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Laser fusion argon-40/argon-39 ages of Darwin impact glass

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Abstract–Three samples of Darwin Glass, an impact glass found in Tasmania, Australia at the edge of the Australasian tektite strewn field were dated using the $^{40}Ar/^{39}Ar$ single-grain laser fusion technique, yielding isochron ages of 796–815 ka with an overall weighted mean of 816 ± 7 ka. These data are statistically indistinguishable from those recently reported for the Australasian tektites from Southeast Asia and Australia (761–816 ka; with a mean weighted age of 803 ± 3 ka). However, considering the compositional and textural differences and the disparity from the presumed impact crater area for Australasian tektites, Darwin Glass is more likely to have resulted from a distinct impact during the same period of time.

INTRODUCTION

Darwin Glass was first discovered and traded by Tasmanian aborigines thousands of years prior to its discovery by Europeans in the middle of the nineteenth century (Storey, 1987). The glass occurs within an area of ~400 (20 × 20) km^2 often as irregular fragments, twisted masses or chunks up to 10 cm in size with color ranging from white/clear, light green, dark green, dark brown to black in western Tasmania, Australia (Fig. 1). All geochemical studies of Darwin Glass (Taylor and Solomon, 1964; Meisel *et al.*, 1990) indicate a terrestrial origin by meteorite impact. This argument was further supported by argon and oxygen isotope data (Zähringer and Gentner, 1963; Taylor and Epstein, 1969) and the discovery of coesite within the glass (Reid and Cohen, 1962). Although no firmly established source can be found, Darwin Crater, a circular depression with negative gravity anomaly located ~7 km southwest of Mt. Darwin (Fig. 1b) was considered as a suggestive meteorite impact crater (Ford, 1972; Fudali and Ford, 1979). This is consistent with the age concordance between Darwin Glass and glasses found in Darwin Crater based on K-Ar and fission track age data (Gentner *et al.*, 1973).

Darwin Glass is generally vesicular and shows flow/layering structures without strain in thin section marked by bands of elliptical bubbles or vesicles, which is a characteristic texture often observed in Muong Nong-type tektites as they have landed as plastic glasses near the source craters (Barnes, 1963).

Geographically, Darwin Glass occurs close to the edge of the strewn field of Australasian tektites, named australites, when they are found in Australia (Fig. 1). Darwin Glass and Australasian tektites have been dated repeatedly using K-Ar and fission track techniques, which yielded a broadly coincident though large range of ages from 720 to 803 ka (Gentner *et al.*, 1969, 1973; Storzer and Wagner, 1980a,b; Izett and Obradovich, 1992; Kunz *et al.*, 1995; Yamei *et al.*, 2000). This coincidence along with the geographic association led some workers (Fleischer and Price, 1964; Gentner *et al.*, 1969; Storzer and Wagner, 1980a,b) to propose that Darwin Glass and Australasian tektites are genetically related despite the fact that the Darwin Glass has distinct textural, geochemical and oxygen isotopic features from Australasian tektites (Taylor and Solomon, 1964; Taylor and Epstein, 1969; Meisel *et al.*, 1990).

The Australasian strewn field covers an immense area (*i.e.*, one-tenth of the Earth's surface) from Southeast Asia through the India Ocean down to Australia (Fig. 1a). By identifying geochemically distinct groups of impact glasses in the field, Meisel *et al.* (1995) proposed multiple, rather than single, impact events for producing the entire strewn field. Noting that the Muong Nong-type tektites are widespread in the field, Wasson (1991, 1995) suggested a so-called "multiple melt pool hypothesis" and argued that these layered tektites should be deposited within a few radii of the source crater and thus many craters and melt pools are required. Taylor (1969) claimed that explosion of a low density comet in the atmosphere would have melted a thin surface layer of terrestrial sediments, thereby forming such widespread occurrence of impact glasses within the strewn field. Although Australasian tektites have been precisely and repeatedly dated using the $^{40}Ar/^{39}Ar$ method (Izett and Obradovich, 1992; Kunz *et al.*, 1995; Yamei *et al.*, 2000), good-quality age data have never been available for Darwin Glass. Before further testing of the above hypotheses, it is obvious that precise dating of the impact glasses in the

