[AMERICAN JOURNAL OF SCIENCE, VOL. 256, JUNE 1958, P. 369-383]

American Journal of Science

JUNE 1958

THE ROLE OF AERODYNAMICAL PHENOMENA IN SHAPING AND SCULPTURING AUSTRALIAN TEKTITES

GEORGE BAKER

ABSTRACT. Primary australite shapes are considered to have been generated in an extraterrestrial environment, but secondary shapes and front surface sculpture arose as a consequence of the development and action of certain aerodynamical phenomena during ultra-supersonic, non-rotary flight earthwards through the atmosphere. Shock waves, boundary layer laminar flow and turbulence in the atmospheric medium traversed by australites at such high speeds, resulted in high temperatures, skin friction and form drag to which the front surfaces and equatorial regions of australites were subjected for a very short period of time. The primary shapes, of which spheres and spheroids constituted the greatest proportion, were cold on initial entry into the earth's atmosphere, and each member of each shape group already possessed pre-formed complex internal flow patterns and bubble-pitted, flow-swirled surface features. Conflict with the atmoshere during ultra-supersonic speeds of earthward passage resulted in considerable diminution in bulk of each australite. This arose from removal of glass in front surface and equatorial regions under the influence of ablation and thin-film fusion-stripping, accompanied by the building up of circumferential flanges with plane spiral coiling on the peripheral edges of the otherwise unaffected back surfaces, and the production of small troughs and ridges as newly formed sculptural elements upon the front surfaces. The production of the relatively rare flat, thin varieties of australites, hitherto regarded as difficult of explanation, is readily envisaged under the terms of aerodynamical control at high speeds of flight.

INTRODUCTION

Many diverse and unsuccessful attempts have been made to explain the mode of origin of the shapes and sculpture patterns of australites, since the days when the Rev. W. B. Clarke (1855) wrote that australites appeared "as if cast in a mould", and Walcott (1898) recorded that some people believed australites were originally plastic materials that had been pressed by a saucer-shaped mould in the ground.

Suggestions advanced as explanatory of the shapes and sculptural elements, are inevitably bound up with some particularly favored, but unproven source, advocated for the glassy material composing australites by adherents to the different hypotheses. No one theory has yet succeeded in formulating an adequate explanation for the origin of australite glass and the processes responsible for fashioning it into the shape types found throughout Southern Australia and Tasmania.

Theories put forward during the latter half of the nineteenth and earlier part of the twentieth centuries, have called upon artificial, natural terrestrial and extraterrestrial sources, and still the problem remains incompletely solved. Most earlier theories have been discarded as untenable. Among those receiving favorable consideration, theories relating to an extraterrestrial origin have most to offer in attempting to unravel the mystery of australite formation. An extraterrestrial source for australites is the most adequate for providing explanations of their original shapes, sculpture patterns, internal structures and other features, such as distribution, etc.

A theory that ultimate secondary shapes were produced by the action of aerodynamical phenomena during high speeds of flight is herewith advanced in the belief that it is the most logical and most acceptable, and that it lends strong support to the hypothesis of an extraterrestrial origin for Australian tektite glass. This discussion of the effects of aerodynamical phenomena on australites must of necessity be qualitative, since the aerodynamicists have not yet formulated the answers to all the problems involved.

If australites represent forms of extraterrestrial silicate glass that were already solid on reaching the earth's atmosphere at cosmic velocities the question arises whether they traversed the atmosphere with or without a spinning trajectory.

Up to now, most theories relating to the mode of generation of the shapes of australites (e.g. Walcott, 1898; Fenner, 1934) have favored rotation normal to the direction of propagation through the atmosphere.

The new theory presented herein, does not require rotary motion during atmospheric flight. The evidence from studies of the shapes, structures, sculpture, internal and external flow patterns ("schlieren", etc.) of some 2,000 well-preserved australites (Baker, 1944; 1955a; 1955b; 1956), completely militates against theories invoking rotation through the earth's atmosphere. The greater proportion (approximately 80 percent) of australites were originally primary spheres or oblate spheroids close to spheres, (Baker, 1955; 1956) formed by rapid fusion followed by rapid cooling. Spheres require no rotation for their formation, and there is no reason to suppose that australite spheres rotated on entering or traversing the atmosphere. The remaining 20 percent of australite shape types were obviously originally forms of revolution, but the important point is that they were produced as such at their extraterrestrial birthplace. As pre-formed shapes, they also became modified without rotation playing any part during the atmospheric phase of earthward flight.

Opinions have sharply differed concerning whether tektites could become completely liquid during atmospheric transit. Grant (1909) calculated that if only 1 percent of the energy possessed by meteors entering the atmosphere at 40 miles/sec. was converted into heat by air friction, and this was retained by the body, it would be sufficient to raise the substance of an australite to its melting temperature (1,324°C), and render it completely liquid. On the other hand, it has been calculated that the amount of heat generated by the rapid passage of small bodies of glass through the atmosphere, taken in conjunction with conductivity of the glass, would be insufficient to melt them to the extent that tektites were melted prior to their arrival on earth (cf. Watson, 1935; Opik, 1937; Spencer, 1937).

