RECORDS OF THE GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

No. 1964/12

TITLE: SLAGGY SILICEOUS GLASS OCCURRING NATURALLY ON THE SURFACE AT VARIOUS LOCALITIES IN THE SOUTHERN PART OF WESTERN AUSTRALIA.

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DATE: 9th June, 1964

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SLAGGY SILICEOUS GLASS OCCURRING NATURALLY ON THE SURFACE AT VARIOUS LOCALITIES IN THE SOUTHERN PART OF WESTERN AUSTRALIA

by

A. F. Trendall

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ABSTRACT

The origin of seven specimens of scoriaceous slaggy material collected from the surface over a wide area of southern Western Australia presents a problem. The material is in lumps up to 18 inches across and is reported to be locally very abundant. It is highly (about 60 per cent) vesicular and the solid part consists about equally of small quartz grains, sometimes partly fused, and siliceous glass devitrified to a variable extent. Pieces of charcoal may occur within or adjacent to it. All seven specimens are believed to have the same origin. They resemble material already described from Victoria and South Australia and are thought to originate by rapid fusion of clayey soil at the base of trees struck by lightning. In the appendices it is argued that siliceous glass, described in the literature as due to the burning of haystacks, may have been caused by lightning fusion, and also that the classical fulgurite tubes of fused sand were formed around roots acting as a lightning conductor.

INTRODUCTION

This Record is almost a direct transcript of unpublished Petrologist's Report No. 60, dated 11th May, 1964. It has been reproduced as a Record partly because a wider circulation was needed and partly to incorporate new information and modify the views first set out in the two appendices, as a result of a wider study of the relevant literature. It still represents a progress report on a problem not finally solved.

In February 1964 my attention was drawn by Mr. J. Sofoulis, while we were walking in the company of Dr. Horwitz over a part of the Widgiemooltha 4-mile sheet, to an irregular lump of slaggy material about 18 inches across partly buried in the soil. He had at first taken these to be artificial products but later, through their abundance and wide distribution, had decided that they were of natural origin and probably the result of fusion of soil by lightning.

Since then I have discussed the material with several people in Perth (principally Mr. Merrilees of the W. A. Museum, Mr. Morris of Government Chemical Laboratories, Mr. Ewers of C.S.I.R.O., Mr. Hatch of the Forests Department, and Dr. McCall of the University), looked through the relevant published literature, accumulated a total of seven similar specimens, and examined thin sections of three of the pieces; as a result I set out in this report brief descriptions of the material in the possession of the Geological Survey of W. A., summaries of possible origins and of the literature, preliminary conclusions and suggestions where best to look for further evidence.

Although the problem may seem only slightly related to geological fundamentals, it has at least two aspects which give it significance: firstly, there is a suggestion that these objects are genetically connected with tektites, and secondly, if they are the result of fusion by lightning, then age determinations of the separated glass could throw light on the longevity of land surfaces.

I am grateful to all the persons mentioned above for their co-operation and discussion, to the Government Chemical Laboratories for the analysis below and to Mr. W. H. Cleverley, for further information received after the original report was written.

DESCRIPTION OF AVAILABLE MATERIAL

List of specimens.

The seven specimens in the Survey collection are listed below:-

1. 9504 (Collector unknown; about 1900). Locality: near Gooseberry Hill. Remarks: This piece about 4 inches across has the comment "from burnt Eucalyptus", and has a piece of charcoal

embedded in it. Nothing more is known about it.

2. R851 (Collector A. F. Trendall; February, 1964). Locality: south-east part of Widgiemooltha sheet. Remarks: This is part of the piece to which Mr. Sofoulis first drew my attention. It is very fresh-looking.

3. R852 (Collector J. Sofoulis; received March, 1964). Locality: Widgiemooltha sheet. Remarks: A typical piece; more weathered than R851 in appearance.

4. R853 (Collector J. Sofoulis; received March, 1964). Locality: Lake Cronin. Remarks: Picked up much earlier when the collector first suspected that the material was not artificial.

