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Bottle-green microtektites from the South Tasman Rise: Deep-sea evidence for an impact event near the Miocene/Pliocene boundary

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Abstract–Forty-eight bottle-green microtektites (BGMTs) were found in a core sample recovered from Ocean Drilling Program Site 1169, located along the western flank of the South Tasman Rise in the southeastern Indian Ocean. Biostratigraphic evidence loosely constrains the age of the Site 1169 BGMTs to an interval spanning the late-middle Miocene to earliest Pliocene (12.1–4.6 Ma); incomplete core recovery and a major stratigraphic hiatus prevented a more precise age determination. This broad range of biostratigraphic ages indicates that these microtektites predate the Australasian strewn layer by at least 3.83 Ma, and perhaps by as much as 11.33 Ma. Furthermore, the REE signatures of the Site 1169 BGMTs are incongruent with those of typical Australasian ejecta, indicating that the Site 1169 BGMTs are not part of the larger Australasian strewn field. Among the various australite subgroups, the Site 1169 BGMTs are most similar in age to the HNa/K australites. However, numerous compositional discrepancies indicate that these two ejecta populations are also unrelated; the great distances separating Site 1169 from HNa/K australite-bearing localities also makes a shared provenance unlikely. Therefore, we conclude that the Site 1169 BGMTs were formed by a late Miocene impact that is distinctly separate from the Australasian and HNa/K australite events, though the location of this impact is unknown.

INTRODUCTION

The Australasian tektite strewn field blankets nearly 10% of the Earth's surface and is spread out over parts of southeast Asia, much of Australia and Tasmania, and the surrounding Indian and Pacific Ocean basins (Barnes 1963; Chapman 1964, 1971; Glass 1967, 1972; Cassidy et al. 1969; O'Keefe 1976; Prasad and Sudhakar 1999). Ejecta materials from this immense strewn field vary considerably in size, shape, and chemical composition (e.g., Taylor 1962; Barnes 1963; Chao 1963; Chapman and Scheiber 1969). It has been noted that as many as ten different "subfields" may be subsumed within the Australasian strewn field (Koeberl 1990). Hence, compositional heterogeneities among the austral components (= australites) of this enormous strewn field have been used to identify and map different geochemical subgroups across vast tracts of the Australian mainland (e.g., Chapman and Scheiber 1969; Chapman 1971; Mason 1979).

The highly variable chemical compositions of australites have fueled speculation that some of these tektite subgroups represent separate impact events that have been conflated with the Australasian strewn field. This view is corroborated by the discrepant chronometric ages yielded by different impact materials that were initially presumed to be part of the Australasian strewn field (Fleischer et al. 1969; Storzer 1985; Storzer and Müller-Sohnius 1986; Bottomley and Koeberl 1999). To complicate matters, the seemingly straightforward task of delineating stratigraphic relationships among different australite subgroups has been obfuscated by such factors as: 1) discontinuous geological exposure over the vast geographic distances encompassed by the Australasian strewn field; 2) the diverse geological settings and sedimentary facies in which the ejecta are preserved; and 3) a paucity of biostratigraphic (fossil) evidence to constrain the ages of host strata. Moreover, subaerial agents of erosion/transport have reshuffled the stratigraphic distributions of many tektites in the Australian geologic record (Fudali 1993; Shoemaker and Uhlherr 1999), a process proven to be the bane of several stratigraphic studies (e.g., Gill 1965a, 1965b, 1970; Lovering et al. 1972). The presence of late Eocene-aged (34–35 Ma) North American tektites in Plio/Pleistocene sediments of the U. S. Coastal Plain testifies to the ease with which ejecta materials can be reworked in continental sedimentary records (King 1964; Storzer et al. 1973).

In contrast, the stratigraphies of ejecta layers tend to be more faithfully preserved in deep-ocean basins where relatively continuous sedimentation minimizes the adverse effects of sediment mixing. Microtektites (<1 mm) associated with the Australasian strewn layer are typically confined to a discrete stratigraphic interval positioned directly atop the Brunhes-Matuyama geomagnetic reversal in deep-sea records, thereby establishing an unequivocal age of ~0.77 Ma for this strewn field (Glass 1967; Glass and Heezen 1967). Hence, ejecta preserved in deep-sea sedimentary sequences provide important insight into the geographic extent, frequency, and relative ages of impacts and their associated strewn fields.

Here, we report the discovery of several dozen microtektites in a deep-sea core sample retrieved by Ocean Drilling Program (ODP) Leg 189 from an offshore location positioned at the southernmost fringe of the Australasian strewn field. Biostratigraphic evidence indicates that these microtektites were produced by an impact that dates back to a time interval spanning the latest-middle Miocene to earliest Pliocene (12.1–4.6 Ma). The potential implications of these microtektites are considered, and we explore the possibility that they are part of a strewn field that is separate and older than the well-documented Australasian strewn field.

