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THE UNIVERSITY OF CALIFORNIA

LA-1126

June 13, 1950

THERMAL EFFECTS OF ATOMIC BOMB EXPLOSIONS ON SOILS AT TRINITY AND ENIWETOK

by

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CHEMISTRY, GENERAL

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Table of Contents

	Page
Abstract	1
Introduction	2
Fused Sands from Trinity	2 - 13
A. Description of Site and Samples Collected	2 - 3
B. Petrographic Examination of Samples	4 - 8
C. Spectrographic Analysis	8 - 11
D. Estimation of the Amount of Glass Formed	11 - 13
E. Estimation of the Amount of Energy Used to Form the Glass	13
Coral Sands from Eniwetok	14 - 15
References	16

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ABSTRACT

Samples of soils from Trinity and Eniwetok, thermally altered as a result of the test shots of 1945 and 1948, were examined. At Trinity a crust of vescicular silicate glass covers the ground over an area of about 2000 feet diameter. The amount of glass formed is estimated as 17×10^8 grams. Petrographic evidence indicated that temperatures exceeding 1470° C were reached throughout this area. Spectrographic analyses of samples of glass and parent soil showed that the melt was not superheated by more than a few hundred degrees in any portion of the area sampled. The amount of energy which went into forming the glass is estimated as $(4.3 \pm 0.5)10^{19}$ ergs.

Because of exceptionally unfavorable conditions on Eniwetok, no definite information could be obtained from the examination of samples of coral sands collected after the "Sandstone" shots.

Introduction

It was hoped that the examination of soils, thermally metamorphosed as a result of atomic bomb explosions might yield information on maximum ground temperatures reached and the amount of energy absorbed by the ground. Samples of silicate glass from Trinity and of coral sands collected after the "Sandstone" tests were examined. In the case of the Trinity samples fairly reliable information was obtained. Because of the physical characteristics of the Eniwetok soil and its alteration products their examination failed to supply any definite information desired.

Fused Sands from Trinity

A. Description of Site and Samples Collected.

As a result of the test shot fired at Trinity on July 16, 1945, the ground at the site is covered extensively with a crust of siliceous glass formed by the fusion of arcose sand which constitutes the soil in this region. Samples of glass and underlying soil were collected at the site on July 6, 1949. In spite of the four years elapsed since the test shot, field conditions did not indicate extensive changes of the material, nor was any evidence of alteration found during subsequent petrographic examination of the samples.

The central area of about 100 foot radius surrounding the tower foundation is devoid of continuous glass cover. The slight depression of this area suggests that what melt has been formed here was removed by the force of the blast. Some evidence of this is also provided by spherical beads of glass 2 to 5 mm in diameter, which are found sparingly scattered in the central area and which apparently have been formed while air-borne.

Surrounding the barren central area and extending outward to the distance of about 700 feet from the tower position is a zone in which the glass cover is continuous except for the interruption by cooling cracks. The thickness of the glass crust varies irregularly averaging 1 to 2 centimeters. The only systematic variation observed was the notable thickening of the crust on any slope facing the tower.

In the peripheral zone extending from 700 feet to 1000 or 1100 feet from the tower location the glass forms a discontinuous lacy pattern, eventually grading into vermicular bodies and scattered pellets of sand held together by minor amounts of glass.

The following samples of glass and underlying soil were collected at the site:

1-4: South and at distances of 100, 200, 500 and 1000 feet from the tower foundation.

5-7: East at distances of 100, 250 and 750 feet from the tower.

8-14: North 100, 200, 300, 400, 500, 700 and 1000 feet from the tower.

15: West 1000 feet from the tower.

16: Several glass beads found near the tower site.

In all cases the disposition of the pieces provided reasonable assurance that the samples collected were formed on the ground and in the immediate vicinity of the sampling point.

