78235

Shocked Norite
199 g; 4.0 x 5.0 x 5.5 cm, 3.5 x 4.0 x 5.0 cm (2 pieces)

INTRODUCTION

Samples 78235-238 were chipped off the top of the Station 8 Boulder after it had been rolled over completely *(see section on the Station 8 Boulder).* The chips fell in the dirt, from which they were then collected. The sample bag also included more than 200 g of dirt that may include additional fragments of this important rock. Sample 78237 was combined with 78235 because these two pieces were found to fit together. Samples 78236 and 78238 are also from the top surface of the boulder; 78255 is from the bottom. These samples are all very similar.

Sample 78235 is a heavily shocked plutonic norite of cumulate origin with a glass coating and glass veins (Fig. 1). Some of the glass veins are continuous with the glass coating. The degree of shock was sufficient to convert some of the plagioclase to rnaskelynite. Except for the glass and the shock features, this rock is a coarse-grained (5-10 mm), pristine, igneous lunar norite (about half plagioclase and half orthopyroxene). It has an initial crystallization age of about 4.4 b.y., making it one of the oldest lunar rocks sampled during the Apollo missions.

PETROGRAPHY

Dymek et al. (1975), McCallum and Mathez (1975), Jackson et al. (1975), Sclar and Bauer (1975 and 1976), Steele (1975), and the astronauts have all described 78235 as a shocked norite. James and Flohr (1983) consider it the best example of the Mg suite of lunar norites (Fig. 2).

78235 has a well-preserved, coarse-grained (5-10 mm) cumulus texture where cumulus plagioclase (~50%) and cumulus orthopyroxene (~50%) form distinct layers (Jackson et al., 1975; McCallum and Mathez, 1975).

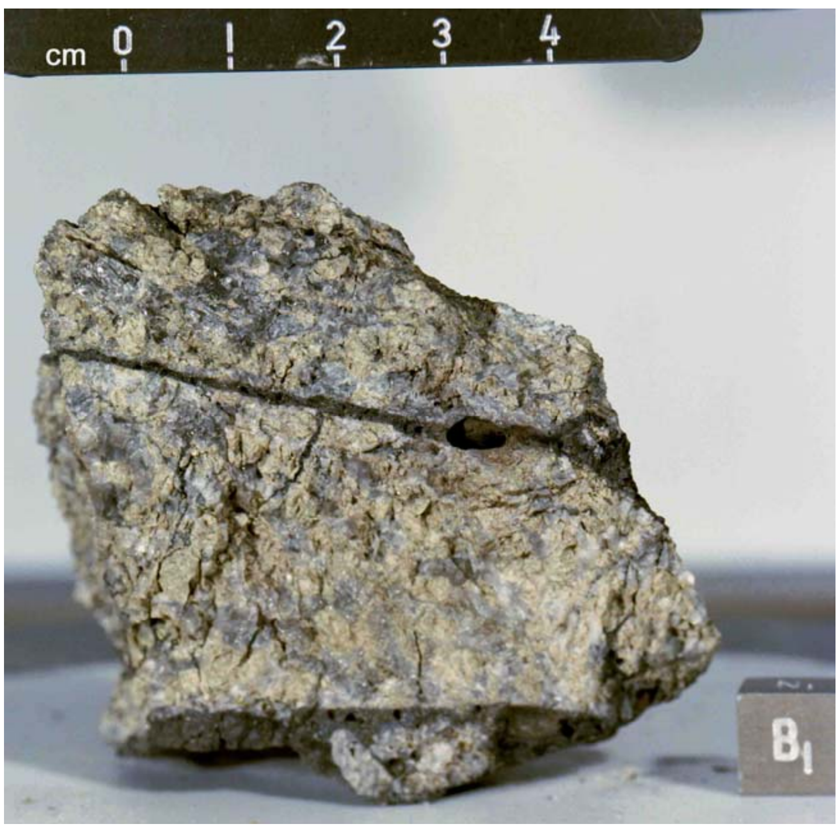

Figure 1: Photograph of 78235. Cube is 1 cm. S73-15180.

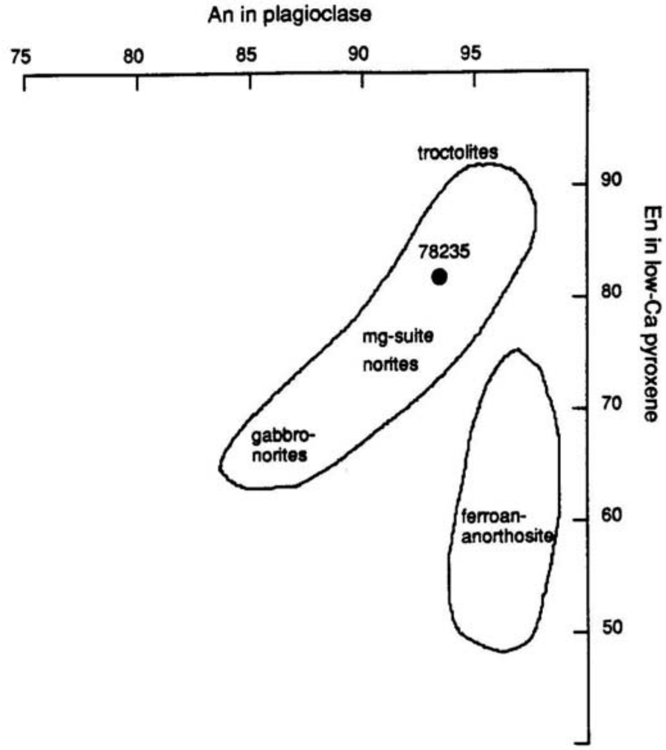

Figure 2: Plagioclase pyroxene compositional diagram for 78235. 78235 is one of the best examples of the Mg-suite norites. Fields from James and Flohr (1983).

