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NATURAL TERRESTRIAL MASKELYNITE

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Abstract

Maskelynite occurs in the rocks of the central peaks of Clearwater West and Manicouagan craters, Quebec, Canada. Optical, X-ray and infrared absorption properties are similar to those of maskelynite in the Shergotty meteorite and in an artificially shocked gabbro. Heated maskelynite reverts to crystalline plagioclase, indicating only slight structural disordering unlike fused plagioclase glass. Experimental evidence suggesting that more than 50 kilobars shock pressure is required to form maskelynite, supports a meteorite impact origin for the craters.

Introduction

A clear, glassy pseudomorph of plagioclase was described in the Shergotty basaltic achondrite by Tschermak (1872) and named maskelynite. He reported maskelynite of labradorite composition as clear, colorless laths with fine lines exactly like plagioclase in ordinary light, but completely isotropic under crossed nicols. Associated pyroxenes were described as turbid due to fine irregular cracks of mechanical origin. Tschermak concluded that maskelynite was a transformation of plagioclase produced by remelting or by mechanical means. A mechanical transformation of Stillwater gabbro to a rock resembling shergottite was achieved by Milton and DeCarli (1963) by shock-loading the gabbro at 250 to 350 kb peak pressure and a calculated temperature of no more than 350°C. They advocated restricting the term maskelynite to a noncrystalline phase clearly pseudomorphous after crystalline feldspar. Duke (1963) restudied the Shergotty meteorite in detail and suggested the maskelynite resulted from a passage of a strong shock wave through the meteorite.

Terrestrial samples containing isotropic material conforming to Milton and DeCarli's definition have been collected from two large probable ancient meteorite craters in the Canadian Shield (Beals, *et al.* 1963). Kranck (1963) described a gabbroic rock cropping out on a small island near the center of West Clearwater lakes (56°12.3N–74°29.4W) as containing glass in some of its plagioclase. This transformation he attributed to volcanic heat, an interpretation endorsed by Currie (1965). Samples

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from the same island were collected by Dence and Shoemaker in 1962 and compared by Dence (1964, 1965) to the gabbro artificially shocked by Milton and DeCarli. From the comparison the glassy phase at Clearwater West was called maskelynite. This supported the petrographic evidence of shock deformation given by MacIntyre (1961) and the meteoritic origin for the craters suggested on broader grounds (Dence, *et al.* 1965). The results at Clearwater Lake renewed interest in the similar 65 km diameter Manicouagan structure and the similarity was sustained when maskelynite was found in 1963 by Dence on two peaks (51°25.2N to 51°26.3N; 68°35.9W) of the anorthosite massif which dominates its center.

Petrography and Field Relationships

Shergotty maskelynite occurs as clear laths of medium grain size uniformly intergrown with pigeonite, augite, apatite and opaque minerals. The pyroxenes show varying degrees of deformation much like that described by Reid and Cohen (1967) for orthopyroxenes in enstatite achondrites. The maskelynite is clear and colorless, appearing in plane light exactly like plagioclase with traces of composition zone boundaries and cleavages visible. It is entirely isotropic with the exception of a few patches of low birefringence.

The West Clearwater gabbro is a medium-grained (0.3 to 0.5 mm grain size) basic member of the Archean plutonic complex of northern Quebec. The gabbro is massive and equigranular with clear or altered maskelynite and remnant plagioclase comprising about 50% of the rock along with orthopyroxene, clinopyroxene, green amphibole, brown biotite and accessory opaque minerals. Fresh maskelynite appears bluish in hand specimen and clear and colorless in thin section. Alteration to white carbonate and zeolite or brown devitrified glass is common. As in Shergotty maskelynite original grain boundaries, twin composition planes and cleavages are preserved intact. Patches of remnant plagioclase show effects of severe strain in the development of planar structures similar to the deformation lamellae reported in strained quartz (Carter, 1965). In some cases the structures are concentrated in bands resembling kink bands. Birefringence may vary from nearly normal to zero within a grain either gradually or discontinuously. Discontinuities commonly occur at original twin composition planes or within the fine sets of planar deformation structures. The selective transformation of twin lamellae of one orientation when the intergrown lamellae are less severely affected indicates the importance of orientation and primary structure in controlling the process. Associated mafic minerals appear optically and from X-rays to be entirely crystalline and to have undisturbed grain boundaries, even when completely enclosed in maskelynite. However, pyroxenes exhibit undulatory extinction, disoriented domains, and fractures.

