15016   MEDIUM-GRAINED OLIVINE-NORMATIVE   ST. 3   923.7
                MARE BASALT

INTRODUCTION: 15016 is a medium-grained, very vesicular (Fig. 1) olivine-normative basalt. It crystallized about 3.4 or 3.3 b.y. ago.

15016 is the only sample collected at Station 3, an unscheduled stop on a mature mare surface. The area has abundant, subdued 10 cm- to 1 m-diameter craters. The sample appeared to be representative in shape, burial, and filleting of the other nearby large fragments; an adjacent rock of similar size was also vesicular. 15016 is light brownish gray, blocky and sub-rounded, and tough. Its lunar orientation is known and it was embedded in soil only at one end. It apparently has no zap pits, despite its long exposure age (~300 m.y., below).
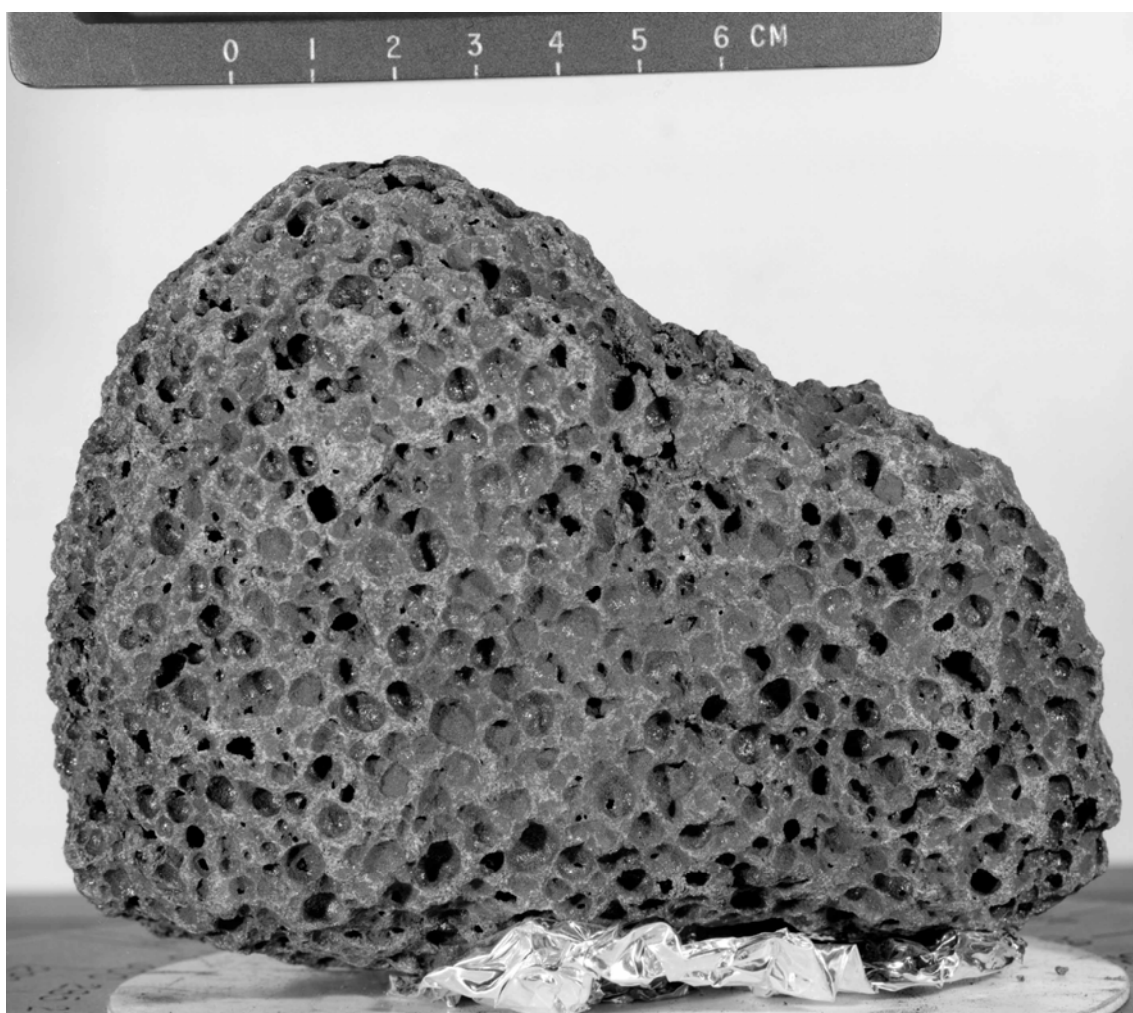

