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Establishing the link between the Chesapeake Bay impact structure and the North American tektite strewn field: The Sr-Nd isotopic evidence

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Abstract–The Chesapeake Bay impact structure, which is about 35 Ma old, has previously been proposed as the possible source crater of the North American tektites (NAT). Here we report major and trace element data as well as the first Sr-Nd isotope data for drill core and outcrop samples of target lithologies, crater fill breccias, and post-impact sediments of the Chesapeake Bay impact structure. The unconsolidated sediments, Cretaceous to middle Eocene in age, have $\varepsilon_{Sr}^{t = 35.7\ Ma}$ of +54 to +272, and $\varepsilon_{Nd}^{t = 35.7\ Ma}$ ranging from −6.5 to −10.8; one sample from the granitic basement with a T^{Nd}_{CHUR} model age of 1.36 Ga yielded an $\varepsilon_{Sr}^{t = 35.7\ Ma}$ of +188 and an $\varepsilon_{Nd}^{t = 35.7\ Ma}$ of −5.7. The Exmore breccia (crater fill) can be explained as a mix of the measured target sediments and the granite, plus an as-yet undetermined component. The post-impact sediments of the Chickahominy formation have slightly higher T^{Nd}_{CHUR} model ages of about 1.55 Ga, indicating a contribution of some older materials. Newly analyzed bediasites have the following isotope parameters: +104 to +119 ($\varepsilon_{Sr}^{t = 35.7\ Ma}$), −5.7 ($\varepsilon_{Nd}^{t = 35.7\ Ma}$), 0.47 Ga ($T^{Sr}_{UR}$), and 1.15 Ga ($T^{Nd}_{CHUR}$), which is in excellent agreement with previously published data for samples of the NAT strewn field. Target rocks with highly radiogenic Sr isotopic composition, as required for explaining the isotopic characteristics of Deep Sea Drilling Project (DSDP) site 612 tektites, were not among the analyzed sample suite. Based on the new isotope data, we exclude any relation between the NA tektites and the Popigai impact crater, although they have identical ages within 2σ errors. The Chesapeake Bay structure, however, is now clearly constrained as the source crater for the North American tektites, although the present data set obviously does not include all target lithologies that have contributed to the composition of the tektites.

INTRODUCTION

Tektites are glass bodies produced during hypervelocity impact events by melting of near-surface lithologies (see, for example, Shaw and Wasserburg 1982; Horn et al. 1985; Glass 1990; Koeberl 1994) that are ejected from the source crater at an early stage of cratering and deposited in geographically and stratigraphically defined strewn fields far off their point of origin. According to Artemieva (2002), the most favorable conditions for tektite production are impact angles between 30 and 50°; the molten material travels at velocities on the order of 10 km s^{-1} in the expanding vapor plume. During final settling at velocities of some tens of meters per second, cooling produces the shapes that are a characteristic feature of tektites.

At present, four tektite strewn fields are known, i.e., 1) the Australasian of 0.79 Ma age, for which a source crater has not yet been discovered; 2) the 1.07 Ma Ivory Coast strewn field, related to the Bosumtwi crater, Ghana; 3) the 15 Ma Central European ("moldavite") strewn field, produced in the Ries event; and 4) the 35.5 Ma North American (NAT) strewn field, whose source crater is the topic of this contribution. In addition, some impact melt glasses, such as the urengoites in Russia (Deutsch et al. 1997), display properties similar to those of the classic tektites, except that the extent of the regional distribution of these "tektite-like" objects is unknown due to the low number of samples.

Chemically more variable than normal tektites are microtektites and microkrystites (e.g., Glass and Burns 1987; Glass et al. 2004a). By definition, the size of both types of

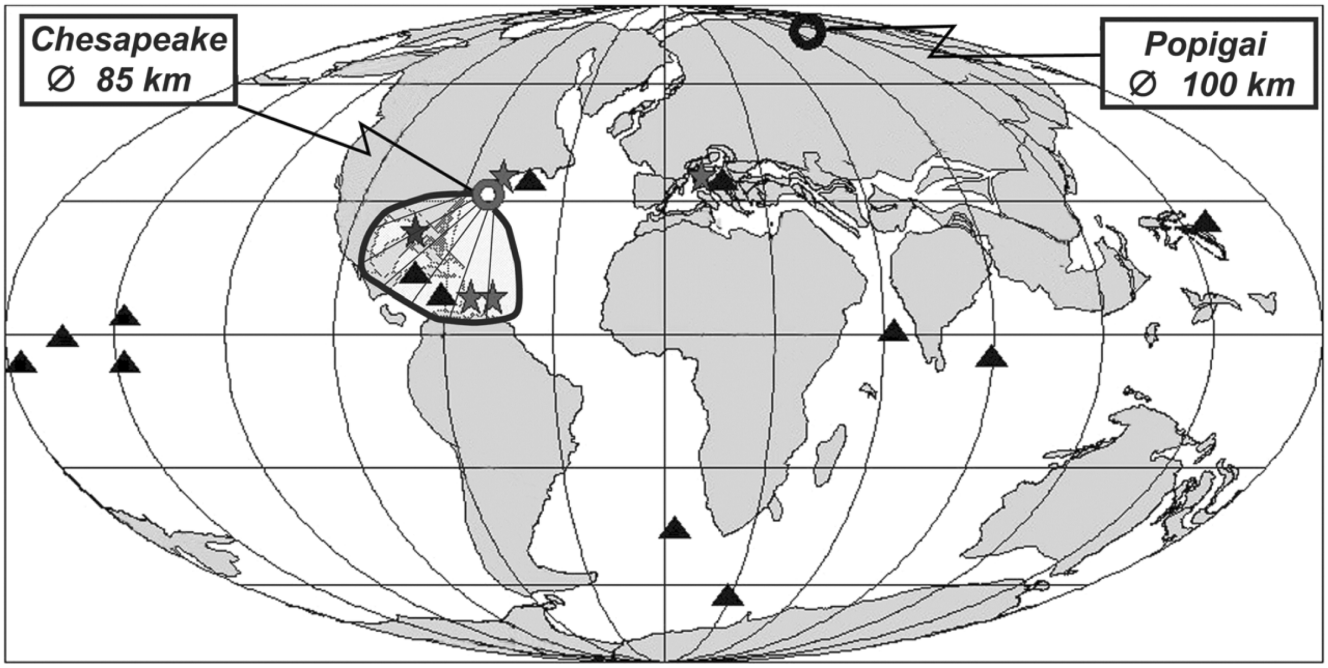

Fig. 1. The global distribution of ejecta material in the Upper Eocene (according to Simonson and Glass 2004) and the locations of the Popigai and Chesapeake Bay impact craters. Plate tectonic reconstruction for t = 35 Ma was done with the Internet tool by Schettino and Scotese (2001). Ø = diameter of the final crater. Triangles stand for locations containing Popigai ejecta material, stars for those with Chesapeake Bay–related ejecta. The North American tektite strewn field is outlined by a black line. Note that, according to Collins and Wünnemann (2005), the final Chesapeake Bay impact crater would have had only a diameter of about 40 km if it had formed on land.

objects ranges up to 1 mm (although spherules up to about 2 mm have also been reported). Microkrystites probably represent condensates from the most energetic part of the expanding vapor plume; they contain characteristic primary quench crystals (e.g., Smit et al. 1992; Glass et al. 2004a). Several stratigraphic levels with microtektites and microkrystites are known, with the global layer at the Cretaceous/Tertiary (K/T) boundary being the most prominent example (for reviews, see Smit 1990; Schulte and Kontny 2005). The occurrence, the stratigraphic distribution of such "spherule layers," their relation to other ejecta debris, and the correlation to respective source craters (if known) have recently been reviewed by Koeberl and Martinez-Ruiz (2003) and Simonson and Glass (2004).

LATE EOCENE IMPACTS

The Late Eocene is a period of major environmental changes, including accelerated global cooling (e.g., Prothero et al. 2003, and references therein), with a sharp temperature drop of about 2 °C just before the Eocene/Oligocene (E/O) boundary (Vonhof et al. 2000; Bodiselitsch et al. 2004). At least two distinct, closely spaced impact spherule layers have been identified in upper Eocene marine and terrestrial sediments (e.g., Glass 2002, and references therein). The characteristics of these two spherules layers are:

1) The younger one covering an area of at least 8 × 10^6 km^2 in the Gulf of Mexico, the Caribbean Sea, and the western North Atlantic (Fig. 1) contains tektite fragments, microtektites, shocked mineral and rock fragments, as well as reidite, a high pressure polymorph of zircon (e.g., Glass 1989; Glass et al. 2002). Using ^{40}Ar/^{39}Ar laser probe techniques, Glass et al. (1986) established an age of 35.4 ± 0.6 Ma (2σ) for tektite fragments from Barbados, which is indistinguishable from ^{40}Ar/^{39}Ar plateau ages for bediasites of the NAT strewn field (Bottomley 1982). The ^{40}Ar/^{39}Ar step-heating dating on microtektites from Deep Sea Drilling Project (DSDP) site 612, located in offshore New Jersey, USA, yielded 35.2 ± 0.3 Ma and 35.5 ± 0.3 Ma (Obradovich et al. 1989), and new data by Horton and Izett (2005) resulted in a weighted mean total fusion ^{40}Ar/^{39}Ar age of 35.3 ± 0.2 Ma (2σ) for four North American tektites. When seismic data and results from shallow drill cores indicated the presence of an impact structure underneath the Chesapeake Bay at the Atlantic coast of Virginia and Maryland, a connection of the NAT and the North American spherule layer to the Chesapeake Bay impact event was discussed (e.g., Poag et al. 1994; Koeberl et al. 1996; Glass et al. 1998; Montanari and Koeberl 2000; Whitehead et al. 2000). Poag et al. (2004) assume a diameter of about 85 km for the Chesapeake Bay impact structure, yet such a large size has been questioned by Collins and Wünnemann (2005), who note that the crater would only be about 45 km in diameter had it formed on land. Recent findings indicate that debris related to the Chesapeake Bay impact event has a much

wider distribution than outlined above: Harris et al. (2004) described the presence of shocked quartz from Georgia, USA. Bodiselitsch et al. (2004) reported two closely spaced Ir anomalies at the Late Eocene section of Massignano, Italy; the lower one contains shocked minerals and other impact debris and is correlated with the Popigai impact event (see below), whereas the upper one is most likely correlated with the Chesapeake Bay impact event. The approximately 35 Ma old Chesapeake Bay impact structure is the target of a major international scientific drilling effort financed and coordinated by the International Continental Scientific Drilling Program (ICDP) and the U.S. Geological Survey (USGS) (cf. Edwards et al. 2004); this successful drilling commenced in September 2005 and was concluded in December 2005. Studies of the drill core samples will allow a more detailed correlation between rock types than presently possible.

