

## The composition of anomalous plagioclase glass and coexisting plagioclase from Mistastin Lake, Labrador, Canada

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**SUMMARY.** Anorthosite country rocks near the fissure vents of an andesitic resurgent caldera contain coexisting crystalline plagioclase, pseudomorphous plagioclase glass, and anomalously dense, massive plagioclase glass. Glass pseudomorphous after labradorite (An 53) has the composition of oligoclase (An 17). Large masses of dense plagioclase glass have compositions near An 53, but relict crystalline plagioclase within them has compositions near An 80. Devitrification products of this glass have potassium-rich compositions. These compositions are compatible with partial thermal melting in a high-temperature, moderate-pressure pulse. Such a pulse might be associated with a confined chemical explosion.

MISTASTIN LAKE (fig. 1) is an oval basin roughly 12 miles long by 8 broad, centred near  $55^{\circ} 52' N.$ ,  $63^{\circ} 23' W.$ , marking the site of a deeply eroded Triassic volcanic caldera (Currie, 1968). Andesitic flows and breccias were erupted from two roughly concentric ring fractures, one approximately following the present shore line, and the other following the shore of the central island. Numerous dikes are also present on this island. Although the presently existing remnants of the flows are restricted to the immediate vicinity of the fractures, they originally covered most or all of the area within the outer ring fracture.

The country rocks affected by the volcanic activity are of Precambrian age, mainly composed of coarse augen granodiorite. A prominent band of white anorthosite passes obliquely across the lake, extending several miles in both directions (fig. 1). Where this band is crossed by dikes of andesite, plagioclase glass is present within the anorthosite. This note reports physical and chemical analyses of this glass, coexisting crystalline plagioclase, and plagioclase from unaltered country rocks.

*Petrography and field relations.* In outcrops remote from the lake, the anorthosite is composed of roughly 95 % cataclastic coarse plagioclase, 2 % diopsidic pyroxene, 2 % hypersthene, and 1 % opaque. Plagioclase displays perfect fine albite twinning, and rare pericline twinning. Fine oriented hairs, too small for optical work, are visible in most large grains of plagioclase. Electron micro-probe traverses across these hairs show a high K content, and they are assumed to be exsolved potash feldspar. The composition of this plagioclase, as shown in table I, was determined by universal-stage determination of extinction angles (Slemmons, 1962), by double-variation measurement of refractive indices in Na-light on grain mounts (Emmons, 1943), by

measurement of refractive index of fragments fused in an oxyacetylene flame (Schairer *et al.*, 1956), and by rapid-method chemical analysis of picked fragments. These methods give results in good agreement with one another, and suggest a remarkably

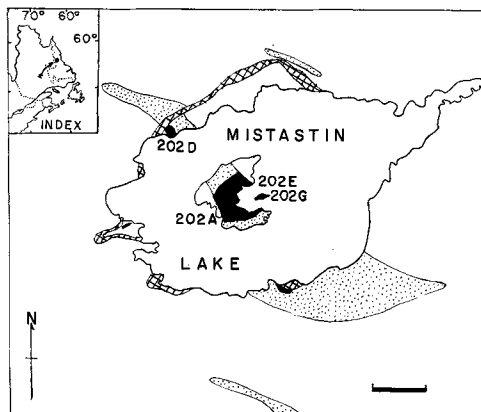


FIG. 1. Geological sketch of the Mistastin Lake area, Labrador. The anorthosite band is shown by the stipple pattern, while the blank areas represent other Precambrian rocks. The main area of occurrence of the Triassic andesite is shown by the hachure, and the areas of occurrence of plagioclase glass by solid black. Andesite dikes on the central island are too small to show on this scale. Numbers show locations of analysed specimens. The scale bar (lower right) represents a length of two miles. The centre of the lake lies near  $55^{\circ} 52' N$ ,  $63^{\circ} 23' W$ .

TABLE I. *Composition of crystalline plagioclase from unaltered anorthosite, Mistastin Lake, Labrador. Chemical analysis by J. L. Bouvier*

	Mean	Range	Composition deduced	N*	Chemical analysis
Extn.† angle	$29.1^{\circ}$	$26.8-31.0^{\circ}$	An 53 (48-59)	49	SiO <sub>2</sub> 55.7
$\gamma$	1.5626	1.560-1.567‡	An 52 (46-59)	27	Al <sub>2</sub> O <sub>3</sub> 27.5
$\beta$	1.5572	1.555-1.562	An 52 (46-59)	27	Fe <sub>2</sub> O <sub>3</sub>    0.6
$\alpha$	1.5543	1.552-1.558	An 52 (46-59)	27	CaO 10.1
$n_{\S}$	1.5303	1.530-1.531	An 53	11	Na <sub>2</sub> O 5.4 K <sub>2</sub> O 0.7
Chemical composition from analysis An 50.1, Ab 45.8, Or 4.1					Sum 100.0