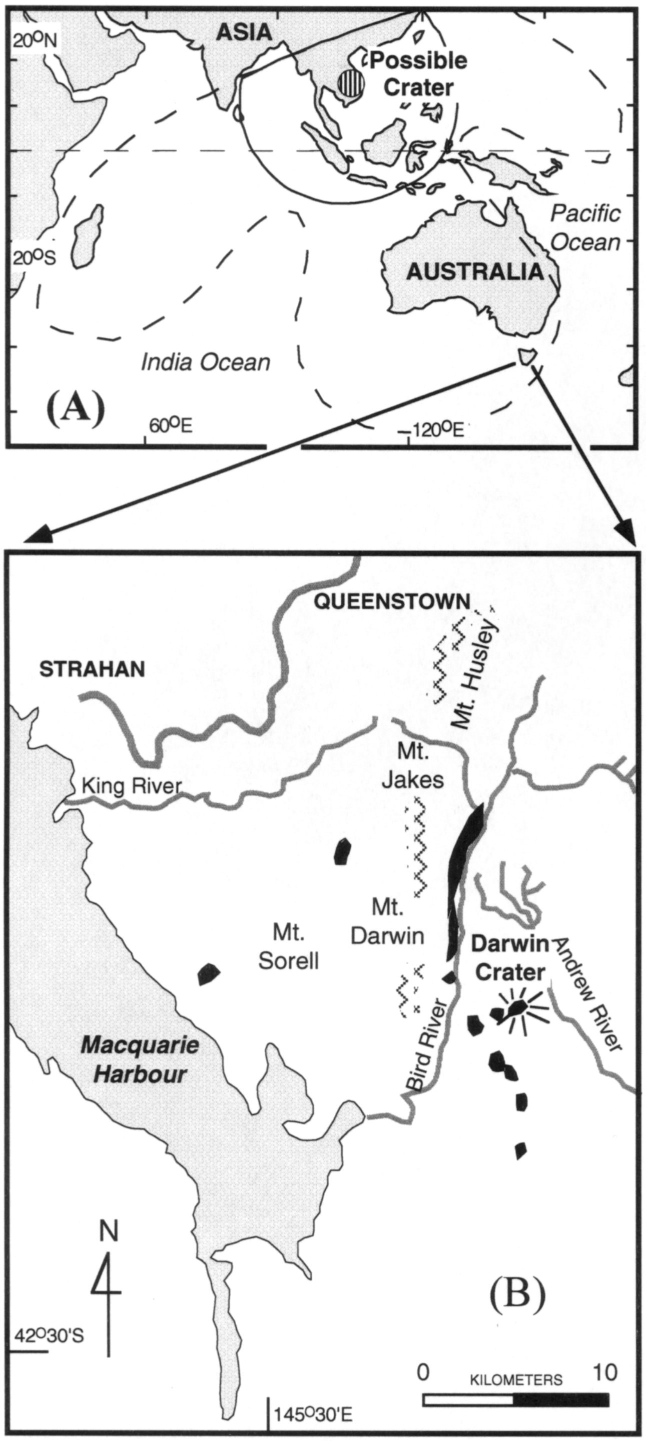

FIG. 1. (a) Geographical distribution of the tektites and microtektites of the Australasian strewn field. The shaded area marks the possible impact site for the glasses. The dashed line delimits the area in which tektite and microtektites have been found, whereas the solid line outlines that for unmelted impact ejecta (shocked quartz, coesite and stishovite). Adopted from Glass and Pizzuto (1994) and Schnetzler and McHone (1996). (b) Map showing the site of recoveries of Darwin glasses (shown in dark areas) and the location of the Darwin Crater (after Barnes, 1963; Ford, 1972).

strew field is urgently needed. This study presents the first set of precise $^{40}Ar/^{39}Ar$ age data for Darwin Glass samples that constrains the temporal and causal relations between these two types of impact glasses.

SAMPLES AND ANALYTICAL METHOD

Massive chunky black Darwin Glass fragments were collected from a ~15 cm thick soil–gravel horizon, located approximately 20–30 cm beneath the surface near Bird River, Tasmania, Australia (Fig. 1). Three glass samples (DC1, DC2 and DC3) with the least internal bubbles were extracted from these fragments for laser $^{40}Ar/^{39}Ar$ single-grain fusion dating.

Samples were washed, crushed and sieved. After sieving, glass chips in the size range of 140–250 μm were ultrasonically cleaned in distilled water, then dried and handpicked to remove visible contamination and fragments with bubbles. The glass chips were then irradiated together with the LP-6 Biotite standard (Odin *et al.*, 1982) and known composition salts in the VT-C position for 30 h at the THOR reactor in Taiwan. In order to monitor the neutron flux in the reactor, three aliquots of the LP-6 standard weighing between 6 and 10 mg were stacked with the samples in an irradiation canister ~9 cm in length. After irradiation, standards and samples were totally fused using an US LASER Nd-YAG laser operated in continuous mode for fusing the glass grains in single steps. The gas was purified by two Zr-Al getters and was analyzed on a VG3600 mass spectrometer at the National Taiwan University, Taipei, Taiwan. The J values were calculated from the argon compositions of the LP-6 biotites with a $^{40}Ar/^{39}Ar$ age of 128.4 ± 0.2 Ma, which was calibrated according to the age of the Fish Canyon biotite by assuming it has the same age as the Fish Canyon sanidine (28.02 ± 0.28 Ma; Baksi *et al.*, 1996; Renne *et al.*, 1998). The mean of J-values obtained from the monitor standards was adopted in age calculations because the gradient of neutron flux across the canister appears to be 0.52%, which is rather small. The isotope interferences caused by Ca, K and Cl were monitored by analytical results for the co-irradiated salts. Ages were calculated from Ar isotopic ratios after corrections had been made for mass discrimination, interfering nuclear reactions, procedural blanks and atmospheric Ar contamination. Analytical procedures are outlined in detail by Lo *et al.* (2001). Results of the $^{40}Ar/^{39}Ar$ analyses are shown in Table 1 and plotted as isotope correlation diagrams in Fig. 2.

ANALYTICAL RESULTS

Fusion of 33 single grains was carried out for sample DC1, which gave an age range from 731 to 868 ka and a total gas age of 808 ± 8 ka (Table 1). The data points plot linearly in the $^{36}Ar/^{40}Ar$–$^{39}Ar/^{40}Ar$ isotope correlation diagram yielding an intercept age of 814 ± 16 ka and a trapped argon composition with $^{40}Ar/^{36}Ar$ ratio of 295.5 ± 0.5, with a value

