THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report

of

Committee on Thesis

The undersigned, acting as a Committee of the Graduate School, have read the accompanying thesis submitted by William Owsley George for the degree of Master of Science. They approve it as a thesis meeting the requirements of the Graduate School of the University of Minnesota, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science.

Clinton R. Stauffer
Chairman

Frank F. Grout

F. H. MacDougall

April 29th 1929

THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report

of

Committee on Examination

This is to certify that we the undersigned, as a committee of the Graduate School, have given George Owsley George final oral examination for the degree of Master of Science. We recommend that the degree of Master of Science be conferred upon the candidate.

Minneapolis, Minnesota

April 29th 1920

Clinton R. Stauffer
Chairman

F. H. MacDougall

Frank F. Grout

W. H. Emmons.

THE RELATION OF THE PHYSICAL PROPERTIES OF NATURAL GLASSES TO THEIR CHEMICAL COMPOSITION.

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A thesis submitted to the Graduate School of the University of Minnesota by

William Owsley George

In partial fulfillment of the requirements for the degree of Master of Science.

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June, 1920.

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I Introduction

A Purpose and scope.

The natural glasses, varying widely in composition, also show considerable variation in hardness, color, diaphaneity, fusibility, magnetism, solubility, specific gravity, and index of refraction. The specific gravity data have been slowly accumulating for a long time and about one hundred fifteen tested analysed samples are reported. With the exception of those given in a paper by Stark in 1904, very little data on the index of refraction of glasses has been published. Data on other physical properties are, as a whole, conflicting and unreliable. A number of new determinations have been made. As a result, it seems likely that simple tests will give fairly reliable information as to composition.

The physical properties of natural glasses in relation to their chemical compositions are nowhere described in a comprehensive manner. References, which will be cited in a later paragraph, have been made to the physical properties of glasses as a class, such as pitch-stone, basalt glasses, etc., and in specific cases. But generalizations are few, and in some cases erroneous. Much data is available in the literature, but it is so scattered that it is not readily available for determinative work and the need of a compilation is shown by several recent papers referring to natural glass saying that glasses can be classified only by chemical analyses.[1]

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1 (a) "Glass must be computed from an analysis. One can usually surmise its composition from the character of the phenocrysts and the appearance of the rock as a whole." Johannsen, Albert J., A Quantitative Mineralogical Classification of Igneous Rocks. Jour. Geol. vol XXVIII, p. 43, 1920.
(b) "The exact magmatic relations of a vitric tuff can only be

B Nature and occurrence of natural glasses.

All igneous rocks which are not crystalline are said to be glassy or are called natural glass.

As stated by Pirsson,[2] "The condition which will cause a magma to solidify as a glass are evidently those which are unfavorable to crystallization, extremely quick cooling in the first place and, probably to some extent, rapid loss of mineralizers in the second." These conditions which nearly always attend the extrusion of rocks and in rarer instances intrusions, cause the rocks to become highly viscous in a very short time, thus retarding or preventing the migration of molecules necessary for crystallization. The classification of natural glasses is loose, no universally accepted system having been adopted.

The following is a partial list of names commonly used in classifying natural glasses: Obsidian, pitchstone, perlite, vitrophyre, pumice, lava, scoria, ash, tachylite, lapilli, vitro-andesite etc., tuff, palagonite, hyalomelane, wichtisite, and moldavite which is meteoric in origin.

Glasses are best named on the basis of texture and are qualified by the name of the crystalline rock of corresponding chemical composition, such as rhyolite pumice, dacite perlite, andesite obsidian, etc. Some are distinguished on the basis of luster,

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determined by chemical analysis, but it may be noted that the glass of fresh felsic varieties is usually clear and colorless; that of basaltic ones colored brown." Pirsson, Louis V., The Microscopical Character of Volcanic Tuffs. Amer. Jour. Sc. vol XL, pp. 198-199, 1915.
(c) Harker, Alfred, Petrology for Students, p. 132, 1895.
(d) Rosenbusch, H., "Microscopische Physiographic," II, p. 912, 1896
2 Pirsson, Louis V. "Rocks and Rock Minerals." 1908.

such as obsidian and pitchstone.

It is generally supposed that pitchstones have a high content of water. Weinschenk and Johannsen[3] in discussing mineralizers say: "The chemical composition of pitchstone proves the presence of water in the volcanic magma. This rock solidified rapidly under high pressure, and has a water content of 10% or more ...." Reinisch[4] gives the water content of unaltered pitchstones as six to eight per cent and in some cases even eleven per cent. A study of the analyses of natural glasses published in U.S.G.S. Prof. Paper #99 by H. S. Washington, shows that thirty-five obsidians, presumably rhyolitic, average 1.44% water. A few rhyolitic perlites average about 3% water, eight analyses of pumice show an average water content of 3%. Seventeen pitchstones, mostly rhyolitic, average 5.12% of water. The range for each group, however, is wide.

It is a well known fact that highly acid rocks have a greater tendency to solidify as natural glass than the more basic magmas and perfectly pure glasses of basic composition are exceedingly rare. The cause of this is generally attributed to the fact that basic rocks solidify at lower temperatures than the more acid rocks. However, natural glasses occur in practically all phases of eruptive rocks as residue or matrix of partially crystalline rock.

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3 Weinschenk and Johannsen, "Fundamental Principles of Petrology," p. 18, 1916.

4 Reinisch, Reinhold, "Petrographisches Pratikum," II, p.22, 1904.

In a general discussion of natural glasses, Iddings[5] says, "As the thoroughly glassy forms of many varieties of rocks present much the same general appearance and are with difficulty distinguished from one another, they have all been classed together as obsidian. Thus the term has come to signify any volcanic glass which has a small percentage of water and is almost if not wholly free from porphyritic crystals. But since the more siliceous rocks have a greater tendency to cool as glasses than the more basic ones, most of the volcanic glasses belong to acid rocks." The published analyses range in silica content from about 40% to 82%.

A number of writers have shown by analyses that natural glasses differ in composition from the related crystalline rocks. As early as 1884 Diller[6] observed that volcanic dust contains a higher percentage of silica than the lava to which it belongs. Volcanic sand is composed chiefly of crystalline fragments and contains a higher percentage of silica than the lava to which it belongs. Perhaps the most extreme case is a set of analyses made by Prof. Ditmar[7] of the rocks of the Dunoon Dyke. The rock as a whole contains only 47.36% silica, while the glassy segregation veins contain 68.05% silica. Similar observations were made by Teall[8], Becker[9] and others.

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5 Iddings, J. P., U.S.G.S. Annual Report, 7, p. 290, 1885-6
6 Diller, J. S., Science, May 30, 1884, p. 562.
7 Trans. Royal Soc. Edinburgh, Vol. XXXV, p. 44, 1888.
8 Teall, J. J. H., "British Petrography," pp. 42-43, 1888.
9 Becker, George F., U.S.G.S. Monograph, XIII, 1888.

Lagorio[10] in 1887 made one of the best detailed studies on the process of crystallization and showed the relation of the composition of natural glass to that of the rock as a whole. He showed that as a general rule, especially in rocks of medium composition, the content of silica and alkalis increases in the glassy portions of the rock. Lacroix[11] cites two analyses to show that a glass related to leucite tephrite differs in composition from the rock as a whole, the glass being lower in MgO, CaO, K_2O, TiO_2, but higher in SiO_2, Al_2O_3, FeO, Na_2O.

In brief, it may be said that glasses are more acid and contain more alkali than related crystalline rock, or the crystalline portion of same rocks; the potash especially increasing in proportion to the soda.

C Source of data.

The data used in this paper were obtained from a large number of publications and from personal observations and determinations on actual specimens. Special mention should be made of the compilation of analyses by H. S. Washington, published as Professional Paper No. 99, of the U. S. Geological Survey. For various reasons some of the data had to be rejected. Among those were six analysed pumice rocks. The specific gravities published for these were obviously too low for reasons explained in the discussion of specific gravity. Five specimens proved to contain too many crystals. Three other specimens were discarded because the discrepancy was large. Whether the error was in experimental work

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10 Lagorio, A., op. cit.
11 Lacroix, M. A.,"Etude Mineralogique des Produits Silicates de l'Eruption du Vesuve" Nouvelles Archives du Museum (4) IX p. 43.

or simply typographical, it seems clear that these three results should not carry much weight against the one hundred fifteen or more which agree fairly well among themselves.

Some of the chemical data were obtained by averaging the figures for a certain locality. Estimates of composition on the basis o f locality, even as to the name of the rock are liable to be in error. Seven or eight specimens from the Lipari Islands were similar and analyses from that locality are much alike; a large number of analyses for the various eruptions of Vesuvius were remarkably concordant. On the other hand, four specimens from Hlinik, Thal, Hungary, according to analyses, are rhyolite, trachyte, and andesite. Published determinations show a range of 2.232 to 2.414 in specific gravity and the indices of refraction are all near 1.506.

II The following is a list of analyses together with references and explanatory notes:

(The analyses are not to be taken as quotations because such constituents for which only a trace was reported are omitted, as they have no bearing on the subject. Those reported as not determined are also omitted.)

A Glasses Analysed or Composition Estimated.

	1	2	3
Hardness			About 5.5
Color	Black	Black	Gray to Black
Color-under microscope	Colorless	Colorless	Colorless
Specific Gravity	2.389	2.37	2.38
Index of Refraction	1.488±5(a)	1.490±3(a)	1.496±2 (a)
SiO_2	75.01	74.93	74.01
Al_2O_3	12.27	13.11	13.08
Fe_2O_3	0.80	.51	1.38
FeO	2.78	.77	1.21
MgO	0.08	.23	Tr
CaO	1.87	.30	.13
Na_2O	3.36	5.64	5.78
K_2O	2.80	4.28	4.31
H_2O+	0.25	.28	.16
Others	H_2O- 0.13	H_2O- .04	H_2O- .10
	TiO_2 0.33	TiO_2 .07	TiO_2 .11
	P_2O_5 0.02		
	SO_3 0.07		
	S 0.02		
	MnO 0.06		
	Cl 0.13		
Total	99.98	100.16	100.27

	4	5	6
Hardness	About 5.5(a)	6-7(a)	
Color	Black	Gray and Black	Black
Color-under microscope	Colorless	Gray and Brown	Greenish-Gray
Specific Gravity	2.25	2.56	2.58
Index of Refraction	1.496±2(a)	1.505±2(a)	1.5340
SiO_2	70.17	68.10	51.60
Al_2O_3	11.83	15.50	19.81
Fe_2O_3	0.93	3.20	2.24
FeO	None	None	5.48
MgO	0.06	0.10	2.17
CaO	0.76	3.02	3.95
Na_2O	3.85	4.20	8.20
K_2O	3.74	3.13	5.24
H_2O+	8.72		
Others	TiO_2 0.17	H_2O 3.72	0.58
		TiO_2 0.15	Cl 0.43
		P_2O_5 0.05	
		BaO 0.06	
Total	100.23	101.23	99.70

(a) Determined by the writer.