5. R854 (Collector W. H. Butler; received March 1964 from Mr. Merrilees). Locality: Cowarna Downs. Remarks: The collector's comments are "surface - considerable quantities - scattered for miles - mostly on west slopes of low hills - nearest mine said to be about 15 miles away". It was collected in May 1962 and a note accompanying the specimen reads "Examined and sectioned at University Department of Geology - said to be slag - might be natural - bushfire - deep root or hollow log acting as chimney".

6. R855 (Collector uncertain; received April, 1964 from Mr. Turnbull). Locality: Ardath. Remarks: This small piece is reputed to be associated with the temporary emission of gas and dust from a fissure in the ground known as the "Ardath blow-hole".

7. R856 (Collector W. H. Butler; received May, 1964) (from Mr. Merrilees). Locality: Cowarna Downs. Remarks: More material from the same place as R854.

Field Occurrence

Five of the seven specimens are known to be from pieces lying "on" or "at" the surface. The large lump from which I collected R851 had about half its bulk (18 inches diameter and spheroidal) buried and the exposed half closely resembled a small termitary in general appearance. Unfortunately I did not at this time appreciate the importance of examining the details of its relationship to the enclosing earth.

For reasons given later, I am not inclined to attach much weight to the note "from burnt Eucalyptus" referring to 9304. Nor do I think that the "Ardath blow-holes" can be taken into very serious consideration until the present nebulous reports about them have been examined more closely (as indeed they should be).

Distribution

The specimens come roughly from between latitudes 30°-33°S and longitudes 116°-123°E. This is a comparatively limited area of the State but it is not known whether this area has any significance as a true limit of occurrence or whether it is merely an accidental limit of collection. The latter is strongly suspected. Within this area Mr. Butler's evidence (see R854, above) is very strongly suggestive that within the area the material is locally very much more abundant than the average.

Since the original report was written I have been informed by Mr. W. H. Cleverley, Head of the Department of Geology at the Kalgoorlie School of Mines, that he has been aware of the existence of this problematical slag for several years and had, independently of Mr. Sofoulis, come to the conclusion that its distribution was not consistent with an artificial origin. He had considered both lightning-strike and bushfire origins and knew of two localities with an association between burnt trees and exceptionally large surface spreads of the material. I hope to be able to visit these in due course.

Macroscopic Appearance and Density

All of the specimens are slaggy in appearance, and all but R855 are highly scoriaceous and vesicular. The broken surfaces show black to dark reddish brown opaque structureless material full of bubbles (mainly spheroids; sometimes irregular) and with variable amounts of small quartz grains. The general shape of the fragments is irregularly branching and coral-like. R855, although vesicular, is much more solid on the cut surface and is greyish in colour with many almost white patches; the shape of the whole piece cannot be inferred from the specimen available. The outer limit of fusion seems to be sharply marked by a smoothly curved and rather shiny bounding surface which is mamillary in R851 and much smoother in 9504. 9504 is exceptional in having a tendency for a planar arrangement of the lobes, like certain stratiform coral reefs. Both R853 and 9504 have indentations in this surface whose regular pattern suggests the impression of some confining body. 9504 and R855 have, trapped in irregularities of the lobate branches, small pieces of charcoal.

Small rectangular prisms cut entirely within the outermost bounding surface were cut from R851, R854 and R857 (an additional piece from the Widgiemooltha sheet not listed above). The volumes were obtained by measuring the edges, and the bulk densities of each, including vesicles, were 1.06, 1.11 and 0.85 respectively. Each piece was then ground to powder and the densities of the powders were determined by pycnometer. The valves were 2.59, 2.84 and 2.52. Thus these pieces contained 59%, 61% and 66% of vesicles respectively.

Microscopic Appearance

I have not made any attempt at a systematic petrographic study of this material, as I believe that in a short time enough further material will be available to see the petrographic needs of the problem more clearly. The following notes summarise the main features of R851, R854 and R855.