Postcumulus enlargement of these minerals eliminated all but a few percent of the intercumulus liquid. Plagioclase (An_{93-95}) and ortho-pyroxene ($WO_3En_{78}Fs_{19}$) are homogeneous, with no compositional variation among cores, rims, and interstitial grains. Interstitial zones contain a remarkable suite of accessory minerals formed at a late stage from a fractionated, trapped liquid. In decreasing order of abundance they are silica, apatite, REE-rich whitlockite, Fe-Ni-Co alloy (Co - 2.6%; Ni = 2.4%), diopside, chromite, troilite, niobian rutile, zircon, and baddeleyite.

Sporadically distributed through the orthopyroxene and localized in the pyroxene at specific sites along orthopyroxene-plagioclase interfaces are ameboid patches and veinlets. These consist of the four-phase assemblage iron-chromite-diopside-silica (Sclar and Bauer, 1975 and 1976). This mineral assemblage is probably just part of the mesostasis of the cumulate (McCallum and Mathez; E1Goresy et al., 1976), but Sclar and Bauer argued that it had a shock origin.

The rock has been heavily shocked, resulting in partial destruction of the original cumulus texture in some areas. Plagioclase has been partially maskelynitized and locally even melted, while the orthopyroxene shows undulatory extinction, cracking, and mosaicism. Some of the cracking of the pyroxene is obviously due to the expansion of the partially maskelynitized plagioclase (Fig. 3). A brown, vesicular, partially devitrified glass fills fractures in the rock. Flow banding in the glass is defined by crystallites of metal and troilite. Spherical globules (~20 µm) of metal and metal plus troilite in the glass have compositions within the meteorite range, indicating meteoritic contamination of the glass.

Sclar and Bauer (1975 and 1976) have studied the shock features in 78235. The presence of maskelynite indicates that the shock pressure was between 300 and 400 kbar, and the occurrence of glass veins may mean that the rock experienced pressures in excess of 500 kbar. Sclar and Bauer (1976) have speculated that fine oriented rods of metallic iron in the plagioclase and maskelynite are due to subsolidus reduction of iron during shock.

MINERAL CHEMISTRY

McCallum and Mathez (1975) and Dymek et al. (1975) have analyzed the minerals in 78235. Pyroxene and

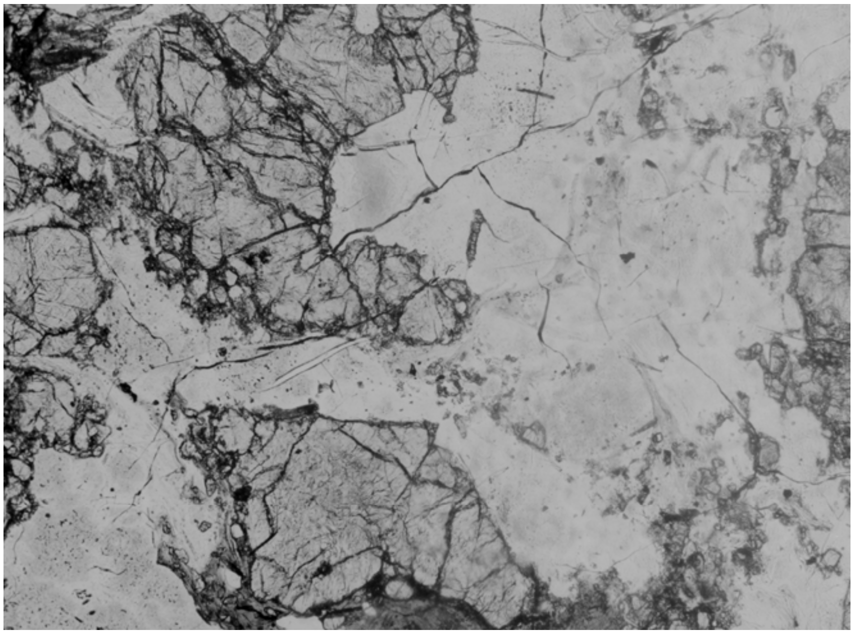

Figure 3: Photomicrograph of thin section 78235,41. Field of view is 3 x 4 mm.

plagioclase are uniform in composition (Figs. 4 and 5). Dymek et al. report high Al, Ti, and Cr in small diopside grains in 78235 ($Wo_{47}En_{45}Fs_8$; $A_{12}O_3$ = 2.86, TiO_2 = 1.01, and Cr_2O_3 = 1.11). McCallum and Mathez have used the compositions of the pyroxenes to estimate a temperature of equilibration of ~800 °C.

