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ABSTRACT

Aouelloul crater glass is studied from the point of view of the hypothesis that it is formed by impact on the local (Zli) sandstone. It is noted that the chemical analyses of the two materials do not agree in a satisfactory way even if the most significant discrepancies, namely those in Fe and H_2O are overlooked.

The possibility that the water has escaped during a phase of shock heating is examined; it is found that the impact theory does not allow sufficient time, under the conditions of gravity and temperature, for the bubbles of water vapor to escape.

The formation of the relatively homogeneous matrix glass is also difficult to understand in terms of calculated diffusion coefficients. It is particularly hard to understand how the additional iron found in the glass could have diffused through the very viscous material in the very brief time available.

The region of gray glass noted by Chao and coworkers as enriched in iron is found to be impoverished in silica and enriched in most of the other oxides, so that it resembles one of the less silicic tektites.

Measurements of the diffusion borders around lechatelierite bodies indicate that diffusion has, in fact, been negligible in the Aouelloul material.

The data do not support the hypothesis of impact origin for the Aouelloul glass. They are easier to reconcile with the original suggestions by Campbell-Smith, Hey, and Monod that the Aouelloul glass

is a kind of tektite and is of extraterrestrial origin. It may, in fact, be an example of the "parent bodies" suggested by some theorists to explain the distribution of tektites.

PHYSICAL CHEMISTRY OF THE AOUELLOUL CRATER GLASS

The Aouelloul Crater

The crater of Aouelloul lies in the Mauritanian Adrar, about 40 kilometers southwest of Chinguetti at 20° 15'N, 12° 41'W. The best way to reach it is by the local airline from Nouakchott to Atar, and thence by jeep or landrover. The trip from Atar takes about four hours; it follows the route toward Chinguetti as far as the Pass of Amojjar; a short distance beyond the pass, the trail forks, and the right fork leads past the crater. A guide is needed for some stretches of the trail, which are not marked because of shifting sand.

The crater was found by Monod (1952). It is about the size of a college football stadium (diameter 250 meters); and this fact gives confidence that the phenomena at the crater are small enough to be comprehensible, particularly in the light of the studies of much larger artificial explosion craters. The walls are from 6 to 30 meters in height. On the north, the wall is low; it is possible to drive a vehicle into the crater at this end.

The crater is formed in level beds of Ordovician sandstone which extend for scores of kilometers in all directions without serious tilting. There is no local volcanism. No volcanic ash has been reported at or near the crater by any of the students.

The crater itself is composed of tilted blocks of the local sandstone. This is of two kinds: the Oujeft sandstone (O_2 in the French notation) and, overlying it, the Zli sandstone (O_3). The Zli has been eroded away over most of the area around the crater; there are only a few hillocks which remain.

Along the crater rim, and inside the crater, measurements of the dip and strike show that the beds slope outward in most places (Monod, 1952; the present writer's few hasty measurements are in agreement with Monod's). In some places, however, there is a definite inward tilt. Chao et al (1966b) have attempted to explain these unexpected dips on the ground that the blocks have been overturned, in accordance with the Shoemaker theory of crater origin. It is possible, however, to determine which face of a block was originally uppermost by means of marks called tigillites. These are the burrows of an unidentified Paleozoic animal (Häntzschel, 1962). It has been established that the curvature observed in sedimentary layers between these burrows is always convex upward; by this test the blocks are not overturned. Attention was directed specifically to this point by J. Sougy, of the Department of Geology of the University of Dakar, who accompanied the present writer to the site.

The inward tilting of these anomalous blocks may be due to undermining. At the Pass of Amojjar, it can be seen that where the canyon cuts into the cap rock of the plateau on which the crater lies, the rock has been undermined by weathering, and has tilted downward slightly. Likewise on the crest of the crater itself, at least one rock was noted by J. Sougy which seemed to have broken into three parts: the outermost part was tilted upward; the middle one was more nearly level; and the innermost part was tilted downward as if in response to undermining. It thus appears to be possible to explain the anomalous inward tilt of some blocks.

The rock forming the crater walls is well-exposed on the crest of the rim and on the inner wall of the crater. Nowhere in the crater has any indication of shock metamorphism been found by any of the visitors to the site. The only indication of the forces which formed the crater is the outward dip of the sandstones of the wall, and the breakup of the rock into large blocks. One possible explanation for the lack of shock effects is the fact that the crater has been severely eroded, so that what now appear as the outside walls are in fact only the weathered stumps of higher walls which were formed by the impact. This explanation is rendered plausible by the evidence noted in many places that erosion proceeds rapidly wherever the cap rock is broken.

