In search of the Australasian tektite source crater: The Tonle Sap hypothesis

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Abstract—The source crater for Australasian tektites remains to be positively identified. We suggest that Tonle Sap, a roughly oval lake in south-central Cambodia, may represent the remnant of that crater. The size of the lake (about 100 km x 35 km), location (Indochina), inferred geologic age (recent), and orientation of the lake, as well as the geographical distribution of tektites, are consistent with this suggestion. The elongated shape of the lake with its long axis pointing toward Australia may be the result of an oblique impact of a NW to SE-moving object a few km in diameter. The absence of a raised rim and a central peak may be related to a low impact angle, soft target rocks, or high post-impact erosion and sedimentation rates. The scarcity of Muong Nong-type (layered) tektites near Tonle Sap may be due to extensive post-impact alluvial deposition, which buried the tektites. The chemical composition of Upper Indosinias formation sandstones from Phnom Batheay was determined. There are significant differences between the composition of indochinite tektites and these rocks, which are thus unlikely to represent tektite source rocks.

INTRODUCTION

Tektites are natural glasses that are the product of melting of terrestrial rocks during hypervelocity impacts, followed by rapid cooling and solidification. They are mm to cm in size and occur in at least four strewn fields on the Earth: North American (34 Ma old), Central European (moldavite; 15 Ma old), Ivory Coast (1.1 Ma old), and Australasian (0.8 Ma old). Strewn fields are geographically extended areas over which tektite material is found. Tektites found within any of these strewn fields are related to each other with respect to their petrological, physical, and chemical properties as well as their age (*e.g.*, Barnes, 1963, 1990; Chao, 1963). The chemical composition of tektites is similar to the composition of upper crustal material (*e.g.*, Taylor, 1973; Koeberl, 1986, 1994).

Three classes of tektites have been recognized: (a) normal or splash-form, (b) aerodynamically ablated, and (c) Muong Nong-type (layered). Ablated tektites are found mainly in Australia where they occur as flanged buttons. Muong Nong-type tektites, named after the type-locality in Laos, are usually considerably larger than normal tektites. Single masses of up to 24 kg have been described. They have a blocky appearance and display a layered structure with abundant vesicles (*e.g.*, Koeberl, 1992). Some contain inclusions of shocked minerals and other high-pressure indicators (*e.g.*, zircon, chromite, rutile, corundum, cristobalite, and coesite; Glass and Barlow, 1979). Muong Nong-type tektites are found almost exclusively in Indochina, in the countries of Laos, Viet Nam, Thailand, Cambodia, and adjacent areas of China. Microtektites have been found in deep-sea cores in three of the four strewn fields. They are generally less than about 1 mm in diameter and have compositions and ages that are the same as or close to those of large tektites.

The Australasian strewn field has, by far, the largest area of the four known fields. Tektites have been found from China and Indochina (southeast Asia) to Australia, a distance of over 5000 km. Recent analyses of the location and quantity of microtektites and shocked impact debris in deep-sea cores show a non-uniform distribution within the strewn fields (Glass and Wu, 1993), conceivably in the form of "rays", which may help to define the location of the source crater.

Until now, no source crater has been identified for Australasian tektites, even though it is certainly one of the larger craters formed on the Earth during geologically recent times. A variety of structures has been proposed for the Australasian tektite source crater. For example, Weihaupt (1976) suggested a location in Wilkes Land, Antarctica; Dietz (1977) proposed the Elgygytgyn crater in Siberia, and Glass (1979) suggested the Zhamanshin crater; Hartung and Rivolo (1979) considered an oval feature in northern Cambodia; Schnetzler *et al.* (1988) inferred a location in the South China Sea from satellite gravity data and assumed that the crater is now buried by sediment; Wasson (1991) proposed that the tektites were produced by many small impacts all over Indochina, but this suggestion has substantial problems (Blum *et al.*; 1992; Schnetzler, 1992; Koeberl, 1992, 1994). A search for impact structures in Thailand did not yield any obvious candidates (McHone *et al.*, 1994).