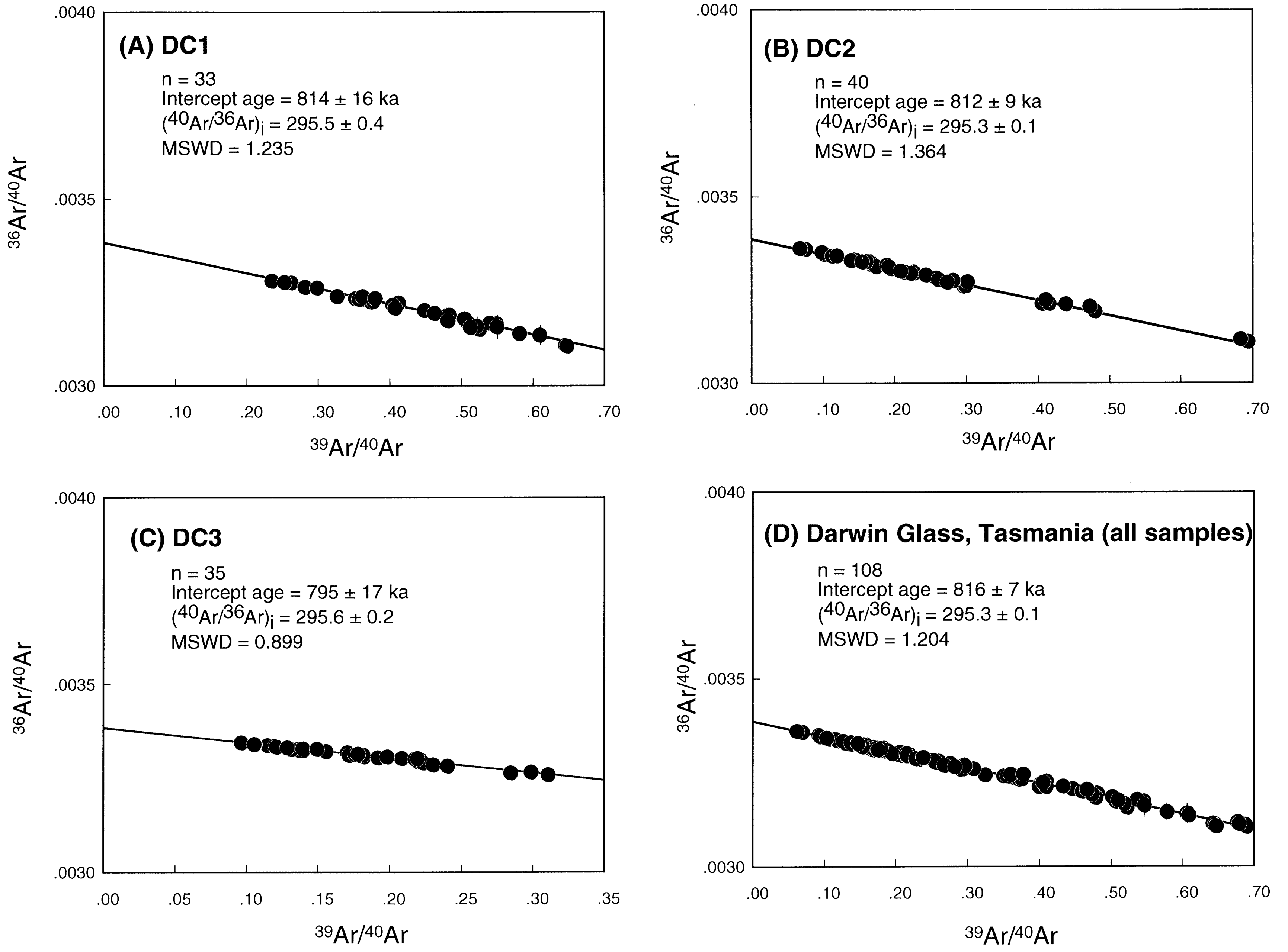

FIG. 2. ^{36}Ar/^{40}Ar–^{39}Ar/^{40}Ar isotope correlation diagram for (a) DC1, (b) DC2 and (c) DC3. Regression of the ^{40}Ar/^{39}Ar dating results for all three samples, assuming that they were produced by the same impact event, is shown in (d). Data points are presented by solid circles, with $\pm 1\sigma$ error ellipse.

TABLE 1. Results of $^{40}Ar/^{39}Ar$ laser single-grain fusion analyses.