Outside the crater, on the east especially, is found the Aouelloul crater glass. It is found chiefly in the <u>regs</u>; these are areas in which the sand has blown away, leaving a thin layer of desert pavement. Glass has been reported by Monod (1952) around the crater, but both Monod and Chao (personal communication, 1964) found that it was most abundant on the east side. Chao found that the strewn field of the glass extended 500 meters to the east. The present writer found glass at distances up to 1 kilometer from the crater center, again on the east side, although he did not investigate other directions, except northeast, where there appeared to be considerably less glass. Distances were measured by means of an automobile odometer starting from the base of the outside wall of the crater; distances from crest to base were obtained by pacing; and distances from the center to the crest were taken from the map of Monod.

There are grains of sand, chiefly quartz, adhering to the glass. Campbell-Smith and Hey (1952b) regarded this as "fused or fritted" into the glass surface. A piece about 1 centimeter long was therefore treated with 2 normal HCl for 30 minutes followed by 10 minutes in an ultrasonic cleaner; all the grains came off. It appears likely that they are only cemented on with impure Fe_2O_3. They do not appear to be portions of the internal quartz and lechatelierite weathering out of the surface, for with a hand lens, the exterior grains are perfectly distinct in color and transparency, while with the same lens, the interior bodies of pure silica are essentially indistinguishable from the matrix glass.

Studies of the Glass

Campbell Smith and Hey (1952b) and also Monod (1952) took the attitude that the glass of the Aouelloul was of extra-terrestrial origin, having been wrenched off a glass meteorite which formed the crater. They connected it with Darwin Glass and the latter with tektites. Most other investigators (Cohen, 1963, Chao, 1966a, b, El Goresy, 1965) have regarded the glass as an impact glass formed from the local sandstone. Chemical studies of the glass have sought to resolve this divergence of views.

Campbell-Smith and Hey showed that the composition of the glass is very much different from one kind of local sandstone, and resembles Darwin Glass. Chao, et al. (1966a), however, pointed out that there are two kinds of local sandstone. They found that the Oujeft has the composition found by Hey and Campbell-Smith; it is much more silicic than the glass (Table I, Cols. 4, 5). On the other hand, Chao et al. found that the Zli sandstone (Cols. 6, 7) has a silica content which resembles that of the glass.

The comparison of the Zli sandstone as analyzed by Chao, et al. (1966a), with the Aouelloul glass shows a number of discrepancies. (Table 1). The largest discrepancy is in the water content; that for the sandstone was determined by Chao, et al; that for the glass was found by Senftle and Thorpe (1968) to be about 0.02%, or 1 to 2 orders of magnitude less than the sandstone. The iron is 3 to 4 times higher in the glass than in the sandstone. Special explanations are available for these discrepancies: the water might have been volatilized during the impact, and as Chao, et al. point out the iron might have mixed into the sandstone from a hypothetical impacting iron meteorite. Reasons will be given below why neither of these explanations will work; here we discuss only the remaining oxides.

If the t-test is applied to the measurements it is found that the probability P of obtaining measurements on the glass and the sandstone which agree no better than those for P_2O_5 is much less than 0.01. For CaO, the t-test gives 0.01; for MgO and TiO_2, 0.05.

The overall probability of no better agreement can be estimated by the χ^2 method, comparing the values of the probability, p, as found by the t-test with a uniform distribution of values of p between 0 and 1. Dividing the whole interval into 10 steps, the overall probability of no better agreement is found to be less than 0.001. The test strongly suggests that there are real chemical differences between the Zli sandstone and the Aouelloul crater glass, even beyond the obvious differences in water and iron content.

When examined by microprobe, the Aouelloul glass shows three phases: a. lumps of essentially pure lechatelierite (sometimes partly quartz) (SiO_2 more than 98%) of the order of 60 microns in diameter; b. a matrix glass; c. streaks of gray glass with nickel-iron spherules. The composition of the matrix is shown in Table 2. There is some variation in the composition of the matrix glass, but the silica content lies in general below 85%. Where the microprobe shows silica in the 90's, there is usually reason to suspect that the field of the microprobe is overlapping the edge of a lump of lechatelierite.

By contrast, the sandstone shows the following three types of composition: quartz grains (roughly 80%) which are pure SiO_2; grains of potash feldspar (roughly 10%), with 17% K_2O and interstitial material (roughly 10%) of somewhat variable composition.