R851. Two sections of this rock were cut, in both of which the bulk of the area is covered by rounded bubbles. The intervening solid network (what may be called the material which holds all the bubbles together) has seven constituents: clear isotropic glass, glass cloudy with brown feathery crystallites, quartz grains, relatively coarsely crystalline pryoxene, dense material probably consisting of finely crystalline pyroxene, melilite, and other miscellaneous fragments. In both slides the first three constituents form well over 90% of the solid volume of the slag. The quartz grains are 0.1-0.5 mm. across and subrounded to subangular. They are noticeably cracked, presumably due to thermal shock, and a few are wholly or partly (along cracks) fused to lechatelierite. The feathery crystallites are pale brown and have an extinction angle of about 40^{o}. They are probably pyroxene; locally they are apparently gradational into pyroxene laths about 0.1 mm. long and also into patches of randomly felted laths probably also of pyroxene. There is a small patch of melilite in one slide.

R854. As in R851 holes form most of the slag. The solid material is partly clear colourless glass criss-crossed with a meshwork of bright green aegirine-augite laths up to 1 mm. long and 0.05 mm. across; these are almost random but there is a local tendency towards a radiate pattern. These areas with a clear-cut distinction between glass and crystals grade into areas where the pyroxene is finer and colourless, with a larger extinction angle, and where the intervening glass is cloudy and brown; the end-stage of such a gradation is reached where separate components are indistinguishable in a slightly polarising almost opaque devitrified glass. Quartz grains are rare in the thin section cut; they are rounded and show no evidence of fusion. There are two patches, each about 3 mm. across, of aggregates of platy melilite crystals of a.g.d. 0.1 mm. Each crystal is zoned to a rim of gehlenite.

R855 differs from the foregoing slags in that undevitrified glass is very rare. It occurs mainly in parts of the rock where either pyroxene in elongate laths or tabular melilite crystals are best developed and reach about a millimetre in greatest diameter. As in the previous specimens these two minerals seem to be locally mutually exclusive in the process of crystallisation. Over most of the area of the slide fine-grained melilites or pyroxenes lie at random in a dense structureless devitrified glass and there are many irregular vaguely defined areas where no crystalline structure is resoluble at all. In places a sharply defined boundary between a well crystalline and a poorly crystalline area becomes gradational and vague as it is followed across the slide. One large (7 mm.) quartz grain appears in the 3 slides cut; it shows signs of partial fusion in one part of the edge.

Chemical Composition

Analysis 'A' below is of M851 by the Government Chemical Laboratories. Analysis 'B' is of a piece from near Paris gold mine (near Widgiemooltha) not examined by me, and analysed at the C.S.I.R.O. laboratory.

	'A' wt.%	'B' wt.%
SiO_2	64.9	59.2
Al_2O_3	9.12	13.0
Fe_2O_3	5.75	9.4
CaO	12.0	10.4
MgO	3.27	5.7
Na_2O	2.05	2.0
K_2O	1.64	1.1
MnO	0.02	n.d.
TiO_2	0.06	n.d.
P_2O_5	0.15	n.d.
Cu	n.d.	0.01
H_2O+	0.41	n.d.
Total	99.37	100.8

Analyst (B): C. E. S. Davis

TABULATION OF NATURAL GLASSES

A genetic classification of naturally formed siliceous glasses is given below, with examples and selected references. The principal or original author's preferred origin is accepted for the purpose of this review; some criticisms relevant to the present problem appear later.

1. Volcanic glass.
   Examples too numerous to list.

2. Fusion by friction during faulting.
   Pseudotachylyte. Few good examples of extensive fusion.

3. Extra-terrestrial glass (may be impact fusion).
   Meteorites (Maskelynite); Tschermak, 1872.

4. Fusion by meteoritic impact heat (impactite).
   Meteor crater (Barringer crater); Rogers, 1930
   Wabar, Arabia; Spencer, 1933
   ?Aouelloul, Sahara; Smith and Hey, 1952.
   Henbury, central Australia; Spencer, 1933
   ?Kofelsite; Suess, 1936.

