70035

High-Ti Mare Basalt
5765 g, 15 x 23 x 10 cm

INTRODUCTION

70035 is a brown microporphyritic, vesicular basalt (Apollo 17 Lunar Sample Information Catalog, 1973), which contains 5-10% vugs (average 3 mm, up to 1 cm diameter). There is a slight coarsening of grain size towards the vugs, which contain projecting crystals of silica. The bottom of the original sample (70035, 0) contains patches of an injection glass. Patches of brownish debris in the glass may be powdered glass or soil retained on the surface. Zap pits are present on all surfaces, except B 70035 was collected

approximately 40 in east of the lunar module, between the LM and SEP sites. Whole-rock analysis confirmed the high-Ti nature of this basalt (~13 wt% TiO_2). Rb-Sr and K-Ar dating methods yield a crystallization age of 3.7-3.8 Ga.

PETROGRAPHY AND MINERAL CHEMISTRY

70035 is a plagioclase-poikilitic, ilmenite basalt (Papike et al., 1974), or equivalent to a Type III basalt of Papike et al. (1973) and Brown et al. (1973) or Type 1B basalt of Brown et al, (1975). Brown et al. (1974) reported

spinel minerals in 70035 as having ulvospinel rims with chromian-ulvospinel cores andpyroxferroite-type rims to the pyroxenes, which suggested that 70035 has an affinity with the Type II Apollo 17 high-Ti basalt group described by these authors. This basalt is comprised mainly of titanaugite (1-3 mm), ilmenite (< 1-2 mm), and plagioclase (1-3 mm) (Fig. 1). Euhedral to subhedral ilmenite, minor (~1%) subhedral ulvospinel, and armalcolite (< 1%) inclusions are present in subhedral titanaugites, which in turn are poikilitically enclosed in late-stage plagioclase (Fig. 1). Minor olivine (0.5-1 mm) is
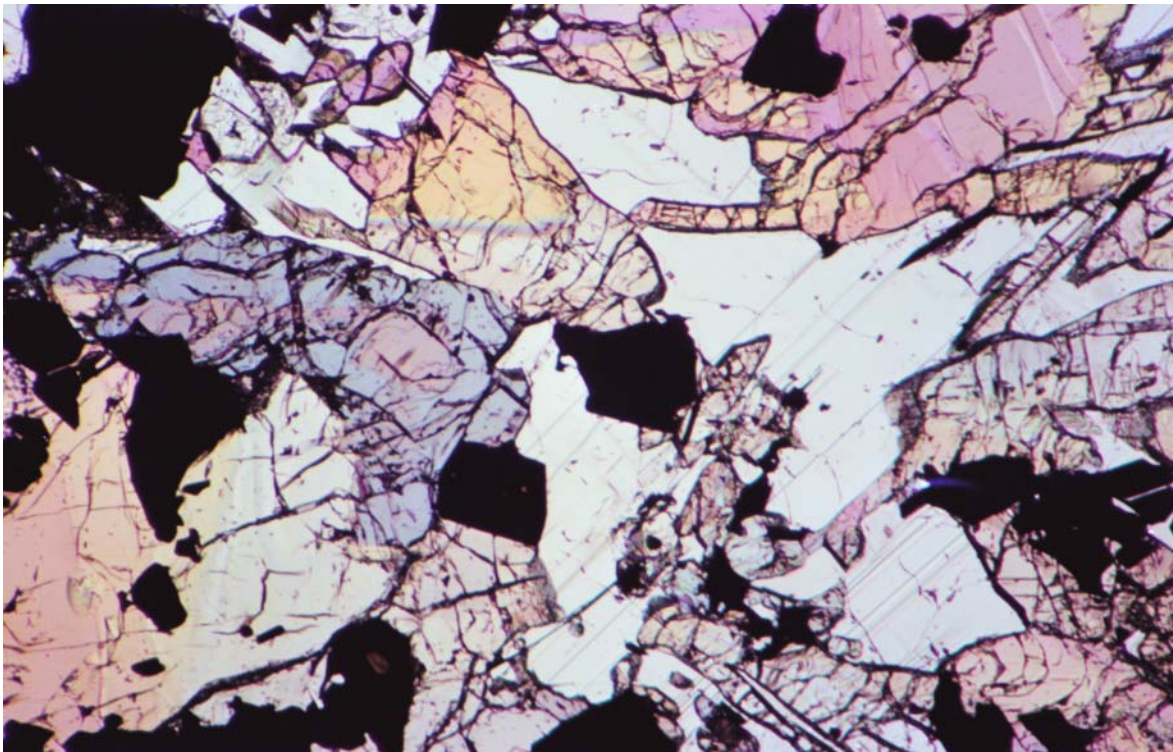