A careful search over rather large areas of the Aouelloul glass samples was conducted, using the microprobe in the tràversing node, and recording the results on a tape. Neither in this way nor in any other way was any region found in the Aouelloul glass whose composition matched the potash feldspar grains of the sandstone. Neither was any region found whose composition was comparable to the interstitial material of the sandstone. Similar tracings run over the sandstone yielded evidence of feldspar grains at the rate of approximately 1 feldspar grain for every 10 quartz grains.

In the regions characterized as "sandstone inclusions" (Chao, 1966b) the phases found are the lechatelierite (or quartz) and matrix glass. In these regions, the interstitial glass was approximately as silicic as elsewhere (85% ± 2%, estimated from standardized traces) which means that the bulk composition of these regions must be more silicic than that of the glass as a whole. It is quite contrary to what would be expected if these regions were really partially fused Zli sandstone; in that case, since the volume of the silicic inclusions is greater in the inclusions, the glass composition would have to be more basic if the bulk composition is to remain the same.

A study was made of the diffusion borders around the silica lumps. Since the surfaces of the lumps are not perpendicular to the surface planes of the thin sections, the sections were mounted on a universal stage, and the angles of inclination, θ, between the surfaces of the lumps and the surfaces of the thin sections were measured. At these points, the gradient of composition was measured for silicon and aluminum and potassium. It was found that the measurements could be represented in a satisfactory way by an error curve of the form

$$V = \frac{1}{2} V_o \left(1 + \frac{1}{2} \operatorname{erf} \frac{a+x}{2\sqrt{\kappa t}}\right)$$

where: V is the percentage of the element at any point; V_o is the quantity on the richer side, at a large distance from the boundary.

κ is the diffusion coefficient

t is the time

x is the coordinate measured in the surface perpendicular to the boundary

a is the x coordinate of the particle surface before diffusion began.

The constant $\sqrt{\kappa t}$ occurring in this formula may be called the raw diffusion length. It was determined (See Fig. 2) by matching a theoretical curve to the experimental points. The raw diffusion length was corrected for slope at a typical point by multiplying by cos θ. The corrected values of the diffusion length on one grain were 2.4, 2.4, 2.7 for SiO_2, K_2O and Al_2O_3 respectively. The results are so close to the resolving power of the microprobe that they can only serve as upper limits to the true diffusion lengths; even as such, however, they appear to be useful in the discussion below on the formation of the matrix glass.

A microprobe study was made of the streaks of gray glass in which Chao, et al.(1966b) found nickel-iron spherules. In agreement with Chao, et al. it was found that the region of the spherules was slightly enriched in iron. It was a surprise, however, to find that the region was also enriched in aluminum, magnesium, sodium and titanium, and impoverished in silicon. An analysis was made by microprobe, following the techniques described by Walter (1967) and employing his microprobe standards. The results, with their standard deviations, are given in Table 2, both for the gray glass and for the matrix glass which forms the majority of the material. The composition of the gray glass is seen to be generally similar to that of a silica-poor tektite such as an Ivory Coast tektite; the abundances of Na_2O to K_2O are unlike the Ivory Coast tektites, however, and more like the moldavites.

TABLE 2

	Matrix Glass	Tektite-like Glass
SiO_2	84.2 ± 0.3	68.9 ± 0.4
Al_2O	7.8 ± 0.5	18.6 ± 0.6
All Fe as FeO	2.0 ± 0.3	4.2 ± 0.3
MgO	1.4 ± 0.04	1.5 ± 0.06
CaO	0.4 ± 0.06	0.9 ± 0.07
Na_2O	0.4 ± 0.07	0.6 ± 0.10
K_2O	2.4 ± 0.2	2.8 ± 0.2
TiO_2	0.5 ± 0.06	1.2 ± 0.09
MnO	0.05 ± 0.004	0.12 ± 0.006

NOTE: The tektite-like glass was analyzed at two points; the matrix glass was analyzed at three points for SiO_2, Al_2O_3, FeO, CaO, K_2O, and at 4 other points for SiO_2, MgO, Na_2O, TiO_2, MnO. Errors represent internal agreement only. Since SiO_2 was used as a criterion in choosing the points, the error in SiO_2 is likely to be underestimated.

A chart (Fig. 3) prepared from the microprobe scans in Fe $K\alpha$ radiation shows the occurrence of iron in this region. The dark blobs are chiefly lechatelierite bodies; the streak across the center is the gray glass; the small white spots are the nickel-iron spherules; and the background is the matrix glass. A few scans have also been made in Al $k\alpha$ radiation. They show that it is, if anything, more concentrated to the band of gray glass which contains the spherules. The boundaries of the aluminum-rich region are indefinite, and there are no points observed either in the scan or in the numerical data with 100% Al_2O_3; hence, it is not likely that the observed aluminum is due to grinding powder caught in voids, for example.