Practically all the suggested craters or locations mentioned above have subsequently been rejected as the sources for the Australasian tektites based on their geographic location, chemical and isotopic composition, size, or age (see review in Koeberl, 1992, 1994). Another possibility is that the crater exists on land in southeast Asia but has not yet been recognized due to the effects of rapid erosion (Schnetzler, 1992) or burial (Stauffer, 1978). The distribution of tektites within the strewn field was analyzed by Stauffer (1978), who concluded that the crater may lie buried beneath the Mekong river delta, and later by Schnetzler (1992), who suggested an area in central Indochina based on several factors, including distribution of splash-form and Muong Nong-type tektites. We essentially concur with Stauffer's analysis but conclude instead that the source of Australasian tektites may be the basin occupied by the Tonle Sap lake, which is about 300 km northwest of the Mekong river delta. A preliminary version of this suggestion has been discussed in abstract form (Hartung, 1990; Hartung *et al.*, 1992a,b).

THE TONLE SAP HYPOTHESIS

Could the elongated Tonle Sap lake in western Cambodia (Fig. 1), 100 km long and about 35 km wide in the dry season, be related in some way to the source of Australasian tektites? The following reasons seem to argue against this possibility. (1) Many investigators believe the crater will be found in northeastern Indochina, because greater numbers of layered tektites have been found in that area (V. Barnes, pers. comm., 1989; Wasson, 1991; Schnetzler, 1992). (2) Neither Tonle Sap nor the basin containing Tonle Sap is circular. (3) The Tonle Sap basin does not display structural features expected for a young, large impact crater, such as a central peak or a raised rim.

