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Occurrence, Distribution, and Age of Australian Tektites

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ABSTRACT

Chalmers, R. O., E. P. Henderson, and Brian Mason. Occurrence, Distribution, and Age of Australian Tektites. *Smithsonian Contributions to the Earth Sciences,* number 17, 46 pages, 17 figures, 10 tables, 1976.—Extensive field work has shown that the Australian strewnfield is less extensive than previously thought, being essentially restricted to the region south of latitudes 24° to 25°S. The few australites found north of this region probably represent specimens transported by man. Throughout much of the desert interior australites are weathering out of a late Pleistocene or early Recent horizon in a well-consolidated calcareous red sandy aeolianite; field evidence indicates that in most places they are found essentially where they fell, or stream erosion and sheet wash has transported them short distances and concentrated them in claypans and playas. Distribution within the strewnfield is irregular and can be ascribed to: (1) original nonuniform fall; (2) burial by recent deposition; (3) removal by erosion. Australites (excluding the doubtful HNa/K type) show a continuous range of composition from 80% to 66% SiO_2 with related variations in other major constituents, which is reflected in the range of specific gravities (2.36–2.52) and refractive indices (1.493–1.529). The composition range is not uniform over the strewnfield, the high-silica australites being concentrated along a northwest trending band extending from western Victoria to the Lake Eyre region. Other noteworthy features are: (1) a variation in the average size of australites from place to place, those on the Nullarbor Plain being notably smaller (average <1 gram) than those of other regions (average 3–5 grams); (2) the occurrence of many large australites (>100 grams) in the southwestern part of Western Australia.

Unsolved problems include: (1) the inconsistency between geological age (7000–20,000 years BP) and K–Ar and fission track ages (700,000–860,000 years); (2) the relationship, if any, between australites and the "microtektites" in Indian Ocean sediments; and (3) the source region of the australite material.

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Introduction

Australian tektites were first made known to science by Charles Darwin. In 1844, in his book *Geological Observations on the Volcanic Islands Visited during the Voyage of H.M.S. Beagle,* he described and illustrated a specimen (Figure 1) he received from Sir Thomas Mitchell in Sydney in January 1836. Mitchell had collected it "on a great sandy plain between the rivers Darling and Murray," presumably during his exploration of the Darling River valley in 1835. (The location ascribed to this australite by Baker (1973)—approximately 34°20′S, 143°10′E—appears to be erroneous, since Mitchell did not travel south of 32°30′S, near the present site of Menindee, on his 1835 journey.) Darwin compared this australite to obsidian, but noted that it was found "several hundred miles from any volcanic region," suggesting that it might have been transported either by aborigines or by natural means. The suggestion that it might have been a transported specimen was a prescient one; very few australites have been found along the Darling, and the exceptional quality of Darwin's specimen would attract an aboriginal. Additional records of the occurrence of tektites in Australia are scattered through nineteenth- and twentieth-century literature from 1855 to the present. This information is summarized in the classic monographs of Suess (1900) and Baker (1959a).

FIGURE 1.—Front, back, and side view of the australite given to Charles Darwin by Sir Thomas Mitchell in 1836; specimen is 26 × 22 × 7 mm (Institute of Geological Sciences, London).

Suess introduced the terms "tektites," defining them essentially as glassy meteorites, and "australites" as those tektites found in Australia. Tektites occur in four general regions of the world. The first and largest is the Indoaustralian region (Von Koenigswald, 1960), encompassing, besides Australia, Hainan Island and the adjacent mainland of China in the extreme southern section of Kwangtung Province, Vietnam, Cambodia, Laos, and Thailand (indochinites), the Philippines (philippinites), Malaysia (malaysianites), and Indonesia. Barnes (1963) introduced the term "indomalaysianites" to refer to tektites from Malaya, Java, Borneo,

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and the adjacent small islands of Billiton and Bunguran, and those few other Indonesian islands on which an occasional specimen is found. Outside the Indoaustralian region two more geographically defined groups are moldavites (vltavines) from the Moldau (Vltava) River valley and areas further to the east in Czechoslovakia, and bediasites from Texas. Finally, tektites are found on the Ivory Coast, West Africa. Materials sometimes classed as tektites, but distinct from them in appearance and composition, are silica glass from the Libyan Desert and Darwin Glass from Mt. Darwin in Tasmania.

The australites occupy a unique position among the tektites. Their strewnfield is by far the most extensive of any of the above-named groups. They show a wider range of composition (e.g., 66%–80% SiO_2) than most tektite groups. Whereas practically all other tektites have been found in alluvial deposits and have lost their original surface by abrasion or solution, many australites have been recovered with their original surface well preserved, showing delicate markings produced by aerodynamic ablation. This enables significant deductions to be made regarding their original form and its modification during passage through the Earth's atmosphere.

Interest in tektites as a group, and australites in particular, has waxed and waned from time to time. Comparatively little research on australites was reported in the first thirty years of this century. Then Dr. Charles Fenner, in a series of papers published between 1933 and 1955, provided a large amount of new information on numbers, forms, and distribution. Commencing in 1937, Dr. George Baker wrote a large number of papers on australites, especially those from localities in Victoria and South Australia. In 1959 his comprehensive monograph "Tektites" was published, with a very full bibliography, although one early reference not listed is Clarke (1869) He continued to expand and interpret the data available on these enigmatic objects until his death in 1975.

International interest in tektites greatly increased after World War II as part of a general increase in interest in meteorites. Suess originally had postulated an extraterrestrial origin for tektites. The discovery that tektites show no evidence of cosmic-ray bombardment in outer space (Anders, 1960, and Viste and Anders, 1962) indicates a relatively brief flight while outside the Earth's atmosphere, and thus supported the suggestion by Nininger (1943) that a meteorite impact on the moon was the mechanism that sent tektites to Earth. When plans were being made for manned moon landings, scientists at the National Aeronautics and Space Administration began an intensive study of all things connected with the moon, including tektites. Chapman and Larson (1963) further adduced a great deal of aerodynamic evidence to substantiate the theory of lunar origin. On the other hand, the work of Taylor (1962, 1966) and Taylor and Kaye (1969) showed that the composition of tektites was comparable to that of sedimentary rocks of the subgreywacke type. Bouska (1968) considered that all tektites from the entire Indoaustralian region might have been derived from impact on igneous rocks, but that tektites from other regions were derived from sedimentary rocks. These findings suggested a possible origin by meteoritic impact on Earth and not on the moon. This possibility was strengthened by the discovery that moldavites had the same K-Ar age as the Ries crater in southern Germany and that the Ivory Coast tektites were the same age as the glass in the Bosumtwi crater in Ghana (Cohen, 1963, Gentner et al., 1963, Faul, 1966). As a result, the extraterrestrial origin once widely accepted was seriously challenged, and an origin due to large-scale impact on Earth gained favor.

Because of this increased interest, the demand for research material has steadily expanded, and the requirements therefor have become more rigorous, in terms of exact locality, mode of occurrence, and quality of preservation. On this account, we organized in 1963 an expedition designed to provide more and better documented material for our respective institutions: the Australian Museum (Chalmers), the Smithsonian Institution (Henderson, and Mason since 1964), and the American Museum of Natural History (Mason, 1963 and 1964). The success of the 1963 expedition, and the questions it raised about the geological occurrence, distribution, and age of australites led to further lengthy journeys in 1964, 1965, 1966, 1967, and 1969 (Figure 2), which covered most of the strewnfield on the continent. (Australites have also been found on Tasmania, but we have not investigated these occurrences). Special efforts were made to investigate the more remote regions in the arid interior, and to follow up any promising leads. In addition, much time

FIGURE 2.—Routes of field expeditions, 1963–1967.

was devoted to defining the northern margin of the strewnfield, an arduous and, in terms of specimens, a rather unproductive exercise.

Besides the support of our respective institutions, we are greatly indebted to the National Geographic Society for a grant financing the initial expedition and continuing support for the later journeys. A grant from the National Science Foundation supported Henderson in 1963, and one from the Smithsonian Research Foundation aided Mason in 1967. In addition, the award of a fellowship by the John Simon Guggenheim Foundation enabled Mason to spend several months at the Australian National University in Canberra in 1969 on laboratory investigations and fruitful discussions with Australian colleagues. During our travels we have been given great assistance and enjoyed generous hospitality through the sparsely populated interior of Australia. It is not feasible to name everyone who helped us in our work, but special mention is due to the following: Mr. Frank Nicholls of Pindera, N. S. W.; in one of our prime collecting regions near Lake Torrens, Dr. and Mrs. G. C. Gregory, Mr. Noel Smith, Mr. J. Moroney and Mr. R. Craigie; in another prime collecting area in the region of the eastern edge of Lake Eyre and the Birdsville Track, the late Mr. G. Patterson of Farina, Mr. K. Price of Muloorina, Mr. Kevin Oldfield of Clayton, Mr. Brian Oldfield of Etadunna, and Mr. G. Bell of Dulkaninna. Actual assistance in collecting was given by Mr. H. S. St. J. Disney, Mr. H. O. Fletcher, Mr. R. Lossin, Mr. D. Hamlyn, Mr. P. Robinson, Dr. and Mrs. L. E. Weiss, the late Mr. A. A. Walker, and Mr. D. F. Walker. On one field trip Mr. D. F. Walker provided a second vehicle. In other areas the cooperation of the following is acknowledged: Mr. J. E. Johnson of Adelaide, Mr. P. D. Boerner of Alice Springs, Mr. Barton Jones, Mr. W. H. Cleverly, and Mr. K. Quartermaine of Kalgoorlie, and Mr. and Mrs. C. Smith of Earaheedy Station, northeast of Wiluna. We are indebted to curators of major australite collections for much useful information, especially Dr. A. W. Beasley of the National Museum of Victoria, Dr. D. W. P. Corbett and Miss J. M. Scrymgour of the South Australian Museum, Dr. D. Merrilees of the Western Australian Museum, and Mr. D. H. McColl of the Bureau of Mineral Resources, Canberra. We also thank Dr. Dean Chapman for many illuminating discussions and for the use of some of his unpublished information.

Geographical Distribution and Relative Abundance

In Table 1 a large number of australite collections are listed giving the numbers, weights, and geographic coordinates of each collection. The majority of these collections were made by us, and, for these, exact localities and mode of occurrence are recorded in our field notes. Some of the collections listed were presented or loaned by individuals. Others were purchased. The repositories for all these collections are shown. The numbers in Table 1 are only a rough indication of the relative abundance of australites at the different localities. Some localities, for example Pine Dam in the Lake Torrens region, have been collected intensively and repeatedly. Other localities represented one or two man-hours of rapid reconnaissance. Nevertheless, within the range of our journeys, the relative abundance, as illustrated in Figure 3, has some basic significance. It is apparent to us that australites did not fall uniformly over the whole strewnfield. In certain regions, for example that on the northeast margin of Lake Torrens, australites are notably abundant; other regions, situated no great distance away and similar in geology, topography, and climate are much less productive or apparently quite barren. Thus, on the western edge of Lake Torrens, on Arcoona Station, near Woomera, only about 60 australites have been found in some 40 years of collecting by Michael Mudie. Another example of a relatively unproductive area is on Pindera in the far northwestern corner of New South Wales. Here, over a period of about 50 years, 155 specimens were collected first by V. C. W. Nicholls and later by his son Frank. Admittedly in these two instances the australites have been found by graziers engaged in their day-to-day duties and not specially searching for them. Even within a productive region the abundance varies greatly within comparatively short distances.

Of course, the productivity of an area depends not only upon the original density of fall of the australites, but also on subsequent events, in particular (1) erosion, (2) deposition, (3) distribution by animals or man, and (4) prior collecting.

Erosion may operate either to concentrate or to disperse australites, depending upon local conditions. On the Nullarbor Plain, which covers a large area straddling the South Australia–Western Australia border, australites appear to be randomly and rather sparsely distributed over most of its extent. However, small shallow circular depressions (known locally as "dongas") frequently provided somewhat more productive collecting, the australites presumably being concentrated by sheet wash accompanying the rare heavy rains. Over much of the arid interior, wind erosion (deflation) is the principal agency for exposing australites. On the other hand, in regions of moderate to strong relief, stream erosion is likely to bury the rare australites in the mass of alluvium, and rapidly destroy all but the large specimens. Deposition of recent alluvium and especially wind-blown sand makes many large areas unrewarding to collect. None were found in interdune areas where the floors were silted up by the action of rivers such as Cooper Creek, Strzelecki Creek, and Diamantina

TABLE 1.—Number, weight, and current location of australites acquired by Australian Meteorite Expeditions, 1963–1967, ordered approximately from east to west (AM = Australian Museum, AMNH = American Museum of Natural History, SI = Smithsonian Institution)

Locality	Latitude/ Longitude	Number	Total wt. (g)	Where preserved	Notes
Pindera (1963)	29°27' 142°29'	3 3	12 15	SI AMNH	gift F. Nicholls
Pindera (1966-7)	"	6	13	AM	
Pindera	"	36	154	AM	gift V.C.W. Nicholls
Currawilla	25°09' 141°20'	3	6	AMNH	
Mooraberree	25°16' 140°58'	2	13	AMNH	
Durrie	25°53' 140°06'	1205	2315	AM	gift G. Hume
Durrie	"	99	98	SI	bought from G. Hume
Cuddapan	25°48' 141°15'	82	143	SI	bought from G. Hume
Mutooroo	32°29' 140°50'	1	16	AM	
Oakvale	32°59' 140°47'	31	149	SI	gift W. Crack
Frome Downs	31°14' 139°55'	7	19	SI	
Wilpena Creek	31°04' 139°42'	15	34	AM	
Yunta	32°27' 139°32'	1	2	AM	
Waukaringa	32°14' 139°27'	1	5	AM	
Mannahill	32°25' 139°59'	97	126	SI	gift N. Bartlett
Motpena (1964)	31°12' 138°15'	3	11	AM	
Motpena (1967)	"	33	59	SI	
Motpena	"	76	198	SI	gift R. Craigie
Beltana (1966)	30°54' 138°12'	236	585	AM	
Beltana (1967)	"	212	666	SI	
Pine Dam (1963)	30°25' 138°02'	49 97 97	139 262 260	SI AMNH AM	
Pine Dam (1964)	"	340	553	SI	

TABLE 1.—Continued

Locality	Latitude/ Longitude	Number	Total wt. (g)	Where preserved	Notes
Pine Dam (1965)	30°25' 138°02'	19	47	AM	
Pine Dam (1967)	"	76	81	SI	
Mt. Victory Well (1964)	30°25' 137°51'	4	16	AM	gift G.C. Gregory
Mt. Victory Well (1966)	"	202	300	AM	
Mt. Victory Well (1967)	"	6	4	SI	
Busheowie	30°13' 137°53'	18	136	AM	gift B. Murray
Mulgaria (1964)	30°14' 137°38'	218	361	AM	
Mulgaria (1965)	"	95	121	SI	gift D. Hamlyn
Mulgaria (1967)	"	12	15	SI	
Andamooka Island	30°53' 137°40'	1	8	AM	
Finniss Springs	29°33' 137°16'	5	62	AMNH	gift G.C. Gregory
Lake Arthur	29°32' 138°46'	9	13	AM	
Lake Eyre South	29°14' 137°43'	14	94	AMNH	
Clayton River	29°15' 138°08'	6	22	AMNH	
Dulkaninna (1964)	29°06' 138°20'	54	99	AMNH	
Dulkaninna (1967)	"	59	62	AM	
East Peachawarinna (1964)	29°03' 138°19'	72	179	AMNH	
East Peachawarinna (1967)	"	47	55	SI	
East Peachawarinna (1967)	"	8	16	AM	
West Peachawarinna	29°03' 138°17'	7	33	AM	
East Tankamarinna	28°57' 138°27'	5	48	AMNH	

TABLE 1.—Continued

Locality	Latitude/ Longitude	Number	Total wt. (g)	Where preserved	Notes
West Tankamarinna	28°58' 138°18'	299	492	AM	
Mulka	28°18' 138°48'	11	20	AMNH	
N.W. of Mulka	28°12' 138°24'	15	40	SI	gift J. Findley
Mungeranie	28°10' 138°30'	38	88	SI	coll. J. Dunn; gift G.C. Gregory
New Kalamurina (1964)	27°44' 138°15'	1	0.5	AMNH	
New Kalamurina (1967)	"	1	1	AM	
Alton Downs	26°08' 138°58'	1	1.3	AMNH	
Simpson Desert	26°24' 137°27'	13	36	AM	gift R. Syme
Charlotte Waters	25°55' 134°55'	38	162	SI	
Macumba	27°15' 135°42'	19	70	SI	
Ooldea	30°38' 132°03'	58	47	SI	
Near Watson	30°31' 131°20'	21	18	SI	
SE of Cook	30°58' 130°42'	24	7	SI	
N of Cook	30°10' 130°25'	14	25	SI	
Denman	30°40' 129°58'	170 66	92 46	SI AM	bought from railwayman
S of Hughes	30°55' 129°42'	28	23	AM	
N of Hughes (1965)	30°30' 129°30'	894 452	452 254	SI AM	
N of Hughes (1967)	"	91	69	SI	
NE of Deakin	30°30' 129°05'	50	26	AM	
N of Deakin	30°32' 128°59'	93	49	AM	
Eucla	31°43' 128°55'	2	11	SI	

TABLE 1.—Continued

Locality	Latitude/ Longitude	Number	Total wt. (g)	Where preserved	Notes
N of Forrest	30°20' 128°05'	4	5	AM	
Mundrabilla	30°56' 127°31'	14	13	AM	
Loongana	30°57' 127°02'	2	0.5	AM	
N of Loongana	30°15' 127°02'	8	4	AM	
Lake Yin-darlgooda	30°42' 121°54'	79 72	360 274	SI AMNH	
Lake Wilson	26°01' 129°36'	28	51	SI	
Mt. Davies	26°11' 129°07'	21	152	SI	bought from natives
SE of Earaheedy	25°50' 121°58'	112	210	SI	
S of Earaheedy	25°40' 121°34'	36	53	SI	
Granite Peak	25°38' 121°20'	100	467	SI	gift E. Juniper
Millrose	26°24' 120°57'	1	28	SI	

(Warburton) River. Many parts of the arid interior are sandplains with the sand fairly well fixed by the desert vegetation. Aeolian deposition, rather than erosion, is dominant in the regions of these sandplains. Australites may, however, be picked up in local blow-outs or found in the debris around the holes made by such animals as wombats and rabbits.