Figure 1. Macroscopic view, pre-splitting, showing vesicularity. S-71-46986

PETROLOGY: 15016 is a porphyritic olivine-normative basalt (Fig. 2) with yellow-green olivine and light brown pyroxene phenocrysts. Its most conspicuous character is its vesicularity, like 15556 and 15529, and is the reason the sample was noticed and collected. The sample has been described by Brown et al. (1972a), Papike et al. (1972), Bence and Papike (1972), and Kushiro (1972, 1973). Brown et al. (1972) quote 45% vesicles. Like other olivine-normative basalts, the sample contains ~70% mafic minerals. Some x-ray diffraction data is reported by Papike et al. (1972), and microprobe data for pyroxenes by Bence and Papike (1972) and Kushiro (1972, 1973).

The sample differs from the isochemical basalt 15555 in its texture: it has lathy, not poikilitic feldspars, and cooled faster. The groundmass is subophitic to intersertal. The olivine phenocrysts are zoned, with a total range of Fo_{72-7} (Kushiro 1972). Compared with 15555, the pyroxene compositions are truncated at both ends (Bence and Papike, 1972) (Fig. 3), leading Brown et al. (1972) to state that there are no detectable pigeonites. However, all other authors refer to the low-Ca pyroxene phase as pigeonite. The pyroxenes, the second crystallizing phase, are complexly zoned, with pigeonitic cores and with the transition to augitic rims barely discernable. A sharp reversal to low-Ca augites, correlated with increasing Ti/Al, corresponds with the onset of plagioclase crystallization (Bence and Papike, 1972; Kushiro, 1972, 1973). Plagioclases are zoned from $An_{94-80.7}$ (Kushiro, 1972). Other phases include chromite, Cr-ulvospinel, cristobalite, ilmenite, and traces of FeNi metal. The vesicles have ilmenite plates lined around them. Engelhardt (1979) tabulates ilmenite paragenesis.