2) The older spherule layer (e.g., Glass et al. 1985; Glass and Burns 1987) is known to occur in the Pacific, North and South Atlantic, the Indian Ocean, and the Antarctic Sea, as well as in Italy. This geographic spread (Fig. 1) indicates a global distribution of this ejecta layer, although the number of documented spherule occurrences is much less than for the K/T boundary. This second Late Eocene spherule layer includes melanocratic (dark) and leucocratic microkrystites, clear glass particles (microtektites) as well as shocked minerals (Clymer et al. 1996; Langenhorst 1996), a platinum group element anomaly, and exotic Ni-rich spinel crystals (e.g., Pierrard et al. 1998; Glass et al. 2004b, and references therein). Compared to dark varieties at given silica content, the light-colored microtektites are enriched in CaO and MgO and depleted in Al_2O_3, FeO, TiO_2, and the alkali elements. In undisturbed sections of deep-sea cores from the western Atlantic Ocean, this layer is separated from the upper one by 5–25 cm of sediments (equivalent to 3–20 kyr deposition; Glass et al. 1985, 1998; Glass and Koeberl 1999), yet separation of both layers turned out problematic in the past at several locations (for discussion, see Poag et al. 2004 and references therein). This second layer is commonly referred to as the clinopyroxene (cpx) spherule layer, as cpx-bearing microkrystites form the prominent characteristic of this ejecta deposit (e.g., Glass and Koeberl 1999). Although the microtektites of both layers are geochemically very similar (e.g., Glass et al. 1998), isotopic data (Shaw and Wasserburg 1982; Ngo et al. 1985; Stecher et al. 1989) indicate that these older microtektites and microkrystites belong to an ejecta layer different to the one represented by the North American tektites (Fig. 2).

Compared to glassy ejecta in other strewn fields, the microkrystites and associated microtektites of the older (lower) Late Eocene "spherule layer" show large variations in ε_{Sr}, and especially in ε_{Nd} (e.g., Stecher et al. 1989). On the basis of the isotope data, the global spherule layer was assigned to a cratering event different from Chesapeake, namely Popigai (e.g., Vonhof 1998; Whitehead et al. 2000; Liu et al. 2001). The Popigai impact crater, Siberia, which is about 100 km in size is dated at 35.7 ± 0.2 Ma (2σ) ($^{40}Ar/^{39}Ar$ step-heating data; Bottomley et al. 1997), and thus the two largest Cenozoic impact craters originated within a time span of just a few thousand to hundred thousand years (e.g., Odin and Montanari 1989; Montanari and Koeberl 2000).

A detailed geochemical and Sr,Nd isotope survey of target and impact melt lithologies finally established that the very broad range of Popigai target lithologies indeed represents the precursor material for melanocratic and leucocratic microkrystites as well as for the associated microtektites (Kettrup et al. 2003). Moreover, the isotope compositions and model parameters of the ejecta material allow constraining their origin from the uppermost layers at lithologically different and geographically defined parts of the Popigai target area. This explains why the microtektites and microkrystites of the cpx spherule layer display much more variable geochemical compositions compared to tektites from other strewn fields.

In their study, Kettrup et al. (2003) employed isotopic fingerprinting techniques, which have been used successfully in a number of investigations regarding questions on how and where tektites and other glassy ejecta material originates in an impact event (e.g., Tilton 1958; Taylor and Epstein 1962; Shaw and Wasserburg 1982; Horn et al. 1985; Ngo et al. 1985; Blum et al. 1992; Stecher et al. 1989; Deutsch et al. 1997; Stecher and Baker 2004). In general, these ejecta materials display restricted ranges in Pb, Sr, Nd, and O isotopic signatures, which in turn help to characterize the target material at the (unknown) source crater in terms of geochemical parameters, such as mean crustal residence time or timing of the last Rb/Sr fractionation event. The concept behind this approach is that general geochemical characteristics of the precursor lithologies, and especially isotopic compositions, remain unchanged in the impact melting process, which in turn enables unambiguous assessment of the provenance of the ejecta. Although no solid proof exists, it is also assumed that vaporization-condensation to form microkrystites does not change the isotope ratios of Pb, Sr, and Nd.

This paper presents major and trace element data, as well as Rb/Sr and Sm/Nd isotope data for post-impact sediments directly capping the within-crater breccia lens, for one sample of the breccia fill of the Chesapeake Bay crater, sedimentary target rocks likely to have been present near the surface of the impact site, and a basement granite sample, in comparison to data for bediasites from the NAT strewn field.

SAMPLES AND ANALYTICAL TECHNIQUES

Poag et al. (2002, 2004, and references therein) provide much detail on the Chesapeake Bay structure, including information on the crater fill, target materials, and post-impact formations. Samples investigated in this study are thought to

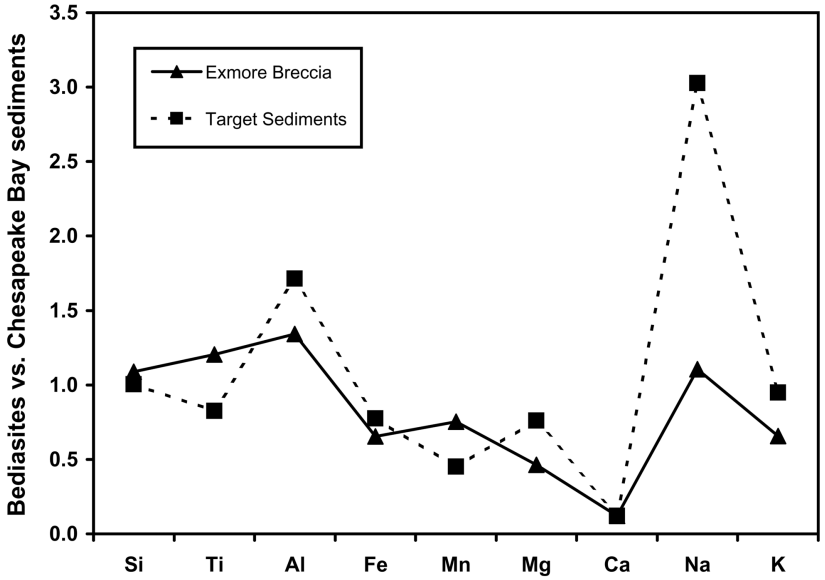

Fig. 2. a) The elemental ratios of the average composition of bediasites versus those of average Exmore breccia (Poag et al. 2004) and average target sediment (this work) for major element abundances.

cover most of the important target rocks at the Chesapeake Bay impact site. The samples analyzed include a granitic basement sample, Exmore breccia from the Exmore core, and several specimens of the sediments overlying the basement that range in age from Cretaceous to Eocene. Among target samples, we have analyzed 1) sedimentary lithologies, which are unconsolidated siliciclastics ranging in composition from clays and silts, to the dominant shell-rich quartz sands (see Poag et al. 2004 for details of the geological setting and stratigraphy), and 2) one clast of the crystalline basement.

1) Samples CR-1 and CR-2 are from the Jamestown core, Virginia, USA (37°14′N, 76°47′W), at the depths of 261.8–261.9 and 272.9–273.1 ft, respectively. Sample CR-3 is from the Dismal Swamp core, North Carolina, USA (37°37′N, 76°44′W), at a depth of 776.8–777.0 ft. All three samples represent non-marine sediments of the lower Cretaceous Potomac formation.

Samples PR-3 and PR-4 from the Pamunkey River outcrops, Virginia, USA, both belong to the Paleocene Aquia formation; samples PR-1 and PR-5 are from the Pamunkey River, Virginia, representing the lower Eocene Nanjemoy formation, and sample PR-2, which is also from the Pamunkey River, represents the middle Eocene Piney Point formation. All the latter are undisturbed marine target sediments. The location of the Pamunkey River outcrops is at about 37°46′N and 77°20′W, approximately 30 to 50 km outside the crater rim (see Poag et al. 2004).

2) The pinkish granite fragment Ba2372 from core Bayside #2 was a single piece several cm large with green staining (chlorite) along the fractures. Carefully avoiding these altered parts, we cut out a piece from the central part of the sample. Preliminary U-Pb dating results for zircon point to a Neoproterozoic crystallization age for this type of basement lithology (625 ± 11 Ma [2σ]; SHRIMP data; Horton et al. 2004).

The Exmore breccia sample is inferred to be an average of the target lithologies that contributed to the crater fill breccia (from the Exmore core at 1283.1 ft depth).

Samples CH-1, from the Windmill Point core at 448.45 ft, and CH-2, from the Exmore core at 1206.75 ft depth, are both from the late Eocene Chickahominy formation, which is the earliest neritic post-impact formation lying conformably on the breccia lens (Poag et al. 2004).

Three bediasites, T8-2267 (Brazos County, Texas, USA), T8-2061 (Grimes County, Texas, USA; meteorite collection of the University of Münster), and Be 8402 (University of Vienna; precise location unknown) were also analyzed. Bediasites are the most common species of the NAT strewn field and have been analyzed here to allow comparison with the existing database for NA tektites (Shaw and Wasserburg 1982; Ngo et al. 1985; Stecher et al. 1989). The samples were uncrushed solid pieces from the central parts of the respective tektites, cleaned according to procedures described by Ngo et al. (1985).