Figure 1: Photomicrograph of 70035,14. Field of view = 2.7 mm.

poikilitically enclosed in the plagioclase or occurs as anhedral cores to the larger and more abundant pyroxenes (Fig. 1). Cristobalite and native Fe (< 0.2 mm) form interstitial phases. Modes have been reported by Brown et al. (1975) from 70035,16 as 0.9% olivine, 23.7% opaques, 25.9% plagioclase, 47.5% clinopyroxene,1.6% silica, and 0.4% mesostasis.

Zonation of the constituent minerals is most pronounced in the clinopyroxenes. Cores of subcalcic titanaugite grade discontinuously into Mg-pigeonite (due to olivine resorption - Brown et al., 1975), with later compositions approaching pyroxferroite (Papike et al., 1974) (Fig. 2). All pyroxene compositions possess Ti:Al ratios of 1:2 (Fig. 3). The Al/Si ratio of the pyroxenes decreases with increasing Fe/Mg ratio, reaching a constant Al/Si ratio of ~0.3 at an Fe/Mg ratio of ~1.0 (Fig. 4). The amount of Al^{VI} decreases as TiO_2 increases in the pyroxenes (Fig. 5). Papike et al. (1974) suggested that this trend was a result of slower cooling, allowing plagioclase to nucleate shortly after pyroxene such that it was in competition for Al.

Olivines which are poikilitically enclosed in plagioclase are usually more forsteritic than those forming the cores of pyroxenes. Plagioclase shows little zonation (~An_{47-88}) from core-to-rim. A study of the zonation of plagioclase in 70035 by Crawford (1973) concluded that the earliest plagioclase is characterized by low FeO/ (FeO + MgO) and $K_2O/(K_2O + Na^{20})$ ratios, high TiO_2 contents, and forms the cores of plagioclase grains. The core is also the most calcic region of the plagioclase in 70035, and zones smoothly out-wards to more sodic-rich compositions (~Ab_{20}). Most commonly the zoning is asymmetric, reflecting longer contact with magma on one growing side of the crystal (Crawford, 1973). Delaney and Sutton (1991) studied Fe-Mn-Mg systematics in plagioclase in 70035 and found that Fe/Mn variations correlate with Fe/(Fe + Mg) variations, reflecting fractionation of a silicate magma. Further, they found that Fe/Mn variations in highland samples are offset to higher Fe/(Fe+Mg), relative to mare basalts, consistent with the highlands representing prior plagioclase separation. Delaney et al.

(1992) used synchrotron-based x-ray absorption near edge spectroscopy (XANES) on 70035 plagioclase, and found that it may be possible to use this method to determine Fe^{3+}/Fe^{2+} ratios in situ in thin sections.

Ilmenites often contain small (<0.005 mm wide) exsolution lamellae of chromite and rutile and some blebs (< 0.1 mm) of metallic Fe. This reaction, in addition to the breakdown of ulvospinel to ilmenite + Fe metal, was reported by Haggerty (1973) and El Goresy and Ramdohr (1975a,b,c) as evidence for an endogenic late-stage reducing gas mixture during the crystallization of these basalts. El Goresy and Ramdohr (1975a,b,c) noted evidence for two reduction reactions in 70035. Muhich et al. (1990) found variations in Fe/Mg in ilmenite from 70035 that correlate with the amount of exsolution exhibited. They found that Mg is enriched in ilmenite with abundant exsolution relative to grains with no exsolution.

Ilmenites are generally equant, almost amoeboidal (Papike et al., 1974). The Mg# of ilmenites is approximately 10-12, with Cr_2O_3 never exceeding 1 wt%. Roedder and Weiblen (1975) reported both high-K (6.27 wt% K_2O) and anomalous low-K (0.037 wt% K2O) melt inclusions in the ilmenites of 70035. The high-K inclusions were attributed to late-stage silicate-liquid immiscibility, but the origin of the low-K inclusions is obscure. Armalcolite in 70035 exhibits little compositional variation (Haggerty, 1973).
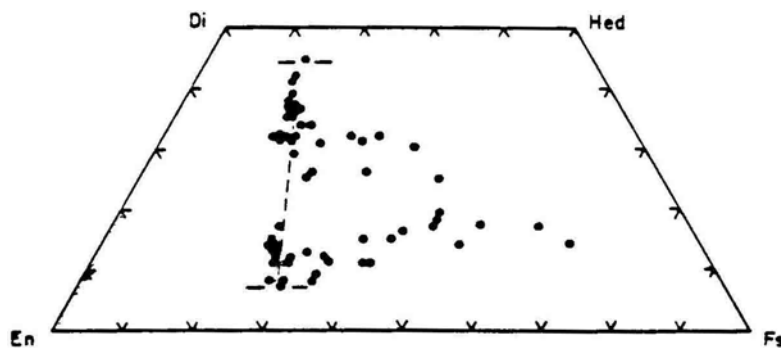

