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Lunar Noritic Fragments and Associated Diopside Veins

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Abstract

Fragments composed of coarse (1–2 mm) orthopyroxene ($En_{77}Fs_{20}Wo_3$-$En_{81}Fs_{16}Wo_3$) and attached plagioclase (An_{92}-$An_{94.5}$) are a conspicuous minor component in Apollo 17 soils collected at the base of the Sculptured Hills. Although the textures of the fragments are ambiguous, they are possibly plutonic igneous. The fragments are mineralogically similar to rock 78235, a coarse-grained shocked norite with probable cumulate texture. Two of the samples contain small areas of possible igneous mesostasis rich in Si, Al, K, Na, Ba, and P. The apparent restriction of these norite fragments to the Sculptured Hills may indicate that this and topographically similar areas are underlain by coarse-grained noritic igneous intrusions or cumulate bodies.

Veins composed mainly of diopside ($En_{48}Wo_{48}Fs_4$-$En_{48}Wo_{47}Fs_5$) with associated chromite (55.6 percent Cr_2O_3), Fe–Ni–Co metal, silica and troilite, and other narrow veinlets of metal, occur in several of the orthopyroxene grains, and appear to result from intrusion and crystallization of fluid (melt or vapor). The source of the fluid is enigmatic.

Introduction

Coarse-grained rocks with grain sizes greater than 1 mm are rare among the returned lunar samples. Grain sizes of both mare and highlands rocks, whether igneous, metamorphic, or cataclastic, are most commonly in the range of tenths of millimeters. In mare areas, coarse-grained rocks composed largely of olivine, clinopyroxene, ilmenite, and/or plagioclase are presumably produced from Fe–Ti basalt magmas by slow cooling and/or crystal accumulation at near surface conditions. In the highlands, large single crystals or coarse-grained polycrystalline fragments little affected by impact events might also be high-level cumulates (from feldspathic basalt magmas), but there is the possibility that some represent samples of deep-seated igneous and metamorphic rocks produced by large scale lunar processes.

We have noted six unusually large single crystals of orthopyroxene with attached plagioclase and mesostasis in Apollo 17 1–2 mm soil samples 78442,2, 78422,2, and 78502,17 from station 8 near the base of the Sculptured Hills. The first two samples were obtained from a trench while the third was collected some 30 meters up-slope near a small crater. Associated with these orthopyroxene crystals are complex veins containing diopside, chromite, metal, silica and troilite, and other veinlets of metal. We present here details of the texture and mineralogy of the fragments, and make some interpretations concerning their origin.

Textural Observations

The orthopyroxene crystals are equant and range in maximum dimension from 1.1 to 2.2 mm. No silicate exsolution or zoning features were observed optically, and strain effects are slight. Plagioclase grains are either attached to, or enclosed by, five of the orthopyroxene crystals (Fig. 1). The original grain size of the plagioclase and the overall texture of the rocks are difficult to gauge because only crystal fragments of plagioclase remain. However, the extent of some pyroxene-plagioclase interfaces suggests that the attached plagioclase grains were originally about as large as the pyroxenes. By analogy with terrestrial rocks, the geometries of most of the pyroxene-plagioclase interfaces could be assigned to either igneous or metamorphic processes, although textures such as the plagioclase "embayment" in orthopyroxene 78502,17A12 (Fig. 2a) are perhaps more typical of plutonic igneous rocks. The textures could also be those of igneous cumulates (with the possible exception of the apparently included plagioclase grains in orthopyroxene 78502,17A36). No mosaic