Major and trace element contents were determined using standard X-ray fluorescence spectrometry (University of the Witwatersrand) and instrumental neutron activation analysis at the University of Vienna (for details of the methods, see Reimold et al. 1994 and Koeberl 1993, respectively). The Rb-Sr and Sm-Nd analyses were performed with thermal ionization mass spectrometers at the Zentrallabor für Geochronologie, Universität Münster (ZLG Münster). For details of the analytical techniques and data treatment, see the footnotes to Table 2 and Deutsch et al. (1997).

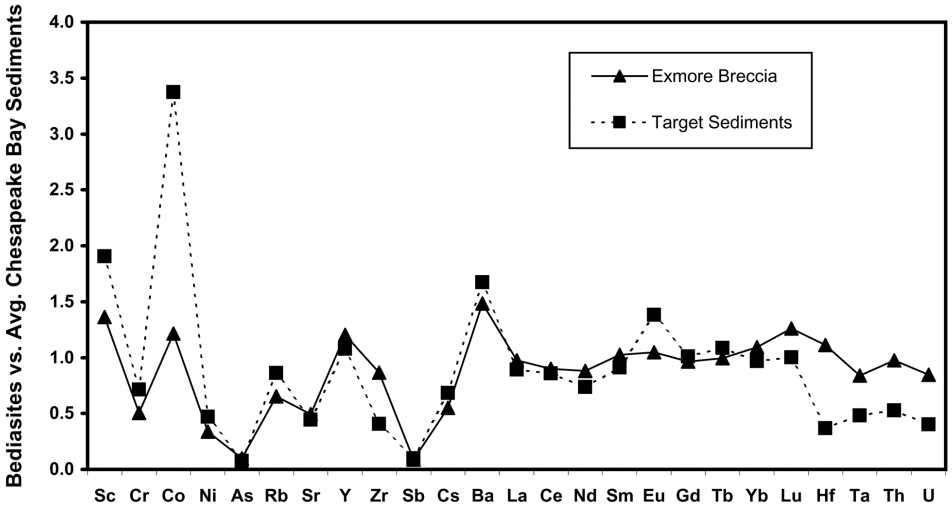

Fig. 2. *Continued.* b) The elemental ratios of the average composition of bediasites versus those of average Exmore breccia (Poag et al. 2004) and average target sediment (this work) for trace element abundances.

RESULTS

Major and Trace Elements

The major and trace element compositions of the eight sediment samples (PR-1 to PR-5; CR-1 to CR-3), which are thought to be representative of the upper target rock section, are reported in Table 1a. This table also gives data for two samples of post-impact sediments (CH-1, CH-2) and the average composition of the Exmore crater fill breccia for comparison. This average composition is based on chemical analyses of 40 Exmore breccia samples from three drill cores. The Exmore breccia is assumed to be a representative mixture of the target rocks at Chesapeake Bay (cf. Poag et al. 2004). In order to allow better comparison with the average composition of the NA tektites (average bediasites and georgiaites) (Table 1b), we recalculated all of the compositions on a volatile-free basis. The ratios between the average composition of bediasites, the Exmore breccia, and an average calculated from the target sediments, are shown in Figs. 2a and 2b for major and trace elements. It is immediately obvious that neither the average crater fill breccia nor the average target sediment is a precise match for the elemental composition of the tektites. This is not too surprising, given the range of compositions exhibited by the various target sediments. For example, the silica content ranges from about 50 to 90 wt% (volatile-free), and the CaO content varies from 0.2 to 20 wt%. For recalculation of the target sediment compositions to a volatile-free basis, the loss on ignition was taken into account, yet the effects due to natural decarbonation or volatilization cannot be assessed.

Compared to the Exmore breccia and the target sediments, the tektites are depleted in volatile trace elements (e.g., Br, As, Sb, Zn), but abundances of the more refractory or lithophile elements match within a factor of about two those in the tektites. This is illustrated in Fig. 3, which shows the chondrite-normalized rare Earth element (REE) distribution patterns of the target sediments in comparison with data for average Exmore breccia, bediasites, and georgiaites. Both types of tektites have quite similar REE patterns, yet significant differences in the total REE abundances. This compositional range would be even more extended if tektites from DSDP site 612 (Glass et al. 1998) or microtektites (Glass et al. 2004a) were included. We note, however, the close similarity between the REE patterns of the tektites and those of some of the target lithologies, as well as the Exmore breccia. The data, however, does not allow us to uniquely assign a specific target sediment, or even a combination thereof, as precursor of the tektites. Unknown amounts of loss of volatile components, weathering and alteration of the lithologies that were analyzed (see also Poag et al. 2004), and the possibility of missing components make it impossible to make such a specific assignment based on chemical compositions alone. The proper evaluation of a link between the Chesapeake Bay target materials and the tektites therefore requires the use of isotopic data.

Radiogenic Isotopes

Table 2 gives the results of the isotope analyses, which have been previously published in part in an abstract (Deutsch 2004). The target sediments display a wide spread in Rb and Sr concentrations, Rb/Sr ratios (0.0718 to 2.08), $^{87}Sr/^{86}Sr$ ratios, and Sr model ages T^{Sr}_{UR}. The latter range from 0.24 Ga up to 2.14 Ga (PR-2), which exceeds the T^{Nd}_{CHUR} model age of this sample (0.95 Ma) and is considered geologically unrealistic. The variations in the Rb and Sr contents may reflect different amounts of phyllosilicates and feldspar in the

Table 1a. Major and trace element composition of post-impact and target sediments from the Chesapeake Bay crater area, and for the Exmore breccia (crater fill).

	CH-1 Chickahominy Fm.	CH-2 Chickahominy Fm.	PR-1 Nanjemoy F. Potapaco M.	PR-2 Piney Pt. F. Bed A	PR-3 Aquia F. Paspotansa M.	PR-4 Aquia F. Piscataway M.	PR-5 Nanjemoy F. Woodstock M.	CR-1 Potomac F. JT 261.8–261.9	CR-2 Potomac F. JT 272.9–273.1	CR-3 Potomac F. DS 776.8–777.0	Exmore breccia[a]			
											Average	Std. dev.	Range minimum	Range maximum
SiO_2	40.01	46.35	65.92	55.77	65.35	54.25	73.42	83.38	89.69	65.40	64.47	10.14	32.65	85.31
TiO_2	0.61	0.67	0.79	0.50	0.84	1.18	1.28	0.67	0.14	1.17	0.58	0.22	0.02	0.92
Al_2O_3	13.44	13.86	9.16	3.75	7.97	4.50	5.87	7.07	4.00	15.88	9.44	2.86	3.12	16.13
Fe_2O_3	9.75	4.89	9.26	4.04	6.55	5.82	5.56	1.32	0.78	5.26	5.92	2.73	0.76	18.61
MnO	0.06	0.06	0.08	0.07	0.07	0.10	0.08	0.04	0.01	0.02	0.04	0.02	0.01	0.09
MgO	2.71	1.66	1.78	0.88	0.89	0.84	0.72	0.23	0.00	0.53	1.25	0.62	0.06	3.82
CaO	10.19	10.44	0.70	17.33	0.34	16.34	0.92	0.33	0.20	0.31	4.91	5.33	0.34	26.78
Na_2O	0.42	0.74	0.18	0.16	0.16	0.27	0.19	1.23	0.84	0.78	1.28	0.41	0.12	2.14
K_2O	2.69	2.00	3.35	1.38	1.80	1.97	1.67	2.35	2.52	0.91	2.92	0.90	1.65	7.24
P_2O_5	0.21	0.09	0.14	0.13	0.08	0.05	0.06	0.02	<0.01	0.03	0.37	0.56	0.04	2.93
LOI	18.98	18.39	8.13	15.52	15.35	14.53	9.50	2.73	1.00	8.81	8.03	4.69	0.43	22.78
Total	99.07	99.15	99.49	99.53	99.40	99.85	99.27	99.37	99.18	99.10	99.21			
Sc	11.2	10.6	10.3	4.49	7.67	6.58	7.13	3.28	1.23	8.02	8.76	3.54	2.02	17.3
V	101	99	123	73	111	132	75	45	18	99	105	28.1	20	138
Cr	128	103	142	56.6	85.2	91.9	66.5	16.5	7.3	19.9	89.0	31.9	11.4	180
Co	3.50	5.59	6.77	3.70	4.29	2.57	3.15	2.93	2.10	3.23	10.2	4.60	1.75	23.2
Ni	40	46	17	13	25	12	24	7	5	18	21.8	9.3	8.0	56
Cu	3	<2	<2	<2	<2	<2	<2	<6	<6	29	<2			
Zn	117	95	98	55	56	43	64	20	8	38	144	136	11	510
As	29.1	17.1	12.5	18.1	22.2	18.3	16.8	2.81	2.11	0.35	9.28	7.99	0.93	42.3
Se	0.8	0.84	0.4	0.2	0.7	0.9	0.5	0.16	0.08	0.14	0.32	0.25	0.03	1.01
Br	9.5	12.4	1.3	2.4	2.1	1.1	1.5	0.20	0.16	10.1	0.65	0.48	0.02	1.50
Rb	110	84.6	142	58.8	77.8	68.7	65.5	53.5	55.7	29.5	93	25.7	57.5	207
Sr	330	412	68	692	52	698	126	136	123	76	233	94	104	513
Y	23	21	36	14	28	20	30	13	8	17	19.1	5.1	5.0	24.0
Zr	165	195	585	320	650	960	1120	145	45	180	244	148	80	776
Nb	13	14	16	10	16	15	20	11	5	20	10.5	2.2	4	15
Sb	1.47	0.87	0.51	0.63	0.80	0.75	0.56	0.14	0.054	0.11	0.52	0.22	0.28	1.30
Cs	5.80	5.67	4.81	2.29	3.78	2.01	2.87	0.59	0.71	1.68	3.01	1.32	0.81	7.84
Ba	171	205	245	75	185	160	165	480	580	205	291	94	51	554
La	26.2	28.6	42.3	33.5	36.8	93.6	40.5	15.8	6.85	6.49	33	28.6	11.3	173
Ce	62.3	52.2	106	85.5	77.9	205	87.7	29.5	15.7	15.6	77.8	89.3	20.2	527
Nd	30.1	26.9	52.9	42.5	39.8	104	45.1	14.7	7.54	7.9	34.5	34.8	10.2	212
Sm	5.04	5.26	9.63	6.37	7.40	18.8	8.32	2.50	1.26	1.23	6.46	5.66	1.78	33.5
Eu	1.11	0.97	1.63	1.03	1.18	1.73	1.21	0.57	0.42	0.36	1.39	1.39	0.26	8.17
Gd	4.45	4.33	6.84	4.64	6.55	14.1	8.11	2.25	0.98	1.22	6.11	4.69	1.90	28.1
Tb	0.62	0.62	1.21	0.71	0.87	1.61	1.25	0.28	0.16	0.22	0.90	0.66	0.27	3.85
Tm	0.33	0.34	0.55	0.35	0.50	0.80	0.76	0.19	0.10	0.12	0.39	0.13	0.16	0.79
Yb	2.03	2.42	3.82	2.25	3.29	4.41	5.33	1.35	0.73	0.85	2.52	0.97	0.99	5.21
Lu	0.31	0.32	0.5	0.33	0.55	0.73	0.80	0.18	0.11	0.12	0.34	0.10	0.14	0.60
Hf	3.65	4.59	17.8	11.9	19.2	35.6	36.2	3.71	1.55	1.77	5.54	2.24	0.89	12.2
Ta	0.78	0.97	1.44	0.87	1.35	1.94	2.16	0.44	0.44	0.21	0.66	0.21	0.13	1.13