B. Petrographic Examination of Samples.

The general features of the Trinity glass and its parent material in the principal distribution zone (100 to 700 feet distant from the tower) have been adequately described by C. S. Ross (1948). The glass was formed by the fusion of an arcose sand composed dominantly of quartz with much potash feldspar, some plagioclase, ferromagnesian silicates, clay minerals and iron oxides. The glass is highly vescicular, the size of bubbles ranging from a few microns to 15 mm. Most of the fused crust is composed of a silicate glass with an index of refraction between 1.50 and 1.52, some ranging upward to 1.56, and exhibiting flow structures. Intimately intermingled with this glass, and with sharp and usually convex boundaries towards it, is a highly siliceous glass with a refractive index ranging downward to 1.459, which corresponds to pure silica glass.

Immediately adjacent its lower irregular surface the crust consists of glass with numerous inclusions and attachments of unaltered or partly assimilated quartz and other minerals composing the underlying soil. Similar inclusions, some up to 2 mm diameter, are present sparingly on the upper surface of the crust. These represent wind-blown sand-grains which settled on the surface while it was still in a molten condition. In the peripheral zone (700 to 1000 feet distant from the tower) the glass contains many inclusions of unfused or partly fused mineral grains.

Small amounts of glass with an index of refraction below 1.460 were found in all the samples. This corresponds to essentially pure silica glass (n = 1.459) and provides evidence that ground temperatures reached throughout the area of 2000 feet diameter exceeded 1470° C, which is the melting point of quartz under conditions of rapid heating, or the temperature at which the rate of transformation of quartz to melt begins to exceed that of the transformation of quartz to cristobalite.

It might be worth mentioning in this connection that it is very uncommon to find evidence of such high temperatures having been reached under natural terrestrial conditions. It is highly improbable that any igneous rocks were formed from melts with temperatures exceeding 1200° C. Lechatelierite or silica glass, indicating formation temperatures in excess of 1470° C, is known only as fulgurites formed by lightning striking silica sand and from impact craters formed by meteorites. (Spencer, 1939).

In order to uncover any systematic variations in the character of the glass grain counts of several samples collected were made establishing the distribution of the glass with respect to the refractive index. Results of this study are given on Table I. To simplify grain counts these were made on samples crushed to pass a screen with a 53 micron aperture and deslimed at about 20 microns. It was established by a duplicate count on a sample which has not been deslimed that such a procedure does not introduce systematic errors in this case.

Table I

Index of Refraction n	Cum. % of Glass Grains with Index less than n	Index of Refraction n	Cum. % of Glass Grains with Index less than n
Sample 100 ft. North		Sample 100 ft. South	
1.4817	9	1.4820	9
1.5017	15	1.5018	16
1.5115	23	1.5112	27
1.5215	48	1.5214	51
1.5250	79	1.5315	87
1.530	90	Mean Index 1.516	
Mean Index 1.515		Median Index 1.521	
Median Index 1.522			
Sample 200 ft. North		Sample 200 ft. South	
1.4807	12	1.4817	12
1.5007	27	1.5015	19
1.5118	43	1.5115	38
1.5209	78	1.5216	88
Sample 300 ft. North		Sample 400 ft. North	
1.4810	9	1.4817	8
1.5010	26	1.5017	17
1.51	80	1.5100	40
1.52	96	1.5200	86
1.53	99	1.5303	96
Mean Index 1.502		Mean Index 1.508	
Median Index 1.505		Median Index 1.512	
Sample 500 ft. North		Sample 500 ft. South	
1.4808	12	1.4820	21
1.5000	24	1.5020	31
1.5105	42	1.5116	51
1.5202	77	1.5216	80
1.5300	93	1.5312	96
Mean Index 1.508		Mean Index 1.504	
Median Index 1.513		Median Index 1.511	
Sample 1000 ft. North		Sample 1000 ft. South	
1.4800	8	1.4830	12
1.5000	12	1.5020	24
1.510	15	1.5108	34
1.520	29	1.5212	51
1.5250	84	1.5318	71
1.5303	90	1.5415	82
Mean Index 1.517		1.5511	91
Median Index 1.522		Mean Index 1.518	
		Median Index 1.520	

All samples were characterized by assymetric distribution curves with two peaks, a principal one between n = 1.50 and 1.53, and a less pronounced peak between n = 1.46 and 1.48.