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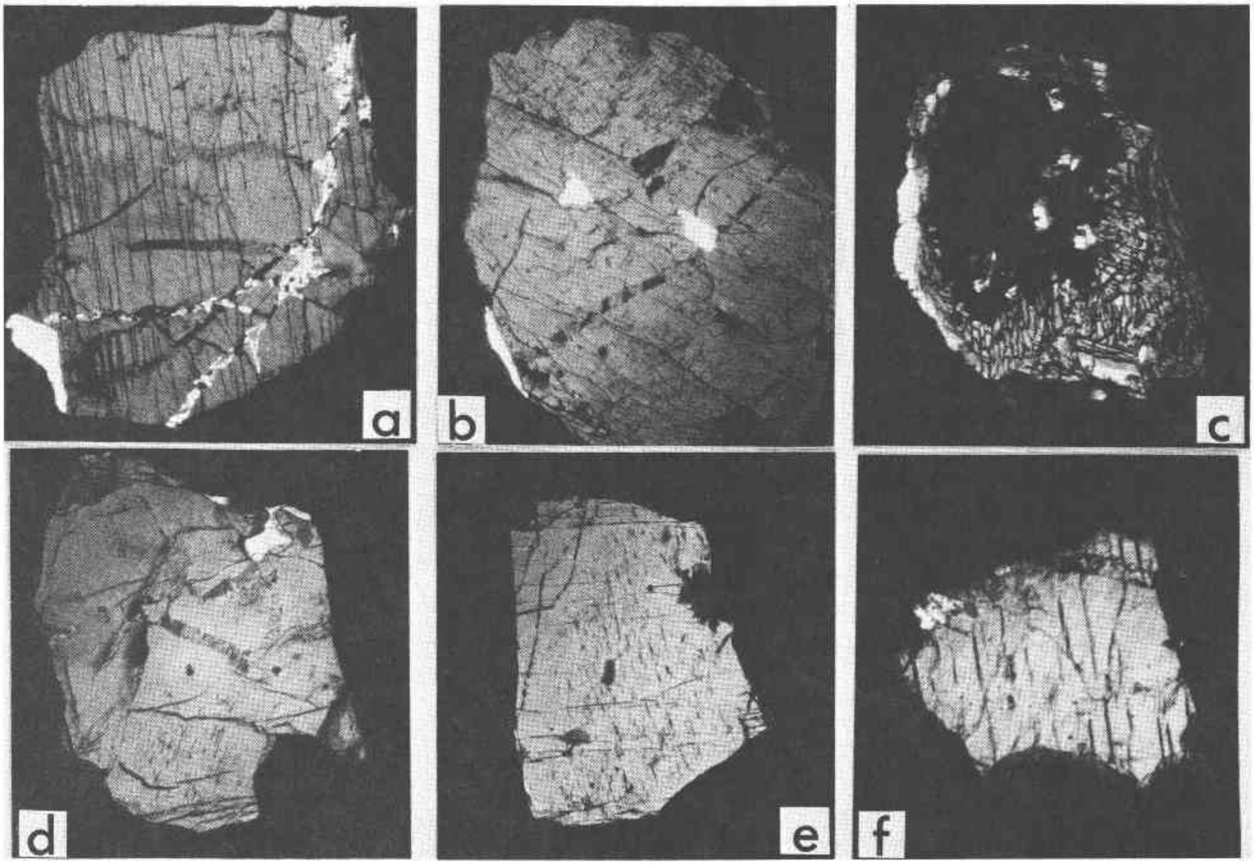

FIG 1. Photomicrographs of the six norite fragments from the Sculptured Hills. (a) Orthopyroxene 78442,2A6 with attached plagioclase (white, lower left) and diopside-rich veins (mainly white). The three dark bands extending right to left within the orthopyroxene are dipping metal veinlets. Width of grain is 1.2 mm. (b) Orthopyroxene 78502,17A36 with attached and included plagioclase (white). Note the dark metal veinlet which is discontinuous at the plagioclase grain boundaries. Width of grain is 1.9 mm. (c) Orthopyroxene 78422,2A5 with attached plagioclase (white, left) along a gently curved interface. The center of the orthopyroxene grain was plucked during thin section preparation. Width of grain is 1.5 mm. (d) Orthopyroxene 78502,17A12 with plagioclase "embayment" (white, upper right) and metal veinlets (center). A very small mesostasis area is barely visible halfway along left margin. Width of grain is 1.5 mm. (e) Orthopyroxene 78502,17A9 with narrow diopside-rich veins (dark, upper left) and mesostasis area (dark, upper right). Width of grain is 1.2 mm. (f) Orthopyroxene 78422,2A17 with small attached plagioclase grain (white, upper left). Width of grain is 1.1 mm.

textures characteristic of annealed metamorphic rocks are present.