Table 1a. *Continued.* Major and trace element composition of post-impact and target sediments from the Chesapeake Bay crater area, and for the Exmore breccia (crater fill).

W	1.6	1.6	2.6	0.8	2.5	1.2	2.8	0.6	0.5	0.6	1.25	1.04	0.10	5.20
Ir (ppb)	<0.5	<0.8	<0.6	<0.3	<0.7	<0.7	<0.7	<0.2	<0.2	<0.3	0.4	0.3	0.1	0.7
Au (ppb)	<1	<2	<1.5	<2	<2	<2	<0.8	<0.6	<0.5	<1	0.8	0.5	0.1	2.4
Th	10.0	9.29	13.6	9.07	13.2	38.4	15.6	6.36	1.88	3.11	7.17	3.71	2.62	21.8
U	5.81	6.31	7.38	3.95	6.22	8.17	6.52	1.55	0.68	0.57	2.17	0.90	0.86	5.04
K/U	3858	2641	3783	2911	2412	2009	2134	12,634	30,882	13,304	13,275	4309	5152	25,388
Zr/Hf	45.2	42.5	32.9	26.9	33.9	27.0	30.9	39.1	29.0	101.7	53.9	56.1	16.2	304
La/Th	2.62	3.08	3.11	3.69	2.79	2.44	2.60	2.48	3.64	2.09	5.57	5.90	1.40	31.2
Hf/Ta	4.68	4.73	12.4	13.7	14.2	18.4	16.8	8.43	3.52	8.43	8.42	2.05	5.24	13.7
Th/U	1.72	1.47	1.84	2.30	2.12	4.70	2.39	4.10	2.76	5.46	3.59	1.75	0.52	10.7
La_N/Yb_N	8.72	7.99	7.48	10.1	7.56	14.3	5.13	7.91	6.34	5.16	8.32	2.82	6.23	22.4
Eu/Eu[a]	0.72	0.62	0.61	0.58	0.52	0.32	0.45	0.73	1.16	0.90	0.66	0.17	0.15	0.85
La/Sc	2.34	2.70	4.11	7.46	4.80	14.22	5.68	4.82	5.57	0.81	3.95	2.77	2.10	16.39
Th/Sc	0.89	0.88	1.32	2.02	1.72	5.84	2.19	1.94	1.53	0.39	0.87	0.48	0.37	3.16
Rb/Cs	19.0	14.9	29.5	25.7	20.6	34.2	22.8	90.7	78.5	17.6	35.2	14.6	16.3	75.2

[a]Exmore breccia data from Poag et al. (2004). Fm. = formation; M. = member; JT = Jamestown, DS = Dismal Swamp core (depth in feet).
Major elements in wt%, trace elements in ppm, except as noted. All Fe given as Fe_2O_3.

Table 1b. Major and trace element composition of target sediments and crater fill breccia from the Chesapeake Bay impact structure, compared to data for average bediasites and georgiaites; recalculated on volatile-free basis.

	CH-1 Chickahominy F.	CH-2 Chickahominy F.	PR-1 Nanjemoy F. Potapaco M.	PR-2 Piney Pt. F. Bed A	PR-3 Aquia F. Paspotansa M.	PR-4 Aquia F. Piscataway M.	PR-5 Nanjemoy F. Woodstock M.	CR-1 Potomac F. JT 261.8–261.9	CR-2 Potomac F. JT 272.9–273.1	CR-3 Potomac F. DS 776.8–777.0	Exmore[a] breccia	Bediasite[a] average (n = 21)	Georgiaite[a] average (n = 24)
SiO_2	49.49	56.90	71.79	66.07	77.28	63.49	81.19	85.74	90.60	71.78	70.15	76.37	81.8
TiO_2	0.75	0.82	0.86	0.59	0.99	1.38	1.42	0.69	0.14	1.28	0.63	0.76	0.51
Al_2O_3	16.63	17.02	9.98	4.44	9.43	5.27	6.49	7.27	4.04	17.43	10.27	13.78	11.2
Fe_2O_3	12.06	6.00	10.08	4.79	7.75	6.81	6.15	1.36	0.79	5.77	6.45	4.21	2.79
MnO	0.07	0.07	0.09	0.08	0.08	0.12	0.09	0.04	0.01	0.02	0.04	0.03	0.03
MgO	3.35	2.04	1.94	1.04	1.05	0.98	0.80	0.24	0.00	0.58	1.36	0.63	0.61
CaO	12.60	12.82	0.76	20.53	0.40	19.12	1.02	0.34	0.20	0.34	5.34	0.65	0.45
Na_2O	0.52	0.91	0.20	0.19	0.19	0.32	0.21	1.26	0.85	0.86	1.39	1.54	0.94
K_2O	3.33	2.46	3.65	1.63	2.13	2.31	1.85	2.42	2.55	1.00	3.17	2.08	2.44
P_2O_5	0.26	0.11	0.15	0.15	0.09	0.06	0.07	0.02	<0.01	0.03	0.41		
Total	99.07	99.15	99.49	99.53	99.40	99.85	99.27	99.37	99.18	99.10	99.21	100.05	100.77
Sc	13.9	13.0	11.2	5.32	9.07	7.70	7.88	3.37	1.24	8.80	9.53	13	8.7
V	125	122	134	86	131	154	83	46	18	109	114		45
Cr	158	126	155	67	101	108	74	17	7	22	97	49	
Co	4.33	6.86	7.37	4.38	5.07	3.01	3.48	3.01	2.12	3.55	11.1	13.5	7.5
Ni	49	56	19	15	30	14	27	7	5	20	24	8	7.4
Cu	4	<2	<2	<2	<2	<2	<2	<6	<6	32	<2		
Zn	145	117	107	65	66	50	71	21	8	42	156		
As	36.0	21.0	13.6	21.4	26.3	21.4	18.6	2.89	2.13	0.38	10.1	1	
Se	0.99	1.03	0.44	0.24	0.83	1.05	0.55	0.16	0.08	0.15	0.35		
Br	11.8	15.2	1.4	2.8	2.5	1.3	1.7	0.2	0.2	11.1	0.7	0.1	
Rb	136	104	155	70	92	80	72	55	56	32	101	66	76
Sr	408	506	74	820	61	817	139	140	124	83	253	125	163
Y	28	26	39	17	33	23	33	13	8	19	21	25	18.2
Zr	204	239	637	379	769	1123	1239	149	45	198	266	230	187
Nb	16	17	17	12	19	18	22	11	5	22	11		8.1
Sb	1.82	1.07	0.56	0.75	0.95	0.88	0.62	0.14	0.05	0.12	0.57	0.05	
Cs	7.17	6.96	5.24	2.71	4.47	2.35	3.17	0.61	0.72	1.84	3.28	1.8	1.74
Ba	212	252	267	89	219	187	182	494	586	225	317	470	572
La	32.4	35.1	46.1	39.7	43.5	110	44.8	16.2	6.92	7.12	35.9	35	21.1
Ce	77.1	64.1	115.4	101.3	92.1	240	97.0	30.3	15.9	17.1	84.6	76	46.2
Nd	37.2	33.0	57.6	50.4	47.1	122	49.9	15.1	7.62	8.67	37.5	33	20.6
Sm	6.23	6.46	10.5	7.55	8.75	22.0	9.20	2.57	1.27	1.35	7.03	7.2	4.07
Eu	1.37	1.19	1.78	1.22	1.40	2.02	1.34	0.59	0.42	0.40	1.51	1.58	0.99
Gd	5.50	5.32	7.45	5.50	7.75	16.5	8.97	2.31	0.99	1.34	6.65	6.4	3.44
Tb	0.77	0.76	1.32	0.84	1.03	1.88	1.38	0.29	0.16	0.24	0.97	0.97	0.6
Tm	0.41	0.42	0.60	0.41	0.59	0.94	0.84	0.20	0.10	0.13	0.42		
Yb	2.51	2.97	4.16	2.67	3.89	5.16	5.89	1.39	0.74	0.93	2.75	3	1.91
Lu	0.38	0.39	0.54	0.39	0.65	0.85	0.88	0.19	0.11	0.13	0.37	0.47	0.29
Hf	4.51	5.64	19.4	14.1	22.7	41.7	40.0	3.81	1.57	1.94	6.03	6.7	4.64
Ta	0.96	1.19	1.57	1.03	1.60	2.27	2.39	0.45	0.44	0.23	0.72	0.6	0.57
W	1.98	1.96	2.83	0.95	2.96	1.40	3.10	0.62	0.51	0.66	1.36		
Ir (ppb)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5

Table 1b. *Continued.* Major and trace element composition of target sediments and crater fill breccia from the Chesapeake Bay impact structure, compared to data for average bediasites and georgiaites; recalculated on volatile-free basis.