5. Fusion by lightning.
   (a) of rock (rock fulgurites);
   Saussure, 1786
   Abich, 1870
   Rutley, 1885
   Julien, 1901

   (b) of sand (tubular fulgurites in the commonest sense);
   Withering, 1790
   Fischer, 1928
   Petty, 1936

   (c) of soil (by ball lightning);
   Tempe Downs) Baker, 1953a
   Mt. Remarkable)

6. Fusion by combustion.
   (a) of coal ash as a result of self-combustion of a bituminous coal.
   Leigh Creek, S.A.; Baker, 1953b

   (b) of the "mineral" fraction of vegetation during its own combustion.
   (i) haystack fires; Milton & Davidson, 1946
   (ii) grain fires; Velain, 1878
   (iii) straw fires; Dana, 1898, p.443, fig.7
   Fenner, 1940
   (iv) tree fires; Pruett, 1939
   Milton & Axelrood, 1947 - this material (wood-ash stone) is not a glass.

   (c) of adjacent or contained foreign material during burning of vegetation.
   Macedon glass)
   fused trachyte) Baker & Gaskin, 1946
   fused basalt)

7. Glass of unknown origin.
   (a) Tektites; O'Keefe, 1963
   (b) Darwin Glass; Hills, 1915; Taylor & Solomon, 1964
   (c) Libyan Desert Glass; Spencer, 1934

DISCUSSION

Before the origin of the slag is discussed three basic questions present themselves: (1) were all seven specimens formed in the same way? (2) could the material be of artificial origin? (3) do they collectively resemble any of the known natural glasses sufficiently closely for the same origin to be assumed? These are discussed first.

All the specimens except R855, from Ardath, are so similar in their general clinkery scoriaceous appearance that an assumption that they are cogenetic seems to be reasonable. All except 9504 and R855 are also known to have been found lying on a soil-covered surface; but the surface markings of 9504 and R853 are so similar, and R855 and R854 present so many similarities in thin section, that I believe that R855 was formed by the same process as the others. However, that may be, I assume from this point on that the remaining six are cogenetic, and that evidence from any one can validly be used to erect a hypothesis for the origin of all.

When he first noticed this material Mr. Sofoulis accepted it as an artificial slag. He was later forced to the conclusion that its abundance and wide distribution completely ruled this out. Mr. W. H. Cleverley came to the same conclusion independently, and I assume that Mr. W. H. Butler (see R854, p.5) collected it as natural material. In composition (p.7) it does not resemble furnace products from the smelting of metals and I accept that its origin must be sought in natural processes.

At least three other examples of closely similar (it is not intended here to make a detailed comparison) slags lying at the surface have already been described, one from Victoria (Baker and Gaskin, 1946) and two from South Australia (Baker, 1953). For the Victorian example, Macedon glass, Baker and Gaskin have suggested fusion by a bushfire, and support this argument by reference to two examples of fusion of rock by bushfires. For the South Australian examples Baker has suggested fusion by ball lightning. I believe that both the South Australian and Victorian clinkers have the same origin as all those described in this report and that all are formed by fusion of soil by lightning. Other material referred to in the literature but never closely described, from South Australia (Fenner, 1940) and Victoria (Baker, 1959), and believed by the authors to be the result of straw fires, are probably formed in a similar way (see Appendix I).

Having answered the three questions first put and stated the conclusion to which this discussion will lead, I set out below the arguments for and against a lightning fusion origin of these slags and my directly relevant reasons for challenging a bushfire origin for the Macedon glass.

The range of choice for an origin for natural glass may be seen from the review above. Taking the sub-headings of that review in succession I discount a volcanic origin for all but R855 of the seven slag specimens firstly on the grounds that the conduits for such extensively distributed volcanic glass are unlikely to have gone undiscovered and secondly on the grounds that the fragility of the material strongly suggests that it has been fused in situ. Fusion by friction during faulting is obviously inapplicable for surface material. Any connection with meteorites or tektites I also think unlikely on the grounds of in situ fusion. There remains the possibilities of fusion by lightning or combustion.