DESCRIPTION OF TABULATED DATA.

A. Glasses Analysed or Composition Estimated:

1 Obsidian, Hrafutinnuhryggur, Krabla, Iceland. Wright, F. E., Bull. G. S. Z., vol. 26, p. 260-1915.

2 Obsidian (Biotite-soda Rhyolite of Sitgreave's Peak), San Francisco volcanic field, Arizona. Robinson, H. H., U. S. G. S. Prof. Paper #76, p.108. The specimen contained about 5% microscopic inclusions and was slightly kaolinized.

3 Riebeckite-soda rhyolite of San Francisco Mt., Arizona, Robinson, H. H., U. S. G. S., Prof Paper #76, p. 109. The specimen was almost a perfect glass containing small scattered phenocrysts of orthoclase, apatite, zircon.

4 Obsidian, Milard County, Utah. Cross, W., U. S. G. S., Bull. #168, p. 168-1904. Not analysed but probably represented by analysis #87 of rhyolite glass given by H. S. Washington, U. S. G. S., Prof. Paper #99,p. 125.

5 Dacite-Bear Creek Falls, Shasta County, California. Diller, J. S., U. S. G. S. Bull. 150, #60, p. 215. About two-thirds of the specimen was glass.

6 Glass in Leucite Tephrite (Dike in large block) Vesuvius eruption of 1906, Lacroix, A., Nouvelles Archives du Museum d'Histoire Naturelle (4) IX, p. 45 - 1907.

	7	8	9
Hardness	6-7 (a)	About 5.5 (a)	About 5.5 (a)
Color	Black	Dark Brown	Red and Black
Color-under microscope	Colorless	Brown	Colorless to
Specific Gravity		2.87	2.336 (a) (Brown
Index of Refraction	1.497±3 (a)	1.597±3 (a) (b)	1.488±2 (a)
SiO_2	74.61	46.86	75.52
Al_2O_3	12.68	13.96	14.11
Fe_2O_3	0.09	5.23	1.74
FeO	1.36	4.67	.08
MgO	0.21	7.69	.10
CaO	0.69	9.42	.78
Na_2O	3.68	1.85	3.92
K_2O	4.77	2.02	3.63
H_2O+	1.37	3.43	(
Others	H_2O- 0.04	H_2O- 1.29	H_2O- (.39
	TiO_2 0.08	CO_2 2.19	FeS_2 .11
		TiO_2 1.13	
		P_2O_5 .15	
		BaO .03	
Total	99.58	99.92	100.38

	10	11	12
Hardness	About 7 (a)		
Color	Brown to Green	White to Yellow	White
Color-under microscope	Colorless	Colorless	Colorless
Specific Gravity	2.330 (a)	2.573 (a)	2.389 (a)
Index of Refraction	1.492±5	1.528±4 (a)	1.506±2 (a)
SiO_2	71.44	61.51	67.39
Al_2O_3	(	18.10	15.99
Fe_2O_3	(12.90	2.26	0.56
FeO	(	3.67	1.99
MgO		2.29	0.77
CaO	0.82	6.17	1.63
Na_2O	1.69	3.49	4.74
K_2O	6.56	1.05	4.80
H_2O+	1.07	.77	
Others		H_2O- .03	Loss 2.06 (c)
		TiO_2 .40	
		P_2O_5 .11	
		MnO .04	
	100.01		99.93

(b) Variable
(c) Probably H_2O

7 Obsidian, Conca Cannas, Uras, Mt. Arci, Sardinia. Probably represented by analysis given by H. S. Washington, Am. Jour. Sc., vol. 36, p. 582 - 1913. The specimen contained many opaque crystallites.

8 Basic Pitchstone Ash, Northeast of Meriden, Mass. Emerson, B. K., Bull. Geol. Soc. Am., vol. VIII, p. 77.

9 Obsidian, Obsidian Cliff, Yellowstone National Park. Iddings, J. P., U. S. G. S., Annual Report #7.

10 Pitchstone, Meissen, Saxony. Lagorio, A., Tschermak's Mineralogische Petrographische Mittheilungen, vol. VIII.
Two samples from same locality differ slightly.

11 Lapilli Andesitic, Pelee volcano. Martinique, Heilprin. The analysis given for this specimen is the average of 13 analyses of andesite fragmentals reported by H. S. Washington, in U. S. G. S. Prof. Paper #99. The analyses were very much alike.

12 Rhyolitic Pumice, Mono Lake, Mono County, California. Lindgren, W., U. S. G. S., Bull. 150, #59, p. 149. This is a very pure glass containing only one to two per cent biotite and one to two per cent feldspar.

	13	14	15
Hardness	6-7 (a)	6-7 (a)	6-7 (a)
Color	Black	Green	Black (d)
Color-under microscope	Colorless	Colorless	Brown
Specific Gravity	2.345	2.321(a)	2.728(a)
Index of Refraction	1.498±2(a)	1.497±2(a)	1.533-1.60(e)
SiO_2	74.70	71.56	43.65
Al_2O_3	13.72	13.10	(
Fe_2O_3	1.01	0.66	(33.23
FeO	0.62	0.28	(
MgO	0.14	0.14	2.03
CaO	0.78	0.74	8.70
Na_2O	3.90	3.77	5.43
K_2O	4.02	4.06	6.48
H_2O+	(	5.52	0.61
Others	H_2O- (0.62	P_2O_5 0.16	
	FeS_2 0.40		
Total	99.91	99.99	100.13

	16	17	18
Hardness	About 7(a)	6-7(a)	About 5.5(a)
Color	Black	Gray	Black
Color-under microscope	Brown	Colorless	Brown
Specific Gravity	2.495(a)		2.333(a)
Index of Refraction	1.519±4	1.497±3(a)	1.502±3(a)
SiO_2	61.22	74.65	69.31
Al_2O_3	18.01	14.11	12.47
Fe_2O_3	1.32	1.08	1.72
FeO	4.51	0.29	.55
MgO	.44	0.20	1.16
CaO	1.88	0.80	1.85
Na_2O	6.49	2.81	3.36
K_2O	5.93	4.59	4.41
H_2O+	.46	1.40	4.70
Others	TiO_2 .42	TiO_2 0.21	
		MnO 0.11	
		BaO 0.08	
	100.68	100.33	99.55

(d) Weathers to yellow

(e) Variable, mostly above 1.56; light brown portion less than 1.573; darker portion-1.573.

13 Black Obsidian, Yellowstone National Park, Obsidian Cliff. Iddings, J. P., U. S. G. S. Annual Report 7, pp. 282-88. Very nearly pure glass.

14 Pitchstone, Silver Cliff, Colorado. Cross, W., U. S. G. S. Annual Report #17, Part II, p. 320, 1897. Specimen contains very few crystals. Cross describes color as yellow, green, brown, red, and black. The specimen examined was green.

15 Tachylite (Basalt Glass) Bobenhousen, Hesse, Germany. Probably represented by analysis given by Lagorio. Tschermak's Mineralogische Petrographische Mittheilungen, vol. VIII, p. 492, #90.

16 Trachyte Obsidian (Phonolitoid) Gough's Island, South Atlantic. Pirsson, L. V., Am. Jour. Sc. vol. 45, 3d series, 1893. The rock contains many pores, but very few crystals. Specific gravity as published, 2.21, evidently erroneous.

17 Perlite, Deer Creek Meadows, Tehama County, California. Probably represented by this analysis which is given by H. S. Washington, U. S. G. S., Prof. Paper 99, p. 81, #18.

18 Pitchstone, Arran, Scotland. Not analysed, but composition given is the average of two analyses from that locality listed by H. S. Washington in U. S. G. S. Prof. Paper #99. Under the microscope the specimen is dusty with crystallites. Two specimens from same locality were observed which differed slightly. The Index of Refraction and Specific Gravity given are averages of the two.

	19	20	21
Hardness	About 7 (a)	About 5.5 (a)	
Color	Black	Black	Gray
Color-under microscope	Greenish to Brownish gray	Pale	Light brown
Specific Gravity	2.37	2.52	
Index of Refraction	1.498±2(a)	-(b)-	1.501±1(a)
SiO_2	72.56	53.10	69.51
Al_2O_3	12.33	20.70	15.61
Fe_2O_3	.80	0.07	0.56
FeO	.82	4.77	1.27
MgO	Tr.	1.77	0.61
CaO	Tr.	3.18	2.80
Na_2O	5.36	9.10	3.43
K_2O	3.08	5.84	2.81
H_2O+	(	0.70	
Others	H_2O- (4.59	TiO_2 0.47	Loss 3.63(c)
	99.74	99.70	100.23

	22	23	24
Hardness		6-7(a)	About 7 (a)
Color	Gray	Gray	Greenish gray
Color-under microscope	Colorless	Colorless	Colorless
Specific Gravity			
Index of Refraction	1.504±2(a)	1.497±4(a)	1.504±4(a) (d)
SiO_2	76.75	73.84	71.60
Al_2O_3	12.32	12.47	12.44
Fe_2O_3		.32	1.00
FeO	1.36	.90	.65
MgO	None	.25	.06
CaO	1.18	1.08	1.90
Na_2O	3.55	2.88	3.30
K_2O	3.98	5.38	4.22
H_2O+	(	(	(
Others	H_2O- (0.54	H_2O- (2.76	H_2O- (4.59
			TiO_2 0.25
			ZrO_2 .01
			P_2O_5 .08
			MnO_2 .06
			SrO .03
			BaO .03
		99.88	100.22

(b) Sodium-light
(c) Probably H_2O
(d) Variable.

19 Rhyolite Pitchstone, Checkerboard Creek, Montana. Pirsson, L. V., U. S. G. S. Bull. 139, p. 124-5.

20 Glass from Leucite Tephrite, Vesuvius, eruption of 1906. Lacroix, M. A., Nouvelles Archives du Museum d'Histoire Naturelle, 4th Ser. 1907, p. 43.

21 Andesitic Tuff, Stillwater Creek, California. Diller, J. S., U. S. G. S. Bull. #150, #79, p. 212. 75% glass, containing hornblende and feldspar and opaque crystals.

22 Glass base from Dacite Lassen Peak, California. Hague and Iddings, Am. Jour. Sc. 3d Ser. vol. 26, p. 232 1883. Specimen contained radiating needle-like microlites.