Discussion

The interstitial glass, if produced from the sandstone, must have been melted, freed of water, partially fined (freed from bubbles) and homogenized. The process of melting might in principle have occurred instantaneously as a result of shock; but the other processes demand time, and are therefore troublesome to understand. The time available for the glass-forming process must have been only a fraction of the time of flight from the crater to the regs outside the ground.

We must first try to explain how the 2% water of the Oujeft sandstone (including 0.5 - 1.6% bound water) could escape almost completely from a glass melt in this very brief time. When the Z1i sandstone is heated in the laboratory, it is converted into a vesicular foamy mass, very different from the solid glass actually found in the field. The rate of rise V of a bubble in glass is given by the formula

$$V = -\frac{2}{9} r^2_b \rho g/\eta$$

where r_b is the radius of the bubble, ρ the density of the liquid, g the acceleration of gravity and η the viscosity of the liquid. A minimum value for the viscosity of the pieces on arrival at the ground is given by the fact that they have not adhered to the local sand. According to Professor A. Cooper (verbal communication) the viscosity at which glass no longer adheres is about 10^{10} poise. Under a gravitational acceleration of 980 milligals, a 1 mm. bubble would rise through glass of viscosity 10^{10} poises and density 2.4 g/cm^3 at the rate of 1.3 x 10^{-10} cm/sec. Clearly the bubbles could not escape after the tektite had reached the ground. Neither could they escape while the tektite was in ballistic trajectory, because at this time the effective gravitational force would be zero except for the effects of air resistance. They would therefore have to escape during the instant of the shock itself; but it has been pointed out (O'Keefe, 1964) that any accelerations capable of removing a bubble from a mass of molten glass will be much greater than the forces required to smash it to droplets.

The bubbles now found in the Aouelloul glass constitute about 10% by volume at most. At atmospheric pressure and a temperature of 1700°C, the water vapor contained in these bubbles would add about 5 ppm to the total H_2O content of the glass.

It thus appears that the hypothesis of impact melting at the Zli sandstone does not give a satisfactory explanation of the low water content of the Aouelloul crater glass.

The physics of the process of homogenization also leads to contradictions when applied to the hypothesis that the Aouelloul glass is made from the Zli sandstone. The grains of potash feldspar of the sandstone must not only have melted but must have diffused into the glass so completely that they cannot be found. In the more homogeneous parts of the glass, it is necessary to suppose that the quartz has also dissolved including grains up to 50 microns in diameter, which form about 35% of the sandstone, as found by point counts. The diffusion length required here is considerably greater than the diameter of the larger grains, i.e., greater than 50 microns.

It is obvious that the mechanism of dissolution here cannot be diffusion, since the diffusion length is only about 2.5 microns. The time required to dissolve the 50-micron grains by diffusion should be about 100 times as long as the time required to produce the observed diffusion boundaries, if the diffusion follows Fick's law (rate of diffusion proportional to concentration gradient).

The observed value of the diffusion length is a plausible one, as can be shown by the application of the theory of diffusion (O'Keefe, 1966). The theory was developed by Einstein starting from Stokes' Law, and is referred to as the Stokes-Einstein theory. It is necessary to insert a value of the temperature; this is not likely to exceed about

1700°C, since at this temperature quartz melts, and there are some unmelted portions of quartz grains present. These quartz grains are shattered and hence have not crystallized in the medium. It cannot be supposed that the grain was at a significantly different temperature from the matrix glass, because the time required for heat to diffuse into a quartz grain can be calculated from the observed value of the thermal diffusivity, by the approximate equation $Ct/a^2=1$, where C is the diffusion coefficient for the transport of heat, t the time, and a the particle diameter. We take 5×10^{-3} cm^2/sec for the thermal diffusivity (Wosinski, et al., 1967), and 2.5 to 5×10^{-3} cm for a. We find that the time required for the heat to penetrate is of the order of 5 milliseconds or less. The viscosity at this temperature would be equal to or greater than the moldavite viscosity, 10^3 poises (Volarovich and Leontieva, 1939, extrapolated) whence the Stokes-Einstein relation gives a coefficient $D = 10^{-8}$ cm^2/sec for self-diffusion in the glass. When the chunk of glass struck the ground, the viscosity at its surface was at least 10^{10} poises, as noted above; and this implies, by the Stokes-Einstein relation, a diffusion coefficient not greater than 10^{-15} cm^2/sec; hence, diffusion of matter at the surface had stopped. Thus, the time available for diffusion of matter at the surface of the chunk was less than the time required for a ballistic trajectory from the center to the ground outside. For the nearer deposits of glass, the calculated time of flight is on the order of 5 seconds. The diffusion length can be roughly estimated from the relation $Dt/a^2=1$; it is found to be about 2 microns. Thus, it is very hard to see how 50-micron grains which form over 1/3 of the sandstone could have dissolved.