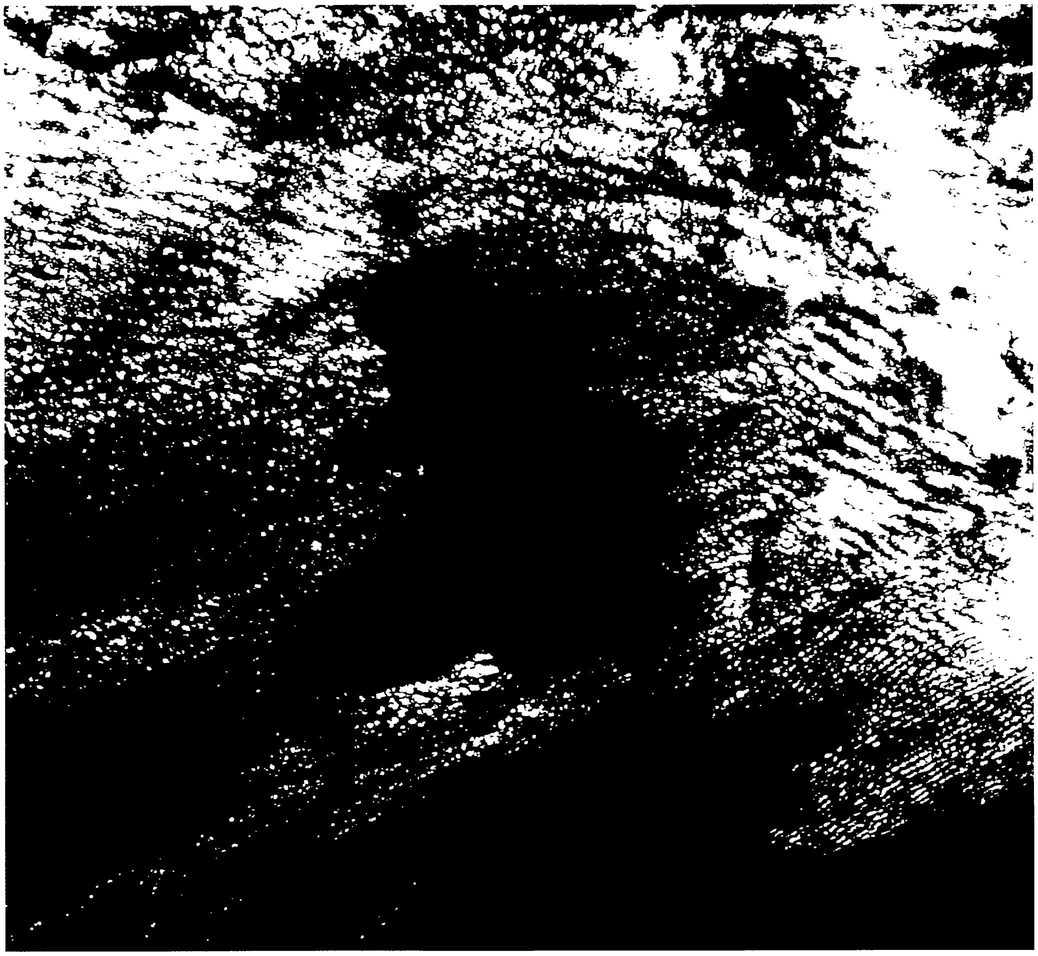

FIG. 1. Space Shuttle photograph of Lake Tonle Sap in Cambodia (image STS61B-49-097).

However, several observations support the hypothesis that the Tonle Sap basin does, in fact, represent the source crater for Australasian tektites.

The Basin

The presence of a lake as large as Tonle Sap in a region with a tropical climate is unusual. Lakes are, in general, short-lived geologic features and have a readily identifiable reason for their existence. It is generally believed (*e.g.*, Hutchison, 1989) that the Tonle Sap basin is a result of tectonic activity, but no detailed studies have been made to support this idea. There are several faults in Indochina as the result of the collision of India and Eurasia, and some have affected the southeastern part of Thailand and the southern part of Cambodia (*e.g.*, Huchon *et al.*, 1994). *Per se*, however, this does not provide evidence against a crater being superimposed on a series of fault zones.

Location

The geologic map by Rasmussen and Bradford (1977) indicates that two alluvium units surround Tonle Sap, one distinctly younger than the other. This unit may have been deposited after the tektite-producing impact, thereby burying the tektite-bearing horizon and preventing the discovery of tektites where young alluvium reaches a significant thickness. Thus, a sampling bias may exist for Muong Nong-type tektites, which favors the recovery of these tektites in the northeastern part of Indochina, even though the ejected material, including tektites, was distributed more uniformly.

Based on differences of microtektite abundances and grain-size distributions observed in samples obtained from deep sea operations in the waters of southeast Asia and Australia, it is possible to determine the crater location that best explains the spatial distribution of microtektites and their corresponding size distributions (Glass and Wu, 1993). That location was determined to be at about 11.5°N and 106°E, just southeast of Tonle Sap (Glass, 1993).

Size

Previously, the Australasian tektite source crater was suggested, from chemical and isotopic considerations, to have dimensions of 50–100 km (Blum *et al.*, 1992; Koeberl, 1994), or a minimum of 40 ± 7 km, based on microtektite masses (Glass, 1993). Tonle Sap is about 100 km long and up to 35 km wide. These dimensions probably represent minimum values if the structure is interpreted as an impact crater, because sediments have partially filled what was once a larger lake. If we assume the young alluvium indicated on the geologic map of Cambodia is sediment deposited on the floor of a lake that was contained in an impact crater or basin, then the basin could be larger than the present lake by up to a factor of four.

Shape

The Tonle Sap lake (and basin) is not circular (Fig. 1). Laboratory experiments (Gault and Wedekind, 1978) and observations of craters on Mars and the Moon have shown that a small fraction of all impacts is oblique and produces elongated, segmented, or double craters (*cf.*, Fig. 13 in Schultz and Gault, 1990). Recently, several elongated crater structures that have resulted from oblique impacts were reported in Argentina (Schultz and Lianza, 1992). If the Tonle Sap basin impactor approached the Indochina peninsula at a low angle (<10°), then the resulting basin would have had a non-circular or elongated shape. Therefore, the shape of Tonle Sap is consistent with an oblique impact.

