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MINERALOGY AND PETROLOGY OF FRAGMENTS FROM THE LUNA 24 CORE

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[Plate 1]

CONTENTS

Luna 24, the Soviet lunar mission of August 1976, recovered a 170 g core of regolith material from Mare Crisium, on the eastern limb of the Moon. This paper describes the petrology and mineralogy of five rock fragments and the 75–106 μm fine fractions from three levels in this core. Nearly all the minerals analysed are derived from the basaltic rocks native to Mare Crisium, very few are transported highland material. The proportion of highland material occurring as glass fragments in the fine fractions is larger than that which is present as mineral fragments.

1. Introduction

In August 1976 the Soviet Luna 24 mission successfully recovered a 160 cm core sample from the Mare Crisium area of the Moon. Stratified regolith material weighing 170 g was returned to Earth; the method of collection and a general description of the core is given in Florensky *et al.* (1977). Preliminary chemical data have been reported by Barsukov (1977), Barsukov *et al.* (1977) and by Tarasov *et al.* (1977). This was the third successful Russian unmanned sampler to visit the eastern limb of the Moon, following Luna 16 to Mare Fecunditatis and Luna 20 to the Apollonius highlands, between Fecunditatis and Crisium. Samples from the 90, 125, 170 and 196 cm levels were allocated to research groups in the United Kingdom. In this paper we report our studies on the petrology and mineralogy of five millimetre-sized fragments from the Luna 24 core, two from the 90 cm level and three from the 196 cm level. We also present our analyses of a portion of the 75–106 μm fine fraction from the 90, 125 and 196 cm levels. Extensive studies on other levels of this core are reported in Merrill & Papike (eds) (1978).

2. The rock fragments

One of the rock fragments, a basalt from the 90 cm level, is illustrated in figure 1*a*. For microprobe analysis we preferred to mount our fragment allocation as chips in resin rather than to prepare thin sections, since less material is destroyed and the mounting resin may be subsequently dissolved and the rock fragment recovered for further investigation. The disadvantage of this procedure, however, is that it limits petrographic study to reflected light microscopy. The plagioclases in the basalt, the darker, lath-shaped crystals, range in size from

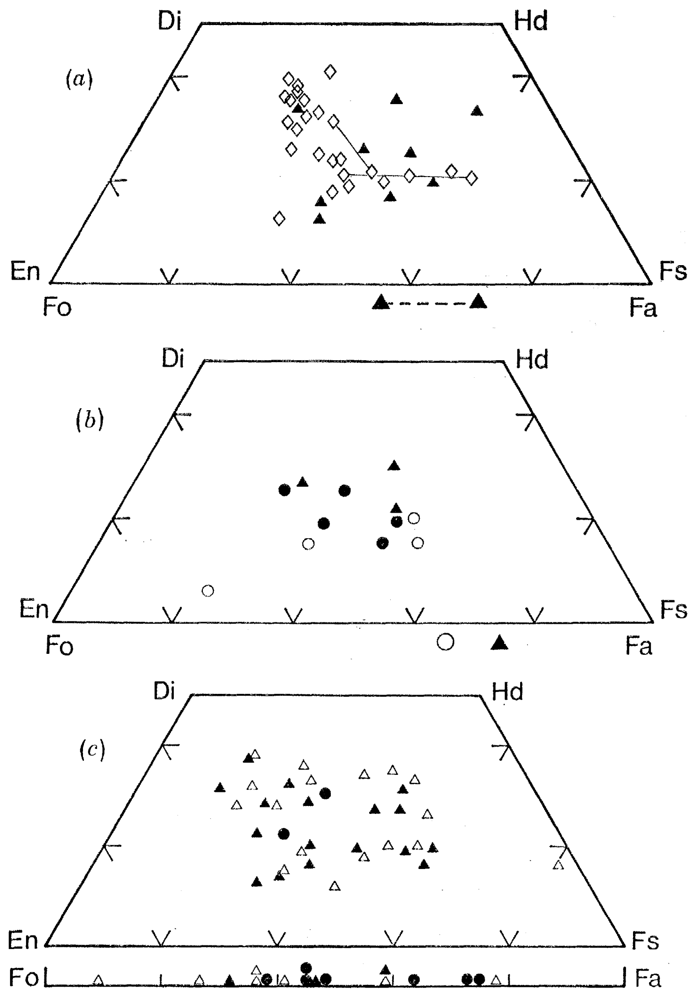

Figure 2. (*a*) Pyroxene compositions found in the basalt (triangles) and the pyroxenite (diamonds) from the 90 cm level of the Luna 24 core. Di, diopside, $(CaMg)SiO_3$; Hd, hedenbergite, $(CaFe)SiO_3$; En, enstatite, $MgSiO_3$; Fs, ferrosilite, $FeSiO_3$. The olivine composition range is also indicated: Fa, fayalite, Fe_2SiO_4; Fo, forsterite, Mg_2SiO_4.