McCallum and Mathez (1975) and Steele (1975) report analyses for whitlockite, apatite, chromite, rutile, and baddeleyite. The Nb content of the rutile is extremely high (~14% by Steele and ~5% by McCallum and Mathez). About 10% of the REE in the rock are tied up in the whitlockite. Nyquist et al. (1981) report a few grains of K-feldspar ($Or_{90.8}Ab_{2.1}An_{7.1}$).

Bersch et al. (1991) precisely determined the composition of the pyroxene. Hansen et al. (1979) and Steele et al. (1980) measured the trace element contents of the plagioclase. Hinthorne et al. (1977), Steele et al. (1980), and Papike et al. (1994) determined the trace elements in plagioclase and pyroxene by ion microprobe analysis. Winzer et al. (1975) measured the compositions of plagioclase and orthopyroxene separates by isotope dilution mass spectroscopy (Fig. 6). Delaney and Sutton (1991) attempted to determine the Fe/Mn ratio in plagioclase in 78235 using the new synchrotron x-ray technique. Palme et al. (1984) discussed trace elements in plagioclase.

McCallum and Mathez, Hewins and Goldstein (1975), and Mehta and Goldstein (1980) have studied the provenance of iron metal in 78235 (Fig. 7; also see figure in section on 78238).

Steele (1975) has shown that orthopyroxene with space group P21 ca in 78235 means that this rock is of plutonic origin. Takeda et al. (1982) studied the orthopyroxene ($Wo_3En_{76}Fs_{21}$) in 78236 by combined single crystal x-ray diffraction and TEM techniques and showed that there was no augite exsolution with (100) in common. They found abundant Guinier-Preston zones, several unit cells wide, in the pyroxene. Takeda's microstructural data favor Nyquist's thermal model for cooling of 78236 because formation at 4.4 b.y. may have produced exsolution lamellae in the orthopyroxene during cooling below 1000 °C in the lunar crust. Takeda proposed that 78236 was excavated when this rock reached about 1000 °C and then cooled more slowly at moderate temperatures to produce the Guinier-Preston zones.

Irving et al. (1974) also studied orthopyroxene with associated diopside from coarse fines in the soils adjacent to 78235.

WHOLE-ROCK CHEMISTRY

It should be remembered that 78235 is a coarse-grained rock, and that small sample splits of a coarse-grained rock may not represent the whole rock. Winzer et al. (1975) have determined the major element and rare earth element content of the whole rock: glass, pyroxene, and plagioclase separates form their small sample split of 78235 (Table 1, Fig. 8). Blanchard and McKay (1981) have determined the

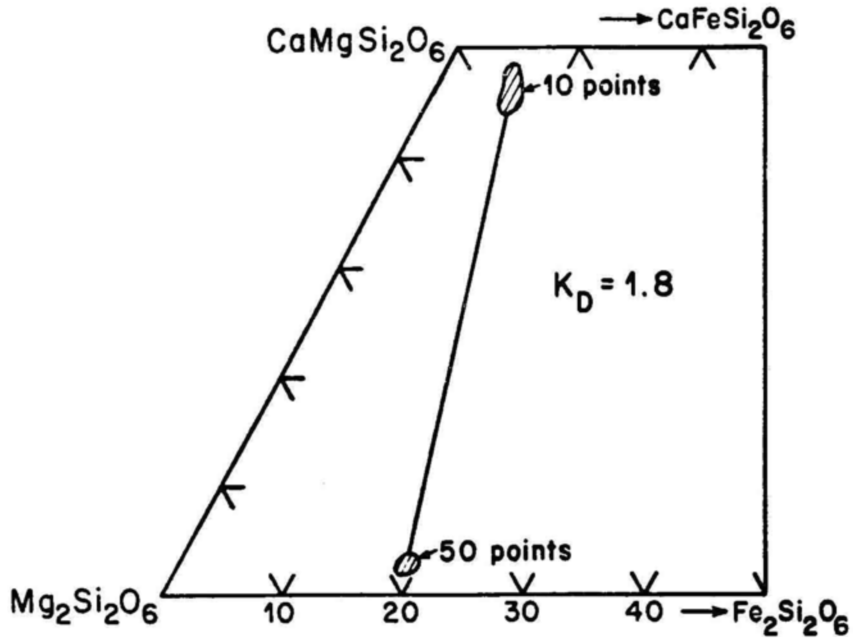

Figure 4: Pyroxene quadrilateral. From McCallum and Mathez (1975).

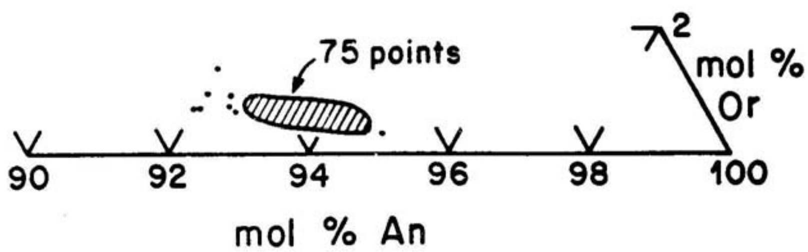

Figure 5: Plagioclase composition diagram. From AcCallum and Mathez (1975).