EXPERIMENTAL PETROLOGY: Low pressure crystallization experiments were conducted by Humphries et al. (1972) with fO_2 buffered at Fe^0/FeO equilibrium. The sample has a high temperature olivine + spinel liquidus (Fig. 4a), with pigeonite crystallizing at 1170°C, and plagioclase at ~1150°C. Humphries et al. (1972) prefer a (minority) interpretation that 15016 is a mafic accumulation from a liquid multiply saturated with olivine, pigeonite, and plagioclase. Kesson (1975, 1977) also conducted low-pressure crystallization experiments (Fig. 4b), on a synthetic 15016-15555 composition, providing mineral compositional data and residual liquid compositions. Later crystallization of spinel in her experiments than in those of Humphries et al. (1972) is attributed by Kesson (1975, 1977) to the "unreasonably high fO_2" of the Humphries et al. (1972) experiments. O'Hara and Humphries (1972) in discussing the effects of Fe-loss on experimental results, claim that Kesson's (1975) experiments were not immune from chemical changes.
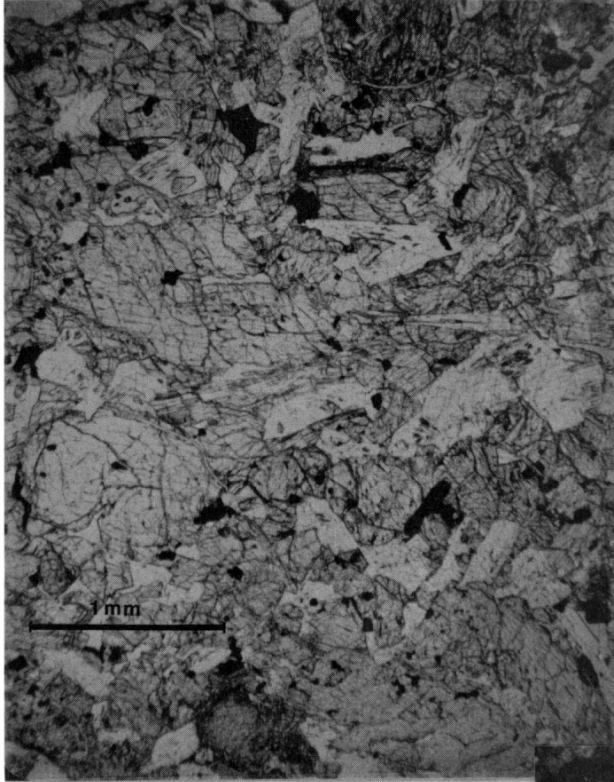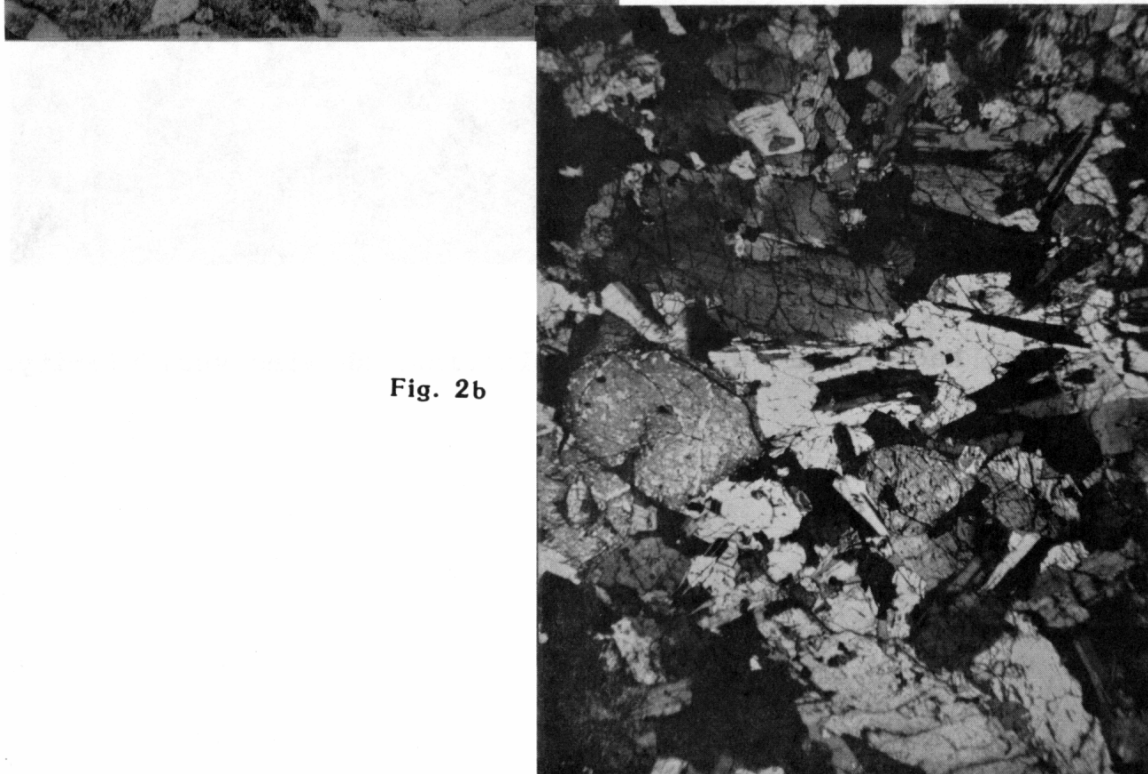
Fig. 2a