23 Rhyolitic Perlite, Yellowstone National Park. Iddings, J. P., U. S. G. S. Bull. #150, #61, p. 153. About one per cent of the rock is composed of quartz grains.

24 Rhyolite glass, West slope of Burton Peak, 50 feet below summit. Bullfrog, Nevada. Emmons, W. H., U.S.G.S. Bull. 407, #12. Analysis is for Rhyolite #15 which according to Bull. 407 is similar to #12. The rock is about 95% glass containing crystals of quartz, orthoclase, hornblende, hypersthene, and augite.

	25	26	27
Hardness	6-7 (a)		6-7 (a)
Color	Black & pearl gray bands.	Gray	Black
Color-under microscope	Colorless	Colorless	Colorless
Specific Gravity	2.202(a)		
Index of Refraction	1.497±3(a)	1.506±4(a)	1.48±2 (a)
SiO_2	74.37	68.22	75.78
Al_2O_3	12.65	12.41	12.39
Fe_2O_3	2.58	1.00	0.22
FeO	n.d.	1.36	1.25
MgO	0.20	0.18	0.31
CaO	1.22	0.95	0.81
Na_2O	3.87	3.38	4.00
K_2O	4.57	3.97	4.64
H_2O+	0.22	4.82	
Others	H_2O- 0.02	H_2O- 3.42	
		TiO_2 0.34	
		P_2O_5 0.11	
	99.70	100.16	99.81

	28	29	30
Hardness			6-7(a)
Color	White	White	Black
Color-under microscope	Colorless	Colorless	Colorless
Specific Gravity			
Index of Refraction	1.516±3(a)	1.506±5(a)	1.488±5(a)
SiO_2	68.68	68.57	74.05
Al_2O_3	12.69	16.90	13.85
Fe_2O_3	1.14	1.14	
FeO	1.17	1.17	
MgO	1.14	0.66	0.07
CaO	1.11	0.39	0.90
Na_2O	1.23	2.73+	4.60
K_2O	5.58	4.63-	4.31
H_2O+	{	4.07	2.20
Others	{7.99		
	100.73	100.26	99.98

7.19.4m

25 Obsidian, Forgia, Vecchia Lipari, Aeolian Islands. Bergeat, A. Ab. Much. Ak., XX, p. 111, 1899.
Banded Liparite Obsidian with black and pearl gray bands.

26 Bhyolitic Tuff. Belshaw's Ranch, John Day Basin, Oregon. Calkins, F. C., Bull. U. of Calif., Dept. Geol. vol. III, p. 167, 1902.
Specimen was estimated to contain about 98 per cent glass.

27 Rhyolitic Obsidian, Mono Lake, California. Lindgren, W., U.S.G.S. Bull. 150, p. 151.

28 Volcanic Dust, Gallatin Valley, Gallatin Co., Montana. Peale, A. C., U.S.G.S. Folio #24, also Iddings, J. P. U.S.G.S. Bull. 150, p. 146. Specimen was slightly kaolinized but free from microlites.

29 Volcanic Ash, Ravalli County, Montana. Rowe, J. P., Bull. U. of Montant, #17, p. 9, 1903. The average of three analyses was used as an estimate of the composition.

30 Scoria. The specimen is almost certain to have the composition given for Scoriaceous Rhyolite in U.S.G.S. Annual Report vol. 8, p. 380 by Russell.

	31	32	33
Hardness	6-7(a)		
Color	Black	Black, gray & green	Dark gray green
Color-under microscope	Colorless	Brown	Very light green and brown
Specific Gravity			
Index of Refraction	1.483±1(a)	1.527±2(a)	1.517±6 (a)
SiO_2	71.12	54.83	68.29
Al_2O_3	13.85	20.17	10.45
Fe_2O_3	2.35	4.77	2.09
FeO	2.78	3.86	5.54
MgO	0.30	1.93	0.41
CaO	1.77	4.12	0.35
Na_2O	4.29	3.04	6.03
K_2O	3.35	7.38	4.76
H_2O+	.38	0.46	3.13
Others: H_2O-	.02		0.11
TiO_2	.32		0.84
ZrO_2			0.03
P_2O_5			0.10
SO_3			0.06
MnO	.10		0.17
Cl	.02		

	34	35	36
Hardness	About 7 (a)		
Color	Black	Black	Black, Yellow and Brown
Color-under microscope	Dark Green	Colorless to Brownish gray	Brown, Yellow, Black granules
Specific Gravity			
Index of Refraction	1.506±4(a)	1.529±5(a)(b)	1.58±(a)(c)
SiO_2	65.81	66.51	47.36
Al_2O_3	14.01	16.37	18.49
Fe_2O_3	(	2.26	7.27
FeO	(4.43	2.13	4.73
MgO	.89	0.95	3.21
CaO	2.01	2.67	9.05
Na_2O	4.15	4.72	2.99
K_2O	6.08	3.19	6.45
H_2O+	2.70	0.69	.53
Others: H_2O-		0.13	.06
CO_2		0.00	
TiO_2		0.52	.42
P_2O_5		0.16	.56
SO_3			.22
MnO			.18
BaO			.04
Cl			.09
	100.08		

(b) Variable
(c) Variable

31 Obsidian, Iceland. The average of five analyses of Obsidians from Iceland, taken from U.S.G.S. Prof. Paper #99, is given as an estimate of the composition of this specimen.

32 Trachite Pumice, Arso Stream, Arso Ischia, Naples, Italy. The composition stated is the third analysis by H. S. Washington in Am. Jour. Sc. vol. viii, 1899, p. 290 which probably represents the specimen examined.

33 Glassy Pantellerite, Pantelleria, Italy. H. S. Washington, Jour. Geol. vol. 21, p. 706, 1913. The average of analyses A, B, C, and D, is here listed as an estimate of the composition of the specimen which is about 25 per cent crystalline.

34 Dacite Pitchstone. Dike near shore of Island of Eigg, N. B. The composition of the specimen is somewhat doubtful, but the analysis given by J. W. Judd in Quart. Jour. Geol. Soc. vol 46, p. 379, is submitted as an estimate. Under the microscope the powdered rock appeared to be about 25 per cent crystalline.

35 Dacite Vitrophyre, 20 miles west of Kelvin, Arizona. Composition doubtful, but estimate was made from one analysis published in U.S.G.S. Prof. Paper 12, p. 92, and from ten analyses published by H. H. Robinson in Prof. Paper #76. The specimen contained about 60% glass.

36 Ash from Vesuvius eruption of 1886. The composition is estimated from 16 analyses of ash and lava from the various eruptions of Vesuvius which are published in U.S.G.S. Prof. Paper #99 by H. S. Washington. Some of the rock was opaque.

	37	38	39
Hardness		About 5.5(a)	About 5.5(a)
Color	Brown	Black & Gray	Black
Color-under microscope	Brown	Brown	Colorless, Yellow and Brown
Specific Gravity		2.85	2.894(a)
Index of Refraction	1.56±1(a)	1.56±1(a)	1.612±9(a)
SiO_2	41.79	48.70	49.52
Al_2O_3	14.02	17.07	17.28
Fe_2O_3	14.36	4.65	9.19
FeO	1.11	6.65	7.67
MgO	10.73	4.24	2.66
CaO	10.55	9.72	7.45
Na_2O	1.99	4.62	3.66
K_2O	.91	1.71	1.05
H_2O+		0.17	.54
Others	CO_2 3.29	TiO_2 1.87	TiO_2 .19
	P_2O_5 .66	ZrO_2 0.28	P_2O_5 .09
	SO_3 .12	MnO .07	MnO .69
	CuO .08		
	MnO .28		
	FeS_2 .01		

	40	41	42
Hardness	6-7(a)	6-7(a)	
Color	Green	Black	
Color-under microscope	Colorless	Colorless	
Specific Gravity	2.903(a)		
Index of Refraction	1.610±	1.480±2(a)	1.605
SiO_2	48,95	74.91	49.74
Al_2O_3	17.65	13.12	12.36
Fe_2O_3	4.54	0.11	1.64
FeO	6.29	0.63	10.08
MgO	4.00	0.19	8.83
CaO	8.26	0.65	10.88
Na_2O	4.78	4.30	2.45
K_2O	1.75	4.47	0.55
H_2O+	0.15	0.30	0.17
Others	TiO_2 1.96		H_2O- 0.05
	P_2O_5 0.30		TiO_2 2.49
	MnO 0.03		P_2O_5 0.41
			S 0.04
			Cr_2O_3 0.04
			NiO 0.05
			MnO 0.14
			SrO 0.07
			Cl 0.10
			V_2O_5 0.02
			MoO_3 0.01
			100.12

37 Palagonite, Basalt Tuff, S. W. base of Punch Bowl, Oahu, Hawaiian Islands. Composition estimated from three analyses from this locality published by H. S. Washington in U.S.G.S. Prof. Paper #99. The rock is said to contain 5 to 10 per cent calcite and is partly oxidized.

38 Tachylite (Basalt glass) Giessen, Hesse, Germany. Composition estimated from 8 analyses published by H. S. Washington in U.S.G.S. Prof. Paper #99. The specimen was about 15% crystalline.

39 Kilauea Lava (Basaltic) Kilauea, Hawaii. Composition estimated from ten analyses of Kilauea lava published by H. S. Washington in U.S.G.S. Prof. Paper #99. Another specimen, "Pele's Hair" had the same index of refraction.

40 Basalt Glass, Aetna, Sicily. Composition estimated from seven analyses of Basalt from Aetna, published in U.S.G.S. Prof. Paper #99 by H. S. Washington. The specimen was entirely glass.

41 Rhyolite Obsidian, Mono Lake, California. Composition estimated from two analyses published by H. S. Washington U.S.G.S. Prof. Paper #99.

42 Lava dipped from Halemaumau, Kilauea Crater, Hawaii. Day-Shepherd Bull. Geol. Soc. Am. vol. 24, 1913, p. 586. Merwin describes the glass as follows: "Glass with 1% feldspar and trace of crystals either magnetite or pyroxine. Index 1.605, lining of bubbles slightly higher."

