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Physical distribution trends in Darwin glass

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Abstract–Darwin glass formed by impact melting, probably during excavation of the 1.2 km diameter Darwin crater, Tasmania, Australia. The glass was ejected up to 20 km from the source crater and forms a strewn field of >400 km^2. There is at least 11,250 m^3 of glass in the strewn field and relative to the size of the crater this is the most abundant ejected impact glass on Earth. The glass population can be subdivided on the basis of shape (74% irregular, 20% ropy, 0.5% spheroid, 6% droplet, and 0.7% elongate) and color (53% dark green, 31% light green, 11% black, and 5% white). The white glasses contain up to 92 wt% SiO_2 and are formed from melting of quartzite. Black glasses contain a minimum of 76 wt% SiO_2 and formed from melting of shale. Systematic variations in the proportion of glasses falling into each of the color and shape classes relative to distance from the crater show: 1) a decrease in glass abundance away from the crater; 2) the largest fragments of glass are found closest to the crater; 3) small fragments (<2 g) dominate finds close to the crater; 4) the proportion of white glass is greatest closest to the crater; 5) the proportion of black glass increases with distance from the crater and 6) the proportion of splashform glasses increases with distance from the crater. These distribution trends can only be explained by the molten glass having been ballistically ejected from Darwin crater during impact and are related to 1) the depth of excavation from the target rock stratigraphy and/or 2) viscosity contrasts between the high and low SiO_2 melt. The high abundance and wide distribution of ejected melt is attributed to a volatile charged target stratigraphy produced by surface swamps that are indicated by the paleoclimate record.

INTRODUCTION

Darwin glass was formed during a meteorite impact on the island of Tasmania, Australia, at about 800 ka (Loh et al. 2002). After prolonged historic uncertainty, recent petrographic and chemical studies have concluded that the source of the glass is the proposed 1.2 km diameter Darwin crater, located at 42°18.39′S 145°39.41′E (Howard 2008; Howard and Haines 2007). During investigations into the origin of Darwin glass, thousands of samples of the glass were collected. The glass fragments were recovered from locations throughout the >400 km^2 strewn field (Fig. 1). The first objective of this paper is to describe the physical appearance of the collected glass fragments and to define a series of sub-populations on the basis of shape and color. The second objective is to reveal systematic variations in the proportions of recovered glasses falling into the defined shape and color classes relative to distance from the crater. Trends in the glass abundance and size relative to distance from the crater are also described and the volume of melt in the strewn field is estimated. This work shows that relative to the size of the crater, Darwin glass is the most abundant impact glass on Earth.

The exact mechanisms behind impact glass and tektite formation remain speculative. However, all aspects of the composition and petrography of tektites and impact glasses indicate that these are terrestrial in origin (e.g., Taylor and McLennan 1979; Koeberl 1986, 1994). Described trends in the distribution of Darwin glass can only be explained by the molten glass having been ejected from Darwin crater during impact. These data thereby provide independent evidence to support the impact origin of Darwin crater. Trends in the distribution of Darwin glass also reveal processes of melt ejection that may aid in further understanding the distribution and origin of impact glasses and tektites elsewhere.

Geochemistry of Darwin Glass and Target Rocks

The focus of this paper is on the physical properties and distribution trends in Darwin glass, relative to Darwin crater,

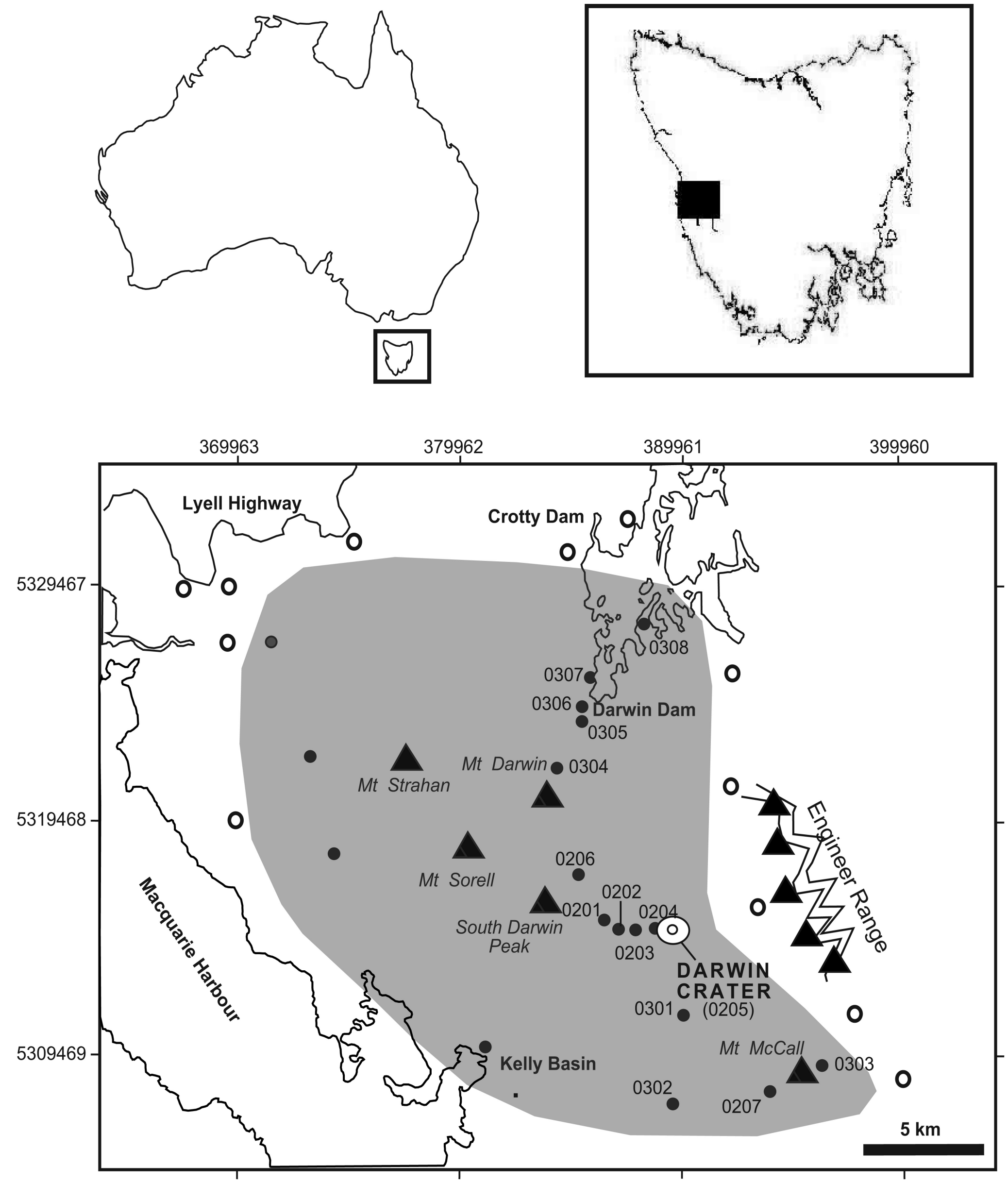

Fig. 1. The Darwin glass strewn field. Triangles are mountains. Closed circles are sites where glass has been found in residual gravels. Open circles are sites where residual gravels are free of glass and these define the limits of the strewn field that is shaded grey. Site numbers refer to sample locations for recovered glasses used in distribution studies. Abundance estimates are based only on a 50 km^2 area surrounding Darwin crater. Coordinate numbers are Australian Map Grid (AMG) Units.

that provide evidence for a genetic relationship between the glass and crater independent of the corroborating petrographic, geochemical and isotopic evidence published elsewhere (Howard and Haines 2007; Howard 2008). However, to provide a framework for later discussion that attempts use the glass distribution trends to gain insights into the impact process, it is necessary to briefly describe the geochemistry of Darwin glass and its relationship to the target rocks at Darwin crater.