Morphology

Morphologically, the Tonle Sap basin does not seem to be a crater. It appears as an extremely flat alluvial plain. There is no uplifted rim surrounding the basin and no central peak. The Tonle Sap lake itself is only a few m deep. The shallow expression is, however, consistent with oblique impact because such craters excavate less deep than "normal" impacts (*e.g.*, Schultz and Gault, 1990; Schultz and Lianza, 1992, and references therein). The only significant topographic features present in the region surrounding the lake are isolated hills, or "phnoms," which appear to penetrate through the alluvium at random locations. With only one exception, every hill is composed of a different rock type and appears unrelated to neighboring hills. Little is known about their origin (Hutchison, 1989).

Age

The presence of lakes requires an explanation in terms of a recent event or ongoing processes. Tonle Sap is surrounded by sediments of Quaternary age (Rasmussen and Bradford, 1977). The formation age of the lake is not well constrained or well studied. Hutchison (1989) puts the formation of the basin in the late Cenozoic (Oligocene or later), while Carbonnel (1963) concluded that the basin had formed as recently as about 5000 years ago. This age range (0.005 to 34 Ma) is at least not inconsistent with the 0.8-Ma age of Australasian tektites. It should also be noted that the time of general tectonic activity in this area does not need to be identical with the time of formation of the depression now occupied by the Tonle Sap lake.

Orientation

The azimuth from north of the long axis of Tonle Sap is estimated to be 134 ± 3°. This range may be compared with the range of azimuths from Tonle Sap to the eastern and western extremes of tektite find localities on the continent of Australia, 135° to 165° from north, respectively. These represent maximum values because the rotation of the Earth during the tektite flight has not been taken into account. The general agreement between the Tonle Sap orientation and the directions towards the most distant tektite localities is in agreement with the idea of an impactor moving NW-SE. Early high-velocity impact ejecta are thrown out predominantly in the downrange direction (*e.g.*, Schultz and Gault, 1985, 1990) and remain remarkably collimated because of ballistic shadowing (Schultz and Sugita, 1994). Thus, the distribution of tektites in Australia requires a properly oriented source crater. Tonle Sap fulfills this condition and is, therefore, at least in this respect, a much better candidate than any of the previously identified structures.

DISCUSSION

With the Tonle Sap hypothesis in mind, the geological characteristics of the region (Rasmussen and Bradford, 1977; Hutchison, 1989) can be studied to find if they are consistent with an impact origin.

During the dry season the Tônlé Sab river flows out of the lake to the southeast and joins the Mekong river at Phnom Penh. However, during the wet season, when the Mekong river floods, the flow of the Tônlé Sab river reverses direction, so that sediment borne by Mekong river flood waters is deposited in the Tonle Sap basin. That this is a significant sedimentation process becomes clear when one realizes the Mekong is the 11th longest river on Earth, and its discharge rate is among the top 10 (Rasmussen and Bradford, 1977). This unusual behavior would cause the Tonle Sap basin to fill more rapidly than otherwise might be expected, judging from the relatively small size of the Tonle Sap watershed alone. This characteristic further attests to the youth of the basin and is consistent with its formation on a short time scale. It is possible that the effects of erosion and sedimentation over an interval of 0.8 Ma could have destroyed the basin rim and filled in the basin so completely that the feature has become unrecognizable.

Based upon the 1:200,000-scale geological maps of Dottin (1972), we determined that the elevation of the contact between "old" and "young" alluvium was constant at ~20 m. The present lake surface elevation varies between 2 and 11 m above sea level, depending on the level of the Mekong river (Rasmussen and Bradford, 1977). This is consistent with the view that at some time in the past the Tonle Sap lake surface stood ~9 m higher than its present maximum level. This could be due to higher Mekong river flood levels or a higher level of a natural dam, maybe associated with the impact, between the Tonle Sap lake and the Mekong river. Eventually, the dam would have failed, thus allowing the elevation of the lake surface to be controlled by the Mekong river, as it is today. Considering the low present-day elevation above sea level (Rasmussen and Bradford, 1977), the floor of Tonle Sap could, at some time, have been lower than sea level and the lake could have occupied a closed basin.