The Mont de Babel anorthosite at Manicouagan is a member of a major basic and ultrabasic complex set in high grade Grenville gneisses. Unlike many Grenville anorthosites which have a cataclastic texture the Mont de Babel rocks have been completely recrystallized in the Grenville orogeny. The anorthosite has a post-kinematic metamorphic texture with no sign of the cataclastic structure commonly found in many Grenville anorthosites. It is a massive, equigranular, medium grained rock (average grain size 0.5 to 1 mm) of interlocking anhedral garnet, pyroxene, amphibole and accessory minerals. It is cut by widely-spaced bands, 1 to 10 cm in thickness, of clinopyroxenes, orthopyroxene, yellow-brown amphibole, garnet, opaque and other accessory minerals with some plagioclase and scapolite. Deformation associated with the Manicouagan structure is seen in outcrop as faults offsetting the sharply-defined mafic bands and as irregular veins and networks of glassy "pseudotachylite" commonly 1 to 5 cm wide. In fresh hand specimens up to 25% of the plagioclase is replaced by maskelynite distributed in irregular pods or lenses up to several millimeters wide. Both maskelynite and feldspar are commonly altered to thomsonite, particularly along grain boundaries or in ovoid patches. Iron-bearing minerals are stained with iron oxide. The altered rock is a salmon-pink color and is mainly developed near the margins of the massif.

In thin section, relationships duplicate those at Clearwater West crater. Whole plagioclase grains and portions of others have been transformed into maskelynite without disrupting original grain boundaries (Fig. 1), cleavages or twin composition planes. Severe internal strain is indicated by the development of sets of planar structures in grains which retain some birefringence and can be seen grading into isotropic patches. Gradational changes in birefringence are accompanied by changes in optic axial angle from $2Vx = 98°$ in areas of little strain to $2Vx = 62°$ in highly strained regions. Mafic minerals are completely crystalline and undeformed except for unusually intense internal fracturing and cleavage.

Maskelynite from both Clearwater and Manicouagan is completely isotropic and amorphous in X-ray powder patterns obtained with a Philips 114.6 mm diameter camera using CuKα radiation. Their refractive indices are compared in Table 1 with those of Shergotty and of artificial maskelynite. In each case the refractive index of the maskelynite is higher than that of glass of the same composition produced by heating at atmospheric pressure (Schairer, *et al.* 1956). This was confirmed for the Manicouagan material by powdering and fusing a small

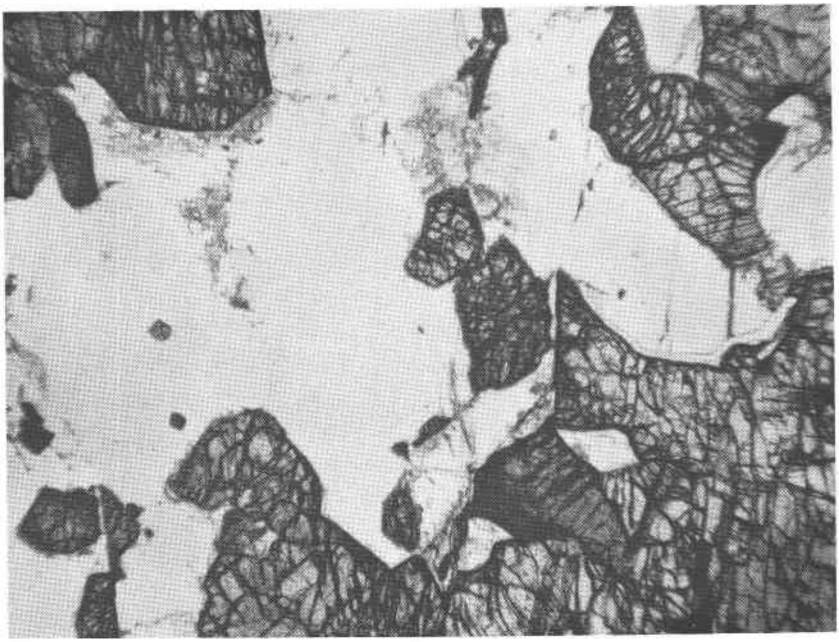

FIG. 1. Photomicrograph of Manicouagan anorthosite: maskelynite, colorless; pyroxene and garnet, dark; secondary zeolite, light grey. Plane-polarized light, ×38.

portion of the plagioclase in a high temperature melting furnace at 1500°C. The refractive index of this glass is 1.532.