\* no. of measurements

†  $\alpha'$ : (010) on sections normal to [100]

‡ of 27 measurements of  $\gamma$ , 21 fell between 1.562 and 1.563

§ refractive index of fused fragments

|| total iron as Fe<sub>2</sub>O<sub>3</sub>; computed in anorthite molecule.

uniform plagioclase composition, which, disregarding Or content, averages An 53, with an extreme range of An 46 to 59. Zoning is not optically detectable.

The horseshoe-shaped central island, and a small island standing almost in the exact centre of the lake, display moderate to severe metamorphism of anorthosite,

including widespread fracturing, optically anomalous plagioclase and plagioclase glass. Plagioclase glass is also found on the north shore of the lake, in a restricted area of brecciated anorthosite associated with an andesite dike.

In outcrop, glass-bearing rocks are noticeably browner or redder than the usual greyish-white anorthosite. Nodules of massive pale brown glass up to several cm diameter are common, and the rock has a distinctive conchoidal fracture, with vitreous fracture surface. Some outcrops consist of 65 to 90 % glass. A few outcrops on the small central island consist entirely of drawn-out threads of heterogeneous glasses, forming a vesicular lineated rock. In thin section, the xenomorphic granular texture of anorthosite is generally preserved, even in rocks consisting mainly of glass, but the straight grain boundaries typical of the unaltered rock are replaced by wavy or scalloped boundaries. Rocks containing more than 60 % glass commonly lack grain boundaries, displaying instead an irregular set of cracks. Plagioclase in glass-bearing rocks displays a variety of departures from normal optical character ranging from lack of twinning through development of lamellar structures to partial or complete vitrification. The plagioclase is commonly charged with a large number of poorly oriented opaque and fluid inclusions. Cleavage is well developed, but albite twinning is rare, and where present one set of twins is vitrified, commonly with irregular glass stringers joining the vitrified twins (fig. 2). Where twinning is absent, water-clear glass occurs as irregular patches, commonly along grain boundaries, which grade into crystalline material. Glass pseudomorphously replacing plagioclase, and displaying relict cleavage, can be distinguished from large masses of glass that show no traces of pre-existing structure (fig. 3). Commonly there is a noticeable difference in refractive index between massive and pseudomorphous glass. Relicts of pseudomorphous glass may appear even in rocks composed mainly of massive glass. Minor alteration to thomsonite and analcime occurs along cracks in the massive glass, and locally fine vermiform patches (fig. 5) occur in the glass, possibly devitrification products.

Nine determinations of the refractive index of picked grains of the pseudomorphous glass ranged from 1.518 to 1.538, with mean 1.529; 13 determinations of the refractive index of picked grains of the massive plagioclase glass ranged from 1.530 to 1.541, with mean 1.539, and the density of 9 picked grains of this massive glass ranged from 2.55 to 2.60, mean 2.59. The refractive indices of this type of glass cover a small range and are comparable to those of some maskelynite (Bunch *et al.*, 1967). Both density and refractive index are abnormally high for thermally melted plagioclase of composition An 53 ( $n$  1.5303,  $D$  2.54).

The pyroxene associated with the plagioclase and plagioclase glass shows severe undulatory extinction and an unusual golden brown shade. The birefringence is slightly lower than normal. However, pyroxene appears entirely crystalline, both optically and to X-rays.

*Microprobe analyses.* In order to examine the composition of coexisting plagioclase and plagioclase glass, four glass-bearing thin sections were selected for examination on an ARL electron microprobe. They were a section showing traces of pseudomorphous glass surrounding twinned crystalline material (202 A; fig. 2), a section

containing about 25 % densified glass as a matrix, and containing twinned crystals in process of conversion to glass (202E; fig. 3), a slide composed of about 87 % maskelynite and densified glass, with residual crystalline material (202D; fig. 4), and (4) a slide composed of 96 % densified glass with streaks that appear to be devitrification products (202G; fig. 5).