Geochemical analyses in Howard (2008) show 2 groups of glass. Group 1 is composed of: SiO_2 (85%), Al_2O_3 (7.3%), TiO_2 (0.05%), FeO (2.2%), MgO (0.9%), and K_2O (1.8%). Group 2 has lower average SiO_2 (81.1%) and higher average Al_2O_3 (8.2%), FeO (+1.5%) and MgO (+1.3%) abundances. The glass, target rocks and crater-fill samples have concordant REE patterns, a narrow range in key trace element ratios (La/Lu = 5.9–10; Eu/Eu* = 0.55–0.65) and overlapping trace element abundances (Howard 2008). $^{87}Sr/^{86}Sr$ ratios for the glasses (0.80778–0.81605) fall in the range (0.76481–1.1212) defined by the rock samples (Howard 2008). Mixing models using target rock compositions successfully model the glass for all elements except FeO, MgO, Ni, Co, and Cr in

Group 2 that may be related to the projectile (Howard 2008). These models show that average, or Group 1 glass derives from melting of 43% shale and 57% quartzite while average Group 2 glasses are predominantly formed from melting of shale (66%) (Howard 2008).

The color variation in Darwin glass appears to be controlled by the abundance of FeO and the low SiO_2 (high FeO) glasses are preferentially black (Meisel et al. 1990; Howard 2003, 2004, 2008; Fig. 5). The lowest SiO_2 (76 wt%) black glass samples are from Group 2 and mixing models show these are derived from almost pure shale melts (Howard 2008). In contrast, the highest SiO_2 (92 wt%) white glasses are near pure quartzite melts (Howard 2008). The lower the SiO_2 content of a melt, the lesser its viscosity (Hess 1989). The >15 wt% difference in SiO_2 abundance between black and white glasses will produce viscosity contrasts (Hess 1989) that have important implications to the later interpretation of observed glass distribution trends.

Field Occurrences of Darwin Glass

As most previously studied samples of Darwin glass were collected during road construction, and later from road base, the stratigraphy of the glass occurrence was poorly defined. Early visitors fossicking for Darwin glass (e.g., Conder 1934) noted its association with gravels dominated by angular quartz fragments and capped by a thin (<50 cm) peat layer. This glass-gravel association is pervasive throughout the strewn field and the thickness of the glass bearing gravel horizon ranges from a few centimeters to several metres. The angular and blocky nature of quartz fragments in the gravel indicates a local provenance. Quartz veins pervade country rocks across the strewn field and cropping out veins are actively weathering to release free quartz fragments. This suggests that these gravels are residual deposits produced by in situ weathering. Transport of the quartz fragments, especially on flat areas, is likely to have been largely vertical and hence the thickest (up to ~2 m) gravel deposits are found on flat ground above the valley floors. Winnowing of fine material and down slope transport has been confined to the hilltops and at above 500 m (Derbyshire 1972) ice has removed peat and quartz fragments. The process has not been completely efficient because fine fragments of glass (and quartz) are still found on hilltops. On mid and low slopes winnowing is likely to have been very limited given the high abundance of fine quartz gravel and small glass fragments. The fine surface features observed on glass fragments recovered from the residual quartz deposits also suggest that the glasses have not been significantly transported laterally by high-energy processes such as floods. In simulated fluvial transport experiments, the glass fragments are quickly damaged (Fig. 2). Therefore, there is no evidence that the glass found in residual gravel deposits has been significantly laterally transported since the impact at about 800 ka.

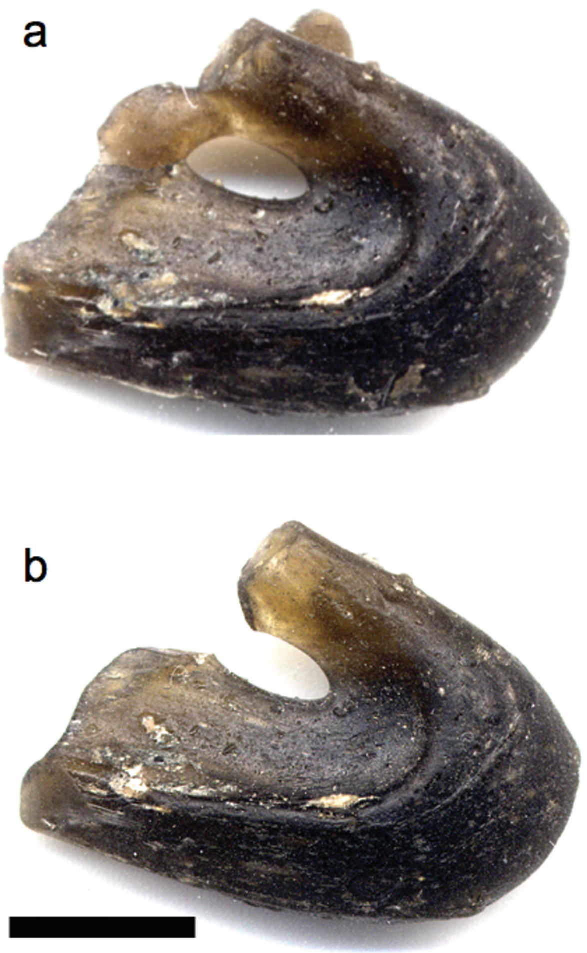

Fig. 2. Simulated fluvial transport of Darwin glass. The glass was very gently tumbled in a loosely packed container of hydraulically equivalent quartz gravel, simulating transport as traction load in a fluvial setting. Scale bar = 1 cm. a) Darwin glass sample after recovery. Note closed tail and small droplet adhering to the larger glass sample. b) Darwin glass sample after 8 h simulated fluvial transport. Note tail has been broken and eroded and the fine droplet detached. The pronounced flow ridge on the leading edge of the sample has also been abraded. For color versions of these and all other images see online version available at http://digitalcommons.library.arizona.edu/holdings/journal?r=uadc://azu_maps/.

RESULTS

Color Distribution in Darwin Glass

Four color classes encompass the range of variation observed in Darwin glass: white; light green; dark green and black (Fig. 3). Based on 4223 specimens, the Darwin glass strewn field consists of 5% white, 31% light green, 53% dark green, and 11% black glass fragments (Table 1). White glass is almost exclusively found closest to the crater where it may comprise up to 8% of recovered fragments. White fragments are almost exclusively small (<2 g). Light and dark green glass is most abundant closest to the crater and

Fig. 3. Darwin glass color classes. Scale bar = 1 cm. a) Dark green glass. b) Black glass. c) Light green glass. d) White glass.

there is a general decrease in the proportion of these colors away from the crater. These observations are controlled by the most pronounced color trend relative to distance from the crater that is the abundance of black glass that increases with increasing distance from the crater; this is most pronounced in the northwest direction at sites 0305-7 (Fig. 4).

Darwin Glass Shape Classes

Five shape classes encompass the range of variation in Darwin glass: spheroid, droplet, elongate, ropy, and irregular. The shape classes are defined below and pictured in Fig. 6.