Figure 2: Quadrilateral plot for pyroxenes in plagioclase-poikilitic basalt 70035.
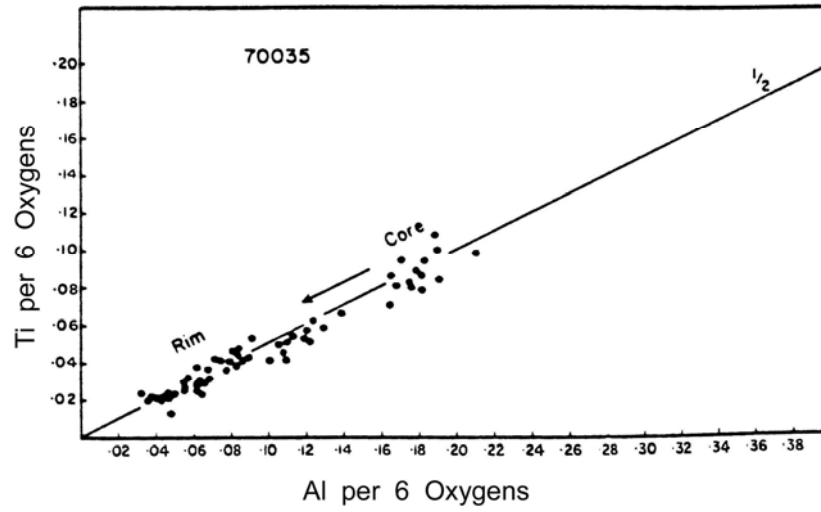
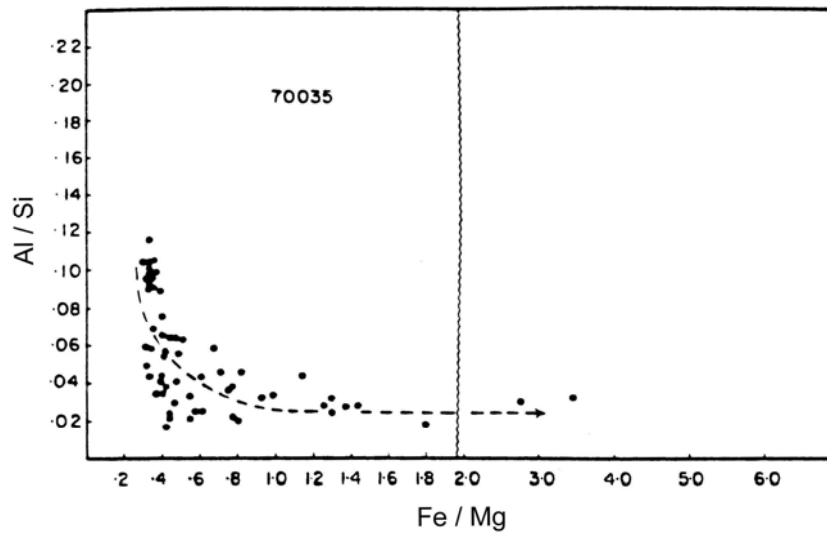Figure 3: Ti-Al plot for pyroxenes in plagioclase-poikilitic basalt 70035