If an origin by combustion is proposed, then only fusion of foreign material during bushfires is applicable. (Only one reference to glass formed by burning of a tree (Pruett, 1939) exists and I have not yet been able to refer to this; it is still a possibility but the positive evidence for lightning set out below is strongly against it.) Baker and Gaskin (1946, p.100), in discussing the Macedon glass, have admitted that temperatures in bushfires approaching the 1800°C necessary for extensive fusion of quartz (Rogers, 1946) are not known (Mr. Hatch, Forests Dept., confirms this) but argue that such temperatures may be reached by drawing air through burning charcoal at high speed. They picture a situation such as the combustion of a tall hollow tree where these conditions would be reached. They then cite two supposed examples of rock fusion by bushfires, one from Macedon and the other from Mount Franklin (both in Victoria). The Macedon example consists of a thin fused surface skin on a piece of trachyte, similar to the fused surface skin originating from lightning strikes and known as rock fulgurites (e.g. Rutley, 1885- the only reference so far seen by me). The Mt. Franklin occurrence is more complex. Although Baker and Gaskin (1946 pp.97 and 98) say that pieces of carbonized wood were found still embedded in the re-fused outer surfaces of basalt fragments caught up in a partially burnt-out tree trunk, it is clear that what they actually found was a fallen partly burnt tree trunk about 2 feet in diameter with "films, gobbets and flat cakes" of glass on basaltic soil scattered around it.

A photograph of one piece of "fused basalt" shows that its general appearance is exactly similar to any of the Western Australian slag specimens under discussion. R855 and 9504 both have pieces of charcoal embedded.

Now if, to raise the temperature high enough to make a slag of this type, it is necessary to postulate some special bush-fire conditions (such as a hollow tree acting like a factory chimney) it is unlikely that any of the burning charcoal involved would survive the intensity of the blaze as unburnt charcoal or that conditions would be sufficiently stable in the heart of the natural furnace for any piece of charcoal to leave an impression on the molten material. Surely no tree burning sufficiently fiercely to generate a temperature of 1800°C would ever remain only partly burnt, and no charcoal in contact with a glass at that temperature would remain charcoal unless oxygen were absent? If there is no good reason to suppose that pieces of basalt were actually caught up in the burning tree the recorded situation seems to fit closer with a hypothesis that the tree in question was struck and felled by lightning which passed to the ground and fused the soil. It is for this reason that I doubt whether much weight can be attached to the note "from burnt Eucalyptus" on 9504. A person would naturally so describe a piece of slag found on the ground below a "burnt" (lightning-struck) tree.

The only argument against a lightning fusion hypothesis for the Macedon glass given by Baker and Gaskin (1946, pp.95-98) is that it does not resemble the known tubular sand fulgurites. This is true, but it is more reasonable to suppose that elongate tubular fulgurites are formed when lightning strikes sand (8 analyses given by Frondel, 1962 have 88-99% silica) and that irregular scoriaceous fulgurites result when lightning strikes soil. Baker (1953a, p.30) has himself noted a resemblance between Macedon glass and the lightning-formed Tempe Downs and Mount Remarkable sinters, which have 69 and 64% silica respectively and as lightning of equal energy is as likely to strike soil as sand the absence of its effects would be more remarkable than its presence.

Returning to the association of charcoal with R855 and 9504 of the present collection and with the Mt. Franklin glass of Baker and Gaskin (1946) I suggest that this is more reasonably explained by the distillation of wood fragments contained in the soil during lightning fusion. In this way a piece of wood in contact with soil fused in situ at 1800°C would be converted to charcoal without combustion, while in the relatively undisturbed conditions the glass would retain the impression of the charcoal as it cooled.

The irregularly lobed shape of almost all the fragments has already been noted. In these lobes the bubbles are still spheroidal and there is no evidence of flow. I regard this as further evidence of static fusion _in situ_.

One difference between the three Western Australian slags sectioned and any other described fulguritic or "bushfire" glass is in the presence of abundant crystals up to a millimetre long of easily recognisable minerals - melilite and pyroxene. This suggests a comparatively low rate of cooling. The exact time taken for such crystallisation is not certain, but is likely at least to be of the order of tens of minutes and may be several hours. It is difficult to visualise the fierce combustion of a tree ending in such a way that the material is held at a high temperature for such a period while at the same time unburnt charcoal remains in contact with the slag, but if it is supposed that these slags were fused by lightning at a shallow depth in the soil, then the slow cooling is explained particularly as the first-cooled vesicular edge would provide good additional heat-insulation for the interior. The extreme vesicularity of the material is to be expected with rapid fusion of clay, since water vapour will be produced instantly.