Prior collecting strongly affects the return from any locality. Johnson (1964) records collecting 1451 australites in 15 man-hours from the floor of Lake Wilson, a playa about 1½ × 1 mile in extent in the far northwest of South Australia; our visit in 1965 produced 28 australites in 18 man-hours. Johnson's party evidently harvested a crop which had accumulated probably over a period of hundreds or perhaps thousands of years; our collection represents a gleaning of the few they had overlooked. Our experience with some of the claypans in the Pine Dam area which have been re-collected at a later date suggests that a systematic search over a limited area will net a major fraction of the australites present (perhaps 75%–95%), and few will be recovered on later visits to the same area. This indicates that, even in localities where australites are relatively abundant, the slow rate of natural erosion (mainly deflation in the arid interior) results in a very slow release of australites from the matrix in which they are buried. Of course, in humid regions such as the Port Campbell area of Victoria, where Baker and others have collected successfully over many years. the abundant rainfall and accelerated erosion caused by roadmaking and other human activities have provided a continually prolific source of australites.

It may be of interest to sum up our experiences

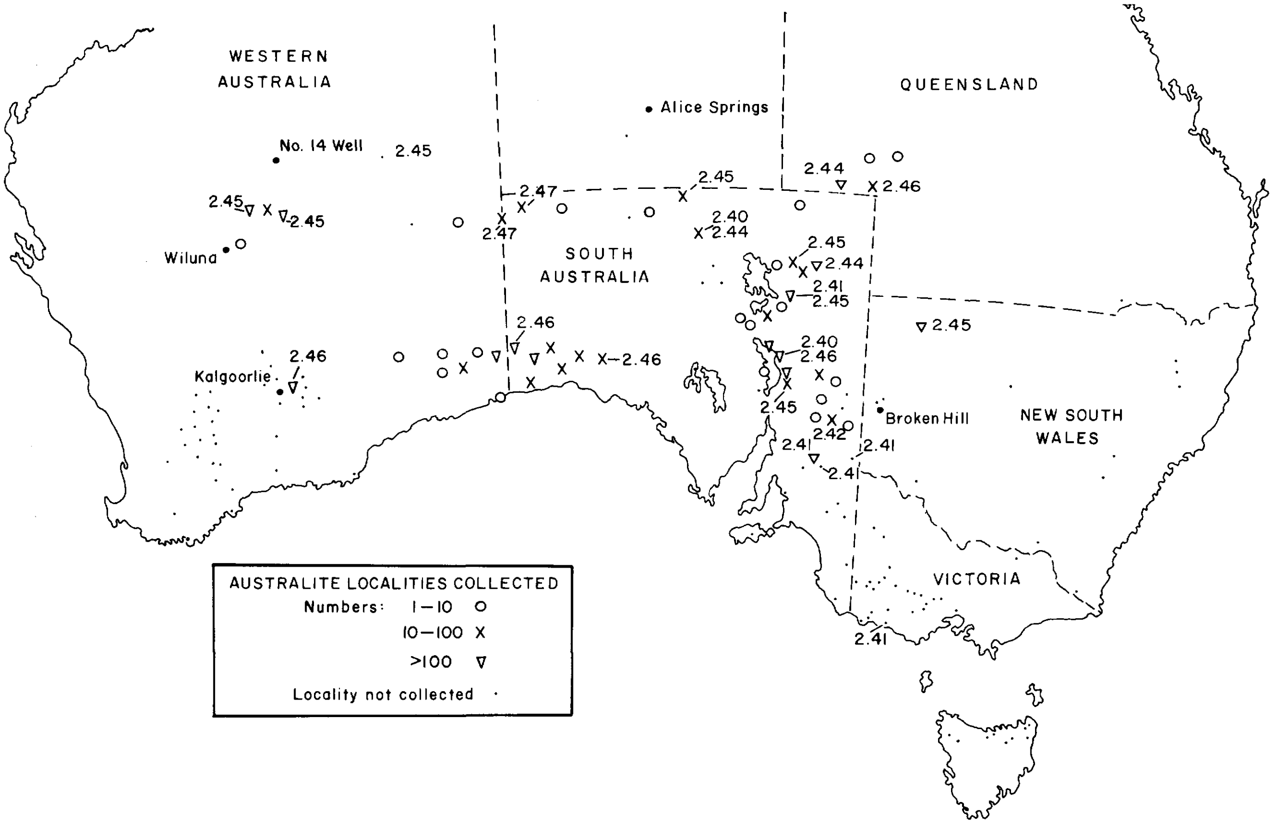

FIGURE 3.—Australite localities collected during the Australian Meteorite Expeditions, 1963–1967; the symbols indicate the numbers of individual specimens examined, and are not indicative of the total number of specimens found at any locality. The figures give the peak specific gravities for the larger collections, along with some data from published papers (Table 7).

in regard to productivity. We have found that, in areas where australites are relatively abundant and have not been intensively collected, a return of 3–4 per man-hour is about normal, although even within such areas the recovery rate will vary quite widely. A record collection of 81 in one man-hour was made in 1965 in a shallow depression in the Nullarbor Plain north of Hughes; a return visit to the same locality in 1967 netted 9 in one man-hour.

MODE OF OCCURRENCE

Over much of the area in which we have collected (excluding for the moment the Nullarbor Plain), the topographic, geologic, and climatic conditions are extremely similar throughout.

Most of the country is extremely flat, an integrated drainage pattern is practically absent (except close to large intermittent rivers such as the Frome and the Cooper), and the topography is longitudinal sand dunes (seif dunes), usually 30–60 feet high, separated by interdune corridors occupied by claypans at their lowest spots. Wind erosion is dominant, and the runoff from rare heavy rains produces only local erosion and deposition around the individual claypans. The claypan surfaces are the natural collecting grounds for australites.

The geological setting is remarkably uniform over vast areas, and is illustrated in Figure 4 by sections through dunes and claypans at Motpena and Myrtle Springs (Pine Dam) in the Lake Torrens region of South Australia. There are essentially three formations represented:

1. Unconsolidated sand forming the crests of the dunes and veneering large areas of the interdune corridors.

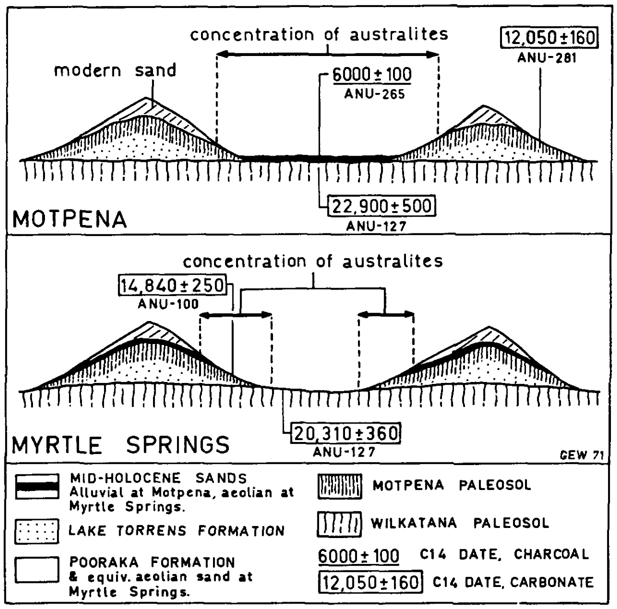

FIGURE 4.—Schematic sections through the late Quaternary sediments and paleosols at Motpena and Pine Dam, Myrtle Springs, showing the areas within interdune corridors where australites are commonly found (Lovering et al., 1972).

2. A well-consolidated calcareous red sandy formation, almost certainly an aeolianite, which is widespread in every area we visited.

3. A calcareous red-brown formation containing abundant carbonate nodules that forms the floor of the claypans in the interdune corridors.

These three formations in the Pine Dam area have also been noted by Corbett (1967).

Williams and Polach (1971) have suggested a late Quaternary chronology for the events that have occurred over the last 38,000 years in the Lake Torrens plain, including the deposition or accumulation of the above three formations. They have named formation 2 the Lake Torrens Formation (deposited ca. 20,000–16,000 BP) capped by the Motpena paleosol (formed ca. 16,000–12,000 years BP); formation 3 has been named the Pooraka Formation (deposited 30,000 BP and earlier) capped by the Wilkatana paleosol (formed on the Pooraka Formation prior to the deposition of the Lake Torrens Formation). The Wilkatana paleosol is covered by mid-Holocene sands in many of the interdune corridors.

Williams and Polach (1971) noted that in the Lake Torrens plain, as in all arid and semi-arid regions of the world, accumulations of carbonate nodules form well-developed horizons in soils and paleosols of both alluvial and aeolian origin. They determined the ages cited above by carbon 14 dating of carbonate nodules from these horizons. Carbonate nodules are invariably thickly scattered on the surfaces of both the Motpena and Wilkatana paleosols.

At Pine Dam a total thickness of about 12 feet of the Motpena paleosol is exposed. Within this thickness two layers of carbonate nodules occur, one about two feet from the top and the second some six feet lower. The carbonate nodules in the upper layer are small (fingertip size and smaller); those in the lower layer are larger (up to fist size) and much less friable.

Our experience indicates that in the Pine Dam area the australites occurred originally in a horizon at or near the top of the Motpena paleosol. One australite has been found partly embedded in the Motpena paleosol at Motpena (Lovering et al., 1972) and another in the Motpena paleosol near Pine Dam by R. O. Chalmers in 1969. Several have been found partly embedded in mid-Holocene alluvial and aeolian deposits at Motpena (Lovering et al., 1972) and the Pine Dam area (Corbett, 1967).

Some 8 miles southwest of Beltana railway station and about 10 miles north of the Motpena locality there is an isolated area measuring about 5 by 4 miles of Lake Torrens Formation lying on a surface of rocks of Proterozoic age. The area is low and eroded, revealing areas of Motpena paleosol, dated by Lovering et al. (1972) at 12,540 years BP (their Nilpena locality). Dunes of unconsolidated sand lie on this paleosol (Figure 5). Interdune corridors run between the low dunes, but erosion has not proceeded far enough to produce the bare claypan floors characteristic of the Pine Dam area. Australites occur both on the eroded paleosol and in the shallow interdune corridors; a group of them, of larger than average size, is shown in Figure 6.

In deeply deflated interdune corridors, as in the Pine Dam area, the claypan floors consist of the Wilkatana paleosol and many australites are found lying on this surface. Sheet wash during heavy rain has no doubt moved them from the margins of the claypan where they have been shed from the Motpena paleosol.

FIGURE 5.—Erosion remnants of Motpena paleosol partly covered by unconsolidated sand, southwest of Beltana Station, South Australia; australites were found on the bare surface in the foreground.

Australites are not found everywhere the Motpena paleosol is exposed in the Lake Torrens region, nor where formations resembling the Motpena paleosol outside the Lake Torrens region are exposed. The principal reason for their absence in what might be regarded as a favorable environment is that they presumably fell within a very short time interval while this formation was being deposited, and thus mark a thin stratigraphic horizon. If the australite horizon is not yet exposed, no australites will be found. If the australite horizon has been eroded away, australites may survive, but will be subjected to rather rapid destruction by sandblasting and transportation. Hence recovery of well-preserved australites near outcrops of this formation is prima facie evidence for the presence of the australite horizon therein.

Of course it is unlikely that the australite strewnfield coincides with the geographical extent of these formations resembling the Motpena paleosol, so the absence of australites at any locality is no evidence that the time interval of australite arrival is not represented therein. For example, we noted typical exposures in western Queensland between Birdsville and Bedourie but our search there failed to find any australites. However, subsequent to our field work in this area Gordon Hume has found between 1000 and 1500 on a large claypan 46 miles east of Birdsville (25°53′, 140°06′), and a considerable number at nearby Cuddapan (25°48′, 141°15′).

THE EXTENT OF THE AUSTRALITE STREWNFIELD

Figure 3 shows localities where we collected between 1963 and 1967. Localities collected by other investigators, notably Fenner (1940), Chapman

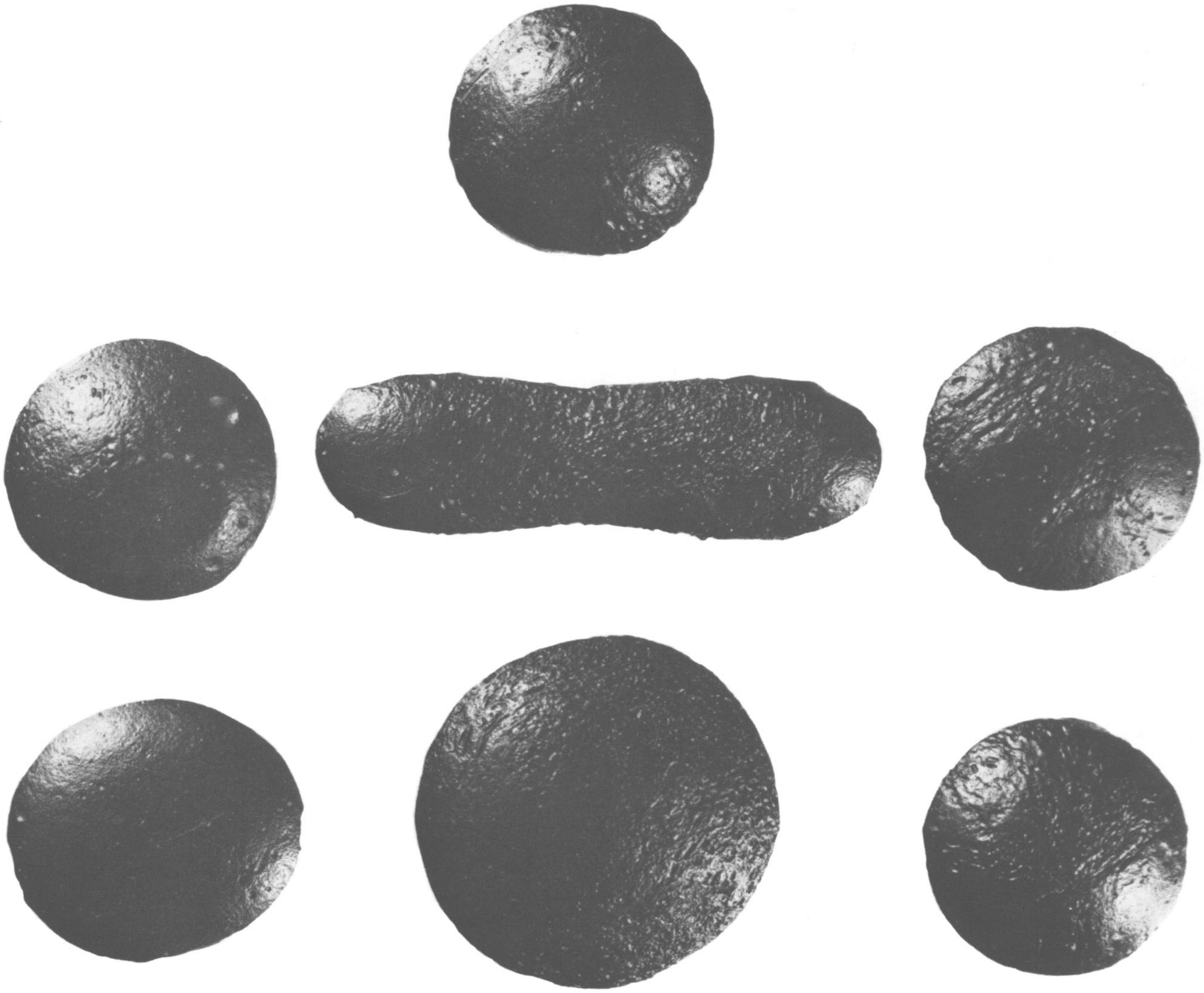

Figure 6.—A group of larger than average australites collected from the area of Figure 5; the central specimen is 54 mm long.

et al. (1964), and Baker (1956, 1959a, 1969b), are shown by dots. Distinctive symbols indicating the numbers we collected at each locality are shown. As will be discussed later, peak values for specific gravities are also shown. It is impossible to show complete data for all localities on a single map of Australia. The reader is referred to the following publications containing maps showing australite localities and/or data on numbers recorded: Baker (1956, 1959a, 1959b, 1961a, 1964a), Barnes (1963), Chapman (1964, 1971), McColl and Williams (1970), and Cleverly (1973, 1974). Although not shown on Figure 3, australites have been found on islands in Bass Strait, and in Tasmania, mainly in the northeast in cassiterite-bearing alluvial deposits.

To some extent, of course, the distribution indicated in Figure 3 and in maps in the above-mentioned publications is an imperfect representation of the strewnfield as a whole. To be established, a locality has to be visited by someone sufficiently observant to recognize australites. However, comparatively little of Australia has not yet been subjected to fairly careful reconnaissance, either by pastoralists, station hands, surveyors, or prospectors, most of whom are excellent observers and unlikely to pass over exotic material like australites. Moreover, we know of instances where pastoralists, having no prior knowledge of australites, were stimulated by the interest we aroused to search intensively and with considerable success in the course of their work on their stations. Most areas where 1000 or more australites have been collected are in arid or semi-arid regions where it is easier to find them than in well-vegetated areas of higher rainfall. Also a locality cannot be established unless the finders pass on the information to persons interested in recording it. Density of population and pastoral or mining activities are other factors that favor the finding of australites. The large number of productive areas around Kalgoorlie and adjacent sites in Western Australia can certainly be ascribed to intensive prospecting for gold as well as to the relative aridity of this region. On the other hand, Broken Hill in western New South Wales has about the same population as Kalgoorlie, the same semi-arid climate, and the surrounding districts have been prospected equally as thoroughly, but relatively small numbers of australites have been found, which again reinforces our belief that the australites did not fall uniformly over the whole strewnfield. Factors that partly explain the concentration of localities in Victoria are that it is the most densely populated state in Australia and that there has been extensive agriculture and mining. McColl and Williams (1970) state that, out of the dozens of australite localities in Victoria, there is only one where more than 1000 have been collected, two where between 100 and 1000 have been collected, and three where between 10 and 100 have been collected. These lie on a southeast-northwest line extending from Victoria through South Australia to the Charlotte Waters region on the South Australian–Northern Territory border. The concentrations are distributed unevenly, and they regard this as being due in the main to the irregular nature of the fall. One major fact supporting this hypothesis is the absence of australites in Eyre Peninsula in South Australia or in its extension to the northwest, to beyond the Trans-Australian Railway. This area is bounded to the west by the Nullarbor Plain and to the east by Spencer's Gulf. Much of the Eyre Peninsula is blanketed by recent sand, but along the railway from Port Augusta to beyond Tarcoola, a distance of some 300 miles, the relief and erosion would surely have been sufficient to have exposed an australite horizon. We regard this apparent absence as significant.