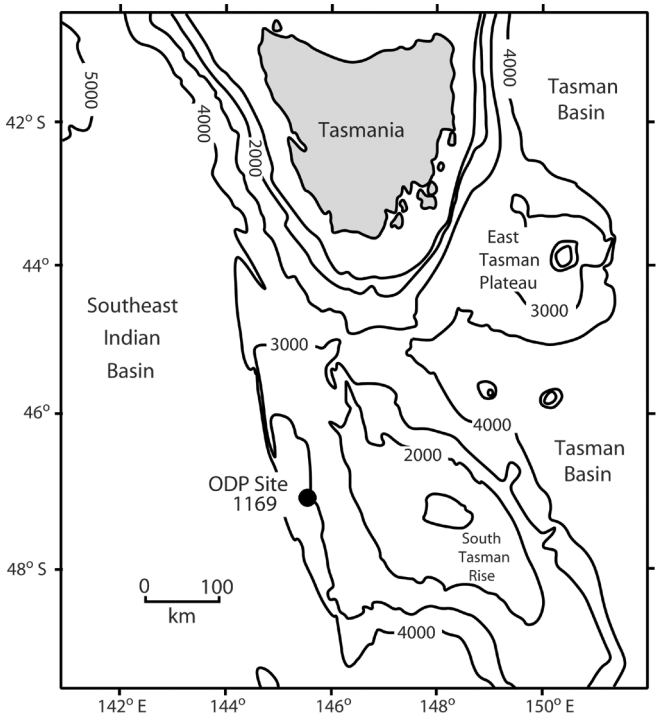

Fig. 1. Map showing location and bathymetric setting of ODP Site 1169; the contour lines are spaced at 1,000 m intervals (after Shipboard Scientific Party 2001).

BIOSTRATIGRAPHIC CONSTRAINTS ON THE AGE OF MICROTEKTITES

The drill Site (ODP Site 1169) is located along the western margin of the South Tasman Rise (145°14.2′E, 47°3.9′S; Fig. 1) in the southeastern Indian Ocean (Shipboard Scientific Party 2001). We found the microtektites in a core-catcher sample at the bottom of core 22X (202.14 m below sea floor, mbsf). Low core recovery (~40%) unfortunately prevented determination of the exact stratigraphic horizon from which the microtektites were derived (Fig. 2). This setback was due largely to inclement weather conditions at the site during drilling operations. An added complication is that calcareous microfossil assemblages within cores 22X and 23X are poorly preserved, an unanticipated problem given the high carbonate content (>80%) of these nanofossil oozes (Shipboard Scientific Party 2001).

We constrained the age of the microtektite-bearing sample by using a well-established, planktonic foraminiferal biozonation for mid-latitude waters (Kennett and Srinivasan 1983; Jenkins 1993). The ages assigned to these biostratigraphic datums have been calibrated against a magnetochronology (Berggren et al. 1985, 1995; Jenkins 1993). The presence of three marker species (*Globoconella sphericomiozea, G. pliozea,* and *G. puncticulata*) within the microtektite-bearing sample (202.14 mbsf) is suggestive of an earliest Pliocene age (Fig. 2). The co-occurrence of *G. puncticulata* and *G. pliozea* indicates that microtektite deposition/redeposition took place sometime after the first occurrence (FO) of the former species (~5.4 Ma; Berggren et al. 1985), but before the last occurrence (LO) of the latter species (~4.6 Ma; Jenkins 1993). We place the LO of *G. pliozea* at 201.07 mbsf, approximately 1 meter above the microtektite-bearing sample (Fig. 2). Thus, based on the LO of *G. pliozea,* the sample from which the microtektites were recovered is assigned to the lowermost foraminiferal subzone of the Pliocene (Zone SN12a), and is considered to be older than 4.6 Ma. This age assignment is supported by the presence of forms intermediate between *G. sphericomiozea* and *G. puncticulata,* an evolutionary transition that coincides with the Miocene/Pliocene boundary (Kennett and Srinivasan 1983).

However, the microtektite-bearing sample was found to lie directly atop a highly condensed stratigraphic interval that has been subjected to intense carbonate dissolution (208–213 mbsf), and specimens of the age-diagnostic foraminifer *Paragloborotalia mayeri* were recovered from a sample immediately below this condensed interval at 214.13 mbsf near the bottom of core 23X (Fig. 2). The presence of *P. mayeri* at 214.13 mbsf places this sample firmly within Zone SN7, constraining its age to 11.4–12.1 Ma (Berggren et al. 1995). This finding has two important implications for constraining the age of microtektite deposition/redeposition. First, it establishes that the microtektite-bearing sample rests close to, or directly atop, a major unconformity that has removed much of the late Miocene. This raises the possibility that the microtektites have been reworked up-section from the