Small patches (~0.05 and ~0.3 mm across) of possible igneous mesostasis are present in embayments on the margins of two of the orthopyroxene crystals (78502,17A9 and 78502,17A12). Two rounded grains (~50 μm across) of orange-brown spinel occur at the boundary betwen orthopyroxene and mesostasis in sample 78502,17A9 (see Fig. 2b), and a similar spinel grain is closely associated with the mesostasis of sample 78502,17A12.

Networks of diopside-rich veins varying in width from 10 to 40 μm were observed in orthopyroxenes 78442,2A6 and 78502,17A9, which were sampled from sites 30 meters apart (Figs. 1a, 1e). The veins have the appearance of infilled pre-existing fractures. Grains of chromite, metal, and rare troilite (10–50 μm in maximum dimension) and small patches of polycrystalline silica occur sporadically throughout the veins of both samples. The troilite is commonly in close association with metal and silica. Because of the narrowness of the veins, the diopside does not give the appearance in thin section of a continuous vein-filling phase; in places the full width of the veins is occupied by chromite, metal, or silica, and in one case a λ-shaped grain of chromite occupies the junction between two veins (see Figs. 2c, 2d).

Very thin (0.1 to 0.2 μm wide) veinlets of metal were observed in four of the orthopyroxene crystals (Figs. 1 and 2), and seem to emanate from diopside-rich veins, if present (Fig. 1a). These veinlets are confined to the orthopyroxene and appear to stop abruptly at plagioclase interfaces.

Mineralogic Data

Microprobe analyses of the six orthopyroxene crystals (Table 1) indicate that they are bronzites with a limited range in composition from $En_{77}Fs_{20}Wo_3$ to $En_{81}Fe_{16}Wo_3$, the Mg/Fe ratio being the main difference among the six crystals. The Al_2O_3 contents are relatively low (~1.0 percent), and the Al could be entirely tetrahedrally coordinated. The Cr_2O_3 contents are high (0.6–0.7 wt percent), but fall within the ranges observed for pyroxenes from both ANT rocks (Taylor *et al*, 1973) and Fe–Ti basalts (Dowty, Prinz, and Keil, 1973). All the orthopyroxenes are very homogeneous in major elements, but slightly inhomogeneous in some minor elements (*e.g.*, Ca, Al, and Ti). Precession photographs of 78422,2A17 show diffraction symmetry