North of Tonle Sap about 150 km the south-facing Chuor Phnum Dangrek Escarpment rises up to a level 100 m higher than the elevation of the Tonle Sap lake surface. Over an arc of about 90°, the escarpment is roughly concentric with respect to the lake or basin. It may be that this escarpment represents the limit of rocks which were faulted and moved downward and inward to compensate to some extent for the mass removed from the basin during the impact.

COMPOSITION OF ROCKS FROM NEAR TONLE SAP

Despite severe political and logistical difficulties, an exploratory trip to Cambodia was made in 1992 January. Four field trips were made in the vicinity of Phnom Penh. In addition, two trips were made by air to Siem Reap, which is at the northwest end of Tonle Sap and near the archeological site of Angkor Wat. Locations of Phnom Penh, Tonle Sap, the Mekong river and the

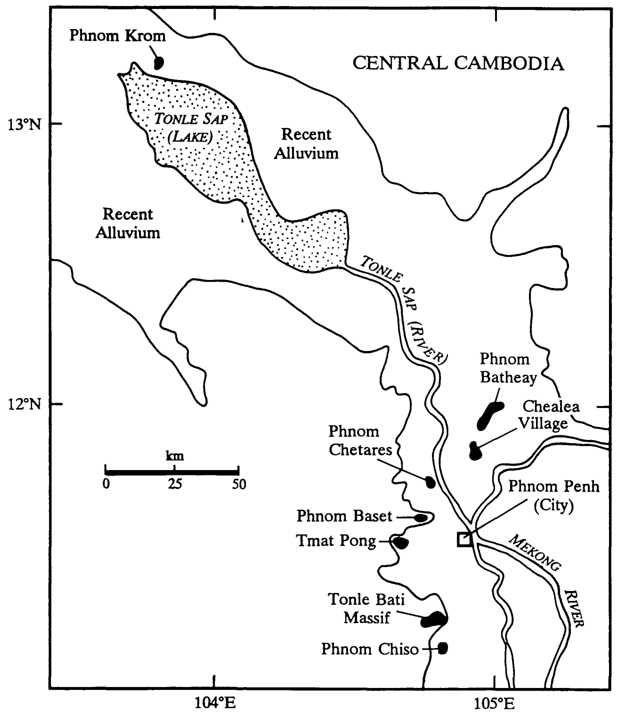

FIG. 2. Map of area around Tonle Sap showing locations where samples were collected. All but one are near Phnom Penh and away from the proposed impact site. Only Phnom Krom is near, or possibly inside, the basin. Tonle Sap Lake is surrounded by young alluvium; for more details, see Rasmussen and Bradford (1977).