#	Atmosphere (%)	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$	Age (ka)
DC1 Darwin Glass, Tasmania							
1	92.91	0.54339×10^{-2}	0.23243×10^{-2}	0.13161×10^{-1}	0.17568×10^{1}	0.32330×10^{3}	823 ± 73
2	91.96	0.48413×10^{-2}	0.64333×10^{-3}	0.13849×10^{-1}	0.15842×10^{1}	0.32724×10^{3}	839 ± 23
3	93.24	0.60410×10^{-2}	0.67349×10^{-3}	0.14002×10^{-1}	0.19431×10^{1}	0.32165×10^{3}	868 ± 23
4	96.93	0.12638×10^{-1}	0.10611×10^{-2}	0.14895×10^{-1}	0.38812×10^{1}	0.30711×10^{3}	793 ± 34
5	93.74	0.62665×10^{-2}	0.10257×10^{-2}	0.13866×10^{-1}	0.20040×10^{1}	0.31980×10^{3}	830 ± 29
6	94.09	0.63483×10^{-2}	0.65827×10^{-3}	0.14147×10^{-1}	0.20224×10^{1}	0.31858×10^{3}	791 ± 18
7	95.34	0.78792×10^{-2}	0.17701×10^{-2}	0.14107×10^{-1}	0.24707×10^{1}	0.31357×10^{3}	764 ± 39
8	94.39	0.66666×10^{-2}	0.71887×10^{-3}	0.14182×10^{-1}	0.21156×10^{1}	0.31735×10^{3}	786 ± 31
9	95.57	0.88419×10^{-2}	0.55298×10^{-2}	0.13997×10^{-1}	0.27621×10^{1}	0.31239×10^{3}	813 ± 29
10	94.37	0.66449×10^{-2}	0.12183×10^{-2}	0.13968×10^{-1}	0.21094×10^{1}	0.31744×10^{3}	787 ± 27
11	95.75	0.92604×10^{-2}	0.13601×10^{-2}	0.14667×10^{-1}	0.28865×10^{1}	0.31171×10^{3}	816 ± 27
12	96.63	0.11714×10^{-1}	0.13984×10^{-2}	0.15015×10^{-1}	0.36109×10^{1}	0.30825×10^{3}	811 ± 24
13	93.74	0.58092×10^{-2}	0.28056×10^{-2}	0.13735×10^{-1}	0.18597×10^{1}	0.32013×10^{3}	769 ± 17
14	94.73	0.71889×10^{-2}	0.12093×10^{-2}	0.13992×10^{-1}	0.22712×10^{1}	0.31592×10^{3}	794 ± 18
15	95.16	0.80163×10^{-2}	0.13522×10^{-2}	0.14178×10^{-1}	0.25179×10^{1}	0.31410×10^{3}	809 ± 25
16	95.49	0.87113×10^{-2}	0.10447×10^{-2}	0.14610×10^{-1}	0.27244×10^{1}	0.31274×10^{3}	816 ± 19
17	95.85	0.10004×10^{-1}	0.21775×10^{-2}	0.14438×10^{-1}	0.31129×10^{1}	0.31116×10^{3}	860 ± 37
18	94.51	0.69571×10^{-2}	0.12595×10^{-2}	0.13900×10^{-1}	0.22039×10^{1}	0.31679×10^{3}	802 ± 22
19	95.74	0.91283×10^{-2}	0.22788×10^{-2}	0.14252×10^{-1}	0.28459×10^{1}	0.31177×10^{3}	805 ± 37
20	94.99	0.79397×10^{-2}	0.93904×10^{-3}	0.14325×10^{-1}	0.24985×10^{1}	0.31469×10^{3}	831 ± 16
21	95.52	0.86227×10^{-2}	0.14659×10^{-2}	0.14472×10^{-1}	0.26962×10^{1}	0.31269×10^{3}	803 ± 23
22	91.89	0.48221×10^{-2}	0.19756×10^{-2}	0.13459×10^{-1}	0.15792×10^{1}	0.32748×10^{3}	844 ± 14
23	95.88	0.90234×10^{-2}	0.11441×10^{-2}	0.14498×10^{-1}	0.28096×10^{1}	0.31137×10^{3}	769 ± 24
24	97.10	0.14136×10^{-1}	0.12614×10^{-2}	0.15555×10^{-1}	0.43304×10^{1}	0.30634×10^{3}	837 ± 25
25	93.87	0.59218×10^{-2}	0.35619×10^{-2}	0.13817×10^{-1}	0.18926×10^{1}	0.31961×10^{3}	767 ± 18
26	93.42	0.57824×10^{-2}	0.16949×10^{-2}	0.13832×10^{-1}	0.18577×10^{1}	0.32126×10^{3}	808 ± 26
27	96.52	0.11036×10^{-1}	0.24518×10^{-2}	0.14767×10^{-1}	0.34071×10^{1}	0.30874×10^{3}	789 ± 51
28	92.77	0.51726×10^{-2}	0.17026×10^{-2}	0.13651×10^{-1}	0.16762×10^{1}	0.32406×10^{3}	800 ± 87
29	93.55	0.61089×10^{-2}	0.26675×10^{-2}	0.14024×10^{-1}	0.19582×10^{1}	0.32054×10^{3}	836 ± 84
30	95.89	0.86055×10^{-2}	0.23027×10^{-2}	0.15387×10^{-1}	0.26804×10^{1}	0.31147×10^{3}	731 ± 36
31	97.02	0.13124×10^{-1}	0.22449×10^{-2}	0.15360×10^{-1}	0.40258×10^{1}	0.30675×10^{3}	800 ± 39
32	93.83	0.62318×10^{-2}	0.95238×10^{-2}	0.12966×10^{-1}	0.19905×10^{1}	0.31941×10^{3}	812 ± 37
33	94.02	0.66507×10^{-2}	0.38904×10^{-2}	0.13906×10^{-1}	0.21186×10^{1}	0.31856×10^{3}	839 ± 23
J-value = 0.00372420 ± 0.00002828							
Total gas age = 808 ± 8 ka							
DC2 Darwin Glass, Tasmania							
1	98.39	0.24018×10^{-1}	0.17306×10^{-2}	0.17243×10^{-1}	0.72419×10^{1}	0.30152×10^{3}	779 ± 27
2	91.86	0.45242×10^{-2}	0.30164×10^{-2}	0.13231×10^{-1}	0.14839×10^{1}	0.32798×10^{3}	795 ± 13
3	96.99	0.13012×10^{-1}	0.12264×10^{-2}	0.15357×10^{-1}	0.39927×10^{1}	0.30686×10^{3}	800 ± 26
4	97.42	0.14934×10^{-1}	0.96154×10^{-3}	0.15743×10^{-1}	0.45583×10^{1}	0.30523×10^{3}	783 ± 16
5	94.29	0.67417×10^{-2}	0.13219×10^{-2}	0.13956×10^{-1}	0.21413×10^{1}	0.31762×10^{3}	809 ± 10
6	97.98	0.20334×10^{-1}	0.22884×10^{-2}	0.16269×10^{-1}	0.61610×10^{1}	0.30299×10^{3}	831 ± 26
7	98.18	0.20727×10^{-1}	0.36248×10^{-2}	0.16279×10^{-1}	0.62667×10^{1}	0.30234×10^{3}	760 ± 55
8	97.35	0.14884×10^{-1}	0.16564×10^{-2}	0.15211×10^{-1}	0.45465×10^{1}	0.30547×10^{3}	804 ± 27
9	97.19	0.13841×10^{-1}	0.26582×10^{-2}	0.15062×10^{-1}	0.42370×10^{1}	0.30611×10^{3}	794 ± 24
10	98.39	0.24371×10^{-1}	0.35582×10^{-2}	0.17141×10^{-1}	0.73482×10^{1}	0.30151×10^{3}	792 ± 24
11	98.25	0.21110×10^{-1}	0.65995×10^{-2}	0.16078×10^{-1}	0.63771×10^{1}	0.30209×10^{3}	744 ± 58
12	99.22	0.48692×10^{-1}	0.29402×10^{-2}	0.21710×10^{-1}	0.14530×10^{2}	0.29840×10^{3}	756 ± 11
13	92.06	0.46037×10^{-2}	0.24038×10^{-2}	0.13361×10^{-1}	0.15062×10^{1}	0.32716×10^{3}	787 ± 14
14	96.28	0.11223×10^{-1}	0.40819×10^{-2}	0.14773×10^{-1}	0.34729×10^{1}	0.30944×10^{3}	859 ± 28
15	99.30	0.54659×10^{-1}	0.80539×10^{-2}	0.22489×10^{-1}	0.16294×10^{2}	0.29810×10^{3}	766 ± 45
16	94.90	0.80480×10^{-2}	0.33672×10^{-2}	0.14234×10^{-1}	0.25343×10^{1}	0.31490×10^{3}	857 ± 31