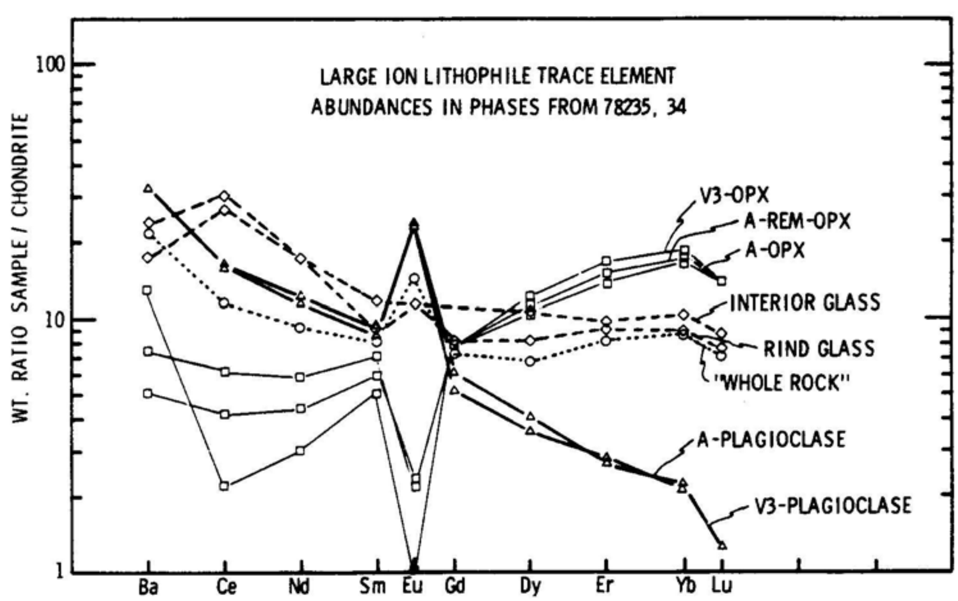

Figure 6: Normalized rare earth element diagram for mineral separates from 78235. From Winzer et al. (1975).

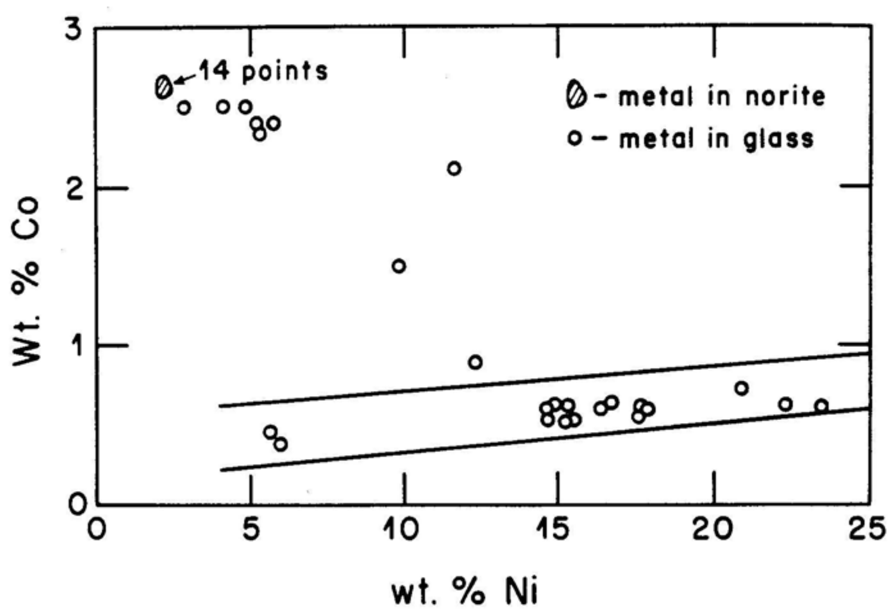

Figure 7: Ni and Co concentrations of metal particles in 78235. The metal grains in the pristine part of the rock have low and uniform Ni contents, while the metal grains in the glass are high in Ni, indicating two different origins for metal in the rock. Data from McCallum and Mathez (1975).

