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Tektite origin by hypervelocity asteroidal or cometary impact: Target rocks, source craters, and mechanisms

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ABSTRACT

Tektites are natural glasses that occur on earth in four distinct strewn fields (North American, Central European, Ivory Coast, and Australasian). Geochemical arguments have shown that tektites have been derived by hypervelocity impact melting from terrestrial upper crustal rocks, most likely sediments. The contents of Be-10 in tektites are evidence for a derivation of tektites from surface rocks, thus precluding an origin from greater depth in the crater. For two of the four tektite strewn fields (Ivory Coast, Central European), a possible connection to impact craters (Bosumtwi, and Ries, respectively) has been suggested on the basis of chemical, isotopic, and age data. No clear crater identifications have been made for the North American or Australasian strewn fields, although there are good candidates for both. Even though the geochemistry of tektites is in unequivocal favor of an origin by impact melting of terrestrial rocks, the unambiguous demonstration of the presence of an extraterrestrial contribution to the chemistry of tektites remains a problem. However, recent osmium isotope studies have shown that there is a clear meteoritic signature in at least some tektites. The exact mechanism of tektite formation is still not obvious, although some facts become increasingly clear. Tektite production requires specific impact conditions—otherwise there would be many more tektite strewn fields connected to the 150 or so known impact craters. Tektites are produced by nonequilibrium shock melting of surficial rocks, and the superheated melt may be subjected to a plasma phase during which they are subjected to partial reduction. They are then lofted through the atmosphere (probably in the wake of the expanding vapor cloud), quenched, and distributed over a geographically extended area—the strewn field. Some tektites solidify in a near-vacuum and re-enter the atmosphere. During the re-entry they melt again and form ablation-shaped tektites. Larger tektites, from a lower part of the target stratigraphy, are only distributed closer to the source crater. Many of them are more inhomogeneous melts and show a layered structure; they are called Muong Nong–type tektites. The study of tektites and the identification of possible new strewn fields provide important contributions toward the understanding of impact cratering.

INTRODUCTION

Tektites are a group of natural glasses that have puzzled mankind for many centuries. The Australian Aborigines used them for tools and probably as jewelry, and in Indochina they ended up in temples. After centuries of collecting, and decades of study, we are now closer to an understanding of their origin. First, though, we need to describe what tektites are. They are chemically homogeneous, often spherically symmetric objects that are in general several centimeters in size, and occur in four known strewn fields on the surface of the earth (Fig. 1): the North American, Central European (moldavite), Ivory

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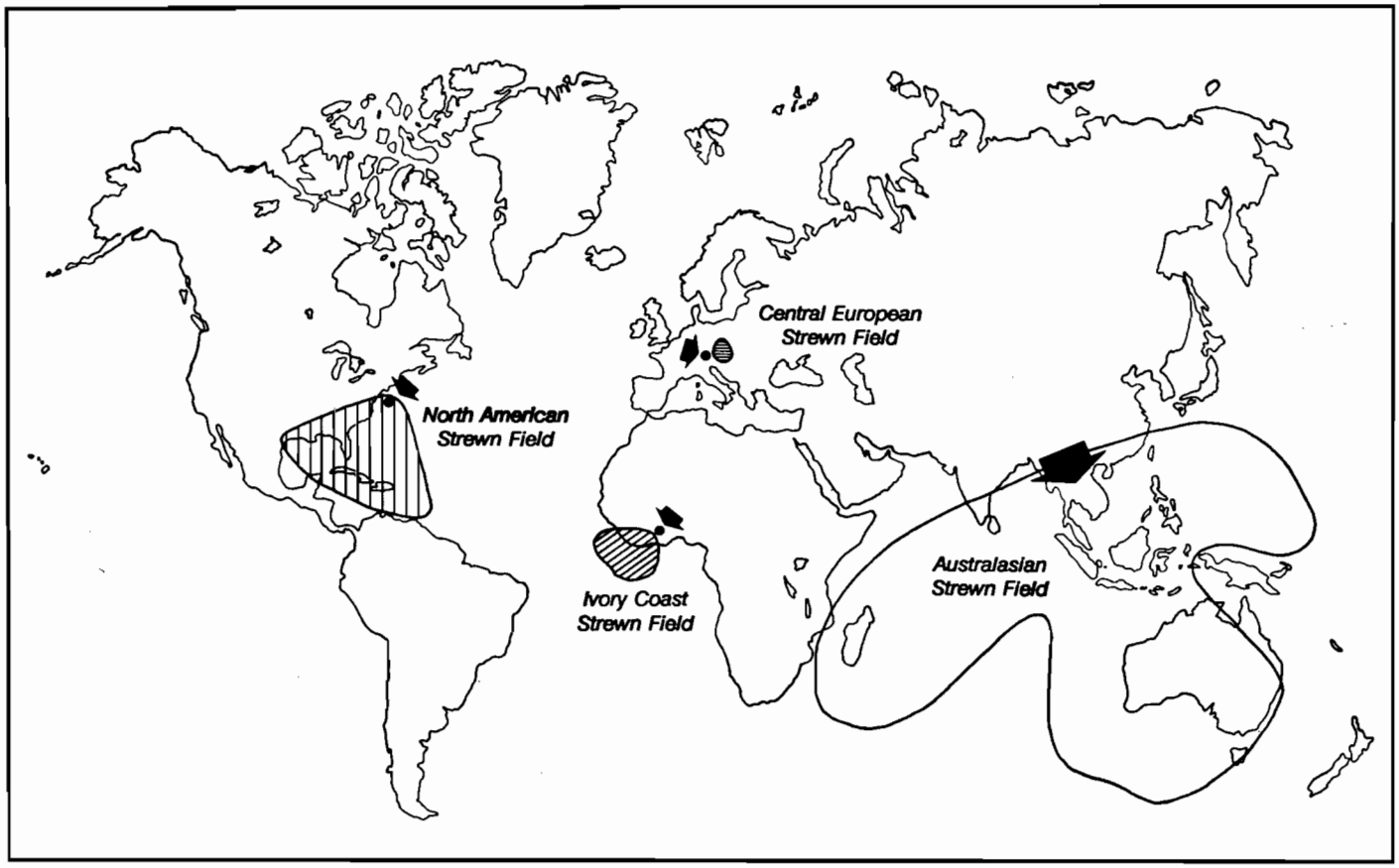

Figure 1. Location and extension of the four tektite strewn fields on earth. The arrows mark the location of the known source craters (Ries and Bosumtwi craters) or suspected crater locations.

Coast, and Australasian strewn fields (Barnes, 1963a; O'Keefe, 1963). Strewn fields can be defined as geographically extended areas (in the case of tektites larger than just a few square kilometers) over which tektite material can be found. At this point, I am proposing to change the more commonly accepted name "moldavite strewn field" to "Central European strewn field" because the other three strewn fields are known under their geographical names. Also, moldavites have now not only been found in the Czech Republic, but also in Germany and Austria (e.g., Koeberl et al., 1988).

Tektites found within such strewn fields are related to each other with respect to their petrological, physical, and chemical properties as well as their age. Table 1 gives a summary of the properties of tektites found in the four known strewn fields. Any discussion of the origin of the tektites needs to explain the similarity of tektites in respect to age and certain aspects of isotopic and chemical composition within one strewn field as well as the existence of tektite material with different compositions present in each strewn field (Taylor, 1973; King, 1977; Koeberl, 1986a, 1988a, 1990).

The occurrence of tektite glasses is not restricted to the continents. Since the mid-1960s, microtektites have been found in deep-sea cores of three of the four strewn fields (see, e.g., Glass, 1967, 1968, 1969, 1972; Cassidy et al., 1969). They are generally less than 1 mm in diameter and show a somewhat wider variation in chemical composition than tektites on land but with an average composition that is very close to that of "normal" tektites. However, if high-Mg microtektites are excluded from the discussion, the difference in the compositional range between microtektites and *macro*tektites is more perceived and due to different analytical methods than real. The analyses of normal tektites are usually performed as bulk analyses, whereas microtektites are analyzed by electron microprobe. On a micrometer scale, larger tektites are often more inhomogeneous than individual microtektites (Delano, 1992; B. P. Glass, written communication, 1993). Microtektites have been very important for defining the extent of the strewn fields as well as for constraining the stratigraphic age of tektites and to provide evidence regarding the location of possible source craters. Some new finds of tektite material on Barbados and in Deep Sea Drilling Program (DSDP) Site 612 samples (see, e.g., Thein, 1987; Koeberl and Glass, 1988; Glass, 1989) have yielded larger *micro*tektites as well as what seem to be fragments of tektites, and blur the traditional distinction between microtektites and *macro*tektites.