Irregular Glass

Irregular shaped Darwin glass ranges in size from fragments of a few millimeters in diameter to chunky masses up to 15 × 8 cm in size. These glasses have rough contorted shapes and are the most varied in appearance. They may, or may not, show pronounced layering and flow structure in hand specimen.

Ropy Glass

Ropy samples of Darwin glass are rod-like and vary up to 100 mm in length, with typical length/width ratios of around 5:1. The ropy texture is defined by parallel longitudinal ridges that are generally twisted along the length of the sample. The ends of the ropy glass samples are almost always broken to reveal a vitreous fracture surface.

Splashform Glass

Elongate shapes are predominantly rod-like and are between 10 and 40 mm in length and up to 10 mm in diameter. Some elongate samples are bent and have bulbous ends referred to as “phallic” by Suess (1914) in his description of the glass. Droplet shapes are between 5 and 50 mm in length. The small droplets are often highly vitreous and may be translucent. Some droplets have pitted surfaces and the interior of these pits may have a polished surface suggesting that these are vesicles. The droplets are typically asymmetrical with bent tails and sloping rounded faces. They may appear ‘squashed’ and the tails are almost always broken leaving a vitreous fracture surface. Spheroid shaped glasses are between 1 and 20 mm diameter and vary from perfect spheres through to discs. They generally have a vitreous lustre and some samples may be translucent and shine with a gem like quality in direct light.

Shape Distribution in Darwin Glass

Based on 4223 specimens, the Darwin glass strewn field consists of 0.5% spheroid, 6% droplet, 0.7% elongate, 20% ropy, and 74% irregular-shaped fragments of glass (Table 2).

Table 1. Color distribution in Darwin glass.

Site	Distance from crater (m)	Azimuth (deg. from crater)	n	White f (% of sample)	Light green f (% of sample)	Dark green f (% of sample)	Black f (% of sample)
0201	3000	280	17	–	41	53	5.9
0202	2500	272	85	–	33	56	11
0203	2000	270	3126	5.2	36	54	4.4
0204	500	270	365	7.9	31	52	9
0205	0	0	3	–	33	67	–
0206	4500	290	13	–	38	46	15
0207	7500	238	266	2.3	12	50	35
0301	3500	265	80	2.5	13	59	26
0302	7000	180	9	–	–	67	33
0303	8500	130	14	–	–	14	86
0304	8000	327	33	3.0	6	27	64
0305	9000	335	15	–	–	13	87
0306	9200	338	145	–	1	29	70
0307	10500	340	10	–	–	10	90
0308	12000	355	42	–	21	55	24
All sites			4223	4.8	31	53	11

n = number, f = frequency.

Irregular glass shapes always dominate the sample at any location in the strewn field. Ropy glass shows a decrease in abundance relative to the other shapes with increasing distance from the crater. Conversely, the proportion of droplet, spheroid and elongate shapes is greatest at sites >3000 meters from the crater (e.g., >5 crater radii). If the specimens classified as "splashform" (spheroid, droplet and elongate shapes) are combined and plotted relative to distance from the crater a trend is defined that shows the proportion of splashform shapes increasing with increasing distance from the crater (Fig. 7). The variation in combined splashform abundance has significant scatter, and this is consistent with field observations that show that the distribution of splashform shapes across the strewn field is patchier than the distribution of the irregular and ropy shapes.

Color and Shape

The color distribution in each of the respective shape classes for 2869 samples is illustrated in Fig. 8. For all colors of Darwin glass an irregular morphology is most common. The proportions of light green, dark green and black glass with irregular morphologies is relatively consistent and varies between 67% (black) and 72% (light green). However, white glass is almost exclusively (94%) irregular in shape. Ropy morphologies are most common in the dark green (28%) and light green (23%) glasses. Spheroid, droplet and elongate shapes comprise only 7% of the total sample, however, 26% of the recovered black glasses have spheroid (3%), droplet (21%) or elongate (3%) shapes. In contrast, only 4% of light green glasses and 3% of dark green glasses have droplet shapes and only a single white droplet was observed. Elongate and spheroid shapes comprise ≤1% of light green, dark green and white glasses.

Size Distribution in Darwin Glass

At 10 sites across the strewn field uncontrolled excavations were conducted with the aim of collecting all visible glass fragments, thus providing representative samples from which the average size distribution in Darwin glass could be estimated. The size was determined by weighing each individual glass fragment (Table 3). Based on 799 specimens, the average fragment of Darwin glass weighs 1.6 g. The largest fragment recovered in these excavations weighs 30 g—far from the largest piece of Darwin glass ever collected that weighs just less than 1 kg and was found proximal to the crater between sites 0203 and 0204 (Ramsay Ford, unpublished data). There is also a rumored find of a similar sized fragment in the 1980s, however, as it is illegal to collect the glass without a permit, most finds by fossickers are kept secret. Using the average weight of recovered glass fragments, little correlation with distance from the crater is observed because of the high abundance of very small (<2 g) glass fragments close to the crater that result in low average weight determinations. Maximum recovered glass weights are more revealing. In Fig. 9 it can be seen that, excluding site 0306, there is evidence for a decrease in the maximum recovered glass weight with increasing distance from the crater. Rather than an anomaly, site 0306 is typical of the patchy distribution of the glass at large distances from the crater.

Abundance of Darwin Glass

At 9 sites within a 50 km^2 (10 × 5 km) area surrounding the crater controlled excavations were conducted in order to estimate the abundance of glass present. At each site 0.03 m^3 (10 standard prospectors' pans) of glass bearing gravel was sieved through 1 and 0.5 cm mesh sieves. The determined