The farthest north we have collected australites is on Currawilla Station in southwestern Queensland (25°09′, 141°20′). At Mooraberree Station, about 30 miles further west, some 40 have been collected over 30 years, which is an indication of how sparsely they are distributed in this region. About 70 miles to the southwest, as already mentioned, abundant australites have been collected on claypans in the vicinity of Durrie station by Mr. Gordon Hume. Further west along the Birdsville-Bedourie road conditions are favorable for finding australites, but we had no success and local people had found none. In our travels along the Birdsville Track from Marree to Birdsville, collecting was good until north of Cooper Creek. We were successful in only three localities between here and Birdsville, viz., in an area of big sandhills east of Ooroowilanie towards the Cooper, at Alton Downs at latitude 26°06′ on the eastern border of the Simpson Desert where only one was found, and at Kalamurina, latitude 27°50′, where only two were found. A few miles north of where the Cooper crosses the Birdsville Track many hundreds have been found near Mulka (Tables 1 and 7). A collection from Mungeranie is also listed in Table 1.

We have not investigated the region of the Simpson Desert, one of the largest uninhabited regions remaining in Australia (latitude 23°30′ to 27°30′ and longitude 132°50′ to 139°00′). But Mr. R. C. Sprigg, who has traveled extensively there, informs us that while australites are common throughout the southern part they become progressively less abundant the further north one goes, until north of latitude 25° few if any are found. This statement is supported by the absence of any reference to australites in Madigan's (1946) account of the 1939 Simpson Desert Expedition. Madigan would have been familiar with australites because Fenner (1935) records a collection in his possession. The main desert area crossed by the expedition from east to west lay between latitudes 24° and 25°. From latitude 25° to Birdsville in latitude 25°54′ the route went southeast. In about

1967 Mr. Robin Syme, a member of a geophysical exploration team working in the Simpson Desert, made a small collection which he presented to the Australian Museum. He stated that larger collections were made by other members of the exploration team. The locality was about 125 miles south-southwest of Birdsville at latitude 26°23′ and longitude 137°27′. The nearest named locality is Peelicanna Native Well.

The Charlotte Waters strewnfield covers quite a large area extending from Finke to about 50 miles south into South Australia, and 70 miles east into the western fringes of the Simpson Desert. About seven or eight thousand have been collected here (Fenner, 1940). Beyond Finke in the Northern Territory they are rare or absent. Specimens in the South Australian Museum are stated to have come from Henbury (latitude 24°35′), and specimens in the Australian Museum collection from 5 miles north of Alice Springs (latitude 23°37′), but nothing is known in either case of the circumstances in which they were found. Fenner (1935) quotes Charles Chewings, a geologist with intimate knowledge of the Northern Territory, as having neither heard of nor seen a single specimen north of the MacDonnell Ranges. Our experience confirms this, and enquiries of the aboriginals from Alice Springs northwest to the Western Australian border and beyond to Halls Creek were also negative. Jensen (1915) states: "Mr. William Laurie informs me that obsidian buttons are common about Bullock's Head about 40 miles from Tanami on the Granite Road." The latitude of this place is 20°25′, which is well north of the apparent northern border of the australite strewnfield. However, the original report is hearsay unsupported by specimens and no confirmation has been forthcoming in the 60 years since the report was made (Cleverly, pers. comm.).

Australites are abundant near the South Australian–Northern Territory corner (26°00′, 129°00′), where many thousands have been collected by the aboriginals and traded through the Department of Aboriginal Affairs in South Australia. In Western Australia, just over the border west of this corner, Baker (1961a) records australites at Wingellina. We found a few near the Cavenagh Range, 60 miles to the west of Wingellina. We found none on a traverse 100 miles north from Mt. Davies towards the Rawlinson Range. Mr. R. C. Sprigg informs us that none were found during his travels in the region of the Northern Territory–Western Australia border. Our northernmost collecting locality in Western Australia was Earaheedy Station (25°40′, 121°00′). North of here the country is uninhabited for several hundred miles although most of it has been traversed during geological explorations. Mr. D. McColl of the Bureau of Mineral Resources, Canberra, has informed us that he has reports of australites north and east of Earaheedy at 24°32′, 125°03′ and 22°15′, 125°13′. If the latter is correct the known strewnfield would be extended considerably to the north. Unfortunately we have been unable to confirm this. Talbot (1910), who made an extensive geological survey along the Canning Stock Route from Wiluna to Halls Creek, records "obsidianites" near No. 14 Well and notes, "I did not see one anywhere else, although a careful look out was kept for them. One would not expect to find them among the sand ridges as they would be covered by drifting sand, but there were several areas along the stock route whose conditions were just as favorable for their preservation and exposure as in this locality." Apart from this record (which may, however, have been transported specimens) there are few australite localities north of the 25th parallel of latitude.

Distribution by man probably explains the occasional discovery of one or a few australites in regions north of the apparent border of the strewnfield. They have been reported from Wodgina (21°11′, 118°40′), but this is an old mining district and prospectors would have come from many parts of Australia and could have brought them with them. The presence of australites in gold-bearing gravels in New South Wales and Victoria gave rise to the idea of australites as being talismans in the search for gold, and many prospectors valued them as such. There are specimens in the Australian Museum collection from Halls Creek, but since this is the northern terminus of the Canning Stock Route they may have been picked up by drovers traveling the route and discarded in Halls Creek. Transport by man is also indicated by the recovery of australites in mining camps in New Zealand and California. These were undoubtedly carried by prospectors from Australia. Also, australites are attractive as crop stones for large birds such as the emu *(Dromaius novae-hollandiae)* and the bustard or plain turkey *(Eupodotis australis).* Fenner

(1949) records a plain turkey shot in South Australia which had 49 australites and two other black stones in its crop. But large birds range much less widely than man so probably do not distribute australites over long distances.

There are a number of references to the utilization by aboriginals of australites as agents of healing and magic and ceremonial objects, and also records of complete and broken specimens (some of which are definitely artefacts) in aboriginal campsites. It is therefore certain that aboriginals have transported australites. Baker (1957), Johnson (1963, 1964) and Edwards (1966) deal with the significance with which aborigines regard australites, and record occurrences in campsites in Victoria, South Australia, and in Western Australia adjacent to the Northern Territory–South Australian border. Edwards comments: "The Australian aboriginal used australites in mythology and for the manufacture of implements. The latter use appears to be of minor importance and mainly confined to areas where suitable stone materials are in short supply." Our own experience confirms this; we found aborigine-worked australites common only on the Nullarbor Plain and on Earaheedy Station, areas where the silicified rocks preferred for implements are totally lacking. In the far north of Western Australia, C. E. Dortch (Cleverly and Dortch, 1975) found six australite specimens in prehistoric rock-shelter occupation sites within the area now largely inundated by Lake Argyle in the Ord Valley. Five of these were flaked artefacts. The authors concluded that this occurrence probably resulted from long-range trade, dating to the late Pleistocene, between the prehistoric inhabitants of the Ord Valley and more southern regions where australites occur naturally. Some years ago the owner of Marion Downs, a station 35 miles south of Bouila in northwest Queensland (23°20′, 139°40′), reported that an aboriginal there had a large round australite core, chipped at the edges; he stated that he had carried it for long distances over many years and obviously treasured it. Another example of aboriginal interest in australites is afforded by the discovery of a 77.5-gram oval at Pindera, in the far northwest of New South Wales. The finder, Frank Nicholls, an experienced anthropological observer and collector of australites, stated that it was in an old aboriginal campsite on the edge of a gibber plain.

We devoted considerable time and effort to establishing a northern boundary for the strewnfield. Naturally this is a difficult task, and absolute certainty in delineating such a boundary is not to be expected. The difficulties can be seen from our discussion on the mode of occurrence of australites. Nevertheless, the map shows a remarkable dearth of localities north of latitude 25°. We have checked as many of these localities as possible and have made careful enquiries regarding australites throughout our journey in this region. If the local people, especially aboriginals, have never seen australites in their regions, it is a reasonable conclusion that they have not fallen there. On the basis of all the evidence we have been able to gather, an east-west zone along 24°–25° latitude appears to mark the northern limit of the australite strewnfield.

Australites in Relation to the Indoaustralian Strewnfield

The australites are usually grouped with the tektites found in southeast Asia, the Philippines, and Indonesia in a single strewnfield, the Indoaustralian (von Koenigswald, 1960) or Australasian (Chapman, 1964) strewnfield (Figure 7). This grouping is based not only on geography, but also on (1) chemical similarity—the range of australite compositions is duplicated by analyses of tektites from other parts of the strewnfield; and (2) similar potassium-argon ages—tektites from throughout the strewnfield give approximately the same age of 750,000–950,000 years, within margin of error.

However, there are significant differences between tektites within this vast region. The characteristic aerodynamically shaped, flanged forms of the australites are unknown in other parts of the strewnfield, except perhaps in a few specimens from central Java. Australites are much smaller than tektites from the Philippines and Indochina. They usually weigh less than 10 grams (the largest australite ever found was 437.5 grams) whereas tektites from the Philippines and Indochina may weigh more than 1 kilogram. On the basis of morphological differences von Koenigswald (1960) divided the strewnfield into three zones—northern, central, and southern—as indicated in Figure 7.

The continuity of the Indoaustralian strewnfield is not entirely convincing. Tektites appear to be

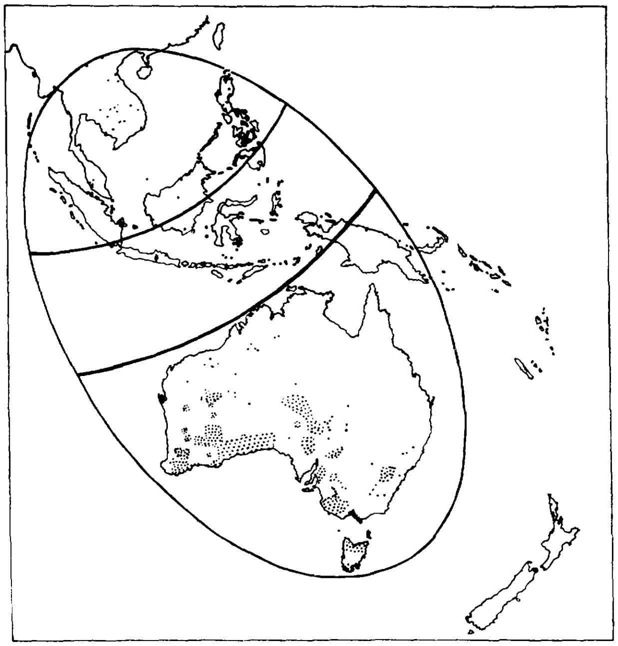

FIGURE 7.—Distribution of Indoaustralian tektites, according to Von Koenigswald (1960); our data indicate that the few occurrences shown near the northwestern crest of Australia probably represent transported specimens.

absent from the northern half of Australia, and none are known from New Guinea. In Indonesia tektites are common only in central Java and on Billiton Island; a few have been recorded from Borneo and the island of Bunguran, two from the Island of Flores, but none from Sumatra, Celebes, Timor, or the smaller islands. In the Philippines most of the tektite localities are on the island of Luzon. If the whole strewnfield was produced by a single shower, it was remarkably unevenly distributed.

The extent of the Indoaustralian strewnfield, however, is considerably increased if the microtektites discovered by Glass (1967) in thirteen deep-sea sediment cores from the Indian and western Pacific Oceans are accepted as belonging to the same event that produced the tektites. Glass (1972) summarizes his conclusions as follows:

> These glassy particles, called microtektites, represent a portion of the Australasian tektite-strewnfield as indicated by their appearance, geographical occurrence, age of deposition, age of formation (fission track age), petrography, physical properties, and chemical compositions. Present theories of tektite origin suggest that tektites were formed by impact and thus deposited over the entire strewnfield instantaneously (geologically speaking). Thus the Australasian microtektite layer provides a chronostratigraphic horizon throughout much of the Indian Ocean including the area south of Australia.

The age of this horizon, according to Glass, is 700,000 years BP, coincident with the Brunhes-Matuyama magnetic reversal. However, this age is inconsistent with the stratigraphic age of australites established by Gill (1970) and Lovering et al. (1972). Not all tektite researchers accept the identity of microtektites with tektites. Von Koenigswald (1968) and others have suggested that microtektites might be volcanic glass, and Baker (1968a) has suggested that they are beads of plant-silica glass produced by forest fires. Baker and Cappadona (1972) point out that all well-preserved australites, even the smallest, have their primary forms modified by aerodynamic ablation, whereas none of the microtektites show this feature. Microtektites have not been recorded from the Australian landmass; we searched for them in the sedimentary horizon of the Pine Dam australites, but found none.

Physical Properties and Chemical Composition

FORM

Australites are distinguished from other tektites by their variety of well-defined forms, and unique surface features produced by ablation during passage through the Earth's atmosphere. These features may be preserved in pristine perfection in specimens recovered soon after exposure in humid regions like the southwest coast of Victoria. In arid areas in the Lake Torrens–Lake Eyre region where we have collected, preservation is never so perfect, even in freshly exposed specimens which have not undergone transportation. They probably suffered some sandblasting during burial, and subsequent exposure by recent deflation has further affected them. Nevertheless, we have found some remarkably fine specimens in these areas (Figure 8). In many localities transportation subsequent to exposure has caused severe abrasion and removed all or a large part of the original surface. However, even these eroded specimens can be readily classified as to form.

Grant (1909) noted that the various shapes of australites could all be derived from the five pri-

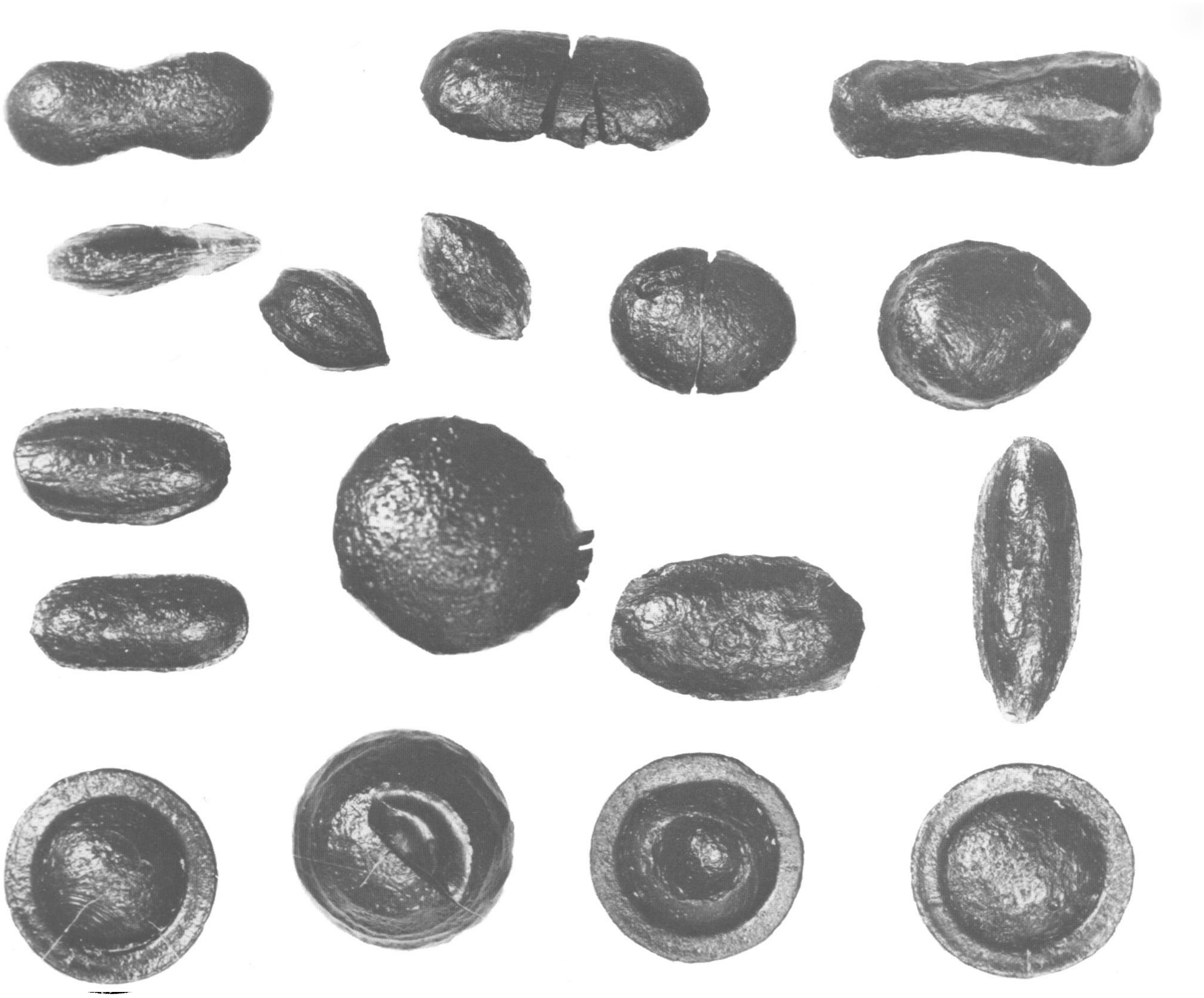

FIGURE 8.—Well-preserved australites showing a variety of forms from the Pine Dam area, South Australia; the largest button is 25 mm in diameter.

mary forms which a mass of liquid is capable of assuming. These primary forms are: (1) the sphere (possible only with no rotation); (2) the oblate spheroid (stable at low speeds of rotation); (3) the prolate spheroid (stable, if at all, only at high speeds of rotation); (4) the dumbbell (hourglass); and (5) the apioid (pear- or tear-shaped). Fenner (1938) recognized the sphere as the primary form from which the secondary round forms, cores, buttons (sometimes flanged), and lenses, were derived.

Baker (1963b) has established the three principal phases of shaping and sculpturing of tektites as primary, secondary and tertiary. The primary phase was the generation of original shapes as described by Grant (1909); the secondary phase that produced by ablational modification during passage through the Earth's atmosphere; the third phase that due to terrestrial weathering. He states that "only in the australites and perhaps a few javanites are all three phases distinctly evident. The secondary phase is so far unrecognized among other tektites. In most tektite strewnfields the tertiary phase has been especially dominant, tending to destroy the features of the other phases."