TABLE 1. *Continued.*

#	Atmosphere (%)	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$	Age (ka)
DC2 Darwin Glass, Tasmania *(Continued)*							
17	94.67	0.68739×10^{-2}	0.30437×10^{-2}	0.13710×10^{-1}	0.21741×10^{1}	0.31628×10^{3}	768 ± 13
18	96.32	0.11125×10^{-1}	0.16346×10^{-2}	0.14596×10^{-1}	0.34414×10^{1}	0.30935×10^{3}	843 ± 18
19	96.63	0.11068×10^{-1}	0.28988×10^{-2}	0.14739×10^{-1}	0.34130×10^{1}	0.30837×10^{3}	765 ± 20
20	98.82	0.34919×10^{-1}	0.41461×10^{-2}	0.18257×10^{-1}	0.10470×10^{2}	0.29984×10^{3}	828 ± 45
21	97.84	0.19669×10^{-1}	0.56872×10^{-2}	0.16602×10^{-1}	0.59688×10^{1}	0.30346×10^{3}	862 ± 66
22	94.91	0.78522×10^{-2}	0.41255×10^{-2}	0.14023×10^{-1}	0.24733×10^{1}	0.31498×10^{3}	836 ± 34
23	97.68	0.17509×10^{-1}	0.41718×10^{-2}	0.15837×10^{-1}	0.53249×10^{1}	0.30413×10^{3}	823 ± 58
24	96.83	0.12835×10^{-1}	0.63405×10^{-2}	0.15589×10^{-1}	0.39451×10^{1}	0.30736×10^{3}	833 ± 31
25	98.38	0.25030×10^{-1}	0.24445×10^{-2}	0.17518×10^{-1}	0.75464×10^{1}	0.30150×10^{3}	816 ± 37
26	97.39	0.15809×10^{-1}	0.21134×10^{-2}	0.15540×10^{-1}	0.48253×10^{1}	0.30522×10^{3}	841 ± 31
27	98.99	0.36474×10^{-1}	0.28463×10^{-2}	0.19446×10^{-1}	0.10917×10^{2}	0.29931×10^{3}	741 ± 39
28	98.25	0.21564×10^{-1}	0.26964×10^{-2}	0.16539×10^{-1}	0.65138×10^{1}	0.30207×10^{3}	760 ± 20
29	97.32	0.15205×10^{-1}	0.24883×10^{-2}	0.15764×10^{-1}	0.46452×10^{1}	0.30552×10^{3}	831 ± 38
30	96.76	0.11865×10^{-1}	0.47218×10^{-2}	0.15461×10^{-1}	0.36517×10^{1}	0.30779×10^{3}	788 ± 30
31	98.68	0.31365×10^{-1}	0.24094×10^{-2}	0.18420×10^{-1}	0.94205×10^{1}	0.30035×10^{3}	830 ± 61
32	97.97	0.18079×10^{-1}	0.56964×10^{-2}	0.15645×10^{-1}	0.54816×10^{1}	0.30320×10^{3}	744 ± 58
33	98.71	0.29646×10^{-1}	0.18694×10^{-2}	0.18565×10^{-1}	0.89036×10^{1}	0.30033×10^{3}	769 ± 7
34	98.25	0.22418×10^{-1}	0.17570×10^{-2}	0.17224×10^{-1}	0.67714×10^{1}	0.30205×10^{3}	794 ± 25
35	96.75	0.11886×10^{-1}	0.39828×10^{-2}	0.14745×10^{-1}	0.36589×10^{1}	0.30782×10^{3}	792 ± 61
36	96.60	0.12231×10^{-1}	0.21169×10^{-2}	0.15079×10^{-1}	0.37699×10^{1}	0.30822×10^{3}	853 ± 16
37	94.94	0.74269×10^{-2}	0.27136×10^{-2}	0.14253×10^{-1}	0.23401×10^{1}	0.31508×10^{3}	785 ± 14
38	95.23	0.79662×10^{-2}	0.28509×10^{-2}	0.14061×10^{-1}	0.25004×10^{1}	0.31387×10^{3}	791 ± 29
39	97.83	0.17800×10^{-1}	0.25554×10^{-2}	0.15810×10^{-1}	0.54053×10^{1}	0.30366×10^{3}	784 ± 47
40	97.49	0.16289×10^{-1}	0.17297×10^{-2}	0.15718×10^{-1}	0.49661×10^{1}	0.30486×10^{3}	832 ± 20
J-value = 0.00372420 ± 0.00002828							
Total gas age = 802 ± 7 ka							
DC3 Darwin Glass, Tasmania							
1	97.47	0.15069×10^{-1}	0.22463×10^{-2}	0.15509×10^{-1}	0.45971×10^{1}	0.30506×10^{3}	776 ± 27
2	97.80	0.18458×10^{-1}	0.12332×10^{-2}	0.16352×10^{-1}	0.56054×10^{1}	0.30368×10^{3}	822 ± 19
3	97.75	0.17478×10^{-1}	0.16259×10^{-2}	0.16024×10^{-1}	0.53125×10^{1}	0.30395×10^{3}	800 ± 25
4	98.40	0.24865×10^{-1}	0.18274×10^{-2}	0.17503×10^{-1}	0.74955×10^{1}	0.30144×10^{3}	800 ± 33
5	98.29	0.24701×10^{-1}	0.24945×10^{-2}	0.17213×10^{-1}	0.74547×10^{1}	0.30180×10^{3}	854 ± 44
6	98.30	0.24293×10^{-1}	0.14664×10^{-2}	0.17327×10^{-1}	0.73312×10^{1}	0.30178×10^{3}	833 ± 46
7	98.47	0.26233×10^{-1}	0.19753×10^{-2}	0.17560×10^{-1}	0.79008×10^{1}	0.30118×10^{3}	808 ± 54
8	98.05	0.19751×10^{-1}	0.29004×10^{-2}	0.16513×10^{-1}	0.59809×10^{1}	0.30281×10^{3}	778 ± 63
9	98.38	0.25880×10^{-1}	0.18995×10^{-2}	0.17721×10^{-1}	0.78023×10^{1}	0.30148×10^{3}	848 ± 45
10	97.38	0.15128×10^{-1}	0.22007×10^{-2}	0.15606×10^{-1}	0.46192×10^{1}	0.30533×10^{3}	807 ± 21
11	96.33	0.10583×10^{-1}	0.54493×10^{-2}	0.14366×10^{-1}	0.32748×10^{1}	0.30944×10^{3}	800 ± 35
12	97.65	0.16068×10^{-1}	0.19240×10^{-2}	0.15831×10^{-1}	0.48906×10^{1}	0.30438×10^{3}	766 ± 26
13	98.69	0.29783×10^{-1}	0.18508×10^{-2}	0.18111×10^{-1}	0.89461×10^{1}	0.30038×10^{3}	784 ± 55
14	98.90	0.35721×10^{-1}	0.41420×10^{-2}	0.19041×10^{-1}	0.10702×10^{2}	0.29959×10^{3}	791 ± 76
15	98.64	0.28486×10^{-1}	0.15563×10^{-2}	0.18287×10^{-1}	0.85628×10^{1}	0.30059×10^{3}	782 ± 53
16	97.92	0.18855×10^{-1}	0.23682×10^{-2}	0.15994×10^{-1}	0.57185×10^{1}	0.30329×10^{3}	795 ± 43
17	97.91	0.19573×10^{-1}	0.62474×10^{-2}	0.16328×10^{-1}	0.59358×10^{1}	0.30326×10^{3}	830 ± 46
18	97.54	0.16922×10^{-1}	0.24962×10^{-2}	0.16160×10^{-1}	0.51553×10^{1}	0.30465×10^{3}	848 ± 20
19	98.56	0.28230×10^{-1}	0.28553×10^{-2}	0.17838×10^{-1}	0.84926×10^{1}	0.30083×10^{3}	819 ± 42
20	98.52	0.26491×10^{-1}	0.22892×10^{-2}	0.17495×10^{-1}	0.79746×10^{1}	0.30103×10^{3}	791 ± 28
21	98.41	0.24336×10^{-1}	0.43680×10^{-2}	0.17322×10^{-1}	0.73356×10^{1}	0.30143×10^{3}	778 ± 41
22	97.54	0.15354×10^{-1}	0.25444×10^{-2}	0.14912×10^{-1}	0.46800×10^{1}	0.30481×10^{3}	768 ± 29
23	97.97	0.19101×10^{-1}	0.20089×10^{-2}	0.16157×10^{-1}	0.57896×10^{1}	0.30311×10^{3}	784 ± 59
24	97.95	0.18535×10^{-1}	0.20539×10^{-2}	0.15925×10^{-1}	0.56203×10^{1}	0.30323×10^{3}	770 ± 31
25	96.55	0.11032×10^{-1}	0.24115×10^{-2}	0.15106×10^{-1}	0.34050×10^{1}	0.30864×10^{3}	782 ± 19