Tektites found on land have been subdivided traditionally

TABLE 1. SUMMARY OF QUALITATIVE INFORMATION ON THE FOUR TEKTITE STREWN FIELDS

	North American	Central European	Ivory Coast	Australasian
Tektites in strewn field	Bediasites, Georgiatites	Moldavites	Ivory-Coast tektites	Australites, Indochinites, Thailandites, Philippinites, and others
Geographical localities of tektite finds	Texas, Georgia, Barbados, DSDP Site 612	Czechoslovakia, Austria, Germany	Ivory Coast	Australia, Thailand, Laos, Cambodia, Vietnam, Indonesia, China, Philippines, etc.
Muong Nong–type tektites present	Yes, but rare (DSDP Site 612)	Yes, very rare	No	Yes, abundant
Microtektites present	Yes	No*	Yes	Yes

*Not known; maybe because there are no deep-sea occurrences in the Central European strewn field; no microtektites are known on land from any of the other strewn fields either.

into three groups (Fig. 2): (a) normal or splash-form tektites, (b) aerodynamically shaped tektites, and (c) Muong Nong–type tektites (sometimes also called layered tektites). The first two groups differ only in their appearance and some of their physical characteristics (see, e.g., O'Keefe, 1963; Chao, 1963; O'Keefe, 1976). The aerodynamic ablation results from partial re-melting of glass during atmospheric re-entry after it was ejected outside the terrestrial atmosphere and solidified through quenching. Aerodynamically shaped tektites are known mainly from the Australasian strewn field where they occur primarily as flanged-button australites. The shapes of splash-form tektites (spheres, droplets, teardrops, dumbbells, etc., or fragments thereof) have sometimes erroneously been described as aerodynamical forms; they, however, result from the solidification of rotating liquids, and not atmospheric ablation. Muong Nong–type tektites were named after the type locality in Laos (Lacroix, 1935). They are usually considerably larger than normal tektites (samples of up to 24 kg have been described; Koeberl, 1992a) and are of chunky, blocky appearance. Muong Nong–type tektites show a layered structure with abundant vesicles. Microscopic examination of the layers shows bands of lighter and darker color (which should not be confused with schlieren) and mineral inclusions (zircon, chromite, rutile, corundum, cristobalite, etc.; Glass, 1970, 1972; Glass and Barlow, 1979) and coesite (Walter, 1965) have been described from Muong Nong–type tektites.

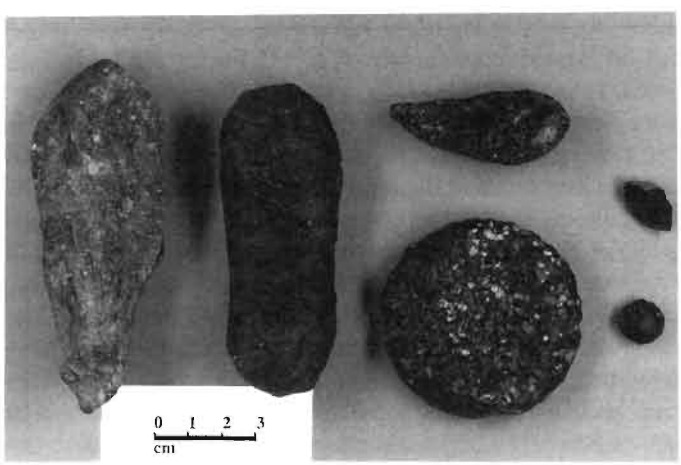

Figure 2. Photograph showing the three major types of tektites, all from the Australasian strewn field. Far left: fragment of Muong Nong–type tektite (sample MN8311) (Koeberl, 1992a); left: dumbbell-shaped splash-form tektite from Thailand; right top: tear drop–shaped splash-form tektite from Da Thiên (Vietnam); right bottom: flat disk-shaped splash-form tektite from Thailand; far right top: broken flanged australite showing aerodynamical abrasion (sample USNM 3468); far right bottom: core (button) of abraded aerodynamically shaped australite from South Australia.

Mainly due to chemical studies, it is now commonly accepted that tektites are the product of melting and quenching of terrestrial rocks during hypervelocity impact on the Earth. The chemistry of tektites is in many respects identical to th composition of upper crustal material (Taylor, 1973; Koeberl, 1986a). Trace elements are very useful for source rock comparisons: many trace element ratios in tektites are indistinguishable from those in upper crustal rocks. The chondrite-normalized rare-earth-element (REE) patterns of tektites are very similar to those of shales or loess, and have the characteristic shape and total abundances of the post-Archean upper crust. The determination of the exact source rocks of tektites is complicated because a variety of target rocks was apparently sampled by the impact.

In the following sections, I attempt to summarize the ar-

guments regarding source rocks, target stratigraphy, and crater of origin for tektites from all four strewn fields.

TEKTITE SOURCE ROCKS

Trace element geochemistry of tektites

Any discussion of tektite origin needs to take the geochemistry of tektites into account. The basic assumption is that the geochemistry of tektites provides information on the geochemistry of the source rocks from which the tektites were produced. Reviews of this subject as well as detailed tables of the major and trace element composition of all tektite groups have been published by Koeberl (1986a, 1990); therefore, I will only summarize some basic concepts here.

In general, the geochemistry of tektites is almost identical to the composition of the terrestrial upper crust. This very fundamental observation was established mainly by Taylor and coworkers, who, since the early 1960s, have performed detailed geochemical studies of many tektite types (see, e.g., Taylor, 1962a, 1962b, 1966, 1973; Taylor and Sachs, 1964, Taylor and Solomon, 1964, Taylor and Kaye, 1969, and Taylor and McLennan, 1979). Of particular use in establishing such a relationship are trace elements: the ratios of, e.g., Ba/Rb, K/U, Th/Sm, Sm/Sc, Th/Sc, K versus K/U, in tektites are practically the same as those in upper crustal rocks. Because of these chemical studies, it is now commonly accepted that tektites are the product of melting and subsequent quenching of terrestrial rocks during hypervelocity impact on the Earth.

The rare earth elements (REE) are a group of elements of great genetic significance because geochemically they behave very similar to each other; with the possible exception of Eu and Ce, which may show a characteristically different behavior depending on the redox conditions (e.g., Henderson, 1984). Their absolute abundances as well as their chondrite-normalized abundance patterns are very characteristic for different rock types of different provenance (e.g., Taylor and McLennan, 1985), and so they can be used to infer the type and composition of the tektite parent rocks. The chondrite-normalized REE patterns of tektites are very similar to those of shales or loess, and they have the characteristic shape and total abundances of REE distributions in the post-Archean upper crust. Figure 3 shows the condrite-normalized REE pattern of the average present (post-Archean) upper crust in comparison with the REE patterns of average Muong Nong–type tektites and average australites. The patterns are clearly very similar, with almost identical slopes, light(I)REE/heavy(H)REE or La/Yb ratios, and Eu anomalies. The australite has slightly higher REE abundances compared to the upper crust or the average Muong Nong–type indochinites.

As also shown in Figure 3, the average REE patterns of post-Archean upper crustal rocks are different from those of Archean upper crustal rocks, with post-Archean sediments showing a characteristic negative Eu anomaly that is absent from Archean sediments (e.g., Taylor and McLennan, 1985). We therefore conclude that Archean sediments are implausible as source materials for the four known Cenozoic tektite strewn fields (which would also be unlikely because of their limited surface expression). This is particularly evident from the inset in Figure 3, which is a plot of the REE concentrations normalized to the average post-Archean upper continental crust. The REE pattern of the Archean crust is quite distinct, while those of the Muong Nong–type tektites and australites are very similar to the average crustal REE pattern. The small deviations (especially the slight HREE enrichment) are probably due to incorporation of a slightly higher fraction of relict minerals. No Ce anomalies, which are characteristic of laterites and similar weathered rocks (Braun et al., 1990), were found in any tektites.

A more extensive discussion of the use of REEs to estimate the source-rock type was given by, e.g., Taylor and McLennan (1979) and Koeberl (1992a). The latter author concluded from REE patterns that loess (which is not known from Indochina) may not have been a prominent source of the Australasian tektites. Most rock types (such as basalts, ocean crust, deep-sea sediments) other than upper crustal sediments can be excluded as source rocks because of their different REE patterns (e.g., Henderson, 1984). None of the trace-element ratios or REE patterns are anywhere near lunar or other extraterrestrial values, for which an abundance of data exist for comparison (e.g., Schnetzler, 1970; Taylor, 1973, 1982). The REE patterns of upper crustal rocks, such as shale, sandstone, graywacke, granites, and related rocks, are the result of geochemical processes on or close to the surface of the Earth, through mixing, weathering, erosion, and transport. These processes do not operate on water- and atmosphere-less bodies. The REE patterns of tektites are therefore an elegant and rather unrefutable argument against any extraterrestrial origin still advocated occasionally (e.g., O'Keefe, 1976; Futrell, 1986a, 1986b; O'Keefe, 1987; Futrell, 1991) and are in exclusive agreement with a terrestrial origin.