INFRARED SPECTROGRAPHY

Its high refractive index indicates maskelynite is a dense glassy phase. Its apparent gradation into crystalline plagioclase suggests that it is less

TABLE 1. PROPERTIES OF MASKELYNITE

Sample	Composition	Refractive Index			
		Crystals (mean)	Maskelynite n_M	Fused Glass n_F	$n_M - n_F$
Shergotty	An_{50}	1.558	1.547	1.528[1]	0.019
Clearwater West	An_{58}	1.563	1.544	1.536[1]	.008
Manicouagan	An_{54}	1.560	1.541	1.532[2]	.009
Artificial[3]	An_{80}	1.573	1.562	1.557	.005

[1] Schairer *et al* (1956).
[2] Schairer *et al* (1956); confirmed by melting powdered crystals at 1500°C (this work).
[3] Milton and DeCarli (1963).

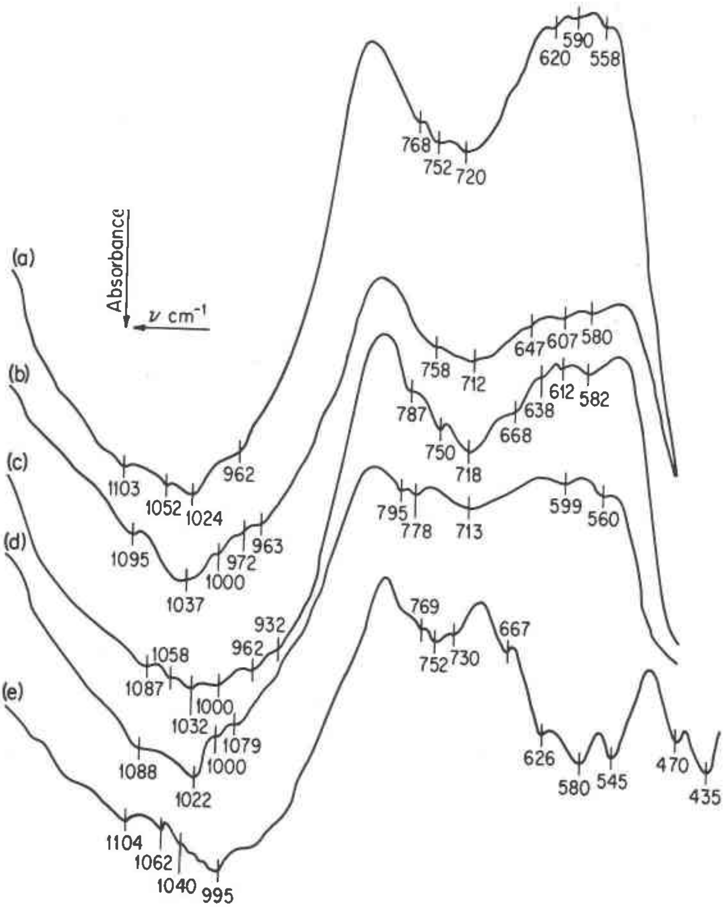

FIG. 2. Infrared absorption spectra of (a) artificially fused plagioclase, (b) Clearwater West maskelynite, (c) Manicouagan maskelynite, (d) Shergotty maskelynite, (e) crystalline plagioclase An_{54} in region 530 to 1200 cm^{-1}.

ordered than the crystalline but more ordered than the thermally-fused plagioclase glass. Infrared spectrophotometric methods were utilized to further investigate the ordering in maskelynite. Absorption analyses in the near infrared region (4000 to 400 cm^{-1}) were obtained using a Beckman Model IR-9 spectrophotometer; a Model IR-11 was used for analyses in the far-infrared (600 to 33 cm^{-1}).

Absorption spectra of artificially fused plagioclase, Clearwater, Manicouagan and Shergotty maskelynite and crystalline labradorite (An_{54}) are shown in Figure 2. There is a progressive loss of detail in the spectra from the crystalline plagioclase through terrestrial maskelynite and Shergotty maskelynite to fused plagioclase. The terrestrial maskelynite spectra are similar to that of artificially shocked plagioclase reported by Lyon (1964). The intermediate position of maskelynite between crystalline and fused plagioclase is most clearly shown in the far-infrared absorption spectra in the region 580 to 380 cm^{-1} (Fig. 3). In this region the Si-O-Si or Si-O-Al absorption band, (Cohen and Roy, 1965), which is controlled by the ordering between Si and O or Al and O, shifts from a peak at 380 cm^{-1} in crystalline plagioclase to 480 cm^{-1} in fused plagioclase. Maskelynite of the same composition (An_{54}) shows a peak position at 405 cm^{-1}, indicating a state of disorder intermediate between the crystalline and "fused glass" states.