Figure 4: Al/Si-Fe/Mg plot for pyroxenes in plagioclase-poikilitic basalt 70035.
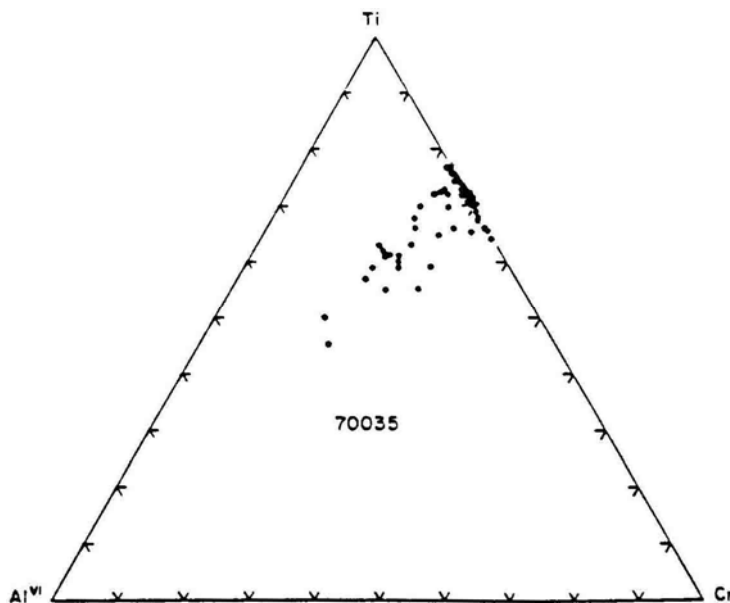
Figure 5: plot for pyroxenes in plagioclase-poikilitic basalt 70035.

WHOLE-ROCK CHEMISTRY

The relatively coarse grain size of 70035 has introduced into whole-rock analysis the problem of sampling errors. This led Rhodes et al. (1975, 1976) to put 70035 into their class U (unclassifiable) of Apollo 17 basalts, as the whole rock chemistry did not conform to the A, B, and C groups delineated by finer-grained basalts. These authors used the analysis reported by LSPET (1973) (Table 1). Shih et al. (1975) only analyzed trace-element abundances from two samples of 70035 (,1 and ,6) by isotope dilution and INAA. These authors concluded that the source must be LREE-depleted with clinopyroxene, olivine, and ilmenite left in the refractory residue after ~20% partial melting. This would produce the LREE-depleted REE profile of 70035 (Fig. 6), which exhibits a negative Eu anomaly ([Eu/Eu*]$_N$ ~0.61) and is consistent with the low abundances of other LIL elements. The

analysis of Shih et al. (1975) agrees well with that of LSPET (Table 1).

Hughes and Schmitt (1985) obtained "Zr/Hf ratios and other elemental data" for 70035 by coincidence-anticoincidence counting and normal counting techniques during INAA. However, although reporting the Zr/Hf ratio for 70035 (29.5±4.7), Hughes and Schmitt only reported Hf abundances (4.9±0.2 ppm). These authors concluded that significant fractionation of Zr from Hf had occurred during lunar evolution from an initial value of ~35.

The work on sulfur by Gibson and Moore (1974) reported the abundance of sulfur in 70035,1 as 1580 ± 40 μgS/g (Table 2). These authors noted that Apollo 17 high-Ti basalts contain similar sulfur abundances to Apollo 11 basalts, but much higher than those from Apollo 12 and 15. Gibson and Moore (1974) noted a negative correlation between S content and percent native Fe in

Apollo 17 high-Ti basalts and concluded that a portion of the native iron may have resulted from desulfuration prior to crystallization. Gibson et al. (1976) reported the amount of metallic Fe in 70035 as 0.147%, This study was undertaken to confirm the desulfuration hypothesis of Gibson and Moore (1974). Gibson et al. (1987) reported the abundance of hydrogen in 70035 as 2.2 μgH/g. The analysis of 70035 was included in a much larger study for the purpose of pin-pointing hydrogen-rich lunar materials.

ISOTOPES AND AGE DETERMINATIONS

Basalt 70035 has been analyzed for the following isotopes: Rb-Sr (Evensen et al., 1973; Nyquist et al., 1974,1976; Bansal et al., 1975); K-Ar and Ar-Ar (Stettler et al., 1973); Sulfur (Gibson and Moore, 1974; Gibson et al., 1975). Published isotope data are summarized in Table 2. The Rb-Sr methods dated 70035 at 3.82±0.06 Ga (Evensen et al.,

Table 1: Whole-rock chemistry of 70035.

	70035,1[1]	70035,1[2]	70035,6[2]
SiO_2 (wt%)	37.84		
TiO_2	12.97		
Al_2O_3	8.85		
Cr_2O_3	0.61	0.27	0.25
FeO	18.46		
MnO	0.28		
MgO	9.89		
CaO	10.07		
Na_2O	0.35		
K_2O	0.06	0.04	0.05
P_2O_5	0.05		
S	0.15		
Nb (ppm)	20		
Zr	205	217	200
Hf			
Ta			
U		0.091	0.12
Th			
W			
Y	75		
Sr	176	174	161
Rb	0.7	0.461	0.628
Li		8.7	8.1
Ba		62.1	79.5
Cs			
Be			
Zn	4		
Pb			
Cu			
Ni	2		
Co			20.7
V			
Sc			82.5
La		4.79	7.04
Ce		16.4	23.4
Nd		18.2	25.9
Sm		7.63	10.5
Eu		1.82	1.88

Table 1: (Concluded).