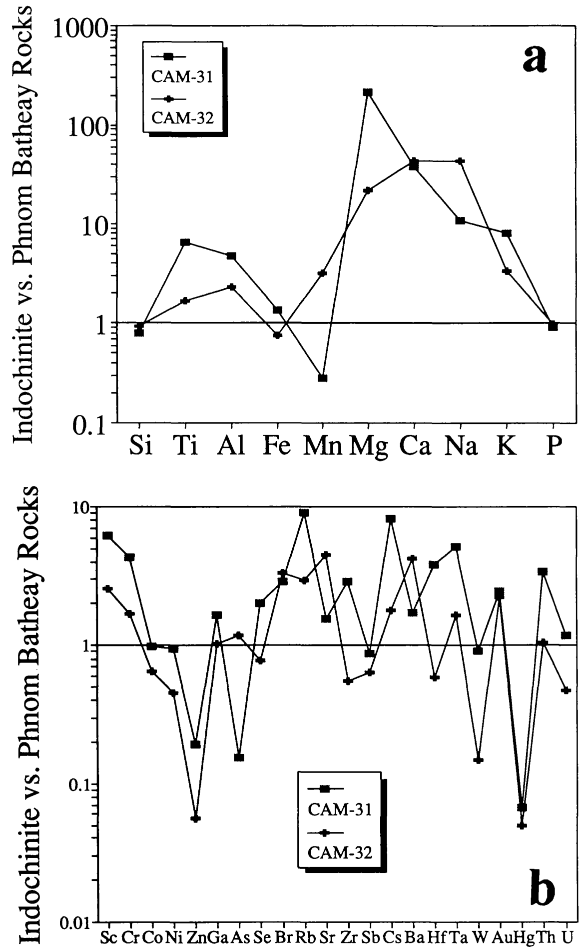

FIG. 3. Comparison of major (a) and trace (b) element chemical composition of average indochinites and Upper Indosinias rocks from Phnom Batheay, showing significant differences, especially in Mg, Ca, and Na content.

sites from which samples were collected, are shown in Fig. 2. For security reasons, only limited sampling was possible. The phnoms located to the southeast of Tonle Sap lake contain a wide variety of rock types which appear unrelated. It may be that these rocks represent the variation in bedrock types present under the Tonle Sap-Mekong river alluvial plane. We report here some first results of chemical analyses of samples from Phnom Krom and Phnom Batheay, which were selected because of their proximity to Tonle Sap and exposure of Indosinias sandstone, respectively. Sandstones, siltstones, and conglomerates of the Mesozoic Upper Indosinias Formation appear to underlie the older alluvium. These rocks may even have been exposed at the time of the basin-forming impact and may have been involved in the tektite production.

At Phnom Krom (Fig. 2), a quarry exposes a sequence of compact cinerites, ferruginous scoria, various rhyolite breccias, dark sandstones, and various conglomerates (Dottin, 1972). We analyzed a very fine-grained (aphanitic) grey rock (CAM-9), occurring along a zone of alteration 2–4 cm thick, which may have been associated with hydrothermal activity along a pre-existing crack. Phnom Batheay is located near the village of Batheay on Route Nationale 6. It is a butte made of Upper Indosinias sandstone, intruded at its base by a vein of acidic rhyolitic rock. We analyzed two different samples of Indosinias sandstone (CAM-31, CAM-32).

The major element analyses were done with standard XRF techniques, and trace elements by neutron activation analysis following methods described by Koeberl (1992). The results of the analyses are given in Table 1, together with data for Australasian tektites. The comparison with tektite values is shown in Figs. 3a,b for major and trace elements. There are significant differences in chemical composition between the average indochinite tektite composition and the composition of either rock. We conclude that none of the rocks analyzed has a composition similar to that expected for the tektite source rocks.

CONCLUSIONS

In summary, many aspects of the Tonle Sap lake and basin are consistent with the hypothesis that this basin is the source crater for Australasian tektites. Alluvia of different ages are present around the lake. While the older alluvium may have been part of the pre-impact target rocks, the younger alluvium, which was deposited since the impact, has obscured the crater and covered local tektite occurrences. The Chuor Phnum Dangrek Escarpment may be related to the basin and could be interpreted as a mega-terrace. The hypothesis admittedly suffers from the lack of a raised rim and central peak at Tonle Sap. However, this is expected for an oblique impact, which produces a very shallow crater structure that is extremely susceptible to erosion (*e.g.*, Schultz and Lianza, 1992). The distribution of tektites in Australia, which represent the early high-velocity downrange ejecta resulting from an oblique impact, fits very well with the orientation of the Tonle Sap lake. The chemical composition of Upper Indosinias rocks from Phnom Batheay, which were initially thought to resemble tektite source

TABLE 1. COMPOSITION OF SANDSTONES FROM PHNOM KROM AND PHNOM BATHEAY, AND COMPARISON VALUES FOR AVERAGE INDOCHINITES AND MUONG NONG TYPE TEKTITES