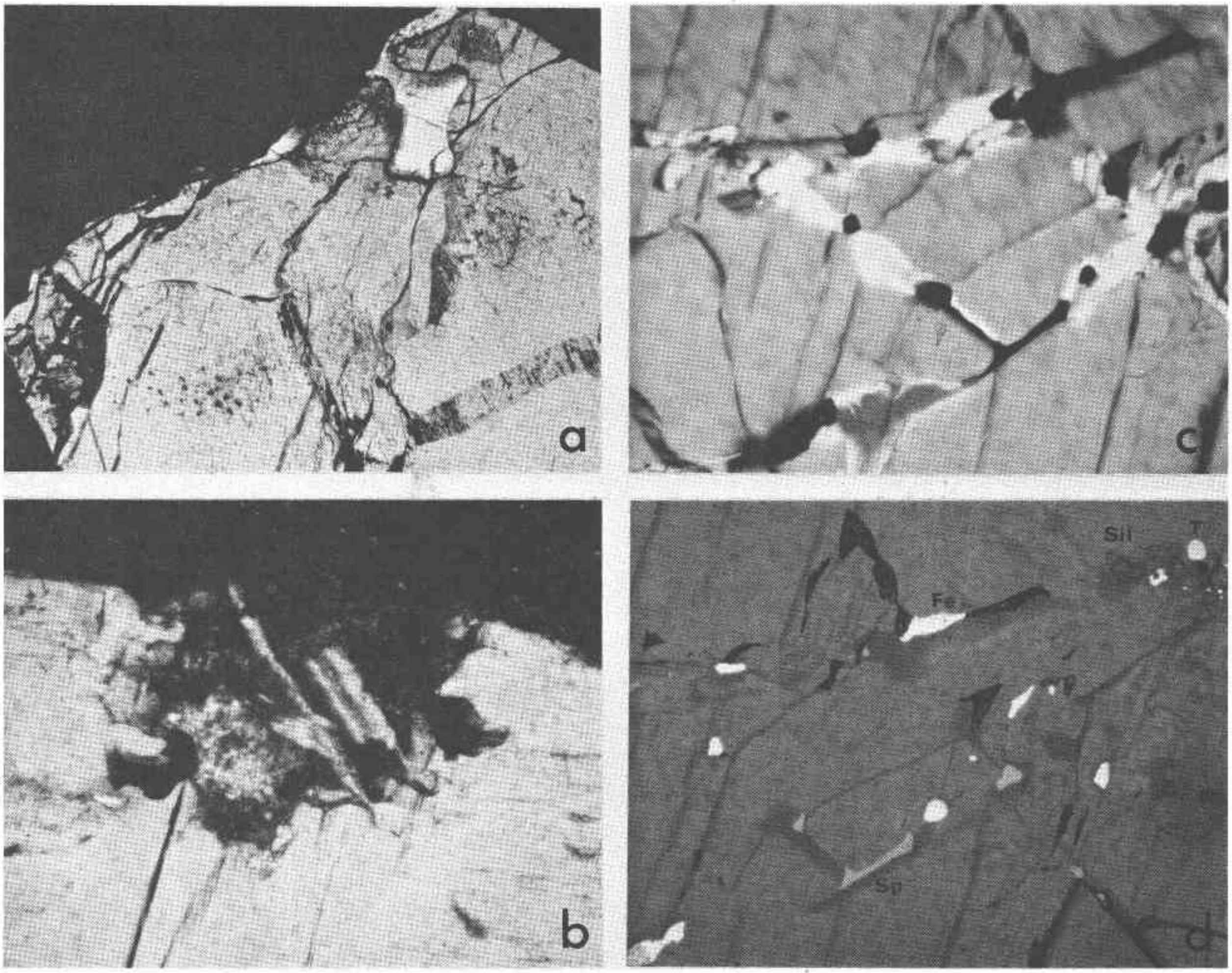

FIG. 2. (a) Detail of textural relationship between plagioclase (white, upper right) and orthopyroxene in sample 78502,17A12. Note the dark metal veinlets at center right and lower right. Width of field is 1.2 mm. (b) Detail of mesostasis patch on the edge of orthopyroxene 78502,17A9. Top part of view is epoxy. Note the elongate silica grains (light) in a devitrified glassy base, and the two Mg-Al chromite grains (black) on the left and right margins of the patch. Width of field is 550 μm. (c) Detail in transmitted light and crossed nicols of diopside-rich veins in orthopyroxene 78442,2A6 (lower right of Figure 1a). Note the textural relationships of chromite and metal (black) to the diopside (white to gray). Width of field is 310 μm. (d) Detail in reflected light of diopside-rich veins in orthopyroxene 78442,2A6 (including part of the area in Figure 2c). The diopside is not clearly visible. Chromite (Sp) appears light gray and metal (Fe) appears white. The light grain at upper right is troilite (T) associated with polycrystalline silica (Sil, dark gray). Black areas are pits. Width of field is 360 μm.

