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Large Aerial Bursts: An Important Class of Terrestrial Accretionary Events

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ABSTRACT

Large aerial bursts similar to the 1908 Tunguska bolide but much larger in magnitude have surely been responsible for many catastrophic events in the history of the Earth. Because aerial bursts produce shallow (or even negligible) craters, their existence is difficult to document in the geological record. Even aerial bursts as small as Tunguska deposit enough energy to melt ~1 mm of dry soil. Silica-rich glass formed in such melts has the potential to survive in the soil for many Ma, thus a potential indicator of large aerial bursts is glass that was formed as thick regions within silicate melt sheets. The layered tektites from Southeast Asia and the Libyan desert glass may have formed by a combination of sedimentation and downslope flow of silicate melt heated by radiation from large aerial bursts. The alternative, formation of layered tektites as crater ejecta, cannot account for observations such as uniformly high ^{10}Be contents, the orientation of the magnetic remanence field, and the absence of splash-form (e.g., teardrop or dumbbell) tektites in regions where layered tektites are common. The largest asteroids or comets make craters no matter what their strength. Recent reviews suggest that, for events in the energy range up to 10^{19}–10^{20} J (about two orders of magnitude larger than the Meteor Crater impact), aerial bursts are more likely than cratering events, and the layered tektites of Southeast Asia imply the existence of aerial bursts one to two orders of magnitude larger still. Key Words: Aerial burst—Airburst—Tektites, layered—Melt sheet—Tunguska-like events. Astrobiology 3, 163–179.

INTRODUCTION

INTERPLANETARY OBJECTS large enough to make craters are continually accreting to the Earth. Any object having a surface density (mass per unit area) appreciably greater than that of the column of air it must displace during its atmospheric passage can (if it avoids fragmentation) reach the Earth's surface with a sizable fraction of its cosmic velocity. The surface density of the Earth's atmosphere is 1,033 g cm^{-2}. To match this surface density the radius r (in cm) required of a spherical meteoroid having a density ρ (in g cm^{-3}) falling perpendicular to the Earth's surface must be equal to $0.75 \times (1{,}033/\rho)$. For an iron meteoroid with a density of 7.9 g cm^{-3} the calculated radius is 98 cm; for a chondrite with a density of 3.5 g cm^{-3} the radius is 2.2 m. Of course,

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most meteoroids do not fall vertically, and fragmentation during flight can lead to greatly enhanced frictional drag; both of these effects lead to reduced velocities.

The mean preatmospheric velocity of asteroidal meteoroids is 18 km s^{-1} (Shoemaker *et al.*, 1990). A typical p wave velocity in crustal rocks is 5 km s^{-1} (Winkler and Murphy, 1995). If an interplanetary projectile strikes the Earth's surface at >5 km s^{-1} it creates a shock wave that moves faster than the sound speed within the minerals of the target rock, with the result that crystal structures are distorted or destroyed. The shock wave carries an appreciable fraction of the energy to a depth several times greater than the radius of the projectile. The combination of energy deposition and shock wave reflection leads to the formation of a hypervelocity explosion crater (Melosh, 1989). By now ~150 impact craters having diameters ≥1 km have been documented on the surface of the Earth (Grieve, 1997).

However, not all large accretionary events produce craters. The remarkable Tunguska event occurred in central Siberia on the morning of June 30, 1908. A large (~40 m) meteoroid was totally disrupted at an altitude of ~8 km, with the resulting explosion (here designated an aerial burst, but airburst is a synonym) having an energy of roughly 15 MT (TNT equivalent) (Vasilyev, 1998). For comparison, the kinetic energy of the object that made Meteor Crater was only a few times larger, ~50 MT, but its energy is still not well defined (Melosh, 1989, p. 114). When the Tunguska epicenter was first investigated 2 decades after the explosion, it was found that the blast wave leveled trees over an area of ~2,000 km^2. However, no crater that could be connected to this event was found on this trip or during subsequent field investigations.

It is now recognized that many small (10–100-cm diameter) meteoroids break up high (>40 km) in the atmosphere, a clear indication that they were structurally very weak (Ceplecha *et al.*, 1998); the large Šumava fireball expended essentially all its 0.5 MT (TNT equivalent) energy above 65 km (Borovicka and Spurny, 1996). In this paper I examine some of the environmental effects associated with the accretion of weak objects to produce aerial bursts many orders of magnitude larger than that at Tunguska.

Because the craters resulting from large aerial bursts are shallow or nonexistent, the record of these events is not preserved in topographical relief that is recognizable millions of years after the event. The record may, however, be preserved in the glassy objects called layered tektites. We (Wasson, 1995; Wasson *et al.*, 1995) suggested that the layered tektites found in Southeast Asia (SE Asia) may be the record of a melt sheet produced by an aerial burst; despite the large amount of energy deposited only 780 ka ago, no crater can be associated with the Australian tektites. Wasson and Moore (1998) and Wasson and Boslough (2000) ascribed a similar origin to the Libyan desert glass (LDG).

REVIEW OF INFORMATION ABOUT TUNGUSKA AND SOME RELATED EVENTS

The atmospheric passage of the Tunguska fireball occurred at about 0700 local time on June 30, 1908 in a thinly populated (by Tungus nomads whose main occupation was raising reindeer) region near the Podkammenaya (Stony) arm of the Tunguska River. The first field investigations occurred 19 years after the event, a reflection of the troubled political situation in Russia at the time. These investigators still obtained numerous eyewitness reports, particularly from the Vanovara trading post ~70 km away.

These early field investigations revealed that trees were toppled radially outwards from the epicenter over an area of ~2,200 km^2, and that extensive charring of the forest debris occurred in a central area of ~200 km^2. The maximum thermal pulse at ground zero was estimated to be 238 J cm^{-2} (Korobeinikov *et al.*, 1983). This is sufficient to heat 0.16 g (~0.7 mm) of dry continental crust to 1,500K and melt it.

Facts about the Tunguska event are summarized in Table 1. Most estimates have high associated uncertainties, some of which are conveyed by the quoted ranges.

From the modeling viewpoint one of the most important facts about Tunguska is the mean altitude of the detonation; most researchers use 8 km. This altitude is mainly obtained by modeling the pattern of destruction in the underlying forest; it is not inconsistent with eyewitness accounts. Although most past researchers concluded that the high altitude of the explosion implied that the meteoroid was very weak, and therefore probably a comet, Sekanina (1983, 1998) and others (Chyba *et al.*, 1993; Hills and Goda, 1998) argue

TABLE 1. SUMMARY OF FACTS REGARDING THE TUNGUSKA FIREBALL

Date and time of fall	*June 30, 1908 ~0700 local time*
Location	61°N, 102°E
Angle of path (vertical = 90°)	7–40°
Altitude of explosion	5–10 km
Explosive energy	(4–17) × 10^{16} J = (10–40) MT TNT
Meteoroid mass (if v = 36 km s^{-1})	(6–25) × 10^{10} g = (60–250) kT
Area in which forest flattened	2,150 km^2
Forest area ignited by radiation	200 km^2
Maximum thermal fluence	238 J cm^{-2}

Based on information summarized by Vasilyev (1998).

that weak cometary materials could not have penetrated so deeply into the Earth's atmosphere along the inferred trajectory, and that the strength was more like that of a compact anhydrous chondrite. Perhaps the compromise interpretation of Lyne *et al*. (1998) is the most reasonable: the object could have been a chondrite coming in at a low (10–20°) entry angle or a comet coming in at a high (>50°) entry angle. However, it appears to me that the available models are not yet detailed enough to properly constrain the interaction of a large, weak (sandpile) projectile with the atmosphere, particularly if entry velocities are high (>40 km s^{-1}), and the entry angle moderately high.