The same conclusions can be drawn from REE abundances and patterns of the other three tektite strewn fields. The REE patterns (as well as other trace element abundances and ratios) of North American tektites are in direct agreement with a derivation from upper crustal rocks (e.g., Koeberl and Glass, 1988; Koeberl, 1988c). In case of the two strewn fields that have been linked to specific craters, trace element studies have strengthened the evidence for a link. Extensive comparisons have been made between the trace element composition of upper freshwater molasse samples which were presumably present at the site of the Ries crater and those of the moldavites (e.g., Koeberl et al., 1985; Engelhardt et al., 1987). Analyses of rocks from the Bosumtwi crater in Ghana have shown close similarities to the Ivory Coast tektites (e.g., Jones, 1985).

Muong Nong–type tektites

This important subgroup of tektites allows some direct conclusions regarding source rocks and origin. Muong

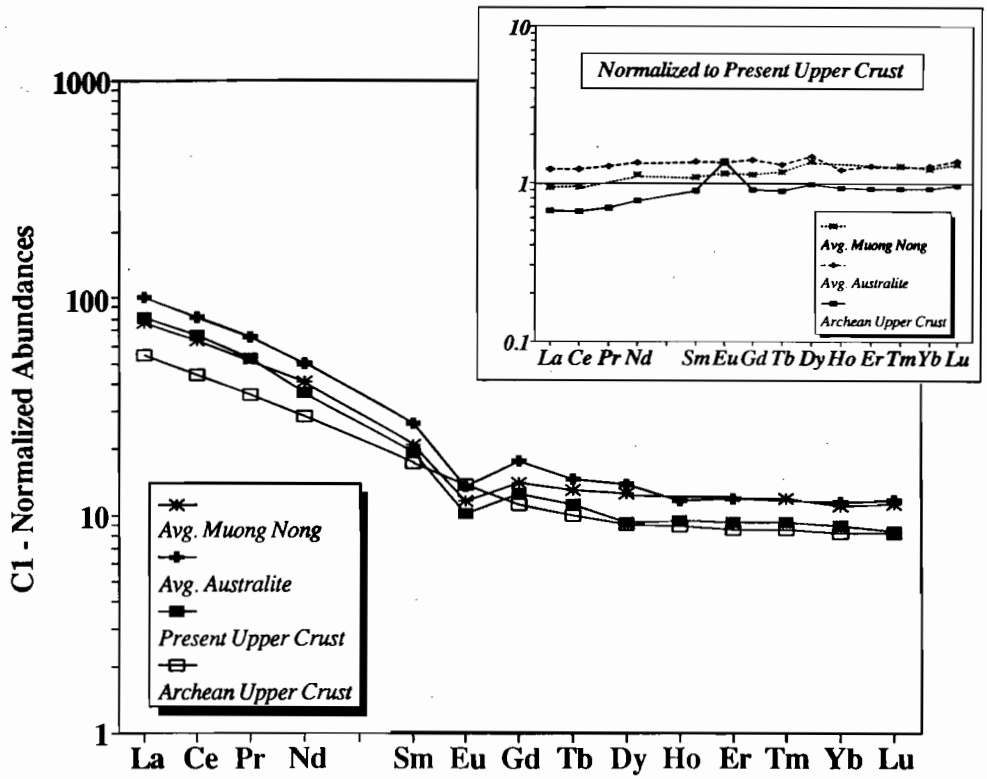

Figure 3. Chondrite-normalized REE patterns of average Muong Nong–type tektites and australites compared to the present upper crust and the Archean upper crust. Data sources: Koeberl (1986a, 1992a), Taylor and McLennan (1979, 1985); see text for details.

Nong–type tektites have first been described from the Australasian strewn field and differ from normal tektites in a few important parameters. They are larger, more heterogeneous in composition, of irregular shape, have a layered structure, and show a much more restricted geographical distribution (see, e.g., Chapman and Scheiber, 1969; Futrell and Fredriksson, 1983; Koeberl, 1986b, 1988b, 1992a; Schnetzler, 1992). Their average major element chemistry and their age are (within normal variations) identical to those of normal tektites. Muong Nong–type tektites are abundant in the Australasian strewn field, but recently a few samples that are most probably Muong Nong-type tektites have also been found from the Central European (Meisel et al., 1989; Glass et al., 1990) and North American (Wittke and Barnes, 1988; Koeberl and Glass, 1988) strewn fields. Muong Nong–type tektites show some important peculiarities in their chemical composition: they are chemically less homogeneous than normal tektites, and there are differences in composition between the layers. Furthermore, water and other volatile elements are enriched in Muong Nong–type tektites compared to splash form tektites—or just less depleted in comparison to the source rocks.

The water content in Muong Nong–type tektites is slightly higher than that in splash-form tektites (Koeberl and Beran, 1988). The most significant volatile enrichments are shown by the elements Cl, Zn, and Br (see, e.g., Müller and Gentner, 1973; and Koeberl, 1992a). The abundance of these elements can be used to determine the character of doubtful samples (i.e., Muong Nong–type versus splash form; see, e.g., Glass et al., 1990; Meisel et al., 1989). The volatile element enrichment in Muong Nong–type tektites is most likely because they were exposed to lower temperatures of formation than splash-form tektites. They have probably formed from the same or a very similar source material, but were less thoroughly heated and have therefore lost less of their volatile element content than the splash-form tektites. Volatile element contents in Muong Nong–type tektites are comparable to, or only slightly lower than, the ones in upper crustal sedimentary rocks (see discussion in Koeberl, 1992a), while splash-form tektites show considerable depletions. Matthies and Koeberl (1991) found a similar behavior of the F and B content in impact glasses versus target rocks at different craters. Wasson et al. (1990) found that the average Th/U ratios in splash-form tektites are higher than in upper crustal rocks and Muong Nong–type tektites, which is due to a lower U content in splash-form tektites. They suggested that U may behave as a volatile element during tektite formation. However, other elements more volatile than U do not show a difference. The Th/U ratios in tektites are the same as those in sedimentary

rocks which are high because of oxidation of U^{4+} to U^{6+} and removal as soluble $[UO_2]^{2-}$ (McLennan and Taylor, 1980).

Muong Nong–type tektites occur mainly as silica-poor and silica-rich varieties, although there are a number of samples that have intermediate compositions. Koeberl (1992a) concluded that it is unlikely that Si-poor Muong Nong–type tektites have originated from Si-rich Muong Nong–type tektites by vapor fractionation of silica (see also below). Mixing of different source rocks (as probably evident by layering and different relict mineral compositions in Si-rich and Si-poor Muong Nong–type tektites) is in better agreement with the observed compositions (Koeberl, 1992a; Schnetzler, 1992). Some volatilization and vapor fractionation has certainly taken place during tektite formation, but was limited to volatile elements and was not responsible for major element variations.

Muong Nong–type tektites may be the key to some important questions. Their inhomogeneity may indicate that they have preserved the original target rock compositions much better and therefore they may be the missing link between target rocks and tektites. Impact glasses with petrographic and chemical characteristics similar to Muong Nong–type tektites (e.g., Koeberl and Fredriksson, 1986) have been described from the Zhamanshin impact crater. Because of the larger size and irregular shape of Muong Nong–type tektites, we may assume that they have not traveled far from their source crater.

Relict and shock metamorphic phases

Another crucial link to sedimentary rocks is provided by the occurrence of relict minerals in some tektites. Lechatelierite—the amorphous remainder of partly digested quartz grains—is well documented in tektites (e.g., Chao, 1963) and indicates quartz-rich precursor rocks. Muong Nong–type tektites contain unmelted relict inclusions, in contrast to splash-form tektites (Barnes, 1963b; Glass, 1970, 1972; Glass and Barlow, 1979). The minerals identified so far include zircon, chromite, quartz (Glass, 1970), corundum (plus SiO_2), rutile and monazite (Glass, 1972), all showing evidence of various degrees of shock metamorphism. Muong Nong–type indochinites can be divided into two groups: those with low refractive indices (<1.503) contain mineral inclusions while those with high refractive indices (>1.513) do not (Glass and Barlow, 1979; Glass and Koeberl, 1989). Glass and Koeberl (1989) found that the only trace element that shows a significant difference between the two groups is Ta, being higher in the low–refractive index group. The type of mineral inclusions present, as well as their size and shape, suggests that a fine-grained, well-sorted sediment was the tektite parent material.

Independent evidence for shock comes from the presence of coesite in Muong Nong tektites by Walter (1965) (which was previously found in Darwin glass; Reid and Cohen, 1962). The presence of coesite in tektite glass was confirmed by Glass et al. (1986a). Glass (1987) and Bohor et al. (1988) found coesite and shocked minerals associated with tektites in a layer containing an impact debris, tektite fragments, and microtektites at DSDP Site 612 in the North American tektite strewn field, supporting the association of tektites with shocked minerals.