Fig. 2b

Figure 2. Photomicrograph of 15016,144, same field and scale
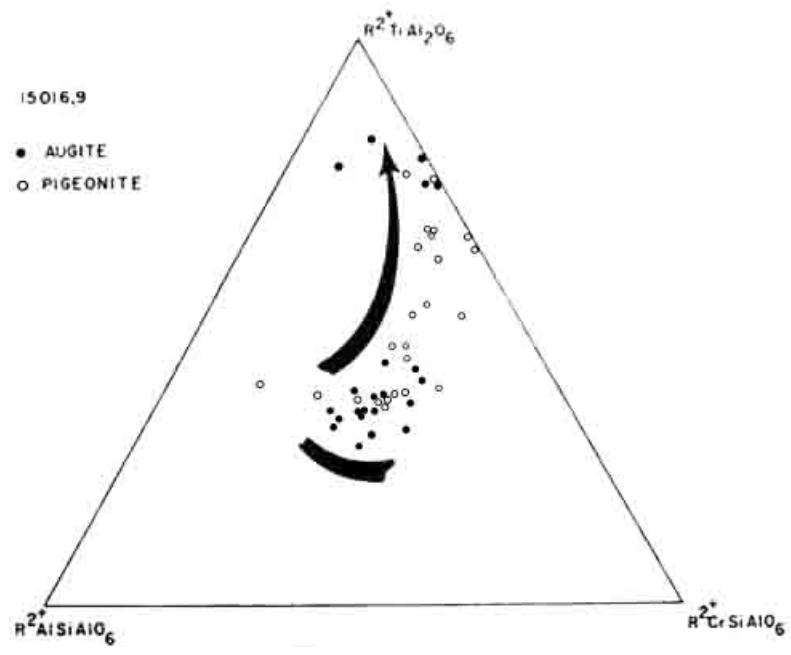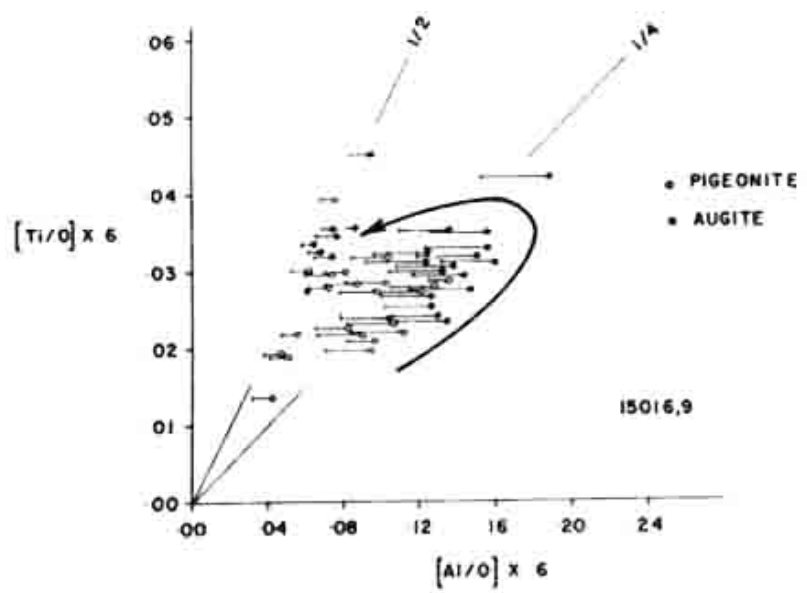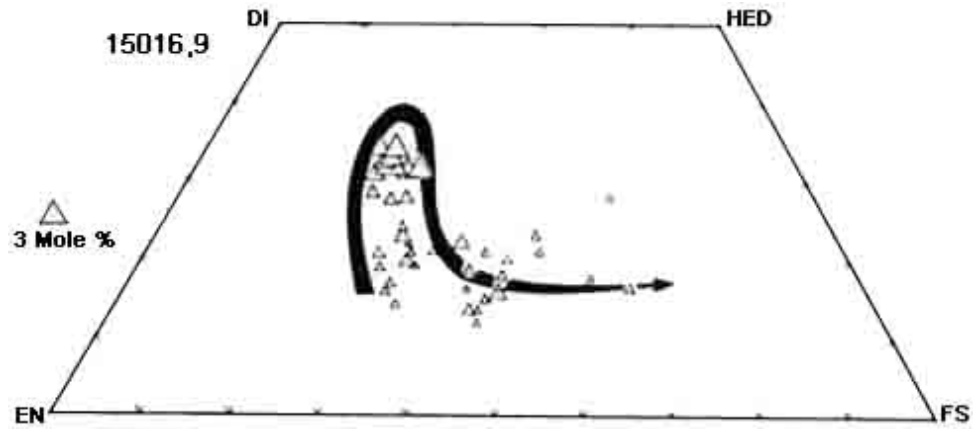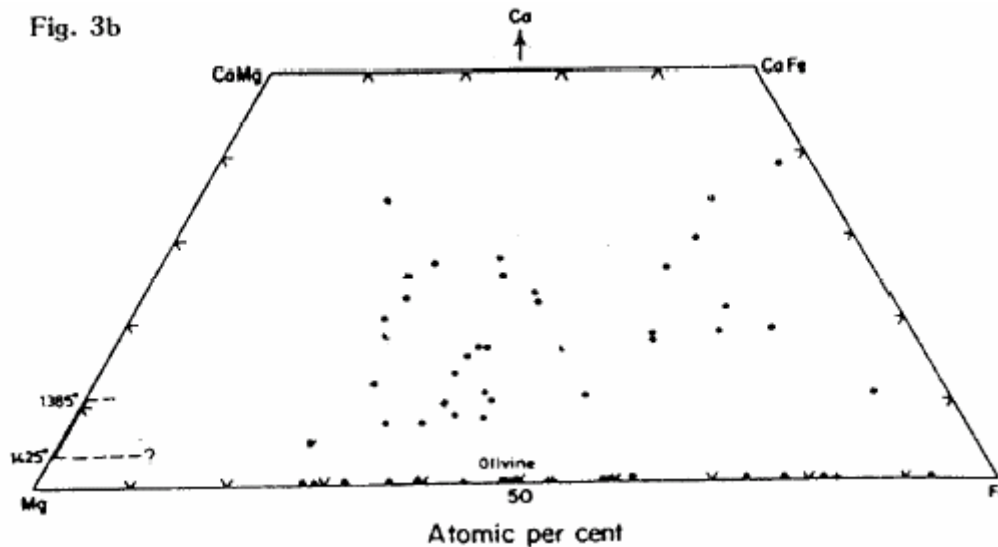(a) transmitted light; (b) crossed polarized