		43		44		45
Hardness		5.5-6(a)		6-7(a)		
Color		Gray		Red		White to Pink
Color-under microscope		Colorless		Colorless		Colorless
Specific Gravity						2.45
Index of Refraction		1.497±4(a)		1.488±4(a)		1.488±4(a)
SiO_2		70.50		63.63		66.22
Al_2O_3		14.28		18.02		15.63
Fe_2O_3		0.75		3.39		2.91
FeO		1.22		.77		2.14
MgO		0.49		1.40		1.41
CaO		1.00		2.97		3.28
Na_2O		3.62		4.22		4.37
K_2O		5.28		2.94		2.14
H_2O+		2.86		1.98		1.81
Others	H_2O-	0.10	H_2O-	.54	TiO_2	0.78
	TiO_2	0.47	ZrO_2	.12	MnO	0.32
	P_2O_5	0.11			$CaSO_4$	0.02
	MnO	0.04				
		100.72				

43 Perlite, Uras, Mt. Arci, Sardinia. Washington, H.S., Am. Jour. Sc. vol. 36, p. 582, 1913. Not analysed, but composition is probably represented by this analysis.

44 Obsidian Rhyolite. Trans-Caucasia, Armenia. Composition doubtful. Estimated from 2 analyses published by H. S. Washington in U.S.G.S. Prof. Paper #99.

45 Andesite Pumice, Krakatoa, Straights of Sunda. Composition estimated from eight concordant analyses published by H. S. Washington, U.S.G.S. Prof. Paper #99. The specific gravity is averaged from Specific Gravity data given with the analyses.

B Other data.

The following is a list of specimens which were examined but for which no chemical data were available:

46 Garnet bearing Obsidian; hardness, 6-7(a); color, pearl, under microscope colorless; index of refraction, 1.488±3 (a).

47 Rhyolite Obsidian, Arrowhead, Kern County, California; hardness about 7 (a); color, pearl to black, under microscope colorless; index of refraction, 1.488±4 (a).

48 Perlite, Chaffee County, Colorado; hardness 6-7 (a); color, pearl gray with black nodules, under microscope colorless; index of refraction 1.483± 1.501 (a); the specimen contains small black round nodules of glass which have a lower index than the surrounding glassy matrix.

49 Rhyolite Perlite, Hlinik, Hungary; color gray, under microscope colorless; index of refraction, 1.506±3(a).

50 Pitchstone, Elbingerode, Hartz Mts., Germany; hardness about 7 (a); color gray to pink, under microscope few red spots nearly all colorless; index of refraction, 1.506±4 (a).

51 Pitchstone, East of Las Cruces, New Mexico; hardness about 7(a); color black, under microscope colorless; index of refraction, 1.497±3 (a).

52 Pitchstone, Resinous green, Georgetown, Colorado; hardness about 5.5(a); color green, under microscope colorless; index of refraction, 1.497±4 (a).

53 Trachytpechstein, Hlinik, Hungary; hardness 6-7(a); color gray to black, under microscope some very dark green some colorless; index of refraction, 1.511± (variable) (a).

54 Obsidian from Trachyte Tuff, Procida Ponta di Ricciola; color, dark brown, under microscope dark brown.

55 Trachyte (nearly all glass) Foot of Monte Novo, near Naples, Italy; color brownish gray, under microscope brown to green; index of refraction, 1.488±4(a).

56 Perlitic Andesite, Galetnek, Hungary; hardness 6-7(a); color, pearl gray and white, under microscope glass is colorless; index of refraction, 1.506±4 (a).

57 Tachylite; hardness 6; specific gravity 2.65 - 2.70. (Published in Boricky's Petrog. Studien Bohmens pp. 182-210.

58 Rhyolite Obsidian, Teotihuacan, Mexico; hardness 6-7(a); color, red, under microscope colorless and pinkish brown; index of refraction, 1.496±2(a).

59 Tachylite on Basalt Dike, Kildonon, Isle of Eigg, Inner Hebrides; hardness 6-7(a); color black, under microscope nearly opaque; index of refraction 1.61±1 (variable)(a).

60 Scoria, Ice Springs Craters, Milard County, Utah; hardness 6-7(a); color red, under microscope brown, nearly opaque; index of refraction 1.58±2(a).

61 Tachylite, corner New Mexico, Arizona, Mexico; hardness 6-7(a); color, black, under microscope brown; index of refraction 1.506±4 (a).

62 Crust of Lava, 1858, Vesuvius; color black, under microscope greenish brown; index of refraction, 1.532 - 1.599 (variable)(a).

63 Perlite Andesite Pumice, Hlinik, Hungary; hardness 6-7(a); color, black, under microscope crystals are colorless, glass is brown; index of refraction 1.506±5 (a).

64 Andesite, Hart, Nevada; hardness 6-7(a); color black, under microscope glass is colorless; index of refraction 1.497±3(a).

65 Rhyolitic Obsidian, Hallsheivedal ved Skviddal, E. Iceland; hardness 6-7(a); color black, under microscope brown; specific gravity, 2.370(a); index of refraction 1.504±2(a); the specimen had no label and the name was assumed from the index of refraction and specific gravity.

66 Pitchstone porphyry Spherulites, Spechtshausen, by Tharaud, Saxony; hardness about 7 (a); color red and black, under microscope pink, gray, and black; index of refraction, 1.506±4(a).

67 Glassy basalt, Ani, Trans-Caucasia, Russian Armenia; color, dull pitch black, under microscope colorless, or near it; index of refraction 1.506±4(a); this specimen was obtained from the American Museum of Natural History and was named by E. C. Hovey. The index of refraction indicates that the glass is not a basalt glass.

68 Rhyolite to Dacite Tuff, south of Buffalo Peak, Colorado; color pink, under microscope pink from hematite; index of refraction 1.50±1 (a).

69 Andesitic Pumice, Bridge River District, B. C.; index of refraction 1.506±4(a).

70 Natural glass of Andesite, Mt. Pele; specific gravity, 2.40; index of refraction, 1.4888; (data determined by M. A. Lacroix, in "La Montagne Pelee et ses eruptions, Paris Masson, edit. p. 511 1904).

III The relation of the specific gravity of natural glasses to their chemical composition.

A Previous estimates.

A number of writers have associated a definite range of specific gravity with certain classes of natural glasses, but probably the most general statement has been made by Judd and Cole,[12] which is as follows: "From the glasses of more acid composition basalt-glass is at once distinguished by its higher specific gravity. While ordinary obsidians (rhyolite- and trachyte-glass) have a density varying from 2.3 to 2.5, the average being 2.4 or under, the density of basalt-glass varies from 2.5 to 2.9, the average being 2.7. The basalt-glass of several Scotch localities is of exceptionally high density, between 2.8 and 2.9. The glass, when unaltered, is probably in all cases of less density than the same material in a more crystalline condition." They also state that the general average for basalt glass may be taken as 2.7. Teall[13] observed about the same range in specific gravities. Lagorio[14] analysed and determined the specific gravities of nineteen carefully prepared glasses. His main effort in doing this was to compare the composition of the rock with the composition of the first part to crystallize, but his gravity data are useful in this connection. Pirsson[15] gives the figures 2.3 to 2.7 as the range of specific gravity for natural glasses. The generalizations by

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12 Judd and Cole, Quart. Jour. Geol. Soc. London, vol. 39, pp. 461- 462
13 Teall, J. J. H., "British Petrography", pp. 49-185, 1888.
14 Lagorio, A. "Uber die Natur der Glasbasis, sowie der Krystallisationsvorgaenge im eruptivem Magma." Tschermak's Min. u. Pet. Mit. vol. 8, p. 421, 1887.
15 Pirsson, L. V., op. cit. p. 263.

other writers seem to have been made on the basis of a similar amount of work.

B Method of determining the specific gravity.

Probably the most satisfactory method of determining specific gravity of natural glasses is by use of the picnometer. The glass should be ground to a very fine powder. This helps to eliminate the pores which are especially troublesome in glasses such as pumice and scoria. As previously stated, a number of published determinations for pumice had to be thrown out because the specific gravity given was obviously too low. As long ago as 1880 Cohen[16] noted that the fine pores in some glasses could scarcely be removed well enough to give good values. More recently, M. Stark[17] notes a similar difficulty with Pelee's Hair. The writer made several determinations on a specimen of pumice, grinding it to various degrees of fineness with the result that the specific gravity showed a variation of from 2.249 to 2.389. It was on the basis of these determinations that some of the published results were eliminated.

As an aid to more careful determination, it is well to cover the powdered rock in the picnometer with water and then apply a suction pump to remove any air bubbles which may adhere to the particles of glass.

The various constituents of natural glasses which seem to have a definite relation to specific gravity have been studied individually and are represented by the accompanying diagrams. (See pages 29 & 30.