THEORY OF AUSTRALITE SHAPE AND SCULPTURE FORMATION UNDER THE CONTROL EXERTED BY AERODYNAMICAL PHENOMENA

In view of the foregoing remarks, it becomes necessary to accept as a starting point:

a) the evidence indicating that australites entered the final phase of earthward flight—the atmospheric phase—as cold, non-rotating objects of glass having pre-formed (primary) shapes, and
b) the fact that if australites are in reality glass meteorites, then they traversed the earth's atmosphere at very high speeds.

The following observations and deductions are regarded as providing satisfactory arguments in favor of the above items.

In possession of small primary shapes (spheres, spheroids, apioids and dumbbells), and a few accidental or aberrant shapes, each with a pre-determined complex internal flow pattern ("schlieren") in natural glass with slight inhomogeneities from limited miscibility in the original silicate melt, resulting from very rapid fusion followed by equally rapid cooling, there arrived a time in the Recent epoch of the earth's geological history, when a cloud of australites approached and was drawn into the earth's sphere of attraction. The cluster was limited in size, as evidenced by the confinement of australites to Australia and Tasmania only.

By analogy with meteorites, the speed of transit through the earth's atmosphere was considerable at the onset. Some distance above the earth's surface, the australite cloud was slowed down and thereafter its individual components fell to earth along parabolic paths. Even with the decreased rate of infall, the australites would have traversed the remaining distance to earth in seconds or very few minutes at most. During this short time, but at such high speeds, primary shapes were subjected to considerable front surface modification through heating by air friction. The motion involved during transit was one of forward propagation only, with no rotation whatsoever, although a few forms occasionally provide evidence of having developed a slight wobble due to buffeting at high speeds as a result of form drag.

A short distance above the earth's surface, the australites rapidly lost speed, and descended through the denser, lower layers of the atmosphere at such reduced speeds that they landed without being smashed to pieces on contacting hard ground, and probably without becoming too deeply buried on striking soft earth.

At no time during the atmospheric phase of earthward flight had australites become completely fluid throughout, hence there was no flattening possible, as has been previously suggested, of any of the forms on impact with the ground.

Throughout the zone of the atmosphere where secondary modification took place, the australites were travelling at ultra-supersonic speeds. Under the terms of gas dynamics at such high speed flow, the effects of airflow over their front surfaces played the dominant role in determining their ultimate modified shapes, structures and sculpture patterns. Secondary thin film fusion arose from the heat generated by intensive friction with the atmosphere. It is apparent that during the formative stages of secondary shape development, the nature of the airflow over and past the forwardly directed surface of each australite, was undoubtedly maintained as a steady flow while ultra-supersonic speeds prevailed, but must have changed considerably with the decreased speeds of earthward approach when much nearer the earth's surface.

In experiments relating to fluidal flow past bodies, fluids are made to flow at varying speeds around the bodies, because it has so far proved more practicable to produce and note the effects of flow in moving fluid, the velocity of which can be more readily controlled. With australites, it is required to know the effects of the external streaming of the fluid medium (air) upon the fast-moving objects themselves. Since they are small bodies that travelled at such high speeds through the atmosphere, great stream velocities were generated, and boundary layers in the fluid medium (air) would of necessity be thin layers. Within these layers, all frictional effects between the front surfaces of the australites and the atmosphere took place, and considerable temperature rises resulted.

Density and temperature variations in the earth's atmospheric envelope, throughout the secondary shape formative zone in particular, would have had but very minor effects, if any, on the ultimate character of the newly forming front surfaces of the australites, because of the high speeds of transit. Any very minor density variations existing in the tektite glass itself, are far too insignificant to have effected the issue in any way. The coefficient of thermal conductivity of the glass being low (between 0.002 and 0.0005 cal/cm/°C), the rate of heat transference from the front surface inwards would be of negligible account—the temperature gradient is very steep—so that no heat was conducted through the body of australite glass to the rear surface. Moreover, since the australites traversed the atmosphere so rapidly, there would be insufficient time for frictional heat to raise the interior portions and the rear surface to a temperature (1,324°C) at which a completely molten state could arise. It becomes apparent from studies of their internal flow patterns (Baker, 1944; 1955; 1956) that during the atmospheric phase of flight, the front surfaces were subjected to superficial melting only, at any particular instant. Such melted films did not exceed 0.01 mm in thickness at any one time, under the influence of frictional heat (cf. Dodwell's calculations (*in* Fenner, 1938)) based on Opik's (1937) work on the mechanics of meteor phenomena).

The different character of the rear surfaces of australites, taken in conjunction with the low rate of heat transference, and the fact that regions of "dead air" with low temperatures and pressures developed immediately behind fast-moving objects (see fig. 1), lead to the conclusion that these rear surfaces remained at low temperatures throughout atmospheric flight, and were in no way ablated.

SHAPE ORIGIN OF BUTTON, LENS AND ROUND-CORE FORMS OF AUSTRALITES FROM PRIMARY SPHERES

On the most common of the primary australite forms (spheres), pressure would have been greatest at the front pole, least at the rear during fall to earth. In the initial stages, frictional forces would have been negligible or non-operative at the poles of the sphere, greatest at the periphery (i.e. equatorial regions). They would have been operative to varying degrees between the front polar and the equatorial regions, but absent at the rear pole during sustained steady flight. The effects of frictional forces were thus confined to front surfaces, where they varied somewhat with various arcs of curvature of individual spheres having different radii of curvature, the range of which was limited from 2 mm up to 50 mm.