Maskelynite resembles crystalline plagioclase in showing infrared absorption in the water band region (250 to 200 cm^{-1}). i.e. the O-H-O stretch vibration of absorbed water. Loss of water on heating prevents fused plagioclase from absorbing in this region. The retention of water is a further indication that the maskelynite transformation changes the plagioclase structures less than heating to the melting point.

HEATING EXPERIMENTS

From the above observations it seems apparent that maskelynite from Clearwater West and Manicouagan craters is similar to Shergotty maskelynite and is consistent with the definition suggested by Milton and

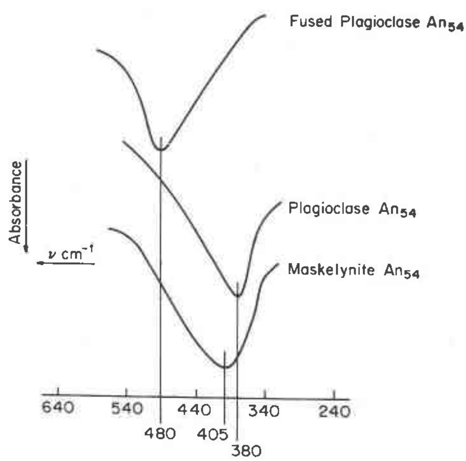

FIG. 3. Infrared absorption spectra of (a) artificially fused plagioclase An_{54}, (b) Manicouagan plagioclase An_{54}, (c) Manicouagan maskelynite An_{54}, in the region 380 to 580 cm^{-1}.

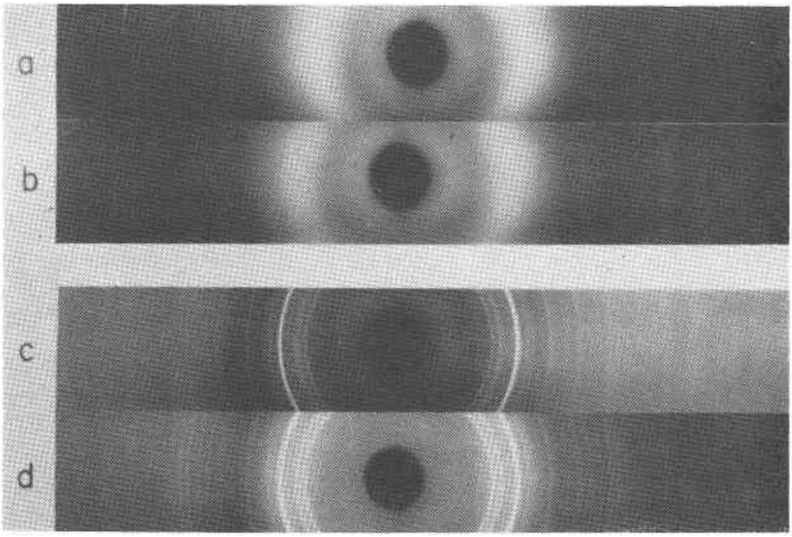

FIG. 4. X-ray powder patterns of (a) artificially fused plagioclase An_{54}, (b) Manicouagan maskelynite, (c) heated maskelynite (900°C for 2 hours), (d) crystalline plagioclase that coexists with maskelynite (Manicouagan).

DeCarli (1963). To complete a preliminary study of natural terrestrial maskelynite a series of heating experiments were performed to investigate maskelynite under various heating and cooling conditions. Maskelynite grains from Manicouagan anorthosite (C-447) heated in a muffle furnace at 900° ± 20° for two hours transformed into either single crystals or polycrystalline aggregates of plagioclase with axial angle (2Vx) between 75° and 90° and mean refractive index of 1.560. An X-ray powder pattern of crushed transformed material indicate that it is crystalline plagioclase (Fig. 4).