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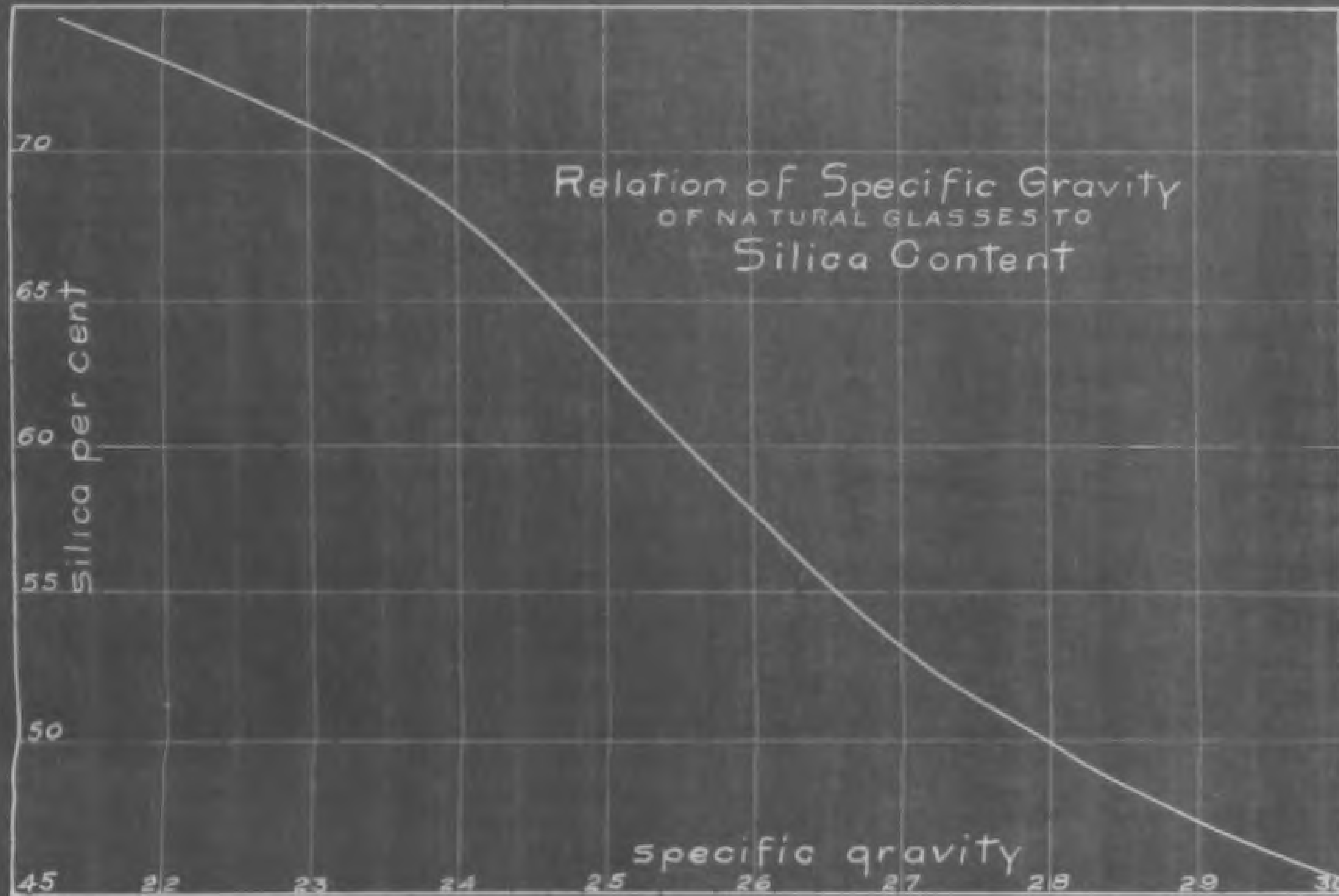
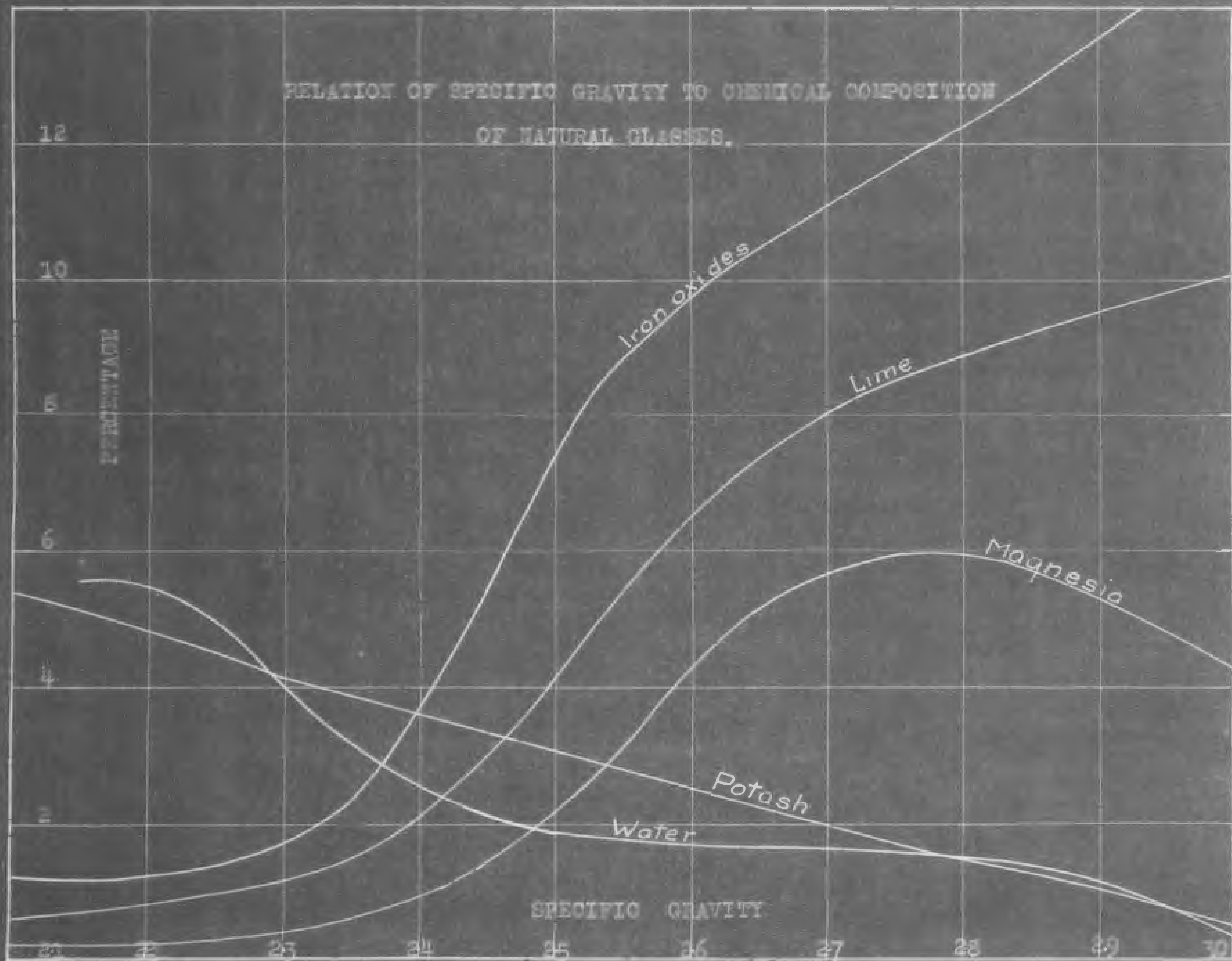
16 Cohen, E., Neues Jahrbuch F. Min. 1880, vol.II, pp. 44-45.
17 Stark, M., Tschermak's Mineralogische u. Petrographische Mittheilungen, 1904, vol. XXIII, p. 550.


Relation of Specific Gravity
OF NATURAL GLASSES TO
Silica Content
silica per cent
70
65+
60
55
50
45
specific gravity
22
23
24
25
26
27
28
29
30


RELATION OF SPECIFIC GRAVITY TO CHEMICAL COMPOSITION
OF NATURAL GLASSES.
PERCENTAGE
12
10
8
6
4
2
SPECIFIC GRAVITY
21
22
23
24
25
26
27
28
29
30
Iron oxides
Lime
Magnesia
Potash
Water

C The relation of the content of silica in natural glasses to the specific gravity.

Silica, having a greater significance and a wider range than any of the other chemical constituents of natural glasses, is probably best suited to show the relationship which exists between natural glasses and their specific gravity. As is shown by the curve (see page 29) rocks containing a high content of silica are low in specific gravity and the more basic rocks are high in specific gravity. Acid rocks contain more water than basic rocks, but the gravity gets below 2.3 only if the water content is high.

D The relation of the content of iron oxides, potash, magnesia, and lime in natural glasses to the specific gravity.

Curves showing the relationship between specific gravity and the content of iron oxides, potash, magnesia, and lime are shown on page 30. Values for each determination were plotted on the diagram and variations from the curves were calculated. The average error for iron oxides is 1.1 per cent, if the specific gravity is less than 2.4; it is 2.2 per cent if the specific gravity is greater than 2.4; the maximum error for all specimens is 5.2 per cent and the average error for all specimens is less than 1.6 per cent. The potash curve is almost a straight line and the average error for ninety-one specimens is less than 1.2 per cent. The curve for magnesia is rather irregular. The errors calculated are as follows: If the specific gravity is greater than 2.4, the average error is 1.8 per cent; if the specific gravity is less than 2.4, the average error is .3 per cent. None of the glasses analysed are high in magnesia, the largest percentage recorded is 12.13 per cent and this analysis is of a doubtful character. The content of lime as shown has an average error of 1.12 per cent. Soda and alumina have such a narrow range in percentage that curves showing their relation to specific gravity would be of little value. The average content of soda in natural glasses is 3.7 per cent; the approximate range of alumina is from thirteen to sixteen per cent.

Usually, the content of water in natural glasses is accidental. Part of the water is primary, part is present by reason of alteration, part is acquired by addition, such as may be the case when igneous rocks come in contact with bodies of water. There is no certain method by which one may determine how much of the water is a primary constituent of the magma.

IV Relation of Index of Refraction to Chemical Composition of Natural Glasses.

A Previous work.

Very few references are found in the literature on the index of refraction of natural glasses. Stark[17] has made a study of the indices of refraction of natural glasses with reference to the content of silica. He examined one hundred thirty-three specimens, thirty-four of which had analyses or estimates of composition; and suggested the application of the Gladstone Law[18] for calculating the index from the composition. This work seems not to have been brought to the attention of recent writers or its value has not been fully appreciated, as there still seems to be some difficulty in classifying natural glasses. Unfortunately, a large part of Stark's data is based on old analyses, such as those in Roth's Tabellen (1884), which are inferior in quality. Some of the specimens used by Stark are duplicated in this paper, but it is desirable to issue the data in an English publication and the additional samples extend the value of the work. Aside from that paper, the writer was able to find only three instances in which the index of refraction of natural glasses has been published, one by Merwin[19] and the other two by Lacroix[20] which indicates that petrographers still regard the index of refraction as an unimportant part of a petrographic description of natural glass.

B Methods used in determining the index of refraction.

The indices of refraction were obtained by the use of the

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17 Stark, Michael, Zusammenhang des Brechungsexponenten naturliches Glaser mit ihrem Chemismus. - Tschermak's Min. u. Pet. Mit. vol.23, pp. 536-550 (1904).
18 Phil. Trans. 337, 1863.
19 Merwin, H. E., Bull. Geol. Soc, Am. XXIV p. 586, 1913.
20 Lacroix, A., Nouvelles Archives du Museum d'Histoire Naturelle (4) IX p. 45, 1907.

Becke[21] line. They range from 1.48 to 1.62 (Stark reports a single sample with index 1.67). Comparisons were made with oils, the indices of which were previously determined in yellow light with goniometer. Mixtures of oil of cloves, turpentine, cedar oil, kerosene, benzene, ethylene bromide, cinnamon oil, brom-naphthalene, were used. Equal parts of those oils which were miscible were used to obtain intermediate determination. According to Ford[22] this method can be considered accurate only to ±.002 and Merwin[23] says that determinations closer than 0.01 are not practical.