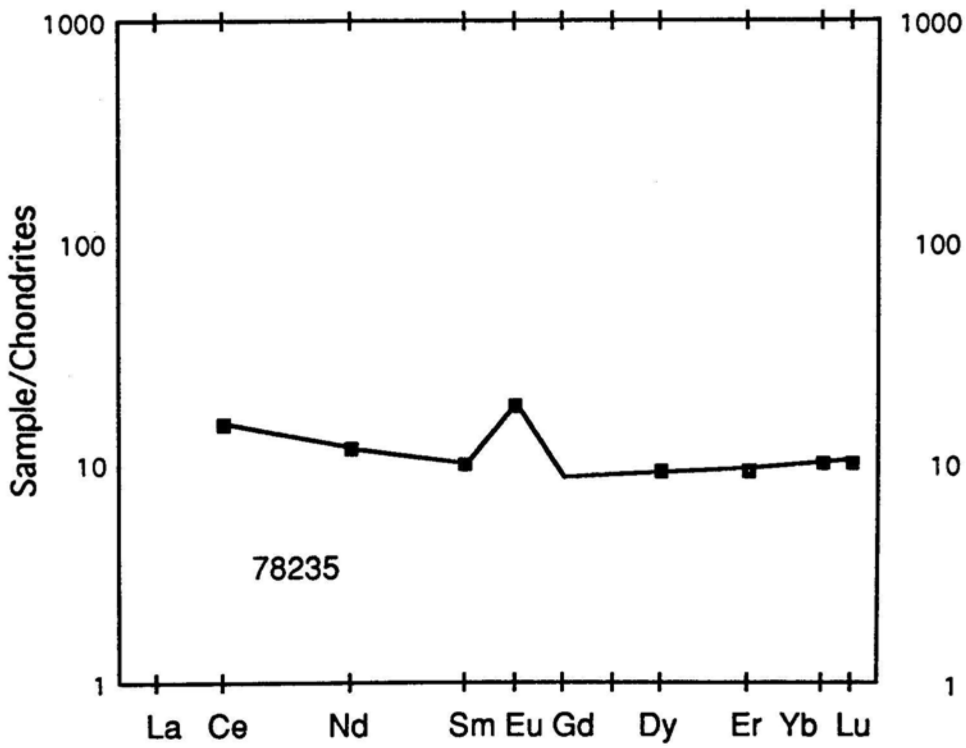

Figure 8: Normalized rare earth element diagram for 78235. Data from Winzer et al. (1975).

composition of 78236, which is in reality another piece of 78235. Warren and Wasson (1978) have analyzed 78255. Warren et al. (1987) analyzed "coarse-fines" sample 78234,5, which they believe to be another piece of 78235-78255. This analysis is included in Table 1 for comparison.

Higuchi and Morgan (1975) reported the trace siderophile and volatile elements in 78235 (Table 2). James (1994) reviewed the siderophile and volatile element composition.

Keith et at. (1974) have analyzed large pieces of 78235 and 78255 and found that the Th, U, and K contents were slightly different in the two samples (Table 3).

The glass coating and glass veins in samples 78235-78255 also give an indication of the bulk composition of this sample. Winzer et al., Sclar and Bauer (1975), Steele, McCallum and Mathez, and Dymek et al. have all analyzed the glass (Table 4).

Glass veins and coating (rind) plot halfway along the tie line from plagioclase to pyroxene (Fig. 9). The glass appears to be formed by in situ melting of the rock without the addition of other rock components. A meteoritic component is indicated by the very high Ni and Ir in the glass.

STABLE ISOTOPES

Mayeda et al. (1975) report typical lunar delta $^{18}0$ (o/oo) values of 5.67 (plagioclase) and 5.41 (pyroxene) for this pristine lunar rock.

RADIOGENIC ISOTOPES

Hinthorne et al. (1977) dated 78235 by the Pb-Pb ion probe method. Ages from three baddeleyites and one zircon in thin section 78235,49 were all consistent at 4.25 ± 0.09 b.y. These data required correction for unspecified molecular ion interferences. It is also difficult to understand how the U-Pb system in the minor phases could not have been affected by the shock melting that is evident in this rock. For these reasons this Pb-Pb age is generally not accepted--although it has generally been confirmed by more recent work.

Premo and Tatsumoto (1991 and 1992) have studied the U-Th-Pb isotopic systematics of 78235 (Table 5) and determined a crystallization age of 4.426 ± 0.065 b.y. with a disturbance at 3.93 ± 0.21 Ky. (Fig. 10). Their work also shows that the Moon had a high U/Pb ratio-about 508. There is also a hint of a mild event (shock?) at about 900 m.y. in their data.

Nyquist et al. (1981), Aeschlimann et al. (1982), and Carlson and Lugmair (1982) have precisely dated 78236 by ^{39}Ar-^{40}Ar, Rb-Sr and Sm-Nd methods (see section on 78236).