The following sequence of events is suggested for the formation of these slags:

1. Instant (0.001 seconds - Rogers, 1946, p.122) raising of temperature to (?) 3,000°C along planar or linear path of discharge through ground.

2. Rapid absorption of excess heat by fusion of clay fraction to vesicular melt. Heat transfer mainly by conduction and shape of fused volume controlled and established at this stage by irregularities in soil structure. Contained quartz grains begin to melt, especially in inner part (and depending on bulk composition of melt). Time: 1-5 seconds?

3. Rapid freezing of peripheral parts as temperature gradient becomes too low for further fusion. Highly vesicular solid margin acts as heat insulator to lessen cooling rate progressively. Time: 10-30 seconds?

4. Slow cooling of internal parts to give coarsely crystalline core. Time: 1-2 hours?

I suggest the name "fulgurite slag" for the material of these bodies.

EVIDENCE REQUIRED

Information needed about these slags comes under the following headings:-

Broad distribution.

The only evidence for a connection with tektites is that their known occurrence corresponds roughly with the tektite strewn-field. I believe that when their existence is widely known, they will be found all over the State (and, indeed, the world) given certain conditions (See Appendix I). This is only a personal guess; its truth or falsehood must be determined by observation.

Immediate environment.

More data are required on the relationship of the slags to their enclosing soil. In particular a correlation must be sought (chemistry, mineralogy) between slags and soil, to ascertain whether they are formed by soil fusion in situ.

Petrology of the slags.

Apart from a fuller collection of data concerning the range of their chemical mineralogical and structural features a study is required of the relationship of vesicularity, crystallisation, quartz fusion, etc. to position of the sample in the mass.

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APPENDIX I - "STRAW SILICA GLASS"

In this Appendix the corresponding section of Petrologist's Report No.60 is first copied in full between quotation marks, and a re-assessment is given at the end.

"Baker and Gaskin (1946, p.100), Baker (1959, p.224) and others (e.g. Frondel, 1962, pp.327-8) have accepted Fenner's (1940, pp.320-1) reference to glass formed by haystack fires as authentic. Fenner's (ibid) description of the mode of occurrence of this material is worth quoting in full: "Not the least interesting of naturally occurring silica glasses are those found from time to time in the country, usually fairly scoriaceous but sometimes massive. This material varies from green to black and smoky-grey, and at times is found in large lumps up to 20-30 pounds in weight. Enquiry usually shows that the material has been found on or near the site where a straw-stack has been burnt". Baker (1959, pp.306-7) has illustrated much "straw silica glass" from Victoria showing clear impressions of straw. Fenner's analyses of 2 samples of such material are admittedly remarkably high in potash, and without access to the material I would not like to be too definite but three points can be made here:-

1. For the reasons discussed above I find difficulty in visualising a mechanism whereby burning material can impress itself on glass fused by the heat of its own combustion.

2. It is difficult to see a reason for the aggregation of siliceous material from a burning haystack into large lumps (cf. Baker, 1959, p.224 - "it is known that a piece of 'straw silica glass' the size of a man's fist, is often left behind after the rather more rapid incineration of a haystack" - how?).

3. Both the preceding difficulties are overcome by supposing that such glass forms by fusion of soil where lightning strikes the ground <u>through</u> a straw stack. As in the formation of charcoal by distillation of wood fragments in a low-oxygen environment at very high temperature already suggested for the fulgurite slags

the rapid impression of distilled straw on the melt would be expected. The lumps would also be expected in a restricted area of entry of the lightning discharge.

Is it therefore possible that both glass and reported haystack fire are both effects of the one cause (a lightning flash), rather than that this glass is caused by the fire independently of other effects? Is this why, in Fenner's account, enquiry only usually shows that such glasses are found on the site of haystack fires?"