(*b*) Pyroxene compositions found in the basalt (triangles) and breccia (filled circles) from the 196 cm level. Open circles represent normative pyroxenes calculated from the bulk compositions of glasses in the breccia. Olivine data from the metabasalt: triangle, determined composition; open circle, normative composition calculated from the bulk analysis.

(*c*) Pyroxene compositions found in the 75–106 μm fine fractions from the 90, 125 and 196 cm levels. Olivine data also indicated. Open triangles, 90 cm level; filled circles, 125 cm level; filled triangles, 196 cm level.

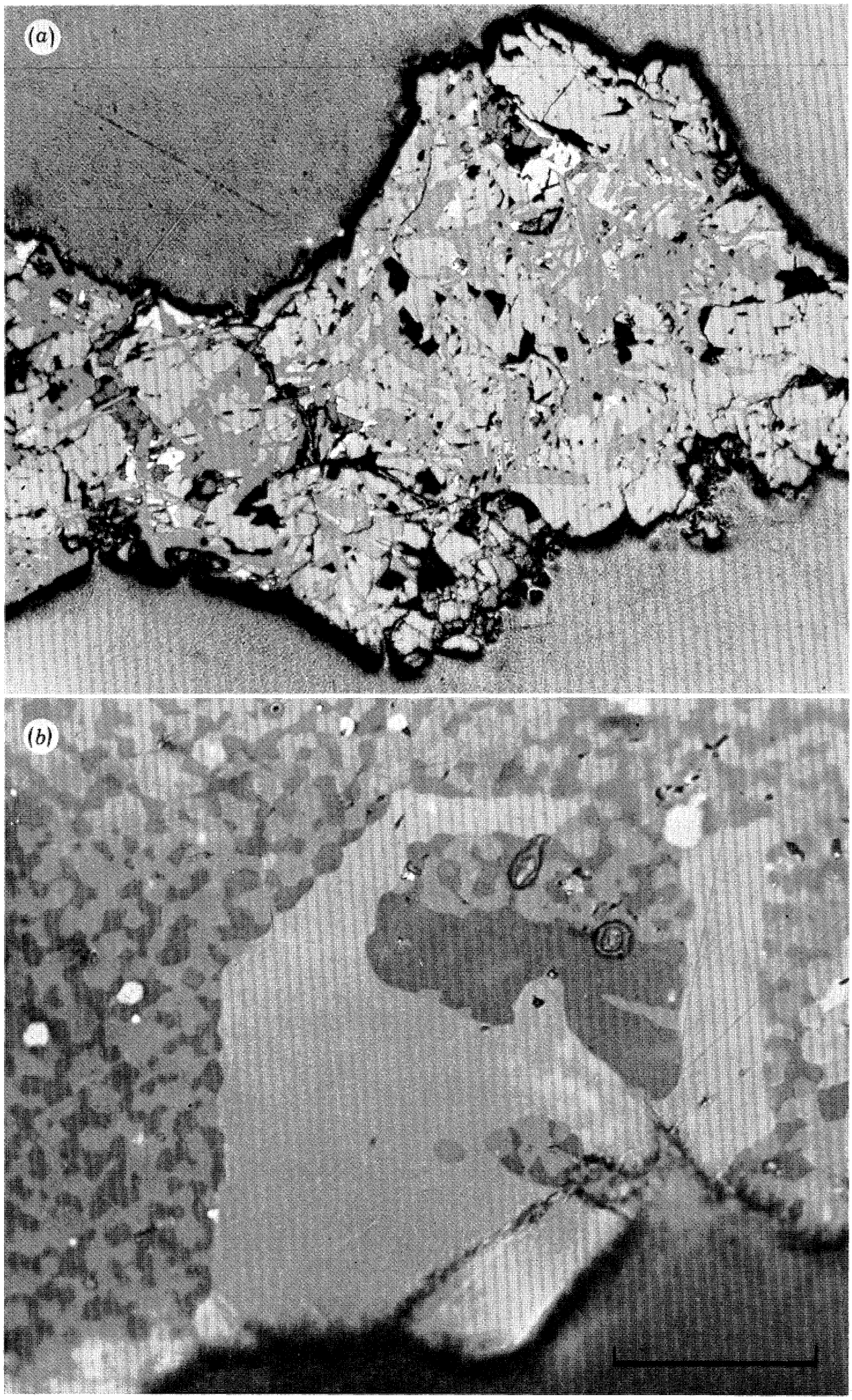

FIGURE 1. (*a*) Reflected light photomicrograph of the mare basalt fragment from the 90 cm level. Field of view is 1.2 mm across.
(*b*) As above but of the metabasalt fragment from the 196 cm level. The large crystal is olivine of Fo_{25}. Scale bar represents 20 μm.

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100 μm by 25 μm downwards, and the pyroxenes are subhedral to anhedral and generally less than 200 μm across. Olivine is present but not common and cristobalite and opaques occur irregularly. The opaques are predominantly a magnesium-poor ilmenite but there are also rare Al–Cr-rich spinels. The pyroxene and olivine data obtained from this basalt are plotted in figure 2*a*, and representative analyses are given in table 1. The pyroxenes range in composition from augite and intermediate pigeonite to more iron-rich ferroaugites. Others, for example Taylor *et al.