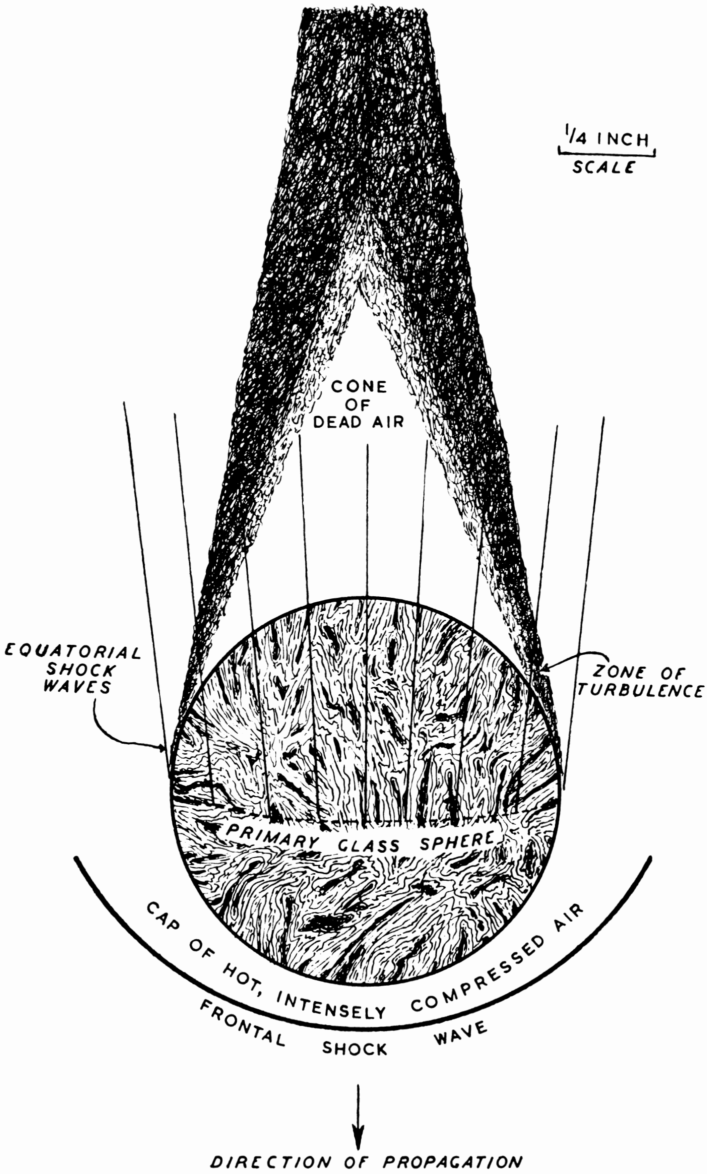

Fig. 1. Diagrammatic concept of the probable form and nature of shock waves and turbulent zones created by a primary sphere of australite glass with pre-determined complex internal flow-line pattern, travelling earthwards in its initial stages of atmospheric flight at ultra-supersonic velocity.

A combination of these pressure and frictional effects on the different sized spheres created an optimum condition of heat stability for each; the degree of viscosity attained by the heated front film was controlled by the temperature developed from frictional resistance of the atmosphere during flight, and hence by the velocity of fall of australites.

Travelling at ultra-supersonic speeds through the "formative zone" of the atmosphere, certain aerodynamical factors operated upon the front surfaces of the initial primary forms, to produce the modified shapes now possessed by australites.

Since the australites would have had high Mach Numbers[1] of approximately 20 to 25 at a height of some 70 to 80 miles above the earth's surface, a state of disturbance of a permanent type was set up in shock waves produced in the air piled up ahead of each form. The shock waves (cf. Durand, 1935) are regarded as sheets where there is a discontinuity of velocity, i.e. they are places where rate of change in velocity and density of the fluid medium (air) become infinite. These shock waves travelled ahead of the fast-moving australites producing them, at the same speed and in the same direction.

The frontal shock wave had an arc of curvature little different from that of the front surface of the australite, and its radius of curvature was but slightly greater. At all other points, such as at the equator of the sphere of australite glass and from any irregularities existing between the front pole and the equatorial regions, subsidiary shock waves moved obliquely to the direction of air flow (see fig. 1).

The shock wave was actually a narrow, almost hemispherical zone of intense compression where greatly increased temperatures arose. Thus, any air that flowed over the front surface of the primary australite sphere, did so only after penetrating the narrow arcuate region of the frontal shock wave. In the broader zone behind the frontal shock wave and ahead of the front surface of the sphere of australite glass, the air expanded to some extent, but high pressures and consequently high temperatures persisted. Due to the viscosity and conductivity of the air in the expansion zone, the mechanical energy produced at ultra-supersonic speeds, was converted into heat. While sufficiently high speeds prevailed, a cap of highly heated compressed air thus travelled ahead of each australite.