The discovery of tektite glass at locations in Barbados and at DSDP Site 612 in the North American strewn field is important because microtektites and tektites (tektite fragments) as well as shocked minerals are found in the same layer (e.g., Thein, 1987; Glass, 1989). Recently, Glass and Wu (1992a, 1993) reported an even more important observation. They showed that several microtektite-bearing layers in cores from the Australasian and North American strewn field contain shocked minerals (quartz and feldspar), vesicular impact glass, and coesite. This discovery provides another direct link of tektites with impact events.

Isotopic evidence

The study of the abundances and ratios of various isotopes is of growing importance in the study of tektites and their source rocks. One of the first isotopic studies was performed by Tilton (1958), who analyzed the isotopic composition of lead in tektites and found it to be in agreement with terrestrial values. Similar conclusions were obtained by Schnetzler and Pinson (1964) for Rb/Sr and by Taylor and Epstein (1969) for oxygen isotopes. There are indications that the isotopic composition of oxygen in some tektites (e.g., moldavites; see Engelhardt et al., 1987) is skewed toward the lighter isotopes in tektites compared to source rocks. This effect may be due to incorporation of isotopically light oxygen from meteoric water which resides in pores of sediments (Engelhardt et al., 1987). However, a recent study by Chamberlain et al. (1993) found no evidence for any modification of oxygen isotope values for Ivory Coast tektites. These tektites have $\delta^{18}O$ values that are virtually identical to those of target rocks from the Bosumtwi crater which has been inferred as the source crater.

The study of the Rb-Sr and Sm-Nd isotopic systems has proven to be of great importance. In a detailed study, Shaw and Wasserburg (1982) have shown that all tektites have distinctive negative ε_{Nd} and large positive ε_{Sr} values, which are uniquely characteristic of old terrestrial continental crust. The Nd model ages of tektites reflect the age of the source terrain of the target rocks, i.e., the age during partial melting of the mantle to form new crust. Surficial processes, such as weathering, do not disturb the Sm-Nd isotopic system. However, the Rb-Sr isotopic system is severely disturbed by increasing the Rb/Sr ratio during weathering and sedimentation. Shaw and Wasserburg (1982) found from the Sm-Nd isotope systematics Precambrian ages for the crustal source terrains of all tektite groups. The Rb-Sr sedimentation age showed a much wider variation for all tektite groups, ranging from very young sediments for the moldavites (recent at the time of the impact; 15 Ma ago) to rocks of about 0.95 Ga for the Ivory Coast tektites.

For the North American tektites, the Rb-Sr/Sm-Nd systematics exclude most of the North American Precambrian shield areas as well as areas that are covered by sediments derived from them. Shaw and Wasserburg (1982) and Stecher et al. (1989) concluded that sediments derived from or incorporated in the Appalachian orogeny provide the best match for North American tektites; the source areas may even include the eastern continental shelf of the North American continent. Although the North American tektites found at Barbados have isotopic compositions that are identical to bediasites or georgiaites (Ngo et al., 1985), the tektite fragments recovered from DSDP Site 612 show a much wider isotopic variation (Stecher et al., 1989) and indicate either a more heterogeneous target, or two impact events at about the same time.

In a recent study, Blum et al. (1992) studied the Rb-Sr and Sm-Nd isotopic systematic of Muong Nong–type and splash-form tektites from the Australasian strewn field and confirmed that the source material was derived from Precambrian crustal terrane with Nd model ages ranging from 1040–1190 Ma. The Rb-Sr system indicates that the sediments that were later melted to form tektites were weathered and deposited about 167 Ma ago and probably were comprised of Jurassic sediments, which are not uncommon throughout Indochina. The Nd and Sr isotopic data suggest that all Australasian tektites were derived from a single sedimentary formation with a narrow range of stratigraphic ages close to 170 Ma. Blum et al. (1992) also concluded from their data that the Rb-Sr isotope systematics are inconsistent with soil or loess as source materials and also practically rule out multiple impact scenarios.

Other isotopic systems, such as boron, carbon, nitrogen, magnesium, or sulfur, have not been explored yet in detail or at all, mainly due to analytical problems caused by the low concentrations of these elements. A first study of $\delta^{11}B$ in tektites shows that abundances and isotopic values for all tektite groups are consistent with sedimentary precursor rocks (Chaussidon and Koeberl, in preparation).

Summary of tektite characteristics

At this point it may be pertinent to summarize the characteristics of tektites and compare them to those of impact glasses from known impact craters. Table 2 provides a compilation of some key parameters as well as a comparison of these parameters between tektites and impact glasses. The "definition" of a tektite has a somewhat historic aspect; however, it should be clear by now that there are some obvious differences between normal impact glasses and tektites. Although tektites have of course originated by impact, they form a subgroup of the general impact glasses. Unfortunately there has been a recent tendency to designate any newly discovered glass that is suspected to be of impact origin as a tektite, or glassy spherule as microtektite, even if these glasses do not fulfill several of the criteria that designate tektites (e.g., Claeys et al., 1992; Izett, 1991; Smit et al., 1992). Glasses found in Haiti that have been shown to be associated with the K-T boundary are among the glasses that have been termed "tektites." These glasses are, beyond doubt, of impact origin (Izett, 1991; Koeberl, 1992b). However, considering the size of the 200–300 km diameter Chicxulub structure, they are found much closer to the source crater than any known tektites. The age of the Haiti impact glasses is indistinguishable from that of the Chicxulub crater, and there are isotopic data that make it likely that Chicxulub is the source for these glasses (Blum et al., 1993). Considering the source, the finding localities, and petrographic characteristics, I consider it to be more proper to use the descriptive term "impact glasses" for such glasses and reserve the term "tektites" and "microtektites" for those glasses that fall in the classical definition of tektites.

TABLE 2. COMPARISON OF TEKTITES AND IMPACT GLASSES

	Tektites	Impact Glasses
Occurrence in strewn field	Yes	No
Source crater known	Yes/no	Yes
Occurrence directly at source crater	No	Yes
Target rocks	Surface rocks	Deeper lithologies
Chemical homogeneity	Large-scale homogeneity (100 mm–mm)	Usually inhomogeneous
Water content (wt%)	0.002– 0.02	0.02– 0.07
Mineral inclusions (includes partly digested quartz)	Rare	Abundant
Shape	Mostly regular, spherically symmetric	Mostly irregular
Ablation shapes	Yes	No
Meteoritic component (abundance in wt%)	<0.02	0.02–0.5
Heavy noble gas content (Ar, Kr, Xe)	Low	High

TEKTITE SOURCE CRATERS

The studies discussed in the previous sections have gradually led to the realization that tektites have formed during hypervelocity impact into post-Archean upper crustal rocks. This conclusion is a major advance over the widely varying views that were held—mainly because of lack of concrete data—since scientists first started to be puzzled by these strange

glasses. However, the identification of some possible source rocks leads to two more crucial questions regarding the origin of tektites: where and how? In the following sections, I will summarize our current knowledge on "where?"

During the past half century, numerous suggestions and educated guesses have been made regarding the location of the possible source craters for the tektite strewn fields. Relatively reliable links between craters and tektite strewn fields have been established between the Bosumtwi (Ghana) and the Ries (Germany) craters and the Ivory Coast and the Central European fields, respectively. However, no large crater with the necessary age has been reliably identified for either the Australasian or the North American strewn field (Grieve, 1991). Table 3 summarizes important quantitative information on all four strewn fields.

Australasian strewn field

For the Australasian field, no crater of the appropriate age is known (Grieve, 1991), although many proposals for possible source craters were made and later discounted. Schmidt (1962) and Weihaupt (1976) suggested that the Wilkes Land gravity anomaly in Antarctica may be the expression of a subglacial crater; however, this was disputed by Bentley (1979). Later, Dietz (1977) proposed the Elgygytgyn crater in Siberia as a source crater for the Australasian tektites, and Glass (1979) suggested the Zhamanshin crater instead. Both craters have subsequently been discounted as tektite source craters on the basis of geographic location, chemistry (Koeberl and Fredriksson, 1986), isotopic data (Shaw and Wasserburg, 1982), size, and, especially, age (e.g., Storzer and Wagner, 1979; Koeberl and Storzer, 1988). Hartung and Rivolo (1979) suggested a circular structure in Cambodia as source crater and the same location was later endorsed by Ford (1988), but field evidence suggests that this and other nearby structures are of volcanic origin (Lacombe, 1967).