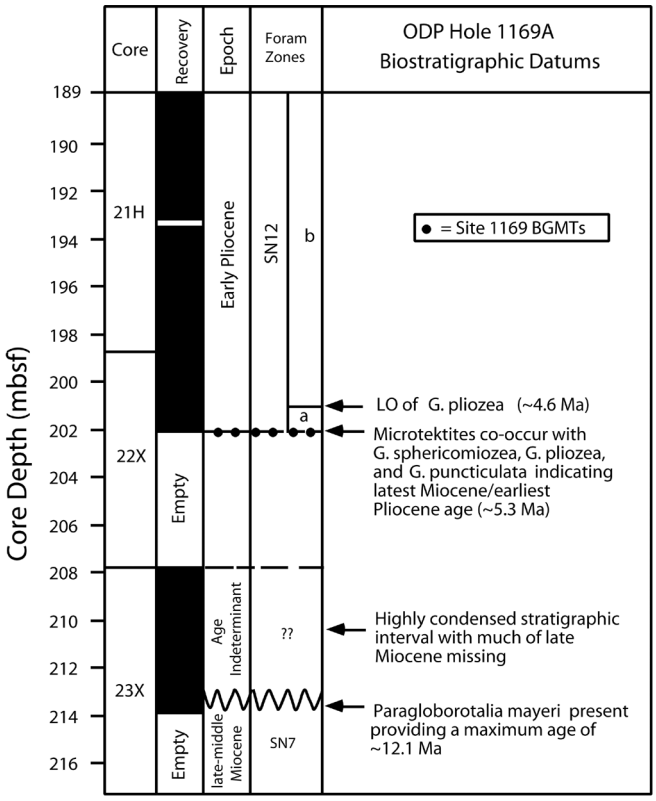

Fig. 2. Biostratigraphy for an upper-middle Miocene to lower Pliocene section recovered from ODP Hole 1169A. The age of the microtektite sample (202.14 mbsf) is constrained with the use of a planktonic foraminiferal biozonation. The precise age determination for the microtektite sample was hampered by incomplete core recovery, an interval of poor microfossil preservation, and a major stratigraphic hiatus (upper Miocene planktonic foraminiferal Zones SN8–SN11 are missing).

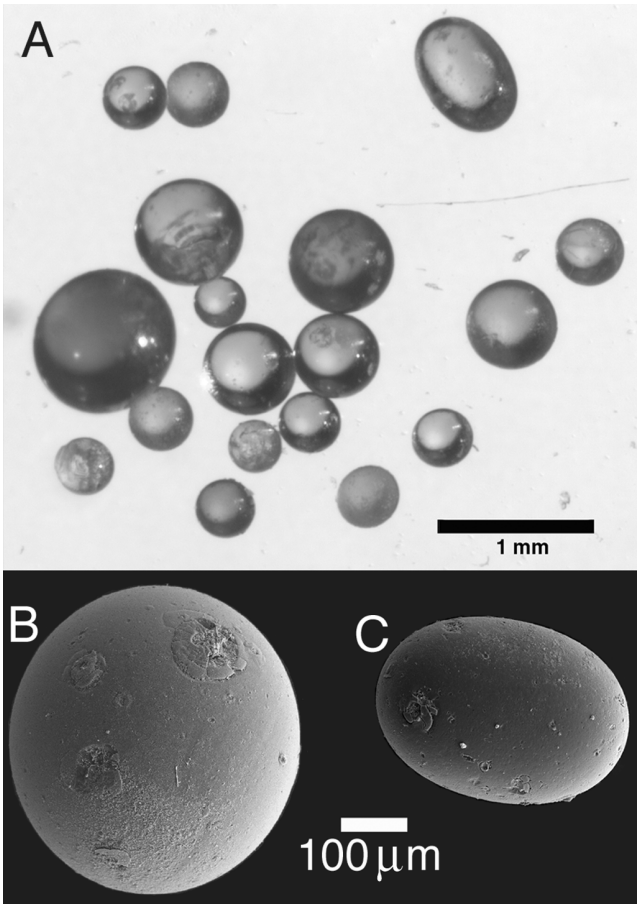

Fig. 3. Magnified images of the Site 1169 BGMTs: a) transmitted light micrograph showing representative subpopulation of bottle-green microtektites; b) scanning electron microscope photograph of spherical microtektite—note the small "micro-crater" in the upper right; c) scanning electron microscope photo of ellipsoidal microtektite. All Site 1169 BGMTs are from an earliest Pliocene sample recovered at 202.14 meters below the seafloor (mbsf).

late Miocene into the basal Pliocene. Second, it indicates that the condensed interval underlying the microtektite-bearing sample is no older than 12.1 Ma (Berggren et al. 1995). Refinement of the biostratigraphy within core 23X was precluded by incomplete core recovery (~68%) and poor microfossil preservation. Therefore, we conservatively ascribe a broad age range of 12.1 to 4.6 Ma (late-middle Miocene to earliest Pliocene) to the Site 1169 microtektites.

DESCRIPTION AND COMPOSITIONAL ANALYSIS OF MICROTEKTITES

A total of 48 microtektites, ranging from 0.10–0.90 mm in diameter, were found in a 20-cm^3 sample of calcareous ooze. All of the microtektites are "bottle green" in color (Fig. 3a). The shapes of the Site 1169 bottle-green microtektites (BGMTs) vary from spherical (Fig. 3b) to ellipsoidal (Fig. 3c), with the former being most common. No splash forms (teardrops, rods, or dumbbells) have been found. Outer-surface textures of the Site 1169 BGMTs are generally smooth, exhibiting no cupping or other signs of exsolution, though some display what appear to be "microcraters" formed possibly by mid-flight collisions (Fig. 3b). The Site 1169 BGMTs are composed of homogeneous glass, possessing no internal vesicles, crystallites, lechatelierite, or other phase inhomogeneities.

Four of the microtektites were analyzed for major and trace elements. The bulk of the microtektites are saved for future analyses requiring more massive samples, in particular, an attempt at radioisotopic dating. Though four is a minimally acceptable sample out of 48, we believe they supply the data necessary to distinguish these microtektites from other Australasian ejecta.