During the initial stages of the processes promoting the development of the ultimate secondary shapes of australites, this cap of hot, compressed air supplied the temperature rise necessary to induce superficial sheet fusion of thin films of the tektite glass on the front surfaces, more especially at this stage in the immediate polar regions. Here, pressure effects were at their greatest and effectively removed the fused film as soon as it formed—partly by fusion stripping, partly as a result of accompanying ablation which involved liquefaction followed by some vaporisation and immediate removal from the heated surface sheet. With the generation of another fused film at the next exposed level, and the progress of further fusion stripping and abla-

[1] The Mach Number (M) is the ratio of the speed of supersonic flow to the speed of sound, so that if $M = 1.0$, the speed of supersonic flow equals the speed of sound (760 m.p.h at the standard sea level temperature of 15°C).

tion, the arc of curvature of the front surface of the sphere was modified, becoming less steep, so that its radius of curvature increased in value; the front polar regions migrated rearwards and a rim was formed separating two now distinct surfaces—the back and the front surfaces. At this stage, the rim was merely a relatively sharp line of demarkation between the two surfaces with their now different arcs of curvature.

The part played by the equatorial skirt of subsidiary shock waves (see fig. 1), would not be expected to be of significant importance at this stage. In these subsidiary shock waves, compression, although high, would not be as intense as in the frontal shock wave, and they would be arranged very obliquely backwards and somewhat detached from the now slightly modified sphere, because of thickening of the boundary layer of air in these regions as induced by the primary australites having such a high Mach Number. Such subsidiary shock waves, however, could have had marked effects in subsequent fusion plucking around the equatorial regions of the larger forms of australites—they could have been responsible for the generation of such secondary shapes as are possessed by the core-like australites, which are forms that seldom developed, or if developed, rarely retained flanges throughout the later stages of earthward flight, but which usually, though not universally, possess characteristic flaked equatorial zones not to be entirely ascribed to subsequent tertiary processes of weathering.

While ablation of the front surface proceeded, turbulence was created behind the fast-moving sphere, arising where the main airflow separated from the equatorial regions. This arose from the action of reverse, secondary reverse, and tertiary laminar flow producing vorticity in the thin boundary layers of air in contact with the front surface. Within the thin boundary layers, arose all frictional effects between the outermost skin of the front surface of the australite and the innermost layer of the air through which it had its trajectory. Stresses produced in this layer of air gave rise to skin friction as a tangential component. Stresses produced in the positions where turbulent flow was produced in the equatorial regions, gave rise to form drag (cf. Whitlock, 1943, chapter V). Within the zone of turbulence and situated behind the rear surface of each fast-moving australite sphere undergoing modification, a cone of virtually "dead air" (see fig. 1), ensured maintenance of the rear surface at temperatures below the fusion temperature of australite glass. Thus, such of the rear surface that remained after the reduction of the original sphere, was unaltered throughout flight, and is left as testimony to the arc of curvature of the original sphere; from it, the radius of the primary sphere can be determined by reconstruction (Baker, 1955; 1956). Moreover, the remnant portion of the rear surface provides evidence of the originally bubble-pitted and flow-swirled character of the sculpture pattern of the primary spheres of glass of extraterrestrial origin.

Continued removal of the front surface films by ablation, reduced the front surfaces of the australite spheres to different extents, as evidenced by studies of curvature—size relationships of the ultimate secondary shapes (Baker, 1955a; 1956). The larger of the spheres (25 to 50 mm across) had become modified to form the normally flangeless core-like types in which equatorial plucking was dominant. In them, the subsidiary equatorial shock waves provided the necessary temperature rise, while the effects of the separation of the main airflow became important in shaping the flaked equatorial zone, for in the equatorial regions occurred the transition zone in which laminar flow in the thin boundary layers ended, and turbulence supervened.

The medium size spheres were progressively reduced in bulk all over their front surfaces, and at a stage when approximately 60 to 65 percent of the original sphere had been ablated, the front pole had passed beyond the position of the original centre of the primary sphere, the arc of curvature of the front surface had become considerably flatter with an attendant increase in radius of curvature, and the equatorial edge of the form had progressively receded (in the form of a rim) beyond the position of the original equatorial zone of the primary sphere. As a consequence, the frontal shock wave became less oblique to the airstream than the original shock wave ahead of the primary spherical form. Pressures are greater in less oblique shock waves, so that increased drag would be expected along the secondarily developing front surface.

Throughout these alterations in the shape and character of the front surface, the radius of curvature of the rear surface remained unchanged, so that the arc of curvature of the rear surface was preserved in character although not in amount, for a stage was now reached where the rim of the form had migrated rearwards to such an extent that only some 30 to 50 percent of the original hemispherical rear surface remained. As the modified form approached the closing phases of its period of ultra-supersonic flight, a situation was reached when glass from the front surface was not entirely whipped away under the influence of skin friction or by turbulent friction in equatorial regions. A condition had been created favorable to flange building, for now equatorial regions (peripheral edge) of the rear surface were less steeply sloping than when the rim was situated in positions agreeing with the equatorial regions of the primary sphere. Moreover, they now slope away from the airstream compared with a slope into the airstream when the rim was migrating from the original front polar regions of the primary sphere towards its original equatorial regions. Under the new conditions, therefore, a more stable position is available for the retention and accumulation of such melted glass as reached the edge of the new shape, although some was still no doubt lost in the turbulent airstream.