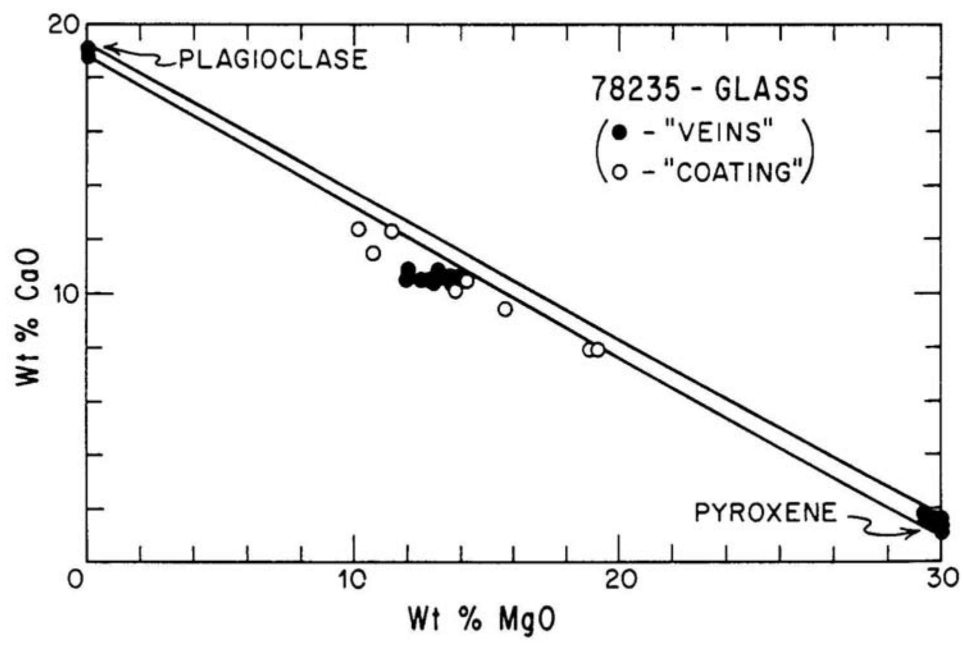

Figure 9: Composition of glass veins in and glass coating on 78235. From Dymek et al. (1975).

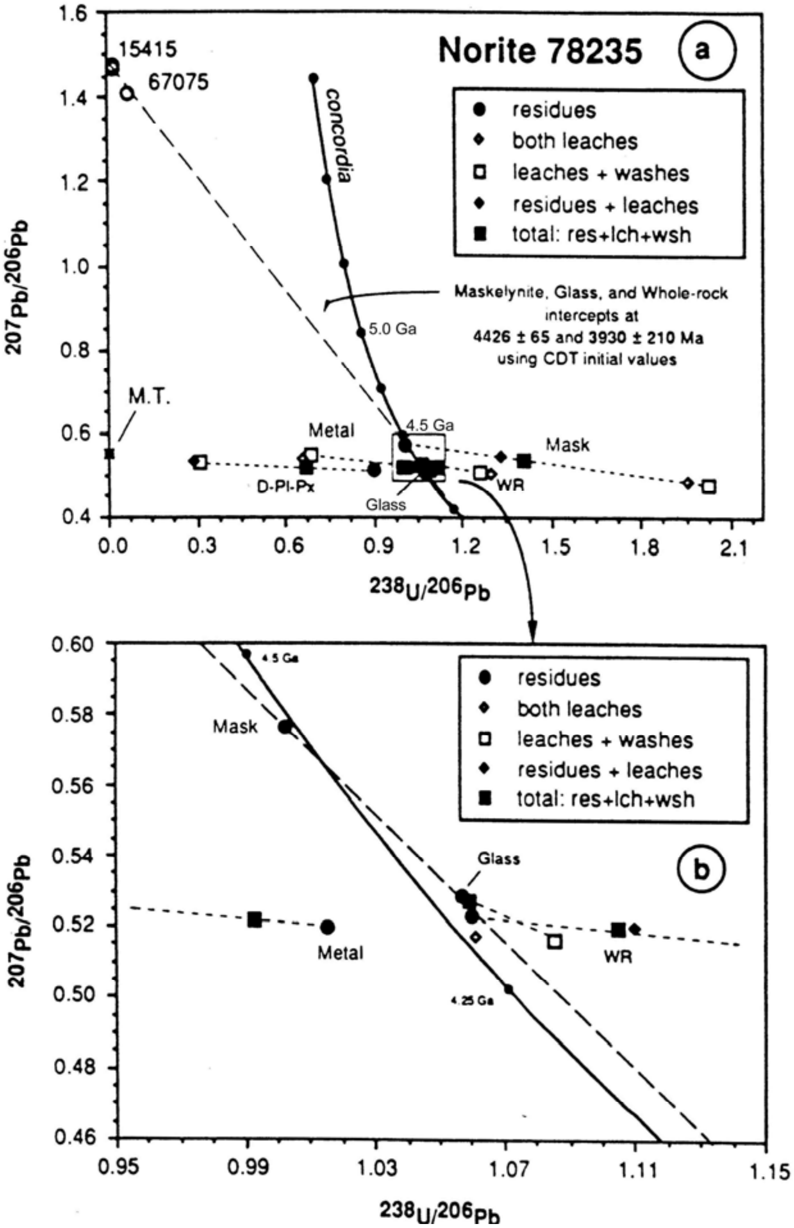

Figure 10: U-Pb Concordia diagrams for 7$2.35 from Premo and Tatsumoto (1991), illustrating the U-Pb behavior of leaches + washes (open squares), both leaches (open diamonds) and residues (solid circles) of mineral separates. Total U-Pb for each separate (combining residue + leaches + wash) is shown as a solid square, and the position of each along a tie line (residue to leaches + wash; short-dashed lines) shows the effect of the leaching procedure on the U-Pb systematics of each separate.