The indices of refraction are likely to show considerable variation. In partly crystalline specimens, this is probably due to the fact that during crystallization certain molecules are used in the formation of the crystal which are selected from the surrounding matrix. These molecules are necessarily factors of the index of refraction. We may expect then, that the glass nearest the crystal will have a different index of refraction than the more distant portion of the matrix. Ransome, Emmons, and Garrey[24] say of a rhyolite rock containing about ninety-five per cent glass, "The ground-mass immediately surrounding the femic crystals is bleached and the resulting halos contrast strikingly with the brown ground-mass.... It is perfectly clear that the ferro-mag-

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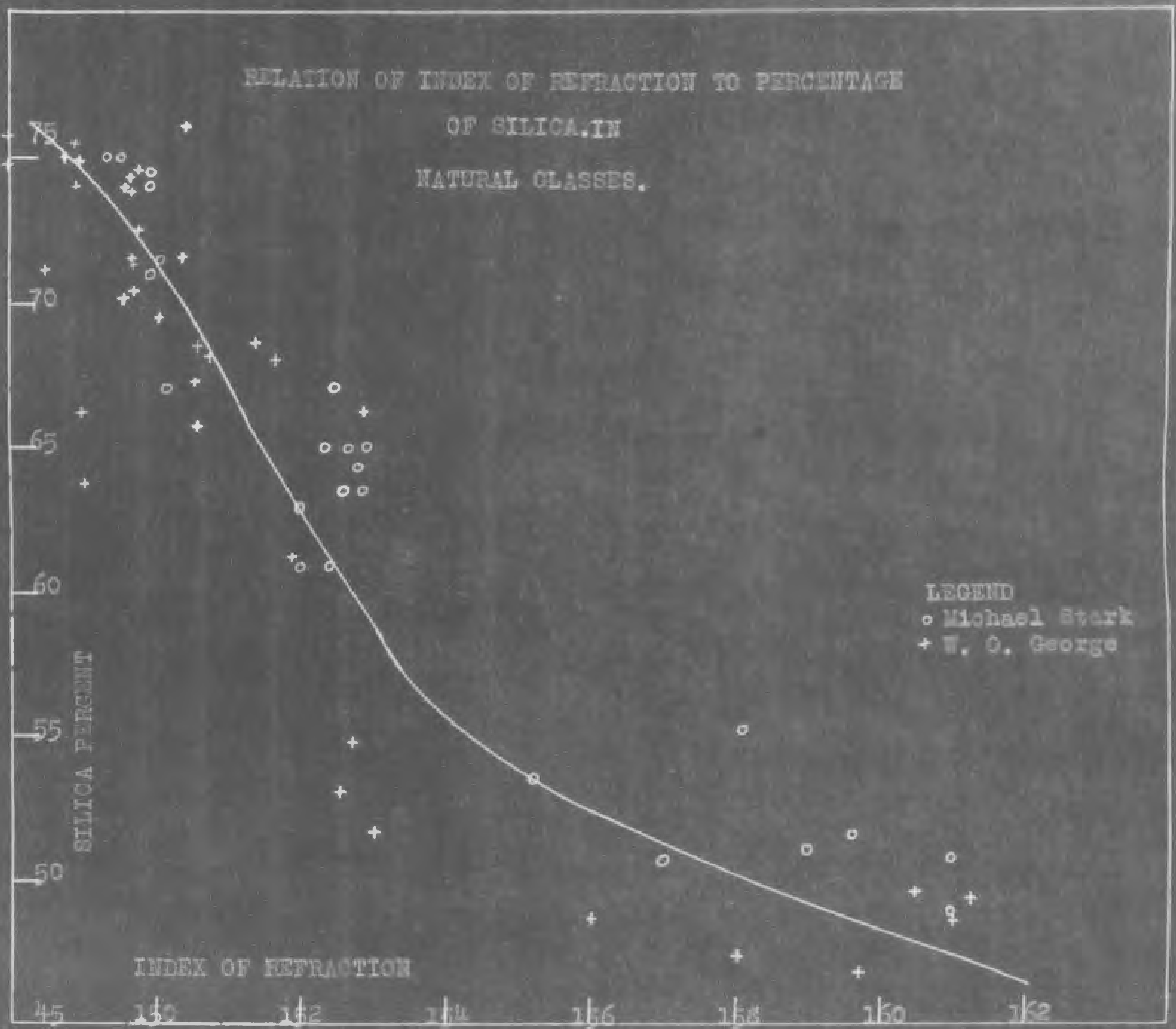
21 Becke, F., Uber die Bestimmbarkeit der Gesteinsgemengteile auf Grund ihres Lichtbrechungsvermogens. Sitzt. Wiener Akad. July, 1893.
22 Ford, W. E. "Chemical, Optical and other Physical Properties of the Garnet Group." Am. Jour. Sc. vol. XL July, 1915, p. 36.
23 Merwin, H. E. "Physics," Journal of the Washington Academy of Sciences, vol. III, #2, Jan. 19, 1913, p. 36.
24 Ransome, F.L., Emmons, W.H., Garrey, G.H. "Geology and Ore Deposits of the Bullfrog District, Nevada." U.S.G.S. Bull. 407, 1910, p. 50.

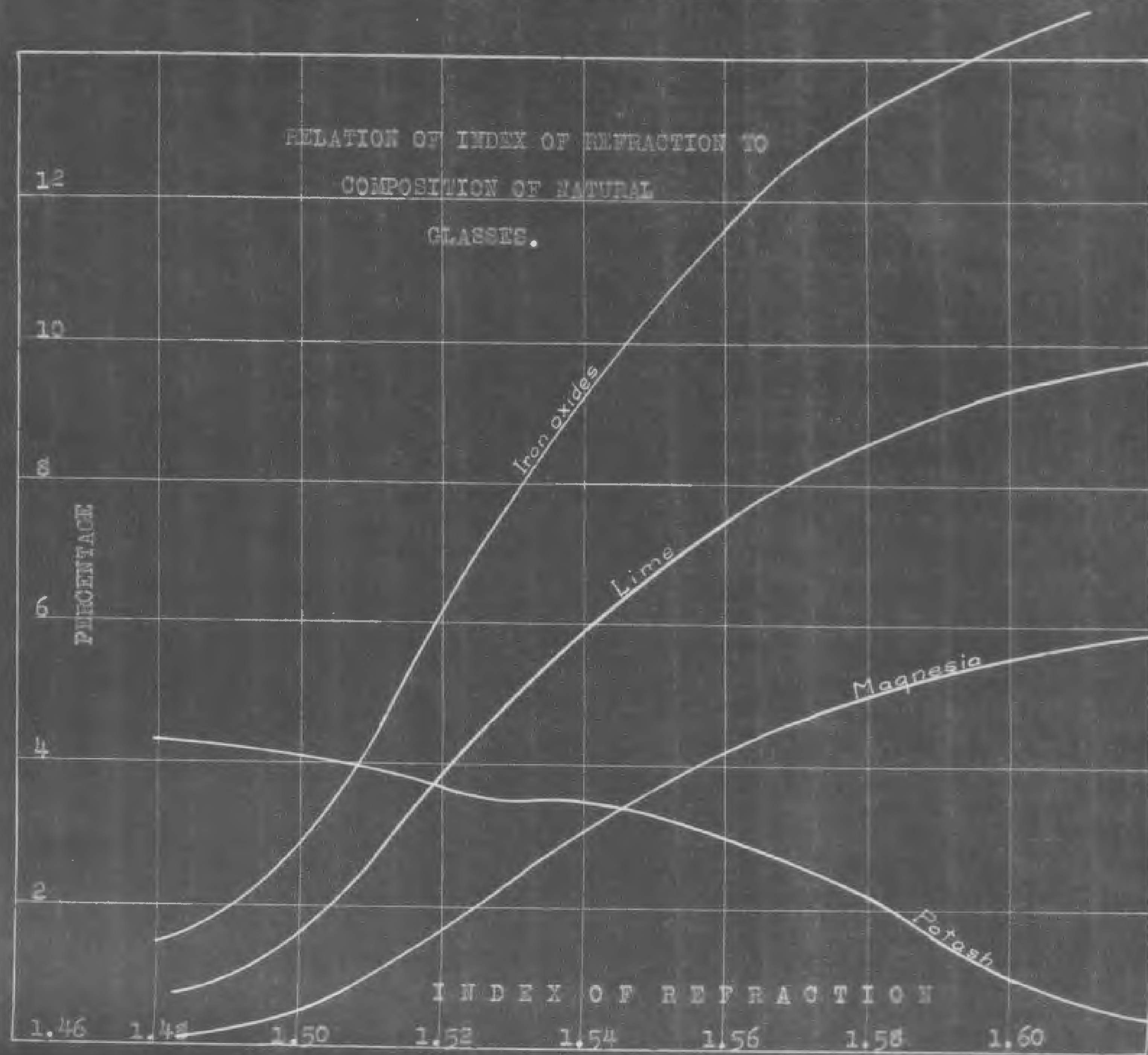

RELATION OF INDEX OF REFRACTION TO PERCENTAGE
OF SILICA.IN
NATURAL CLASSES.
LEGEND
o Michael Stark
+ W. O. George
SILICA PERCENT
INDEX OF REFRACTION
75
70
65
60
55
50
45
1.50
1.52
1.54
1.56
1.58
1.60
1.62

nesium minerals continued to grow after the lava came to rest, and that in the process of growth they absorbed from the still liquid magma those constituents that gave it color." This sort of variation is likely to be found at the edges of intrusives or in the crusts of lava flows. Naturally, the outer edges having cooled quickly are pure glass and retain the composition of the original magma. The inner portions of the magma are partly crystalline and the glassy ground-mass is different in composition from the pure glass. The outside portion of the magma may also be changed by local agencies with which it comes in contact, such as the wall rock of an intrusion or water. The latter is illustrated by a basic pitchstone ash (Specimen #8) near Meriden, Massachusetts.

Stark observed that it was not safe to rely on a determination from one small part of the specimen. He says that peices from a large number of specimens should be pulverized together. Or, if only one specimen is available pieces should be used from several different parts of the specimen. This is especially true of the basic rocks, as they are inclined to show considerable variation in their indices of refraction. The writer observed, however, that those rocks which under the microscope appear to be pure glass and perfectly homogeneous in color, do not show this variation regardless of their composition. The green basalt glass (Specimen #40), from Mount Aetna, is a striking example, but it must be admitted that rocks of this kind are rare.

C The silica-index curve.

The relation of the index of refraction of natural glass to the silica content is best expressed by the curve in the accompanying diagram, page 35. The curve was estimated by plotting the


RELATION OF INDEX OF REFRACTION TO
COMPOSITION OF NATURAL
GLASSES.
PERCENTAGE
12
10
8
6
4
2
Iron oxides
Lime
Magnesia
Potash
INDEX OF REFRACTION
1.46
1.48
1.50
1.52
1.54
1.56
1.58
1.60

values for each specimen as indicated on the diagram. The curve was drawn independently of Stark's results, as the writer did not discover his paper until this part of the work had been completed. Stark's results were then plotted on the diagram as is explained by the legend.

After drawing the silica-index curve on the basis of all the specimens examined, the amount of variation from the curve was calculated in percentage for each specimen. It was found that those specimens for which reliable analyses were obtained had a maximum error of 8 per cent, an average error of 2 per cent. For those specimens of doubtful composition or for which the composition was estimated, the maximum error was 14 per cent, the average error not over 3.4 per cent.