* (1978), have shown that ferroaugites are well represented in the Mare Crisium basalts, and pyroxenes close to hedenbergite have also been reported. Olivines in this basalt range from Fo_{46} to Fo_{29} with CaO contents between 0.3 and 0.4% by mass. Some covariation in the CaO content with Fe:Mg ratio has been reported (Papp *et al.* 1978) and our data fall within the defined field. The plagioclase composition is close to An_{95} with no detectable potassium; in fact potassium was not detected anywhere in the section, by using the microprobe with a detection limit of 0.01%. Very small areas, less than 5 μm across, were found that contained detectable phosphorus. The amount of phosphorus present in these areas was less than 2% by mass but they were too small for quantitative analysis.

Table 1. Representative pyroxene analyses from 90 cm level fragments

	basalt					pyroxenite				
	1	2	3	4	5	6	7	8	9	10
SiO_2	50.7	50.8	51.0	48.3	46.8	50.0	52.2	49.7	49.8	47.8
TiO_2	0.31	0.13	0.44	0.42	1.05	1.02	0.42	0.72	1.09	0.77
Al_2O_3	2.27	0.91	1.01	3.24	1.42	3.41	0.99	1.22	1.24	0.82
Cr_2O_3	1.05	0.46	0.40	0.26	0.14	1.12	0.57	0.33	0.19	0.08
FeO	15.2	23.3	28.3	29.3	30.4	11.73	19.8	24.1	27.9	34.4
MnO	0.29	0.35	0.36	0.39	0.39	0.23	0.32	0.39	0.47	0.54
MgO	13.9	16.9	11.5	8.0	3.64	13.4	19.5	13.8	9.4	6.5
CaO	15.6	5.8	8.0	8.9	14.8	18.3	6.2	8.7	9.4	9.5
Na_2O	—	—	—	—	—	—	—	—	—	—
total	**99.32**	**98.65**	**101.01**	**98.81**	**98.64**	**99.21**	**100.00**	**98.96**	**99.49**	**100.41**
Wo	33.4	12.1	17.4	20.8	33.9	39.7	12.7	18.6	21.3	20.9
En	41.3	49.2	34.6	25.8	11.6	40.5	55.7	41.1	29.5	19.9
Fs	25.3	38.7	48.0	53.4	54.5	19.8	31.6	40.3	49.2	59.2

Analysts: R.H. and A.L.G.