Although a large, compact, and reasonably tough chondrite should have left a trail of small, but recoverable, meteorites along the ground track prior to the final explosion, in this thinly inhabited area such materials could easily have been missed by the local population. Bronshten (2000) insisted that the failure of scientific searches to recover such materials at the epicenter of the aerial burst proves that the Tunguska object was not a chondrite. However, Svetsov (1996) calculated that the final crushing of the projectile would have led to small (typically 1–3 cm) fragment sizes, and that most fragments smaller than ~10 cm would have vaporized. Vaporized materials in the stratosphere would have recondensed as fine particles that fell out far from the epicenter.

There is still another possible factor. Sekanina (1998) speculates that the Tunguska object was a "type-II" fireball in the nomenclature of Ceplecha *et al*. (1998). These are thought to correspond to CM chondrites, compact but weak chondrites rich in hydrated minerals. If the Tunguska object consisted of a CM chondrite, the recovery probability is reduced because hydration and freeze–thaw processes would have caused even large pieces to disintegrate during the 19+ years before serious ground searches were instituted.

The mass of Tunguska object listed in Table 1 (based on an impact velocity of 36 km s^{-1}) is ~10^{11} g. Ceplecha *et al*. (1998) reviewed the data on meteoroid influx to the Earth. In their Fig. 25 the fall rate of a mass this large is estimated to be 10^{-2} $year^{-1}$ (i.e., one event each 100 years). In contrast, some modelers infer lower velocities [e.g., Sekanina (1983), <10 km s^{-1}] at the time of the explosion. A final atmospheric velocity of 3.6 km s^{-1} would imply a terminal mass 100 times larger than listed in Table 1, and a terrestrial event frequency of 10^{-4} $year^{-1}$. Brown *et al*. (2002) interpret data from spy satellites and ground-based acoustical arrays to indicate an annual frequency of 10^{-3} for events depositing 10 MT of energy. I suggest that the uncertainties remain large, but that the value is within 10^{-2}–10^{-3} range.

In summary, there are still large uncertainties about the nature of the Tunguska object, its entry angle, its velocity, and its composition. The important general conclusions are that it occurred within the past 100 years, and that there is general agreement that aerial bursts of this magnitude occur on roughly that time scale. An important specific conclusion is that aerial bursts can be produced both by compact chondrites as well as by comets.

EVIDENCE OF WEAK INTERPLANETARY MATERIALS

Tunguska is one of a continuum that extends down to events <10^3 times smaller. The documented members of the set are the type-III fireballs recorded by the meteor-camera networks (Ceplecha *et al*., 1998) and several events recorded by military satellites (Tagliaferri *et al.*, 1994; Brown *et al.*, 2002).

A particularly important event is the documented fall of the Šumava fireball in 1974 (Borovicka and Spurny, 1996). Because the luminous path was photographed by several stations in the Czech meteor-camera network, the velocity, trajectory, and luminosity were well determined. The results are summarized in Table 2. This remarkable object was so weak that it had disintegrated by the time it had fallen to an altitude of 65 km, far higher than the 35–40-km altitude at which the weakest meteoroids, the hydrated (CM or CI) carbonaceous chondrites, break up.

Another exceptionally weak interplanetary object, Comet Shoemaker-Levy 9 (SL9) was, as a result of a close encounter with Jupiter, captured into Jovian orbit. It was so weak that the close encounter broke it into many pieces. Each fragment developed a coma, indicating the evaporation of H_2O and other ices. Asphaug and Benz (1994, 1996) examined the physics of the breakup, and concluded not only that SL9 had no strength (i.e., was like a sandpile) but also that it had a very low density, only $\sim$0.5 g cm^{-3}. Crawford (1997) modeled the impact of the SL9 fragments on Jupiter, and inferred a still lower density of 0.25 g cm^{-3}.

Many comets are so weak that they break up in interplanetary space far from the Sun or a planet. Weissman (1997) calculates that 27% of long-period comets are lost to "random disruption." The reason these comets fall apart is not clear; Weissman (1997) suggested that is associated with the heating of the nucleus during perihelion passage. That the probability of disruption is greatest on the first perihelion passage is attributed to a selection effect that removes those objects that are weakest first. Levison *et al.* (2002) concluded that 99% of Oort-Cloud comets physically disrupt within the inner Solar System (i.e., when their volatiles have been lost there is no residual asteroid-like object). This implies an extremely low density.

Long-period comets (those with periods $\geq$1,000 year) can impact the Earth with velocities ranging from the escape velocity (11 km s^{-1}) to a maximum of 72 km s^{-1} (if the object has an orbital inclination of 180°). Weissman (1997) noted that the mean infall velocity of long-period comets is 51.8 km s^{-1} and that the energy-weighted mean velocity is 57.7 km s^{-1}.

Both Shoemaker *et al.* (1990) and Weissman (1997) reckon that even comets with nuclear diameters and energies sufficient to excavate a 10-km-diameter crater probably release almost their entire energy in the atmosphere. Shoemaker *et al.* (1990) noted that the size distribution of Earth-crossing comets and asteroids differ, and that at masses greater than $\sim 10^{15}$ g the impact rate from comets exceeds that from asteroids. Combining these two observations leads to the interesting conclusion that, for energies up to 10^{19}–10^{20} J (roughly two orders of magnitude larger than the Meteor Crater impact or the Tunguska event), aerial bursts are expected to be more common than crater-producing events.

AERIAL BURSTS ORDERS OF MAGNITUDE LARGER THAN TUNGUSKA

It is thus clear that aerial bursts that are orders of magnitude larger than Tunguska have occurred in the past. In the previous section I noted the evidence for weak fireballs in the Earth's atmosphere and for the breakup of comets making close passes near planets, near the Sun or even in deep space far from a planet or the Sun. Two circumstances are required to generate aerial bursts appreciably larger in magnitude than Tunguska: (1) The meteoroid must be weak enough to dis-

TABLE 2. SUMMARY OF FACTS REGARDING THE ŠUMAVA, CZECH REPUBLIC, FIREBALL

Date and time of fall	*December 4, 1974*
Angle of path (vertical = 90°)	27.5°
Altitude of major explosions	65–78 km
Explosive energy	$\sim 2 \times 10^{12}$ J = 0.5 kT TNT
Meteoroid mass	5 T
Estimated density	0.1 g cm^{-3}

From Borovicka and Spurny (1996).

rupt (and the fragments slow to terminal velocity) during atmospheric passage, and (2) depending of the meteoroid's strength, the atmospheric entry angle must be relatively oblique. The latter is important not only because it enhances the probability of depositing most of the energy in the atmosphere, but also because it increases the area over which thermal effects will be recorded on the surface of the Earth, and thus the probability that the record may be discovered.