	CH-1 Chickahominy F.	CH-2 Chickahominy F.	PR-1 Nanjemoy F. Potapaco M.	PR-2 Piney Pt. F. Bed A	PR-3 Aquia F. Paspotansa M.	PR-4 Aquia F. Piscataway M.	PR-5 Nanjemoy F. Woodstock M.	CR-1 Potomac F. JT 261.8–261.9	CR-2 Potomac F. JT 272.9–273.1	CR-3 Potomac F. DS 776.8–777.0	Exmore[b] breccia	Bediasite[a] average (n = 21)	Georgiaite[a] average (n = 24)
Au (ppb)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<0.5	<0.5
Th	12.4	11.4	14.8	10.7	15.6	44.9	17.3	6.54	1.90	3.41	7.80	7.6	5.81
U	7.19	7.75	8.04	4.68	7.36	9.56	7.21	1.59	0.69	0.63	2.36	2	1.46
K/U	3858	2641	3783	2911	2412	2009	2134	12,634	30,882	13,304	11,196	8667	13,927
Zr/Hf	45.2	42.5	32.9	26.9	33.9	27.0	30.9	39.1	29.0	101.7	44.1	34.3	40.3
La/Th	2.62	3.08	3.11	3.69	2.79	2.44	2.60	2.48	3.64	2.09	4.60	4.61	3.63
Hf/Ta	4.7	4.7	12.4	13.7	14.2	18.4	16.8	8.4	3.5	8.4	8.4	11.2	8.1
Th/U	1.72	1.47	1.84	2.30	2.12	4.70	2.39	4.10	2.76	5.46	3.30	3.80	3.98
La_N/Yb_N	8.72	7.99	7.48	10.06	7.56	14.34	5.13	7.91	6.34	5.16	8.83	7.88	7.47
Eu/Eu[a]	0.72	0.62	0.61	0.58	0.52	0.32	0.45	0.73	1.16	0.90	0.67	0.71	0.81
La/Sc	2.34	2.70	4.11	7.46	4.80	14.22	5.68	4.82	5.57	0.81	3.76	2.69	2.43
Th/Sc	0.89	0.88	1.32	2.02	1.72	5.84	2.19	1.94	1.53	0.39	0.82	0.58	0.67
Rb/Cs	19.0	14.9	29.5	25.7	20.6	34.2	22.8	90.7	78.5	17.6	30.9	36.7	43.7

[a]Exmore breccia and bediasite data from Poag et al. (2004), georgiaite data from Albin et al. (2000). Fm. = formation; M. = member; JT = Jamestown, DS = Dismal Swamp core (depth in feet). Major elements in wt%, trace elements in ppm, except as noted. All Fe given as Fe_2O_3.

[b]Exmore breccia and bediasite data from Poag et al. (2004), georgiaite data from Albin et al. (2000). Fm. = formation; M. = member; JT = Jamestown, DS = Dismal Swamp core (depth in feet). Major elements in wt%, trace elements in ppm, except as noted. All Fe given as Fe_2O_3.

Table 2. Rb-Sr and Sm-Nd isotopic data for Chesapeake post-impact sediments, target rocks, breccias of the crater fill, and bediasites.

	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr^{a}$ ± 2σ[c]	$T^{Sr}UR$ [Ga]	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd^{b}$ ± 2σ[c]	T^{Nd}_{CHUR} (Ga)	T^{Nd}_{DM} (Ga)
Chesapeake: Post-impact sediments											
CH-1 Chickahominy Fm.	101.4	332.0	0.8846	0.710859 ± 12	0.56	4.434	22.63	0.1184	0.512082 ± 14	1.08	1.54
CH-2 Chickahominy Fm.	96.32	514.1	0.5422	0.709918 ± 10	0.83	4.237	22.15	0.1156	0.512029 ± 9	1.15	1.57
Chesapeake: Crater fill											
Exmore breccia	110.2	211.7	1.506	0.711770 ± 12	0.36	3.777	18.51	0.1234	0.512212 ± 11	0.89	1.40
Chesapeake: Middle Eocene target rocks											
PR-2 Piney Point Fm.	45.90	639.5	0.2077	0.708659 ± 10	2.14	3.943	22.96	0.1038	0.512062 ± 10	0.95	1.36
Chesapeake: Lower Eocene target rocks											
PR-1 Nanjemoy Fm.	120.7	57.92	6.037	0.724504 ± 18	0.24	7.401	37.82	0.1183	0.512108 ± 11	1.03	1.49
PR-5 Nanjemoy Fm.	53.62	112.7	1.377	0.713914 ± 11	0.51	7.580	41.62	0.1101	0.512114 ± 16	0.92	1.37
Chesapeake: Paleocene target rocks											
PR-3 Aquia Fm.	72.65	46.74	4.505	0.725833 ± 12	0.34	6.520	34.73	0.1135	0.512075 ± 24	1.03	1.47
PR-4 Aquia Fm.	73.87	722.0	0.2960	0.708836 ± 11	1.42	4.464	24.88	0.1084	0.512164 ± 12	0.82	1.27
Chesapeake: Lower Cretaceous target rocks											
CR-1 Potomac Fm.	60.92	170.5	1.035	0.711854 ± 24	0.54	2.181	11.75	0.1122	0.512175 ± 23	0.84	1.30
CR-2 Potomac Fm.	53.17	138.7	1.110	0.711567 ± 23	0.48	0.950	5.090	0.1129	0.512284 ± 15	0.65	1.15
CR-3 Potomac Fm.	32.93	83.69	1.139	0.713369 ± 13	0.59	2.060	11.11	0.1119	0.512281 ± 22	0.64	1.14
Chesapeake: Crystalline target rock											
Ba2372 granite	96.08	177.9	1.564	0.718466 ± 11	0.66	4.831	21.77	0.1341	0.512329 ± 11	0.75	1.36
Bediasites											
T8-2061	59.78	129.2	1.339	0.713330 + 13	0.49				0.512392 ± 99		
T8-2267	61.32	119.6	1.484	0.713606 ± 12	0.46				0.512337 ± 13		
Be 8402	69.61	160.9	1.252	0.712403 ± 11	0.47	5.244	26.58	0.1193	0.512330 ± 11	0.61	1.15

a = normalized to $^{86}Sr/^{88}Sr = 0.1194$; b = normalized to $^{146}Nd/^{144}Nd = 0.7219$; c = uncertainties refer to the last significant digits. During the course of this work, analyses of NBS SRM 987 $SrCO_3$ yielded 0.710282 ± 12 for $^{86}Sr/^{87}Sr$ (unweighted mean ± 2 $_m$, VG sector 54, ZLG Münster). Analyses of the La Jolla Nd standard resulted in 0.511861 ±15 for $^{143}Nd/^{144}Nd$ (unweighted mean ±2 $_m$). Blanks were about 0.02 ng for Rb, 0.04 ng for Sr, 125 pg for Nd, and 73 pg for Sm and. Decay constants used in this paper are 1.42×10^{-11} a^{-1} for ^{87}Rb (Steiger and Jäger, 1977) and 6.54×10^{-12} a^{-1} for ^{147}Sm (Lugmair and Marti, 1978). T_{UR}^{Sr}, T_{CHUR}^{Nd}, T_{DM}^{Nd} = time at which a rock last had the Sr, Nd isotopic composition of the model reservoirs UR, CHUR or DM (depleted mantle; see DePaolo, 1981). Fm. = formation.

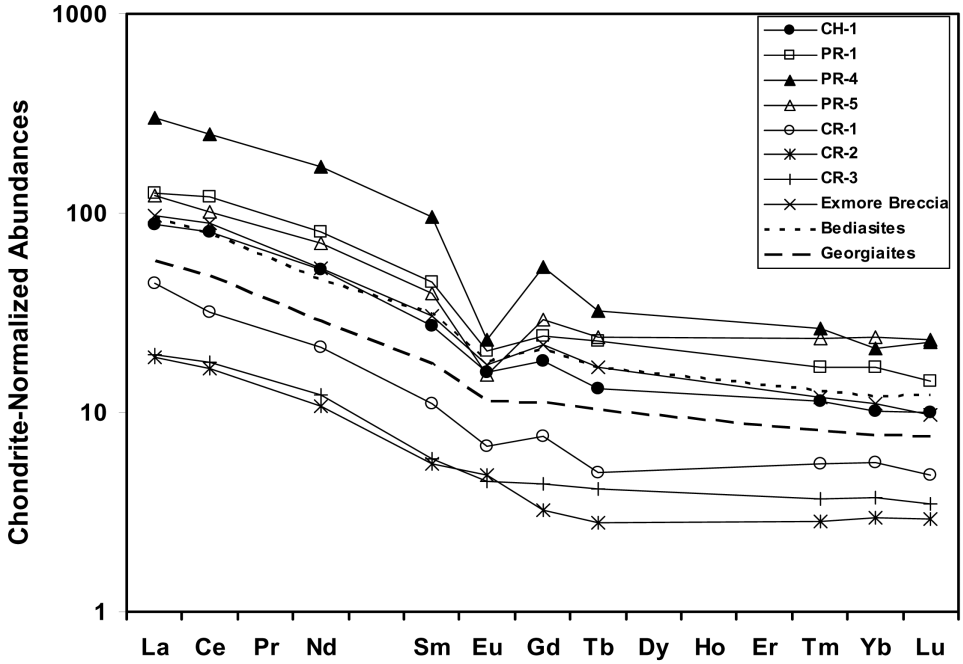

Fig. 3. Chondrite-normalized abundances of representative Chesapeake Bay target sediment samples (this work; Table 1), as well as average Exmore breccia (Poag et al. 2004), bediasites (Poag et al. 2004), and georgiaites (Albin et al. 2000). Normalization values from Taylor and McLennan (1985).