The second fragment from the 90 cm level is best described as a pyroxenite. Although whitish areas were seen on its surface before mounting in resin, when polished only pyroxene could be found. The data obtained from this sample are plotted in figure 2*a*, and representative analyses are quoted in table 1. In the figure the array of pyroxene data for the basalt has a trend towards hedenbergite (Hd), while those for the pyroxenite varies to more iron-rich compositions (Fs). This late stage trend of relatively constant wollastonite content shown by the pyroxenite may be caused by a delay in the precipitation of ilmenite. The iron enrichment of the liquid, the result of fractional crystallization, would then be relieved only by the precipitation of pyroxene. Conversely, if ilmenite were an actively precipitating phase, the coprecipitating pyroxene would probably trend towards hedenbergite. The precipitation of ilmenite will be delayed if the titanium content of the liquid is low, and the pyroxene trends indicated in figure 2 suggest that the basaltic parent liquid had a higher titanium content than the liquid from which the pyroxenite crystallized. Mare basalts with very low titanium contents, less than 1% TiO_2,

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have been reported from the Luna 24 core material by Tarasov *et al.* (1977) and basalts with similar very low titanium contents occur in the Apollo 17 material from Taurus-Littrow (Vaniman & Papike 1977).

From the 196 cm level our three rock fragments are a friable basalt, a glass-rich breccia and a fragment of metabasalt. The metabasalt was part of a 17 mg clast allocated to G. Turner for $^{39}Ar/^{40}Ar$ dating. The basalt is pyroxene rich and representative analyses are plotted in figure 2*b*. The compositions range from $Wo_{29}En_{48}$ to $Wo_{20}En_{35}$. The coexisting feldspar is An_{95}, again with no detectable potassium. The pyroxenes occurring in the breccia are also plotted in figure 2*b*. Their compositions all fall in the field of mare basalt pyroxenes and none of them has a composition that indicates a highland origin. The normative pyroxene compositions are derived from bulk analyses of glasses in the breccia and one of these, the most magnesian, would have had a highland origin. The compositions of glasses will be discussed later.

A polished face of the metabasalt fragment is illustrated in figure 1*b*. It is a vesicular rock consisting of a granulitic intergrowth of pyroxene and feldspar. The grain size is less than 10 μm and most of the particles are too small for microprobe analysis. Data have been obtained on two olivines, each of composition Fo_{25}, and feldspar of An_{95}. A bulk analysis was made by using an integrating, non-dispersive X-ray microanalyser by stepwise movement over five traverses

TABLE 2. MINERAL ANALYSES FROM THE 75–106 μm FINE FRACTION

	1	2	3	4	5	6	7	8
SiO_2	50.8	50.1	48.2	50.0	34.3	38.2	40.9	44.8
TiO_2	0.29	0.23	0.74	0.38	0.05	0.04	< 0.02	—
Al_2O_3	1.14	0.90	1.14	0.27	< 0.02	< 0.02	< 0.02	33.79
FeO	17.5	24.2	30.60	41.20	45.20	23.0	8.94	0.60
MnO	0.36	0.56	0.51	0.71	0.56	0.30	0.10	—
MgO	16.7	15.7	8.55	0.98	18.7	37.4	49.8	0.14
CaO	10.9	6.23	9.03	6.40	0.45	0.18	0.03	18.9
Na_2O	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.56
K_2O	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Cr_2O_3	0.52	0.20	0.18	< 0.01	0.06	0.11	< 0.01	—
total	**98.21**	**98.12**	**98.95**	**99.94**	**99.32**	**99.23**	**99.77**	**98.79**
Wo	22.9	13.3	20.2	16.0	—	—	—	—
En	48.5	46.5	26.5	3.4	—	—	—	—
Fs	28.6	40.2	53.3	80.6	—	—	—	—
Fo	—	—	—	—	42	74	91	—
An	—	—	—	—	—	—		96

1–4, Pyroxenes; 5–7, olivines; 8, feldspar.
Analysts: A.L.G. and R.H.

totalling 2000 μm in length. The results are given in table 3. The bulk contents of TiO_2 (0.89 %) and of Cr_2O_3 (0.28 %) are notable. The normative olivine composition of Fo_{36} is slightly at variance with the determined composition of Fo_{25}. The modal olivines appear to be phenocrystal and show what appear to be corroded borders to the surrounding metabasalt. These data do not allow us to construct a unique history for this rock but some indication of its parentage is given by the low titanium content, which suggests a very low titanium basalt precursor, and the Cr_2O_3 content which is somewhat low for an origin from a regolith aggregate that has suffered a heating and partial homogenization event.