Baker (1959a, 1963b) has provided an extensive discussion of the secondary forms of australites,

TABLE 2.—Form analysis (expressed in percent unless noted otherwise) of australite collections arranged by location (1, Pindera; 2, Motpena; 3, Beltana; 4, Pine Dam; 5, Mulgaria; 6, Peachawarinna; 7, Mulka; 8, Lake Yindarlgooda; 9, Hughes; 10, Nullarbor Plain [Fenner, 1934]; 11, Charlotte Waters [Fenner, 1940]; 12, Port Campbell [Baker, 1956]; 13, Florieton [Mawson, 1958]; * = included with lenses; ** = included with ovals)

Forms	1	2	3	4	5	6	7	8	9	10	11	12	13
Buttons	20.7	19.4	18.7	27.1	28.2	5.1	19.0	1.0	18.0	13.8	13.3	46.9	1.1
Lenses	10.3	25.9	6.0	22.3	19.7	12.8	26.9	13.8	56.0	54.9	63.4	10.9	27.3
Round cores	17.2	13.7	34.6	8.3	11.3	12.8	12.7	35.7	2.0	*	*	3.8	37.5
Ovals	6.9	9.5	3.0	9.1	9.9	18.0	3.2	11.0	2.0	8.4	14.4	19.1	2.8
Oval cores	10.3	6.8	4.0	8.3	8.5	20.5	1.6	10.1	0.0	**	**	2.3	6.2
Boats	20.7	12.1	19.7	8.3	4.2	18.0	19.0	17.4	8.0	8.6	6.2	7.6	13.6
Canoes	3.5	0.5	2.0	5.8	2.8	0.0	3.2	1.0	4.0	4.1	0.2	2.3	2.1
Dumbbells	3.5	4.2	5.0	5.8	8.4	5.1	8.0	7.3	0.0	3.5	1.3	3.1	3.1
Teardrops	6.9	7.9	7.0	5.0	7.0	7.7	6.4	2.7	10.0	6.7	1.2	4.0	6.3
Correlation of Data													
Total number of whole forms	29	190	101	121	71	39	126	109	50	1993	5137	523	797
% of whole forms	67.4	42.0	47.6	39.2	34.8	55.7	49.2	83.2	40.0	50.8	72.6	37.3	54.9
Average weight (g)	4.7	3.6	5.0	3.2	2.3	3.2	2.8	5.1	0.8	0.9	6.5	2.7	3.7
% of round forms	48.2	59.0	59.3	57.7	59.2	30.7	58.6	50.5	76.0	68.7	76.5	61.6	66.0
Number of fragments	14	262	111	188	133	31	130	22	75	1927	1943	879	654
% of fragments	32.6	58.0	52.4	60.8	65.2	44.3	50.8	16.8	60.0	49.2	27.4	62.7	45.1

how they developed from the primary forms and how they have been modified by processes of erosion and abrasion after they fell. Fenner (1934) developed a comprehensive classification of australite secondary forms which has been used with minor modifications by subsequent investigators. In classifying our collections we have adopted Fenner's system with a few alterations (Table 2).

Before setting out our classification it should be mentioned that earlier investigators such as Suess, Lacroix, and others listed by Baker (1959a, pp. 149 et seq.) envisaged the secondary shapes as being derived from glass objects that were molten and viscous as they traveled through the Earth's atmosphere with a rotary motion. This is incorrect. It has been clearly shown by Baker (1959a) and Chapman (1964) that all tektites from the Indo-australian region descended through the Earth's atmosphere as rigid, nonrotating glass objects. The secondary forms of australites, particularly the unique flange, originated by the melting of surface layers by heat generated through friction during flight. The only time complete fusion of tektite glass took place was in the primary forms at the moment of formation.

The classification of forms used is as follows:

Buttons: round forms, when well preserved showing a partial or complete flange and flow ridges on the forward surface. Data on 17 well-preserved australite buttons from Motpena, South Australia, giving weights, radius of curvature and other dimensions, and nature of flow ridges are set out in Table 3, and the specimens are shown in Figure 9.

Lenses: biconvex round forms with a sharp rim. It may be difficult to distinguish a button which has completely lost its flange from a lens. Lenses are smaller than buttons because they represent a further stage of development

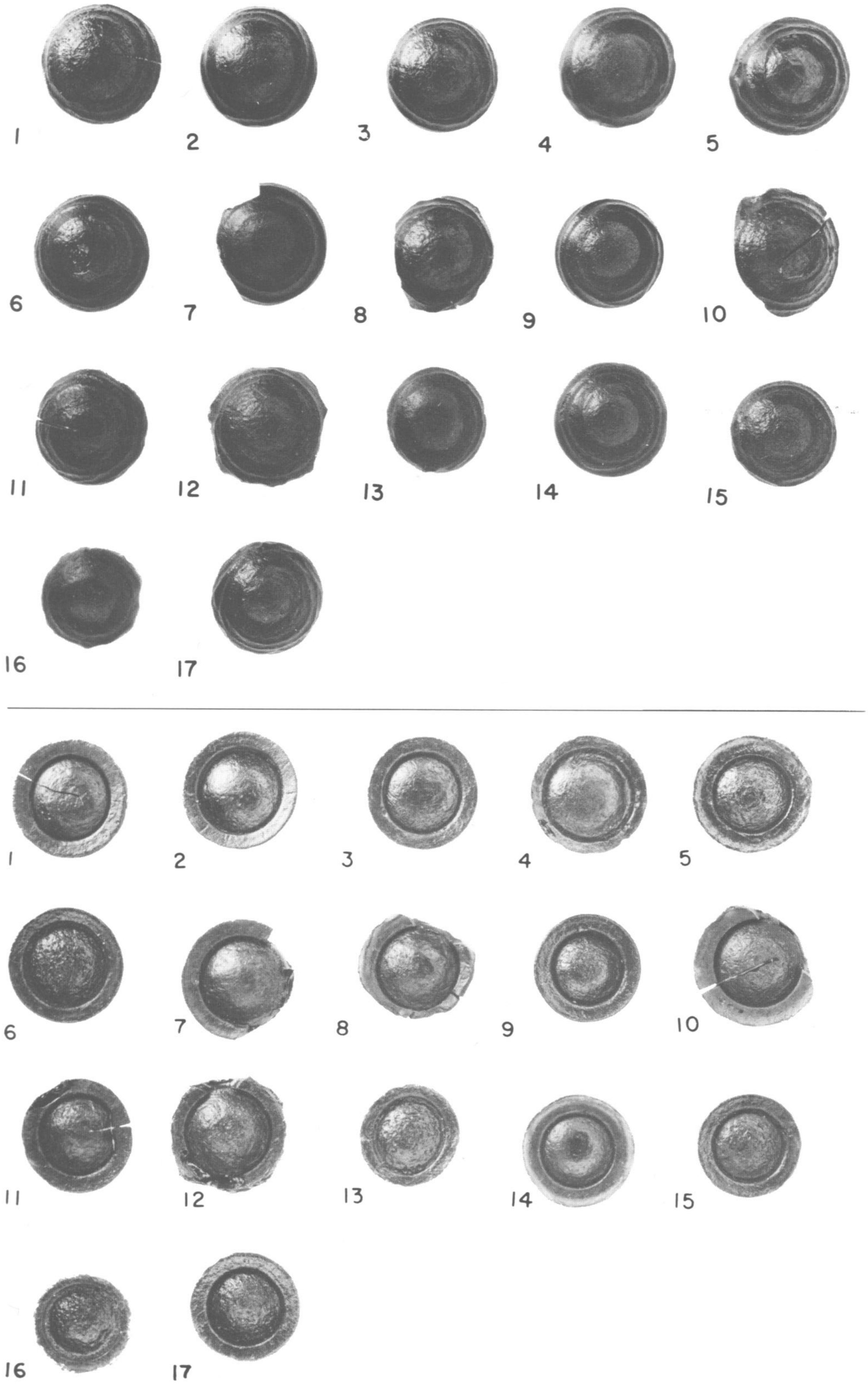

Figure 9.—Anterior and posterior views of seventeen australite buttons from Motpena, South Australia; dimensions, weights, and other data are given in Table 3.

TABLE 3.—Data on 17 well-preserved australite buttons from Motpena Station, South Australia (weights in grams; radius of curvature and other dimensions in millimeters; C = concentric; S.C. = spiral clockwise; S.A. = spiral anticlockwise)

Specimen number	Weight	Radius of curvature		Overall diameter	Diameter of core	Width of flange	Specific gravity	Nature of flow ridges
		Front face	Rear face					
1	5.482	11.2	13.8	23	16	3.2	2.449	C
2	4.853	12.0	11.4	22	17	2.5	2.455	C
3	3.918	11.6	13.2	22	16	3.2	2.455	C
4	4.155	12.0	13.6	22	18	2.1	2.471	S.C.
5	4.107	11.4	10.8	23	15	4.0	2.456	S.C.
6	4.249	12.0	11.0	22	17	2.5	2.449	C
7	4.735	11.0	10.8	23	17	3.0	2.472	S.A.
8	3.948	11.0	10.4	22	15	4.0	2.468	S.C.
9	3.975	11.0	10.2	20	15	2.5	2.477	S.A.
10	5.100	11.4	9.6	24	17	3.5	2.456	C
11	4.234	11.0	11.8	23	15	4.0	2.449	C
12	5.461	11.2	9.6	23	18	2.5	2.460	S.A.
13	2.469	11.2	10.4	20	15	2.5	2.460	S.A.
14	2.980	11.2	10.2	20	15	2.9	2.455	S.A.
15	4.322	10.6	9.6	21	15	3.0	2.445	S.C.
16	2.302	11.1	9.8	20	14	4.0	2.468	S.C.
17	3.004	11.4	9.8	22	15	3.5	2.455	S.C.
Average	4.078	11.3	10.9	22	16	3.0	2.458	
Range	3.044-	10.6-	9.6	20-	14-	2.1-	2.445-	
	5.482	12.0	13.8	24	18	4.0	2.477	
24 australalite buttons from Port Campbell (Baker, 1967b)								
Average	5.337	12.16	10.19	22.5	-	3.5	2.400	
Range	1.916-	8.48-	6.39-	16.5-	-	3.0-	2.373-	
	9.342	13.69	13.55	26		4.5	2.429	

through extreme ablation causing the complete loss of the flange during flight. There is a way in which lenses can be distinguished from flangeless buttons; Baker (1956) has introduced the term "flange band." This refers to vestiges of smooth areas that are sometimes seen at the edge of the posterior surface of round forms. Baker regards "flange bands" as representing the original surfaces of union between the body of the australite and the flange (now completely removed).

Round cores or "bungs": the term "bung" is an indefinite one and applies to large round cores. Cores are thicker and heavier than buttons and originate in two ways:

The first is the flaking away of unstable portions of equatorial regions of primary spheres in process of ablation during atmospheric flight. Baker (1956) considers that these spheres were twice as large as those that gave rise to buttons and lenses. The flaking occurred in the area of greatest frictional drag. The best of such cores shows striking markings on the equatorial zone as though caused by chipping, with no sign of weathering. In general the larger cores ("bungs") form in this way (Baker, 1959a, pl. X, and 1969a, pl. 7). The second way that cores are formed was suggested by Chapman (1964), who introduced the concept of an aerothermal stress shell. This develops during the latter stages of flight of any of the primary forms as the front face is rapidly cooled to temperatures below the strain temperature of the tektite glass. Under certain conditions depending on size, entry trajectory, and tektite composition, and aided by weathering and abrasive processes, the "shell" may partly spall off revealing the original stress profile with flange intact and the inner core-shaped mass (Figure 10 and Chapman, 1964, fig. 4). On further weathering the two parts may become completely detached. Fenner (1935) illustrates this method of formation of a core. In general, smaller cores originate in this way.

(Buttons, lenses, and round cores are derived from primary spheres.)

Ovals: similar to buttons, but oval instead of round; the australite given by Sir Thomas Mitchell to Charles Darwin is a well-preserved flanged oval (Figure 1).

Oval cores: These form in exactly the same way as round cores.

Boats: more elongate than ovals, with straight parallel sides and rounded ends.

Canoes: similar to boats, but smaller, narrower, and pointed at both ends.

Dumbbells: a self-explanatory term used by some observers even when the constriction at the "waist" is barely perceptible; derived from the primary dumbbell form.

Teardrops: a self-explanatory term. According to Chapman (1964) these shapes result when a primary mass of molten glass of very high viscosity is disrupted into many component blobs on cooling soon after initial formation. These component blobs would tend to assume the primary apioid shape. Chapman (1964) has pointed out the tear-

FIGURE 10.—Photographs illustrating the formation of round and elongate cores by spallation of the outer flanged aerothermal stress shell. The specimens are from Mt. Victory Well, Lake Torrens region, South Australia.

drop shapes are much more common in the northern region of Indoaustralian strewnfield than in Australia. Chapman, in this paper, has postulated that the temperature of formation must have become progressively lower as one proceeds from southeast Australia, through southwest Australia, to the northwestern, i.e., the Indomalaysian, region of the strewnfield. Under the heading of teardrops Baker (1959a, 1963b) includes forms such as pear shapes, stopper shapes and aerial bombs.

(All of the above forms, excepting cores of all shapes, and lenses, may have flanges, although cores may show "flange stumps," the very last remnants of a complete flange.)

Bowl-, disc-, and plate-forms: These are very small, thin, and fragile forms (Baker, 1963a) and are so rare that we do not regard them as statistically significant. They are not included in Table 2 (*Form analyses of australite collections*). Data on small fragile forms collected by us are given in Table 4 and the specimens are shown in Figure 11. These may be the very last remnants of almost completely ablated australites that entered the atmosphere as smaller than average-sized primary spheres (Baker 1958). Baker (1940) has also suggested that these fragile forms may have originated as the flakes detached, through frictional drag in the equatorial zones, from large round and elongate primary forms. Baker suggests that these flakes

TABLE 4.—Data on 20 small australites from the Pine Dam area (weight in grams; dimensions in millimeters)

Specimen Number	Type	Weight	Specific Gravity	Length	Width	Depth
1.....	oval bowl	0.0408	2.403	6	5	2
2.....	round bowl	0.0675	2.431	6	6	2
3.....	oval bowl	0.0896	2.449	8	5	3
4.....	elongate bowl	0.0997	2.449	9	4	2
5.....	lens	0.1186	2.460	7	7	2
6.....	oval bowl (chipped)	0.1315	2.450	9	7	2
7.....	oval bowl	0.1344	2.449	9	7	3
8.....	lens	0.1373	2.439	7	5	3
9.....	oval bowl (infolded)	0.1382	2.448	9	5	4
10.....	canoe	0.1397	2.468	11	5	2
11.....	round bowl	0.1436	2.465	6	6	2
12.....	flanged button	0.1496	2.458	9	9	2
13.....	canoe	0.1501	2.455	14	5	2
14.....	teardrop	0.1536	2.447	11	7	2
15.....	teardrop	0.1920	2.469	10	6	3
16.....	lens	0.2285	2.439	8	8	3
17.....	flanged oval	0.2486	2.459	11	9	2
18.....	flanged button (chipped)	0.2512	2.458	13	13	2
19.....	teardrop	0.2858	2.461	11	7	4
20.....	lens	0.3265	2.460	10	8	4

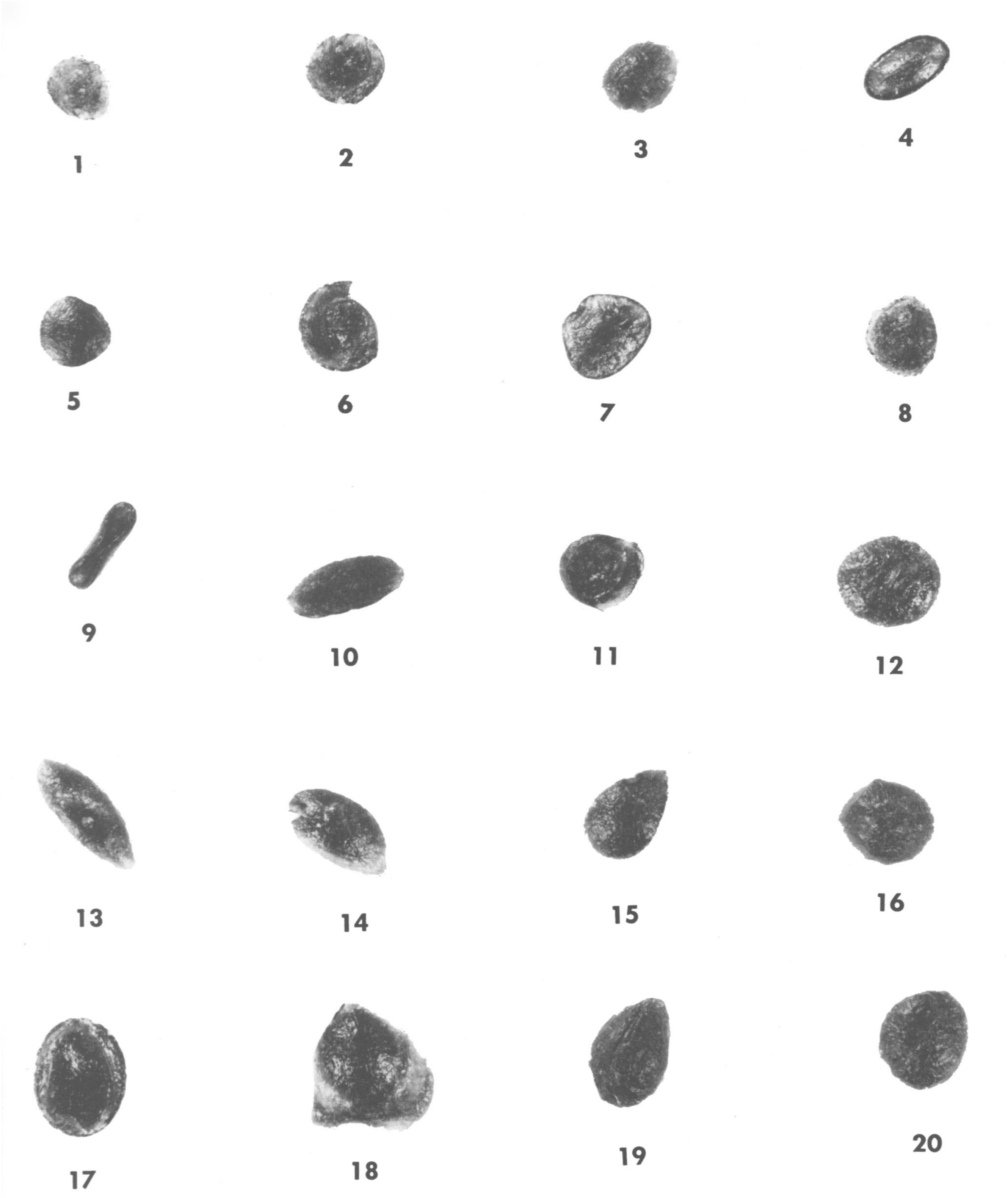

FIGURE 11.—Twenty bowl-, disc-, and plate-form australites from the Pine Dam area, South Australia; dimensions, weights, and specific gravities are given in Table 4.

may still have been travelling with sufficient velocity to have suffered further ablation and thus have assumed regular shapes.