Even a very weak (but moderately large) body can reach the surface if the entry angle is high, close to 90°. Tunguska's entry angle is not well defined; entry angles as low as 7° and as high as 45° are mentioned in literature cited by Vasilyev (1998) and Bronshten (2000). The most probable entry angle for a random meteoroid is 45°. Modeling by Hills and Goda (1998) indicated that a friable meteorite (strength of 1×10^8 dynes cm^{-2}) coming in at an entry angle of 90° and a geocentric velocity of 18 km s^{-1} will deposit more than half its energy in the atmosphere if its radius is <100 m. Larger objects must come in more obliquely if they are to be stopped in the atmosphere. These authors estimated that a 500-m projectile with this strength will lose half its energy at ≥10 km if its entry angle is 20°.

THE TERRESTRIAL ENVIRONMENT BELOW A SUPER-TUNGUSKA SKY

For Tunguska the blast effects were more dramatic than the thermal effects, but thermal effects become relatively more important as the size of the event increases. As the magnitude of the burst increases, the central region finds itself surrounded by an atmosphere that is also hot, and loses its ability to cool itself by radiation in directions other than vertical (into space). Expansion only leads to minor cooling because little work is done by the expanding gas. In an atmosphere that is hot to high elevations (i.e., several scale heights, perhaps 25 km) there is no appreciable overlying piston for the hot gas to push against.

The effect of such a hot sky would be dramatic. Surficial temperatures would reach the boiling point of H_2O within seconds. Living matter would be fully incinerated. With rising temperatures the first step is the evaporation of H_2O including that bound in hydrated minerals and organic matter. If, when this evaporation is complete, surficial temperatures are still >2,000K, anhydrous soil will melt. When molten soil cools it can form a glass that weathers relatively slowly and thus can survive as a record of the event.

Thus, for an event of a given magnitude, the thickness of soil that melts largely depends on the H_2O content of the initial surficial materials. In moist, vegetated areas or regions covered by water, much of the heat energy is expended on the latent heat of vaporization of H_2O and carbonaceous compounds and the heating of the resulting gaseous products, and little melting of the local soil is expected. In contrast, if the surface below the burst is desert-like, the radiation from a relatively small burst (only slightly larger than Tunguska) may be capable of melting several millimeters of sand or soil. Soil introduced into the atmosphere will be heated with still higher efficiency.

When large (>100-km-diameter) craters such as Chicxulub [the Cretaceous-Tertiary (KT) crater] formed, the ejecta were thrown above the atmosphere and scattered all around the globe; reentry of the ejecta into the atmosphere caused large amounts of heating, creating conditions much like those resulting from an aerial burst (Wolbach *et al.*, 1985; Anders *et al.*, 1986). The chief environmental difference between KT and Tunguska-like events is one of scale. The latter incinerate only local areas, whereas KT-type burning events were also produced by ubiquitous ejecta from the primary crater and were global.

LAYERED TEKTITES AS THE RECORD OF LARGE AERIAL BURSTS

Materials that I interpret to be the remnants of melt sheets produced by giant aerial bursts are the layered tektites found over a region having an area of $\sim 7 \times 10^5$ km^2 in SE Asia (from Cambodia to Hainan Island, China) and the LDG found over a region having an area of $\sim 7 \times 10^3$ km^2 in Western Egypt. The layered tektites from SE Asia are also known as Muong-Nong-type tektites, named after the Laotian town where they were first recognized. They were formed ~780 ka ago. This is a mean based of 770 ka obtained using the ^{39}Ar-^{40}Ar technique (a few low values were discarded) by Izett and Obradovich (1992) and a stratigraphic age based on the placement of microtektites ~10 ka below (Schneider *et al.*, 1992) the Brunhes-Matuyama magnetic-reversal boundary dated at 778 ka by Tauxe *et al.* (2000).

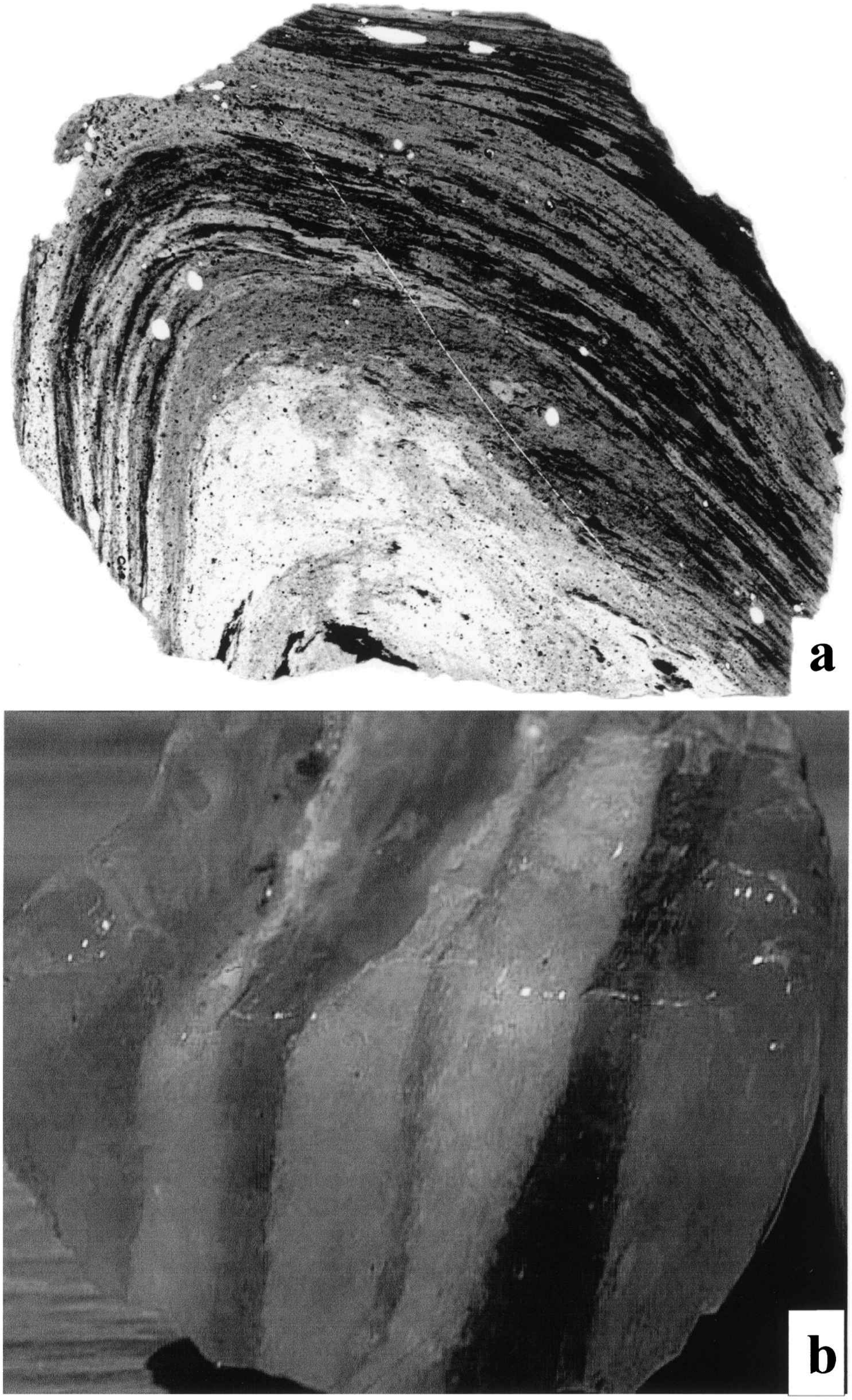

FIG. 1. Examples of SE Asian layered tektite and layered LDG. a: Section through a SE Asian layered tektite is photographed in transmitted light. The layers are marked by differences in opacity. The density of bubbles is higher in the darker regions. The layers curve around an angle of ~130°. Maximum length of the section is 11 cm. **b**: In this broken surface of a large mass of LDG layers have different colors because of variations in bubble content. The darkest layers are essentially bubble-free, the white layers contain a high density of tiny (0.03 mm) bubbles, and the layers of intermediate reflectivity have intermediate bubble contents. Maximum width of the specimen is ~6 cm.