FIGS. 2 to 5. Photomicrographs of anomalous plagioclase glass and coexisting plagioclase. All  $\times 7$ . FIG. 2 (upper left). Photomicrograph of specimen 202A (crossed nicols) showing coexistence of twinned plagioclase (white) and pseudomorphous plagioclase glass (black). Note the irregular glass stringers joining the vitrified albite twins. FIG. 3 (upper right). Photomicrograph of specimen 202E (partly crossed nicols) showing continuous transition from crystalline plagioclase (white with cleavage) through pseudomorphous glass (pale grey with cleavage) to massive glass (darker grey, no cleavage). A difference in refractive index between the two glasses is shown by the very smooth appearance of the pseudomorphous glass compared to rougher appearance of massive glass. FIG. 4 (lower left). Photomicrograph of specimen 202D (crossed nicols) showing dense plagioclase glass (black) in sharp scalloped contact with crystalline plagioclase (white). The white streaks in the glass are due to internal reflections. FIG. 5 (lower right). Photomicrograph of specimen 202G (plane polarized light) showing massive plagioclase glass with devitrified areas (complex vermiform texture). Note the tendency towards crystalline shape of the vermiform patches.

Microprobe analyses for Si, Al, Na, K, and Ca were carried out by analysing at least five different spots within an area of glass or crystal. A minimum of 5 readings for each element at each position was taken, except on glass, where the beam was moved constantly to prevent decomposition of the glass.

Standard samples of approximate composition An 40 and An 60 were analysed between each set of readings on the unknown. These analyses suggest that the results,

quoted in table II, are accurate to approximately  $\pm 2\%$  of amount present for  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$ , and  $\text{K}_2\text{O}$ , and  $\pm 5\%$  of amount present for  $\text{Na}_2\text{O}$ .

Table II shows that the feldspar components sum fairly well to 100% for all the glass analyses. All the analysed materials have plagioclase composition, but the glass is strongly enriched in Na and K relative to surrounding plagioclase where present as pseudomorphous patches in plagioclase. Large masses of dense glass, however, are very close to the composition of the presumed parental feldspar, An 53. Residual crystals in glass-rich rocks are vastly enriched in Ca and Al relative to the surrounding

TABLE II. *Chemical analyses of coexisting plagioclase, massive plagioclase glass, and pseudomorphous plagioclase glass. Analysis by G. R. Lachance*

No.	Phase	Na <sub>2</sub> O	K <sub>2</sub> O	CaO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	Ab	Or	An	Total*
202A	Crystal	5.3	0.3	10.4	27.8	55.2	44.8	1.8	51.6	98.2
	Pseudomorphous glass	6.3	0.6	8.9	24.5	58.3	53.4	3.6	44.3	101.3
202E	Crystal	5.4	0.7	10.1	27.5	55.3	45.6	4.1	50.1	100.1
	Pseudomorphous glass	8.5	1.8	3.4	22.8	60.1	72.0	10.7	16.9	99.6
202D	Massive glass	5.1	1.0	10.4	27.6	55.2	43.1	5.9	51.6	100.6
	Massive glass	5.3	0.8	9.9	27.4	55.4	44.8	4.7	49.1	98.6
202G	Crystals	2.4	0.1	16.3	32.6	47.1	20.3	0.6	80.8	101.7
	Massive glass	5.5	0.7	9.8	27.8	55.4	46.5	4.1	48.7	100.3
	Crystals	6.3	2.0	6.1	15.8	66.1	53.3	11.8	30.3	96.3

\* Computed feldspar composition from content of Na, Ca, and K only.

glass, and approximate An 80 in composition. Apparent devitrification products are remarkably rich in K and do not approach An 53. All of these compositional differences are well outside the limits of variation of the parental anorthosite. Finally, we may note a character that does not appear in table II, namely homogeneity of distribution of K in the glass. All glasses have very homogeneous distribution of this element, whereas the coexisting crystals all showed strong heterogeneity, presumably due to the presence of the threads of potash feldspar previously noted. The process of vitrification has homogenized the distribution of potassium on a small scale.

*Discussion.* The formation of alkali-rich glass from labradoritic plagioclase strongly suggests intervention of thermal melting. In specimens A and E, crystals of composition An 53 produce glass of composition An 17. From the diagram of Bowen (1913) this is very close to the relationship expected from thermal melting at atmospheric pressure, and could be explained as the result of fractional melting of original labradorite crystals. The last crystalline residue resulting from complete melting, beginning at about 1290° and complete at 1450°, would be of composition An 80 $\pm$ . Although the temperatures are affected by increasing pressure, the shape of this loop appears to remain the same up to pressures of at least 5000 bars (Yoder *et al.*, 1956).