Analytical Techniques

Major elemental analyses were performed using the JEOL-JXA-733 Superprobe at MIT, which uses the CITZAF correction package of Armstrong (1995) to reduce the data and obtain quantitative wavelength-dispersive spectrometer

Table 1. Major element concentrations (in wt%) of Site 1169 BGMTs, and analysis statistics.[a]

	Tek. 1 core	Tek. 1 rim	avg.	Tek. 2 core	Tek. 2 rim	avg.	Tek. 3 core	Tek. 3 rim	avg.	Tek. 4 core	Tek. 4 rim	avg.	Avg. core	Avg. rim
N[b]	15	24	–	10	25	–	20	13	–	9	14	–	54	76
Mg#	62.34	62.18	–	61.23	61.01	–	55.60	54.95	–	58.55	58.15	–	–	–
SiO_2	57.27	55.90	56.43	56.70	58.76	58.17	59.34	61.06	60.02	59.44	61.36	60.61	58.29	58.73
	(60)	(220)	–	(80)	(180)	–	(60)	(240)	–	(140)	(280)	–	–	–
TiO_2	0.69	0.73	0.71	0.82	0.76	0.78	0.82	0.78	0.81	0.79	0.75	0.77	0.78	0.75
	(4)	(8)	–	(4)	(6)	–	(4)	(6)	–	(6)	(8)	–	–	–
Al_2O_3	17.10	17.59	17.40	20.09	18.93	19.26	20.27	19.51	19.97	20.17	19.08	19.51	19.34	18.63
	(40)	(120)	–	(40)	(120)	–	(40)	(80)	–	(100)	(160)	–	–	–
Cr_2O_3	0.07	0.07	0.07	0.06	0.08	0.07	0.03	0.05	0.04	0.02	0.06	0.04	0.04	0.07
	(2)	(4)	–	(8)	(8)	–	(6)	(4)	–	(4)	(6)	–	–	–
FeO	8.90	9.12	9.03	7.44	7.19	7.26	6.98	6.82	6.92	6.73	6.46	6.57	7.56	7.60
	(40)	(60)	–	(20)	(20)	–	(20)	(20)	–	(20)	(40)	–	–	–
MnO	0.14	0.15	0.14	0.14	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.14	0.13
	(4)	(4)	–	(6)	(4)	–	(4)	(4)	–	(4)	(4)	–	–	–
MgO	8.27	8.41	8.35	6.59	6.32	6.39	4.91	4.66	4.81	5.34	5.04	5.15	6.22	6.46
	(26)	(46)	–	(16)	(20)	–	(14)	(18)	–	(14)	(20)	–	–	–
CaO	5.35	5.37	5.36	5.95	5.75	5.81	5.08	4.91	5.01	5.28	5.04	5.14	5.35	5.36
	(12)	(22)	–	(20)	(22)	–	(10)	(18)	–	(14)	(20)	–	–	–
Na_2O	0.93	1.19	1.09	0.83	1.03	0.97	0.93	1.05	0.98	0.78	0.90	0.85	0.89	1.06
	(20)	(40)	–	(24)	(20)	–	(24)	(14)	–	(20)	(18)	–	–	–
K_2O	0.46	0.52	0.50	0.32	0.50	0.45	0.46	0.62	0.52	0.30	0.53	0.44	0.41	0.53
	(8)	(22)	–	(4)	(14)	–	(4)	(10)	–	(8)	(20)	–	–	–
Total	99.08	99.12	99.09	98.94	99.45	99.29	98.95	99.60	99.21	98.99	99.39	99.21	99.01	99.32

[a]Core and rim analyses for each of four microtektites. The numbers in parentheses are 2 sigma standard deviations on the final significant digit.

[b]N = number of microprobe analyses; microtektite 1 = 200 μm in diameter; microtektite 2 = 300 μm; microtektite 3 = 400 μm; microtektite 4 = 200 μm. The averages for individual tektites are weighted for numbers of core and rim analysis.

Table 2. Microprobe analysis statistics.[a]

	X-ray counting time	Microprobe counting statistics	Minimum detection limit
SiO_2	40	1.00%	0.042%
TiO_2	40	5.80%	0.022%
Al_2O_3	40	1.00%	0.022%
Cr_2O_3	20	198.00%	0.039%
FeO	60	2.34%	0.036%
MnO	40	35.86%	0.047%
MgO	40	1.72%	0.027%
CaO	20	2.30%	0.020%
Na_2O	5	17.26%	0.090%
K_2O	40	8.62%	0.015%

[a]The X-ray counting time is reported in seconds, the microprobe counting statistics for 2 sigma are in percent of the analysis value, and the minimum detection limits are in wt%.

analyses (Tables 1 and 2). Before each analysis session, the microprobe was calibrated with primary standards, and secondary standards were analyzed as unknowns. The two final secondary standards, ALV-1690-20 and 70-002 are anhydrous glasses that have been characterized at the MIT lab and are used regularly for high-precision glass analysis (Grove et al. 1990; Kinzler and Grove 1992). Both of the anhydrous glass standards were reproduced within 1σ error limits of the analyses.