D The Potash-index curve.

The range in potassium content of the specimens determined is from 0.80 per cent to 5.40 per cent. Present graphically, the relation of the potash content to the index of refraction is shown on page 37. The average variation from the curve for forty seven specimens was less than 1.1 per cent.

E The Iron-oxides curve.

The relation of the percentage of iron oxides of natural glasses to their indices of refraction is shown by the curve on page 37. For those glasses having an index of refraction greater than 1.51, the average error is 2.1 per cent; for those having an index less than 1.51, the average error is 1.16 per cent; the maximum error for all of the specimens was 4.6 per cent. Selecting twenty-two specimens for which the best data was available, the average ~~per cent of~~ error was 1.4 per cent.

F The relation of the per cent of lime and magnesia in natural glasses to their indices of refraction.

The relation of the per cent of lime and magnesia in natural glasses to their indices of refraction is shown by two curves on page 37. If the index of refraction is greater than 1.51, the average error of the estmates of magnesia is 1.64 per cent; if the index is less than 1.51, the average error is 0.31 per cent. For the twenty-three specimens for which reliable data could be obtained, the average error was 0.52 per cent.

The maximum variation from the lime curve was 4.4 per cent. If the index of refraction is greater than 1.51, the average variation from the curve is 1.66 per cent; if the index of refraction is less than 1.51, the average variation from the curve is 0.80 per cent. For those specimens having the best data, the average variation from the lime curve was 0.62 per cent.

G Relation of other constituents of natural glasses to the index of refraction.

Values were plotted showing the relation of water, alumina, and soda content to the indices of refraction of natural glasses. Water content is so erratic and accidental that a curve showing the relation of water content to the index of refraction would be of little value. Curves showing the relation of alumina and soda in natural glasses to the index of refraction would also be of little value, as there is a small range of composition. In making an estimate, it would be safe to say that all glasses contain from thirteen to sixteen per cent alumina. The content of soda in natural glasses has little variation and, as an average is about 3.7 per cent.

H Specimens for which no data on chemical composition were available.

Twenty-one specimens were examined which had been labeled by collectors or petrographers who had studied them. Their indices were determined as follows:

		Index of Refraction
Pitchstones	2 specimens	1.493 - 1.501
"	2 "	1.501 - 1.511
"	1 "	1.511 - 1.524
Rhyolite	1 "	1.482 - 1.493
"	1 "	1.501 - 1.511
Rhyolite Obsidian	2 "	1.493 - 1.501
Obsidian	1 "	1.482 - 1.493
Perlite	1 "	1.482 - 1.493
Trachite	1 "	1.482 - 1.493
Trachite Pitchstone	1 "	1.511 - 1.524
Andesite	1 "	1.482 - 1.493
"	1 "	1.493 - 1.501
"	3 "	1.501 - 1.511
Tachylite	1 "	1.501 - 1.511
Dacite	1 "	1.501 - 1.511

I Comparison of the two methods.

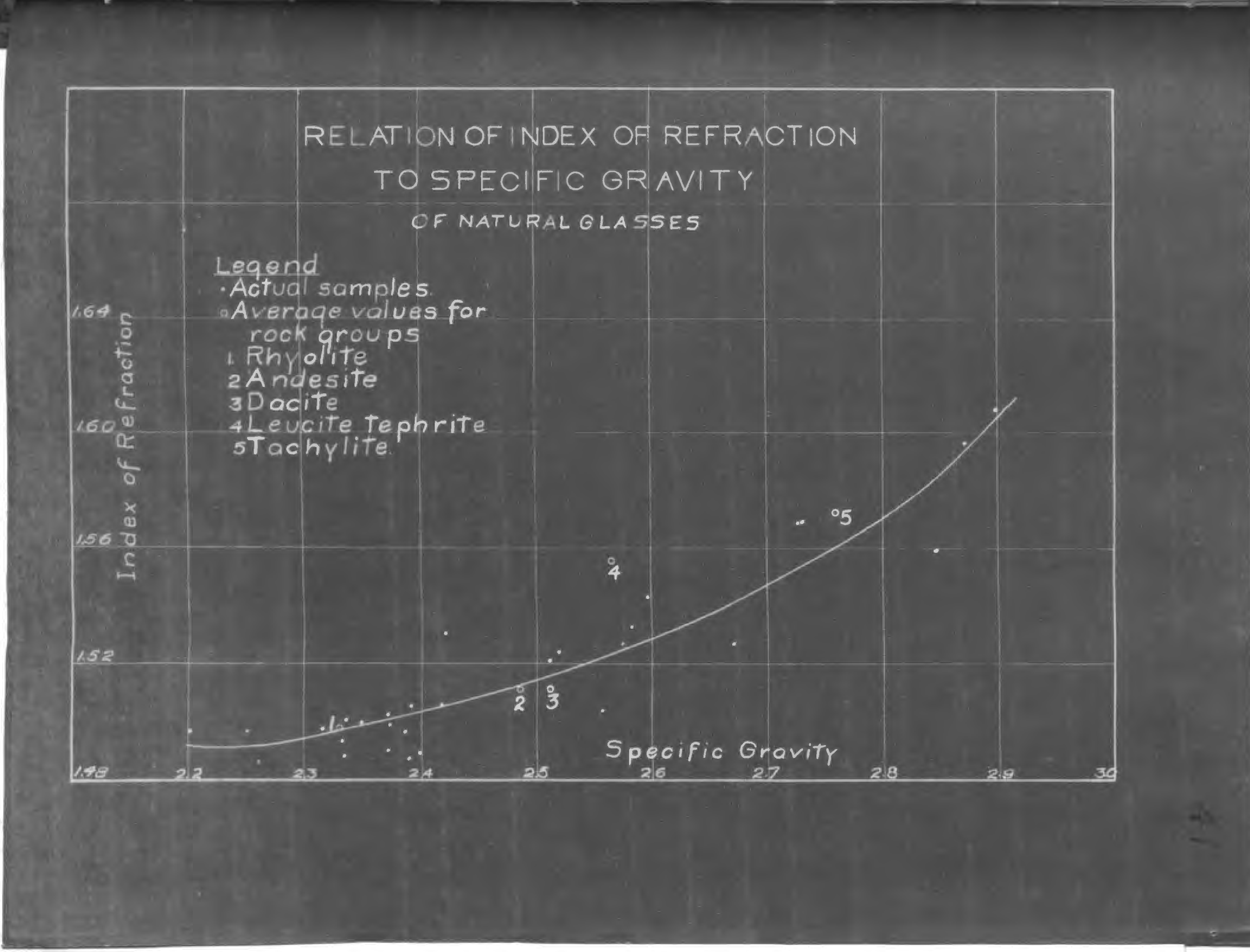
The index of refraction method and the method by specific gravity are compared in the following table and are shown in relation to the curve. The figures given as "Average Error" represent the amount of variation from the curve.

	By Specific Gravity Curves		By Index of Refraction Curves	
	No. of Specimens	Average Error	No. of Specimens	Average Error
Silica	94	4.2%	46	3.4%
Iron Oxides	98	1.6%	43	1.55%
Potash	95	less than 1.2%	47	1.07%
Lime	104	1.1%	46	1.14%
Magnesia	104	1.1%	46	0.83%

The amount of data for specific gravity far exceeds that for the index of refraction, but they probably have the same degree of accuracy.

J Relation of index of refraction to specific gravity.

The relation of the specific gravity to the index of refrac-


RELATION OF INDEX OF REFRACTION
TO SPECIFIC GRAVITY
OF NATURAL GLASSES
Legend
· Actual samples.
▫ Average values for rock groups
1. Rhyolite
2 Andesite
3 Dacite
4 Leucite Tephrite
5 Tachylite.
Index of Refraction
1.64
1.60
1.56
1.52
1.48
Specific Gravity
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
1
2
3
4
5

tion is shown in the diagram on page 41. For most samples a certain index of refraction indicates a particular specific gravity; see Gladstone Law[25]. The components of natural glasses are too numerous to allow accurate correlation. Two points are noteworthy. The points above the line represent alkalic rocks. It was noticed that most of those points which are below the curve represent partially crystalline rocks.

The figures in the following tables represent the average values for all available data including those determined by the writer.

Table of Specific Gravities.

Collector's or Author's Name of Rock	Average Specific Gravity	Range
Obsidian or Rhyolite Glass	2.323	2.13 - 2.42
Pitchstone	2.335	2.22 - 2.51
Perlite	2.346	2.23 - 2.39
Pumice	evidently data are erroneous	
Dacite	2.505	2.45 - 2.55
Trachite	2.411	2.25 - 2.60
Andesite	2.489	2.37 - 2.67
Leucite tephrite	2.562	2.52 - 2.59
Tachylite, Scoria, Diabase & Basalt glass, Palagonite	2.757	2.50 - 2.99

Table of Index of Refraction.

	Index of Refraction	Range
Obsidian or Rhyolite glass	1.492	1.48 - 1.51
Pitchstone	1.500	1.492- 1.506
Perlite	1.497	1.488- 1.506
Pumice	1.497	1.488- 1.506
Dacite	1.511-	1.504- 1.529
Trachite	1.512-	1.488- 1.527
Andesite	1.512+	1.489- 1.529
Leucite tephrite	1.550	1.525- 1.580
Tachylite, Scoria, Diabase & Basalt glass, Palagonite	1.575+	1.506- 1.612

E Alkali types.

Examination of the curve showing the relation of the index of refraction to the specific gravity reveals that most of the points

25 op. cit.

above the curve represent alkalic rocks. This is especially true of glasses ranging from 2.4 to 2.6 in specific gravity. The acid rocks having a specific gravity below 2.4 show little range in alkali content. But those glasses having a specific gravity ranging from 2.4 to 2.6 contain from four to fifteen per cent alkalis. Those rocks having an alkali content below eight per cent, have an average index of refraction of 1.510; those above eight per cent in alkali content have an average index of refraction of 1.522.

Although more data are needed for further confirmation, it may be suggested that a determination of both the index of refraction and the specific gravity may identify the rock more closely than either determination used alone. If, after determining both the index of refraction and the specific gravity, it is found that the index of refraction suggests a more basic rock than is indicated by its specific gravity, the glass may be suspected of being alkalic. The lack of sufficient data and the variability as to the content of iron particularly as to its state of oxidation, make it impossible to plot the distinctions with much accuracy.

V The relation of the composition of natural glasses to other physical properties.