	70035,1[1]	70035,1[2]	70035,6[2]
Gd		11.0	13.5
Tb			
Dy		14.1	18.8
Er		8.40	11.0
Yb		7.79	10.0
Lu			
F			
Cl			
C			
N			
H			
He			
Ga (ppb)			
Ge			
Ir			
Au			
Ru			
Os			

References: 1) LSPET (1973), also quoted in Rhodes et al. (1976);
2) Shih et al. (1975).

Table 2: Isotope data gathered from basalt 70035.

Rb-Sr (Evensen et al., 1973)

	wt (mg)	K (μg/g)	Rb (μg/g)	Sr (μg/g)	Ba (μg/g)	$^{87}Rb/^{86}Sr$ (x10^2)	$^{87}Sr/^{86}Sr$
70035,9							
WR "A"	15.38	532.0	0.577	164.0	62.1	0.996	0.69980 ± 10
WR "B"	14.71	474.0	0.506	158.0	61.1	0.906	0.69973 ± 7
Plag	10.19	1406.0	1.041	657.0	165.4	0.448	0.69947 ± 7
Px "A"	24.12	----	0.389	56.7	----	1.94	0.70028 ± 7
Px "B"	14.58	----	0.357	57.8	----	1.75	0.70013 ± 10
Ilm	15.80	----	0.185	13.5	----	3.85	0.70134 ± 16
Glass	2.83	----	15.307	71.0	----	5.83	0.70241 ± 5

ISOCHRON AGE = 3.82 ± 0.06 AE; Initial = 0.69923 ± 3

Rb-Sr (Nyquist et al., 1974)

	wt (mg)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
70035,1	58.5	0.461	173.7	0.00772 ± 23	0.69967 ± 6
70035,6	53.2	0.628	161.3	0.01126 ± 29	0.69980 ± 6
Plag	4.4	0.0948	687.5	0.00040 ± 4	0.69924 ± 10
Ilm 1	11.9	0.8345	47.79	0.05053 ± 37	0.70195 ± 8
Px	22.7	0.3738	43.73	0.02473 ± 28	0.70059 ± 8
Px + Ilm	26.9	0.6334	52.01	0.03524 ± 39	0.70112 ± 20
Ilm 2	8.9	0.8326	6.01	0.03647 ± 50	0.70016 ± 4

ISOCHRON AGE = 3.73 ± 0.11 AE; Initial = 0.69924 ± 5

K-Ar (Settler et al., 1973)

	Age, High Temp. Plateau (10^9yr)	Ca (%)	K (ppm)
70035,6	3.72 ± 0.07	7.4	390
70035,6	3.75 ± 0.07	7.6	260

Sulfur (Gibson and Moore, 1974; Gibson et al., 1975, 1976, 1987)

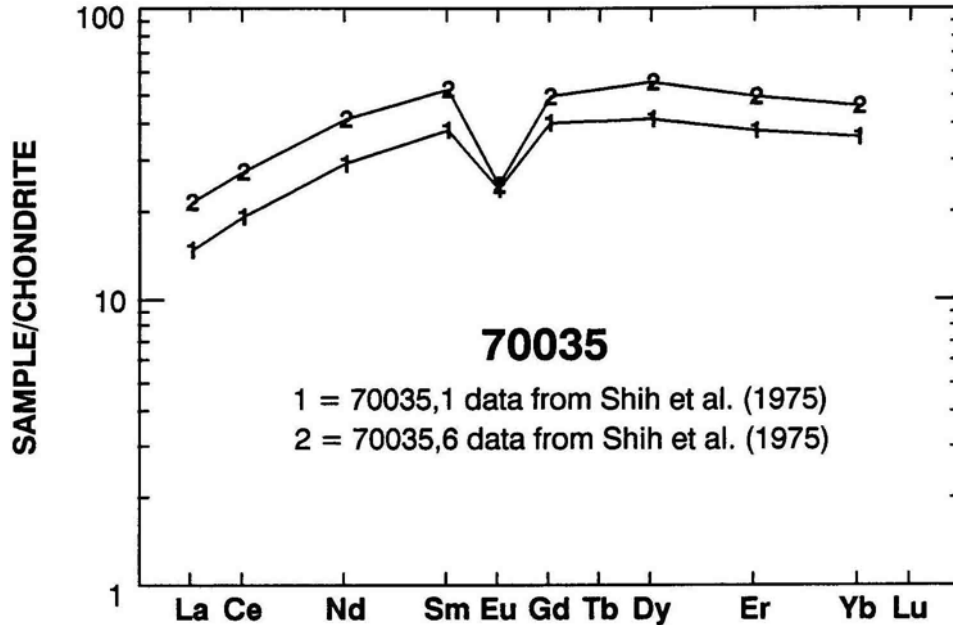|	Total Sulfur		o/oo CDT	$S^{34}S$ % Fe^0	H (μgH/g)
	Combustion μgS/g	Acid Hydrolysis μgS/g			
70035	1580	1240	-0.2	0.147	2.2