The above calculation applies strictly only to the outer surface of the glass; however, it is easy to calculate that diffusion of matter at the center of a typical chunk a few millimeters in radius will also halt after 10 seconds or less, due to conduction of heat to the outside.

We cannot suppose that the homogenization took place in a gaseous state, with the quartz particles existing as dust, because in that case, the nickel-iron spherules would have been exposed to the atmosphere, and would have been at least partially oxidized, as mentioned above. Moreover, from actual studies of volcanoes (McClaine, et al., 1968) and atomic explosion craters, it is known that the result of evaporation and recondensation is not the production of centimeter-size chunks of glass of the same chemical constitution as the original material, but rather the production of small grains whose chemical constitution is much further from that of the original body than the Aouelloul glass is from the Zli.

The effectiveness of diffusion in bringing about homogenization would be greatly increased by stirring. At first sight, the thin sections of Aouelloul glass appear to have been strongly stirred; Campbell-Smith and Hey (1952a, b) emphasize this point. It is unlikely, however, that stirring has played any role in the dissolution of the quartz grains, for the following reasons:

a. There are a number of shattered quartz grains which retain their birefringence. The fragments of a single grain usually retain the same orientation, which indicates that they have not been subjected to shearing strains.

b. In some regions, most of the lechatelierite particles are approximately equant. When glass mixes are stirred while the lechatelierite is dissolving, the grains of lechatelierite develop characteristic tail-like appendages. There are some regions of the Aouelloul glass in which these appendages can be seen; but in others, where they are not seen, the glass is just as homogeneous. Both types of regions can be seen in Fig. 1.

It follows that stirring cannot play a significant role in the homogenization of the glass. The appearance of flow in the matrix glass may be due to its formation from particles slightly varying index of refraction, which have been welded together under pressure, as in a terrestrial welded tuff. Following the compression, there may have been some shear. Since it was shown above that diffusion subsequent to the shock cannot account for the observed degree of homogenization, it follows that the formation of the observed homogeneous glass matrix preceded the formation of the crater. In other words, the glass is not the result of the action of shock on the local sandstone.

The same conclusion follows even more strongly from a consideration of the distribution of iron within the glass. Since the oxides of iron form about 2.4% of the glass, but only 0.6% of the sandstone, it was necessary for Chao, et al. (1966b) to suppose that about 3/4 of the iron came from some other source, presumably the impacting meteorite. In this case, the small spherules noted by Chao would presumably represent the last remnants of the undissolved iron. Then the distance through which the dissolving iron would have to go would apparently be of the order of centimeters at least, since the spherules are by no means common. This would call for diffusion constants of the order of 1 cm^2/sec. In fact, however, even for liquids like water, the diffusion coefficients are on the order of 10^{-5} cm^2/sec. Thus the iron could not have diffused through the glass within the available time.

The same conclusion follows from another argument. Brett (1966) has pointed out that nickel-iron spherules imbedded in glasses which were formed by impact in air are usually greatly enriched in nickel (up to 85%). The reason is that nickel-iron, as such, is not soluble in glass. To dissolve the metals, they must first be oxidized. Iron as is well known, oxidizes much more readily than nickel (standard reduction potentials: Fe, - 0.41; Ni, -0.23, which is why nickel is used industrially to coat iron) so that in air, the iron tends to disappear much faster than the nickel. The problem is rendered especially acute by the fact that on the terrestrial theory of the origin of the glass, the remaining nickel-iron spherules represent only a very small fraction -- much less than 0.01% -- of the original nickel-iron. One would therefore expect strong concentration of the nickel. But actually the observed nickel-iron spherules contain 1.7 to 9% Ni, according to Chao, et al (1966b), which is well within the range of ordinary meteorites (Wood, 1963, Table 11 A, p. 349).

Summing up, we may say that the production of glass of the composition of the Aouelloul crater glass from sandstone of the composition of the Zli sandstone within the time interval fixed by the ballistic trajectory from the crater and the temperature limit fixed by the survival of quartz is impossible; and, in fact, the narrowness of the diffusion borders around the silica masses shows that it didnot happen.

