; 107 <sup>0</sup> E (Off the Vietnam coast, near the mouth of the Mekong River in the South China Sea)	0.83	0.81	0.77
3.	Glass and Pizzuto(1994); Lee and Wei (2000)	12 <sup>0</sup> N;106 <sup>0</sup> E (eastern Cambodia)	0.84	0.83	0.80
4.	Hartung and Koeberl (1994)	13 <sup>0</sup> N; 103 <sup>0</sup> E LakeTonle Sap , South Central Cambodia	0.82	0.85	0.80
5.	Hartung and Rivolo (1979)	13.92 <sup>0</sup> N;106.57 <sup>0</sup> E (NE Cambodia)	0.83	0.84	0.80
6.	Ma et al. (2004)	17 <sup>0</sup> N ; 107 <sup>0</sup> E Song Hong Basin (off Vietnam, South of Gulf of Tonkin)	0.81	0.85	0.81
7.	Schmidt et al. (1993)	14.77 <sup>0</sup> N;105.42 <sup>0</sup> E (Buntharik, Thailand; either the Khorat Plateau or the adjacent Mekong River valley)	0.83	0.85	0.81
8.	Glass (2003)	15 <sup>0</sup> N ; 105 <sup>0</sup> E (SE corner of NE Thailand)	0.83	0.85	0.81
9.	Schnetzler (1992)	16 <sup>0</sup> N;105 <sup>0</sup> E (Southern part of Thailand-Laos border)	0.82	0.85	0.81
10.	Glass and Koeberl, (2006)	22 <sup>0</sup> N : 104 <sup>0</sup> S (NE Laos-SE China-NW Vietnam-Gulf of Tonkin) using unmelted ejecta.	0.78	0.85	0.81
11.	Glass and Koeberl (2006)	18 <sup>0</sup> N;104 <sup>0</sup> E (NE Thailand -Central Laos), using 46 microtektite sites	0.81	0.86	0.82
12.	Entire data – THIS STUDY (61 core sites)	18 <sup>0</sup> N;104 <sup>0</sup> E (NE Thailand - Central Laos), using entire microtektite data of 61 sites, including 15 sites from this study	0.81	0.86	0.82

**\*Using the 40 sites data of Glass and Pizzuto (1994) ; @Considering 46 sites data from Glass and Koeberl (2006)**

**#Entire microtektite data from this study using 61 sites**