TABLE 1. Microprobe Data for Orthopyroxenes, Diopsides, Plagioclases, and Chromian Spinels

Sample	78422,2		78442,2			78502,17				
Fragment	A5 opx	A17 opx	A6 opx	A6 diop	A6 chromite in vein	A9 opx	A9 diop	A9 Mg-Al chromite in mesostasis	A12 opx	A36 opx
SiO_2	54.1	53.6	54.6	54.3	---	54.2	53.7	---	54.2	54.7
TiO_2	0.29	0.22	0.24	0.20	0.96	0.26	---	0.34	0.21	0.26
Al_2O_3	1.0	1.1	1.1	0.23	10.1	1.0	---	25.3	1.1	1.0
Cr_2O_3	0.63	0.69	0.61	0.18	55.6	0.66	---	42.0	0.71	0.65
FeO	12.0	13.4	11.3	2.9	24.9	12.4	3.5	24.3	13.0	11.8
MnO	0.22	0.23	0.22	0.10	0.45	0.23	---	0.29	0.20	0.22
MgO	30.2	29.2	31.0	17.7	5.9	30.0	17.5	7.6	29.8	30.6
CaO	1.6	1.7	1.3	24.8	---	1.5	24.1	---	1.5	1.5
Na_2O	<0.05	<0.05	<0.05	<0.05	---	<0.05	---	---	<0.05	<0.05
Sum	100.0	100.1	100.4	100.4	98.5*	100.3	98.8	100.1**	100.7	100.7
En	79	77	81	48		79	48		78	80
Fs	18	20	16	4		18	5		19	17
Wo	3	3	3	48		3	47		3	3
	Plagioclase								Plagioclase	
mole % An	93.5	92	94.5						92	93.5
mole % Ab	5	6.5	4.5						7	5.5
wt % Fe	0.08	0.13	0.07						0.14	0.13
wt % K	0.10	0.10	0.07						0.15	0.08

* Includes 0.62 percent V_2O_3; ** Includes 0.31 percent V_2O_3.

consistent with space group *Pbca* ($a = 18.22$ Å, $b = 8.85$ Å, $c = 5.21$ Å). No diffractions from a monoclinic pyroxene (as illustrated by Ghose, McCallum, and Tidy, 1973, Fig. 1) were observed; however, several non-pyroxene diffractions were present and several orthopyroxene diffractions (10.02, 802, and 204) showed doubling or a slight diffuseness. Diffraction intensities were estimated to be the same as those of 14310 orthopyroxene illustrated by Ghose, Ng, and Walter (1972). The extra spots on our photos probably result from a small plagioclase grain which was attached to the pyroxene.

Plagioclase compositions range from An_{92} to $An_{94.5}$, and the An content correlates positively with the En content of coexisting orthopyroxene (Table 1). The Fe and K contents are slightly higher in the more sodic plagioclase, but all values fall within the range recognized for lunar plagioclase-rich rocks (Steele and Smith, 1973).

The mesostasis in sample 78502,17A9 consists of several sub-parallel, elongate crystals of silica in a devitrified glassy base relatively rich in Si, Al, K, Na, Ba, and P. The very small mesostasis area in sample 78502,17A12 consists mainly of K–Ba feldspar with minor siliceous glass and a small phosphate grain. One of the associated spinel grains is a Mg–Al-rich chromite (Table 1); the other two spinel grains were beneath the surface of the microprobe sections, but are optically similar to the analyzed spinel.