Since the preceding paragraphs were written a very full description has been published of a quantity of siliceous glass found on the site of two burned haystacks at Gnarkeet, Victoria (Baker, 1963). I find it possible to interpret this material as glass formed by the instantaneous fusion of hay and adjacent, or adhering, soil by lightning. I set out below (1, 2 and 3) points which should be borne in mind in deciding whether the fire could not have been started by lightning, whether entrapped soil did not contribute to the glass, and (4, 5 and 6) some further arguments on the side of fusion of the glass by the lightning stroke that started the fire.

1. Was the fire really due to auto-combustion?
   (a) The hay had dried for 2 months, during which only 13 points of rain had fallen.
   (b) The stacks ignited in calm weather only 31 days after stacking.
   (c) No other stacks ignited in the district.
2. Could lightning have started the fire?
   (a) It started at 1 a.m. when lightning could have passed unnoticed.
   (b) Schonland (1950, pp.38-39) authenticates 'bolts from the blue', or lightning strikes originating from distant (up to 30 miles) clouds.
3. Much foreign material (soil) must have gone into the glass.
   (a) 3% of SiO_2 seems very high for hay, and this is the minimum figure assuming that all the silica from the

325 tons of hay is concentrated in the glass.

(b) Clots of soil (Baker, 1963, p.27) and quartz grains (p.33) are present with the glass.

(c) The only good instances of pure wood ash stone (Milton and Axelrod, 1947) differ radically in silica content from the examples listed by Baker.

4. I still believe that the temperatures necessary for the large-scale fusion of silica in any form would not be attained in, e.g., a haystack fire in calm weather.

5. I still cannot conceive the mechanism of concentration of this material into lumps, its maintenance in a molten state among the flames as the stack burnt and its final receipt of the impression of unburnt hay when it is the combustion of that very hay that is supposed to have kept it fused. On the other hand a lightning-fusion origin would explain why the only unburnt material is the pieces of distilled stalk protected by the glass from the subsequent fire.

6. Is it significant that at the foot of a eucalypt close to the large stack there were 3 or 4 square feet of more massive clinker 4 inches thick, and that this tree was more severely burnt than others nearby? This clinker was in contact with the foot of the tree, and there seems to be no reason why the material should have concentrated there. On the other hand if lightning struck and burned this tree could the flash have run over the surface as a sheet beneath the stacks by some unknown dielectric effect of the hay?

For the final solution of the straw silica glass problem it is necessary that it should be found under haystacks demonstrably ignited by artificial means. Unfortunately this is probably a rare occurrence. Like bushfires, it is probable that lightning ranks high as a cause of haystack fires, followed, a poor second, by cigarette butts.

APPENDIX II - ARE FULGURITES ROOTS?

As in the preceding Appendix the earlier version is first copied between quotation marks and additional notes then follow.

"It has never been questioned in the literature that the irregularly branching tubes of silica-rich glass to which the name "fulgurites" is most typically applied are due to the fusion of sandy soil by direct lightning strikes. The following points, none of which counts for much alone, have accumulated to sow a seed of suspicion in my mind that the formation of these tubes, as well as of the fulgurite slags with which this report is concerned, is associated directly with lightning striking trees or bushes, and that the root-like form of fulgurite tubes is a direct reflection of their origin by fusion of sand adjacent to the roots of lightning-struck trees:-

1. The pieces of charcoal embedded in fulgurite slags were attributed above to distillation of wood fragments in the soil. My impression is that wood fragments are never common in soil and these are slightly more credible as pieces of root, which are.
2. Two occurrences (9504 of this report and the Mt. Franklin "fused basalt" of Baker and Gaskin, 1946) seem to be associated with lightning-struck trees.
3. I have not yet found a reference in the literature to the recovery of a fulgurite from an observed lightning strike on open ground.
4. Lightning most commonly strikes trees, posts, houses, etc.; rarely the ground.
5. The association of lightning and fulgurites was first noted by Withering (1790), "who described a fulgurite from under a tree that had been struck by lightning" (Frondel, 1962, p.324).
6. The structural similarity of fulgurites and roots has been remarked on by many authors (e.g. Rogers, 1946, p.118) and there is indeed a striking resemblance.
7. Fulgurite tubes often occur in groups (Frondel, 1962, p.324). The simplest explanation is that these represent the root system of a single tree or bush.