	CAM-9 P. Krom	CAM-31 P. Batheay	CAM-32 P. Batheay	Indochinite Avg.	Muong Nong Avg.
SiO_2	77.49	90.40	78.08	72.70	78.93
TiO_2	0.66	0.12	0.46	0.78	0.63
Al_2O_3	14.90	2.81	5.81	13.37	10.18
FeO	0.10	3.56	6.46	4.85	3.74
MnO	0.008	0.287	0.025	0.08	0.08
MgO	0.01	0.01	0.10	2.14	1.43
CaO	0.07	0.05	0.05	1.98	1.21
Na_2O	0.02	0.10	0.02	1.05	0.92
K_2O	0.25	0.33	0.79	2.62	2.42
P_2O_5	0.039	0.033	0.031	0.03	0.03
L.O.I.	5.72	1.62	7.23	0.01	0.01
Total	99.26	99.33	99.05	99.61	99.58
Sc	41.5	1.72	4.12	10.5	7.7
Cr	42.8	14.6	37.4	63	60.6
Co	0.14	11.2	17.1	11	12.6
Ni	<5	20	42	19	49
Zn	<4	30	102	5.7	67
Ga	6.2	5	8	8.2	24
As	29.8	5.78	0.76	0.9	4.75
Se	0.65	0.05	0.13	0.1	0.2
Br	0.1	0.08	0.07	0.23	4.12
Rb	10.3	14.4	44.4	130	110
Sr	78	58	20	90	135
Zr	180	87	455	252	280
Ag	0.03	0.04	0.06	n.d.	0.1
Sb	2.88	0.57	0.79	0.5	0.82
Cs	3.11	0.79	3.62	6.5	5.09
Ba	6	210	85	360	341
La	19.1	16.7	32.1	36.5	28.2
Ce	39.2	33.2	61.9	73.1	60.7
Nd	16.9	16.1	28.3	33.2	29.1
Sm	4.28	2.73	6.21	6.6	4.85
Eu	1.03	0.46	1.01	1.22	1.01
Gd	4.3	2.1	6.3	5.24	4.3
Tb	0.72	0.28	0.91	0.85	0.75
Dy	4.1	1.6	5.7	5.58	4.75
Tm	0.39	0.13	0.47	n.d.	0.42
Yb	2.26	0.96	3.24	2.9	2.71
Lu	0.31	0.13	0.44	0.4	0.42
Hf	4.48	1.83	11.9	6.95	8.13
Ta	0.49	0.31	0.96	1.6	1.17
W	3.1	0.32	1.95	0.29	1.02
Ir (ppb)	<1	<1	<1	0.02	<1
Au (ppb)	0.8	0.8	0.9	2	2.1
Hg	1.5	0.03	0.04	0.002	<1
Th	9.82	4.15	13.4	14	11.1
U	1.41	1.78	4.41	2.07	2.48
K/U	1478	1545	1493	10548	8132
Zr/Hf	40.18	47.54	38.24	36.26	34.44
La/Th	1.95	4.02	2.40	2.61	2.54
Hf/Ta	9.14	5.90	12.40	4.34	6.95
Th/U	6.96	2.33	3.04	6.76	4.48
La_N/Yb_N	5.71	11.76	6.69	8.51	7.03
Eu/Eu*	0.734	0.587	0.493	0.634	0.676

Major elements in wt%, trace elements in ppm, except as noted; all Fe given as FeO; tektite data from KOEBERL (1992).

rocks, was determined. Unfortunately the rocks analyzed show no chemical similarity to indochinite tektites. Clearly more work needs to be done before a positive or negative conclusion can be drawn regarding the Tonle Sap hypothesis. The following studies may help to test the Tonle Sap hypothesis: (1) Collecting a more complete set of rock samples from the vicinity of Tonle Sap. (2) Determining a chemical and isotopic composition of these samples and of rock strata believed to be the source of Australasian tektites. (3) Acquiring geophysical data over the Tonle Sap basin. (4) Obtaining shallow drill cores which will sample the alluvium-bedrock contact (the tektite-bearing horizon).

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