3. The 75–106 μm fractions

Analyses of the iron–magnesium silicate grains from the 75–106 μm fines from the 90, 125 and 196 cm levels are plotted in figure 2*c*, which is a summary of the olivine and pyroxene data. Some of the points represent analyses of two or more mineral fragments with identical compositions. In our data the abundance of iron-rich pyroxene grains is low and represented by only one pyroxferroite analysis. This is not compensated for by an overabundance of iron-poor pyroxenes whose presence would imply that a significant proportion of highland material was present in these fines. Although the Luna 24 landing site is only 45 km from the nearest highland front, the proportion of highland material present is very small indeed. While the analyses from our fractions do not indicate a highland origin for any of these pyroxenes, this is not so for the olivines, which range in composition from Fo_{20} to Fo_{75}, with one grain at Fo_{91} (table 2). This compares with the general range in data from other laboratories, for example Papp *et al.* (1978), of Fo_0 to Fo_{84}. Olivine as magnesian as Fo_{91} is rare but has been reported previously from the Luna 24 samples by Taylor *et al.* 1978. Highly magnesian olivines have also been reported from the Apollo 16 drill core 60003. Compositions there run to Fo_{93} for a grain of highland origin and in the same core there is also an exotic olivine quench rock with olivines of Fo_{95} (Vaniman *et al.* 1976). In the Luna 24 core there is a sharp cutoff to the olivine composition histogram at about Fo_{80}. The CaO content of the olivines generally range from 0.3 to 0.5%, indicating a mare basalt origin. The grain of Fo_{91} has 0.03% CaO, which indicates that it is of highland origin.

The feldspars from the fines range in composition from An_{86} to An_{96}. It is possible in some cases to distinguish, on FeO content, feldspars of highland origin from those of mare basalt origin. It was initially suggested by Smith (1974) that the two would be uniquely separated on a plot of FeO against anorthite content, but this is not so, although the trends are still distinctive (Stöffler & Knöll 1977). In essence, it is not possible to distinguish the feldspars from anorthosite–norite–troctolite (a.n.t.) suite rocks from those from KREEP basalts nor from those from high-alumina basalts in the composition range of interest here, which is An_{86} to An_{96}. However, plagioclase with more than 0.6% FeO, whatever its An content, could confidently be given a mare basalt origin. Our data for the feldspars fragments generally show FeO contents greater than 0.5%; these are mare feldspars. Only three have FeO contents of less than 0.3%, but this is not a sufficient condition on which to ascribe a highland origin to them.

4. The glass compositions

The data for Luna 24 glasses, both from the breccia and from the fines, are plotted in figure 3 on a normative olivine–feldspar–pyroxene–quartz diagram; some of the plotted points are averages of three or more analyses. Data for the Apollo mission glasses from the literature are also plotted and represent the results of cluster analysis techniques applied to a very large number of data points, particularly for the Apollo 11–15 data (Reid *et al.* 1972; von Engelhardt *et al.* 1973; Ridley *et al.* 1973). The major fields defined by the compositions of the lunar glasses are those of the mare basalts, the Fra Mauro basalts, both high-K and low-K, and the highland basalts. These fields are designated, respectively, A, B and C in the diagram, and over 90% of the lunar glass analyses fall within them. Two further minor compositional fields are those of the anorthositic glasses and the granitic, or mesostasis glasses. The anorthositic glass compositions have not been considered here since in this method of plotting it is not possible to distinguish between highland and mare feldspathic glasses.

Although in the fines the proportion of monomineralic grains of presumed highland origin is very low, glasses of highland basalt composition are not uncommon. It would seem to be easier to transport glass fragments than mineral fragments in the regolith forming events. Although not indicated in the figure, there is no correlation between glass chemistry and position in the core. The regolith sampled at the Luna 24 site is macroscopically stratified but there seems to be surprisingly little bulk chemical variation of this regolith (Barsukov *et al.* 1977), despite the wide ranges in composition shown by the constituent minerals and glasses. An extreme example of this variation is our single grain of granitic glass. Glass of this type is comparatively rare, but it has been reported from many of the lunar missions. The points plotted in figure 3, field D, represent very few analyses; only one for Luna 24. This fragment occurred in the 196 cm level and showed the remarkably high potassium content of 8.9% (as K_2O) (table 3, column 6). This is to be compared with other lunar granitic glasses which generally contain around 6% K_2O (Roedder & Weiblen 1977). The high potassium level emphasizes the extent of chemical fractionation that has occurred in forming the rocks and regolith at the Luna 24 landing site. Despite this variation, it is possible to decipher a significant part of the history of the regolith from mineralogical and petrological studies of small samples of core material.