Figures 1 and 2 show the structures of these materials. The layers differ in opacity, color, and bubble-content (or porosity); the millimeter-thick parallel layers sometimes curve (as in Fig. 1a) through large angles (often >90°). These regular structures clearly formed by sedimentation and low-speed laminar flow rather than the high-speed turbulent flow expected in impact products ejected at speeds >1 km s^{-1}. A large, ~130° fold is shown in transmitted light in Fig. 1a. Although not easily visible in this image, bubbles are more abundant in dark than in light layers.

The structures of layered tektites and LDG show that they formed by both sedimentary processes and by flow. The LDG sample (Fig. 1b) shows well-defined layers differing in porosities by large factors. It seems clear that these centimeter-thick layers mainly formed by sedimentary processes, perhaps as deposits of local dust introduced into the atmosphere by turbulence. It seems likely that the bubbles reflect the liberation of gases as a result of the breakdown of soil minerals (such as hydrous clay minerals or carbonates) and that the final porosity is correlated with viscosity and thus inversely with the maximum temperature reached by the materials in each layer. Although evidence of flow such as stretched bubbles is sometimes found in LDG, it is generally more ambiguous than in the SE Asian layered tektites.

Two sides of a large layered tektite from SE Asia are shown in Fig. 2. One side (Fig. 2a) shows sets of intersecting cracks (a "bread-crust" texture) that are interpreted to be due to contraction during radiative cooling of this exterior ("upper") surface. The adjacent side (Fig. 2b) shows a large fold; the millimeter-thick layers have been revealed by etching by soil chemicals.

The layered tektites of SE Asia are part of the Australasian tektite field that extends on land from southern China to Tasmania, Australia, a distance of 8,300 km. Microtektites that are part of this field are found from Okinawa to Madagascar, a distance of ~10,500 km. According to Wasson *et al*. (1995) and Wasson (1995), the properties of layered tektites are best explained by an extensive melt sheet formed by melting surficial continental soils. The large samples are attributed to downslope flow of a thin but variably thick melt sheet to produce ponding in topographic lows. Discussed in the following section are several of these key properties that are inconsistent with the traditional view (e.g., Koeberl, 1986) that layered tektites are crater ejecta.

In recent papers Fiske (1996) and Fiske *et al*. (1999) have argued that field recovery of layered tektites from one site in Thailand (Fiske *et al*., 1996) and one in Vietnam (for which no actual observations are reported) is inconsistent with formation by the ponding. I was part of the field team at the Thai site. In my opinion, fragmentation and weathering during the past 780 ka have destroyed much of the original material, and extensive removal of large fragments by several generations of farmers prior to the field work of Fiske and co-authors makes it impossible to use the nature of the excavated materials to reach meaningful conclusions about the initial size or shape of the glassy mass.

Table 3 summarizes information about the five known tektite fields. At 0.78 Ma, the Australasian field is the youngest, and the North American tektites, at 35 Ma, are the oldest. The amount of material recovered from the Australasian field is orders of magnitude larger than that from all the other fields combined. These materials are well preserved because they are so young. It is possible that the North American and the 15-Ma-old Central European tektites were produced in comparable quantities but have been lost by weathering or buried by tectonic or fluvial processes.

Compositions of tektites are about the same as the local continental crust. The Australasian tektites have compositions similar to those of soils or rocks formed from soils (e.g., Wasson, 1991). The LDG contains ~98% SiO_2, similar to the concentration to the adjacent sands of the Great Sand Sea. The layered tektites and LDG are very different in age. The SE Asian layered tektites were formed ~0.78 Ma ago, the LDG ~29 Ma ago.

There is much evidence of flow in the layered tektites and moderate evidence in the LDG. I suggest that the commonly observed folds (e.g., Figs. 1a and 2b) in layered tektites were produced when the interface between layers happened to achieve lower viscosity (e.g., be hotter or less silicic) than the layers on either side. This situation led to a planar break and a brief runaway by the upper layer. Such recumbent folds are not uncommon in lava or obsidian flows.

My interpretation is that the layering common to these materials resulted partly from local variations in fallout fluence, partly from downslope flow of a melt sheet. Downslope flow seems to have been more common among the layered tektites of SE Asia. In order to calculate the required viscosity I assumed that 50 cm of flow occurred