Barnes (e.g., Barnes and Pitakpaivan, 1962; Barnes, 1989, 1990), mainly from studying Muong Nong–type tektites, suggested that the Australasian tektites have originated from an impact of a "diffuse object such as a comet." However, it is not easy to understand how the impact of a cometary nucleus would differ from that of an asteroid because upon passing through the atmosphere any cometary coma would be stripped off. The opinion of Barnes and Pitakpaivan (1962) that the Muong Nong–type tektites had locally formed in melt puddles was reinterpreted by Wasson (1991), who suggested that the tektites originated from a multitude of small craters scattered over all of Indochina. This model encounters substantial problems; the following list gives some examples: small craters produce small to negligible quantities of relatively inhomogeneous impact glasses, as is well known from many impact craters; small impact events are unable to provide the energy to launch the splash form and aerodynamically shaped tektites that are found over a distance of more than 6,000 km; it is not easy to understand why all tektites have very similar chemical and isotopic compositions if they originated from different

TABLE 3. SUMMARY OF QUANTITATIVE INFORMATION ON THE FOUR TEKTITE STREWN FIELDS*

	North American	Central European	Ivory Coast	Australasian
Age (Ma)	35.4	15	1.09	0.77
Area (10^6 km^2)	10	0.3	4	50
Total mass (10^6 t)	300–42,000	5?	20	2,000?
Age of source terrain (from Sm-Nd, in Ga)	0.7	0.9	1.90	1.11
Sedimentation age (from Rb-Sr, in Ma)	400	15	950	175
Possible source crater (Location)	Underwater? (off New Jersey)	Ries (Germany)	Bosumtwi (Ghana)	Tonle Sap? (Cambodia)
Source crater diameter (km)	20 – 30?	24	10.5	50–100

*Data sources: O'Keefe, 1963, 1976; Glass et al., 1979; Storzer and Wagner, 1977, 1979; Shaw and Wasserburg, 1982; Glass et al., 1986b; Koeberl, 1986a, 1989; Koeberl et al., 1989; Glass, 1989; Glass et al, 1991; Blum et al., 1992; Izett and Obradovich, 1992; and references therein.

source materials; the isotopic data are not in agreement with a variety of different source rocks that are required by a multiple impact theory; the crater problem has been multiplied—instead of one missing crater, we are missing a multitude of smaller craters; this model of origin from the Australasian tektites is not consistent with those of the other three strewn fields where good arguments (and even craters) exist for a single impact. As argued before (Koeberl, 1992a; Blum et al., 1992) I suggest that a single large impact crater is a much more plausible source crater of the Australasian tektites.

From detailed fission track work, Storzer and Wagner (1980a, 1980b) suggested that australites may have a slightly different age than other Australasian tektites. They found a corrected plateau age of 0.83 Ma for australites, but only 0.69 Ma for indochinites, and therefore suggested that two different impact events were responsible for the two tektite groups. However, Glass (1986) found no evidence for a second, older (0.8–0.9 Ma), microtektite layer in deep-sea cores, and Izett and Obradovich (1992) found no age difference between australites and other Australasian tektites in their detailed Ar-Ar study. Their best-fit age is 0.77 ± 0.02 Ma, which agrees well with the revised age for the Brunhes/Matuyama geomagnetic polarity reversal with which the Australasian microtektite layer is closely associated; however, the microtektite layer does not directly coincide with the Brunhes/Matuyama reversal, but the Australasian microtektites were deposited about 15,000 years prior to the geomagnetic reversal (Schneider et al., 1992). Therefore it does not seem warranted to split the Australasian tektite strewn field into two fields.

The geographic distribution of Australasian tektites and microtektites is not homogeneous: there are radial and concentric patterns and zones that do not contain microtektite-bearing deep sea cores (e.g., Stauffer, 1978; Schnetzler, 1992; Glass and Wu, 1992a, 1993). In careful analysis of the radial distribution patterns, Stauffer (1978) suggested a crater that may be concealed beneath alluvial deposits of the lower Mekong Valley area. A similar analysis of the North American strewn field suggested that tektites show a ray-like distribution, not unlike lunar crater ejecta (Koeberl, 1989). The same pattern may exist in the Australasian strewn field (Glass and Wu, 1992a, 1993). Schnetzler et al. (1988) suggested a possible off-shore impact location (about 175 km to the east of the Vietnam seashore) from satellite gravity data.

More recently, Hartung (1990) proposed that the lake Tonle Sap (about 100 km long and up to 35 km wide) in Cambodia was created by the Australasian tektite event. The dimensions are probably minimum values as the structure is almost completely filled with alluvium. The location of Tonle Sap is in agreement with chemical and isotopic (Rb-Sr/Sm-Nd) data for tektites, but more detailed studies are necessary. A first expedition to the Tonle Sap area (Hartung et al., 1992a, 1992b) has identified some possible source rocks, but no proof for impact has been found yet (partly due to the inaccessibility of the area; Hartung and Koeberl, 1994). However, the discovery of impact debris in deep-sea cores near the coast of Indochina, as well as the fact that the quantity of both impact debris and microtektites in cores all over the Australasian strewn field increases towards Indochina (Glass and Wu, 1992a, 1993), supports the locations proposed by Stauffer (1978) and Hartung (1990). The distribution of Australasian microtektites leads to a source region in central Cambodia (Glass, 1993). Although no crater has yet been identified for the Australasian tektites, current research is "closing in" on a location.

Ivory Coast strewn field

Ivory Coast tektites were reported first in 1934 from a geographically very restricted area in the Ivory Coast, West Africa. Although some additional specimens have been found later, the total number remains small (a few hundred). The first suggestions that the Bosumtwi (or Ashanti) crater in Ghana was the source crater for the Ivory Coast tektites was made in the early 1960s (e.g., Barnes, 1961). This suggestion was later substantiated by the finding that the tektites and the crater have the same age (e.g., Gentner et al., 1969a, 1969b; Storzer and Wagner, 1977; Koeberl et al., 1989) as determined both by isotopic and chemical studies (e.g., Kolbe et al., 1967; Schnetzler et al., 1966, 1967; Taylor and Epstein, 1966). Most of these studies were based on a comparison of impact glass from the Bosumtwi crater and Ivory Coast tektites.

More recently, detailed field work on the crater was described by Jones et al. (1981). Jones (1985) reported chemical analyses of a variety of country rocks from the Bosumtwi crater. He concluded from his chemical data that the main rocks that were involved in the production of the Bosumtwi impact glasses as well as the tektites were phyllite, graywacke, microgranite, and some mainly granodioritic (Pepiakese) intrusives. The Rb-Sr/Sm-Nd isotopic data of Shaw and Wasserburg (1982) are in agreement with a derivation of Ivory Coast tektites from rocks of the Bosumtwi area. Recent isotopic studies by Chamberlain et al. (1993) show that the Pepiakese intrusive component contributed only about 10% of the total melt. Elevated concentrations of some siderophile elements in the tektites and impact glasses compared to the country rocks may indicate a meteoritic component (e.g., Palme et al., 1978, 1981; see later discussion).

Glass (1968) reported the discovery of microtektites in deep-sea deposits off the West African Coast. Their link to the Ivory Coast tektites was later confirmed by the similarity of the major element composition of the microtektites to that of the tektites (e.g., Glass, 1969; Glass and Zwart, 1979). The age of the microtektites was determined to be identical to those of the Ivory Coast tektites and Bosumtwi glasses (e.g., Gentner et al., 1970; Koeberl et al., 1989), providing further evidence for a link between the tektites and Bosumtwi crater. Recently, Glass et al. (1991) concluded that the geographic variation in the estimated microtektite concentrations at the known deep-sea sites is also consistent with an origin from the Bosumtwi area.

It thus seems that the conclusion—that the Ivory Coast tektites have originated in the same event as the Bosumtwi impact crater—is a safe one. This does not mean, however, that there are no open questions left. On the contrary, we can now use the example of the Ivory Coast tektites as a guide to a better understanding of the tektite production process, to answer such questions as why were tektites made during the Bosumtwi impact, but not in other impacts of similar size?

Central European strewn field

Within Central Europe, tektites have been described from Bohemia and Moravia (now in the Czech and Slovak Republics) as early as the 18th Century. They were especially noted for their green color ("Bouteillensteine"—"bottle stones"), and they were the first tektites ever to be analyzed for chemical composition (by the German chemist M. Klaproth in 1816). After the first finding location, the tektites were names "moldavites," which has become the most widely used name for this group of tektites. Within the last two decades, however, moldavites have also been found in the former East Germany near Dresden, and in Austria, north of Vienna, near the Czech border. As mentioned before, I therefore prefer the term "Central European strewn field." A more detailed account of historical aspects and distribution of the tektites is given by, e.g., Barnes (1963a), O'Keefe (1976), and Koeberl et al. (1988).