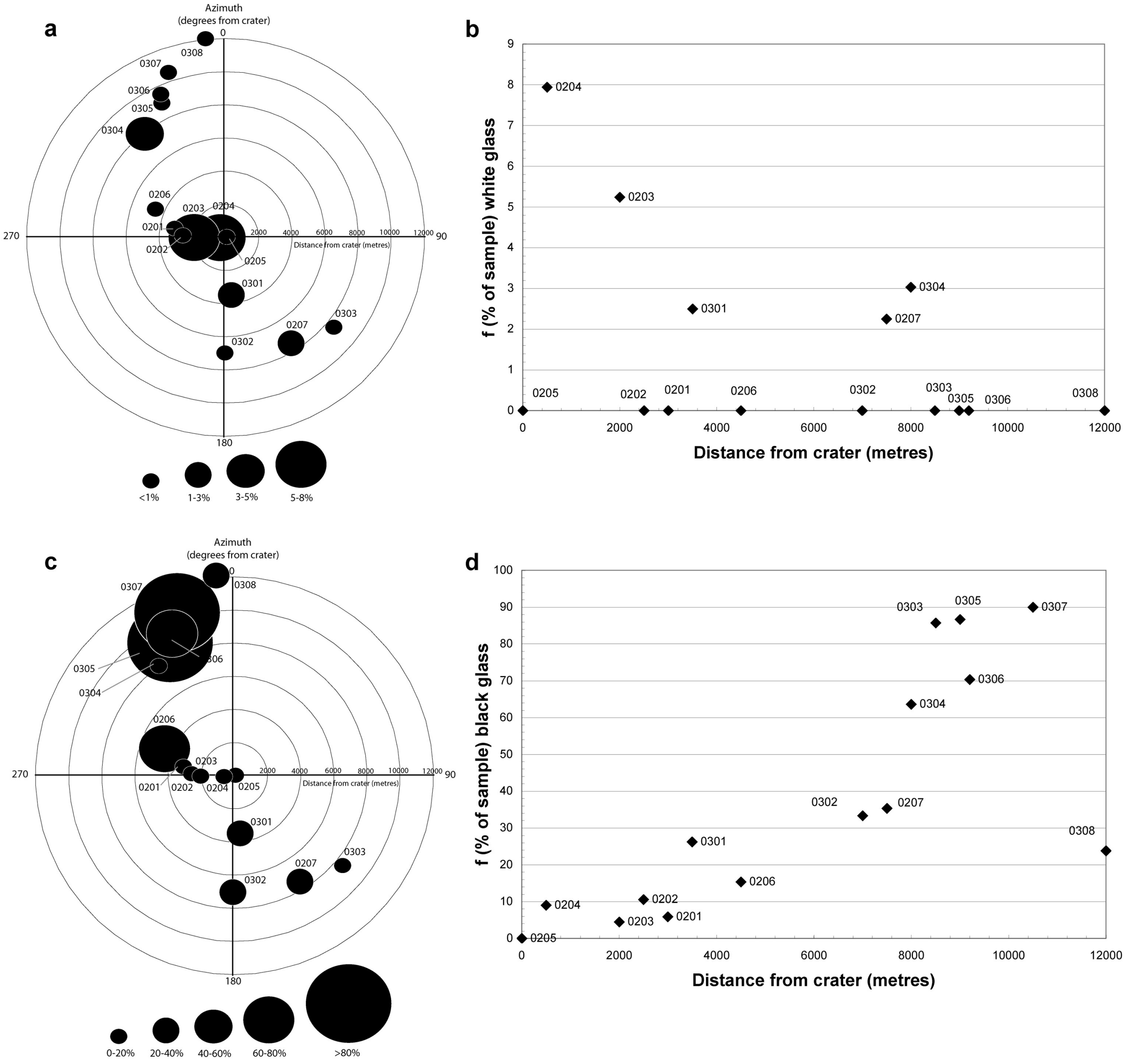

Fig. 4. Color distribution trends in Darwin glass. a) Proportion of white glass fragments recovered versus distance and direction from crater. b) Proportion of white glass fragments recovered versus distance from crater. Relative to the other colors white glass is very rare and found almost exclusively at sites near to the crater. c) Proportion of black glass fragments recovered versus distance and direction from crater. d) Proportion of black glass fragments recovered versus distance and direction from crater. Relative to the other colors there is a clear increase in the proportion of recovered black glasses with increasing distances from the crater.

glass abundance ranges from 0.17 to 47 kg/m^3 across the study area (Table 4) and there is a trend of decreasing glass abundance with increasing distance from the crater.

By estimating the average thickness of the gravel deposits across the 50 km^2 study area, the volume of ejected melt can be approximated. The glass bearing gravel ranges in thickness from several meters to less than 1 cm on peaks. After accounting for thin gravel cover on peaks, a conservative estimate of the average thickness of the glass bearing gravel horizon in the study area is taken to be 15 cm. Excluding the most abundant site (47 kg/m^3) the average abundance of glass in the gravel deposits across the survey region is 3 kg/m^3. Therefore, in the 50 km^2 area it can be estimated that there is approximately 22 500 tonnes of glass. Assuming a specific gravity of 2000 kg/m^3 this represents a melt volume of ~11250 m^3 or 10^{-5} km^3. Errors in estimating the average thickness of the glass-bearing gravel horizon, and the abundance of glass in the horizon, strongly influence melt volume determinations, and it should be noted that the estimates given are considered to be very conservative. As the

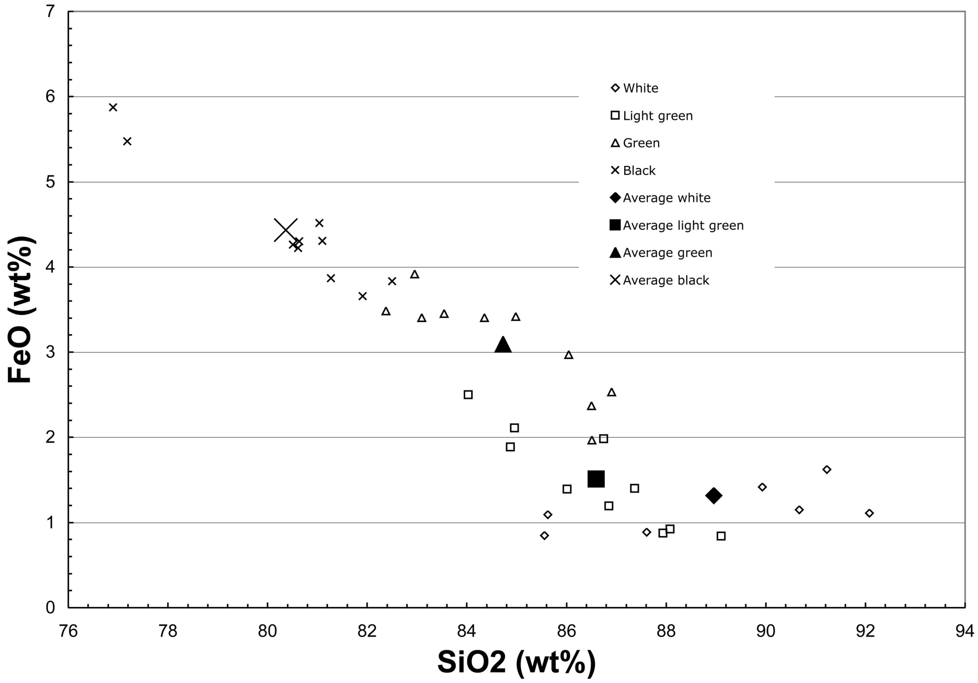

Fig. 5. SiO_2 versus FeO in Darwin glass color classes. Average compositions based on 10 spot analyses of individual glass fragments from each color class, data from Howard (2008).

survey area represents only 1/8th of the strewn field, the true melt volume is much greater—even accounting for a patchy distribution at distance from the crater.

DISCUSSION

The composition of Darwin glass is explained by a mixture of target rocks from Darwin crater and the crater-fill stratigraphy is consistent with that expected in a simple crater in sedimentary rocks, although melt is very rare in the recovered cores (Howard 2004, 2008; Howard and Haines 2007). The described spatial trends in the glasses distribution cannot be related to any point of origin in the strewn field other than Darwin crater. The observed size and abundance distributions of glass fragments in the strewn field are reconcilable with ballistic ejection of melt during the excavation of Darwin crater. Ballistic ejection from the crater is consistent with the largest melt fragments being deposited closest to the crater along with the bulk of the fine material that is rapidly slowed and quenched by interaction with the atmosphere. The continuous distribution of glass from the crater out to a maximum of around 10 km from source does not require removal of the atmosphere by the expanding vapor plume (atmospheric blowout) to explain the observed glass distribution; as for the jetting theory of tektite origin (Melosh 1989). Atmospheric blowout is restricted to impacts that release at least 150 MT energy (Melosh 1989) and this is well beyond the scale of the Darwin impact that is expected to have been <20 MT (Grieve and Cintala 1992). The continuous distribution from the crater, and the presence of >50 μm pure SiO_2 lechatelierite inclusions in the glass, rule out any suggestion that the glass condensed from a vapor distal to the impact site as has been suggested in some models of tektite/microtektite origin (e.g., Artemieva et al. 2002; Elkins-Tanton et al. 2002; Engelhardt et al. 2005). Such a continuous distribution of ejected melt from Darwin crater also excludes any airburst induced melting that might be speculated (e.g., Wasson 2003; Svetsov and Wasson 2007). This may have implications to studies of Libyan Desert Glass and Australasian layered tektites that have a similar morphology to Darwin glass and that, in the absence of a crater, have been suggested to result from airburst (Wasson 2003).