The Hypothesis of Campbell-Smith and Hey

Campbell-Smith and Hey (1952a, 1952b) regarded the Aouelloul crater as the product of impact by a large glass meteorite with a composition like that of Darwin Glass. The match between Darwin Glass and Aouelloul glass is at least as good as that between the Zli sandstone and the Aouelloul glass for most oxides, and the match is much better in the matters of iron and water content.

If the Aouelloul glass is extraterrestrial, then it may be that there is no water in the place from which it comes; hence, the problem of explaining the fining of the glass disappears. Much the same hypothesis is required to explain the origin of the Muong Nong tektites (O'Keefe, 1966). Again, if the material is extraterrestrial, then it is possible that it is a volcanic glass, perhaps deposited from an ash flow. This removes the problems of homogenity. The particles of lechatelierite may be either foreign bodies caught up by the ash flow from the planetary surface, or they may be phenocrysts from the magma.

On the basis of this hypothesis the extension of the strewn field to the east is a simple consequence of the arrival of the parent body from that direction; the chunks of glass were wrenched off during the descent. A similar configuration is seen in the iron around the Barringer crater. The nickel-iron spherules may have been put into the body when it was removed from the planet (or satellite) from which it came. The small quantity of tektite-like glass suggests that this parent body is also the source of the tektites. Note that a relation with tektites is also suggested for the Darwin Glass by the association in time and place with the Australasian tektites

Table 1 also shows a few ordinary tektites whose silica content approaches that of the Aouelloul glass. These are extreme examples, rather than typical tektites; they are listed in order to show that recent work has narrowed the difference between the accepted tektite groups and the Darwin and Aouelloul glasses.

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It is a pleasure to acknowledge my indebtedness to Dr. E. C. T. Chao in the present investigation. It was Dr. Chao who first pointed out to me the possibility that the Aouelloul glass is not an ordinary impact glass. He helped me prepare for my visit to the crater, lent specimens for an unsuccessful search for Al^{26} and lent me the critical specimens in which the tektite-like glass was found. I have also had the privilege of numerous discussions with him throughout this work. Nevertheless, he is in no way to be held responsible for the conclusions which have been mentioned here.

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Figure Captions

Fig. 1: Mosaic of microprobe scans in $K\alpha$ light covering the region of the tektite-like glass. Bright dots are Ni-Fe spherules. Dark spots are chiefly particles of lechatelierite.

Fig. 2: Potassium abundance as a guide to the extent of diffusion at the boundary of a particle of lechatelierite. Circles represent observed points; curve is from theory.

TABLE 1

Comparison of Aouelloul Glass with Local Sands

Oxide	Aouelloul 4 analyses, (1) Min.	 Max.	Oujeft 3 analyses, (1) min.	 max.	Zli 3 analyses, (1) Min.	 Max.	(2)
SiO_2	85.4	86.6	92.8	94.5	84.1	88.9	87.98
Al_2O_3	5.6	6.3	2.0	2.7	5.0	7.4	7.04
Fe_2O_3	0.34	0.74	0.17	0.56	0.50	0.54	0.27
FeO	1.86	2.03	0.04	0.08	0.06	0.12	1.54
MgO	1.00	1.08	0.83	1.0	0.75	1.0	0.76
CaO	0.28	0.34	0.46	0.50	0.500	0.74	0.07
Na_2O	0.24	0.32	0.00	0.28	0.05	0.30	0.11
K_2O	1.87	2.20	0.22	0.71	1.9	2.7	1.07
H_2O^-	n.d.	n.d.	0.13	0.27	0.38	0.69	0.41
H_2O^+	n.d.	n.d.	0.50	0.74	0.55	1.6	
TiO_2	0.54	0.90	0.06	0.13	0.17	0.52	0.78
P_2O_5	0.02	0.06	0.06	0.17	0.12	0.15	n.d.
MnO	0.31	0.58	0.00	0.01	0.00	0.06	n.d.

Notes:

(1) Chao et al., 1966a

(2) Average of analyses by G. A. Ampt and E. Ludwig, quoted in Baker (1958).