Some systematic variations in the distribution were noted. The two samples taken at a distance of 100 feet from the tower gave almost identical distribution curves indicating mean refractive indices of 1.515 and 1.516 respectively. Seven of the samples studied, which were taken at distances between 200 and 700 feet yielded distribution curves which varied in detail (probably reflecting different degrees of mixing between the high and low index glasses), but all indicated a mean index between 1.502 and 1.508.

The 1000 foot sample gave a very flat and more nearly symmetrical distribution curve with a mean index of 1.518. The glass of this sample contained numerous included grains and remnants of quartz and its higher mean index undoubtedly results from its mode of formation by the selective liquation of the more fusible constituents of the sand.

The relatively high mean index of refraction of the 100 foot sample is more difficult to explain and suggested the possibility that this glass may have suffered some compositional change by the boiling off of the more volatile constituents. This would indicate an appreciable degree of superheating in the immediate vicinity of the tower. On the other hand, contamination of the glass in the central area by the iron from the tower and by lime from the concrete of the foundation could also cause local variations of the refractive index.

In order to obtain a measure of what the normal refractive index of glass formed from the Trinity soil would be, two samples of unfused sand were melted in a gas-oxygen flame. The index of refraction of the glass formed from both samples was 1.496 on first melting and rose to 1.500 on prolonged heating.

C. Spectrographic Analyses.

In order to explore further the possibility of the loss of volatile constituents from the original soil on melting, which would indicate temperatures considerably in excess of 1470° C, some spectrographic analyses of samples of glass and the parent sand were made. Qualitative analysis failed to reveal any gross differences between the samples apparent on visual comparison. Since potassium would be the first element abundantly present in the soil to vaporize if fractional distillation of volatile components had taken place, a quantitative analysis of the samples for this constituent was made. The results showed no significant differences in the potassium content of any of the samples collected at the Trinity site, indicating that the melt was not superheated to any appreciable degree in any portion of the area sampled.

One part of each sample was mixed with two parts by weight of spodumene ($LiAlSi_2O_6$) to which 1 % of RbCl was added. The spodumene was to act as a spectroscopic buffer and the rubidium as the internal standard.

Two mg samples of the mixture were weighed into 1 mm deep craters cut in the ends of 1/4-inch graphite electrodes. A drop of one percent solution of lucite in acetone was used to prevent loss of sample by spattering on striking the arc. Exposures were made on a 3-meter Baird grating spectrograph in the region 7200-8500A. Other conditions were as follows:

Electrode separation	4 mm
Excitation: d.c. arc	11 amps.
Filter, yellow	No. 3385
Slit	25 micron
Grating aperture	2 x 3/4 inch
Exposure	35 seconds
Plate	1-N
Development: D-19 at 18.6° C	3 minutes
Analytical line used	K 7699
Internal standard line	Rb 7800

Densities of the lines were measured on a Leeds and Northrup microphotometer and intensities calculated from the characteristic curve determined for the emulsion in the 7600-7800A region.

In order to simplify the spectrographic work, and since no interest was felt in the absolute amount of potassium present, the intensity ratio of the K-line to the internal standard line was used as the measure of variability. Figures representing this ratio are given in Table II. Samples are arranged in three groups corresponding to three spectrographic plates which supplied the data. Sample 10 (unfused sand) was included on each plate to be used as a reference standard. In order to provide a common basis for comparison of all samples the intensity ratio for each sample (mean of triplicate determinations) divided by the intensity ratio of the appropriate exposures of sample 10 (unfused sand) is listed in the last column of Table II.