We thank the Soviet Academy of Sciences for the provision of the Luna 24 samples and the Department of Mineralogy and Petrology, University of Cambridge, for some analytical facilities.

Table 3. Analyses of representative glasses and a metabasalt

	1	2	3	4	5	6	7
SiO_2	45.2	49.3	45.5	43.9	45.9	78.3	46.6
TiO_2	0.81	0.63	0.44	0.17	0.04	0.11	0.89
Al_2O_3	9.77	8.45	21.20	27.4	32.6	10.8	15.1
FeO	19.9	16.8	9.70	4.15	0.83	0.47	19.2
MnO	0.30	0.25	0.14	< 0.01	1.23	< 0.01	0.22
MgO	12.3	10.9	7.08	6.24	0.13	< 0.01	5.90
CaO	9.79	13.4	13.5	16.2	18.3	0.20	12.5
Na_2O	0.12	0.10	0.54	0.12	< 0.01	0.91	0.10
K_2O	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	8.91	< 0.01
Cr_2O_3	0.58	0.49	0.07	0.09	< 0.01	< 0.01	0.28
total	**98.77**	**100.32**	**98.17**	**98.27**	**99.03**	**99.70**	**100.79**
				C.I.P.W. norm			
Q	—	—	—	—	5.24	39.2	—
Or	—	—	—	—	—	52.7	—
Ab	1.02	0.85	4.57	1.02	—	6.2	0.84
An	26.1	22.6	55.4	74.3	88.9	—	40.8
Di	18.7	36.4	9.14	5.02	1.59	0.88	18.1
Hy	33.5	37.5	21.3	10.1	3.22	0.21	48.2
Ol	17.1	1.03	6.69	7.45	—	—	0.36
Cm	0.85	0.72	0.10	0.13	—	—	0.40
Il	1.54	1.20	0.84	0.32	0.08	0.21	1.68

1 and 2, Mare basalt glasses from 24090; 3 and 4, Fra Mauro basalt glasses from 24125 and 24196 respectively; 5, highland basalt glass from 24090; 6, granitic glass from 24196; 7, Bulk analysis of metabasalt from 24196. Analysts: R.H. and A.L.G.

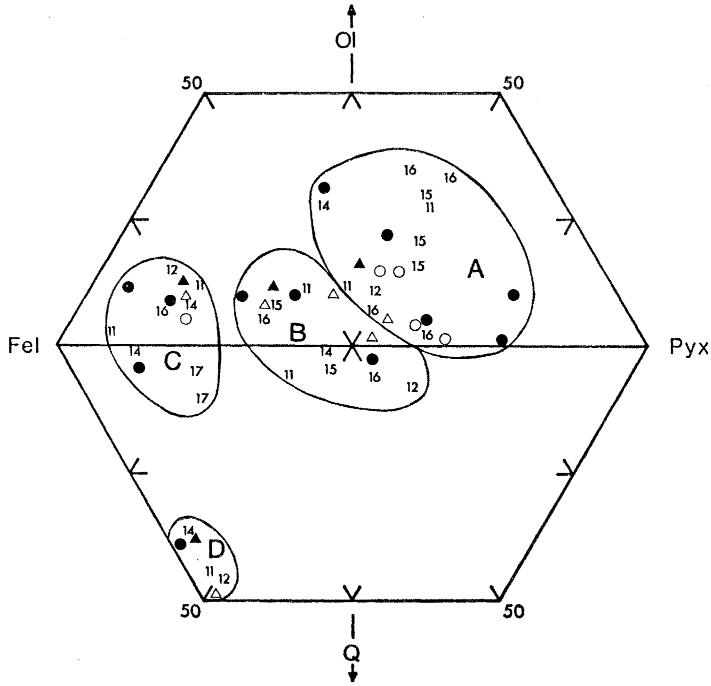

FIGURE 3. Glass data from the fines and breccia plotted on a normative quartz (Q) – feldspar (Fel) – pyroxene (Pyx) – olivine (Ol) diagram. The fields are those of mare basalts (A), Fra Mauro basalts, both high-K and low-K, (B), highland basalts (C) and granitic material (D). The numbers refer to Apollo mission glasses (see text). Filled circles, this work; open circles, Luna 24 data from Merrill & Papike (1978). Luna 16 data (open triangles) from Jakes *et al.* (1972) and Luna 20 data (filled triangles) from Reid *et al.* (1973).