All complete collections such as those made by us in different areas and by Baker in southwestern Victoria contain many fragments, usually exceeding in number the well-preserved complete forms. There was a lack of fragments in some large collections made in earlier periods. Untrained personnel collecting australites would tend to concentrate on well-preserved, relatively large forms, rather than these smaller examples.

Fragmentation occurred after the australites landed on the ground. Australite glass is quite tough and the force of impact would have been quite gentle, since they would have lost their initial high velocity and would be falling under the influence of gravity. Even on hard ground it is unlikely that impact would have caused fracturing. The aerothermal stress shell and other stresses result from the australite being in a state of strain. Such factors as the extreme diurnal temperature variations in semi-arid interior Australia, and the abrasive action of wind-blown sand, and water in times of infrequent but nonetheless violent flash floods, would cause splitting and spalling along lines of weakness created by the stresses.

Pronounced channel-like lines of parting extending deep into many australites are known as "saw-cuts" and in all collections there are many examples of complete forms on the verge of breaking up into numerous fragments due to pronounced development of this feature (Figure 12). Fenner (1934) first suggested the term "saw-cuts" so that no possible implication as to their origin would be conveyed. Baker (1959a) considers that they often form along flow-line structures and most likely represent lines of easiest etching.

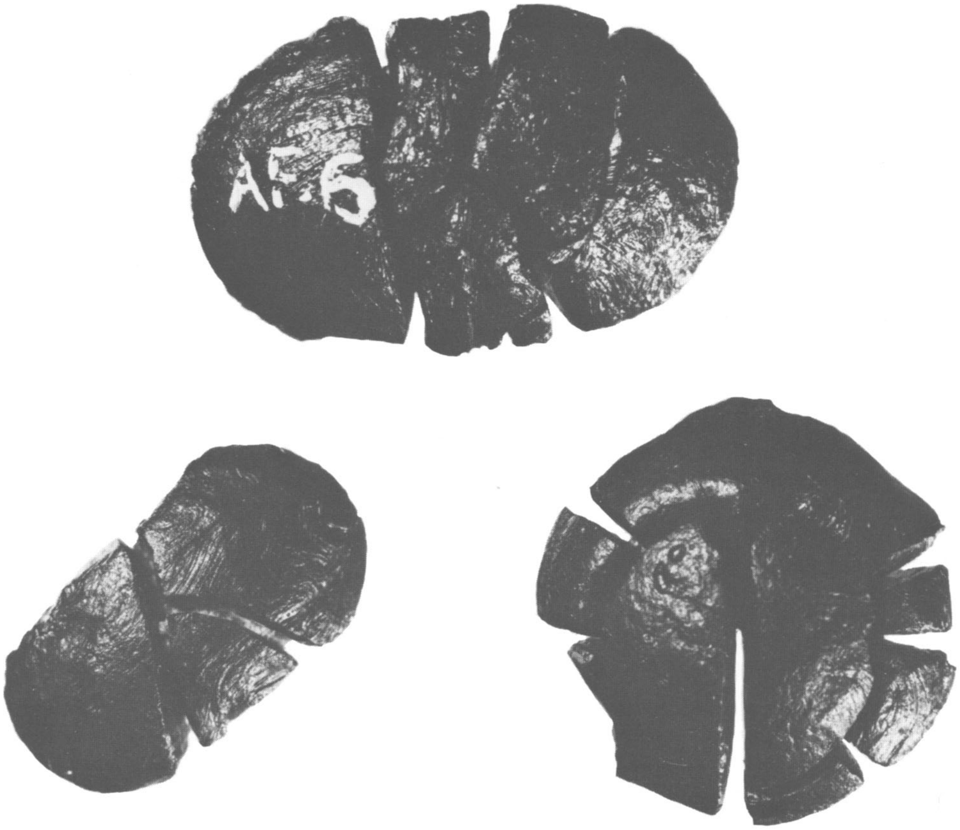

FIGURE 12.—Australites showing "saw-cuts"; the largest specimen (25 mm long) is from Mulgaria, the other two from near Beltana, in the Lake Torrens region of South Australia.

FORM ANALYSIS

For those of our collections which were numerous enough to be statistically significant we analyzed the form distribution. The results are summarized in Table 2, along with comparable data from other investigators. Round types (buttons, lenses, and round cores) predominate in all the collections analyzed. This substantiates the findings of Chapman (1964) who, as already mentioned, noted this fact in contrast to the predominance of teardrop shapes toward the northwest of the entire Indoaustralian strewnfield. Round types in collections from the Lake Torrens localities and Mulka range from 57.7% to 59.3%; percentages for Pindera and Peachawarinna, respectively, are 48.2% and 30.7%. The latter two collections are probably too small for this statistical analysis. The figures for Port Campbell deserve comment. There is a high 61.6% for total round forms, which comprise a high 46.9% of buttons and a low 10.9% for lenses and 3.8% for round cores. These figures, particularly the high percentage of buttons, may reflect the excellent state of preservation in this region or the close and meticulous examination carried out by Baker (1956) who, for example, distinguishes buttons from lenses and small round cores by the presence of "flange bands," a feature that might escape investigators of collections from other localities. As one would expect, high percentages of round cores ("bungs"), the larger forms, are present in collections with high average weight (Beltana, Lake Yindarlgooda, and Charlotte Waters).

It is particularly interesting to note the close correspondence between the form analyses of the Hughes and Nullarbor Plain collections. Hughes is on the Nullarbor Plain, and we made the collection in 1965; the Nullarbor Plain collection described by Fenner (1934) was made by Mr. W. H. C. Shaw, an officer of the Commonwealth Post and Telegraph Department stationed in this area in the period 1910–1930.* The distribution of forms is similar and the average weight is essentially identical. This confirms the small size of australites on the Nullarbor Plain compared to those of other regions. Of the elongate forms, ovals and boats are fairly common, whereas dumbbells, teardrops and canoes are present in lesser numbers. Canoes are smaller and more fragile than the other forms and therefore are destroyed more readily by natural forces.

WEIGHT

The high average weight of the forms from Lake Yindarlgooda, Charlotte Waters, the hitherto unmentioned Mt. Davies area, and Beltana is due to an unusually high percentage of round cores. From the Lake Yindarlgooda collection this may result from geological conditions. There the australites are washed on to the lake floor from lag gravels on higher ground and transportation has probably destroyed many of the smaller forms. The same may apply to the Mt. Davies area in the far northwest of South Australia, which is an area of high relief. We have inspected a large collection (about 2,000) obtained by the South Australian Department of Aboriginal Affairs from aborigines in this area. These are notably large and average about the same as those from Charlotte Waters. The Charlotte Waters collection examined by Fenner (1940) was made by John W. Kennett when he was in charge of the police station there, and many of the specimens were collected by aboriginals. Unfortunately there is no detailed description of the occurrence of australites in this locality. As noted in Table 2 australites from the Beltana area are larger than usual (average weight 5 grams). There is a concentration of large specimens on the eroded surface of the Motpena paleosol. The large round core (33.3 grams) and the large dumbbell (16.1 grams) listed in Table 5 came from here. When one compares the weights of different forms (Table 5) some interesting features are seen. The largest specimens, as might be expected, are the cores. The 36-gram oval core from Lake Yindarlgooda is the largest specimen we have ever found. Australites weighing more than 60 grams are quite rare. A list of those known to us (numbering 121) is given in Table 6, and their distribution shown in Figure 13. Data from Fenner (1955), Baker (1969a and 1972), and Cleverly (1974) are incorporated in this table. Figure 13 further confirms the evidence of Cleverly (based on australites of mass greater than

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*Fenner (1934) quotes Shaw as stating that the majority of these tektites were found in the vicinity of Israelite Bay, near the western margin of the Nullarbor Plain.

TABLE 5.—Maximum and minimum weights in grams for all australites collected, arranged by form

Form	Maximum	Minimum
Buttons	5.7	0.5
Lenses	4.6	0.1
Round cores	33.3	1.0
Ovals	13.4	0.7
Oval cores	36.0	1.5
Boats	16.9	0.9
Dumbbells	16.1	0.5
Teardrops	9.4	0.7
Canoes	1.5	0.5

100 grams) of a remarkable concentration of large australites in the southwestern corner of Western Australia, extending as a belt towards the north-northeast. A minor concentration of large australites is evident in western Victoria, extending northwest to Finke in the Northern Territory (although no australites weighing more than 40 grams are known to us from the central part of this streak in the Lake Torrens region). Cleverly (1974) interpreted the distribution of large australites as indicating a concentration in areas distant from the northern boundary of the strewnfield, suggesting the possibility of a mass gradient away from this boundary. Cleverly considers this to imply a direction of flight southwards from the northern boundary of the strewnfield, at variance with the conclusion of Chapman (1971), who deduced a generally south-north direction for australite flight paths.

The large australites whose locations are plotted in Figure 13 define two linear belts which intersect at approximately 19°S,129°E. This is a remote area about 100 miles southeast of Halls Creek. The Halls Creek 1:1 million map sheet shows an oval ring of hills with a major east-west axis about 30 miles long in this area; geological maps show a rim of upturned Proterozoic quartzites surrounding a core of highly disturbed Archean rocks, suggesting an impact structure. The significance, if any, of this feature to the australite problem remains to be investigated.

The fragile disc-, plate-, and bowl-shaped forms have been described in detail and illustrated by Baker (1963a, 1964b) from the Port Campbell region. The smallest one was an oval shallow bowl weighing 0.065 grams. Baker and Cappadona (1972) have described the smallest complete australite ever found. It is from 6 miles north-northeast

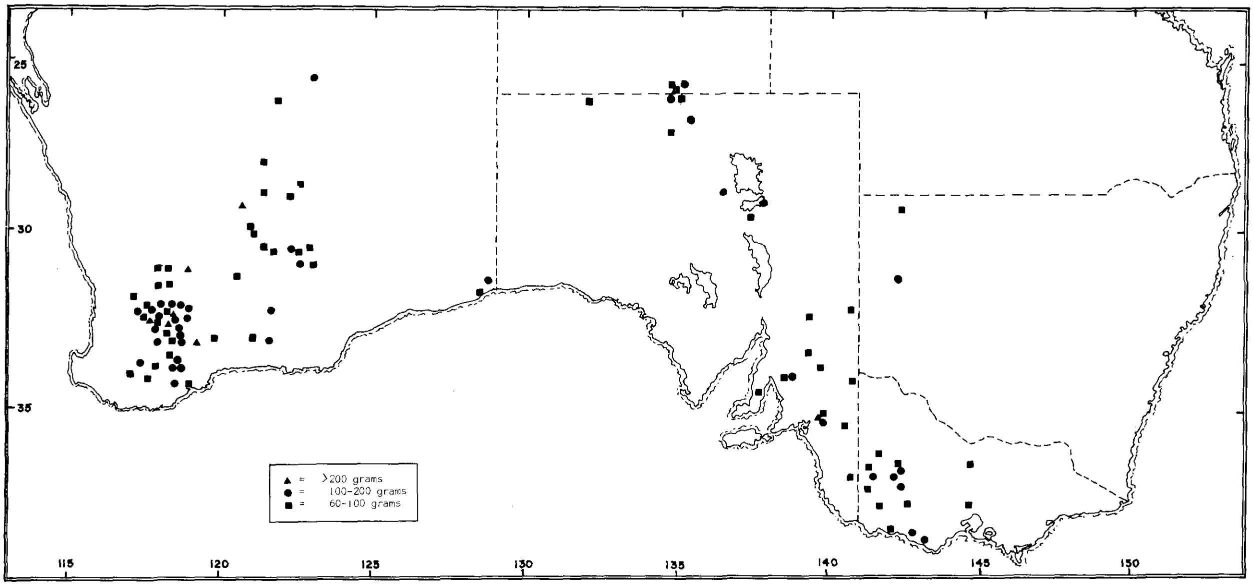

FIGURE 13.—Geographical distribution of large australites listed in Table 6.

TABLE 6.—Weight, form, and present location of large australites (over 60 grams), listed in order of decreasing weight (AM = Australian Museum, Sydney; BM = British Museum (Natural History), London; BMR = Bureau of Mineral Resources, Canberra; GCLWA = Government Chemical Laboratories of Western Australia, Perth; GMM = Geological and Mining Museum, Sydney; GSWA = Geological Survey of Western Australia, Perth; NMV = National Museum of Victoria, Melbourne; SAM = South Australian Museum, Adelaide; WAM = Western Australian Museum, Perth; WASM = Western Australian School of Mines, Kalgoorlie; UA = University of Adelaide, Department of Geology; UM = University of Melbourne, Department of Geology: references without a date are personal communications; WHC = W. H. Cleverly; WHC & JMS = W. H. Cleverly & J. M. Scrymgour)

Locality	Coordinates	Weight (grams)	Core shape	Where preserved	Reference
Notting, W.A.	32°27', 118°14'	437.5	broad oval	WAM 13238 (cast)	Cleverly, 1974
Newdegate, W.A.	33°06', 119°02'	243.1	round	WAM 12318	"
near Warralakin, W.A.	31°08', 118°41'	238.0	broad oval	WASM 8925	"
near Kondinin, W.A.	32°30', 118°07'	233.9	broad oval	H. Biggin	"
Lake Yealering, W.A.	32°36', 117°37'	218.6	round	WAM 4455	"
Karoonda, S.A.	35°09', 139°54'	207.9	narrow oval	SAM T1159	Fenner, 1955
Lake Ballard, W.A.	29°21', 120°36'	200.3	broad oval	L.P. Berryman	Cleverly, 1974
near Babakin, W.A.	32°10', 118°06'	197.2	round	WAM 13364	WHC
Narrogin or Narembeen, W.A.	- - - -	194.8	broad oval	WAM 12992	Cleverly, 1974
near Notting, W.A.	32°27', 118°05'	194.4	round	WAM 12884	"
near Ongerup, W.A.	33°48', 118°28'	184.1	round	WAM 12293	"
Cuballing, W.A.	32°49', 117°11'	176.0	dumbbell	GSWA R2024	"
near Toolondo, Vic.	36°58', 142°05'	173.6	boat	NMV E4753	Baker, 1972
Graball, W.A.	32°02', 118°34'	168.3	round	WAM 12843	Cleverly, 1974
Corrigin, W.A.	32°22', 117°54'	168.0	round	GCLWA 1678	"
near Chillilup, W.A.	34°29', 118°25'	167.3	round	WAM 13237 (cast)	"
Western Victoria or Teetulpa, S.A.	- -	154.0	round	K. Blackham	WHC
between Narrogin and Merredin, W.A.	- -	152.0	round	WAM G8978	Cleverly, 1974
near Ongerup, W.A.	33°52', 118°21'	151.3	dumbbell	GSWA	"
near Charlotte Waters	26°10', 134°50'	149.3	round	G. Latz	WHC & JMS
near Corrigin, W.A.	32°21', 117°52'	147.0	round	WAM 3491	Cleverly, 1974
near Eucla, W.A.	31°40', 128°51'	142.0	round	lost	Fenner, 1934
Port Campbell, Vic.	38°37', 143°02'	141.6	boat	NMV 11402	Baker, 1969a
near Balaklava, S.A.	34°02', 138°20'	141.0	broad oval (frag.)	SAM G1391	WHC & JMS
near Goroke, Vic.	36°45', 141°36'	135.1	oval	NMV 11401	Baker, 1969a
Lake Grace, W.A.	33°06', 118°28'	134.5	round	AM DR 7533	Cleverly, 1974
Lake Grace, W.A.	33°06', 118°28'	132.7	round	AM Clarke	WHC
near Kulin, W.A.	32°40', 118°26'	131.5	narrow oval	WAM 12264	Cleverly, 1974

TABLE 6.—Continued

Locality	Coordinates	Weight (grams)	Core shape	Where preserved	Reference
Penwortham, S.A.	33°55', 138°38'	132.0	round	L. French	WHC & JMS
Kulgarin, W.A.	32°30', 118°42'	126.8	broad oval	R. Pugh	Cleverly, 1974
Hamilton Station, S.A.	26°40', 135°05'	121.2	broad oval	SAM T1392	WHC & JMS
Koralta Station, NSW	31°27', 142°18'	118.0	round	BMR R18277	WHC & JMS
Wickepin East, W.A.	32°45', 117°44'	116.9	broad oval	F. Davis	Cleverly, 1974
Lake Buchanan, W.A.	25°30', 123°00'	116.1	round	WAM 12960	"
Lower Norton, Vic.	36°47', 142°04'	115.9	round	NMV E2730	Baker, 1969a
Laing, Vic.	38°22', 142°49'	115.8	dumbbell	A. Halford	"
Narembeen, W.A.	32°04', 118°23'	114.6	broad oval	GSWA 1/5327	Cleverly, 1974
Babakin, W.A.	32°07', 118°01'	113.1	broad oval	SAM T191	"
near Karoonda, S.A.	35°04', 139°57'	113.0	round	- -	Fenner, 1955
Lake Wallace, Vic.	37°02', 141°18'	111.3	round	NMV E1986	Baker, 1969a
Moulyinning, W.A.	33°14', 117°56'	111.2	round	WAM 10613	Cleverly, 1974
Norseman, W.A.	32°12', 121°47'	110.6	round	SAM T427	"
Central Australia	- -	110.1	boat	GMM 17408	WHC & JMS
Brookton, W.A.	32°22', 117°02'	109.8	round	WAM 12090	Cleverly, 1974
E. Goldfields, W.A.	- -	108.3	round	WASM 10199	"
Narembeen, W.A.	32°04', 118°50'	107.5	narrow oval	WASM 8950	"
Charlotte Waters, N.T.	25°55', 134°55'	103.0	round	?	WHC & JMS
Salmon Gums, W.A.	33°03', 121°44'	102.4	round	WASM 9421	Cleverly, 1974
near Kurnalpi, W.A.	30°28', 122°09'	101.1	broad oval	C.B. Jones	"
Karonie, W.A.	30°59', 122°39'	100.8	broad oval	SAM T509	"
William Creek, S.A.	28°55', 136°21'	100.7	broad oval (frag.)	G. Hume	WHC & JMS
Muloorina, S.A.	29°10', 137°51'	99.6	oval	SAM T1287	D.W.P. Corbett
near Kalgoorlie, W.A.	30°49', 121°29'	98.1	-	BM 1916, 372	J. Hall
Nullarbor Plain	- -	98.0	oval	SAM T520	Fenner, 1955
Rosanna, Vic.	37°45', 144°58'	97.1	dumbbell	NMV 11365	A.W. Beasley
Lowaldie, S.A.	35°04', 139°59'	96.0	dumbbell	SAM T1296	D.W.P. Corbett
Kulin, W.A.	32°42', 118°08'	95.7	round	WAM 12316	D. Merrilees
Kaniva, Vic.	36°33', 141°17'	95.9	boat	UM 3045	Baker, 1959a
Lake King, W.A.	33°05', 119°33'	95.7	round	A.J. Thompson	WHC