TABLE 1. *Continued.*

#	Atmosphere (%)	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$	Age (ka)
DC3 Darwin Glass, Tasmania *(Continued)*							
26	97.30	0.14917×10^{-1}	0.26458×10^{-2}	0.15645×10^{-1}	0.45589×10^{1}	0.30562×10^{3}	822 ± 23
27	98.78	0.32393×10^{-1}	0.27409×10^{-2}	0.18703×10^{-1}	0.97193×10^{1}	0.30004×10^{3}	796 ± 42
28	96.49	0.11586×10^{-1}	0.23983×10^{-2}	0.14766×10^{-1}	0.35767×10^{1}	0.30870×10^{3}	835 ± 25
29	97.83	0.18906×10^{-1}	0.27273×10^{-2}	0.16501×10^{-1}	0.57391×10^{1}	0.30356×10^{3}	832 ± 38
30	97.38	0.15259×10^{-1}	0.30617×10^{-2}	0.15890×10^{-1}	0.46586×10^{1}	0.30531×10^{3}	814 ± 22
31	98.08	0.21689×10^{-1}	0.26248×10^{-2}	0.16830×10^{-1}	0.65632×10^{1}	0.30260×10^{3}	843 ± 35
32	98.76	0.32521×10^{-1}	0.25542×10^{-2}	0.19141×10^{-1}	0.97589×10^{1}	0.30008×10^{3}	809 ± 66
33	98.35	0.22685×10^{-1}	0.12613×10^{-2}	0.17138×10^{-1}	0.68446×10^{1}	0.30172×10^{3}	755 ± 45
34	97.14	0.14436×10^{-1}	0.37874×10^{-2}	0.15165×10^{-1}	0.44198×10^{1}	0.30617×10^{3}	843 ± 32
35	97.23	0.13824×10^{-1}	0.97665×10^{-3}	0.15252×10^{-1}	0.42299×10^{1}	0.30598×10^{3}	781 ± 15
J-value = 0.00372420 ± 0.00002828							
Total gas age = 802 ± 9 ka							

J-value = Weighted mean of three fusions of irradiated standard LP-6 Biotite having a calibrated $^{40}Ar/^{39}Ar$ age of 128.4 ± 0.2 Ma, based on Fish Canyon Sanidine (28.02 ± 0.28 Ma) (Baksi *et al.*, 1996; Renne *et al.*, 1998). The age is obtained by using the following equations:

$$\text{Age} = \frac{1}{\lambda}\ln\left(1 + J\frac{^{40}\text{Ar}^*}{^{39}\text{Ar}_K}\right), \text{and}$$

$$\frac{^{40}\text{Ar}^*}{^{39}\text{Ar}_K} = \frac{\left[^{40}\text{Ar}/^{39}\text{Ar}\right]_m - 295.5\left[^{36}\text{Ar}/^{39}\text{Ar}\right]_m + 295.5\left[^{36}\text{Ar}/^{37}\text{Ar}\right]_{Ca}\left[^{37}\text{Ar}/^{39}\text{Ar}\right]_m}{1 - \left[^{39}\text{Ar}/^{37}\text{Ar}\right]_{Ca}\left[^{37}\text{Ar}/^{39}\text{Ar}\right]_m} - \left[\frac{^{40}\text{Ar}}{^{39}\text{Ar}}\right]_K$$

where $[\ ]_{Ca}$ and $[\ ]_K$ = isotope ratios of argon extracted from irradiated calcium and potassium salts and $[\ ]_m$ = isotope ratio of argon extracted from irradiated unknown.
Age (ka) = the age is calculated using the decay constant: $\lambda = 5.543 \times 10^{-10}$ years^{-1} (Steiger and Jäger, 1977).
The quoted error is 1σ and includes the standard error in *J*-value, but not the error in interference correction factors.
Total gas age = the age and error calculated from the sum of total gas from all fusions; the error includes the error in *J*-value.

of mean square of weighted deviates (MSWD) = 1.235 (Fig. 2a). Similarly, sample DC2 gave $^{40}Ar/^{39}Ar$ ages in the range of 741–862 ka and the sum of gas compositions suggesting a total gas age of 802 ± 7 ka (Table 1). Regression of the data points in the isotope correlation diagram indicates an intercept age of 812 ± 9 ka with an initial $^{40}Ar/^{36}Ar$ value of 295.3 ± 0.1, which is indistinguishable from the atmospheric composition (MSWD = 1.364; Fig. 2b). In contrast, DC3 glass yields a $^{40}Ar/^{36}Ar$ initial value of 295.6 ± 0.2 (MSWD = 0.899) and an intercept age of 795 ± 17 ka, which is slightly lower than its respective total gas age (802 ± 9 ka), although both ages agree with each other within ±1σ. The age range (755–854 ka), total gas age (802 ± 9 ka) and intercept age (795 ± 17 ka) of DC3 appear to be consistent with the respective values of the other two samples.