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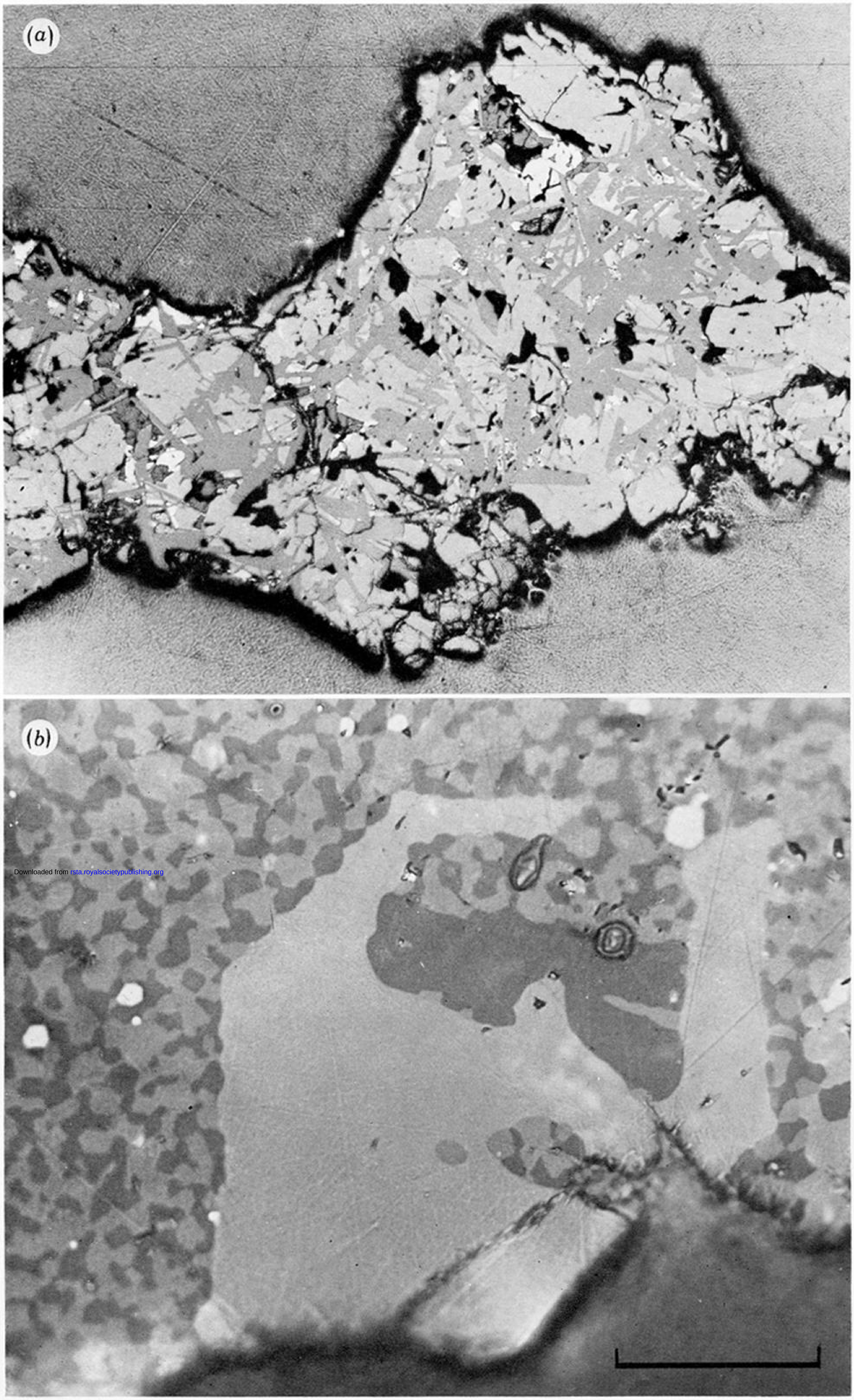

FIGURE 1. (*a*) Reflected light photomicrograph of the mare basalt fragment from the 90 cm level. Field of view is 1.2 mm across.

(*b*) As above but of the metabasalt fragment from the 196 cm level. The large crystal is olivine of Fo_{25}. Scale bar represents 20 μm.