TABLE 6.—Continued

Locality	Coordinates		Weight (grams)	Core shape	Where preserved	Reference
Warrnambool, Vic.	38°23',	142°03'	94.0	dumbbell	SAM T1158	Fenner, 1955
Edjudina Station, W.A.	29°	122°	92.6	round	I.R. Williams	WHC
Horsham, Vic.	36°45',	142°15'	90.8	round	NMV 5204	Baker, 1961c
Wellington, S.A.	-	-	90.5	- -	BM 1935, 252	J. Hall
Hexham Station, Vic.	-	-	90.3	- -	BM 1926, 393	"
Charlotte Waters, N.T.	25°55',	134°55'	90.0	- -	G. Hume	D. H. McColl
near Cockburn, S.A.	32°10',	140°58'	89.8	oval	D.H. McColl	"
near Edenhope, Vic.	37°04',	141°20'	89.6	round	NMV 16869	A.W. Beasley
Todmorden, S.A.	27°04',	134°49'	89.0	dumbbell	SAM T638	Fenner, 1955
Victoria	-	-	88.9	- -	BM 1927, 1167	J. Hall
Finniss Springs, S.A.	29°35',	137°28'	88.8	boat	SAM T579	Fenner, 1955
Corop, Vic.	36°28',	144°48'	88.5	boat	UM 3046	Baker, 1959a
Jubuk, W.A.	32°20',	117°38'	86.8	broad oval	WAM G7566	Cleverly, 1974
Baandee, W.A.	31°35',	117°58'	86.7	round	WAM 12176	"
near Corrigin, W.A.	32°	117°	85.7	round	N. Rendall	WHC
Lorquon, Vic.	36°10',	141°45'	83.7	boat	NMV E336	A.W. Beasley
near Renmark, S.A.	34°10',	140°45'	83.5	teardrop	SAM T91	Fenner, 1955
E. Goldfields, W.A.	-	-	83.4	round	WASM 10306	W.H. Cleverly
Ernabella area, S.A.	26°	132°	80.0	oval	C. Collyer	D.H. McColl
near Corrigin, W.A.	32°	117°	79.5	round	N. Rendall	WHC
Laverton, W.A.	28°49',	122°25'	78.1	oval	WAM 12167	D. Merrilees
Diamantina R., S.A.	-	-	78.0	teardrop	SAM T92	Fenner, 1955
Pindera N.S.W.	29°27',	142°29'	77.5	oval	F. Nicholls	R.O. Chalmers
Cheyne Beach, W.A.	34°21',	118°57'	76.7	round	WAM 12972	D. Merrilees
Leonora, W.A.	28°54',	121°20'	75.3	round	SAM T508	D.W.P. Corbett
near Muntagin, W.A.	31°	118°	75.1	round	WASM 10545	WHC
near Merredin, W.A.	31°31',	118°07'	75.0	round	WAM 12935	D. Merilees
Frances, S.A.	36°41',	140°59'	74.5	round	SAM T28	D.W.P. Corbett
near Boorabbin, W.A.	31°14',	120°21'	74.5	- -	M. Alexander	WHC
Maroona, Vic.	37°25',	142°52'	74.3	boat	NMV E1270	A.W. Beasley
Wongawol, W.A.	26°07',	121°56'	74.2	teardrop	WAM ESS22	Cleverly, 1974
Nungarin, W.A.	31°11',	118°06'	73.6	round	WAM 12145	D. Merilees

TABLE 6.—Continued

Locality	Coordinates	Weight (grams)	Core shape	Where preserved	Reference
Wooganellup, W.A.	34° 117°	73.1	round	WAM ESS 86	WHC
Nullarbor Plain ?	- -	72.5	oval	SAM T1077	D.W.P. Corbett
near Morgan, S.A.	33°50', 139°50'	72.3	oval	NMV E3965	Baker, 1968b
Merino, Vic.	37°45', 141°35'	71.8	dumbbell	NMV E1236	A.W. Beasley
Kurnalpi, W.A.	30°32', 122°14'	71.3	round	WASM 2215	W.A. Cleverly
Mount Barker, W.A.	34°36', 117°37'	70.7	round	WAM 10643	D. Merrilees
Lake Yindarlgooda, W.A.	30°38', 121°57'	69.5	-	CBC Jones	WHC
Nyabing, W.A.	33°31', 118°10'	69.1	round	WAM 12885	D. Merrilees
Crown Point, N.T.	25°40', 134°40'	68.7	boat	SAM T129	Fenner, 1955
Gindalbie, W.A.	30° 121°	68.2	-	R.L. Jones	WHC
Coonana, W.A.	31° 123°	67.6	-	CBC Jones	WHC
near Narembeen, W.A.	32°33', 118°13'	66.7	dumbbell	WAM 12321	D. Merrilees
near Esperance, W.A.	33° 121°	66.2	-	WAM ESS 1	WHC
near Lameroo, S.A.	35°28', 140°26'	66.0	oval	R.G. Kimber	D.H. McColl
near Yunta, S.A.	32°21', 139°20'	65.0	round	UA 18361 (missing)	"
near Kalgoorlie, W.A.	30° 121°	64.9	round	UA 18357	"
Kalgoorlie, W.A.	30°49', 121°29'	64.7	boat	SAM T547	D.W.P. Corbett
near Maitland, S.A.	34°26', 137°40'	64.3	dumbbell	G. Young	D.H. McColl
near Boorabbin, W.A.	31° 120°	64.1	-	WAM 12802	WHC
near Florieton, S.A.	33°49', 139°25'	63.6	oval	UA	D.H. McColl
Lake Grace, W.A.	33°06', 118°23'	63.5	round	WAM 10549	D. Merrilees
Balaklava, S.A.	34°08', 138°24'	63.0	round	SAM T128	D.W.P. Corbett
near Agnew, W.A.	28°00', 121°10'	62.9	boat	WAM 12110	D. Merrilees
Charlotte Waters, N.T.	25°55', 134°55'	62.5	oval	SAM T232	D.W.P. Corbett
Balaklava, S.A.	34°08', 138°24'	62.2	round (frag.)	SAM	D.H. McColl
Central Australia	- -	62.0	round	SAM T1070	D.W.P. Corbett
Eucla, W.A.	31°40', 128°51	62.0	boat	SAM T332	"
Bullaring, W.A.	32°30', 117°44'	61.0	round	WAM 10671	D. Merrilees
Babakin, W.A.	32°11', 117°58'	60.8	round	WAM 12942	"
near Gnowangerup, W.A.	33°52', 117°53'	60.6	round	WAM 12163	"

of Princetown on the south coast of Victoria. It is an oval bowl and weighs 0.025 grams. Since these forms are extremely fragile few survive lengthy exposure to the elements, but we have collected some in the Lake Torrens region at Mulgaria, Mt. Victory Well, and Pine Dam. A few have been found in the Lake Eyre region at Peachawarinna. A particularly productive spot was a small area in one of the claypans near Pine Dam. We were somewhat puzzled by a remarkable concentration of small australites and australite fragments over a limited area near the middle of the pan. We noted that this area was a few inches higher than the surrounding pan floor, but the significance was not realized until later, when during laboratory experiments it was found that these thin fragile forms actually float in water because of the surface tension. Occasional rains flooding the pans with a few inches of water presumably concentrated these fragile forms by floating them on to the dry areas slightly higher than the rest of the pan floor. The smallest was an oval bowl weighing 0.0408 grams and the largest was a lens weighing 0.3265 grams. In Table 4 the weights and dimensions of twenty of these fragile forms from this area are listed, and they are illustrated in Figure 11. In these fragile forms the central core is always much reduced in volume relative to the secondarily developed circumferential flange.

Specific Gravity

Summers (1913), on the basis of rather sparse data, recognized a significant regional trend in the specific gravities of australites. He wrote:

> I have stated elsewhere that there seemed to be a somewhat provincial distribution of the australites in respect to composition and specific gravity. As one would naturally expect, the specific gravity of a specimen, except where modified by the occurrence of occluded vesicles, gives a good indication of the composition of the australite. My present impression is that the less acid forms are concentrated along the borders of the belt and that the acid ones are commoner along the central line running from Melbourne towards the Lake Eyre district.

This prescient suggestion apparently fell into limbo. Some thirty years later, Baker and Forster (1943) published an extensive study of the specific gravities of 1,086 australites. From their results they decided that the specific gravity values show a definite gradient from east to west. They wrote: "In graph 19, the silica percentage in australites is seen to be highest in those forms with the lower specific gravities. From this, and the specific gravity values set out in Table 5, it is concluded that less acid forms occurring in the western portions of Australia give way to more acid varieties in the eastern parts of the australite strewnfield." And in a later section they used their data to deduce the manner of formation of the strewnfield: "Since the specific gravities of australites show a significant decrease from north of west to south of east across Australia, the extraterrestrial body from which the australites were shed traversed the island continent from north of west to south of east." However, despite these categorical statements, it now appears that Summers' suggestion of a central low-density belt is more nearly correct, and this has been confirmed by McColl and Williams (1970).

Figure 14 presents the specific gravity distribution recorded by Baker and Forster. They found specific gravities varying from 2.30 to 2.50, with most of the values (94.5%) occurring between 2.36 and 2.47. The values show a single sharp peak at 2.40. Later work has shown that these data present a distorted picture of specific gravity distribution over the whole strewnfield, since the great majority of the specimens they measured came from the belt of low specific gravity extending from western Victoria through eastern South Australia to Lake Eyre and beyond. Chapman et al. (1964) measured specific gravities of large numbers of specimens from individual localities in Australia, and their results are summarized in Table 7, along with data for our collections, and those for some of the larger localized collections measured by Baker, and Baker and Forster. (For the latter the figure in the "Peaks" column is the mean value because they did not plot the individual data.)

The data in Table 7 show that the specific gravity range at any one locality is not particularly distinctive, but the specific gravity distribution, as established by the peak or peaks, is. Three distinctive geographical groupings appear (Figure 3):

1. A single peak at 2.45–2.47, which characterizes all the Western Australian localities, plus their extension on the Nullarbor Plain into South Australia, and at Lake Wilson in the extreme northwest of South Australia; this peak also characterizes collections from northeast South Australia

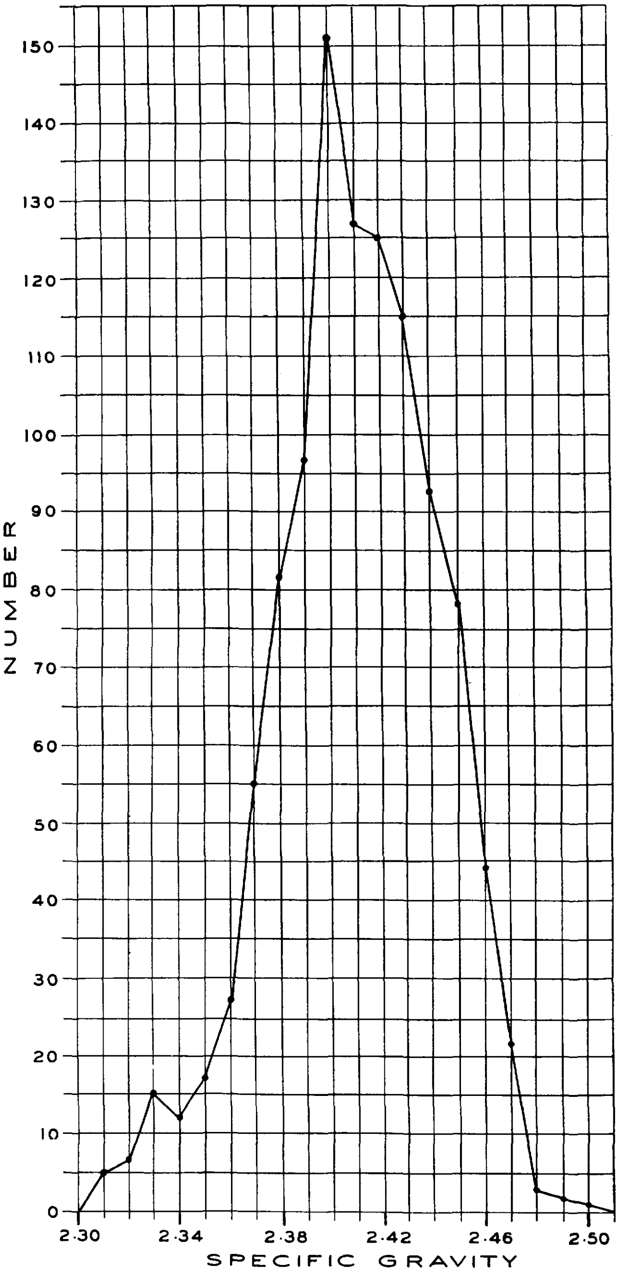

FIGURE 14.—Specific gravity distribution for 1086 australites from different parts of Australia (Baker and Forster, 1943).

and adjoining localities in Queensland and New South Wales.

2. A single peak at 2.40–2.42, characteristic of Port Campbell and other localities in western Victoria; similar populations are present in southeastern South Australia (e.g., Oakvale, Morgan, Mannahill).

3. Two peaks, one at 2.40–2.41 and one at 2.45–2.46, characteristic of localities in the Lake Torrens–Lake Eyre region. This region of two-component populations does not seem to extend north beyond Macumba to Charlotte Waters, nor northeast beyond Cooper Creek to Mulka and Mungeranie. The 2.40 peak is not present in the Motpena collection, although this belongs geographically with the other localities in the Lake Torrens area.

The simplest explanation of this geographical distribution is clearly the early suggestion of Summers that a band of tektites of low specific gravity extends from western Victoria to the Lake Eyre district, this band being apparently superimposed on a widely distributed population of significantly higher specific gravity. The two-population nature of the australites from the Lake Torrens–Lake Eyre region is well shown in the specific gravity distribution plot for 761 australites which we collected in this region in 1964 (Figure 15). We are indebted to Dr. Dean Chapman for the specific gravity determinations incorporated in this plot.

It is difficult to obtain meaningful data for the northeastern part of the strewnfield, comprising localities in eastern New South Wales and southeastern Queensland. Our searches in these regions have been unproductive, and specimens are rare in collections. However, Chapman and Scheiber (1969) analyzed two specimens from Liverpool and Uralla, in eastern New South Wales; these have high specific gravities (2.489, 2.482) and low SiO_2 contents (66.9%, 68.1%).

REFRACTIVE INDEX

Numerous measurements of the refractive index of australites have been reported in the literature, and we have made several during the course of this investigation. Within any australite some variability of refractive index is usually found; this variability can readily be detected in thin sections (Figure 16), which show complex flow patterns marked by schlieren with slightly differing refractive indices. The variability within a single australite can be of the order of 0.003; however, in making refractive index determinations by the im-

TABLE 7.—Specific gravities and peak(s) for localized collections of australites (* = mean value, not peak)

Locality	Number of Specimens	Specific Gravity Range	Peak(s)	Reference
Granite Peak	46	2.402-2.458	2.452	Mason, unpublished
Earaheedy	85	2.420-2.459	2.453	"
Kalgoorlie area	420	2.385-2.485	2.455	Chapman et al., 1964
Nullarbor Plain	634	2.390-2.475	2.445	"
Hughes	240	2.413-2.476	2.459	Mason, unpublished
Ooldea	56	2.428-2.475	2.457	"
Wingellina	135	2.391-2.491	2.470	Baker, 1961a
Lake Wilson	986	2.395-2.505	2.465	Chapman et al., 1964
"	28	2.415-2.498	2.475	Mason, unpublished
Charlotte Waters	420	2.385-2.495	2.445	Chapman et al., 1964
"	29	2.392-2.484	2.439*	Baker and Forster, 1943
Macumba	19	2.380-2.466	2.395, 2.440	Mason, unpublished
William Creek	96	2.367-2.472	2.426*	Baker and Forster, 1943
Mulka	259	2.355-2.485	2.435	Chapman et al., 1964
"	275	2.365-2.557	2.440	Baker, 1969b
"	99	2.398-2.465	2.440	Mason, unpublished
Mungeranie	38	2.402-2.481	2.445	"
Peachawarinna	45	2.380-2.468	2.408, 2.453	"
Mulgaria	87	2.376-2.474	2.401, 2.458	"
Pine Dam	75	2.368-2.476	2.395, 2.462	"
Beltana	67	2.388-2.470	2.405, 2.445	"
Motpena	123	2,395-2.481	2.445	"
Mannahill	97	2.370-2.459	2.419	"
Oakvale	31	2.386-2.450	2.409	"
Morgan	148	2.348-2.437	2.405*	Baker, 1968b
Port Campbell	78	2.355-2.465	2.405	Chapman et al., 1964
"	555	2.305-2.465	2.397*	Baker and Forster, 1943
Pindera	155	2.270-2.470	2.450	Chapman, unpublished
Durrie	99	2.385-2.487	2.440	Mason, unpublished
Cuddapan	82	2.390-2.488	2.459	"

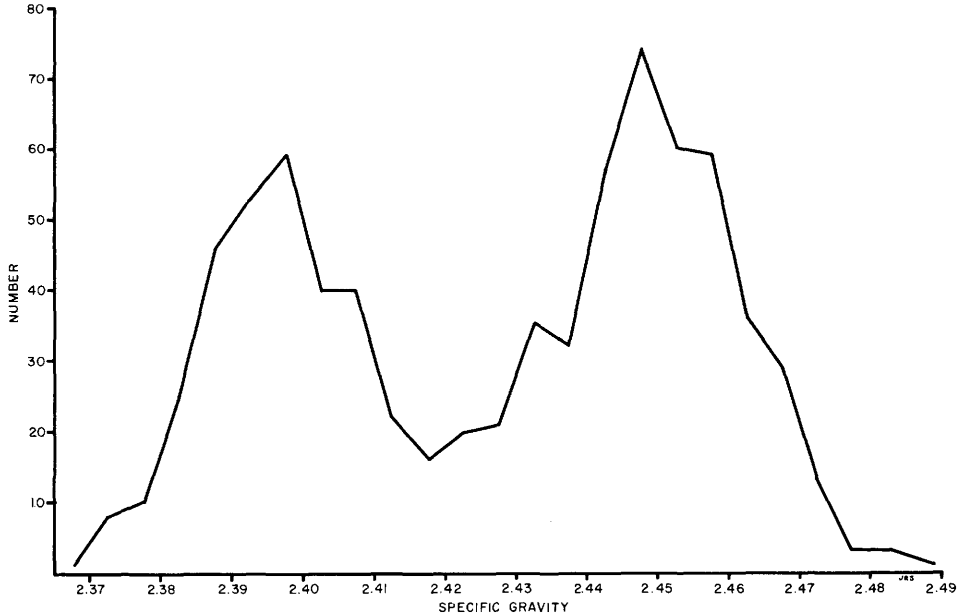

Figure 15.—Specific gravity distribution for 761 australites from the Lake Torrens–Lake Eyre region; specific gravity determinations by Dr. Dean Chapman.

mersion method it is usually possible to arrive at a reasonable mean value.