Regarding distribution (Barnes, 1963a) and chemical composition (e.g., Delano and Lindsley, 1982), the moldavites can be divided into two main groups, the Bohemian and the Moravian moldavites. No microtektites were found to be associated with the Central European strewn field, which may not be surprising because microtektites are only found in deep sea sediments. As for the Ivory Coast tektites, a link to a near-by crater has been proposed: the Ries crater in southern Germany was found to be of exactly the same age (15 Ma) as the moldavites. Subsequent studies of the stratigraphy of the crater (see review by Hörz, 1982) have shown that different ejecta from the Ries crater can be linked to a certain orderly stratigraphic succession of the target rocks. The moldavites were interpreted to be high-speed ejecta derived from the uppermost layers of rock. This view has been strongly supported by chemical and isotopic studies.

The major and trace element composition of the moldavites can be explained if they have been derived from the so-called Upper Freshwater-Molasse unit (OSM, from a German term), but not from any of the deeper stratigraphic units at the Ries crater (see, e.g., Delano and Lindsley, 1982; Koeberl et al., 1985; Delano et al., 1987; Engelhardt et al., 1987). The same conclusion can be drawn from isotopic studies: the Sm-Nd isotope systematics agree with the age of the oldest known basement at the Ries crater, while the Rb-Sr isotope systematics point to a very young sediment derived locally from rocks around the Ries crater, probably the OSM units (Graup et al., 1981; Shaw and Wasserburg, 1982; Horn et al., 1985). Considering the abundance of evidence, the conclusion that the moldavites were derived from the Ries crater is inevitable. However, just as for Bosumtwi, we have to ask why tektites were produced from the Ries, but not from most other craters.

North American strewn field

Earlier, North American tektites were only known from an area near Bedias, Texas (since 1936), and some rare specimens from Georgia (e.g., Barnes, 1963a). Two individual finds were reported to be from Martha's Vineyard and from Cuba; the first location has been discounted, while the latter probably represents a genuine tektite location (see Koeberl, 1988c, 1989, for discussion). The extent of the North American strewn field was defined by findings of microtektites in a number of deep sea sediments (see, e.g., Glass et al., 1973, 1979, 1985). On the basis of stratigraphic, compositional, isotopic, and age data they were identified to be part of the North American tektite field. Other spherules of clinopyroxene composition, which were found in several cores throughout the Caribbean Sea and even the Pacific, were earlier thought to be associated with the North American tektite strewn field, but later shown to be part of different event (e.g., Glass et al., 1985).

The discovery of tektite fragments associated with microtektites in deep-sea deposits (now on land) on Barbados extended the occurrences of "normal" tektites within the strewn field (Glass et al., 1984). Chemical analyses (Koeberl and Glass, 1988), isotopic studies (Ngo et al., 1985), and age data (Glass et al., 1986b) showed that, without doubt, the Barbados tektites are North American tektites. From their Rb-Sr/Sm-Nd isotopic studies, Shaw and Wasserburg (1982) concluded that the source rocks from which the North American tektites were derived were crustal material that formed very late in the Precambrian (Sm-Nd model age 0.62–0.67 Ga), which excludes most of the Precambrian shield areas of North America, as well as sediments derived from these areas. The Rb-Sr data are less significant here than they were for the Australasian tektites, but are in agreement with derivation from a sediment.

In 1987, microtektites, tektite fragments, and impact debris was discovered in a relatively thick layer in a core at DSDP Site 612 (e.g., Thein, 1987). The chemical composition of the DSDP Site 612 tektites and microtektites is similar to that of other North American tektites, but there are some important differences, e.g., lower Na and higher K contents in the 612 tektites (Koeberl and Glass, 1988). Stecher et al. (1989) found that the Rb-Sr/Sm-Nd isotopic composition of the 612 tektites shows a much wider scatter than that of the North American tektites (but they may still be on a mixing line with the other tektites). In addition, no agreement has been reached regarding the question if the 612 tektites are in a layer identical in age to that of the other North American microtektites (as proposed mainly by Glass, 1989), or if they are in a

different layer. The North American microtektite layer is not directly associated with the Eocene-Oligocene boundary, but slightly (≥0.5–1 Ma) older (e.g., Glass et al., 1986a; Keller et al., 1987), no matter how many different impact layers exist in the late Eocene. Keller et al. (1987) argued for at least three different late-Eocene impact layers, and Miller et al. (1991) additionally maintain that the Site 612 tektites are 0.5–1 Ma older than the other North American tektites and propose three to four late Eocene impacts. Such a flurry of impacts is not only difficult to understand, but the proposed age difference (based on biostratigraphy) does not agree with precise radiogenic age determinations, which do not show any such differences (see also discussion by Glass, 1989, and Miller et al., 1991). However, if the layer at Site 612 is indeed older than the North American microtektite layer, then it belongs to either another strewn field (which has not yet been established) or at least to another impact event.

However, the slight differences in elemental and isotopic composition, and the dispute about the exact stratigraphic location, may require some caution in the question regarding the source crater. Just as for the Australasian strewn field, many locations have been suggested as the North American tektite source crater, mainly based on similarity in age. Among the suggestions were, for example, Popigai, Siberia (Dietz, 1977); Wanapitei, Canada; Mistastin, Canada; and Bee Bluff, Texas (Wilson and Wilson, 1979; King, 1979), all of which were later discounted on basis of distance, exact age, isotopic constrains, size, and other criteria (e.g., Storzer and Wagner, 1979; Shaw and Wasserburg, 1982; Ngo et al., 1985; Koeberl, 1989; Glass, 1989; Stecher et al., 1989). For the distribution of the tektites in the strewn field, Koeberl (1989) suggested that the North American tektite source crater may be located at or near the eastern coast of the North American continent, maybe underwater. Such a location is also supported by the findings of Glass and Wu (1992a, 1993). This would have made the Montagnais crater, 200 km southeast of Nova Scotia, the first underwater crater ever discovered (Jansa and Pe-Piper, 1987), an attractive candidate, but unfortunately neither its age (51.5 Ma; Bottomley and York, 1988) nor the isotopic systematics (Stecher et al., 1989) agree with those of the North American tektites.

In a newer development, Poag et al. (1992) have discovered evidence that a marine boulder bed beneath Chesapeake Bay and the surrounding Middle Atlantic Coastal Plain is likely to be of impact origin. From seismic profiles, they also identified a possible underwater impact crater about 40 km north-northwest of DSDP Site 612. The structure is of irregular shape, probably because of slumping and the rebound after the impact. It is estimated that, at the time of the impact, the location was not deeper than 1000 m under water; the post-impact diameter may have been around 25 km (C. W. Poag, personal communication, 1992). The authors suggest that the crater may have been responsible at least for the impact products at DSDP Site 612, maybe even for the North American strewn field. If the North American tektites and the DSDP 612 glasses were formed in different events, the "New Jersey shelf" crater may well be responsible for the latter; however, a diameter of about 25 km, if confirmed, may be too small for the whole North American strewn field.

TEKTITE PRODUCTION PROCESSES

In the earlier sections I have discussed the tektite source rocks, and in the immediately preceding sections I reviewed the possible locations from which the tektites were derived. Here I want to summarize our current understanding of the tektite-producing impact processes—admittedly the least understood part of tektite origin. An attempt to present physical (or mathematical) models of a tektite-forming impact is not possible at this time, because only educated guesses about such detailed models exist (Melosh, 1989). I will therefore try to approach the question in a different way by describing a variety of processes which we *do* know to operate during tektite formation, and thus assembling a number of pieces of the puzzle, but still leaving some blank spots open.

Volatilization

Volatilization has most likely affected the composition of tektites in the Australasian strewn field. However, it is important to discuss the extent of volatilization and vapor fractionation from the melt. Walter and co-workers (e.g., Walter and Carron, 1964; Walter, 1967; Walter and Clayton, 1967) have suggested that vapor fractionation was very important in tektite formation, explaining compositional differences because silica is volatilized at high temperatures and oxygen fugacities. Molini-Vesko et al. (1982) have shown that the silicon isotope systematics in tektites are contrary to what would be expected if selective silica volatilization has taken place, and that therefore vapor fractionation may not have played a significant role. This result is supported by potassium isotope studies of Humayun et al. (1994), who found that tektites have potassium isotopic compositions identical to those of terrestrial rocks and that there is no evidence for volatilization. Ridenour (1986) analyzed K, Rb, and Li in indochinites and suggested that some element correlations are in favor of selective volatilization, but acknowledged that imperfect mixing of different source materials would also explain the data. There is little doubt, however, that the most volatile elements (e.g., the halogens, Cu, Zn, Ga, As, Se, Pb) were volatilized from the source rocks upon melting because the Muong Nong–type tektites, suspected to have experienced the lowest temperatures of all tektites, still have a much higher complement than the splash-form tektites (Koeberl, 1992a).