The microtektites were mounted in a 1" epoxy disk, polished, and carbon-coated. During polishing, the microtektites were abraded to less than their full radius, giving access to a cross-section of not quite the full diameter while allowing the microtektite to remain firmly embedded in the epoxy. The analyses were performed with a 10 μm in diameter beam spot size, using a 10 nA beam current and an accelerating voltage of 15 kV, measuring oxide components SiO_2, TiO_2, Al_2O_3, Cr_2O_3, FeO, MnO, MgO, CaO, Na_2O, and K_2O (Table 1). The P_2O_5, S, and NiO contents of the Site 1169 BGMTs were below detection limits, which are 0.071%, 22 ppm, and 65 ppm, respectively. Na_2O was measured for a short period because it is easily excited to migrate away from the beam.

Each microtektite was analyzed multiple times as close to its rim as possible, and multiple times near the center, and averages were calculated for rim and core (Table 1). The oxides measured in all analyses taken totaled between 98.7 and 101.2, indicating little or no water content. There is no systematic change in glass analysis totals from rim to core, indicating that if there is small water content it is not related to seawater contamination or to dehydration during flight.

Laser ablation analysis for trace elements was performed at Boston University using a Merchantek/New Wave 213 nm Nd:YAG laser ablation system, coupled to a VG/TJA PlasmaQuad ExCell ICP-MS. The microtektites were ablated

using a 10 Hz repeat rate, 0.81 mJ/pulse beam energy (50% maximum) and a 30-μm beam spot size, moving across each microtektite at a rate of 10 μm per second, measuring a variety of trace elements. While analyses with significantly smaller errors have been produced in the Boston University laboratory (Kelley et al. 2003), the smaller spot sizes necessitated by the microtektites produced lower quality data than typical. Therefore, we consider the microprobe data for MgO, FeO, and Cr_2O_3 concentrations to be of higher quality in this particular case. Aside from these notable exceptions, we report elements with acceptable analysis errors in Table 3.

For each analysis, 30 seconds of background data were taken (with the laser off), followed by ablation and continuous measurement along the longest transect of each microtektite. Since major elements vary radially, it is expected that trace element levels might show similar heterogeneities within the microtektites. The microtektites are too small to get accurate replicate spot analyses, necessitating the use of time-averaged transects. USGS basaltic glass standards NIST-612 and BCR-2G were also analyzed in the same session (e.g., Pearce et al. 1997; Kelley et al. 2003, and references therein). The resulting counting data were averaged over the data plateau, had the average background values subtracted from it, and then normalized using $^{47}TiO_2$ as an internal standard (microprobe data) and both USGS standard10 BCR-2G and NIST-612. The average of the normalizations from the two standards is reported here, and errors are given as the difference between the two normalizations.

DISCUSSION

Though the Australasian is geographically the closest of the mapped strewn fields and known to contain bottle-green microtektites, detailed sampling across the Bruhnes/Matuyama geomagnetic reversal—the stratigraphic level correlative with the Australasian strewn layer (e.g., Glass 1967)—failed to uncover any such ejecta in the Site 1169 record. This line of negative evidence rules out any notion

Table 3. Trace element concentrations in ppm for the Site 1169 BGMTs from laser ablation ICP-MS analysis.[a]

	Tek. 1	Tek. 2	Tek. 3	Tek. 4	Average		Accuracy
Li	26	26	30	24	26		28%
Mg	48390	39790	39890	29240	39328		23%
Sc	30	32	34	29	31		33%
Ti	4263	4753	4831	4676	4631		3%
V	167	83	80	53	96		30%
Cr	512	320	161	152	286	NIST only	–
Fe	56530	52860	59080	39110	51900	BCR only	–
Co	37	30	25	14	27		27%
Ni	18	15	18	6	14	BCR only	–
Rb	10	6	13	6	9		11%
Sr	480	420	520	450	470		7%
Y	20	19	21	20	20		15%
Zr	140	154	150	153	149		17%
Nb	5	6	6	6	6		21%
Ba	590	490	600	470	540		19%
La	24	22	23	20	22		3%
Ce	55	50	50	52	51		5%
Pr	7	6	7	6	6		7%
Nd	26.2	25.2	29.5	24.8	26		6%
Sm	5.1	5.2	6.2	5.6	6		14%
Eu	1.3	1.3	1.4	1.3	1		23%
Gd	5.7	5.4	6.0	5.2	6		13%
Dy	4.7	3.6	5.2	3.8	4		13%
Er	1.9	1.6	2.6	2.3	2		24%
Tm	0.3	0.3	0.3	0.4	0		16%
Yb	2.0	1.8	2.9	2.3	2		8%
Lu	0.4	0.4	0.4	0.2	0		17%
Hf	3.6	3.3	4.0	4.0	4		12%
Ta	0.5	0.5	0.4	0.4	0		14%
Pb	0.2	0.3	0.1	0.2	0		15%
Th	5.6	6.6	7.2	6.6	6		25%
U	0.8	0.3	0.2	0.0	0		8%

[a]The data has been normalized to both standard NIST-612 and BCR-2G using $^{47}TiO_2$ as the internal standard. The data is the average of the two normalizations except where noted. Replicate analyses were not possible due to small sample sizes; accuracy is estimated as the average difference between the two normalizations. An accuracy of 3% on the internal standard (TiO_2) is within variability of the samples themselves.