Splashform tektites are acknowledged by most workers to have formed from the rotation of ejected melt under the influence of surface tensions (Baker 1958; Ford 1988; Elkins-Tanton et al. 2003). Droplets are the most common splashform Darwin glass. Droplets are likely to form from the breakup of the fluid (melt) mass (Elkins-Tanton et al. 2003). Prolonged transport as fluid provides more opportunity for this break up and, as such, the observed increase in the proportion of splashform shapes with increasing distances from Darwin crater is to be expected. Low melt viscosities also enhance the breakup process (Elkins-Tanton et al. 2003) and this is interpreted to explain the preferential development of droplet shapes in the least viscous low SiO_2 black melt. The patchy distribution of splashform shapes at distance from the crater may imply transport of the separating melt fragments was in discrete turbulent cells. Irregular glasses found in overlapping distributions with splashform shapes are

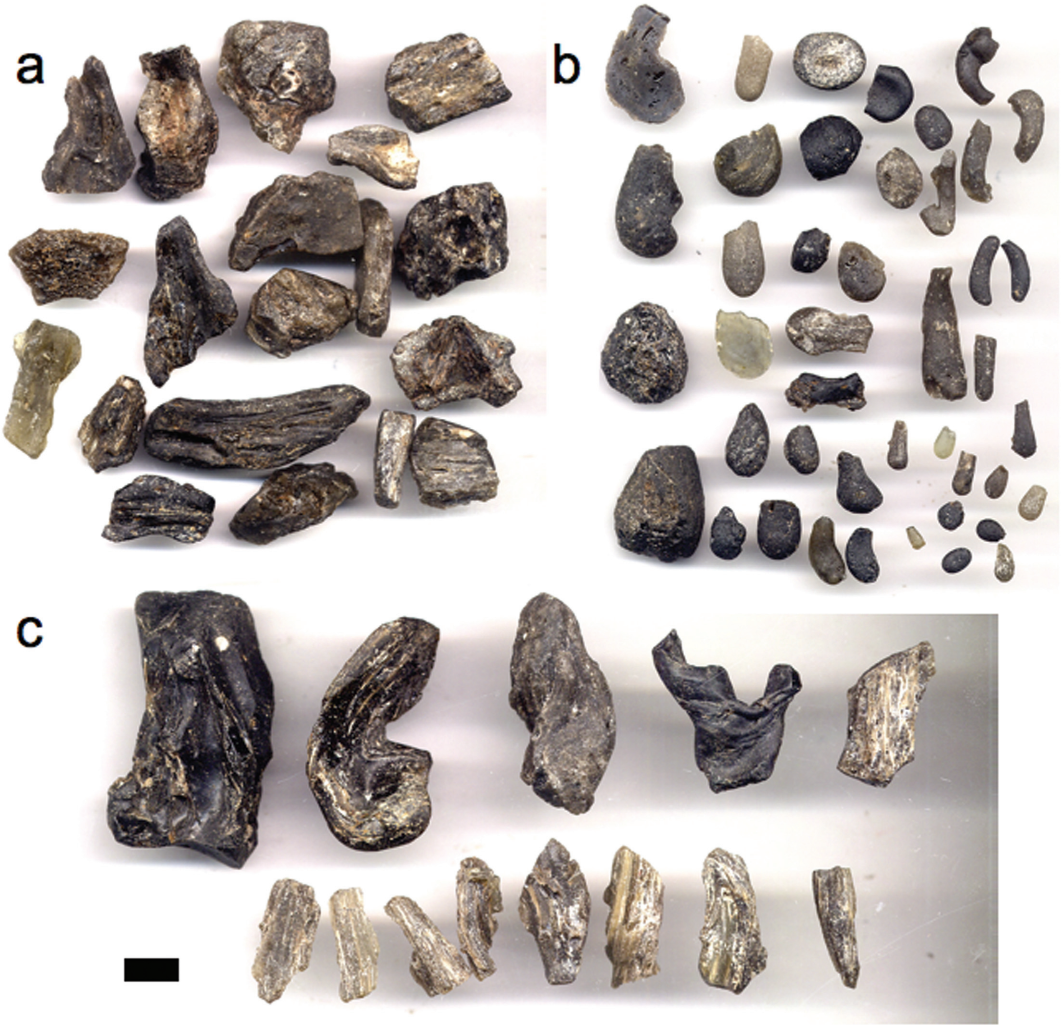

Fig. 6. Darwin glass shape classes. Scale bar = 1 cm. a) Irregular glass. b) Ropy glass. c) Splashform glass. For color versions of these and all other images see online version available at http://digitalcommons.library.arizona.edu/holdings/journal?r=uadc://azu_maps/.

interpreted to have quenched without significant separation or break up from the bulk fluid mass.

There is a known relationship between depth of melting and distance of ejection from the crater that sees the uppermost units ejected furthest (Melosh 1989). The Keel Quartzite is the uppermost formation in the target stratigraphy, and it is commonly associated with minor interbedded pelites or shales (Howard and Haines 2007; Howard 2008). Elsewhere on the west coast of Tasmania, where complete sections are exposed, the top ~60 m of the Keel Quartzite is seen to be a pelite unit (Blisset 1962). As such, derivation of black melt from impact melting and ejection of a uniform uppermost target rock layer, composed of pelite, could explain the increase in the proportion of black glass observed at large distances from the crater. Deriving black melt from the interface of the projectile and uppermost target rock surface is also consistent with the evidence for preferential suspected projectile contamination in some black glasses (Howard 2003, 2004, 2008).

In the absence of a coherent upper pelite unit in the target rock stratigraphy, that without outcrop near to the crater is speculative, the preference for black Darwin glass to be the most widely distributed may also be interpreted to relate to viscosity contrasts as follows. The geologic evidence indicates that the uppermost formation in the target stratigraphy was the Keel Quartzite (Howard and Haines 2007). This quartzite formation contains minor interbedded pelite and the lithological transition occurs over a very narrow spatial range that can be observed even at the thin section scale (Howard and Haines 2007). During impact melting of interbedded quartzite and pelite, the impact produced glasses of varied compositions. As the black and white glasses formed from impact melting of interbedded pelite and quartzite, at essentially the same level in the target stratigraphy, shock temperatures are likely to have been similar (>1700 °C on the basis of lechatelierite inclusions). The low SiO_2 black glasses were preferentially distributed far from the crater, while the white glasses were deposited almost

Table 2. Shape distribution in Darwin glass.

Site	Distance from crater (m)	Azimuth (degrees from crater)	n	Spheroid f (% of sample)	Droplet f (% of sample)	Elongate f (% of sample)	Ropy f (% of sample)	Irregular f (% of sample)
0201	3000	280	17	–	5.9	–	–	94
0202	2500	272	85	1.2	3.5	–	11	85
0203	2000	270	3126	0.13	4	0.42	27	68
0204	500	270	365	–	1.1	0.27	32	67
0205	0	0	3	–	–	–	–	100
0206	4500	290	13	–	14	–	7.1	71
0207	7500	238	266	3	28	3.4	11	55
0301	3500	265	80	2.5	14	3.8	15	65
0302	7000	180	9	–	–	11	–	89
0303	8500	130	14	7.1	7.1	–	7.1	79
0304	8000	327	33	–	21	–	12	67
0305	9000	335	15	–	–	–	–	100
0306	9200	338	145	0.69	14	0.69	6.9	77
0307	10500	340	10	–	–	–	10	90
0308	12000	355	42	7.1	10	2.4	7.1	74
All sites			4223	0.5	6	0.7	19	74

n = number, f = frequency.

exclusively at the crater. One way to explain this might be that the low SiO_2 black glass is derived from melting of pelite units in the Keel Quartzite and a lesser viscosity promoted fragmentation and separation from the bulk melt during ballistic ejection from Darwin crater. Fragmentation and separation of less viscous black melt from the bulk melt may have resulted in wider dispersal and the preferential development of splashform shapes. This interpretation is consistent with the observed distribution of the higher viscosity ($>SiO_2$) white melt that results from melting of the quartzite units and is almost always a frothy irregular shape and found close to the crater.