Table II

	Sample	Description	Intensity Ratio K 7699/Rb 7800 Indiv.	Mean(r)	Ratio of r for Sample to r for Sample 10
Plate 1					
	10	Unfused sand (composite)	1.20, 1.12, 1.14	1.15	
	11	Unfused sand 200 ft. south	1.19, 1.14, 1.12	1.15	1.00
	12	Glass, 100′ North	1.11, 1.11, 1.17	1.13	0.97
	13	Glass, 200′ North	1.14, 1.19, 1.13	1.15	1.00
	14	Glass, 300′ North	1.09, 1.13, 1.11	1.11	0.96
	15	Glass, 400′ North	1.17, 1.16 1.10	1.14	0.99
	16	Glass, 500′ North	1.11, 1.14, 1.18	1.14	0.99
	17	Glass, 700′ North	1.14, 1.19, 1.11	1.14	0.99
	18	Glass, 200′ South	1.20, 1.01, 1.16	1.12	0.97
Plate 2					
	10	Unfused sand (composite)	1.15, 1.05, 1.17 1.16,	1.13	
	18	Glass, 100′ South	1.09, 1.18, 1.11	1.13	1.00
	20	Glass, 500′ South	1.11, 1.02, 1.10	1.08	0.95
Plate 3					
	10	Unfused sand (composite)	1.21, 1.22, 1.25	1.23	
	21	Glass, 1000′ South	1.29, 1.09	1.19	0.97
	22	Glass, 100′ East	1.26, 1.28, 1.30	1.28	1.04
	23	Glass, 250′ East	1.25, 1.27, 1.31	1.28	1.04
	24	Glass, 1000′ East	1.33, 1.17, 1.25	1.25	1.01
	25	Glass, 1000′ West	1.31, 1.06, 1.29	1.22	0.99
	26	Glass, 1000′ North	1.21, 1.16, 1.23	1.20	0.97
	27	Glass beads from central area	1.09, 1.24, 1.23	1.19	0.97
	28	Sample 10 after 10 min. fusion in gas-oxygen flame	1.11, 1.14, 1.07	1.11	0.90

The only significant variation was exhibited by sample 28 which represented the original soil fused and heated for about 10 minutes in a gas-oxygen flame.

The rate at which different constituent elements of the original soil burn out in a d.c. arc operated at 11 amperes was also investigated by the spectrographic laboratory. Results are summarized in Table III. The maximum temperature of a positive crater of a d.c. arc operated under these conditions is given as 3700° C by MacPherson (1941).

Table III

Element	Time (seconds)	
(Abundant Constituents of Soil)		
K	9	
Mg	35	(maximum intensity 20-30 sec.)
Ca	45	(maximum intensity 20-30 sec.)
Al	45	(maximum intensity 20-30 sec.)
Si	45	
(Constituents present Sparingly)		
Pb	5	
Na	7	
Cr	15	
Mn	25	
Cu	35	
Ti	35	
Fe	35	

D. Estimation of the Amount of Glass Formed.

In order to arrive at a figure representing the mean weight of glass per unit area, 24 specimens collected at distances varying between 200 and 700 feet from the tower were weighed and their areas measured. Results of this work are given in Table IV.

Table IV

Sample	Weight Grams	Area Sq. In.	G. per Sq. In.
N 200'	14.16	3.90	3.63
"	9.28	1.99	4.66
"	4.73	1.27	3.73
S 200'	24.36	5.43	4.48
"	18.47	4.24	4.35
"	15.97	3.86	4.13
E 250'	40.74	7.72	5.28
"	49.98	8.28	5.28
"	32.23	5.02	6.22
N 300'	30.43	6.41	4.73
"	19.55	4.08	4.79
"	12.41	2.59	4.79
N 400'	16.49	4.80	3.46
"	14.90	3.51	4.24
"	8.94	2.31	3.87
N 500'	27.00	4.83	5.59
"	30.95	4.83	6.41
"	16.25	3.01	5.40
S 500'	9.09	2.54	3.58
"	8.42	1.96	4.30
"	6.79	1.52	4.59
N 700'	26.01	5.12	5.08
"	11.51	2.05	5.62
"	9.14	2.08	4.39
Mean			4.72

No systematic variations in the weight per unit area with increasing distance from the source were noted. The figures show random variations between 3.6 and 6.4 grams per square inch with a mean at 4.72 grams per square inch.