Figure 6: Chondrite-normalized rare-earth element profiles of 70035.

1973) and 3.73 ± 0.11 Ga (Nyquist et al., 1974). Evensen et al. (1973) reported an initial $^{87}Sr/^{86}Sr$ ratio for 70035 of 0.69923 ± 0.00003 (Fig. 7a) and concluded that this age represented an early age of mare flooding, which was episodic until 3.1 Ga. Nyquist et al. (1974) reported an initial $^{87}Sr/^{86}Sr$ ratio of 0.69924 ± 0.00005 (Fig. 7b) and noted that this low initial ratio was similar to that of the source of low-K Apollo 11 basalts, but lower than that of the source of Apollo 12 and 15 basalts. Nyquist et al. (1976) proposed a two-stage evolution for the source of 70035: 1) from 4.6-4.4 Ga, the source evolved with an $^{87}Rb/^{86}Sr$ of -0.05; 2) at 4.4 Ga, the source experienced a depletion which resulted in an $^{87}Rb/^{86}Sr$ ratio of ~0.005 until eruption at 3.7-3.8 Ga.

Two independent age determinations by Stettler et al. (1973) of 70035,6 using the K-Ar method, yielded ages of 3.72± 0.07 Ga and 3.75±0.07 Ga (Fig. 8). These authors noted the similarity between the age of 70035 and those of the low-K/high-Ti basalts at Tranquility Base. Stettler et al. (1973) reported exposure ages for 70035 of 95-100 Ma (^{38}Ar). These ages were also quoted by H6rz et al. (1975). Drozd et al. (1977) reported a Kr exposure age of 122± 3 Ma. Eberhardt et al. (1974) reported two $^{37}Ar/^{38}Ar$ exposure ages for 70035,6 of 95 and 100 Ma.

The sulfur isotopic composition of 70035 was reported by Gibson et al. (1975) as $S^{34}S$ CDT = -0.2.

MAGNETIC STUDIES

The magnetic study of Pearce et al. (1974a,b) demonstrated that 70035 is magnetically similar to basalts from other missions. However, Apollo 17 basalts as a whole contain a greater range of Fe^o contents. The magnetic data reported by Pearce et al. (1974a,b) is presented in Table 3.

EXPERIMENTAL

Green et al. (1975) demonstrated that the source region for 70035 and other high-Ti basalts was not one in which ilmenite was the refractory residual, contrary to the conclusion of Shih et al. (1975). Furthermore, at high pressure, Ti-oxide was never a liquidus phase.