that the Site 1169 BGMTs are dislodged Australasian ejecta that fell down the drill hole into late Miocene/earliest Pliocene sediments. Thus, our biostratigraphic evidence constrains the age of the Site 1169 BGMTs to a time interval spanning the latest-middle Miocene to earliest Pliocene (12.1–4.6 Ma), much older than the Pleistocene (~0.70–0.77 Ma) ages assigned to the main Australasian field (Zähringer 1963; Fleischer and Price 1964; Glass 1967, 1978; Gentner et al. 1970; Zwart and Glass 1976; Izett and Obradovich 1992). Furthermore, the Site 1169 BGMTs show enough compositional differences to suggest they represent a separate impact event. In particular, significant differences between the light REE signatures of the Site 1169 BGMTs and Australasian tektites demonstrate their separate provenance (Fig. 4). The Site 1169 BGMTs are clearly not part of the larger, younger Australasian strewn field.

Nevertheless, the enormous Australasian strewn field is composed of multiple generations of ejecta (e.g., Fleischer et al. 1969; Storzer 1985; Storzer and Müller-Sohnius 1986), making it possible that the Site 1169 BGMTs are related to a subgroup of tektites that was mistakenly assigned to the larger Australasian field. Hence, three australite subgroups garner attention: 1) HCa australites defined by relatively high calcium contents (2–6 wt%, compared to 4.9–6.0 wt% for Site 1169 BGMTs) that have been recovered from the Tasmanian region near Site 1169; 2) HMg australites distinguished by relatively high MgO contents (2–8 wt%, compared to 4.7–8.3 wt% for Site 1169 BGMTs) that intergrade with those of bottle-green microtektites; and 3) "high-soda" (HNa/K) australites that have high sodium/potassium ratios and radioisotope ages older than Australasian ejecta (e.g., Chapman and Scheiber 1969; Cassidy et al. 1969; Bottomley and Koeberl 1999). The HNa/K australites are also differentiated from Australasian ejecta by their unusually high oxygen isotopic ratios (10.7–11.0‰) and unique strontium isotopic compositions (Taylor and Epstein 1969; Compston and Chapman 1969). The major element compositions of Australasian "normal" and "bottle-green" microtektites are included for historical and comparative purposes (e.g., Glass 1972; Frey 1977).

The major-element data show that the calcium contents of the Site 1169 BGMTs are distinctly higher than those reported for HMg australites and Australasian bottle-green microtektites with similar MgO contents (Fig. 5a). Initially, we suspected that these high calcium contents might reflect a possible relationship with HCa australites, an interpretation also supported by the overlapping geographic distributions of these two ejecta populations (Fig. 5b). However, an unexpected finding is that the calcium contents of HNa/K australites are as high, if not higher than those of HCa australites, making them very similar to those of Site 1169 BGMTs (Fig. 5a).

The comparable calcium contents of Site 1169 BGMTs and HNa/K australites are of interest because various

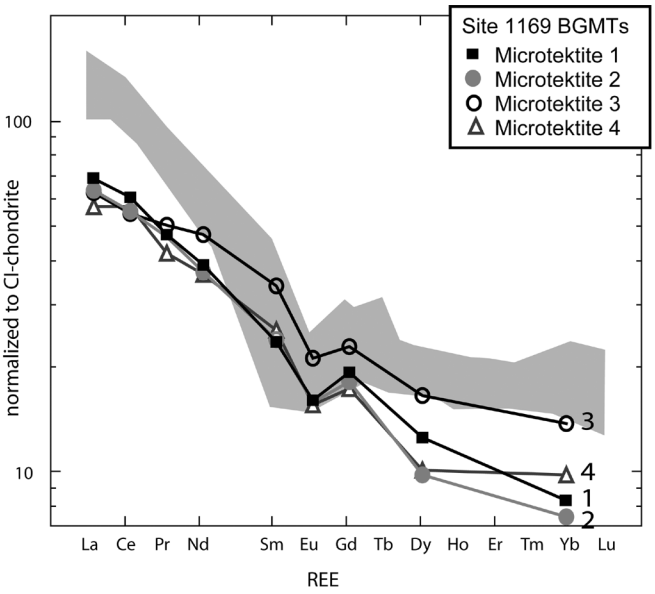

Fig. 4. Rare earth element signatures of Site 1169 BGMTs plotted with data from Australasian tektites (shaded region). The Australasian data are from Koeberl (1990), and all data are in ppm normalized by chondritic values (Anders and Grevesse 1989). The Site 1169 BGMTs are identified by number.

chronometric studies have shown that HNa/K australites are much older than Australasian ejecta (Fleischer et al. 1969; Storzer 1985; Storzer and Müller-Sohnius 1986; Bottomley and Koeberl 1999). Radioisotope analyses (K/Ar dating) have pushed the age of HNa/K australites back to 11.0 ± 0.5 Ma, revealing that these enigmatic tektites have been reworked from their original stratigraphic position and incorporated into younger sedimentary deposits that happen to also contain Australasian tektites (Storzer and Müller-Sohnius 1986). More recently, the radioisotope age of the HNa/K australites was refined to 10.2 ± 0.5 Ma through the use of the Ar^{40}/Ar^{39} dating system (Bottomley and Koeberl 1999). This early-late Miocene age (~10.2 Ma) for the HNa/K australites falls within the broad range of biostratigraphic ages (4.6–12.1 Ma) assigned to the Site 1169 BGMTs. Thus, the chronological evidence indicates that the Site 1169 BGMTs are most similar in age to HNa/K australites.