Melt Ejection Velocity, Flight, and Cooling Times

There is no evidence that ejected fragments of Darwin glass were molten when they landed, or that the melt flowed across the ground surface as has been suggested in "melt pool" models of impact glass and Australasian layered tektite formation (e.g., Wasson 2003). Recovered Darwin glass is completely free of fused soil or incorporated mineral grains that would be expected if the glass had contacted the ground when molten. Some of the recovered fragments show ancient fractures with an identical lustre to non-fractured surfaces—these are interpreted to have formed on landing and indicate that the melt had solidified in flight enough to fracture on striking the ground surface.

Immediately after impact the initial ejection velocities of melt from Darwin crater may have been very high at up to the earth escape value of 11.2 km/s (Artemieva 2008). However, as the impact was not large enough to remove the atmosphere, the ejected melt would have been rapidly slowed and its flight out to a maximum 20 km from source can be considered in ballistic terms (Artemieva 2008). This is consistent with the observations of the glass distribution such as the high abundance of fine fragments close to source that indicate there was a significant degree of interaction with the atmosphere and subsequent slowing and cooling of the ejected melt. Under ballistic conditions, the ejection velocity for the most widely dispersed melt (20 km from source) can be estimated using the ballistic range—velocity formula (Melosh 1989; Equation 6.1.1).

Ejection angle is critical in determining the velocity of the melt. The topographic setting of Darwin crater means that any melt ejected at less than approximately a 10- degree angle would not escape the valley that hosts the crater or clear the adjacent mountain ranges to reach its maximum range of 20 km from the crater in the NW direction. This constrains the maximum ballistic ejection velocity for the most distal melt to around 850 m/s. The time of flight can also be determined from the ballistic range—velocity formula and at 850 m/s melt ejected to 20 km from source was quenched before landing solid in slightly less than 30 seconds. These estimated distances and flight times are beyond the range predicted by recent models of glass ejection from small craters (Artemieva 2008) and this is interpreted to relate to the presence of abundant volatiles as discussed below.

In contrast to Darwin glass, many tektites in the Australasian field still landed or encountered a dense atmosphere when molten enough to be warped in shape (Nininger and Huss 1967). This highlights a well-known difference in the formation of impact glasses and splashform tektites stricto senso. With a higher energy of formation, splashform tektites are ejected and transported many hundreds of kilometers. These remain hot during transport in some form of "expanding melt plume" without interaction

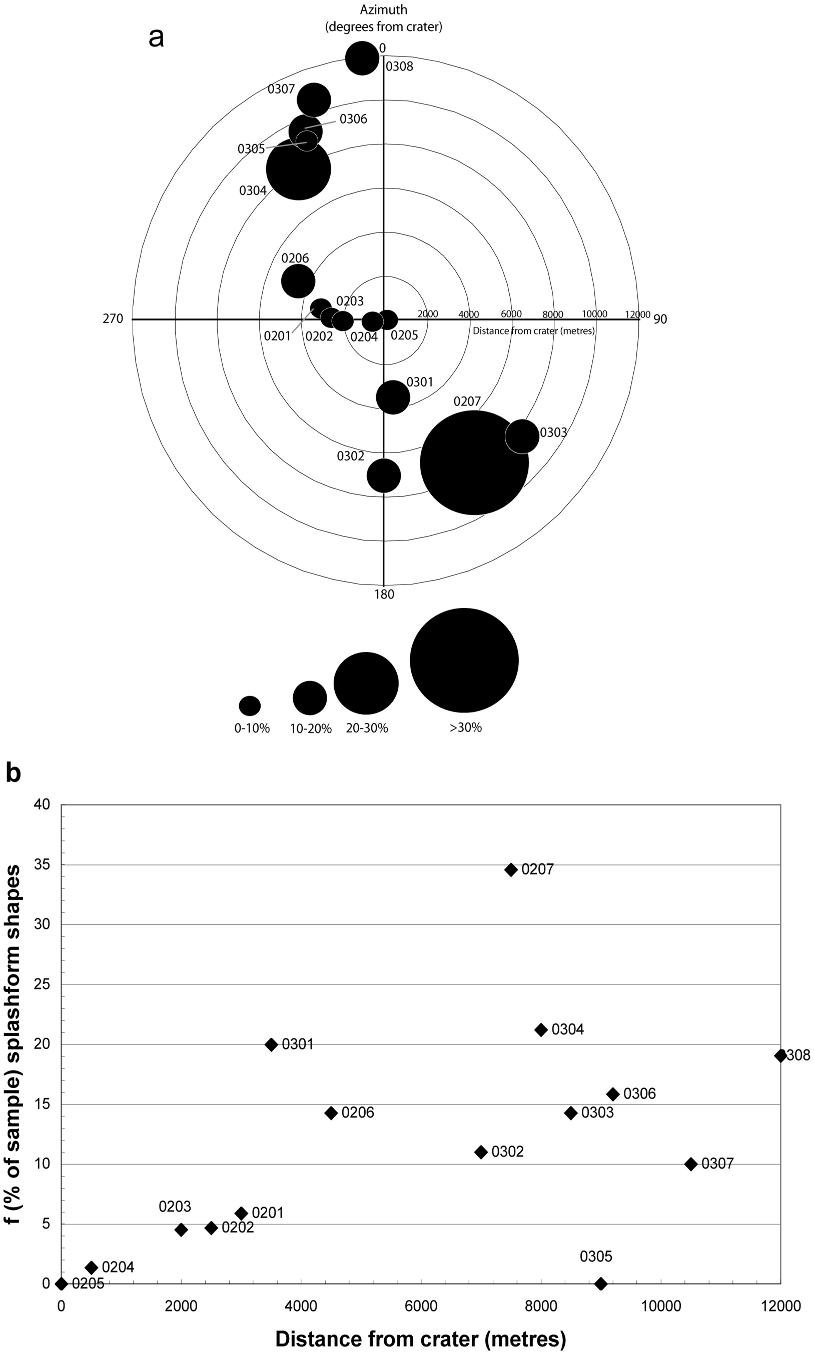

Fig. 7. Shape distribution trends in Darwin glass. a) Proportion of recovered splashform shape glasses versus distance and direction from crater. b) Proportion of recovered splashform shape glasses versus distance from crater. The glasses classified as splashform (spheroidal, elongate and droplet shapes) have been combined. There is a clear increase in the proportion of splashform shapes recovered with increasing distances from the crater.

with the atmosphere to promote cooling and fallout as for Darwin glass (e.g., Artemieva et al. 2002).