8. There is no satisfactory explanation of the central cavity in fulgurite tubes.

9. Fulgurite tubes are irregularly distributed and are locally concentrated.

Consider these points in conjunction with the following hypothesis:-

Lightning most commonly strikes trees or bushes. If these are growing in very sandy soil, the resistivity of this will be higher than that of the green wood. An enormous current will flow momentarily through the roots, generating enough heat to fuse a thin layer of the adjacent sand and distill the wood to charcoal; in the processes gas will be produced and distend or puncture the tube locally and before freezing the tube may collapse slightly on to the carbonised root. Smouldering downwards of the surface-ignited tree will later gradually reduce the carbon to ash. Alternatively gas from the distilled root may froth up the whole of the fused material with the remnants of the root (Rogers, 1946, fig.2). Such branching systems of fulgurite tubes may, after lowering of the surface by erosion, appear as groups of small fulgurites; parts of the tubes may well be transported elsewhere and confuse the evidence for their real mode of occurrence. If, on the other hand, the trees are growing in clayey soil (and if this is damp and the particular trees have a high resistivity) the discharge may, on reaching ground level, prefer to run directly from the tree into the soil on one side or other, and a lump of fused soil may be formed in the soil close to the foot of the tree. Any roots nearby will be distilled to charcoal and the tree will be partly burnt.

The main feature of this hypothesis is that it supposes a complex inter-relationship between the three factors of soil, vegetation and occurrence of electric storms in the control of fulgurite distribution and type. Important consequences are that fulgurite tubes would give indications of paleoclimate (they occur in the Kalahari and Sahara, for example) and that distribution would be expected to be erratic. The hypothesis fits well with certain minor puzzling points (W. H. Butler - "mostly on west slopes of low hills" for R854 above is easily compatible with vegetation control). Although I forecast above a world distribution of fulgurite slags, it may well be that only eucalypts have the required electrical characteristics needed for their formation.

Before swallowing the hypothesis too enthusiastically the fulgurite literature needs to be looked into more fully, however; the ideas set out in this Appendix do only represent a suspicion."

The literature on fulgurites is large and has never been completely compiled. Barrows (1910) lists 60 references and in the subsequent 54 years another 64 papers have probably appeared. From my own reading of a representative collection, in the first place to see whether any association with roots had been described, it appears that the foregoing appendix has two outright mistakes:-

1. Lewis (1936, p.57) and Fenner (1949, p.138) have both suggested that fulgurites may form around roots acting as a conductor for lightning discharge. My first sentence was thus at fault.

2. Pfaff (1822), Wicke (1859), Van Bastelaer (1883), Wood (1910) and Simpson (1931) have all reported the finding of fulgurite tubes after observed strikes. All of these except Van Bastelaer are on open ground, where roots from cleared or dead trees may have taken the discharge, but Van Bastelaer's description is of the formation of a fulgurite in a heap of building sand.

On the other hand Verco (1907) gives an additional description of a fulgurite beneath a struck tree, and Fiedler (1817; 1822), Spiess (1897), Geinitz (1902), Lewis (1936) and Van Tassel (1955) all record an association between roots and fulgurites. Schonland (1950, p.56), in an authoritative account of the behaviour of lightning, states that when lightning strikes dry ground 'the discharge current does not spread evenly through the earth but is concentrated in those layers which conduct electricity better than others', and mentions water pipes and telephone cables. Schonland (ibid, p.58) accepts Lewis' (1936) suggestion that roots cause fulgurites, since roots, like pipes, could have greater conductivity than dry sand.

I summarise my present view of the fulgurite tube situation as follows:-

1. There is evidence of a fulgurite-root association.
2. It is physically to be expected that lightning would follow roots in dry sand, especially if these were old and carbonised.
3. Tube fulgurites can be formed in the absence of roots.
4. The shape of fulgurites, their irregular distribution, and their concentration in groups, all still support the idea that most fulgurites represent roots.