Given that MSWD values (0.899–1.364) of data regressions of these samples are close to unity, and that the isotope correlation analysis is considered to be able to accommodate deviations from atmospheric $^{40}Ar/^{36}Ar$ composition in the samples (see McDougall and Harrison, 1999, for discussion), the intercept ages should be more reliable than the respective total gas ages, although they generally match with each other (Table 1 and Fig. 2a–c). Overall, the obtained intercept ages for the Darwin samples range from 795 ± 17 ka to 814 ± 16 ka (Fig. 2) and match with each other within ±1σ. This age concordance suggests that Darwin glasses dated in the present study most likely originated from the same impact event. In order to achieve the best age estimate, all data were plotted together in an isotope correlation diagram (Fig. 2d). The regression of all data results in an intercept age of 816 ± 7 ka with a MSWD value of 1.204 and a $^{40}Ar/^{36}Ar$ initial value of 295.3 ± 0.1 for the trapped argon. As shown in Table 1 and Fig. 2a–c, more than 91% of argon in the samples is trapped argon with $^{40}Ar/^{36}Ar$ composition ranging 295.3–295.6, which perfectly agrees with the present-day atmospheric value (295.5), indicating that the trapped argon is mainly atmospheric and was held tightly in the glass during melt solidification after impact. In other words, the noble gas components of Darwin Glass is mainly derived from the atmosphere and there is no sign of excess argon contamination from the country rocks or the impactor during the impact processes (Zähringer and Gentner, 1963; Matsuda *et al.*, 1989).

DISCUSSION AND CONCLUSION

Our result coincides with a fission track age (810 ± 4 ka) reported by Storzer and Wagner (1980a,b), but is apparently older than K-Ar and fission track ages (0.73 ± 0.04 and 0.72 ± 0.02 Ma, respectively) reported by Gentner *et al.* (1969, 1973) for Darwin Glass. Fleischer and Price (1964) obtained an even lower fission track age of 0.65 ± 0.1 Ma for Darwin Glass. Based on a broadly concordant fission track date of 820 ± 5 ka for the Australasian tektites, Storzer and Wagner (1980a,b) concluded that Darwin Glass and Australasian tektites are genetically related. Recently, tektites in the Australasian strew field have been repeatedly dated by $^{40}Ar/^{39}Ar$ methods yielding ages ranging from 761 ± 17 ka to 816 ± 7 ka for australites, indochinites and philippinites (Izett and Obradovich, 1992; Kunz *et al.*, 1995; Yamei *et al.*, 2000). The $^{40}Ar/^{39}Ar$ ages obtained here in the range of 795–814 ka with a best age estimate of 816 ± 7 ka for Darwin Glass match very well with the $^{40}Ar/^{39}Ar$ ages reported for tektites in the Australasian strewn field (Izett and Obradovich, 1992; Kunz *et al.*, 1995). More significantly, the age range (796–815 ka) and the overall weighted mean age (816 ± 7 ka) are all in reasonable agreement (within $\pm 2\sigma$) with the $^{40}Ar/^{39}Ar$ ages recently reported by Yamei *et al.* (2000) for Australasian tektites ranging from 761 to 816 ka with a weighted mean age of 803 ± 3 ka. This agreement in precise age data using modern techniques reconfirms the previous notation that the impact events for the Darwin Glass and Australasian tektites occurred almost coincidently in the Mid-Pleistocene.

However, Darwin Glass and Australasian tektites seemingly have different geochemical and isotope compositions (Taylor and Solomon, 1964; Taylor and Epstein, 1969; Meisel *et al.*, 1990). For example, Darwin glasses usually contain higher SiO_2 and water concentrations (>0.047 wt%) and lower concentration of cation oxides than Australasian tektites (Chao, 1963; Gilchrist *et al.*, 1969; Glass, 1990). At least two geochemically distinct groups of Darwin Glass have been identified, which are thought to result from incomplete mixing of quartzite and shale in the Darwin crater area. During impact processes, both enrichment and losses of volatile elements by the impacting bodies or ultrabasic rocks were observed for Darwin Glass (Taylor and Solomon, 1964; Taylor and Epstein, 1969; Meisel *et al.*, 1990). In contrast, Australasian tektites are more uniform in composition, and very likely had post-Archean alluvial sediments such as the Jurassic alluvium deposits in Indochina as precursor material (Shaw and Wasserburg, 1982; Koeberl, 1990; Schnetzler, 1992; Blum *et al.*, 1992). The contrast in chemical composition argues against a common origin for Darwin Glass and Australasian tektites (Taylor and Solomon, 1964; Taylor and Epstein, 1969; Meisel *et al.*, 1990, 1995).

As mentioned above, Ford (1972) and Fudali and Ford (1979) suggested a circular depression near Mt. Darwin to be the possible source crater for Darwin Glass on the basis of gravity anomaly data. The suggestion has been supported by geochemical, isotopic and dating investigations on the glasses and target rocks (Taylor and Solomon, 1964; Taylor and Epstein, 1969; Genter *et al.*, 1973; Meisel *et al.*, 1990). In addition, petrographic textures of Darwin glasses are similar to Muong Nong-type tektites indicating that these glasses formed under low temperature and pressure conditions during the impact processes, and landed around the crater while the glasses were still plastic (Barnes, 1963; Ford, 1988; Schnetzler, 1992; Koeberl, 1994). The texture character is consistent with an impact glass source in western Tasmania. Given the fact that Tasmania is several thousand kilometers away from the most probable impact site for the Australasian tektites in Indo-China (Fig. 1; see McCall, 2001, for a recent review), it is very unlikely that Darwin Glass and Australasian tektites should have resulted from the same impact event, although the chronometric data indicated they were formed synchronously. Thus, the hypothesis that Darwin Glass and Australasian tektites were formed through different impacts (Gentner *et al.*, 1969, 1973; Storzer and Wagner, 1980a,b; Meisel *et al.*, 1995) can be further substantiated.

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REFERENCES

BAKSI A. K., ARCHIBALD D. A. AND FARRAR E. (1996) Intercalibration of $^{40}Ar/^{39}Ar$ dating standards. *Chem. Geol.* **129**, 307–324.

BARNES V. E. (1963) Detrital mineral grains in tektites. *Science* **142**, 1651–1652.

BLUM J. D., PAPANASTASSIOU D. A., KOEBERL C. AND WASSERBURG G. J. (1992) Neodymium and strontium isotopic study of Australasian tektites: New constraints on the provenance and age of target materials. *Geochim. Cosmochim. Acta* **56**, 483–492.

CHAO E. C. (1963) The petrographic and chemical characteristics of tektites. In *Tektites* (ed. J. O'Keefe), pp. 51–94. Univ. Chicago Press, New York, USA.

FLEISCHER R. L. AND PRICE P. B. (1964) Fission track evidence for the simultaneous origin of tektites and other natural glasses. *Geochim. Cosmochim. Acta* **28**, 755–760.

FORD R. J. (1972) A possible impact crater associated with Darwin Glass. *Earth Planet. Sci. Lett.* **16**, 228–230.