Explaining the High Abundance of Darwin Glass

At 1.2 km in diameter, Darwin crater is at the lower limit of scaling equations that model melt production. Based on the equation of Grieve and Cintala (1992) approximately 0.0012 km^3 of melt is produced during excavation of a 1.2 km diameter crater. Of this around 1–3% of fully melted material (~10^{-5} km^3) is expected to be ejected to within a few crater radii (Orphal et al. 1980; Grieve and Cintala 1992; French 1998). This is consistent with the measured minimum estimate of the volume of glass in the 50 km^2 study area

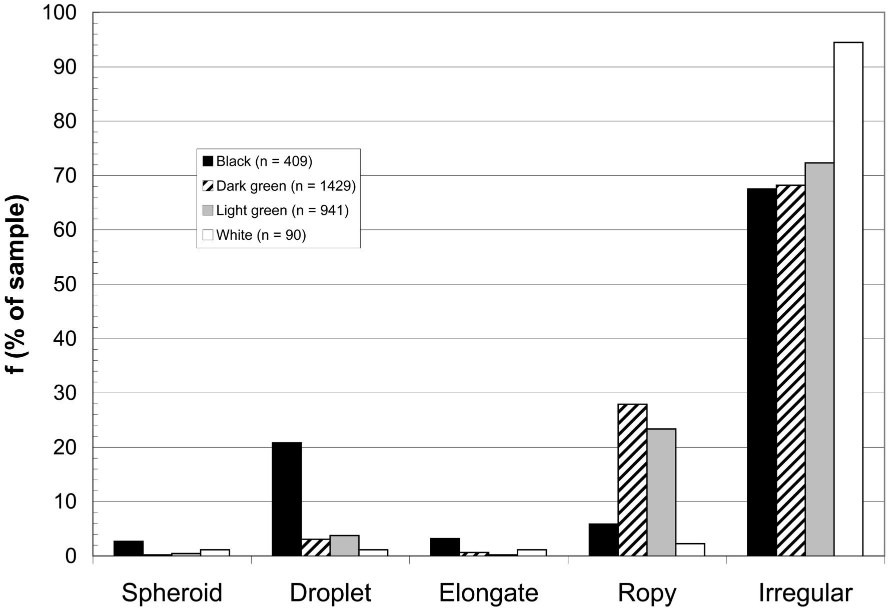

Fig. 8. Color versus Shape in entire glass sample. Dark and light green irregular shapes dominate finds. White shapes are almost exclusively irregular in form. Droplet and spheroid shapes are preferentially black in color.

Table 3. Size distribution in recovered Darwin glass.

Site	Distance from crater (m)	Azimuth (degrees from crater)	n	Average weight (g)	f (% of sample) glasses <2 g	Maximum weight (g)
0203	2000	270	380	1	91	30
0204	500	270	9	1	96	19
0207	7500	238	68	1.6	75	10
0301	3500	265	81	2.2	72	26
0303	8500	130	15	0.56	93	4.5
0304	8000	327	34	1.3	85	7.2
0305	9000	335	15	1.6	66	2.9
0306	9200	338	144	2.3	69	21
0307	10500	340	10	2.1	60	6.0
0308	12000	355	43	0.78	95	4.1
All sites			799	1.6	80	30

n = number, f = frequency.

surrounding the crater (10^{-5} km^3 or ~11,250 m^3). If the remaining >350 km^2 of the known strewn field is considered, modelled estimates of ejected melt volume are significantly too small. For all other studied craters, predicted melt volumes exceed measured volumes (Kieffer and Simonds 1980; Grieve and Cintala 1992). This indicates that relative to the size of the suspected source crater, Darwin glass is the most abundant ejected impact glass known on Earth.

Impacts into sedimentary rocks are predicted to produce equivalent or greater volumes of melt than impacts into crystalline rocks (Kieffer and Simonds 1980). However, this is not observed in most field investigations that show craters formed in thick sedimentary cover are associated with less melt than craters in crystalline targets (Kieffer and Simonds 1980; Grieve and Cintala 1992); although this may change with increasing recognition of sedimentary melts within craters (e.g., Osinski et al. 2003a, 2003b). Kieffer and Simonds (1980) explain this as relating to the increased volatile contents of typical sedimentary, relative to crystalline, rocks that they suggest promotes an unusually wide dispersal of melt and inhibits the development of coherent in-crater melt. X-ray fluorescence (XRF) analyses of target rocks from Darwin crater show that the volatile contents of these rocks are low (Howard 2008). The porosity of these target rocks is also very low at 1–2% in the quartzite and <1% for the shale (Great South Land Minerals, unpublished data). These low volatile contents and porosities result from low-grade regional metamorphism of shales and extensive cementation in the quartzites. Therefore the fact that the target stratigraphy is entirely sedimentary does not appear to aid in explaining the high abundance and wide distribution of ejected Darwin glass.