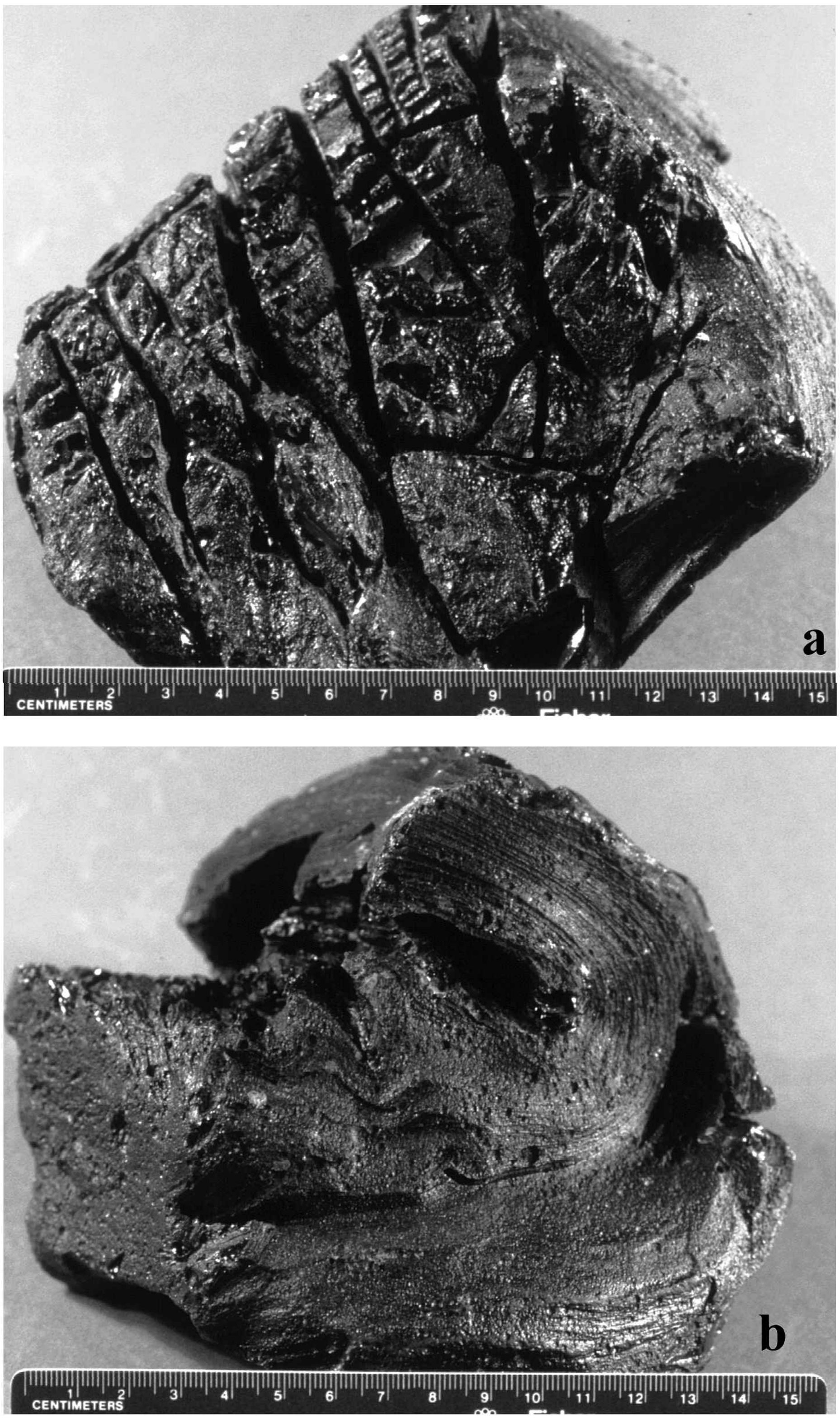

FIG. 2. Two surfaces of a large layered tektite from SE Asia. a: The upper image shows a bread-crust texture produced by rapid contraction during cooling; it was thus the exterior (or "upper") surface. **b**: The lower image shows fine layers that describe a 180° bend; this surface is oriented 90° relative to the upper left edge of the side shown in the upper image.

TABLE 3. THE FIVE TEKTITE FIELDS

Field	*Location*	*Age (Ma)*	*Crater?*
Australasian	SE Asia, Australia	0.78	None found
Ivory Coast	Ivory Coast	1.1	Bosumtwi
Moldavite	Czech Republic	15	Ries
Libyan Desert	Egypt	29	None known
North American	Texas, Georgia	35	Chesapeake Bay?

Layered tektites are found in the Australasian and Libyan Desert fields.

down an inclined plane with a slope of 0.05 during 200 s. Rearranging equation (6–18) of Turcotte and Schubert (1982, p. 235) gives the viscosity η as a function of the flow velocity v, the density of the liquid ρ, and the liquid thickness perpendicular to the plane y (where the total thickness is h):

$$\eta = [\rho \times g \times \sin a\ (h^2 - y^2)]/2v$$

In cgs units the values I used are $\rho = 2.5$, $g = 981$, $\sin a = 0.05$, $h = 0.5$ [just greater than the estimate by Schmidt *et al.* (1993) of the mean thickness of 0.4], $y = h/2$, and $v = 0.25$. These yield a viscosity η of 48 poise, suitable for the generation of the flow observed in layered tektites.

The viscosity of tektitic materials depends on the temperature and the mean SiO_2 content; a typical mean content is 730 mg/g, the mean Indochinite composition listed by Schnetzler and Pinson (1963). In Fig. 3 I plot the results for tektite compositions ($713 \leq SiO_2 \leq 730$ mg/g) of Hoyte *et al.* (1965), Klein *et al.* (1980), and Persikov (1987) on a log viscosity versus $1/T$ diagram. High-temperature trends are roughly linear on such a diagram. All are based on extrapolations of experimental studies to higher temperatures, partly augmented by fitting model equations provided in these papers. Only Klein *et al.* (1980) reported data within the range in Fig. 3. These show similar trends; the differences probably mainly reflect errors associated with extrapolating the trends. A dashed line across the bottom of the diagram shows the 50-poise viscosity calculated above. Vertical lines show temperatures at 100° intervals.

The higher the SiO_2 content, the higher the viscosity at any particular temperature. For the viscosity of LDG I show two sets of data of Bockris *et al.* (1955). One is for a mixture of 961 mg/g SiO_2 and 39 mg/g K_2O and was measured at temperatures of 1,873–2,023K (data points shown by symbols). The other is for pure SiO_2 measured at several temperatures, the highest at 2,473K (data points scatter, are not plotted). The viscosity of LDG should be intermediate between these curves. The trends plotted in Fig. 3 document that the temperatures required to achieve viscosities as low as 50 poise are ~2,300K for SE Asian tektites and >2,500K for LDG.

We (Wasson, 1995; Wasson *et al.*, 1995) noted that the necessity to maintain such high temperatures for several minutes implies that the melt did not immediately cool by radiation into a cooler environment. This indicates that the surrounding environment out to an optical depth ≥1 was at the same temperature or higher.

Wasson *et al.* (1995) estimated the mean thickness of the melt sheet in SE Asia to be ~4 mm. If we assume that the sky temperature was ~2,500K (>2,300K to enhance conductive heat transport), we can estimate the time necessary to create a melt thickness of 4 mm by radiative heating. The thermal diffusivity of fused silica is $\sim 1 \times 10^{-2}$ cm^2 s^{-1}, which yields a diffusion length of 1 cm in 100 s. If heat was also transported by melt flowing through a permeable, porous soil, the depth of heat transport would be greater (or one could transport heat to a depth of 1 cm in a shorter period).

In the past the layered tektites were ascribed to ejection from craters. However, studies of known craters have yielded no evidence that large (e.g., >10 L) amounts ("bombs") of fully molten materials (free of unmelted clasts) are ever ejected from terrestrial craters. For example, the "flaedle" (0.1–1-L volume, pancake-shaped glassy materials) that are present in the suevite at the Ries Crater and seem to have solidified in flight always contain several percent clasts (Hörz, 1965). Any ejecta that was still molten when it landed on a cool surface would have quenched and mixed with unmelted rocks. There seems to be no scenario that would either (1) generate