Usselman et al. (1975a) compared ilmenite compositions from Apollo 17 high-Ti mare basalts with those in the $FeOTiO_2-Al_2O_3-Cr_2O_3-Fe$ system, using ilmenite compositions from 70035 for comparison. These authors concluded that observed ilmenite compositions only slightly reflect the composition of the original magma.
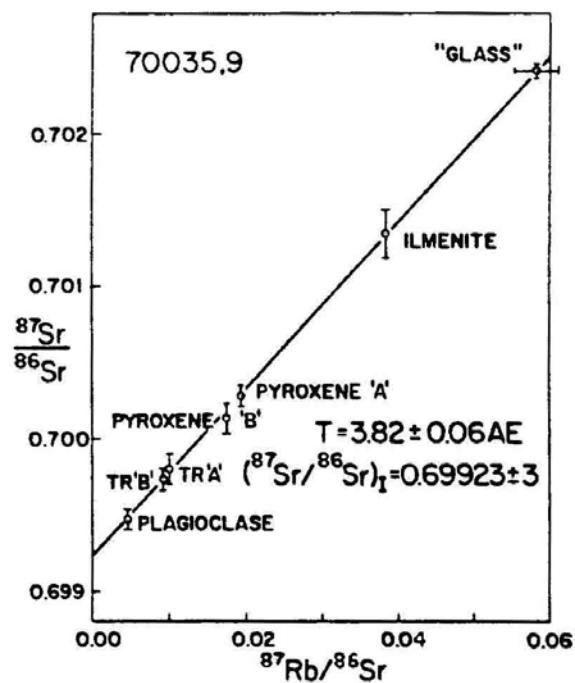
Figure 7a: Rb-Sr internal isochron for 70035. TR "A" and "B" are two total rock samples; pyroxene "A" and "B" are two aliquots of the pyroxene separate; "glass" is float in liquid of density 2.55 of plagioclase separate of 25-37p size.
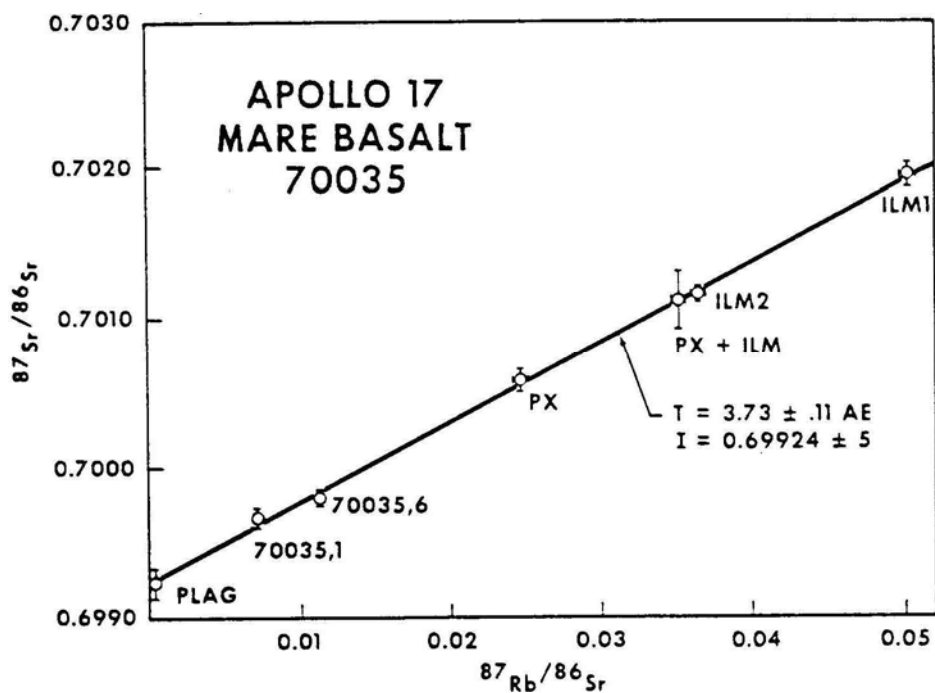

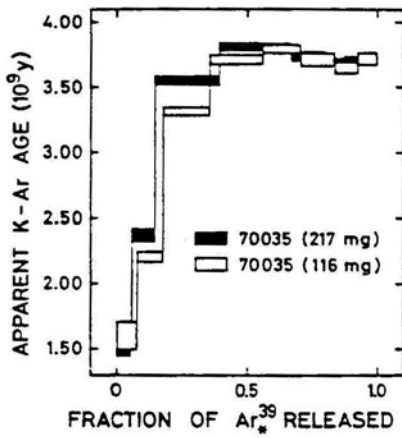Figure 7b: Rb-Sr mineral isochron for Apollo 17 high-titanium mare basalt 70035.

Figure 8: Ar^{40}-Ar^{39} release curves of two samples of the 70035 subfloor basalt. The age is similar to those of basalts found at Tranquility Base.

extensive re-equilibration of ilmenite with the fractionating liquid and ferromagnesian minerals has occurred. Usselman et al. (1975b), from crystallization experiments, calculated the cooling rate for 70035 to be < 1 °C/hour.

PROCESSING

This sample was subdivided by sawing during the early years of the program (Figs. 9-11). Two pieces larger than 1.5 kg remain intact. Eleven thin sections have been cut from three potted butts. They are sections ,7 ,8 ,19 and ,20 from ,3 sections ,13-18 from ,2; and section ,95 from ,94. Eight pieces of 70035 (ranging from 64 g to 120 g) have been mounted and allocated as long-term displays. Thin sections ,15 and ,18 are also allocated to the educational display program managed by the Public Affairs Office at the Johnson Space Center.