A Hardness

The hardness is rarely mentioned in a petrographic description of natural glass. Pirsson[25] says that the hardness of all glasses is greater than ordinary window glass which it scratches. Judd and Cole[26] say, "The hardness of basalt-glass appears to be not very different from that of orthoclase, varying from 5.5 to 6.5. Though probably, as a rule, softer than obsidian, the difference is not sufficient to distinguish it readily from that rock. But, on the other hand, the hardness of basalt-glass is so much greater than that of the palagonites and other hydrated materials of that class that it serves as an easy means of distinction between the altered and unaltered forms." Luquer[27] expresses the opinion that a sample from Mexico with a hardness of 8 to 9 is a basaltic glass. No other examples are known.

The following shows the hardness of forty-one specimens which were determined by the writer.

Hardness	Number of Specimens	Name of rock.
About 7	7	Pitchstone
	2	Obsidian rhyolite
	1	" trachite
	1	" andesite
Between 6 & 7	9	Rhyolite obsidian
	3	Perlite rhyolite
	2	Pitchstones (1 trachite)
	1	Dacite glass
	6	Basalt glass
Less than 6	4	Obsidian rhyolite
	2	Pitchstones (1 basaltic)
	1	Leucite tephrite glass

25 op. cit. p263
26 Judd & Cole, Quart. Jour. Geol. Soc. London, vol 39, 1883, pp. 450-451
27 Luquer, L. McA., Am. Jour. Sc. vol. 17, p. 94, 1904.

The glasses which have a hardness of 5.5 to 7 seem to range from basalt to rhyolite and determinations of hardness seem to be of little value. There is a possible exception, however, in pitchstones. Most of the pitchstones examined had a hardness of 7 or greater which is rather surprising because most pitchstones have a relatively high content of water. The hydration of minerals usually results in a decrease in hardness.

None of the specimens examined by the writer had a hardness of 8 and it is doubtful if any of them have a hardness much greater than 7.

B Color.

In most text books it is stated as a general rule that under the microscope acid glasses are colorless and basic glasses are colored. This statement is too general and the exceptions too numerous to be made a basis of determination. Rosenbusch[28] mentions the fact that under the microscope some rhyolites are yellow and green and some basic glasses are colorless. Reinisch[29] says that rhyolite pitchstones are yellowish, greenish, or brownish in thin sections. It has been noted by Rosenbusch[30] and probably others that the green colors in natural glasses are inherent in the glass itself, but the blacks and browns are dependent on the presence of dark crystals and crystallites. The abundance of these is responsible for certain glasses being almost opaque, as mentioned below.

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28 Rosenbusch, H., "Microskopische Physiographie der Massigen Gesteine." 1896.
29 Reinisch, R., Petrographisches Praktikum, II, page 27.
30 op. cit. p. 691.

The writer observed the following exceptions to the usual relation of color and composition:

1 East Iceland glass, #65 is brown in thin particles.

2 Red Obsidian, Yellowstone Park, #9, is red from what are probably are submicroscopic particles.

3 Rhyolite from Teotihuacan, Mexico, #58, is similar to #2.

4 Pitchstones from Arran, Scotland, #18, Spechtshausen, Saxony, #66, and Checkerboard Creek, Montana, #19, are colored in thin particles.

5 Trachytes are best illustrated by obsidian from Gough's Island, South Atlantic, #16, which is brown under the microscope. Others may be green.

6 Basalt from Aetna, Sicily, #40, and an iron bearing basalt from Rowno, Wolynien are colorless in small particles.

The following table is the result of the writer's observations:

		In Hand Specimen	In thin pieces under the Microscope
Rhyolite,Ash,Pumice, Tuff	4	White to Gray	Colorless
Obsidian	20	Black,Greenish, Reddish, Brown, Gray	All colorless
Rhyolite Perlite	6	Gray spotted	All colorless
Rhyolite Pitchstone	9	Black, Greenish, Pink	6 colorless,3 Brown,Pink,Gray,&
Trachite glass	7	Black, Red, Green, Brown, Gray	All but 1 (Green. Green or Brown.
Dacite glass	5	Black and Gray	2 colorless, Green Brown,Gray.
Andesite glass	13	Black and Gray	5 Brown,5colorless 3 variable.
Leucite tephrite, glass of Vesuvius	6	Black, Brown	Brown and Green
Basaltic glass	19	Black, Brown, Green	14 Brown,1Yellow, 1 Green, 3 colorless.

C Diaphaneity.

Judd and Cole[31] and Teall[32] say in general that basalt glass may be distinguished in thin sections by its opacity. The basalt glass from Mt. Aetna, specimen #40, and probably others are exceptions. It is doubtful whether any generalizations as to the opacity of natural glasses may be made for determinative purposes.

D Fusibility.

It is claimed that basalt glasses are more easily fusible than acid glasses. Judd and Cole[33] say that basalt glasses may be distinguished by their easy fusibility. Acid glasses also fuse readily, especially if they contain water. They then melt with intumescence. Judd and Cole also say that the product of fusion basalt glass is an opaque black-brown or black bead. It may be that the fusion of basic glasses gives a dark bead and the acid glasses a light bead, but this is not always true and a determination on that basis is unreliable.

E Magnetism.

Undoubtedly, basic glasses are more inclined to be magnetic than acid glasses, but the statement made by Judd and Cole[34] that the striking magnetic properties of basalt glasses enable one to distinguish them from other vitreous rocks is not without exception. A number of basalt glasses were tested by the writer which were not at all magnetic.

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31 op. cit. p. 461
32 op. cit. p. 184
33 op. cit. p. 451
34 op. cit. p. 461

F Solubility.

Although in general basic glasses may be more soluble than acid glasses, the differences in solubility are not such as to warrant classification on that basis. Penck[35] Rosenbusch[36] and others have argued in favor of abandoning any attempts at classification on that basis.

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35 Zeitschrift der deutschen geologischen Gesellschaft, vol XXXI, 1879, p. 531, et seq.
36 op. cit. p. 445, 1877.

VI Application of Data.

A Relative value of physical properties in making determinations.

Of all the data compiled in this paper for the determination of natural glasses, the most useful is undoubtedly the index of refraction. It has the advantage of facility and a wide range of application. Doubtful cases are usually apparent and may be confirmed by the specific gravity which may give additional information. Textural qualifications are obvious.

B Application to thin sections.

The fact that balsam has an index of refraction of 1.540±2 extends the range of application to thin sections. The ordinary method of determining the index of refraction requires that one powder a portion of the specimen and select the oil for comparison. This of course, is impossible in the thin section. By referring to the index of refraction of glasses in several classes it will be seen that rhyolite, trachite, dacite, and andesite glasses have, as far as is known, an index of refraction less than 1.54. The rare leucite tephrite that may have indices less than 1.54, but the average for this glass is 1.55. The basalt glasses have indices well above 1.54. Nine of the eleven specimens of basalt glass determined by the writer were above 1.54 and the two exceptions were probably erroneously labeled. By the use of the Becke line one can compare the index of balsam with the index of the glass in question and determine at once whether the glass is basaltic without the thin section.

Iddings[37] remarks "in naming. . . partly glassy rocks. . . the

37 Iddings, J. P., "Igneous Rocks", vol. II, p. 326.

composition of glassy portions is sometimes ignored, so that rocks called by the same name often differ considerably in composition. There are rocks that have been called limburgite, for example, that contain notable amounts of felsic components, and...rocks with extremely small amounts of feldspar or nephelite have been given the same names as rocks with notable amounts of these minerals." It should be possible by a rapid estimate of the index of refraction to avoid the most serious of these errors without the necessity of a chemical analysis.

C Application to friable rocks.

There are a number of rocks, such as ash, tuffs, etc., which cannot be cut into thin sections. Determinations may be made easily in these cases by powdering the rock and making comparisons with oils of known indices of refraction.

D Differences between isotropic minerals and natural glasses.

Some isotropic minerals, such as analcite, have been confused with natural glasses.[38] Analcite has an index of refraction of 1.487 and a specific gravity of 2.25±. These figures would indicate a glass containing over 70 per cent silica, but analcite is rarely found in acid rocks and if found in a basic rock, the index of refraction should at once distinguish it.

Other isotropic minerals may present similar problems. The case of "Ramosite," first described as a mineral by N. W. Perry[39] and later described by Luquer[40] as a glass, is an example. However,

38 See Pirsson, L. V., "Analcite Group of Igneous Rocks," Jour. Geol. vol. IV, p. 683, 1896.
39 Perry, N. W., Trans. Am. Inst. Min. Engrs. vol. 12, pp. 628-9.
40 Luquer, Lee McA., Am. Jour. Sc. 17, p. 94, 1904.

Ramosite has a hardness of 8 to 9 and a specific gravity of 3.83. Both figures are far from the range of any glasses either in published data or those observed by the writer.

VII Conclusions.

The range of composition in natural glasses is practically that of the common crystalline rocks including a few alkalic types. Corresponding physical properties, namely, the index of refraction and the specific gravity are nearly linear functions.

Classification may be made on the basis of the index of refraction, but the specific gravity may give additional information. Fusibility, color, hardness, solubility, and magnetism, are found to be unreliable indications of the nature of the glass. In detailed studies there are found suggestions of further application.

A specific gravity below 2.3 may be taken to mean a content of water because the most siliceous and feldspathic rocks have a specific gravity as high as 2.3 in the absence of water.

Strange as it may seem, the hardness of several pitchstones (water bearing glasses) is greater than the average of similar obsidians, and a hardness more than 7 may be taken to indicate water in the glass.

The importance of the distinction in crystalline rocks between alkalic and subalkalic rocks led to a special attempt to correlate the amount of alkali with some physical properties. The only suggestion that can be made is that alkalic glasses show a higher index than subalkalic rocks of the same density.

VIII Acknowledgments.

The work on this paper was started by Martin Van Derlinden, who was a graduate student in the Department of Geology in the University of Minnesota, and whose sudden death in January, 1920, brought an end to his investigations. Mr. Van Derlinden wrote a large number of letters to various men in different parts of the United States in quest of analysed specimens of natural glass. The specimens he obtained form a part of those studied by the writer.

To Henry S. Washington, of the Geophysical Laboratory, Carnegie Institute, of Washington, the writer is especially indebted for a number of specimens and his interest in the work. It should be mentioned here that without his admirable work, Professional Paper #99, of the U.S.G.S. publications, it would have been almost impossible to write this paper.

To W. H. Tomlinson and others who have contributed a number of specimens, the writer wishes to express his thanks.

Dr. Frank F. Grout, of the University of Minnesota, proposed the subject and suggested the possible results of its study. His patient supervision has made the work in his laboratory interesting and delightful.

Department of Geology,
University of Minnesota,
April, 1920.