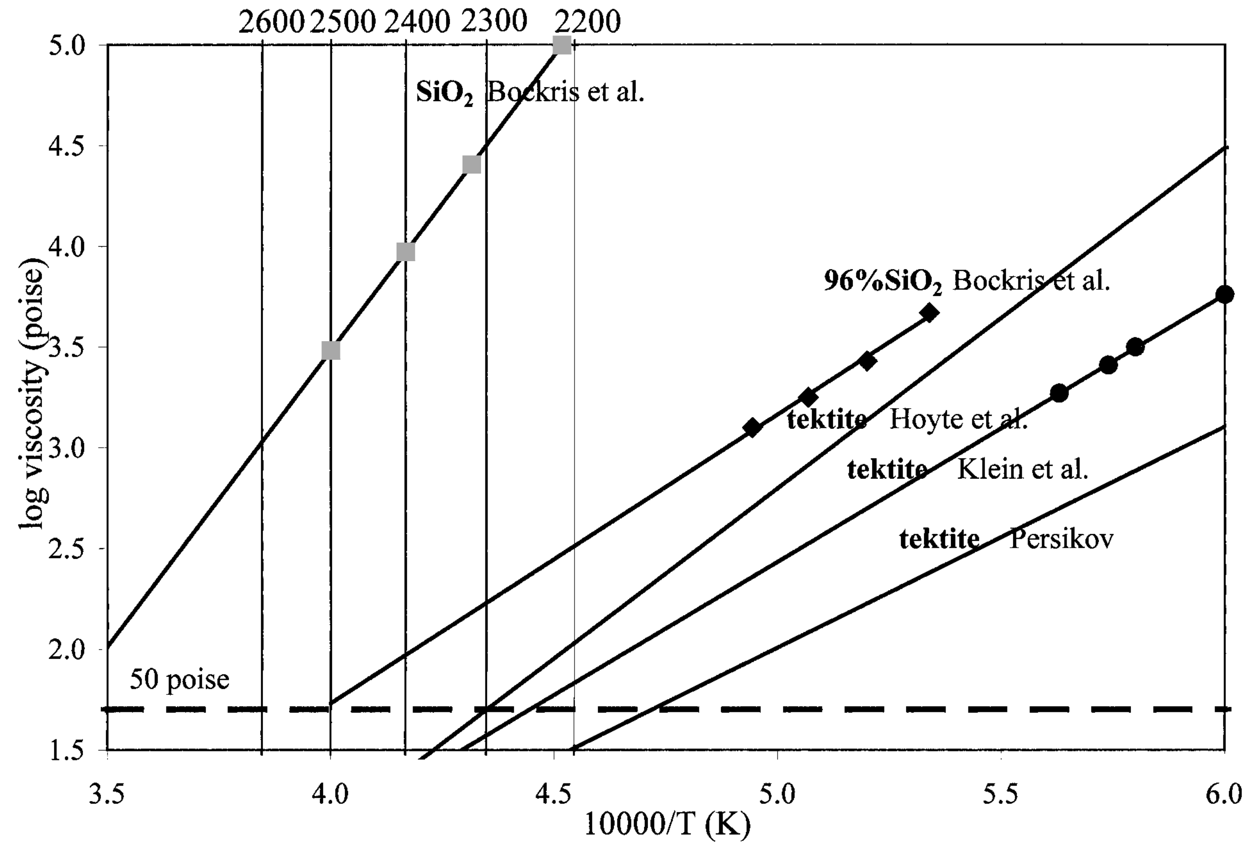

FIG. 3. Temperature dependence of the viscosity of tektitic and silica-rich glasses. Viscosities of SE Asian tektites are from Hoyte *et al.* (1965), Klein *et al.* (1980), and Persikov (1987). Viscosities for SiO_2-rich glasses are from Bockris *et al.* (1955). Laboratory data are shown by symbols. All data must be extrapolated down to the viscosity range (50 poise) needed to produce flow. See text for details.

finely stratified linear or smoothly curving melts or (2) allow the chilling to a glass of large masses (>10 kg) while in flight. In addition, melt production is most efficient at the bottoms of relatively large craters (e.g., Melosh, 1989), whereas, as summarized below, layered tektites have high ^{10}Be contents (Aggrey *et al.*, 1998; Ma *et al.*, 2001) requiring that much or most of the target have been a surficial soil originating <1 m from the surface.

The idea that LDG was formed as a melt sheet was first mentioned by Seebaugh and Strauss (1984). However, these authors envisioned the melt to have formed at the bottom of a giant crater rather than by radiant heating from an incandescent sky. It is surely not possible to produce and preserve well-ordered structures consisting of subplanar layers mainly differing in their contents of tiny bubbles (Fig. 1b) at the bottom of a large crater.

PROPERTIES OF LAYERED TEKTITES INCONSISTENT WITH FORMATION AS EJECTA FROM LARGE CRATERS

Wasson and Heins (1993) and Wasson *et al.* (1995) summarized several facts that are inconsistent with the formation of tektites as ejecta from large (>10-km-diameter) crater.

One of the first problems recognized as inconsistent with ejecting layered tektites from craters (without production of a melt sheet) is that there are large regions of SE Asia that contain only layered tektites (Wasson, 1991; Schnetzler, 1992; Wasson *et al.*, 1995; Fiske *et al.*, 1999). The "splash" ("spin-form" is a better descriptive) tektites that obtained their characteristic shapes (dumbbells, teardrops) by spinning during flight are not found in these regions.

Wasson *et al.* (1995) carried out the most detailed investigation; they sampled ~20 spots in a region having dimensions of ~40 × 130 km in the southeast corner of Northeast Thailand and found only layered tektites. Schnetzler and McHone (1996) and Fiske *et al*. (1999) investigated sites in a band crossing southern Laos and central Vietnam, and made similar observations. The only plausible explanation that has been proposed is that the splash forms that returned to the Earth's surface in this region fell into the still molten melt and were subsumed by it. These two field studies are consistent with Wasson's (1991) estimate that the region that produced layered tektites was ~1,100 km long in a NNE-SSW direction, and ~800 km across in the perpendicular direction. If we assume that the shape was elliptical, these dimensions yield an area of 6.9×10^5 km^2; if the distribution was patchy the area covered would have been smaller, perhaps by a factor of 2. Fiske *et al*. (1999) estimated that the area in which all tektites are layered has an area $\sim 5 \times 10^4$ km^2, and that the remaining areas in which layered tektites are recovered also contain splash tektites.

Figure 4 shows the magnetic remanence relative to the plane of the layering measured in nine SE Asian layered tektites by de Gasparis *et al*. (1975). The mean dip of the field relative to the layering is 20 ± 10°. This is the same as the inclination of the geomagnetic field (20 ± 5°) observed at ~16°N latitude in SE Asia today (Bloxham, 1995). It is likely that the field 0.77 Ma ago was similar. It is not clear whether the magnetic carrier was precipitated from the glass during cooling or is a phase produced during later processes in the soil, but this doesn't matter as long as the latter occurred while the original orientation was present. These results require that the layers were formed by flow or deposition, either of which generates layers parallel to the local slope of the Earth's surface. In contrast, if the layering was produced during ejection or flight in roughly spherical ejecta [despite the implausible requirements for solidification of bodies as large as 1,000 kg (Fiske *et al*., 1999) in flight] after landing and rolling on the Earth the layers should have been randomly oriented with respect to the Earth's geomagnetic field. I suggest that the remanence should again be measured, but with the samples oriented relative to surfaces that show bread-crust layering. This should lead to tighter constraints on the dip of the field.

Perhaps the most important diagnostic regarding the formation of layered tektites is their relatively high content of ^{10}Be, a radioactive isotope with a half-life of 1.5 Ma that is produced in the atmosphere by cosmic rays. It collects on aerosols, is scavenged by rain, and (on the continents) collects in soils. Materials below the soil layer are essentially free of ^{10}Be.