COSMOGENIC RADIOISOTOPES AND EXPOSURE AGES

Some of the Apollo 17 samples (including 78235) provided a unique opportunity to study the energy spectrum (and potential angular anisotropy) of the incident proton flux from the August 1972 solar flare (Rancitelli et al., 1974; Keith et al., 1974). Table 3 compares the induced activity of 78235 with 78255, from the underside of the boulder.

Drozd et al. (1977) have determined an exposure age of 292 ± 14 m.y. for 78235 using the ^{81}Kr-Kr method. Aeschlimann et al. (1982) reported an Ar exposure age of 300 m.y. for 78236.

SURFACE STUDIES

The original catalog (Butler, 1973) notes that the glass coating on 78235 is pitted and in places cracked by spalls from micrometeorite craters. Larger pits have penetrated the glass to the crystalline rock beneath.

PROCESSING AND DISTRIBUTION

The largest piece remaining of 78235 weighs 112 g. Thin sections of sample 78235 have been widely distributed to undergraduate: students as part of the JSC educational thin section set (Meyer, 1987).

Table 1: Whole-rock chemistry of 78235.
a) Winzer et al. (1975b); b) Warren et al. (1987); c) Dymek et al. (1975)

Split Technique	,34 (a) INAA	78234 (b)* INAA	78235 (c) calculated
SiO_2 (wt%)	49.5	50.93	49.8
TiO_2	0.16	0.25	0.08
Al_2O_3	20.87	14.36	18.4
Cr_2O_3	0.23	0.40	0.31
FeO	5.05	7.33	6.02
MnO	0.08	0.126	0.10
MgO	11.76	16.43	14.5
CaO	11.71	9.24	10.5
Na_2O	0.35	0.25	0.3
K_2O	0.061	0.055	0.05
P_2O_5	0.04		
Nb (ppm)			
Zr		29	
Hf		1.66	
Ta		0.25	
U		0.22	
Th		0.62	
Sr		107	
Rb		–	
Ba	79.6	53	
Ni		11.5	
Co		29.3	
Sc		13	
La		3.3	
Ce	9.16	8.6	
Nd	5.4	4.5	
Sm	1.49	1.49	
Eu	1.03	0.7	
Tb		0.38	
Dy	2.26	2.73	
Er	1.47		
Yb	1.64	2.33	
Lu	0.241	0.35	

Table 1: (Concluded).

Split Technique	,34 (a) INAA	78234 (b)* INAA	78235 (c) calculated
Ga		2.9	
Ge (ppb)			
Ir		<15	
Au		15	

*78234 is a "coarse-fine" fragment from the same sample bag as 78235 (see text).

Table 2: Data for 78235.
From Higuchi and Morgan (1975).

	Sample 78235,31	Sample black glass
Ir (ppb)	0.135	25.9
Os (ppb)		
Re (ppb)	0.0117	1.66
Au (ppb)	0.421	5.08
Ni (ppm)	12	450
Sb (ppb)	0.079	1.1
Ge (ppb)	18.9	131
Se (ppb)	7.5	176
Te (ppb)	<0.8	3.5
Ag (ppb)	0.4	0.96
Br (ppb)	6.4	6.7
Bi (ppb)	0.05	0.41
Zn (ppm)	1.5	2
Cd (ppb)	2.9	5.4
Tl (ppb)	0.023	0.038
Rb (ppm)	0.922	1.1
Cs (ppb)	64.3	80.3
U (ppb)	360	200

Table 3: Solar flare induced activity from large solar flare, August 1972.
From Keith et al. (1974).

	Sample 78135	Sample 78235	Sample 78255
dpm/Kg			
^{26}Al	42 ± 4	77 ± 7	65 ± 6
^{22}Na	74 ± 5	111 ± 8	50 ± 5
^{54}Mn	180 ± 20	55 ± 8	10 ± 5
^{56}Co	240 ± 20	52 ± 9	30 ± 20
^{46}Sc	76 ± 5	1.4 ± .9	<15
^{48}V	18 ± 5	<12	
Th (ppm)	.26	.59	.83
U (ppm)	.107	.196	.227
K (%)	.0525	.049	.059

Table 4: Glass chemistry of 78235.
a) Winzer et al. (1975b); b) McCallum and Mathez (.1975); c) Dymek et al. (1975)

	(a) vein	(a) rind	(b) brown	(c) rind	(c) vein
SiO_2 (wt%)	49.8	49.7	49.32	49.42	48.41
TiO_2	0.19	0.16	0.16	0.16	0.15
Al_2O_3	17.15	17.58	18.64	17.86	18.52
Cr_2O_3	0.35	0.33	0.33	0.35	0.34
FeO	7.52	7.39	7.53	6.97	7.67
MnO	0.12	0.11	0.12	0.10	0.12
MgO	14.98	14.51	13.43	14.25	12.96
CaO	9.92	9.86	10.48	10.24	10.52
Na_2O	0.35	0.34	0.39	0.25	0.39
K_2O	0.06	0.058	0.07	0.06	0.08
P_2O_5	0.08	0.07	0.05	0.05	0.10
S			0.20		
Ba (ppm)	62.5	87.3			
Ce	20.5	23.2			
Nd	9.52	9.48			
Sm	2.04	1.52			
Eu	0.815	0.819			
Dy	2.97	2.34			
Er	1.77	1.66			
Yb	1.91	1.63			
Lu	0.297	0.258			

Table 5: U-Th-Pb analytical data for 78235.
From Premo and Tatsumoto (1991).
(Footnotes may refer to material not included in this catalog.)