Simple thermal melting, however, does not explain the pseudomorphous form of

some of the glass, nor its dense character. As pointed out by Bunch *et al.* (1967), even heating for three minutes at melting temperatures and atmospheric pressure would destroy the pseudomorphous relations, and produce a glass of normal density and refractive index. Bunch *et al.* proposed formation of dense pseudomorphous glass by passage of a shock wave, generated by hypervelocity impact, with peak pressure of 100 to 300 kilobars as demonstrated experimentally by Milton and DeCarli (1963). It was suggested that this shock would slightly disorder the lattice producing a metastable strained phase, maskelynite. In support of this view they quoted infra-red absorption data suggesting that some natural maskelynite has a short range order intermediate between crystalline material and glass. Ahrens and Rosenberg (1968) show that other types of maskelynite formation are possible, since shock-loaded plagioclase can undergo a displacive phase transition to the hollandite structure. Shock decompression of this dense phase can form maskelynite, presumably as a phase trapped between high- and low-pressure crystalline states.

Neither of these processes, however, explains a systematic fractionation of elements between crystals and glass, unless it is assumed that equilibration between plagioclase and hollandite structures concentrates Na in the latter, and this process proceeds to a significant extent during passage of the shock wave. This seems very improbable. Even if such equilibration did take place, the glass produced from inversion of the hollandite-type polymorph would differ in chemical composition and atomic arrangement from the original plagioclase, and could hardly be termed 'disordered plagioclase'. Melting during impact metamorphism is also inadequate to explain fractionation. While temperature rises during impact, Milton and DeCarli (1963) estimated the maximum temperature in their maskelynite-producing experiments not to exceed 350°. If the temperature reached at peak shock pressure were sufficient to melt plagioclase thermally, the residual temperature after passage of the shock wave would certainly be high enough to anneal the glass to low-pressure properties (Chao, 1968; Chao and Bell, 1969). These considerations show that, despite the occasionally pseudomorphous character and anomalous physical properties of the Mistastin Lake glass, it cannot be called maskelynite, as redefined by Milton and DeCarli (1963), nor can it be explained by shock metamorphism.

The most plausible process to fractionate sodium into the glass phase is melting. The high density and refractive index of the glass can be explained by assuming it to be melted and quenched under high pressure. According to the work of Chao and Bell (1969) the index of refraction observed in the dense glass of labradorite composition could arise from melting of labradorite at pressures of approximately 10 kilobars, if the liquid were rapidly quenched.

However, the observation of Bunch *et al.* (1967) that heating times of more than a few minutes would destroy the pseudomorphism of maskelynite remains. This dilemma can be avoided by assuming that the temperature is raised with extreme rapidity, so that small portions of the plagioclase are brought to melting temperature but the melt has no time to react with its surroundings, or to flow. Further, the quench must be equally rapid, since otherwise the properties of the glass would tend to anneal toward those of atmospheric pressure glass (Chao and Bell, 1969).

A possible method of achieving these conditions is a chemical explosion. During combustion, the temperatures and pressures in a confined space rise very rapidly. If the confining walls fail as a result of explosion, the temperature drops very rapidly owing to adiabatic expansion of the gaseous explosion products. Temperatures of 1500 °C and 10 kilobars could easily be reached during a partially confined explosive combustion of hydrogen, for example. The time during which these conditions would be maintained depends on the rapidity of burning of the gas and the nature of the walls. While quantitative estimates are difficult, periods ranging from a fraction of a second to several tens of seconds seem reasonable. Chemical explosions due to combustion of hydrogen are a well-known feature of many volcanic eruptions (Jaggard, 1950). The close association of part of the Mistastin Lake maskelynite with rocks of volcanic appearance suggests a link between the two. The occurrence of maskelynite in the central core of plutonic rocks could be explained by assuming this core to have become saturated with explosive gases along fractures, and a general explosion or series of localized explosions to have occurred.

Dense plagioclase glass at Mastastin Lake appears to be a product of a very rapid rise of temperature and pressure followed by abrupt quenching. The formation of dense glass suggests peak temperatures of approximately 1500 °C and peak pressures not much greater than 10 kilobars followed by rapid quenching. A high-temperature, moderate-pressure pulse of this kind could be produced by chemical explosions, possibly associated with volcanism, but not by shock metamorphism accompanying hypervelocity impact. The composition of coexisting dense glass and plagioclase therefore suggests an endogenic, rather than exogenic origin for this structure. The conclusion that thermal melting forms the anomalous glass suggests that other occurrences of anomalous glass not chemically analysed have been erroneously identified as maskelynite on the basis of their physical properties.

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[Manuscript received 12 October 1970.]