Table 3: Magnetic properties of 70035.
(Pearce et al., 1974).

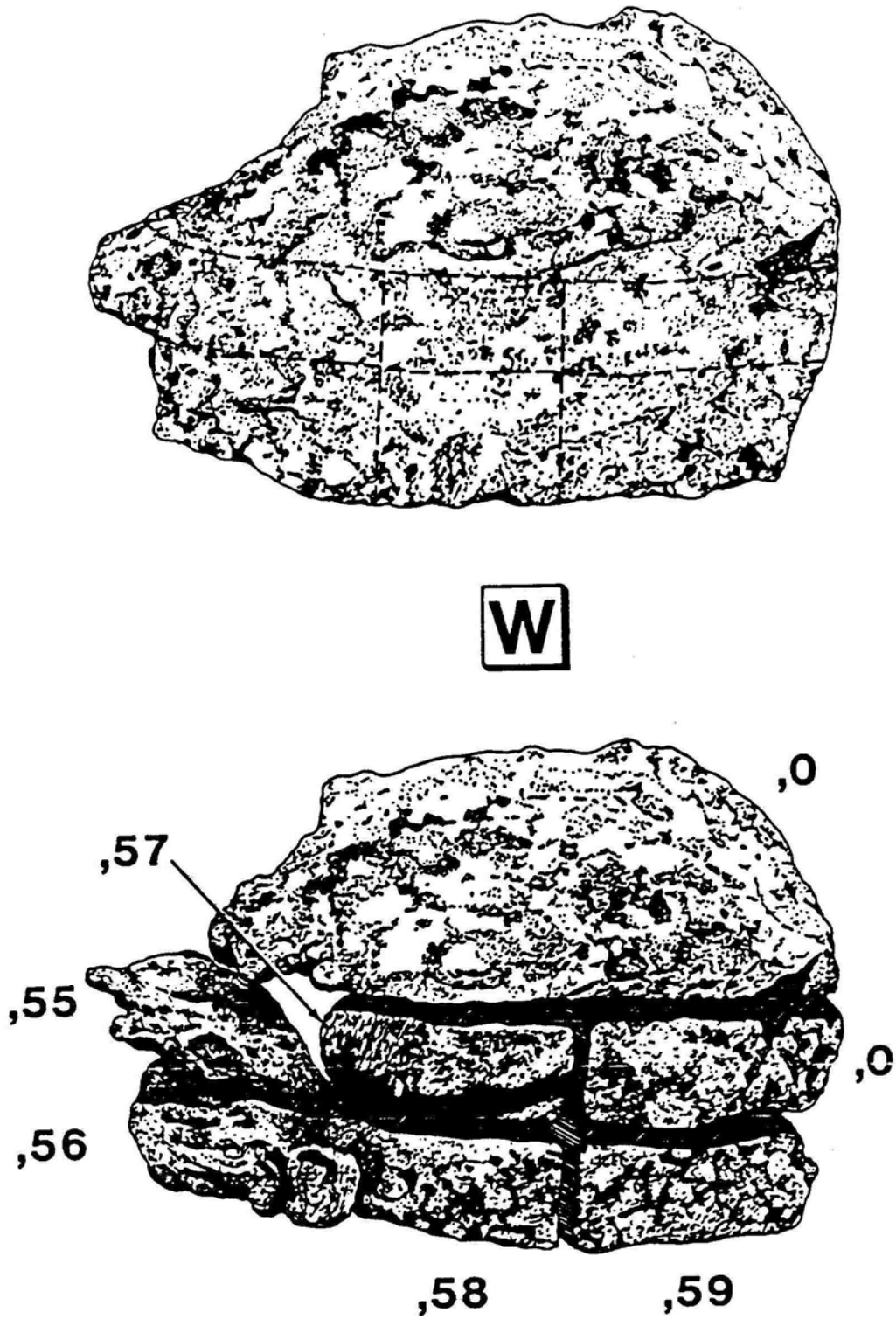|	J_s (emu/g)	X_p (emu/g Oe) *10^6	X_o (emu/g Oe) *10^4	J_{rs}/J_s	H_c (Oe)	H_{rc} (Oe)	Equiv. wt% Fe^0	Equiv. wt% Fe^{2+}
70035,1	0.320	35.2	2.0	0.008	15	--	0.15	16.1

Figure 9: Major subdivisions of 70035,0.

Figure 10: Major subdivisions of 70035,0.

Figure 11: Major subdivisions of 70035,0.