Major element-ratio pairs (Na_2O/K_2O, Al_2O_3/SiO_2, and FeO/MgO) were used to further assess compositional relatedness. The Site 1169 BGMTs register Na_2O/K_2O ratios (2:1) that are distinctly higher than those of HCa and HMg australites and Australasian bottle-green microtektites with comparable FeO/MgO ratios, yet they are still not as high as those (3:1) of the HNa/K australites (Fig. 6a). The lower Na_2O/K_2O ratios and alkali contents of the Site 1169 BGMTs do not necessarily preclude a relationship with HNa/K tektites for similar size-dependent compositional differences are known to exist among Australasian ejecta: microtektites are generally depleted in volatile major elements relative to larger-size tektites (Mason 1979; Prasad and Sudhakar 1999).

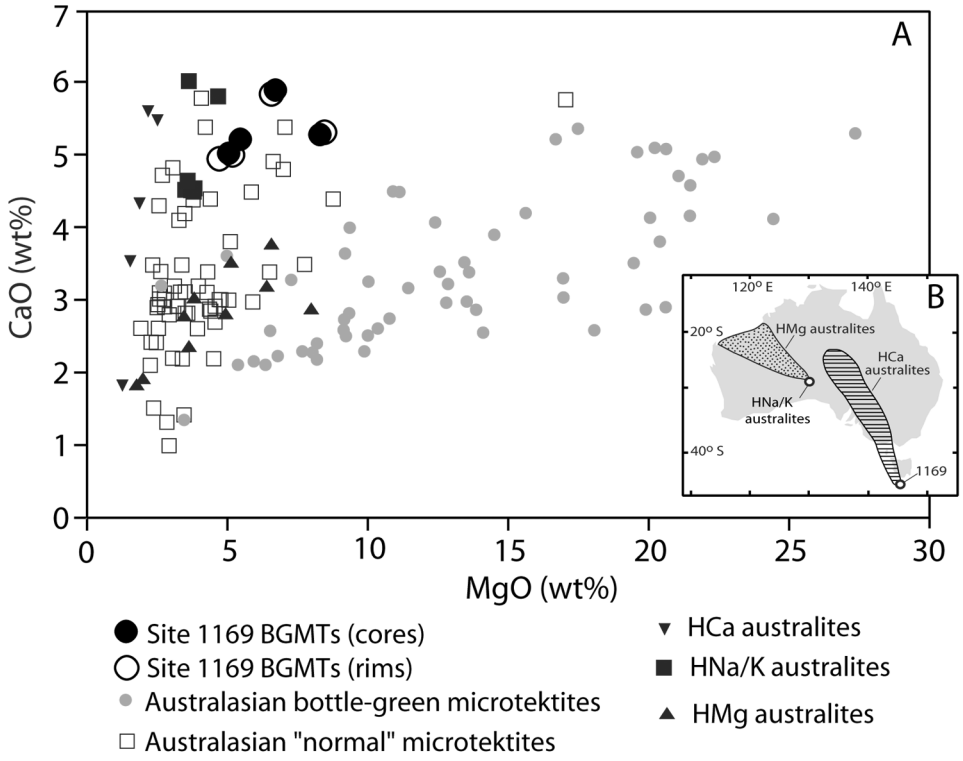

Fig. 5. a) Bivariate plot of wt% CaO and wt% MgO comparing Site 1169 BGMTs to various australite subgroups and Australasian microtektites. Note that the core and rim values for Site 1169 BGMTs are plotted separately. Data sources: HCa, HMg, and HNa/K australites (Chapman and Scheiber 1969); Australasian microtektites (Cassidy et al. 1969; Glass 1972; Frey 1977; Prasad and Sudhakar 1999); b) map showing location of Site 1169 in relation to geographic distributions of HCa, HMg, and HNa/K australites on Australian continent (modified from Chapman 1971).

Microtektites may be depleted in volatile elements due to the higher temperatures they endure during formation; some microtektites almost certainly form through condensation in the vapor plume of the impact. Thus, microtektites are expected to have lower overall volatile contents, among which the most volatile elements will be most depleted. Since Na_2O is more volatile than K_2O, the lower Na_2O/K_2O ratios of the Site 1169 BGMTs may be explained through preferential volatilization.

Added compositional differences emerge when the Al_2O_3/SiO_2 ratios of Site 1169 BGMTs and HNa/K australites are compared; specifically, the Site 1169 microtektites have higher Al_2O_3/SiO_2 ratios (Fig. 6b). This difference partly reflects the lower silica contents (~58 wt%) of Site 1169 BGMTs, a compositional signature common to most bottle-green microtektites (Cassidy et al. 1969; Chapman and Scheiber 1969; Glass 1972; Prasad and Sudhakar 1999). However, the alumina contents of the Site 1169 BGMTs (~19 wt%) are generally higher than those of HNa/K australites (~16 wt%), indicating that these microtektites are derived from a separate provenance.