Extensive series of measurements of refractive index and specific gravity on australites have been reported by Baker (1959a), Chao (1963), and Chapman and Scheiber (1969). The data of Chapman and Scheiber are plotted on Figure 17 along with two determinations on specimens from our own collections selected at the ends of our observed specific gravity range. As has been noted by previous investigators, an essentially straight-line relationship exists between refractive index and specific gravity for the australites, and indeed for all tektites (Barnes, 1940). In Figure 17*a* the line plotted by Barnes on the basis of data for all groups of tektites lies slightly above the line pro-

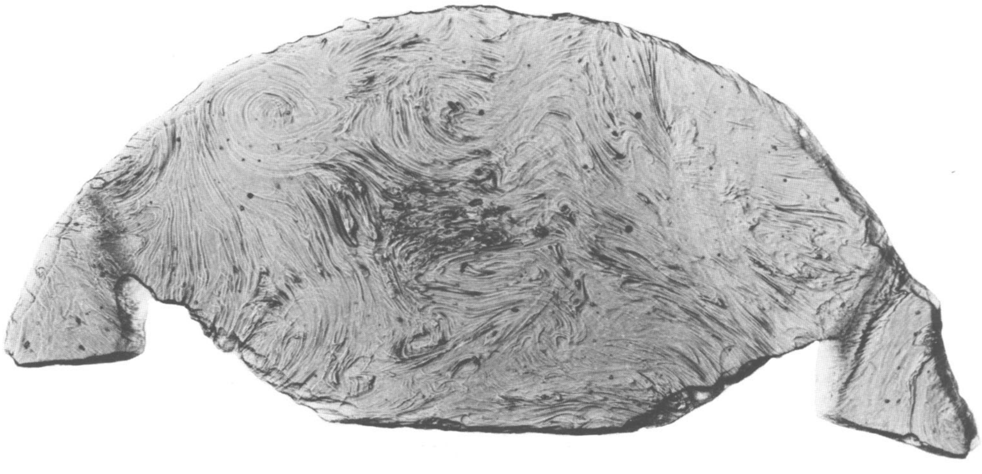

Figure 16.—Thin section of flanged australite button from Motpena, South Australia, showing flow structure and schlieren of differing refractive index.

viding the most satisfactory fit with the australite data, but the difference is small and statistically insignificant.

The data in Figure 17*a* shows a range in specific gravity for australites from 2.36 to 2.52, and of refractive index from 1.493 to 1.529, except for the aberrant HNa/K group described by Chapman and Scheiber (1969), which will be discussed in the next section. The specific gravity range is essentially that indicated by the figures in Table 7, although a few lower specific gravities have been recorded from Port Campbell and Pindera. Lower specific gravities may, of course, be due to bubbles within the australite glass.

The plot of refractive index against SiO_2 percentage (Figure 17*b*) also shows a straight-line re-

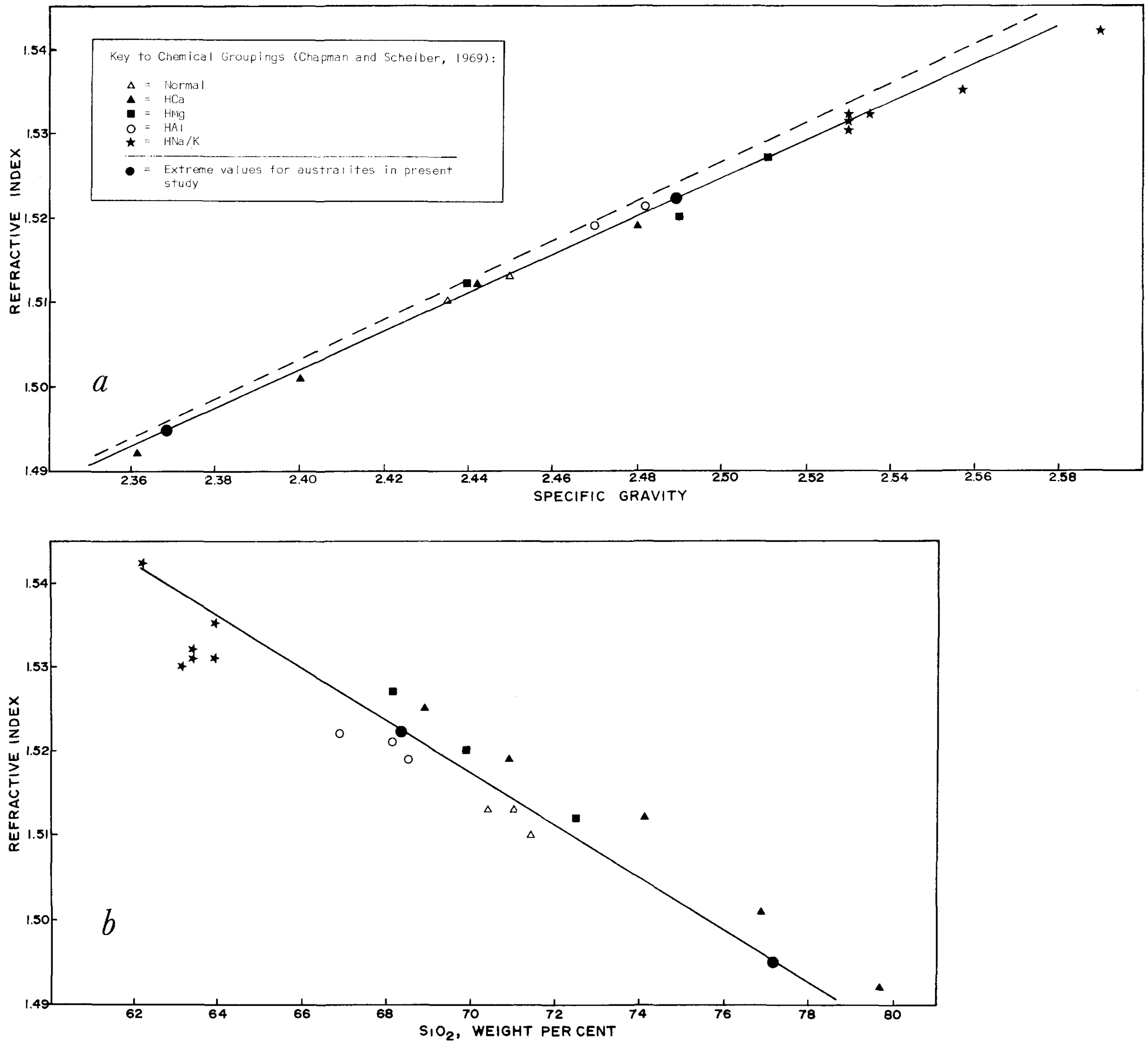

FIGURE 17.—Refractive index/specific gravity (*a*) and refractive index/SiO_2 percentage (*b*) plots for australites. The broken line in the refractive index–specific gravity plot is that determined by Barnes (1940) as a mean for all tektites.

lationship, although the scatter of individual points is somewhat greater than for the refractive index-specific gravity plot. This is presumably due largely to the influence of varying amounts of other components besides SiO_2 on the refractive index. Nevertheless, a measurement of refractive index (or specific gravity) provides a useful approximation (within about ±1%) of the silica content of an australite.

Chemical Composition

A large amount of data on the chemical composition of australites has been published in recent years, mainly by Taylor (1962), Taylor and Sachs (1964), and Chapman and Scheiber (1969). On this account we have limited our analyses to two specimens selected from the extreme values of specific gravity found in our total collections. These analyses are given in Table 8.

Taylor and Sachs (1964) noted that the percentages of all the major elements except calcium diminshed as SiO_2 percentage increased. Calcium showed some degree of negative correlation when graphed, but this was not statistically significant. Significant negative correlation with SiO_2 was also established for the minor and trace elements Cr, Li, Ti, Ni, V, Sc, Ba, Rb, and Cs.

One of the aims of this extensive study of australite composition was to establish whether regional differences in composition existed. Earlier results (Taylor, 1960; Taylor and Sachs, 1961) for the alkali elements suggested a regional variation in composition from east to west across Australia. However, the much larger amount of data assembled by Taylor and Sachs (1964) showed that autralites of widely different composition exist at any one locality, as is also apparent from the specific gravity data (Table 7). The specimens analyzed by Taylor and his co-workers were evidently selected to cover as wide a range of composition as possible, and this procedure did not take into account the marked quantization of composition indicated by the specific gravity data (the significance of which was not apparent when they made their investigations). The only marked regional feature of their analyses is the large number of specimens from Western Australia in the 70%-72% SiO_2 range. Correlating their analytical data with the specific gravity data, however, one can establish two distinct regional populations: (1) that of Western Australia and the Nullarbor Plain, with a density peak of 2.45 corresponding to an SiO_2 content of about 71%, and (2) that of Victoria with a density peak of 2.40 corresponding to an SiO_2 content of about 76%. The Lake Torrens-Lake Eyre region between Beltana and Cooper Creek carries a mixture of these two populations. The specific gravity data for Lake Wilson and Wingellina specimens, and the single analysis of a Lake Wilson specimen (Taylor and Sachs, 1964) suggest that australites from this region, centered on the South Australia-Western Australia-Northern Territory corner, may have a distinctive composition. Their peak specific gravity is significantly higher than that for any other area, and Taylor and Sachs commented on the analytical data for the Lake Wilson specimen as follows: "[This specimen] is unusual in possessing, in addition to the high value for nickel, the highest

TABLE 8.—Chemical analyses of two australites. E. Jarosewich, analyst (C-8 = Pine Dam Area, Lake Torrens; 43-3 = Lake Eyre South)

Oxide	C-8	43-3
SiO_2	77.23	68.35
TiO_2	0.61	0.77
Al_2O_3	10.73	14.19
Fe_2O_3	0.57	0.95
FeO	3.68	4.37
MnO	0.08	0.09
MgO	1.46	2.41
CaO	1.61	4.98
Na_2O	1.23	1.46
K_2O	2.56	2.71
	99.76	100.28
Total Fe as FeO	4.19	5.23
s.g.	2.368	2.489
n	1.495	1.522

amounts of Mg, Fe, Co, and Cr. The concentrations of the other elements are normal for the silica content (69.8 per cent) (1960:250).

Chapman and Scheiber (1969) studied the compositional variations in tektites from the whole Australasian (Southeast Asia and Australia) strewnfield. They comment: "These data are collected herein with little attention to geographic distribution pattern but with emphasis on the information provided as to the chemical nature of the parent rock from which the tektites derived." With this in view they selected 530 specimens for chemical analysis from approximately 47,000 whose specific gravity they had measured. In their 1969 paper they report 60 analyses, of which 22 are Australian specimens. The analyses were classified into a number of chemical groups, and in a later paper Chapman (1971) provided a map showing the geographical distribution of these chemical groups.

Australite analyses were assigned to the following chemical groups:

Normal: The term "normal" is evidently used in the sense "very common." The only chemical criteria listed are CaO>MgO, Na_2O>1.25%, and Ni≤41 ppm. Practically all the analysed australites from Western Australia and the extension of the Nullarbor Plain into South Australia are in this group, and specimens are also present in collections from eastern South Australia and the adjacent area of New South Wales.

HCa: H denotes "high"; for the HCa australites CaO ranges from 1.83% to 5.62%, FeO 3.57%–4.75%, Ni 17 ppm–26 ppm, and Cr 57 ppm–98 ppm. The HCa australites occur only within the low specific gravity "streak" from Victoria through the Lake Torrens–Lake Eyre region, but not all HCa australites have low specific gravity; analysed specimens have specific gravities ranging from 2.361 to 2.501. "HCa" may be something of a misnomer for this group, since some specimens have lower Ca than specimens in other group.

HMg: The chemical criteria are MgO>3.4%, Ni≥210 ppm, and Cr≥210 ppm. This is a relatively rare type among australites, only six analyses being recorded. These australites were collected in central Western Australia and adjacent areas in South Australia and Northern Territory (Lake Margareta, Serpentine Lakes, Lake Wilson).

HAl: Al_2O_3≥14.9%; found only in N.S.W. (Pindera, Liverpool, and Uralla), except for one specimen in Tasmania.

HNa/K: Nine specimens, all from northwest South Australia, comprise this group; they are characterized by an exceptionally high Na/K ratio. Na_2O/K_2O ranges from 2.7 to 3.6, whereas in all other australites and most other tektites this ratio is always less than unity.

The only chemical group that can be readily distinguished on the basis of physical properties (refractive index and specific gravity) is the HNa/K, and as will be seen from subsequent discussion, the identification of this group as tektites is questionable. The HCa group shows practically the full range of refractive index and specific gravity (Figure 17*a*), whereas the remaining groups show a narrower range; however, this restriction in range may simply reflect the limited composition range of the specimens selected for analysis. The specific gravity range for the Kalgoorlie–Nullarbor Plain region (where all specimens are apparently "normal" australites) is 2.385–2.485, practically the complete range for australites. The separate character of the HAl group can be questioned; the three analysed specimens all have low SiO_2 (66.9%–68.5%) and the high Al_2O_3 may simply reflect the low SiO_2, since Taylor and Sachs (1964) have demonstrated the highly significant negative correlation of Al_2O_3 with SiO_2 for all australite analyses.

The HNa/K specimens present a perplexing problem. Chapman and Scheiber found nine through the specific gravity screening of approximately 47,000 specimens of australites and Southeast Asian tektites; we have found none in a similar screening of over 1300 australites. Their composition is distinctly different from all other tektites; Chapman and Scheiber consider them related to the Ivory Coast tektites, but a glance at their CaO/MgO plot (Chapman and Scheiber, 1969, fig. 2) shows that this is hardly tenable, because Ivory Coast tektites cluster at 1% CaO, 3% MgO, whereas the HNa/K specimens cluster at 5% CaO, 4% MgO. The $^{87}Sr/^{86}Sr$ ratio for the HNa/K specimens is 0.704 (Compston and Chapman, 1969), quite different from other australites (0.713–0.718) and Ivory Coast tektites (0.724). In addition, they give a fission-track age of approximately 4 million years (Fleischer et al. 1969). Fleischer et al. conclude that HNa/K specimens represent a unique tektite fall, preceding that of the Australasian strewnfield, which they place at 0.7 million years ago. They comment: "To many observers it may seem odd that a newly identified fall should exist in the very region where a previously known fall had occurred."

In view of the remarkable differences between the HNa/K australites from all other tektites (including the Ivory Coast tektites), the evidence for their identity as tektites requires careful scrutiny.

This evidence is somewhat tenuous, resting as it does on the following statement (Chapman and Scheiber, 1969:6756–6757):

> It might be questioned whether the HNa/K specimens are really tektites. They were found by three different collectors at four different localities in Australia and were intermingled in all cases with numerous australites of ordinary composition. Their shapes include elongates, cores, and fragments not visually distinguishable from the shapes of normal tektites with which they were found. Specific gravity measurements served to cull them from the majority. A meridianal section from AN245, a typical aerodynamic core shape (Figure 14*a*) revealed the same quantitative distribution of residual tensile and compressive stress as in normal australite cores. This attests to rapid cooling. Wafers cut from all but two (AN245 and AN87) of nine analyzed HNa/K australites exhibit glassy inclusions, both bubbly and compact, that are indistinguishable from the lechatelierite of normal tektites. All nine show flow structure. Pieces from three (AN87, AN245, and AN325) were subjected to our standard test of heating to about 1750°C at low pressure (~0.1 atm); each melted without frothing or noticeable vesiculation. They are true tektites.

The illustration (fig. 14*a*), described as "a typical aerodynamic core shape," could equally well be described as a rounded pebble; the material appears to be a homogeneous glass, completely lacking the schlieren so prominent in the accompanying photograph of an australite section. No mention is made of flange remnants on any of the specimens, which would clearly identify them as australites. The chemical composition, as Chapman and Scheiber point out, is closely similar to that of a terrestrial andesite, although their Cr and Ni contents are anomalously high.

So the question arises, if these are not tektites, what are they? They were all found in northwestern South Australia, six of them from a location "south of Lake Wilson, 26°20′S, 129°20′E." To our knowledge no volcanic rocks that might contain obsidian of the composition of the HNa/K specimens are known in that region. However, the mountains to the north, the Mann Range, are high-grade metamorphic rocks of granitic to more basic compositions, and are extensively veined by pseudotachylite, evidently formed along zones of intense shearing. These pseudotachylites are black and glassy, and pebbles resemble eroded australites. Chapman and Scheiber comment that the Rb-Sr data for the HNa/K specimens can be interpreted as indicating parent material representing very ancient times of crystallization, of the order of 2500 million years ago, an age consistent with the Mann Range rocks.