Aggrey *et al*. (1998) summarized the ^{10}Be results of studies of three classes: layered tektites, splash-forms found in Australia, and splash-

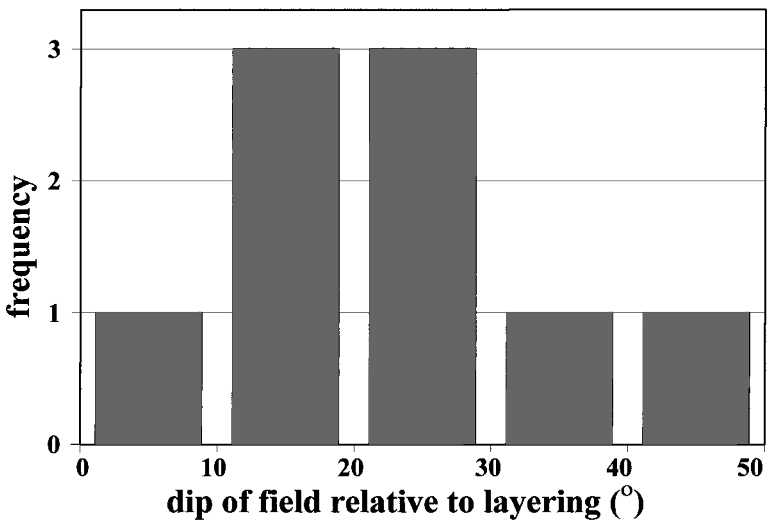

FIG. 4. Histogram showing the dip of magnetic remanence relative to the layering of layered tektites from SE Asia (data from de Gasparis et al., 1975). The dip is similar to the magnetic inclination measured in SE Asia today, 20 ± 5° (Bloxham, 1995).

forms found in SE Asia (most within a few hundred kilometers of the layered tektites). They reported mean ^{10}Be concentrations of 50, 150, and 100 atoms/g, respectively. In a more recent study by the same team, Ma *et al*. (2001) reported a mean of 73 atoms/g in the SE Asian layered tektites, with numerous values overlapping the values of SE Asian splash-form tektites. The ^{10}Be results make it clear that there is a large soil component in all these tektites and, most importantly, that it is not possible to produce any of them by melting precursors originating entirely below the soil layer. To make these tektite ^{10}Be values comparable to present-day soils they must be multiplied by 1.43 to correct for decay during the 0.78 Ma since their formation.

For comparison, the ^{10}Be concentrations present in fresh loess deposited at 34°N at Weinan in central China are ~200 atoms/g, whereas those in mature soils (paleosols) at this location are ~500 atoms/g (Gu *et al*., 1996, 1997). D. Lal (personal communication, 2002) calculates that the ^{10}Be fallout rate is ~2.2 times higher at 34°N than at 16°N, the mean latitude of the layered tektites; this mainly results from the more efficient stratosphere–troposphere exchange at temperate latitudes. If we increase the layered-tektite concentrations by 1.43 to allow for decay and 2.2 to allow for latitude effects, we obtain ^{10}Be concentration of 160 atoms/g (Aggrey *et al*., 1998) and 230 atoms/g (Ma *et al*., 2001), similar to the concentrations expected if the surface was covered by fresh loess when layered tektite formation occurred. Thus, these results are consistent with the inference of Wasson and Heins (1993) that the surface of SE Asia was covered by loess at the time of the Australasian event. The higher ^{10}Be in splash-forms may indicate a higher soil component in these melts.

When melts are produced during the formation of large (≥10-km-diameter) craters most of the melted materials are from well below the soil layer. This is made quite clear from Fig. 7.7 on p. 123 of Melosh (1989); most of the melt is produced deep (depths >>10 m) in the target, and the melt/crater volume ratio increases with increasing crater diameter. The melt sheets that have been mapped at large terrestrial craters are (1) from these melts formed deep with the craters, and (2) in contrast to layered tektites, contain ≥5% of unmelted clastic materials (Grieve *et al*., 1987). R. Grieve (personal communication, 1996) provided us with samples from the Boltysh Crater melt sheet, which is the most clast-free melt sheet he has encountered. We found 10–15% clastic materials in several thin sections we prepared from these samples.

The ^{10}Be data and the absence of clast-free materials among sets of materials clearly linked with known craters underline the need for another model to explain the layered tektites.

TEKTITE FEATURES THAT REQUIRE SPECIAL EXPLANATIONS

The shapes (dumbbells, tear drops) of the so-called splash-form tektites demonstrate that these solidified while spinning in flight. This requires that these objects, which reach masses >1,000 g in the Philippines, have been launched to relatively high altitudes. Some of the Australasian splash-form tektites found in Australia have flanges of remelted materials (creating "buttons" from disks or spheres) indicating that they were initially above the atmosphere, chilled to a glass in flight, and remelted during reentry. An incandescent sky alone cannot account for the trajectories of splash-form tektites that experienced a second melting event.

It appears to be impossible to launch such small objects into long (in some cases, suborbital) trajectories by giving them a single ΔV kick near the Earth's surface. They would inevitably encounter too much atmosphere to achieve high or suborbital altitudes. The only plausible launch mechanism seems to be entrainment in one or more impact-produced plumes, similar in structure to the plumes produced by the tests of nuclear weapons. Because a single crater formed only 0.78 Ma ago having a diameter >5 km should be easily recognizable on the SE Asian continent today, I suggest that this plume formed above a region where much energy was deposited over a moderately large (≥100 km^2) region at or near ground level. Some of the energy was deposited in the troposphere, some during the formation of a series of shallow ("pancake"), overlapping craters. The outlines of these shallow craters could have been degraded by weathering or (if produced on dry Continental Shelf exposed during a glaciation) may now be hidden by sediments.

Perhaps the most difficult feature to accommodate into the melt sheet model are the relict grains of coesite, a polymorph of SiO_2 that can only be produced at high pressures (>40 GPa).

Because such pressures are not created during volcanic or tectonic processes in the Earth's crust, the presence of coesite is a strong indication of production during a cratering impact. Glass *et al.* (1986) and Dass and Glass (1999) documented the presence of such grains in some layered tektites, but they are uncommon. B. Glass (personal communication, 2002) estimates that they are found in ~10–20% of the layered tektites he has studied, and are most common in bubble-rich samples. It would seem that this requires that, in addition to aerial-burst heating effects, there were hypervelocity impacts that occurred close enough to throw ejecta into those parts of the melt sheet that provided coesite-bearing samples. The geographical distribution of coesite-bearing tektites has not yet been investigated.

One possible criticism of the melt sheet model is that it predicts that the melt would envelop small stones that were on the surface of the ground. Wasson *et al.* (1995) noted, however, that the bottommost layer of layered tektites will have been the first material removed by etching and erosion in soils, and that it is unrealistic to expect the contact with gravel to have survived. In addition, field research in Northeast Thailand shows that, even at the present, there are large areas with nearly no rocks on the surface; instead, the ground is covered by a loess-like soil (Boonsener, 1991). This loess was presumably mainly deposited during glaciations, and would have been much thicker at the time of the Australasian event (Wasson and Heins, 1993). Thus few contacts between gravel and tektite glass were produced, and nearly all of those produced will have been destroyed by weathering processes.