The major phase in the veins of samples 78442,2A6 and 78502,17A9 is relatively pure diopside ($En_{48}Wo_{48}Fs_4$ and $En_{48}Wo_{47}Fs_5$). The associated chromite is aluminous with a moderate V_2O_3 content (0.62 percent) and a very high Cr_2O_3 content (55.6 percent; see Table 1), and is thus at the extreme of the compositional range for lunar chromian spinels (*e.g.*, Reid, 1971; Roedder and Weiblen, 1972; Haggerty, 1972; Steele and Smith, 1972a; Nehru *et al*, 1973; Weigand and Hollister, 1973). Troilite was confirmed by analysis. The iron-rich metal phase in one of the veins contains 3.9

percent Ni and 2.8 percent Co, and is thus not atypical of lunar metal (Goldstein and Axon, 1973). An isolated composite grain (~12 μm across) of chromite and metal (1.3 percent Ni, 2.5 percent Co) was noted in orthopyroxene 78422,2A17, and rare tiny inclusions of highly fluorescent silica were encountered in several other samples. As far as could be determined, the very thin metal veinlets in four of the samples are predominantly iron, with Ni and Co contents similar to those of the other metal phases.

Discussion

The most striking aspect of the orthopyroxene grains is their textural and compositional similarity. This suggests that the crystals had a common source, and that similar material may be a characteristic constituent of soils elsewhere on the Sculptured Hills. The fragments have evidently been derived by impact breakup of a coarse grained norite. Although the textures of the fragments are somewhat ambiguous, they may be plutonic igneous. The mesostasis areas are most readily interpreted as patches of residual igneous melt, although other explanations are possible.

The spinel-troctolite cumulate described by Prinz *et al* (1973) is to our knowledge the only coarse-grained lunar terra sample found to date with unequivocal igneous texture. Other spinel troctolite samples (*e.g.*, Dowty, Keil and Prinz, 1974; Steele, 1972) have possible cumulate textures. The Civet Cat norite (Marvin and Stoeser, 1974) and feldspathic peridotite 67667 (Steele, Irving, and Smith, in preparation) have possible plutonic igneous textures now largely obscured by impact brecciation. Finer-grained noritic fragments with igneous textures have been described by Wood (1972) and Reid *et al* (1972). The original textures of the coarse-grained anorthosites (*e.g.*, Wilshire *et al*, 1972; James, 1972; Prinz *et al*, 1973) and rare dunite (Albee *et al*, 1974) have been extensively modified by multiple episodes of crushing and/or crystallization. Troctolitic granulite 76535 (Gooley *et al*, 1974) is one of the rare examples of a coarse-grained lunar rock with metamorphic (annealed) texture.

In view of this dearth of coarse-grained igneous terra rocks, the noritic fragments from the Sculptured Hills are of considerable interest. So far, no larger samples of similar material have been described in detail; however, an obvious candidate is rock 78235, a coarse (1–5 mm) plagioclase—(?) orthopyroxene rock chipped from a boulder at station 8 (Schmitt, 1973). It may be significant that our soil samples from stations 2 and 3 (South Massif) are very similar to those at station 8 except for these noritic fragments. This leads us to suggest that the Sculptured Hills are underlain at least in part by coarse norite, which may explain their distinctive topographic appearance compared with the massifs (*e.g.*, LSPET, 1973). If the rocks are indeed igneous, then we might speculate that the Sculptured Hills and other similar structures mentioned by Schmitt (1973) are the topographic expressions of high level norite intrusions or portions of deeper norite bodies excavated by large impacts. There is a possibility that the norite fragments might be derived from impacting bodies, but there are no chemical features conflicting with a lunar origin.