Chemical Composition and the Origin of Tektites

It is ironic that the two scientists who have contributed most to our knowledge of the chemical composition of australites arrived at diametrically opposed opinions as to their origin, Taylor ascribing a terrestrial source and Chapman a lunar one. At the Third International Tektite Symposium held in Corning, New York, in April 1969, where much of this chemical evidence was presented, an informal vote of the conferees revealed an essentially even split between adherents of the lunar and of the terrestrial origin. The issue was soon to be decisively resolved. The Apollo 11 moon landing on 20 July 1969 and subsequent missions brought back material whose geochemistry almost certainly negates the possibility of a lunar origin for the tektites. The evidence has been summarized by Taylor (1973), as follows:

> The Apollo lunar missions provide critical evidence which refutes the hypothesis of lunar origin of tektites. Tektite chemistry is totally distinct from that observed in lunar maria basalts. These possess Cr contents which are two orders of magnitude higher than tektites, distinctive REE patterns with large Eu depletions, high Fe and low SiO_2 contents, low K/U ratios and many other diagnostic features, none of which are observed in the chemistry of tektites. The lunar uplands compositions, as shown by Apollo 14, 15 and 16 samples and the γ-ray and XRF orbiter data, are high-Al, low-SiO_2 compositions totally dissimilar to those of tektites. The composition of lunar rock 12013 shows typical lunar features and is distinct from that of tektites. The small amounts of lunar K-rich granitic material found in the soils have K/Mg and K/Na ratios 10–50 times those of tektites. The ages of the lunar maria (3.2–3.8 aeons) and uplands ($>$4.0 aeons) are an order of magnitude older than the parent material of the Southeast Asian and Australian tektites, which yield Rb-Sr isochrons indicating ages on the order of 100–300 m.y. The lunar lead isotopic compositions are highly radiogenic whereas tektites have terrestrial Pb isotopic rations. Lunar $\delta^{18}O$ values are low ($<$7 per mil) compared with values of $+9.6$ to $+11.5$ per mil for tektites. In summary, a lunar impact origin for tektites is not compatible with the chemistry, age, or isotopic composition of the lunar samples. A lunar volcanic origin, recently revived by O'Keefe (1970) encounters most of the same problems. Recent lunar volcanism ($<$50 m.y.), if the source of tektites, should contribute tektite glass to the upper layers of the regolith. None has been found.

The disproof of a lunar origin for australites reinforces the quest for a terrestrial source of the parent material. Taylor and Kaye (1969) demonstrated the close match between the average composition of australites, for both major and trace elements, and that of greywacke. They therefore suggested an origin by cometary impact on terrestrial rocks of appropriate composition without specifying potential source locations. Schmidt (1962) postulated a meteorite crater in the Wilkes Land region of Antarctica (approximately 71°S, 140°E) on the basis of striking gravity minima similar to those observed for Canadian meteorite craters, and suggested this would be an appropriate source for the australites. On the other hand Lieske and Shirer (1964), using a digital computer, calculated the trajectories of tektite-like bodies with high initial velocities, with a view to determining whether the debris from an explosive meteorite impact could have attained intercontinental ranges. They regard it as improbable that the small tektites forming the australite strewnfield could have been distributed in their present form by a meteorite impact in Antarctica. Taylor (1969) pointed out that both number and mass of tektites increase towards the northwest corner of the entire Indo-australian strewnfield, the largest recorded specimens being of the Muong-Nong type from Laos, Vietnam, Cambodia, and Thailand; this would suggest a primary source in the region. Kaysing (1970) extrapolated from the data of McColl and Williams (1970) to suggest that Lake Toba in Sumatra was a possible source area for the Australian group of tektites. Taylor (1970) pointed out the consensus of opinion that Lake Toba was a volcano-tectonic depression surrounded by vast quantities of ignimbrite. Analyses of australites are dissimilar to Lake Toba ignimbrite, particularly for the critical elements magnesium, sodium, and potassium, and also for silica. Taylor considers that on these grounds there is no a priori case for considering Lake Toba as a potential source area. It is puzzling that a catastrophic event that sprayed glass over the southern half of Australia and by extension to the Philippines and southern China left no other geological evidences—especially if it occurred as recently as the stratigraphic age of the australites (7000–20,000 years BP) would indicate.

Age and Stratigraphical Relationships

It is perhaps misleading to talk about the age of australites in any general sense. Different procedures devised to "date" australites may in fact be determining the time of a specific event in a lengthy history. Some possible events that may be dated in this context are:

1. The formation of the glass and its cooling to the argon retention temperature, thereby enabling the determination of a potassium-argon age. This assumes no subsequent reheating of sufficient intensity to "reset" the potassium-argon "clock." Fission-track dating is analogous, in that fission tracks accumulate in the glass after solidification and cooling, but may be erased by subsequent reheating.
2. The passage of the australite through the Earth's atmosphere, presumably dated by age determinations on flange material.
3. The time of incorporation in the geological formation where the australite is found, dated by stratigraphy or by radiochemical determinations on associated material. If the australite is found where it fell, the age of the enclosing formation presumably gives the time of fall, which should be identical with event 2; transportation may result in the australite being incorporated in a younger formation, or even apparently in an older formation (e.g., if washed into a cleft in older rocks).

Potassium-argon dating has been applied to australites by a number of researchers. The most comprehensive data are those of McDougall and Lovering (1969), which are reproduced in Table 9: they confirm and extend the earlier work of Reynolds (1960) and Zähringer (1963). McDougall and Lovering comment:

> The apparent K-Ar dates average 0.86 ± 0.06 m.y. (standard deviation), approximately 0.15 m.y. older than found by previous workers. The internal consistency of the K-Ar dates on the australite cores, which have potassium contents ranging from 1.61 to 2.18 per cent suggests that the dates are geologically meaningful, and probably record the time of primary melting. Studies of flanged australites confirm that potassium is depleted in the flanges relative to the associated cores, and show that the flanges have considerably older apparent K-Ar dates than the cores. Because it is agreed that the flanges were formed by subsequent ablation of the primary australite cores, it must be concluded that the flanges contain excess radiogenic argon.

McDougall and Lovering also measured the K-Ar age of a philippinite and found 0.78 ± 0.05 m.y., slightly higher than the ages of 0.68 to 0.73 m.y. given by Zähringer (1963) for five philippinites. Zähringer found that all the tektites he ana-

TABLE 9.—Potassium-argon ages of australites (McDougall and Lovering, 1969)

Locality		% K	Age, m.y.
Kalgoorlie, WA	core......	2.05	0.88 ± 0.03
Leonora, WA	core......	2.19	0.79 ± 0.09
Musgrave Ranges, SA	core......	1.61	0.86 ± 0.07
Florieton, SA	core......	1.79	0.92 ± 0.18
Charlotte Waters, NT	core......	1.71	0.87 ± 0.09
"	flange......	1.64	0.94 ± 0.12
"	core......	1.71	0.75 ± 0.07
"	flange......	1.66	1.05 ± 0.08
Myrtle Springs, SA	core......	1.99	0.81 ± 0.04
"	"	1.92	0.79 ± 0.03
"	core......	1.97	0.91 ± 0.09
"	flange......	1.83	1.16 ± 0.04
"	core......	1.90	0.94 ± 0.21
"	flange......	1.85	1.79 ± 0.04
"	composite flange......	1.89	1.11 ± 0.03
Port Campbell, Vic.	core......	1.81	0.86 ± 0.02
"	flange......	1.66	1.12 ± 0.03
Stanhope Bay, Vic.	core......	1.83	0.95 ± 0.05
"	"	1.82	0.85 ± 0.11
"	flange......	1.72	1.09 ± 0.03

lyzed from different localities in the Indoaustralian region (Indochina, Thailand, Philippines, Billiton, Java, Borneo, and Australia gave the same K-Ar ratio (within experimental uncertainty) and hence showed the same age.

This apparent consistency in age for tektites throughout the vast Indoaustralian region has been cited as important evidence for a common and contemporaneous origin. Nevertheless, nagging uncertainties in the interpretation of the K-Ar ages remain, especially in view of the apparent older ages for flanges. In this connection, the work of Clarke et al. (1966) is significant. They point out that the calculation of the K-Ar ages of tektites rests on the assumption that all ^{40}Ar is expelled from the melt at the time of formation, so that the measured ^{40}Ar is entirely the product of the decay of ^{40}K since the melting event. To test this assumption they made glasses of tektite composition from geologically old materials under carefully controlled conditions to promote complete outgassing. The apparent K-Ar ages of these glasses were measured, and ranged from zero to over 1 m.y. They concluded: "The data indicates that the assumption of complete loss of ^{40}Ar may not be completely valid, and the interpretation of K-Ar dating as applied to tektites may need reevaluation."

The results suggest an alternative explanation of the consistent K-Ar ages of tektites throughout the Indoaustralian region—that they may not be true ages, but represent a limit to the outgassing of preexisting ^{40}Ar in the source materials. If tektites were formed in a catastrophic impact, as envisaged by most researchers, then insufficient time for complete degassing of radiogenic Ar from the source materials is a distinct possibility. However, this interpretation appears to be negated by the fission-track ages (Table 10) of Fleischer and Price (1964), which support the K-Ar ages, although they show a considerable spread. Later work by Gentner et al. (1969) gives fission-track ages for australites of 0.11–0.71 m.y., in agreement with the data of Fleischer and Price.

Fleischer and Price comment as follows:

> The nine australites have four distinct and separate fission track ages which lead to two alternative conclusions as to the true solidification ages: (1) There were at least four different solidification events, or (2) track numbers have been altered over time in such a way as to change at least three ages from their true values. Although we cannot rigorously decide between these two possibilities, we conclude that the second alternative is the more reasonable one, the true age then being 0.70 (±0.04) m.y. There are three reasons for believing this. First is the very good agreement between this value and the ages found for australites by Zähringer (1963) using K-Ar dating. Secondly, we know that simple thermal conditions can give rise to fading (and hence too young ages), while conditions for arriving at too large an age are rare. For samples with as high a uranium content as tektites the only possibility we know of would be the close proximity of a deposit of uranium, which would be a neutron source and hence induce fission. Thirdly, in the 0.13 m.y. old Port Campbell australite there were tracks which showed effects of exposure to elevated temperature. Such tracks have a somewhat blurry and less crisp appearance than do unheated tracks, and are easily distinguished from them. We conclude that the solidification age is 0.70 ± 0.04 m.y., and the other samples were probably heated sufficiently to produce track fading (one sample recently, two about 0.12 m.y. ago and one about 0.34 m.y. ago).

As noted in Table 10, Fleischer and Price examined some flanged australites from Port Campbell, and found that fission-track densities were

TABLE 10.—Fission track ages of australites (Fleischer and Price, 1964) arranged by age (* = flanged specimens; flange and core gave the same age)

Locality	Age, m.y.
Kalgoorlie, WA..........	<0.03
Port Campbell, Vic.......	0.11 ± 0.04
*Port Campbell, Vic.......	0.13 ± 0.02
Kalgoorlie, WA...........	0.34 ± 0.01
Kalgoorlie, WA...........	0.66 ± 0.01
Charlotte Waters, NT.....	0.64 ± 0.16
*Port Campbell, Vic.......	0.69 ± 0.05
*Port Campbell, Vic.......	0.69 ± 0.07
*Port Campbell, Vic.......	0.8 ± 0.2

essentially identical in flange and core. They comment:

> The track density in the flange, which results from ablation by the atmosphere, should measure the time of entry into the Earth's atmosphere; the track density in the core should measure the time of formation of the original tektite, which reached the Earth's atmosphere as a rigid, cold sphere (Chapman and Larson, 1963). The total densities found (303 ± 22/cm^2 for the core and 292 ± 25/cm^2 for the flange) in the three oldest samples are statistically indistinguishable. Therefore the descent onto Earth must have occurred 0.70 m.y. ago, i.e. much longer ago than the 0.005 m.y. deduced from geological evidence (Baker, 1960).

These results imply that the formation of the glass and its passage through the atmosphere were not separated by a detectable time interval. This is consistent with evidence of a rapid flight time. Australites (and other tektites) appear not to have been exposed to appreciable cosmic-ray irradiation. Reynolds (1960) has shown that australites do not contain detectable ^{21}Ne. From the measured neon diffusion rate, the measured cross-section for production of neon from other elements, and from the limit of detectability of ^{21}Ne Reynolds concluded that the australite he measured had a maximum flight time of 28,000 years. Anders (1960) did not find any ^{26}Al in an australite. The sensitivity of the measurement of ^{26}Al (Viste and Anders, 1962) does not, however, preclude a 90,000-year flight time.

The geological data, however, are completely incompatible with the australites having fallen approximately 700,000 years ago. Experienced field investigators agree that australites are found in late Pleistocene or post-Pleistocene formations and not in older deposits. Fenner (1935), on the basis of the extensive evidence collected by him, concluded that they fell in early post-Pleistocene times. Baker (1962), who carefully investigated the australite occurrences near Port Campbell for over thirty years, and who was also familiar with other localities, wrote as follows: "The evidence from the geological occurrence of australites, supported by ethnological and pedological evidence, leads to the conclusion that the age-on-earth of the tektite fall in Australia is about 5,000 years. It is probably not under 3,000 years, nor over 6,000 years." Johnson (1965), discussing specifically the australite occurrence at Lake Wilson, but also drawing on many years of field experience, wrote: "It appears that the australites fell soon after the end of the Pleistocene."

Our own observations are in agreement with these statements. Over most of the vast area we have prospected, australites are associated with a readily recognizable geological formation, a well-consolidated red sand, which is undoubtedly an aeolian deposit. It contains layers of calcareous nodules, some of which are moulds of former tree roots; those layers may represent the B horizons of ancient soils. This geological formation is generally overlain by unconsolidated red sand, usually in the form of seif dunes, the sand derived from the deflation of the underlying formation. Where stream channels exist, they may have cut down into this formation some tens of feet, as on Mulgaria Station. The geological evidence suggests that the red sand formation with which the australites are associated was deposited under semi-arid conditions—arid enough for extensive wind transportation of the constituent sand, but also humid enough for the growth of sand-fixing vegetation and the development of soil horizons. Increasing aridity apparently brought this depositional period to a close, and it was succeeded by an extremely arid period with strong deflation and the development of extensive series of seif dunes. In more recent time the aridity has evidently diminished, since the seif dunes are now essentially fixed by vegetation. The australites are always near the top of the consolidated red sand formation, indicating that they fell shortly before a change to extremely arid conditions. In South Australia this red sand formation containing the australite horizon has been named the Lake Torrens Formation (Williams and Polach, 1971), and its date of deposit set at about 16,000–20,000 years BP. Lovering et al. (1972), therefore, concluded that the australite fall occurred within this time period, although it may have occurred during the development of the Motpena paleosol (12,000–16,000 years BP).

During all our field work we have searched for wood or charcoal associated with australite occurrences, in the expectation of thereby obtaining carbon-14 dating of the australite fall. This search has been unsuccessful. For obvious reasons, wood, even if originally present, is unlikely to survive in an arid or semi-arid environment. That woody shrubs were probably present is indicated by the calcareous moulds of tree roots found in the australite-bearing formation. Better success has been obtained in the Port Campbell area as reported by Gill (1965, 1970). A carefully selected site was excavated using archeological methods, in which the sandy soil was removed inch by inch. Fourteen australite specimens were discovered in situ, at depths of 11 to 14 inches, along with materials for radiocarbon dating. All the australites were found on or up to three inches above a hardpan layer. Seven radiocarbon datings were made of fossil hardpan material, of charcoal at various levels above the hardpan, and of grass tree resin in situ above the hardpan. The oldest date was 7,300 years for carbonized wood fragments in the hardpan. Gill concludes that australites fell prior to the comparatively arid postglacial thermal maximum, which began about 6500 years ago; this is consistent with our deductions from the stratigraphic relations at interior sites.

We are thus faced with what seem to be irreconcilable "facts" regarding the time of fall of australites. Geological evidence shows the fall of australites took place some time during the period 7000-20,000 years BP, whereas K-Ar and fission-track figures show the age of formation to be approximately 700,000–860,000 years BP. There seem to be three possibilities: (1) the figures are wrong, (2) the geology is wrong, or (3) something else is wrong.

It is probably presumptuous to suggest that the 700,000–860,000-year figure is "wrong." It is the result obtained by several independent and experienced investigators, and its significance is apparently strengthened by the fact that tektites throughout the Indoaustralian region, from the Philippines through Indochina, Thailand, and Indonesia to Australia all give this same potassium-argon age. However, it may be permissible to suggest that the interpretation of this figure may be wrong, i.e., that it does not measure the time of solidification of the glass. We do not know what material was melted to form the tektite glass, but it is conceivable that this material contained argon which was not completely expelled during the melting process. Inherited argon would thereby give a spurious and too great age for the time of formation of the glass. On this interpretation the uniformity of tektite age throughout the Indoaustralian region—the youngest age measured for any tektites—may not strengthen the argument of consanguinity, but may instead reflect the limit for argon degassing under conditions of formation of tektite glass. The fact that K-Ar dating for the flange and core of australites has given a greater age for the flange than the core adds to the uncertainty of the K-Ar dating of these objects.

However, this interpretation of the potassium-argon age appears to be vitiated by the fission-track investigation, which supports the 700,000 year age, and, in addition, shows that flange and core have identical fission-track density. This would seem to demonstrate that the australite glass was formed about 700,000 years ago, and that the australites descended through the Earth's atmosphere shortly thereafter.

On the basis of these arguments, therefore, it has been suggested that the geology is wrong. As Schaeffer (1966) states the case: "The geological age does not measure the arrival of these tektites on the Earth as the tektites are detrital to the deposits and were originally deposited in other older formations." While this is certainly true for many, if not most, of the tektite occurrences in other parts of the world, a large number of australite occurrences are certainly not of detrital origin. No one who has seen the Port Campbell localities and examined the many perfectly preserved australites therefrom is likely to argue that these specimens are not being found essentially where they fell. The complete lack of solution etching, even on thin plates weighing as little as 0.03 gram, is a powerful argument against the australites having been subjected to terrestrial weathering, even in situ, for more than a few thousand years. Our own experience in the arid interior indicates that at many locations we were collecting australites essentially where they fell. Delicate surface markings and flanges, which would certainly have been destroyed in a few years exposure to present surface conditions, let alone transportation, are still present on many of the specimens. Their distribution is completely unrelated to stream channels; they are often found on higher ground which is being actively deflated; no detrital material in the same size range, such as stream pebbles, is present. As Lovering et al. (1972) commented, if the australites fell 700,000 years ago they would not be found in the Lake Torrens region, since this area has been aggrading throughout the Pleistocene, and a 700,000-year horizon would be deeply buried.

Having reached an apparently irreconcilable impasse between the physical dating and the geographical dating of the australite fall, one can only turn to the third proposition—something else is wrong. Perhaps this can better be stated as something—some unsuspected factor—has been overlooked. We have no plausible suggestions for this unsuspected factor or factors. It may not be inappropriate, however, to recall other conflicts of this kind, such as that between Lord Kelvin and many geologists as to the age of the Earth, before the discovery of radioactivity completely altered the situation.

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