The trace element signatures of HNa/K australites and Site 1169 BGMTs disclose yet another, more problematic compositional difference. The average Cr (400 ppm) and Ni (14 ppm) concentrations of Site 1169 BGMTs are respectively higher and lower than the Cr (258 ppm) and Ni (713 ppm) concentrations of HNa/K australites (Table 3; HNa/K australite data from Chapman and Scheiber 1969). Linked Cr and Ni discrepancies that covary in a similar manner can be attributed to varying degrees of contamination by the impactor; however, their decoupling with Cr being higher and Ni lower is further evidence that the Site 1169 and HNa/K microtektites formed in separate impact events. We also note that Site 1169 is located at the opposite end of the Australasian strewn field from the site of the HNa/K australites (Fig. 5b), a distance of thousands of kilometers, casting further doubt on a shared provenance.

CONCLUSIONS

Several dozen bottle-green microtektites (BGMTs) were recovered from a core sample (ODP Site 1169) taken along the western flank of the South Tasman Rise in the southeastern Indian Ocean. Biostratigraphic evidence indicates that this earliest Pliocene sample rests directly atop a major stratigraphic hiatus, with much of the late Miocene record missing from this deep-sea sequence. Therefore, it is plausible that the Site 1169 BGMTs are late Miocene constituents that have been reworked into younger sediments of the earliest Pliocene. As a result, we conservatively ascribe the timing of

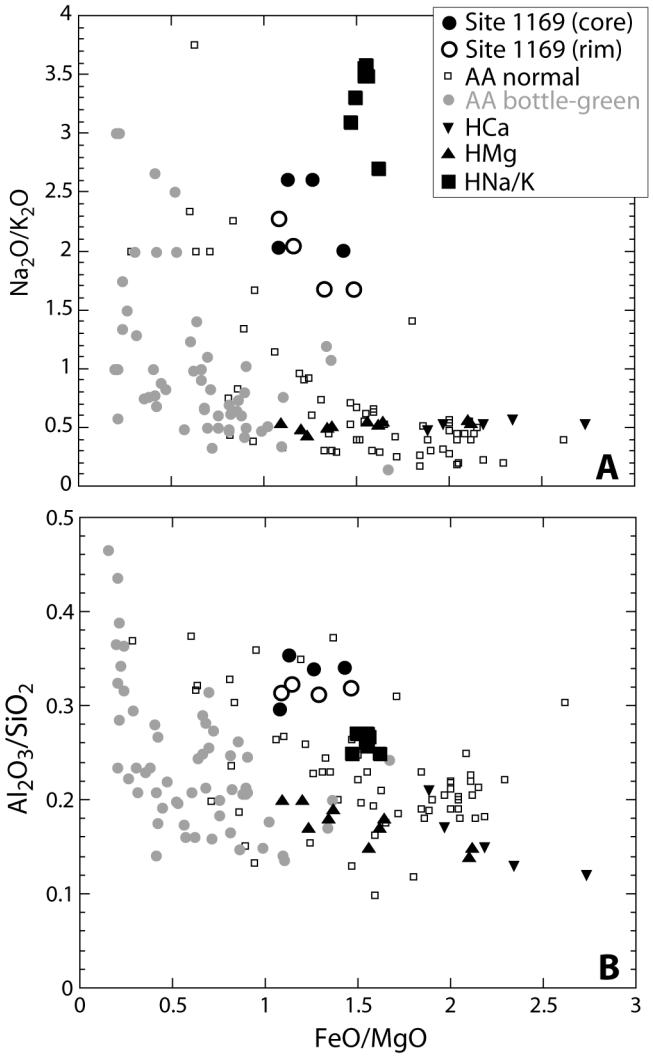

Fig. 6. Bivariate plot of wt% ratios of: a) Na_2O/K_2O and b) Al_2O_3/SiO_2 against FeO/MgO comparing Site 1169 BGMTs to various australite subgroups and Australasian (AA) microtektites. Note that core and rim values for Site 1169 BGMTs are plotted separately. Site 1169 BGMTs exhibit Al_2O_3/SiO_2 and Na_2O/K_2O ratios distinct from the HNa/K australites, though their Na_2O/K_2O ratios approach those of the HNa/K australites. Data sources: HCa, HNa/K, HMg australites (Chapman and Scheiber 1969); Australasian microtektites (Cassidy et al. 1969; Glass 1972; Frey 1977; Prasad and Sudhakar 1999).

microtektite formation to a broad period spanning the late-middle Miocene to earliest Pliocene (12.1–4.6 Ma).

Both the age and the REE signatures of the Site 1169 BGMTs are incongruent with those reported for typical australites, indicating that the Site 1169 BGMTs are not part of the Australasian strewn layer. Therefore, Site 1169 BGMTs are deep-sea sedimentary evidence for a separate impact event that is much older than the well-dated (~0.77 Ma) Australasian event.

Among the various australite subgroups, the Site 1169 BGMTs are most similar in age to the HNa/K australites. However, both major element ratios and trace element evidence suggest that the two populations are unrelated; the great distances separating Site 1169 from HNa/K australite-bearing localities also reduces the likelihood of their sharing a common impact event. Therefore, we conclude that the Site 1169 BGMTs were formed by a late Miocene impact at an unknown location that is separate from the Australasian and HNa/K australite events. The bottle-green microtektites from ODP Site 1169 provide new evidence about the number and frequency of impact events that have occurred during Earth history.

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