Water in tektites

The low water content of tektites has been cited as a main obstacle for tektite production in an impact (O'Keefe, 1976). Data on the water content of tektites are sparse because earlier

the low contents were difficult to quantify. Gilchrist et al. (1969) provided the first reliable water contents of tektites using infrared spectrometry. Later, more infrared analyses were reported by Engelhardt et al. (1987) and Koeberl and Beran (1988). Tektites in general contain about 0.002–0.02 wt% (20–200 ppm) water; impact glasses range up to about 0.06 wt% (600 ppm) water. Muong Nong–type indochinites have an average content of 0.014 ± 0.003 wt% H_2O, compared to an average of 0.008 ± 0.003 wt% H_2O in three indochinites (and 0.011 ± 0.005 wt% H_2O in 12 tektites from various locations of the Australasian strewn field) (Koeberl and Beran, 1988; Gilchrist et al., 1969). This is consistent with the higher contents of other volatile elements in Muong Nong–type tektites (Koeberl, 1992a). The low water content is typical for impact glasses and can be used as convincing evidence for an origin by impact, as has recently been demonstrated by Koeberl (1992b) for the glasses from the Haitian K/T–boundary. It also easily distinguishes tektites from lunar materials, which are bone dry, containing at least six orders of magnitude less water (e.g., Taylor, 1982).

Contrary to earlier belief, it is obviously possible to drive water out of the parent sediments (containing up to several percent water) in the short time available for the tektite production. Glass et al. (1986a, 1988) have shown that atomic-bomb glass—which originated in a short-time, high-temperature event from local sediments—is very dry (0.007 wt% H_2O). The same applies for glasses found at known impact craters. In some preliminary calculations on diffusion coefficients governing the water depletions in tektites, Vickery and Browning (1991) conclude that the calculated depletions are more than sufficient to account for the observed water contents in tektites.

Gases in tektites

Müller and Gentner (1968) studied bubbles in tektites and found that they contain residues of the terrestrial atmosphere at low pressures. Later, Jessberger and Gentner (1972) measured the gas content and composition in bubbles in Muong Nong–type tektites and found that the N_2/Ar ratio, as well as the isotopic ratios of $^{40}Ar/^{36}Ar$, $^{36}Ar/^{38}Ar$, $^{82}Kr/^{84}Kr$, $^{129}Xe/^{132}Xe$, $^{84}Kr/^{132}Xe$, and others, agree very well with the respective atmospheric ratios, providing further evidence for an origin of tektites within the terrestrial atmosphere. Recently, Matsuda et al. (1989) and Matsubara et al. (1991) showed that the ratios of rare gases in impact glasses and tektites are consistent with those of the terrestrial atmosphere, and that, because of its higher mobility, during the long terrestrial residence times, Ne has predominantly diffused into the glass (Matsubara and Matsuda, 1991). Tektites have considerably lower contents of dissolved heavy noble gases than impact glasses, and calculations show that, in order to explain the noble gas contents, tektite glass must have solidified at low ambient pressure, equivalent to a height of about 40 km in the atmosphere (Matsuda et al., 1993). Furthermore, Matsubara et al. (1993) showed that Muong Nong–type tektites contain higher abundances of the heavy noble gases than splash-form tektites (closer to values observed in "normal" impact glasses), and that the isotopic composition of Ne in vesicles in Muong Nong–type tektites is practically identical to that of the terrestrial atmosphere.

The "age paradox"

The Hydra of the so-called age paradox occasionally rears its heads and needs to be addressed at least briefly, even though not part of the tektite formation process. The stratigraphic age of many Australasian tektites found on land was reported to be younger than their radiogenic age, around 7000–24,000 years, and some authors have suggested that this argues against a relationship between microtektites and tektites, and that tektites only fell around 7000–24,000 years ago (e.g., Lovering et al., 1972; Chalmers et al., 1976). On the other hand, Gentner et al. (1970), and others, showed that microtektites found in the Australasian tektite strewn field have the same fission track age of 0.7 Ma, which is in perfect agreement with the stratigraphic age of Australasian microtektites (e.g., Glass, 1978; Glass et al., 1979). Glass and Wu (1992b) have searched deep-sea sediments less than 20000 years old from 46 deep-sea drill cores for evidence for any Australasian microtektites. They did not find any indication for a younger event.

All chemical, isotopic, and age data show unambiguously that microtektites and tektites have been produced in the same event. Also, in all the other strewn fields, generally tektites are not found only in more recent sediments, but sometimes occur in the stratigraphic position corresponding to the formation age. The co-occurrence of tektites, microtektites, and impact debris at Barbados and DSDP Site 612 in the North American strewnfield is of great importance. The evidence for an immediate link with an impact event has been strengthened by the discovery of shocked minerals and impact glasses together with microtektites in several deep-sea sediments of the Australasian and North American strewn fields (Glass and Wu, 1992a, 1993). The combined occurrence of tektites, microtektites, and shocked minerals not only provides proof for the association of microtektites and tektites, but effectively eliminates the age paradox. Furthermore, in a recent study Fudali (1993) showed that the proposed stratigraphic age of 5000–15,000 years for some australites is demonstrably incorrect. He finds a minimum stratigraphic age of 250,000 years for tektite-bearing sediments in Australia. Erosion, transport, and redeposition processes must be held responsible for the apparently young stratigraphic ages, and only one impact/formation event per strewn field needs to be considered.

Meteoritic component in tektites

The geochemistry of tektites from all strewn fields is indistinguishable from that of the recent terrestrial upper crust. No meteoritic component is easily recognizable, which is not

surprising because the meteorite is completely vaporized upon impact. The impact energy is sufficient to vaporize and/or melt a volume of target rocks that is one to three orders of magnitude larger than that of the impactor. However, it is well known from lunar and terrestrial impact melts that they contain up to several percent of meteoritic component (e.g., Morgan et al., 1975; Morgan, 1978; Palme, 1980; Palme et al., 1978, 1979). The identification of a meteoritic component in tektites has proven to be quite frustrating. A few philippinites contained some Ni-rich iron spherules, but this could have been due to in-situ reduction of target rocks (Ganapathy and Larimer, 1983). The Ivory Coast tektites seem to show slightly elevated levels of Ir and other siderophile elements thought to be characteristic of meteorites (Palme et al., 1978, 1981), but of course it was not possible to exclude the target rocks as source. Asaro et al. (1982) and Ganapathy (1982) found enrichments or Ir in drill cores from the North American strewn field at the same position where clinopyroxene spherules (but not microtektites; Keller et al., 1987) had been found, but no meteoritic component was found in the tektites. Moldavites and Australasian tektites have been analyzed, but no significant siderophile-element concentrations were measured, with only one exception: Morgan (1978) found one H-Mg australite (out of six analyzed) that was enriched in platinum-group elements.

Recently, Schmidt et al. (1993) and Koeberl (1993b) found evidence for an Ir anomaly in deep-sea sediments associated with the Australasian microtektite-bearing layer in Ocean Drilling Program (ODP) core 758B (east of Malaysia, in the southern part of the Bay of Bengal). Another interesting development is the discovery of a meteoritic signature (elevated Ir concentrations) in the bottle-green microtektites (Koeberl, in preparation), showing that any meteoritic component is inhomogeneously distributed in the various types of ejecta.

The recent improvement of analytical techniques, however, made it possible to use the very characteristic osmium isotope system to search for the fingerprint of a meteoritic component in tektites (Koeberl and Shirey, 1993a, 1993b). During partial melting of mantle rocks, Re is moderately incompatible, while Os is highly compatible and retained in the residue. Thus melts derived from the mantle at low to moderate degrees of melting have high Re but low Os concentrations, resulting in high Re/Os ratios, and Re concentrations in crustal rocks that are one to three orders of magnitude higher, and Os concentrations one to five orders of magnitude lower than in mantle rocks (see Koeberl and Shirey, 1993b). As a result of the high Re concentrations, crustal rocks accumulate significant abundances of ^{187}Os. On the other hand, meteorites have high Os abundances, and isotopic ratios that are distinct from those of old continental crust are substantially less radiogenic. Meteorites (and mantle rocks) have low $^{187}Os/^{188}Os$ ratios of about 0.11 to 0.18 ($^{187}Os/^{186}Os$ = 0.95–1.5). Isotopic ratios of crustal rocks are variable, depending on crustal extraction age but $^{187}Os/^{188}Os$ ratios of about 0.67 and 1.61 ($^{187}Os/^{186}Os$ = 5.6–13.4) are typical for old crustal rocks. For the study of impact craters and glasses, Os isotopes allow the confirmation of an origin by impact, and an understanding of the mixing between the bolide and target rocks. The absolute abundances of Os as well as the $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ ratios in meteorites are distinctly different from those in old crustal target rocks, and due to the considerably higher concentrations of Os in meteorites, even a very small meteoritic component, otherwise difficult to measure, will yield a characteristic Os isotope ratio. Thus Os isotopes are able to provide proof for the existence and quantification of extraterrestrial components in impact glasses and impact breccias. First results for the Ivory Coast tektites unambiguously show the existence of about 0.05–0.1% meteoritic component (Koeberl and Shirey, 1993a, 1993b). The isotope systematics of other tektites are currently being explored (Koeberl and Shirey, in preparation).