Some of the glass migrating rapidly under pressure from the polar regions of the newly created shape, was, in the fused state, stretched backwards in the airstream on reaching the equatorial regions. It was immediately caught up in eddy currents associated with the turbulent zone (see fig. 3), and a proportion (7 percent of the bulk of the original sphere) became inrolled towards the equatorial edge of the rear surface, without spreading out (in the majority of forms) for very far over that surface. There it chilled and was moulded into a circumferential flange composed of secondarily fused glass with plane spiral coiling of the internal flow structures (fig. 2). Contortion of some of the flow structures resulted from the jamming effects produced by warmer glass being forced against cooler glass in the developing flange.

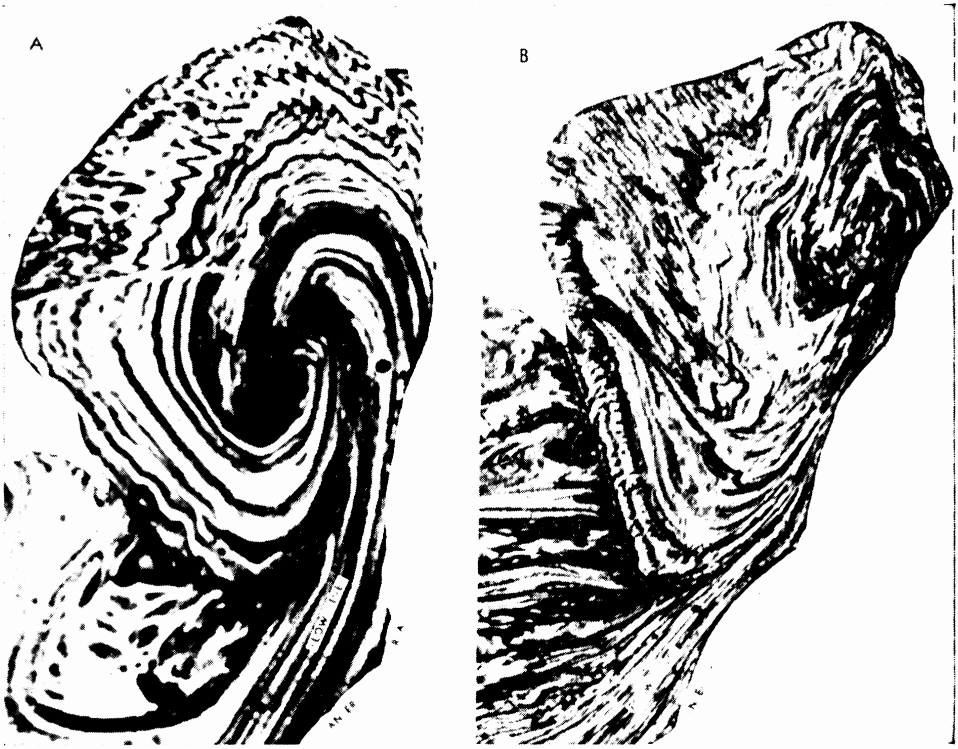

Fig. 2. Enlarged photographs (x20) of thin sections of flanges from button-shaped australites. Showing spirally coiled flow lines contorted in "chin" region and flow lines near anterior surface truncated in the trough structures between ridges. Both specimens from Port Campbell, Victoria.

As an outcome of the turbulence in the separating main airstream, there thus arose a newly created feature in the secondary australite shape, a feature delimiting the newly formed front surface from the remnant portions of the primary rear surface. In the uncoiled state, it is found by measurement along a prominent flow line that the glass of the flange would have been stretched back from the equatorial edge of the secondary shape for a distance equal to three times the present distance across the plane spiral structure, before the process of inrolling occurred. Inrolling was evenly developed all around the circumference of the secondary shape, as evidenced from the examination of a series of radial thin sections cut along the direction of the polar axis of flanged, button-shaped australites.

Approaching the final phases of high speed flight through the earth's atmosphere, the velocity of the newly shaped australite considerably declined. Much lower supersonic speeds prevailed, and the passage through transonic into subsonic phases was close at hand. Small amounts of drag were experienced by the front surface at this stage, with resultant whipping away of thin films of somewhat softened glass from certain areas, thus producing the "troughs" separated by the "ridges" which are so typical of the front surfaces of well-preserved button-shaped australites. This final, smaller-scale sculpturing effect is best evident from thin section studies (Baker, 1944), which reveal that the trough structures cut across the last-developed secondary flow line structures revealed immediately below the front surface (see fig. 2). These effects were rather more pronounced nearer the equatorial edges of the secondary form, more particularly on the front surfaces of the flange structures, for here the frictional forces created by the separation of boundary layer flow into the main airstream, were still operative to a lesser degree in the final phases of supersonic flight. Such forces were responsible for the complex "wrinkling" effects shown by the ridges on anterior surfaces of flanges near their equatorial edges.

At this stage of secondary shape development, aerodynamical flow phenomena had become far less effective in removing fused glass from front surfaces; temperatures were evidently not nearly as high as at earlier stages, and the work of the aerodynamical flow phenomena was largely confined to putting the finishing touches to the sculpture features. The equatorial skirt of subsidiary shock waves possessed by the original sphere at the onset of conflict with the atmosphere, had now been replaced by less oblique subsidiary shock waves attached to the small projections provided by the ridge structures on the front surface (fig. 3).