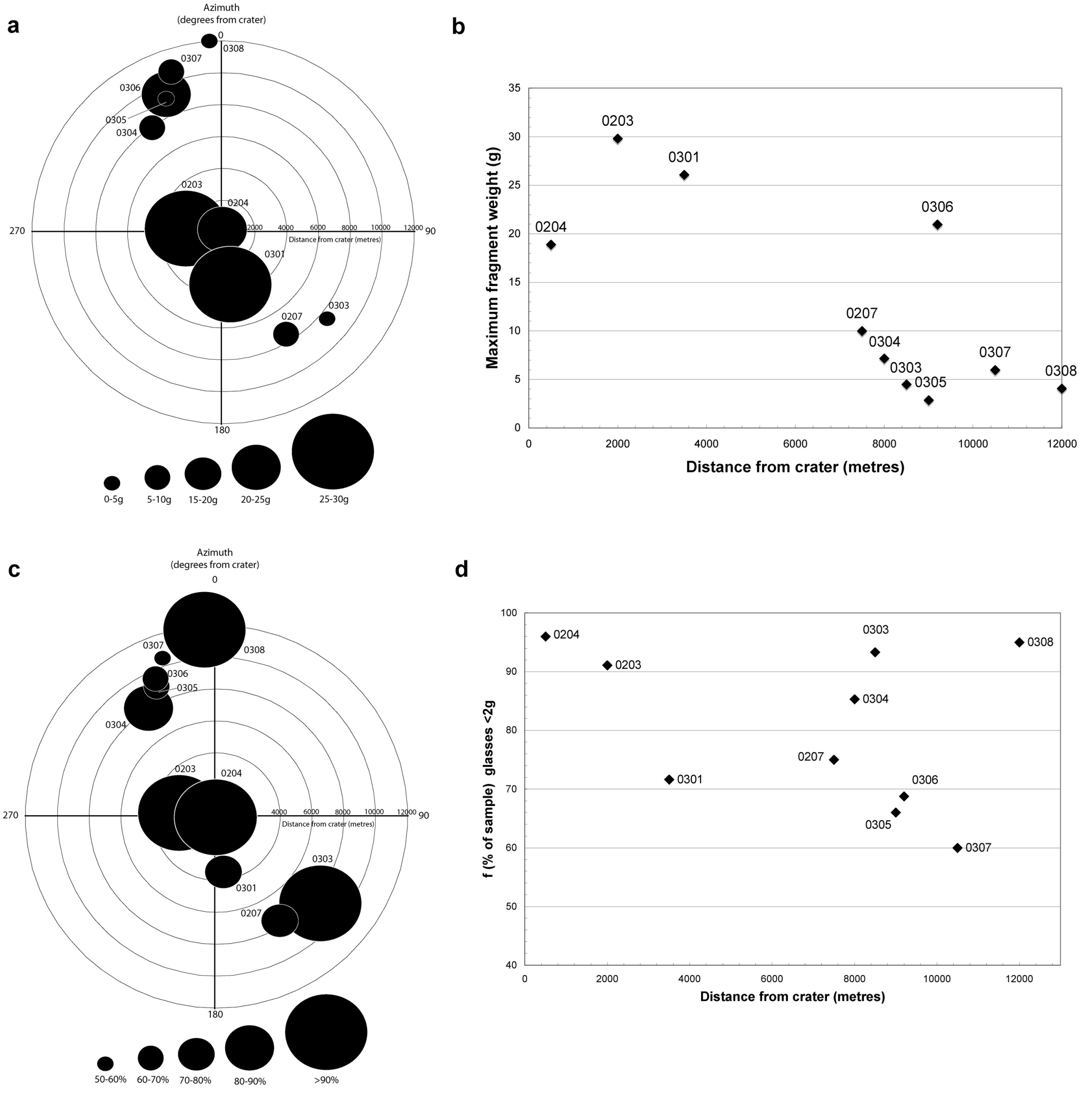

Fig. 9. Size distribution trends in Darwin glass. a) Maximum weight versus distance and direction from crater. b) Maximum weight versus distance from crater. There is a clear trend showing a decrease in the maximum weight of recovered glass fragments with increasing distance from the crater. Consistent with this trend is the fact that the largest known fragment was collected between sites 0204 and 0203 (R. J. Ford, unpublished data). c) Proportion of recovered finds weighing <2 g versus distance and direction from crater. d) Proportion of recovered finds weighing <2 g versus distance from crater. Small <2 g fragments are rapidly slowed by the atmosphere and dominate recovered glass finds close to the crater. At the most outlying sites almost all finds are <2 grams.

Enhanced Target Rock Volatility Induced by Interactions with Water

The most explosive volcanic eruptions are phreomagmatic—or involve the interaction of ascending magma with ground/sea waters (Fisher and Schmincke 1984). The addition of water to a melt, of any composition, greatly increases volatility and generates far higher energy eruptive explosions (Zimanowski et al. 1986; Kurszlaukis et al. 1998). Underground nuclear explosions also indicate a larger cavity excavation in rocks with high water contents (Butkovich 1971). Theoretical studies of large impact events indicate that an impact onto ice can produce an order of magnitude more melt and vapor than for any other terrestrial material (Pierazzo et al. 1997).

Darwin crater is one of the wettest parts of Australia and

Table 4. Abundance of recovered Darwin glass finds.

Site	Distance from crater (m)	Azimuth (degrees from crater)	Recovered glass abundance (kg/m^3)
0201	3000	280	0.74
0202	2500	272	3.5
0203	2000	270	47
0204	500	270	17
0205	0	0	0.17
0206	4500	290	0.44
0207	7500	238	0.26
0301	3500	265	1.5
0304	8000	327	0.78
Average			8

receives at least 3500 mm of rain per year. The floor of the valley containing Darwin crater is a swamp and outcropping rocks are commonly seeping. During rain events sheet flow is common. Palynomorphs recovered from the lowest laminated lake sediments in the crater stratigraphy (immediately above the crater-fill), are dominated by tree ferns (*Cyatheaceae sp.*), followed by grasses, daisies (*Asteraceae sp.*) and heath (*Epacridaceae sp.*), along with conifers (e.g., *Nothofagus gunnii; Nothofagus cunninghami, Lastrobus Franklinii*), wattles (*Acacia sp.*), Sheoak (*Casuarina sp.*) and rare Waratah (*Proteaceae sp.*). McPhail et al. (1993) reported similar assemblages from poorly defined sample locations between 50–60 meters depth in Darwin crater drill core (DDH1). The abundant ferns, grasses and daisies are interpreted to best represent the immediate environment surrounding the crater as the less common conifer and shrub pollen may have been transported by aeolian processes. The common presence of *Nothofagus sp.* in the recovered samples indicates water was abundant and this is a common tree around the crater today. The genetic characteristics of modern Tasmanian rainforest flora require that valleys such as the Andrew River valley and the valley that hosts the crater have always been refugia for rainforest communities, indicating wet conditions have predominated at low altitudes throughout the Pleistocene (Kirkpatrick and Fowler 1998).

An independent line of evidence that surface swamps existed at the time of the impact comes from the Tasmanian Burrowing Crayfish, *Parastoacides sp.* These live in burrows on swamp plains and in rainforests across west and southwest Tasmania. The crayfish can only survive in burrows associated with standing water or away from standing water but in contact with the water table. Hansen and Smolenski (2002) and Hansen and Richardson (2002) have defined several new species of *Parastacoides* with very limited geographical ranges scattered across the southwest. Genetic characterization of the crayfish species indicates that this is only possible if these isolated species have survived throughout the Pleistocene period in southwest and western Tasmania (Hansen and Smolenski 2002; Hansen and Richardson 2002). Also associated with the crayfish are a host of other endemic species of crustaceans that are specialized for living in pools of water in the burrows (Hansen and Richardson 2002). This work implies that deep waterlogged soils in contact with the water table have existed continuously throughout the Pleistocene at several locations in the southwest and west of Tasmania (Hansen and Smolenski 2002; Hansen and Richardson 2002). In particular, the area around Darwin crater is the hot spot of genetic diversity suggesting a particularly long history of waterlogged conditions in this region (Hansen and Richardson 2002).

This presence of abundant surface water and surface swamps is expected to produce a volatile charged target stratigraphy at the time of impact. This volatile enhancement is likely to be further promoted by infiltration of meteoric (surface) fluids along faults and fractures that are common in the target rocks (Gill and Banks 1950; Blissett 1962; Gee et al. 1969; Fudali and Ford 1979; Brown 1986). There is also the potential for porous sandstone layers to exist within the target rocks and, if present, these are likely to be saturated by H_2O. Based on theoretical studies of impact melt production and cratering (e.g., Kieffer and Simonds 1980; Pierazzo et al. 1997), this volatile enrichment of the target rocks would be expected to promote an increased magnitude explosion and exceptionally efficient dispersal and ejection of melt as the volatiles escape during impact. This model of surface swamps enhancing the target volatility is the most parsimonious explanation for the high abundance and wide distribution of Darwin glass, and highlights the dynamic control of the receiving environment on the nature of the impact process.

CONCLUSION

This study shows that relative to the size of the crater Darwin glass is the most abundant impact glass on Earth. Classification of more than 4000 glass fragments into shape and color classes reveal that an irregular morphology dominates the sample and that splashform shapes are preferentially developed in the least viscous, low SiO_2 black melt. The extremely high abundance of the ejected glass is interpreted to relate to a volatile charged target stratigraphy, resulting from the presence of surface swamps and infiltrating surface water, at the time of impact. The high abundance of ejected glass allows for trends in the distribution of glass relative to Darwin crater to be defined and these show 1) a decrease in glass abundance away from the crater; 2) the largest fragments of glass are found closest to the crater; 3) small fragments (<2 g) dominate finds close to the crater; 4) the proportion of white melt is greatest closest to the crater; 5) the proportion of the black melt increases with distance from the crater and 6) the proportion of splashform glasses increases with distance from the crater.

These distribution trends reflect processes of ballistic transport of melt during impact cratering. The observed distribution trends are also related to the depth of excavation from the target rock stratigraphy and/or viscosity controlled fragmentation and separation of melt during ejection. Darwin crater being the sole source of the glass is the only explanation for these trends. These data are being modelled elsewhere and further necessitate Darwin crater be recognized as an impact structure.

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