Sample/ Fraction	Weight (mg)	% blank Pb	Pb* (ppb)	U* (ppb)	Th* (ppb)	$^{206}Pb/^{204}Pb$†	$^{204}Pb/^{206}Pb$‡	$^{207}Pb/^{206}Pb$‡	$^{208}Pb/^{206}Pb$‡	$^{238}U/^{204}Pb$‡	$^{232}Th/^{238}U$‡
Residues											
WR	67.3	0.30	468	295	363	2862	0.000270	0.5252	0.4185	3913	1.27
						(0.31)§	(8.7)	(0.06)	(0.15)	(8.7)	
D-Pl-Px	110.0	0.43	196	99.0	63.3	5399	0.000064	0.5188	0.5250	13880	0.661
						(2.6)	(57)	(0.06)	(0.18)	(30)	
Mask	52.5	3.1	210	108	253	634.3	0.000643	0.5801	0.6522	1550	2.41
						(0.29)	(44)	(0.25)	(1.5)	(45)	
Glass	22.4	0.72	396	197	667	1146	0.000634	0.5322	0.9162	1657	3.50
						(0.10)	(11)	(0.09)	(0.10)	(11)	
Metal	0.12	11	4220	1880	3790	77.83	0.009667	0.5730	0.8161	95.6	2.08
						(0.11)	(11)	(1.1)	(1.0)	(13)	
Dilute HNO_3 (1N) leaches											
A2-WR	—	1.5	56.5	6.73	123	95.91	0.009911	0.5929	1.379	31.0	18.9
						(0.12)	(1.5)	(0.15)	(0.30)	(2.0)	
A2-D-Pl-Px	—	2.8	18.3	1.88	27.8	598.1	0.000600	0.5482	1.240	412	15.3
						(0.08)	(54)	(0.35)	(0.75)	(55)	
A2-mask	—	4.7	19.2	5.93	38.4	406.7	0.000731	0.6062	1.093	984	6.69
						(0.34)	(73)	(0.40)	(0.82)	(74)	
A2-glass	—	24	8.63	2.37	16.7	86.02	0.002377	0.5635	1.219	278	7.27
						(0.14)	(145)	(3.3)	(4.7)	(150)	
A2-metal	—	67	247	53.4	211	22.59	0.02966	0.6499	1.414	19.2	4.07
						(0.26)	(7.7)	(26)	(35)	(204)	
Dilute HBr (0.1 N) leaches											
A1-WR	—	0.71	152	85.6	638	103.1	0.009424	0.5464	1.585	162	7.70
						(0.69)	(1.1)	(0.11)	(0.33)	(1.3)	
A1-D-Pl-Px	—	0.45	153	17.0	164	1804	0.000373	0.5374	1.465	772	9.95
						(0.50)	(15)	(0.08)	(0.31)	(15)	
A1-mask	—	1.2	103	86.7	601	817.5	0.000748	0.4649	1.541	2940	7.16
						(0.24)	(19)	(0.22)	(0.62)	(19)	
A1-glass	—	11	28.5	11.9	105	175.5	0.000854	0.5097	1.790	1390	9.16
						(0.22)	(190)	(2.0)	(2.6)	(191)	
A1-metal	—	65	342	27.1	369	19.20	0.04959	0.8480	1.986	5.40	14.1
						(0.02)	(11)	(5.1)	(5.5)	(189)	
Water Washes											
W-WR	70.8¶	2.7	25.1	4.63	22.2	29.33	0.03354	0.7157	1.662	16.2	4.95
						(0.12)	(0.46)	(0.13)	(0.19)	(1.5)	
W-D-Pl-Px	113	6.6	6.25	2.08	7.66	99.20	0.007910	0.5664	1.154	98.8	3.81
						(0.21)	(8.5)	(0.70)	(1.5)	(10)	
W-mask	63.5	3.0	25.7	24.4	137	106.7	0.008455	0.5155	1.056	250	5.81
						(0.13)	(3.2)	(0.38)	(1.0)	(3.9)	
W-glass	22.4	23	7.63	3.05	18.6	45.10	0.01506	0.5967	1.403	69.2	6.29
						(0.64)	(18)	(2.8)	(3.1)	(27)	
W-metal	0.12	83	83.3	11.3	30.6	18.52	0.05650	0.8774	1.961	8.10	2.80
						(0.11)	(29)	(25)	(27)	(570)	

* Concentrations for leaches and washes are calculated using the original weight of the sample fraction.
† Measured ratio, uncorrected for blank Pb or mass fractionation.
‡ Corrected for blank Pb (amounts are given in the text) using *Ludwig* (1980, 1985a).
§ Numbers in parentheses are 2-sigma errors given in percent for the values just above them.
¶ Original weights before washing and leaching procedure.