target sediments, as well as contributions from biogenic carbonates. The Sm and Nd concentrations in the target sediments vary by a factor of four, yet with rather homogeneous Sm/Nd ratios (0.1717 to 0.2041); their T^{Nd}_{DM} ages range from 1.14 to 1.49 Ga, and the T^{Nd}_{CHUR} model ages range from 0.64 to 1.03 Ga, whereby the youngest model ages have been determined for samples CR-2 and CR-3 of the Cretaceous Potomac formation. Apparently, material with slightly more ancient Nd model ages contributed to the Paleocene to middle Eocene sedimentation. The model ages T^{Sr}_{UR}, T^{Nd}_{DM}, and T^{Nd}_{CHUR} of the granitic clast Ba 2372 are 0.66, 1.36, and 0.75 Ga, respectively. We note that T^{Nd}_{DM} ages of the Chickahominy formation samples are slightly higher than those of the analyzed target lithologies, which may indicate input of older material to this post-impact sediment.

Of the three bediasite samples, just Be 8402 was fully analyzed; Sm,Nd concentrations for the other two specimens are not available. The bediasites display a slight variation in the Rb/Sr ratio (0.433 to 0.513) and yield quite young T^{Sr}_{UR} (0.46 to 0.49 Ga) and T^{Nd}_{CHUR} model ages (0.61 Ga); these results are in excellent accordance with previously published data for NAT specimens (Stecher et al. 1989 and references therein; Liu et al. 2001).

As shown in the time-corrected (t = 35.7 Ma) ε_{Sr}–ε_{Nd} diagram in Fig. 4, the new data for target sediments, one Exmore breccia, two post-impact sediments, and one granite sample from the Chesapeake Bay impact crater plot into a well-defined field at less negative ε_{Nd}^{t} values in comparison to most target lithologies at the Popigai impact structure (Kettrup et al. 2003). Some data overlap with the sedimentary cover rocks (Cambrian carbonates, Cretaceous sandstones) and Permo-Triassic dolerites occurring in the Popigai area; however, those lithologies differ by much higher Sm/Nd ratios (dolerites) and high T^{Nd}_{CHUR} model ages (sediments: 1.35 to 1.77 Ga) (Fig. 5), combined with unrealistic T^{Sr}_{UR} model ages (sediments) (Fig. 5). We note that our new data does not agree with data for a similar sample suite shown previously in an abstract (Koeberl et al. 2001), perhaps because of standard problems with the earlier data set.

The newly analyzed bediasite Be 8402, bediasites, the georgiaite, and the sample USNM 2082 from the Martha's Vineyard location analyzed by Shaw and Wasserburg (1982), as well as the tektite samples from Barbados (Ngo et al. 1985) occupy a very narrow field in Fig. 4, defined by the granite sample Ba 2372, the Potomac formation, Exmore breccia, and an as-yet unknown component that is labeled "A" in Fig. 4. This latter component should have less negative Nd values than the tektites and relatively unradiogenic Sr isotope compositions. In contrast, tektites from DSDP site 612 off the New Jersey coast (Stecher et al. 1989) plot in Fig. 4 at Nd values in the range of the Chesapeake target rocks, yet toward highly radiogenic Sr isotope compositions. If this material is part of the NAT strewn field—which we consider the best interpretation—the Chesapeake Bay impact must have sampled material with rather high Rb/Sr ratios; this missing component is plotted as "B" in Fig. 4. This view supports an earlier hypothesis by Stecher et al. (1989).

Figure 5 illustrates the quite distinct ranges in Sr and Nd

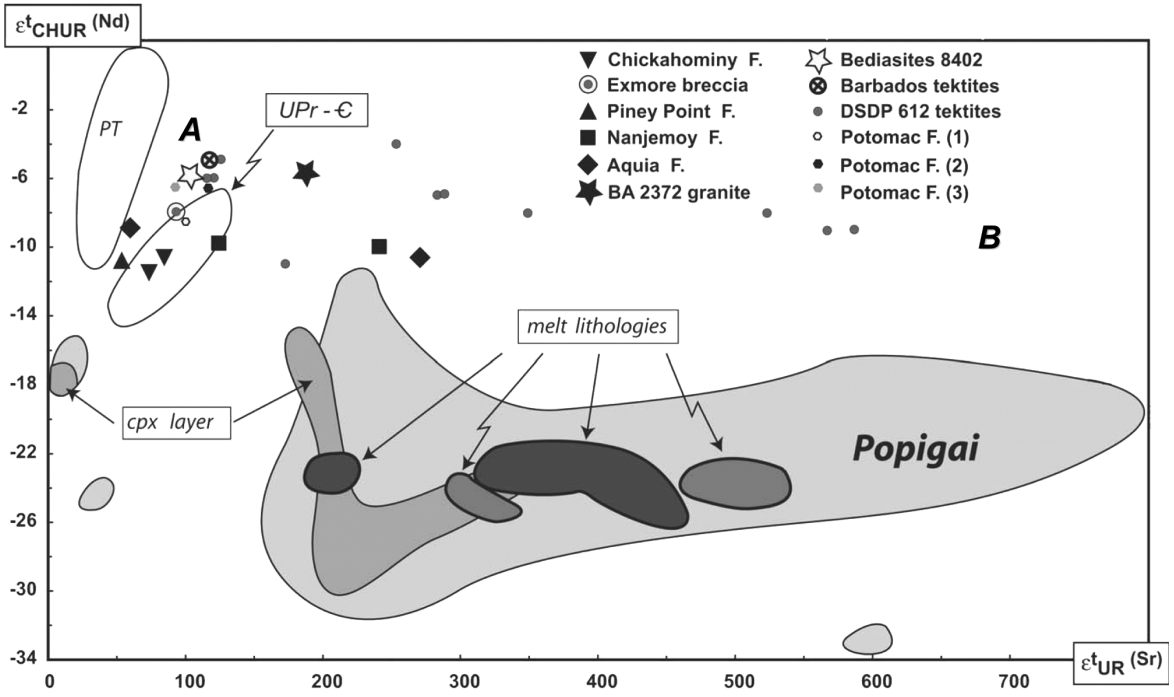

Fig. 4. A time-corrected (t = 35.7 Ma) $\varepsilon^t_{UR}(Sr)$-$\varepsilon_{tCHUR}(Nd)$ diagram for crystalline target rocks (light gray), sedimentary cover rocks, Proterozoic (UPr-ε) and Permo-Triassic (PT) diabase intrusions (white fields), and impactites (dark gray) at the Popigai crater (Kettrup et al. 2003 and references therein), upper Eocene microkrystites and microtektites (medium gray; Whitehead et al. 2000; Liu et al. 2001) and the North American tektites and associated microtektites from offshore sampling sites (Shaw and Wasserburg 1982; Ngo et al. 1985; Stecher et al. 1989), in comparison to target sediments, one Exmore breccia, one granite sample, and post-impact sediments of the Chesapeake Bay impact structure, and the bediasite Be 8402 (this work). Note that bediasites and the Barbados tektites plot in a very small area of the diagram, whereas the location of data points for DSDP 612 samples scatter widely. See Poag et al. (2004) for an explanation of the geological formations in the Chesapeake area. A and B = missing target components; see the text for further explanations.

model ages occupied by Chesapeake and Popigai target materials, NAT, and Upper Eocene microcrystites. The current data allow two conclusions: 1) The impact debris in Late Eocene sediments has distinctive Sr,Nd isotopic characteristics and 2) the stratigraphically older cpx spherule layer is unambiguously related to the Popigai impact event, whereas the younger North American tektite strewn field originated in the Chesapeake Bay impact event.

DISCUSSION

Major and trace element chemical compositions of the Chesapeake Bay target sediments, in comparison with the Exmore breccia (crater fill) and tektite data, do not allow us to uniquely identify a specific source for the North American tektites. For refractory and lithophile elements, including the REEs, the similarity between the tektites and the Chesapeake Bay crater rocks is the greatest, within a factor of about two. Mixing calculations (based on the target sediment data) also does not give reliable results, because of the large proportion of volatile components in these sediments. Besides the volatile elements, it is realistic to assume that the volatiles present in carbonaceous target sediments were lost or fractionated during impact.

It is interesting to note that the Na content of at least the bediasites (Table 1b; Fig. 2a) is higher than that of all analyzed sediments, necessitating source materials as rich in sodium as a precursor to the tektites. There is a variety of possibilities: it is well known from studies of the other three strewn fields (e.g., Montanari and Koeberl 2000 and references therein) that tektites are mainly derived from surficial sediments. For example, the Central European tektites (moldavites) were derived from a thin surface veneer of sediments of immediate pre-impact age that are not present anymore in today's Ries crater (e.g., Horn et al. 1985; von Engelhardt et al. 1987). Our sample suite did not include any upper Eocene sediments that were present on or near the target surface in the Chesapeake Bay area because such rocks are not preserved. In addition, most or all of the target area was covered by shallow ocean water (Poag et al. 2004). Thus, there could have been some contamination of the tektites from sea water residue, e.g., sodium. This is also indicated by boron isotopic data of bediasites (Chaussidon and Koeberl 1995).