A very important problem, however, remains unsolved. Attempts to identify a specific type of meteorite as impactor have so far remained without success, although some suggestions (e.g., an iron projectile for Ivory Coast tektites, or an aubrite for the moldavites; Palme et al., 1981; Morgan et al., 1979) have been made. In their study of the Re-Os isotopic characteristics of Ivory Coast tektites, Bosumtwi impact glass, and Bosumtwi crater target rocks, Koeberl and Shirey (1993b) found that some target rocks have Os contents not significantly different from those of the tektites. This confirms a suspicion by Jones (1985) who argued that the enrichments of Ir, Ni, Co, and Cr in the tektites may be due to elevated contents of these elements in the target rocks due to gold mineralizations in the crater area. However, Koeberl and Shirey (1993b) have been able to show unequivocally the extraterrestrial nature of the Os in the tektites, which also indicated Os and Re fractionation during the impact. It becomes thus clear that isotopic ratios are much better and sensitive indicators than elemental abundances. It may very well be that the problem of identifying the projectile type is close to impossible to solve: recent studies of impact glasses at craters where the meteorite has been preserved have shown that the siderophile elements are fractionated into the melt in a way that is neither linked to their volatility nor any other recognizable factor (Attrep et al., 1991; Hörz et al., 1989; Mittlefehldt et al., 1992a, 1992b). Therefore, even if some siderophile element ratios can be determined, it is not clear how extensively they were affected by fractionation.

Be-10 and the target stratigraphy

The study of cosmogenic radionuclides not only provides further proof of a terrestrial origin of tektites, but also direct evidence on the nature of the sedimentary precursor and the target stratigraphy. Pal et al. (1982) were the first to demonstrate that the ^{10}Be content of Australasian tektites cannot have originated from direct cosmic ray irradiation in space or on earth, but can only have been introduced from sediments that have absorbed

^{10}Be that was produced in the terrestrial atmosphere. This conclusion was supported by additional studies of the concentrations of ^{26}Al and ^{53}Mn by Yiou et al. (1984) and Englert et al. (1984). The concentration of ^{26}Al is of crucial importance: if tektites were ever exposed to cosmic radiation in space to produce the observed ^{10}Be concentration, then the ^{26}Al/^{10}Be ratio must be between 2.7 and 5.4, depending on the details of the irradiation. Middleton and Klein (1987) found that the ^{26}Al concentration in tektites is so low that they were able to measure its concentration in only one sample, giving a ^{26}Al/^{10}Be ratio of about 0.07. In the meantime, ^{26}Al concentrations were measured in several other Australasian tektites, with the same result (F. Tera, 1992, personal communication). This proves that the ^{10}Be in the tektites has its source in atmospheric fallout accumulated in terrestrial sediments.

The study of ^{10}Be is also very important for the understanding of the target stratigraphy. I have shown before, using a variety of arguments (see previous discussions), that tektites seem to have been derived from the surface of the target rocks and cannot have originated from great depth. The understanding of the ^{10}Be distributions provides further proof for this argument. The concentration of ^{10}Be in the environment is a strict function of the depth from the surface. Pavic et al. (1983) and Valette-Silver et al. (1983) have studied ^{10}Be concentrations and their vertical distribution in soils and sediments and found that most of it is concentrated in the upper 20 m. This limit may be variable as a function of different rock types, rainfall rate, and porosity, but probably by less than a factor of 10. Blum et al. (1992) have calculated that mixing of a 200-m column of bedrock into the surficial cover that contains the ^{10}Be explains the ^{10}Be concentrations observed in Australasian tektites.

This observation is critical for our understanding of the tektite production process. Tektites are made exclusively from the top few hundred meters of the target stratigraphy; no other model can explain the ^{10}Be systematics. This may be an unpopular notion as some researchers want to involve deeper stratigraphic units (e.g., Premo and Izett, 1992; see discussion in Koeberl, 1993a). Because of the 1.5 Ma half-lie of ^{10}Be, the concentrations in moldavites and North American tektites have dropped below a measurable level. However, the finding of ^{10}Be is not confined to Australasian tektites, but has also been found in Ivory Coast tektites, and the evaluation of other impact glasses (e.g., Aouelloul) has confirmed the interpretation of the target stratigraphy (Tera et al., 1983a, 1983b; Raisbeck et al., 1988). The absolute concentrations of ^{10}Be in the various types of Australasian tektites allow another important conclusion. The ^{10}Be concentrations in australites are higher than those in indochinites and philippinites, which, in turn, are higher than those in Muong Nong-type tektites (Tera et al., 1983a, 1983b; Pal et al., 1982; Raisbeck et al., 1988; J. Klein, 1992; personal communication). This allows the unambiguous conclusion that australites (which experienced the highest temperatures and are the most distant ejecta) were made from material very close to or at the surface, while the Muong Nong–type tektites originated from a slightly deeper unit, in complete agreement with impact mechanics and compositional data.

Reduction during impact

Tektites are known to be relatively reduced glasses, as shown by their low ferric to ferrous iron ratios (e.g., Fudali et al., 1987). Geochemical arguments were used to infer that, although the tektite glass is now reduced, its precursor materials were more oxidized (e.g., Delano et al., 1987), in agreement with sedimentary sources. The existence of iron spherules in a few tektites and impact glasses was attributed to in-situ reduction of target material. It seems fairly clear that the impact process is reducing, but the reason for that has not been studied. Florenski et al. (1978) suggested that structural changes during quenching may play a role. Recently, Jakes et al. (1991, 1992) have discussed the importance of superheating, and that superheated melts are reduced. This model may very well be valid, although we do not know in which state the tektite material is after impact melting, or, what the size distribution of the melt droplets is. Engelhardt et al. (1987) suggested that the tektite material is completely vaporized to a plasma state, and then recondensed in the form of coalescing droplets. It seems, however, that in such a model the relatively close compositional similarity between the tektites and their source rocks would be lost. I suggest that impact reduction may very well occur in superheated melts, induced by electron transfer in the extremely hot expanding vapor cloud of the impact.

CONCLUSIONS AND REMAINING QUESTIONS

Our understanding of the tektite-production process has substantially improved over the past two decades, mainly due to the collection of more and more high quality data (chemical and isotopic composition, age), and the discovery of some new occurrences of tektites. More and more pieces of the puzzle fall into place, as I have tried to show in the previous chapters. We are still not in possession of the "grand unified theory" of tektite origin, but we share this predicament with some other sciences. I am convinced that over the next two decades we will get much closer to filling the remaining gaps in our understanding. Some of the important open questions that remain follow. Several new occurrences of impact glasses have been found recently (e.g., Smit et al., 1992; Izett, 1991; Koeberl, 1992b; Claeys et al., 1992), which, after careful study, may eventually turn out to be indeed new tektites.

Despite the identification of two tektite-source craters and some good hints regarding the source areas for the remaining two strewn fields, the exact target rocks from which tektites have been produced are, however, not known. There are numerous reasons for this: e.g., during the impact, melting of a variety of target rocks occurred; we still do not understand the

exact physical and chemical processes which may alter the chemical composition during impact (i.e., unspecific fractionation); impact mixing is a nonequilibrium and heterogeneous process; also, tektites are most probably produced in the earliest stages of impact, which are poorly understood. Recent experiments have helped to better understand the ejection and distribution of tektites during the early phases of the impact. Ballistic shadowing helps to confine early high-speed ejecta and helps some of them to escape the atmosphere (Schultz and Sugita, 1994).

Obviously, the production of tektites requires special conditions, because otherwise more than just four tektite strewn fields would be known on earth, as there are about 150 known impact craters (Grieve, 1991, lists 131 craters, and some have since been discovered). It is possible that low-angle impact is important because of the asymmetric distribution of tektites within a strewn field. This is true for all four cases: where craters are known to be associated with tektite fields, the craters are never in the center of the strewn field. Tektite production has to occur before the main excavation phase of the crater formation has started. Numerous arguments have been presented here that show that tektites had to originate from target rock layers close to the surface. For example, it is otherwise not possible to explain their ^{10}Be content. The resulting melts may very well be superheated and are reduced due to electron transfer processes in the expanding vapor plume which is also important in distributing the large quantities of tektite material (on the order of 10^9 t for the two larger strewn fields) over distances of up to 6,000 km. In our attempt to understand the tektite-production process, we only begin to grasp the magnificent and violent magnitude of meteorite impact.

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