(3) Taylor and Solomon, 1964

(4) Chapman and Keil, 1967

(5) von Engelhardt and Hörz, 1965

(6) Cuttitta et al., 1967

(7) V. E. Barnes, 1964

FOLDOUT FRAME

1

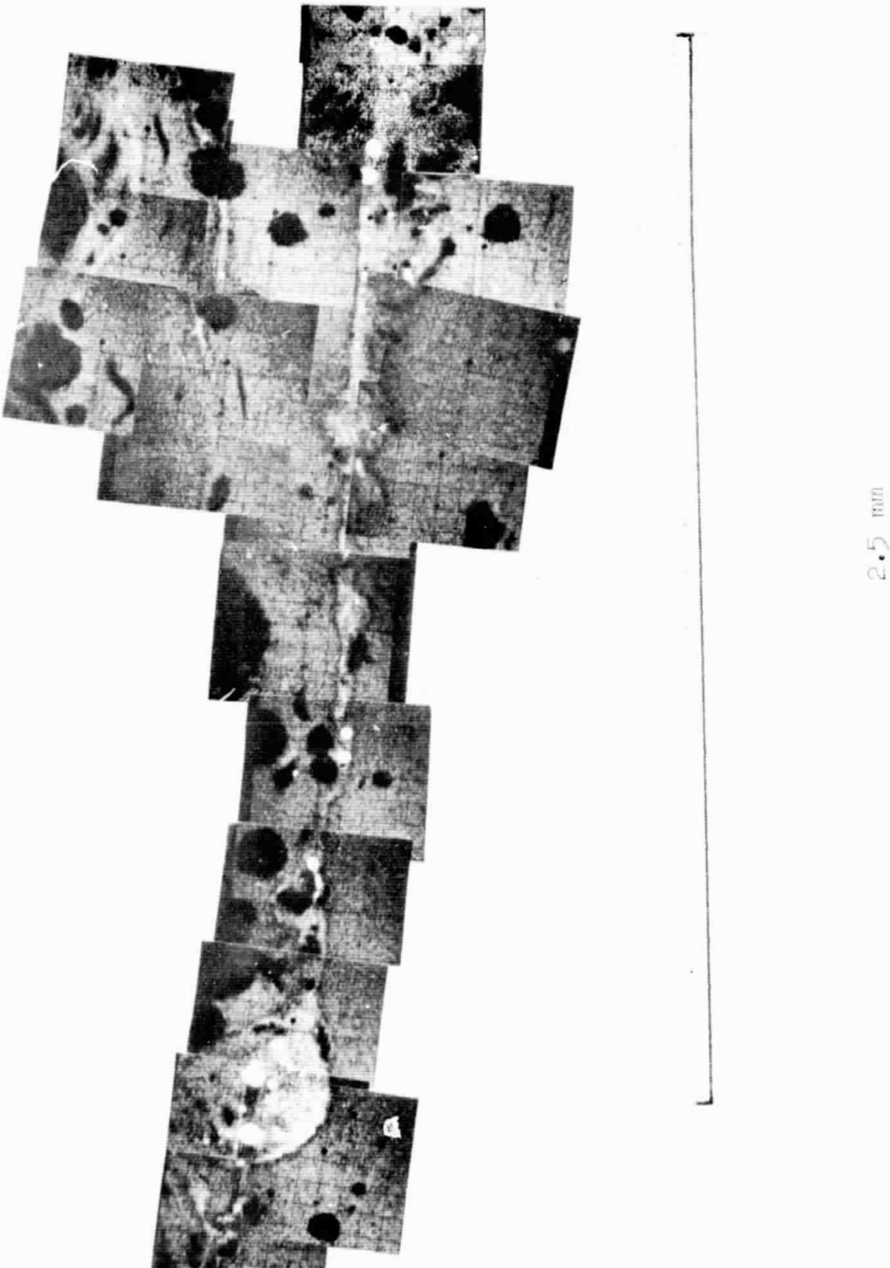
TABLE 1

Local Sandstones, Darwin Glass and Tektites

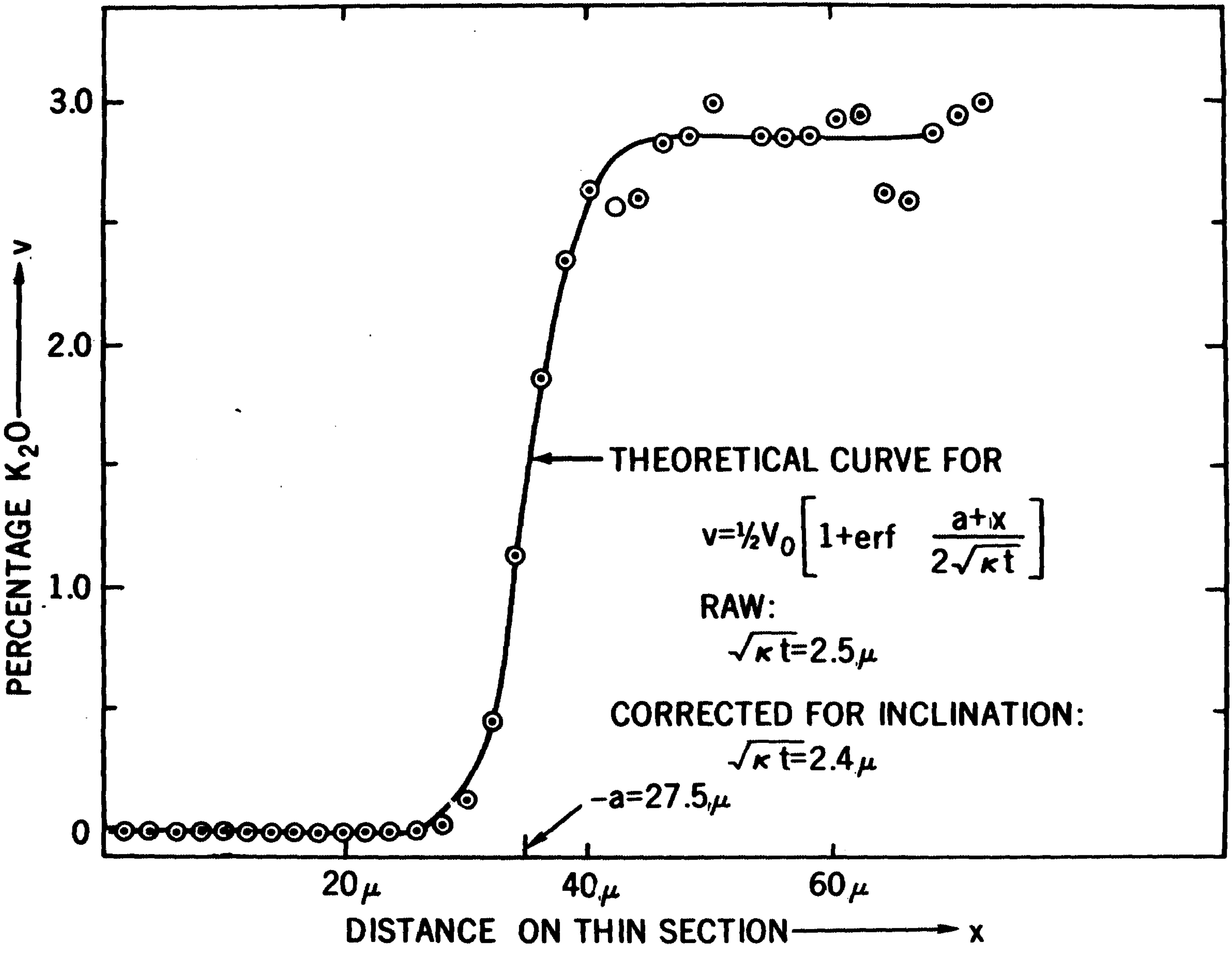
	Darwin Glass and Macedon Glass			Moldavite		Ga. tektite	Muong Nong	
(2)	(3)	Dark (4)	Light (4)	(5)	(5)	(6)	(7)	
87.98	85.62	82.75	87.80	84.48	81.06	83.6	81.36	81.31
7.04	6.64	8.67	6.90	7.79	9.04	9.50	8.87	8.85
0.27	2.34	3.44	1.54	0.21	0.30	0.01	0.39	0.35
1.54	1.66			0.98	1.39	1.82	2.81	2.94
0.76	0.96	2.30	0.90	1.72	1.71	0.42	1.14	1.11
0.07	0.10	0.12	0.04	1.90	2.06	0.40	1.00	1.01
0.11	0.051	0.14	0.02	0.20	0.44	1.19	1.17	1.23
1.07	1.81	1.92	1.64	2.40	3.32	2.51	2.26	2.30
0.41	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	0.12	n.d.	n.d.	--	--	n.d.	0.15	0.11
0.78	0.59	0.54	0.52	0.22	0.52	0.42	0.47	0.48
n.d.	n.d.	n.d.	n.d.	0.01	--	0.03	0.11	0.12
n.d.	n.d.	n.d.	n.d.	0.05	--	0.03	0.12	0.12

FOLDOUT FRAME

2



2.5 mm


PERCENTAGE K_2O → v
3.0
2.0
1.0
0
20μ
40μ
60μ
DISTANCE ON THIN SECTION → x
THEORETICAL CURVE FOR
$v = \frac{1}{2} V_0 \left[1 + \mathrm{erf} \; \frac{a+x}{2\sqrt{\kappa t}} \right]$
RAW:
$\sqrt{\kappa t} = 2.5\mu$
CORRECTED FOR INCLINATION:
$\sqrt{\kappa t} = 2.4\mu$
$-a = 27.5\mu$