Behind each of the subsidiary shock waves attached to the ridges, existed narrow zones of expansion where it was possible for the trough-like structures to be partially scoured out during the very limited time of existence of such subsidiary shock waves. It is not yet clear what the nature of the aerodynamical flow phenomena would have been when considered in terms of the fact that ridges and troughs are concentrically arranged on some front surfaces, while on others, they are spirally arranged in sometimes clockwise, sometimes anti-clockwise fashion (Baker, 1956).

On passing from the supersonic through the transonic into subsonic phases of earthward flight, some of the flanged button-shaped australites evidently lost their flanges, more particularly those with less stable planes of union between flange and central body portion which had been subjected to rather more extensive scouring out of glass from trough regions neighboring the planes of union (see fig. 2). Such a process yielded the relatively common non-flanged, lens-shaped australites which are fundamentally identical with the central body portions of the flanged button-shaped australites.

SHAPE ORIGIN OF THE ELONGATED FORMS OF AUSTRALITES

The operation and effects of aerodynamical flow phenomena at ultra-supersonic speeds, followed by short-duration lesser supersonic and transonic speeds as outlined for the generation of secondary shapes from primary spheres, apply equally as well to the other known primary shapes of australite glass such as the ellipsoidal, dumbbell and apioidal primary forms. The general conditions, however, were possibly rather more complicated for dumbbell-shaped forms which presented bi-polar front surfaces to the shock wave

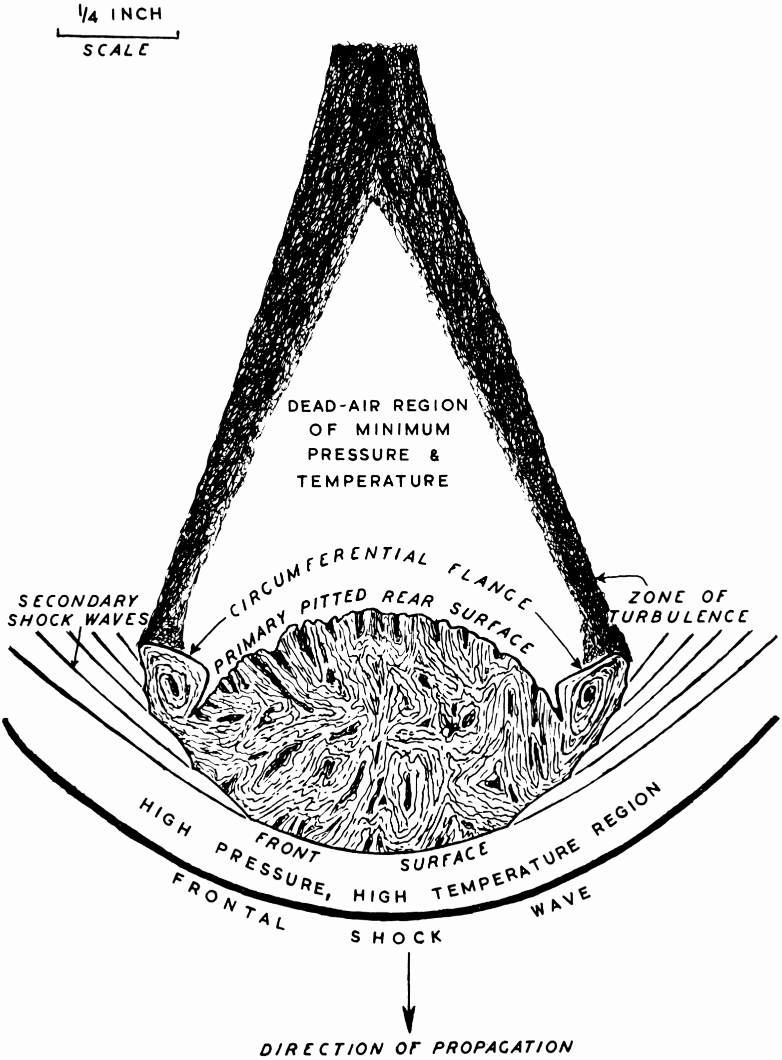

Fig. 3. Radial section of button-shaped australite with circumferential flange, showing complex internal flow pattern and relationship of the newly developed secondary shape to the surmised aerodynamical phenomena created during the end phases of supersonic flight through the earth's atmosphere.

and boundary layer flow phenomena. Nevertheless, identical features such as (a) flanges with plane spiral inrolling structures, (b) ridges and (c) troughs intervening between the ridges, were developed on their front surfaces during the phase of atmospheric flight earthwards, in much the same way as on the button-shaped australites which were modified from primary spheres. Moreover, the development of these features in comparable positions on the modified elongated primary forms of australites, testifies to their stable positions of flight through the atmosphere—nearly all travelled in such a position that their longer axes were maintained normal to the direction of earthward propagation. A very small number of types allied to the apioids, provide evidence of probably having fallen with their long axes parallel with the direction of earthward flight, such forms being of the "aerial-bomb" type.

For all the australite shape types, therefore, shock waves were produced at high speeds of flight, and only in shock waves can a state of steady flow of a permanent type be set up in the medium through which they have their passage, when the motion of the objects is limited to one direction. Under such circumstances, it becomes apparent that the australites in the earthward-falling cluster, behaved more or less in unison, each maintaining its own particular path of flight through the atmosphere, without tumbling about or shooting in all directions. Rotation of the forms was entirely unnecessary about an axis parallel with the direction of flight, and there is evidence to indicate that rotation did not occur; the ultimate secondary shapes and their structures all find satisfactory explanation in terms of the effects of aerodynamical flow phenomena arising at high speeds of flight.