FORD R. J. (1988) An empirical model for the Australasian tektite strewn field. *Austral. J. Earth Sci.* **35**, 483–490.

FUDALI R. F. AND FORD R. J. (1979) Darwin Glass and Darwin Crater. *Meteoritics* **14**, 283–296.

GENTNER W., STORZER D. AND WAGNER G. A. (1969) New fission track ages of tektites and related glasses. *Geochim. Cosmochim. Acta* **33**, 1075–1081.

GENTNER W., KIRSTEN T., STORZER D. AND WAGNER G. A. (1973) K-Ar and fission track dating of Darwin Glass. *Earth Planet. Sci. Lett.* **20**, 204–210.

GILCHRIST J., THORPE A. N. AND SENFTLE F. E. (1969) Infrared analysis of water in tektites and other glasses. *J. Geophys. Res.* **74**, 1475–1483.

GLASS B. P. (1990) Tektites and microtektites: Key facts and inferences. *Tectonophysics* **171**, 393–404.

GLASS B. P. AND PIZZUTO J. (1994) Geographic variation in Australasian microtektite concentrations: Implications concerning the location and size of the source crater. *J. Geophys. Res.* **99**, 19 075–19 091.

IZETT G. A. AND OBRODAVICH J. D. (1992) Laser-fusion $^{40}Ar/^{39}Ar$ ages of Australasian tektites (abstract). *Lunar Planet. Sci.* **23**, 593–594.

KOEBERL C. (1990) The geochemistry of tektites: An overview. *Tectonophys.* **171**, 405–422.

KOEBERL C. (1994) Tektite origin by hypervelocity asteroidal or cometary impact: Target rocks, source craters, and mechanisms. *Geol. Soc. Am. Spec. Paper* **293**, 133–151.

KUNZ J., BOLLINGER K. AND JESSBERGER E. K. (1995) Ages of Australasian tektites (abstract). *Lunar Planet. Sci.* **26**, 809.

LO C-H., WANG P-L., YANG H-C., LIOU Y-S. AND TSOU T-Y. (2001) The laser $^{40}Ar/^{39}Ar$ dating microprobe of National Taiwan University. *Western Pacific Earth Sci.* **1**, 143–156.

MCDOUGALL I. AND HARRISON T. M. (1999) *Geochronology and Thermochronology by the $^{40}Ar/^{39}Ar$ Method* (2nd edition). Oxford Univ. Press, New York, New York, USA. 269 pp.

MATSUDA J., MATSUBARA K., YAHIMA H. AND YAMAMOTO K. (1989) Anomalous Ne enrichment in obsidians and Darwin Glass: Diffusion of noble gases in silica-rich glasses. *Geochim. Cosmochim. Acta* **53**, 3025–3033.

MCCALL J. (2001) *Tektites in the Geological Record: Showers of Glass from the Sky.* The Geological Society, London, U.K. 256 pp.

MEISEL T., KOEBERL C. AND FORD R. J. (1990) Geochemistry of Darwin impact glass and target rocks. *Geochim. Cosmochim. Acta* **54**, 1463–1474.

MEISEL T., BIINO G. G., VILLA I. M., CHAMBERS J. E. AND MCHONE J. F. (1995) Darwin glass and Darwin Crater revisited; multiple impacts in the Australasian strewn field? (abstract). *Meteoritics* **30**, 545.

ODIN G. S. *ET AL.* (1982) Interlaboratory standards for dating purposes. In *Numerical Dating in Stratigraphy* (ed. G. S. Odin), pp. 123–149. Wiley, Chichester, U.K.

REID A. M. AND COHEN A. J. (1962) Coesite in Darwin glass. *J. Geophys. Res.* **67**, 1654.

RENNE P. R., SWISHER C. C., DEINO A. L., KARNER D. B., OWENS T. L. AND DEPAOLO D. J. (1998) Intercalibration of standards, absolute ages and uncertainties in $^{40}Ar/^{39}Ar$ dating. *Chem. Geol.* **145**, 117–152.

SCHNETZLER C. C. (1992) Mechanism of Muong Nong tektite formation and speculation on the source of the Australasian tektites. *Meteoritics* **27**, 154–165.

SCHNETZLER C. C. AND MCHONE J. F. (1996) Source of Australasian tektites: Investigating possible sites in Laos. *Meteorit. Planet. Sci.* **31**, 73–76.

SHAW H. P. AND WASSERBURG G. J. (1982) Age and provenance of target materials for tektites and possible impactites as inferred from Sm-Nd and Rb-Sr systematics. *Earth Planet. Sci. Lett.* **60**, 155–177.

STEIGER R. H. AND JÄGER E. (1977) Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth Planet. Sci. Lett.* **36**, 359–362.

STOREY J. (1987) Darwin glass: Gift from the heavens. *Australian Geographic* **8**, 39–43.

STORZER D. AND WAGNER G. A. (1980a) Australites older than indochinites—Evidence from fission-track plateau dating. *Naturwissenschaften* **67**, 90–91.

STORZER D. AND WAGNER G. A. (1980b) Two discrete tektite-forming events 140 thousand years apart in the Australian–Southeast Asian area (abstract). *Meteoritics* **15**, 372.

TAYLOR H. P. AND EPSTEIN S. E. (1969) Correlations between $^{18}O/^{16}O$ ratio and chemical compositions of tektites. *J. Geophys. Res.* **74**, 6824–6844.

TAYLOR S. R. (1969) Criteria for the source of australites. *Chem. Geol.* **4**, 451–459.

TAYLOR S. R. AND SOLOMON M. (1964) The geochemistry of Darwin glass. *Geochim. Cosmochim. Acta* **28**, 471–494.

WASSON J. T. (1991) Layered tektites: A multiple impact origin for Australasian tektites. *Earth Planet. Sci. Lett.* **102**, 95–109.

WASSON J. T. (1995) The disintegration of the comet Shoemaker–Levy 9 and the Tunguska object and the origin of Australasian tektites (abstract). *Lunar Planet. Sci.* **26**, 1469–1470.

YAMEI H., POTTS R., BAOYIN Y., ZHENGTANG G., DEINO A., WANG W., CLARK J., GUANGMAO X. AND WEIWEN H. (2000). Mid-Pleistocene Acheulean-like stone technology of the Bose Basin, South China. *Science* **287**, 1622–1626.

ZÄHRINGER J. AND GENTNER W. (1963) Radiogenic and atmospheric argon content of tektites. *Nature* **199**, 583.

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