In a similar heating experiment Clearwater West maskelynite grains were transformed into single crystals or polycrystalline aggregates of plagioclase, but only small areas of low birefringence were found in the Shergotty maskelynite. Further heating of Shergotty maskelynite at 1150°C for one hour resulted in its partial transformation to plagioclase. Heating of artificially fused plagioclase and natural plagioclase glass at 900°C for two hours showed no significant change. Results of all powder heating runs are given in Table 2.

Polished thin sections were made of maskelynite-bearing anorthosite from Manicouagan and gabbro from Clearwater West. These thin sections were then heated at 900°C for two hours and cooled slowly in the furnace. Optical examination and Laue patterns showed that the maskelynite portions transformed to single crystals of plagioclase.

Discussion and Conclusions

The observations clearly indicate strong resemblances between natural and experimentally shock-produced maskelynite, and differences between maskelynite and thermally-fused plagioclase glass. Heating above the melting point of labradorite (1400°C at 1 atm), even 3 minutes (a period too short to allow equilibrium melting or escape of volatile elements), would obscure grain boundaries and internal structures, produce glass of normal refractive index, and affect existing micas, amphiboles and pyroxenes. Thus the preservation of mafic minerals and of all grain boundaries, the development of planar structures, the selective transformation of twin lamellae, the high refractive indices when compared with fused glass of the same composition, and the intermediate state of disordering indicated by the absorption spectra all support maskelynite formation by a rapid mechanical rather than a thermal transformation. Similar transformations have been reported for quartz by shock-loading (Wackerle, 1962) and by high-energy neutron bombardment. The latter produces a phase optically isotropic and amorphous to X-rays which can be converted to polycrystalline quartz by heating at 930°C for several hours (Wittels and Sherrill, 1954). Apparently the amorphous form produced

Table 2. Heating Experiments

Starting Material	T°C[1]	Heating Period[2]	Remarks
Maskelynite (Manicouagan)	900	2 hours	Most maskelynite grains transformed to single crystals or crystalline aggregates of plagioclase.
Maskelynite (Clearwater)	900	2 hours	Do.
Maskelynite (Shergotty)	900	2 hours	Small regions of low birefringence.
Maskelynite (Shergotty)	1150	1 hour	Partial transformation to plagioclase.
Pseudotachylite plagioclase glass (Manicouagan)	900	2 hours	Development of small radiating crystallites.
Synthetically fused Manicouagan plagioclase	900	2 hours	No change.
Maskelynite (Manicouagan)	820	4 hours	Small regions of low birefringence.
Maskelynite (Manicouagan)	750	4 hours	No change.
Maskelynite (Manicouagan)	600	6 hours	No change.
Maskelynite (Manicouagan)	360	18 hours	No change.
Maskelynite (Manicouagan)	360	36 hours	No change.

[1] ±20°C.

[2] Heating time at peak temperature.

by bombardment has greater short-range ordering than normal fused silica and the transformation into crystalline quartz on heating is effected by the relaxation of strained bonds rather than by diffusion (Primak, 1958).

The heating experiments reported here indicate maskelynite is a similar metastable strained phase. The original disorder produced in the plagioclase structure from a plagioclase-maskelynite transformation may involve only a slight misorientation of (Si, Al)O_4 tetrahedra; therefore maskelynite would have greater short-range order than fused plagioclase. The plagioclase structure is restored on annealing by relaxation of strain between the short-range domains.

The greater ease with which Clearwater West and Manicouagan maskelynite is annealed when compared with Shergotty, and the relatively high percentage of less-affected feldspar with which they are associated suggest than the terrestrial rocks have been shocked at lower pressures than the meteorite. The few experimental data available have been summarized by Ahrens and Gregson (1964) and indicate that the Hugoniot elastic limit for plagioclase is reached at about 40 to 50 kilobars shock pressure. The formation of planar structures and of maskelynite probably takes place above this pressure in a mixed phase region extending to about 300 kilobars. At higher pressures dense glass is the only phase, there being no known high pressure crystalline form of plagioclase.

In nature only hypervelocity impact is known to produce shock pressures of such intensity. The results support the meteoritic impact origin for the Clearwater and Manicouagan craters. They indicate that in these large terrestrial craters the massive central peaks have been uplifted sufficiently rapidly to preserve large quantities of shocked rocks with fresh, unannealed maskelynite. The alteration that does occur can be attributed to the hydrothermal action of ground water heated to possibly 200°C by energy deposited behind the shock wave and by the frictional heat of the uplift.

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