Among experiments designed to emulate the secondary shapes possessed by australites, perhaps the most significant is one carried out by Dr. E. S. Hills some fifteen years or so ago. Small spheres of paraffin wax, when held under a controlled stream of hot water, developed shapes and structures simulating the shapes and structures of australites as they are found on the earth's surface. No rotation was imparted to the small spheres. The conclusion is that any rotation that did occur during the history of australite formation, was entirely pre-atmospheric phase, when the smaller percentage comprised of ellipsoidal forms, dumbbells and apioids, were produced as the common figures of revolution at their source in some unknown extraterrestrial environment. The rare aberrant forms evidently arose by accident prior to entry into the earth's atmosphere, for where not badly weathered subsequently, some of them show evidence of having been subjected to similar treatment by high speed flow during rapid atmospheric flight, as for the more normal symmetrically shaped australites.

SHAPE ORIGIN OF ROUND DISC-LIKE AND ELONGATED PLATE-LIKE AUSTRALITES

The formation of the rare and special disc-like and elongated plate-like types of australites, which are small, thin forms (1.0 to 1.5 mm thick), and are usually flat or sometimes bowl-like, is difficult of interpretation under the terms of any of the theories of shape development so far propounded. They can be more readily envisaged as resulting from special circumstances of high speed flow, commencing with the very smallest primary forms present in the cloud of australites that entered and survived the effects of rapid traverse through the earth's atmosphere. Thus the round discs derive from the smaller spheres, while the elongated plate-like forms were produced from the smallest spheroids of which we have evidence.

Reduction of the smaller spheres by ablation and fusion stripping while moving at ultra-supersonic speeds through the atmosphere, under the control of the aerodynamical flow phenomena outlined above for other australite shapes, yielded small, flanged button-shaped secondary forms in the first place. These had become reduced to a thickness of from 2 to 4 mm from spheres originally 4 to 10 mm across as determined from the radii of curvature of their remnant rear (primary) surfaces. Moreover, they possessed flanges which were more "flattened" compared with flanges on larger australites, and which constituted a greater bulk of each complete specimen than did the remnant body portions.

During ultra-supersonic flight, it is but a stage further for sustained aerodynamical phenomena to reduce the smallest formed button-shaped objects of australite glass to flat, round (in plan aspect) disc-shaped forms, which consist approximately of 90 percent broad, flat flange with internal flow lines coiled inwards in plane spiral fashion after the manner of flanges on larger australites. The remaining 10 percent of each of these flat forms consists of a minute body portion, and even this is wanting in some disc- and plate-like australites, which are thus fundamentally "flattened" flanges only.

Some of the smallest of the original spheres existing on initial entry into the earth's atmosphere, were probably completely consumed during ultra-supersonic flight, having been dissipated by the processes of ablation and fusion stripping, for ablation depends essentially upon the size of the surface, and with diminishing volume, the relative size of the surface increases—in a somewhat similar, but not identical way, raindrops that reach the earth's surface, have a certain minimum size. For these reasons, australites of microscopic dimensions are unknown.

During formation of the small disc- and plate-like forms of australites, it is evident that as the small primary spheres became smaller and "flattened" by ablation, the nature of the airflow at ultra-supersonic speeds changed considerably, and rather more special aerodynamical conditions than hitherto, were created at a certain stage. The major difference concerns the nature of the frontal shock wave and the consequent pressure forces associated therewith. Whereas the frontal shock wave ahead of the larger forms of australites and ahead of the smaller primary spheres and spheroids, lay obliquely down the airstream, because of their arcuate, convex front surfaces, the shock wave ahead of an ablation-reduced, "flatter" disc- or plate-like secondary modification, would approach normality to the airstream. The shock wave would thus be parallel to and ahead of the gradually "flattening" front surface, and thus more or less normal to the direction of propagation of the object. The shock wave pattern therefore changed from a fundamentally oblique type to a normal type during the all-important formative stages of these special, small secondary shapes. In the oblique shock wave, pressures, which depend upon deflection, were seldom more than 50 percent of the pressures generated when perpendicular (i.e. normal to the airstream) shock waves formed ahead of the "flattened" secondary forms, which presented a perpendicular reflecting surface to airflow.

"Flattening" of thinned, softened small forms occurred near the final phases of atmospheric flight, when the effects of supersonic speeds were diminishing and the transonic region was nearly reached. Frontal shock waves were then perpendicular, and pressures consequently up to 50 percent greater than hitherto, causing increased drag on the front surface. The thinnest forms (1.0 mm) were sufficiently softened to result in bending backward into bowl-shaped forms.

Since the bowl-like forms have small (5 to 6 mm) front surface radii of curvature, oblique frontal shock waves were re-established and pressures thus much reduced for the final stages of supersonic flight. After passing through the transonic region, these thin, disc-, plate- and bowl-like forms of secondary shapes, were no longer heated by frictional resistance at any point, and as cold, no further modified fragile bodies, they traversed the subsonic region to reach the ground undamaged. They are so light and thin that they were evidently wafted down through the lower, denser layers of earth atmosphere, and gently deposited upon the ground. Only in this way can the exceptionally well-preserved disc- and plate-like forms have escaped breakage, and thus account for the preservation of such lightweight forms as the smallest known complete australite—an oval, plate-like form of 1.0 mm thickness, weighing only 0.0645 grams, from the Port Campbell strewnfield, S. W. Victoria.