On the other hand, the Sr and Nd isotopic characteristics of the sediments in the target area reflect their source compositions. The basement granite and the materials of various stratigraphic levels display rather moderate

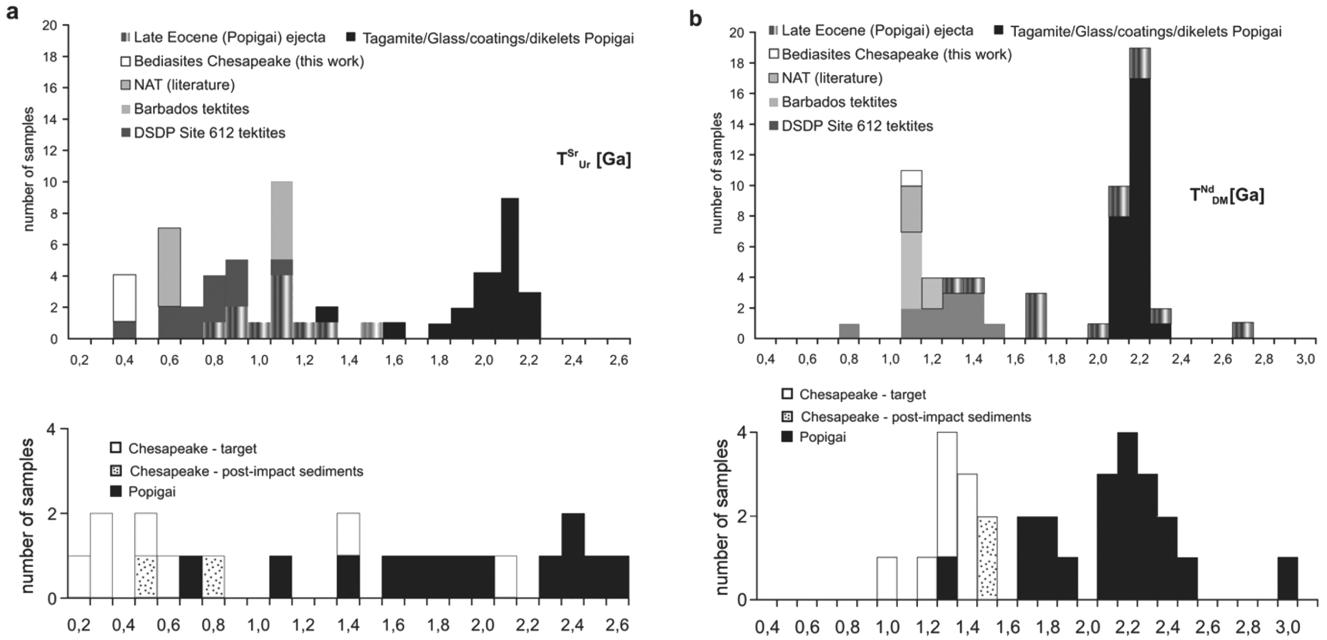

Fig. 5. A histogram of (a) T^{Sr}_{UR} and (b) T^{Nd}_{DM} model ages of (upper) different impact-related lithologies from Popigai, Late Eocene ejecta material ("Popigai ejecta"—microtektites, microkrystites), bediasites (this work), NAT, and Barbados tektites, as well as DSDP site 612 tektites (literature data) and (lower) Popigai (Kettrup et al. 2003), Chesapeake Bay target, and post-impact material (this work). In general, Chesapeake Bay–related materials have lower model ages, although some overlap exists. Sample PR-2 (Piney Point Formation) and PR-4 (Aquia formation) have a T^{Sr}_{UR} model age, which is higher as the respective T^{Nd}_{DM} (2.14 Ga versus 1.4 Ga; 1.4 Ga versus 1.27 Ga), indicating disturbances in the Rb-Sr system. See Fig. 4 for data sources and the text for further explanations.

differences in their Nd values, yet a large spread in Sr values exists among Paleocene to Middle Eocene sediments. As stated, isotopic compositions of NAT samples and DSDP site 612 tektites cannot be modeled using only the new data for Chesapeake target rocks, so at least two components are missing: one with moderately radiogenic Sr and only slightly negative Nd to explain the NAT compositions ("A" in Fig. 4), the other with highly radiogenic Sr and Nd values close to those of the measured sedimentary target rocks to explain the DSDP site 612 tektites ("B" in Fig. 4). In general, however, our data support the suggestion by Shaw and Wasserburg (1982) that the NAT source rocks are located in the eastern United States, most likely in the Appalachian mountain range. The model ages obtained here for the Chesapeake Bay sediments agree with this suggestion. This allows the conclusion that the Chesapeake Bay impact structure is indeed the source of the North American tektite strewn field.

CONCLUSIONS

Using the geographic position as well as age and chemical data, previous studies have suggested that the Chesapeake Bay impact structure is the source of the North American tektites (Poag et al. 1994; Koeberl et al. 1996). Here we report the first Sr-Nd isotope data for samples from the Chesapeake Bay structure, which establish a clear correlation between this impact structure and the 35 Ma tektites and the associated microtektites from the North American strewn field. The isotopic parameters of target sediments, one breccia and one granite sample of the parauthochthonous crater floor, are similar to those of North American tektites, but quite different from the well-constrained isotopic parameters of the heterogeneous target at the Popigai impact structure (Kettrup et al. 2003), which was formed nearly contemporaneous with the Chesapeake Bay structure. Due to these differences, ejecta material in Upper Eocene sediments can now be assigned with high reliability to their respective source craters, i.e., Chesapeake Bay (for the NAT strewn field) and Popigai (for the cpx spherule layer; e.g., Whitehead et al. 2000). Existing isotope data for tektites and spherules as well as published and new data for target rocks substantiate that indeed two (and not more) ejecta layers with different source craters are present in the stratigraphic column, deposited within a very short interval of 20 kyr (or less). Interestingly, strong effects on the biodiversity are not documented for this time interval yet, although some environmental changes (e.g., global cooling and/or warming [both effects are discussed: e.g., Poag et al. 2004]) may be related to the impact events.

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REFERENCES

Albin E. F., Norman M. D., and Roden M. F. 2000. Major and trace element compositions of georgiaites: Clues to the source of North American tektites. *Meteoritics & Planetary Science* 35:795–806.

Artemieva N. A. 2002. Tektite origin in oblique impacts: Numerical modeling of the initial stage. In *Impacts in Precambrian shields,* edited by Plado J. and Pesonen L. J. Berlin: Springer. pp 257–276.

Blum J. D., Papanastassiou D. A., Koeberl C., and Wasserburg G. J. 1992. Nd and Sr isotopic study of Australasian tektites: New constraints on the provenance and age of target materials. *Geochimica et Cosmochimica Acta* 56:483–492.

Bodiselitsch B., Montanari A., Koeberl C., and Coccioni R. 2004. Delayed climate cooling in the Late Eocene caused by multiple impacts: High-resolution geochemical studies at Massignano, Italy. *Earth and Planetary Science Letters* 223:283–302.

Bottomley R. J. 1982. ^{40}Ar-^{39}Ar dating of melt rock from impact craters. Ph.D. thesis, University of Toronto, Toronto, Ontario, Canada.

Bottomley R., Grieve R. A. F., York D., and Masaitis V. L. 1997. The age of the Popigai impact event and its relation to events at the Eocene/Oligocene boundary. *Nature* 388:365–268.

Chaussidon M. and Koeberl C. 1995. Boron content and isotopic composition of tektites and impact glasses: Constraints on source regions. *Geochimica et Cosmochimica Acta* 59:613–624.

Clymer A. K., Bice D. M., and Montanari A. 1996. Shocked quartz in the late Eocene: Impact evidence from Massignano, Italy. *Geology* 24:483–486.

Collins G. S. and Wünnemann K. 2005. How big was the Chesapeake Bay impact? Insight from numerical modeling. *Geology* 33:925–928.

DePaolo D. J. 1981. A neodymium and strontium isotopic study of the Mesozoic calk-alkaline granitic batholiths of the Sierra Nevada and Peninsula Ranges, California. *Journal of Geophysical Research* 86:10,470–10,488.

Deutsch A. 2004. Relating impact debris in the stratigraphic record to the source crater: The Chesapeake case. In *ICDP-USGS workshop on deep drilling in the central crater of the Chesapeake Bay impact structure, Virginia, USA: Proceedings volume*, edited by Edwards L. E., Horton J. W., Jr., and Gohn G. S. Reston, Virginia: U.S. Geological Survey. pp. 49–50.

Deutsch A., Ostermann M., and Masaitis V. L. 1997. Geochemistry and Nd-Sr isotope signature of tektite-like objects from Siberia (urengoites, South-Ural glass). *Meteoritics & Planetary Science* 32:679–686.

Edwards L. E., Horton J. W., Jr., and Gohn G. S. 2004. *ICDP-USGS workshop on deep drilling in the central crater of the Chesapeake Bay impact structure, Virginia, USA: Proceedings volume*. Reston, Virginia: U.S. Geological Survey.

Glass B. P. 1989. North American tektite debris and impact ejecta from DSDP Site 612. *Meteoritics* 24:209–218.

Glass B. P. 1990. Tektites and microtektites: Key facts and interferences. *Tectonophysics* 171:393–404.

Glass B. P. 2002. Upper Eocene impact ejecta/spherule layers in marine sediments. *Chemie der Erde* 62:173–196.

Glass B. P. and Burns C. A. 1987. Microkrystites: A new term for impact produced glassy spherules containing primary crystallites. Proceedings, 18th Lunar and Planetary Science Conference. pp. 308–310.

Glass B. P. and Koeberl C. 1999. Ocean drilling project hole 689B spherules and Upper Eocene microtektites and clinopyroxene-bearing spherule strewn fields. *Meteoritics & Planetary Science* 34:185–196.

Glass B. P., Burns C. A., Crosbie J. R., and DuBois D. L. 1985. Late Eocene North American microtektites and clinopyroxene-bearing spherules. Proceedings, 16th Lunar and Planetary Science Conference. pp. D175–D196.