The occurrence of diopside-rich veins in some of the orthopyroxene crystals is an enigma. Textural relations suggest intrusion into irregular fractures of a fluid (liquid or vapor) broadly similar in composition to diopside (but richer in particularly Fe and Cr), followed by crystallization (or condensation) to diopside, chromite, metal, troilite, and silica. The narrow veinlets of metal observed in some samples appear to be related to the same process. We rule out exsolution from the host pyroxene because the veins are irregular and not related to crystallographic directions, and because the diopside is much too poor in Fe to coexist stably with the host orthopyroxene at any temperature of equilibration (*e.g.*, Kretz, 1963). We favor an extraneous source for the fluid. Numerous speculations can be made about the origin of the fluid, but are not pursued in detail here. Impact melting of the associated norite, of other lunar rocks, or of remnants of an impacting body must be considered. It should be noted that several investigators have reported diopside-bearing metamorphic rocks (troctolitic and anorthositic granulites) among lunar samples (Powell and Weiblen, 1972; Steele and Smith, 1972b; Hlava *et al*, 1973; Gooley *et al*, 1974), thus suggesting that a primitive diopside-bearing rock type is present in the lunar interior. It is conceivable that the diopside-rich veins in our samples might result from intrusion of a liquid associated with such a rock type. Hopefully, larger samples will be found, permitting better evaluation of textures. In the meantime, the present data add to the increasing body of evidence for plutonic rock bodies on the Moon.

Note Added in Proof

Rock 78235 was suggested above as possibly similar to the described norite fragments. Subsequent examination of thin section 78235,40 (see Fig. 3) shows the following mineralogy: 30 percent low-Ca pyroxene ($En_{78-80}Fs_{18-20}Wo_2$), 60 percent plagioclase, and a small patch (circled on Fig. 3) located at a plagioclase-pyroxene interface and composed of fine grained intergrown diopside ($En_{47}Wo_{45}Fs_8$), silica, whitlockite, apatite, Fe metal, chromite, troilite, niobian rutile and baddeleyite. Several veins of dark glass are present and the pyroxene and plagioclase show poor extinction; these features are probably due to shock. Layering of pyroxene is apparent, and was also noted on a macroscopic scale (Apollo 17 Sample Information Catalog). The layering is most readily interpreted as cumulate in origin (as suggested by PET, *Science,* **182,** 666, 1973), although shock deformation may have influenced the texture because some of the glass veins are parallel to the layering. The similar mineralogy of the norite fragments and rock 78235 does indeed suggest a similar origin; the major difference is the degree of shock. The relationship, if any, between the diopside-rich veins observed in the fragments and the mineralogically similar patch in 78235 is not clear.

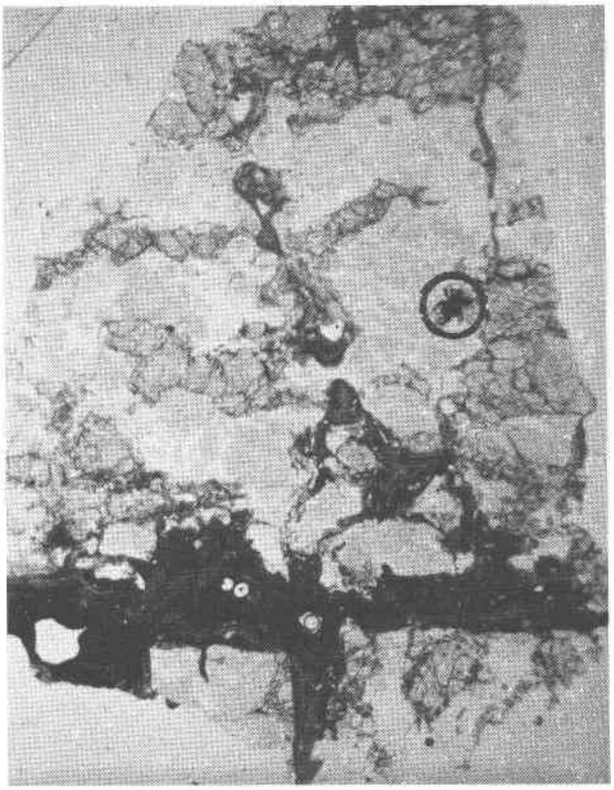

FIG. 3. Plain-light photograph of 78235,40. Black to dark gray areas are glass, medium gray areas with high relief are low-Ca pyroxene, and light areas are plagioclase. Note the prominent layering. All phases are highly shocked. Circled area contains complex mineralogy (see "Note Added in Proof"). Height of figure is 1 cm.

Acknowledgments

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