Assuming glass to have been formed over a circular area of 1000 ft. radius, the total weight of glass at the Site is estimated as:

$3.14 \times 10^6 \times 144 \times 4.72 = 21.34 \times 10^8$ grams or 2350 short tons. This figure is undoubtedly high, since in arriving at it we have neglected: (1) the area of the cooling cracks, (2) discontinuities in the glass cover in the peripheral (700-1000 feet) zone, (3) unfused minerals included and attached to the glass. While it is difficult to evaluate the effect of these errors, it is believed that a better approximation to the amount of slag formed is obtained by revising the figure arrived at above downward by about 15 % to 18×10^8 grams.

E. Estimation of the Amount of Energy Used to Form the Glass.

Since no reliable figures are available on the heat capacity and heat of fusion of all individual minerals in the sand, the heat necessary to form the glass was estimated with the simplifying assumption made that it was derived from pure quartz sand. The error introduced by making this assumption is not believed to be serious.

According to Sosman (1927) the mean specific heat of quartz between 25° and 1470° C is 0.275 calories per degree per gram, this figure including the heat of transformation from low to high quartz at 573° C. The heat of fusion is given as approximately 50 calories per gram. The minimum amount of heat to form the glass at 1470° C is according to our assumptions: $18 \times 10^8 (1445 \times 0.275 + 50) = 80.5 \times 10^{10}$ calories or 3.4×10^{19} ergs. To superheat this melt to the temperature of 2000° C would require an additional expenditure of $18 \times 10^8 \times 187 = 33.7 \times 10$ calories or 1.4×10^{19} ergs. It is unlikely, in the light of the spectrographic evidence adduced above, that any appreciable portion of the glass, now accessible to observation, has been superheated to a higher degree.

Coral Sands from Eniwetok

Thirteen samples of coral sands were examined which were collected at Eniwetok some three weeks after the "Sandstone" shots. It was apparent from examination of these samples, as well as from eyewitness accounts, that this material is singularly unsuited as a source of desired information.

Calcite, exhibiting no evidence of alteration, and some with delicate organogen and oolitic structures preserved, was the major constituents of all samples. Portlandite (calcium hydroxide) was found in one of the samples in amounts of 5 to 10 percent and in very minor amounts (a fraction of one percent to two percent) in five other samples. This constituent was not generally distributed but formed isolated aggregates up to a few mm in diameter consisting of platelets of the mineral in random orientation. Most plates had the largest dimension of 1 to 2 microns, though a few reached the size of 10 microns.

As the result of accidental introduction of constructional material some of the samples contained pellets of glass, some of it highly siliceous with a refractive index of 1.50 and ranging to lime-iron silicate glasses with indices of refraction as high as 1.69. The high index glass was partly devitrified containing dendritic and, occasionally, crystalline inclusions. In one case the inclusions could be identified as larnite or alpha-Ca_2SiO_4 contained in a matrix of glass with the index of refraction of 1.664. Unfortunately, spectrographic analysis of the glass showed the composition to be very complex, significant amounts of MgO and Al_2O_3 being present besides FeO, CaO and SiO_2. Under these circumstances no definite conclusions on the temperature range in which this compound may have been formed are possible.

The same samples which contained the slag pellets also contained minor amounts of unfused quartz. Chitinous remains of marine animals were found in most samples.

Conditions prevailing at Eniwetok were evidently different from those at Trinity. Instead of forming a cover of a viscous melt which protected the ground, except in the immediate vicinity of the tower, the Eniwetock soil formed pulverulent calcium oxide on heating which was largely removed by the blast and subsequent atmospheric disturbances. The remaining soil was probably thoroughly mixed, as evidenced by the coexistence of chitin and delicate organogen calcite structures in the same samples with pellets of portlandite and slag.

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