SOME ASTEROIDS MAY BE AS WEAK AS COMETS

The very low density (1.3 g cm^{-3}) of the asteroid Mathilde (Veverka *et al.*, 1999) suggests that it is a flying rubble pile. It is plausible that sizable fractions of asteroids and comets are primordial materials that were never compacted, and have essentially no strength. Because all chondrites that are tough enough to survive atmospheric passage were probably compacted by impacts, the typical chondritic asteroid may be a mix of materials that varies widely in porosity (from 10–15%, as in the chondrites that survive atmospheric passage, to ≥60%, similar to fresh loess). Thus, many of the asteroids striking the Earth may be strengthless objects. In support of this view is the high fraction of low-strength fireballs observed by the photographic networks. According to Ceplecha *et al.* (1998), only 32% of photographed meteoroids are as strong as anhydrous chondrites. Another 33% are friable, having strengths similar to CM chondrites, and the remaining 35% are designated "cometary" because they break up very high in the atmosphere. It seems likely that the weakest meteoroids include uncompacted primordial material from the inner Solar System in addition to cometary (outer-Solar-System) materials.

ENERGETICS OF FORMATION OF A LARGE (>10^5 KM^2) MELT SHEET

A key question is whether the accretional energy associated with the Australasian tektites was sufficient to heat the atmosphere above the region where the layered tektites are found. In an earlier section I estimated the maximum extent of the area covered by layered tektites to be 6.9×10^5 km^2, and noted that a patchy distribution would reduce this area by something like a factor of 2. Because splash-form tektites are associated with layered tektites in much (perhaps 90%) of the region (Fiske *et al.*, 1999) I use the smaller value in my calculation.

My working model is that the atmosphere was heated from top to bottom. In this situation expansion does not generate work; thus the appropriate heat capacity is constant volume, C_V. A rough estimate of C_V for air is 24 J K^{-1} mol^{-1}. At sea level each square centimeter of atmosphere has a mean mass of 1,033 g. The mean molecular weight of air is 29.0 g mol^{-1}; thus each square centimeter of air contains ~35.6 mol of air. To heat this from 300K to 2,500K requires 1.88×10^6 J cm^{-2}. And to supply this amount of heat to a region having an area of 3.5×10^5 km^2 requires 6.5×10^{21} J.

To estimate the accretional energy associated with the impactor that created the Australasian tektites we use the mass of the impactor inferred by Schmidt *et al.* (1993). These authors and Koeberl (1993) observed small Ir enhancements in deep-sea sediment layers containing high concentrations of Australasian microtektites. Schmidt *et al.* (1993) used an exponential fallout model to estimate the mass of a chondritic impactor to have been ~1.5 ×

10^{15} g, and inferred that the mass of a cometary 50:50 mix of ice and chondritic matter would have been about two times larger. From these masses and assumptions about the impact velocity one can estimate the kinetic energy release; these are given in Table 4. The largest listed value (5.4×10^{21} J) results from a combination of the cometary mass with a velocity of 60 km s^{-1}, slightly higher than the energy-weighted mean value (58 km s^{-1}) quoted by Weissman (1997). Thus our rough estimate of the amount of energy deposited in SE Asia is ~80% of that required to heat the atmosphere above layered-tektite locations. This agreement is adequate since both the mass of the Australasian projectile and the area covered by the hypothetical melt sheet have uncertainties of at least a factor of 2.

A potential problem is how to account for the very large areas in which the SE Asian layered tektites are found. This seems to require oblique entry into the atmosphere and possibly also (similar to many comets) multiple projectiles as a result of breakup in deep space days or weeks prior to atmospheric entry. However, it seems possible that the combination of radiation from hot fireballs (initially >10,000K) and atmospheric shock waves could transmit energy large distances (>100 km) from the site where most of the energy is deposited, and that such effects increased the lateral extent of the heated portion of the atmosphere.

SOME TESTS OF THE MODEL

A clear prediction of the model is that the layered tektites (including LDG) should be rather uniform in composition. During the production of large craters melting will occur in many different stratigraphic layers, each of which is expected to have its own chemical and isotopic signature. In contrast, if the layered tektites are produced by melting loess or desert sand, fine compositions should be relatively uniform from sample to sample, although minor differences reflecting contributions from local rock outcrops should still be present.

Although the loess-like soil in SE Asia today was deposited during more recent glaciations than the one (glacial maximum 20) that was in progress when the tektite event occurred 0.78 Ma ago, it seems likely that the loess sources were nearly the same during the two periods. Thus a good test of the model would be to collect the loess-like sediments and compare them with the compositions of tektites. To the degree that local outcrops make contributions, the same signatures should show up in modern loess and in the tektites recovered from the same localities.

Similarly, the LDG should reflect the composition of the sandy soil that was on the surface at the time of its formation 29 Ma ago. The local land surface may have evolved significantly in that period; R. Giegengack (personal communication, 1999) thinks that as much as 1 km of erosion may have occurred in this period. Schaaf and Müller-Sohnius (2001) analyzed Sr and Nd isotopes in LDG, and found that these are unrelated to the local sandstones, but are consistent with formation from a "sandy matrix" material possibly derived from a "Precambrian Pan-African crystalline basement." It would be of interest to compare their results with data obtained for sandy soils from the general region (i.e., from the Great Sand Sea). If isotopic links are found, the next step would be to examine whether similar surficial features might have been present at the LDG location 29 Ma ago.

TABLE 4. ESTIMATES OF THE ENERGY RELEASED DURING THE AUSTRALASIAN TEKTITE EVENT BASED ON THE CHONDRITIC (1.5×10^{15} G) AND COMETARY (3.0×10^{15} G) IMPACTOR MASSES OF SCHMIDT *ET AL.* (1993) AND ASSUMED INFALL VELOCITIES IN THE ASTEROIDAL TO COMETARY RANGE

Velocity (km s^{-1})	*Chondrite (J)*	*Comet (J)*
20	0.3×10^{21}	0.6×10^{21}
25	0.5×10^{21}	0.9×10^{21}
30	0.7×10^{21}	1.4×10^{21}
35	0.9×10^{21}	1.8×10^{21}
40	1.2×10^{21}	2.4×10^{21}
45	1.5×10^{21}	3.0×10^{21}
50	1.9×10^{21}	3.8×10^{21}
55	2.3×10^{21}	4.5×10^{21}
60	2.7×10^{21}	5.4×10^{21}

See text for details.

SUMMARY

Aerial bursts in which the kinetic energy of the meteoroid is largely deposited in the atmosphere should constitute an important fraction of the accretionary events occurring on the Earth. Although these do not leave recognizable craters in the geological record, those occurring over dry continental areas will often produce melt sheets. The layered tektites of SE Asia and the LDG appear to have formed as melt sheets. There is strong evidence against the formation of widespread, surficial melt in association with large impact craters, and the presence of ^{10}Be in all SE Asian tektites requires that these be made from surficial soil-layer precursors.

When aerial bursts occur in continental areas there will be extensive destruction of life. The above-ground part of the biosphere will be incinerated, and those subterranean life forms that depend on the active storage of energy by surficial plants will also be heavily impacted. The soil beneath the glass will have had a greatly reduced exchange of gases with the atmosphere. An interesting speculation is that events of the sort envisioned may leave virgin areas that, as a result of opportunism by colonizers, may encourage speciation.

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ABBREVIATIONS

KT, Cretaceous-Tertiary; LDG, Libyan desert glass; SE Asia, Southeast Asia; SL9, Comet Shoemaker-Levy 9.

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