Glass B. P., Hall C. M., and York D. 1986. ^{40}Ar/^{39}Ar Laser-probe dating of North American tektite fragments from Barbados and the age of the Eocene-Oligocene boundary. *Chemical Geology* 59:181–186.

Glass B. P., Koeberl C., Blum J. D., and McHugh C. M. G. 1998. Upper Eocene tektite and impact ejecta layer on the continental slope off New Jersey. *Meteoritics & Planetary Science* 33:229–241.

Glass B. P., Liu S., and Leavens P. B. 2002. Reidite: An impact-produced high-pressure polymorph of zircon found in marine sediments. *American Mineralogist* 87:562–565.

Glass B. P., Huber H., and Koeberl C. 2004a. Geochemistry of Cenozoic microtektites and clinopyroxene-bearing spherules. *Geochimica et Cosmochimica Acta* 68:3971–4006.

Glass B. P., Liu S., and Montanari A. 2004b. Impact ejecta in Upper Eocene deposits at Massignano, Italy. *Meteoritics & Planetary* Science 39:589–597.

Harris R. S., Roden M. S., Schroeder P. A., Holland S. M., Duncan M. S., and Albin E. F. 2004. Upper Eocene impact horizon in east-central Georgia. *Geology* 32:717–720.

Horn P., Müller-Sohnius D., Köhler H., and Graup G. 1985. Rb-Sr systematics of rocks related to the Ries crater, Germany. *Earth and Planetary Science Letters* 75:384–392.

Horton J. W., Jr. and Izett G. A. 2005. Crystalline-rock ejecta and shocked minerals of the Chesapeake Bay impact structure: The USGS-NASA Langley corehole, Hampton, Virginia, with supplement constraints on the age of the impact. In *Studies of the Chesapeake Bay impact structure,* edited by Horton J. W., Jr., Powars D. S., and Gohn G. S. Reston, Virginia: U.S. Geological Survey. pp. E1–E29.

Horton J. W., Jr, Kunk M. J., Naeser C. W., Naeser N. D., Aleinikoff J. N., and Izett G. A. 2004. Petrography, geochemistry, and geochronology of crystalline basement and impact-derived clasts from coreholes in the western annular trough, Chesapeake Bay impact structure, Virginia, USA. In *ICDP-USGS workshop on deep drilling in the central crater of the Chesapeake Bay impact structure, Virginia, USA: Proceedings volume*, edited by Edwards L. E., Horton J. W., Jr., and Gohn G. S. Reston, Virginia: U.S. Geological Survey. pp. 28–29.

Kettrup B., Deutsch A., and Masaitis V. L. 2003. Homogeneous impact melts produced by a heterogeneous target? Sr-Nd isotopic evidence from the Popigai crater, Russia. *Geochimica et Cosmochimica Acta* 67:733–750.

Koeberl C. 1993. Instrumental neutron activation analysis of geochemical and cosmochemical samples: A fast and reliable method for small sample analysis. *Journal of Radioanalytical and Nuclear Chemistry* 168:47–60.

Koeberl C. 1994. Tektite origin by hypervelocity asteroidal or cometary impact: Target rocks, source craters, and mechanisms. In *Large meteorite impacts and planetary evolution,* edited by Dressler B. O., Grieve R. A. F., and Sharpton V. L. Boulder, Colorado: Geological Society of America. pp. 133–151.

Koeberl C. and Martinez-Ruiz F. 2003. The stratigraphic record of impact events: A short overview. In *Impact markers in the stratigraphic record,* edited by Koeberl C. and Martinez-Ruiz F. Heidelberg: Springer. pp. 1–40.

Koeberl C., Poag C. W., Reimold W. U., and Brandt D. 1996. Impact origin of Chesapeake Bay structure and the source of North American tektites. *Science* 271:1263–1266.

Koeberl C., Kruger F. J., Poag C. W., and Allsopp H. 2001. Geochemistry of surficial sediments near the Chesapeake Bay impact structure and the search for source rocks of the North American tektites (abstract #1333). 32rd Lunar and Planetary Science Conference. CD-ROM.

Langenhorst F. 1996. Characteristics of shocked quartz in late Eocene impact ejecta from Massignano (Ancona, Italy): Clues to shock conditions and source crater. *Geology* 24:487–490.

Liu S., Glass B. P., Ngo H. H., Papanastassiou D. A., and Wasserburg G. J. 2001. Sr and Nd data for Upper Eocene spherule layers (abstract #1819). 32nd Lunar and Planetary Science. CD-ROM.

Lugmair G. W. and Marti K. 1978. Lunar initial $^{143}Nd/^{144}Nd$: Differential evolution of the lunar crust and mantle. *Earth and Planetary Science Letters* 39:349–357.

Montanari A. and Koeberl C. 2000. *Impact stratigraphy: The Italian record.* Berlin: Springer. 364 p.

Ngo H. H., Wasserburg G. J., and Glass B. P. 1985. Nd and Sr isotopic composition of tektite material from Barbados and their relationship to North America tektites. *Geochimica et Cosmochimica Acta* 49:1479–1485.

Obradovich J., Snee L. W., and Izett G. A. 1989. Is there more than one glassy impact layer in the Late Eocene? (abstract). *Geological Society of America Abstracts with Program* 21: 134.

Odin G. S. and Montanari A. 1989. Radioisotopic age and stratotype of the Eocene-Oligocene Boundary. *Comptes Rendus de l'Academie des Sciences Serie II* 309:1939–1945.

Pierrard O., Robin E., Rocchia R., and Montanari A. 1998. Extraterrestrial Ni-rich spinel in upper Eocene sediments from Massignano, Italy. *Geology* 26:307–310.

Poag C. W., Powars D. S., Poppe L. J., and Mixon R. B. 1994. Meteoroid mayhem in Ole Virginny: Source of the North American tektite strewn field. *Geology* 22:691–694.

Poag C. W., Plescia J. B., and Molzer P. C. 2002. Ancient impact structures on modern continental shelves: The Chesapeake Bay, Montagnais, and Toms Canyon craters, Atlantic margin of North America. In *Deep-Sea Research, Part II,* edited by Gersonde R., Deutsch A., Ivanov B. A., and Kyte F. New York: Pergamon. pp. 1081–1102.

Poag C. W., Koeberl C., and Reimold W. U. 2004. *The Chesapeake Bay Crater.* Berlin: Springer. 522 p.

Prothero D. R., Ivany L., and Nesbitt E. 2003. *From greenhouse to icehouse: The marine Eocene-Oligocene transition.* New York: Columbia University Press. 560 p.

Reimold W. U., Koeberl C., and Bishop J. 1994. Roter Kamm impact crater, Namibia: Geochemistry of basement rocks and breccias. *Geochimica et Cosmochimica Acta* 58:2689–2710.

Schettino A. and Scotese C. R. 2001. New internet software aids paleomagnetic analysis and plate tectonic reconstructions. EOS 82:45.

Schulte P. and Kontny A. 2005. Chicxulub impact ejecta from the Cretaceous-Paleogene (K-T) boundary in NE Mexico. In *Large meteorite impacts and planetary evolution III*, edited by Kenkmann T., Hörz F., and Deutsch A. Boulder, Colorado: Geological Society of America. pp. 191–221.

Shaw H. F. and Wasserburg G. J. 1982. Age and provenance of the target material for tektites and possible impactites as inferred from Sm-Nd and Rb-Sr systematics. *Earth and Planetary Science Letters* 60:155–177.

Simonson B. M. and Glass B. P. 2004. Spherule layers: Records of ancient impacts. *Annual Review of Earth and Planetary Sciences* 32:329–361.

Smit J. 1990. The global stratigraphy of the Cretaceous-Tertiary boundary impact ejecta. *Annual Review of Earth and Planetary Sciences* 27:75–113.

Smit J., Alvarez W., Montanari A., Swinburne N., van Kempen T. M., Klaver G. T., and Lustenhouwer W. J. 1992. "Tektites" and microkrystites at the Cretaceous-Tertiary boundary: Two strewn fields, one crater? Proceedings, 22nd Lunar and Planetary Science Conference. pp. 87–100.

Stecher O. and Baker J. 2004. Pb isotopes established as tracers of provenance for tektites (abstract). *Geochimica et Cosmochimica Acta* 68:A741.

Stecher O., Ngo H. H., Papanastassiou D. A., and Wasserburg G. J. 1989. Nd and Sr isotopic evidence for the origin of tektite material from DSDP Site 612 off the New Jersey Coast. *Meteoritics* 24:89–98.

Steiger R. H. and Jäger E. 1977. Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters* 39:359–362.

Taylor H. P. and Epstein S. 1962. Oxygen isotope studies on the origin of tektites. *Journal of Geophysical Research* 67:4485–4490.

Taylor S. R. and McLennan S. M. 1985. *The continental crust: Its composition and evolution*. Oxford: Blackwell Scientific Publications. 312 p.

Tilton G. R. 1958. Isotopic composition of lead from tektites. *Geochimica et Cosmochimica Acta* 14:323–330.

von Engelhardt W., Luft E., Arndt J., Schock H., and Weiskirchner W. 1987. Origin of moldavites. *Geochimica et Cosmochimica Acta* 51:1425–1443.

Vonhof H. B. 1998. The strontium isotope stratigraphic record of selected geologic events. Ph.D. thesis, Faculteit der Aardwetenschappen, Vrije Universiteit te Amsterdam. Amsterdam, The Netherlands.

Vonhof H. B., Smit J., Brinkhuis H., and Montanari A. 2000. Late Eocene impacts accelerated global cooling? *Geology* 28:687–690.

Whitehead J., Papanastassiou D. A., Spray J. G., Grieve R. A. F., and Wasserburg G. J. 2000. Late Eocene impact ejecta: Geochemical and isotopic connections with the Popigai impact structure. *Earth and Planetary Science Letters* 181:473–487.