Since such forms are symmetrical and reveal no signs of damage on landing, it canot be accepted that they resulted from the flattening of plastic glass on impact with the ground, as advocated by some earlier theories.

SHAPE ORIGIN OF HOLLOW AUSTRALITES

The original shapes of the rare hollow australites were formed at some extraterrestrial source in company with the original forms from which the other shape groups of australites were produced. The presence within them of large internal cavities, had no influence on their external configuration.

Preservation of some hollow forms as complete entities throughout the process of frontal ablation during high speed earthward flight, demands the original development of primary hollow forms (most of which were spheres) possessing an eccentrically disposed internal cavity, so arranged within, that the walls of australite glass were thicker at one pole than at the other.

All the known hollow australites provide evidence that the stable position during earthward flight, was one in which the thickest wall was at the front. Those with sufficiently thick front surfaces, withstood ablation to the same extent as some of the larger of the solid australites. Similar sculpture features were produced upon their front surfaces, and a few examples developed small flange structures (Baker, 1956). In some, the front walls collapsed because they were thinner or were subjected to rather more ablation. Such examples sometimes reveal inrolled edges on remnant portions of the collapsed walls and sometimes show signs of minor secondary flowage of glass over the collapsed edges for short distances on to the typically smooth, "hot-polished" walls of the internal cavity.

CONCLUSIONS

This newly advanced "Aerodynamical Control Theory" of australite shape development, is not only capable of explaining satisfactorily all the characteristic shapes of secondary origin attained by flanged and non-flanged australites, but it also supplies a means for logical explanation of (a) plane spirally coiled circumferential flange structures, (b) relationships between the arcs and radii of curvature of front and rear surfaces of forms of different original size (Baker, 1955a), (c) variations in specific gravity as between cores and flanges of australites (Baker, 1956), (d) the rare colour banding in some flanges and its absence from central body portions (Baker, 1956), (e) the existence of occasional etch pits but no true bubble pits on the front surfaces of australites (Baker, 1956), and (f) the nature of such sculpture features as ridges, troughs and radial flow lines on front surfaces.

The theory thus provides reasons for the existence of two such sharply contrasted surfaces on australites—front surfaces which are virtually free of bubble pits and flow swirls, but which possess such features as ridges, troughs, radial flow lines and occasional etch pits, features which clearly distinguish them from rear surfaces (in well-preserved specimens), and which are of secondary origin. Rear surfaces only possess such initially developed sculptural elements as bubble pits (caused by escaping gas) and flow swirls (caused by flow streaming at the surface of primary shapes, and confined to much less bubble-pitted areas) ; they represent remnants of primary shapes possessing limited original sculptural elements, produced in an extraterrestrial birthplace.

References

Baker, G., 1944, The flanges of australites: Nat. Mus. Victoria (Melbourne), Mem. 14 (1), p. 7-22.

————, 1955a, Curvature—size relationships of Port Campbell Australites, Victoria: Roy, Soc. Victoria, Proc. 67, p. 165-219.

————, 1955b, Australites from Harrow, Victoria: Mineralog. Mag., v. 30, p. 596-603.

————, 1956, Nirranda Strewnfield australites, southeast of Warrnambool, Western Victoria: Nat. Mus. Victoria (Melbourne), Mem. 20, p. 59-172.

Black, J., 1953, The advance to supersonic flight: Discovery (Magazine of Scientific Progress), v. 14, p. 250-255.

Bonney, E. A., 1950, Engineering supersonic aerodynamics: New York, McGraw-Hill Book Co.

Clarke, W. B., 1855, On the occurrence of obsidian bombs in the auriferous alluvia of New South Wales: Geol. Soc. London, Quart. Jour., v. 11, p. 403.

Durand, W. E., 1935, Aerodynamical theory: Berlin, Julius Springer, vol. III, p. 212-243.

Fenner, C., 1934, Australites, part I. Classification of the W. H. C. Shaw Collection: Roy. Soc. South Australia Trans. and Proc., v. 58, p. 62-79.

————, 1938, Australites, part III. A contribution to the problem of the origin of tektites: Roy. Soc. South Australia, Trans. and Proc. 62, p. 192-216.

Grant, K., 1909, Obsidianites—their origin from a physical standpoint: Roy. Soc. Victoria, Proc., v. 21 (2), p. 444-448.

Opik, E., 1937, Researches on the physical theory of meteor phenomena, III: Observatoire Astronomique Université Tartu Publ. 29 (5), 69 p.

Pope, A., 1950, Aerodynamics of supersonic flight: New York, Pitman Aeronautical Publications, Pitman Publishing Corp.

Walcott, R. H., 1898, The occurrence of so-called obsidian bombs in Australia: Roy. Soc. Victoria, Proc. 11 (1), p. 23-53.

Watson, F., Jr., 1935, Origin of tectites: Nature, v. 136, p. 105-106.

Whitlock, T. O., 1943, Elementary applied aerodynamics: Oxford University Press, Humphrey Milford.