Fig. 3a

Fig. 3b

Figure 3. Pyroxene compositional data
(a) Bence and Papike (1972); (b) Kushiro (1973).

High pressure experiments were conducted by Kushiro (1972) and Hodges and Kushiro (1973) in the range 4 to 16 kb (Fig. 5a), and by Kesson (1975, 1977) (Fig. 5b). Kushiro's (1972) experiments were at wustite stability, and have olivine as a liquidus or near-liquidus phase above 15 kb. Plagioclase exists only below 10 kb, and never on the liquidus. Mineral compositional data for some runs is given by Kushiro (1972). Kesson (1975, 1976) obtained rather similar results--olivine the liquidus phase to 12 kb--but spinel always 50°C below the liquidus, again resulting from the lower fO_2 used. A multiple saturation point exists at ~12 kb, 1350°C; assuming some olivine fractionation during ascent, a minimum depth of 240 km to an olivine-pyroxene source is required.

CHEMISTRY: Chemical analyses are listed in Table 1 and rare-earths are shown in Figure 6. In general the data has not been discussed specifically, only in terms of relationships with other olivine-normative basalts by olivine control. The sample is one of the more magnesian members of the group. The sample analyzed by S.R. Taylor et al. (1973) is considerably less mafic in major element composition than other analyses, but the trace elements are similar to those of other analyses. Chappell et al. (1973) suggest that the high Cr abundance is a result of spinel accumulation in 15016.

Data by Ehmann et al. (1972) and Rhodes (1972) is included only in averages of basalts and not presented until later publications. Christian et al. (1972) and Cuttitta et al. (1973) analyzed for Fe^{3+}, finding none, and tabulated "excess reducing capacity." Janghorbani et al. (1973) analyzed for oxygen. Gibson et al. (1975) analyzed for CO, CO_2, H_2, H_2S, AND Fe^0.

Fig. 4a

Fig. 4b

Equilibrium crystallization sequence for 15555-15016 in vacuum. Numbers in olivine field refer to mol % Fo.

15555 - 15016 : MELTING EXPERIMENTS IN VACUUM
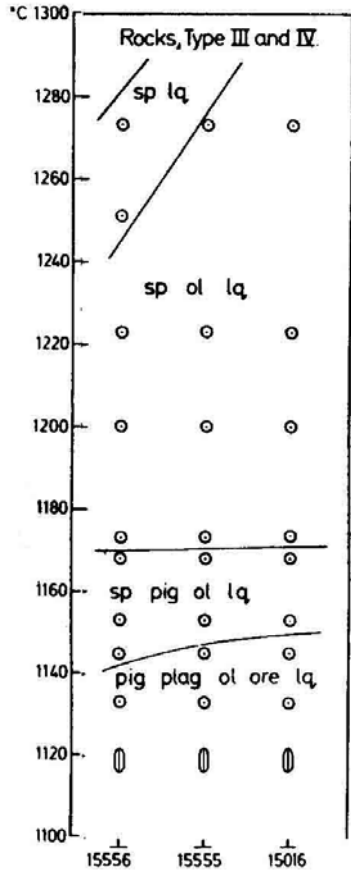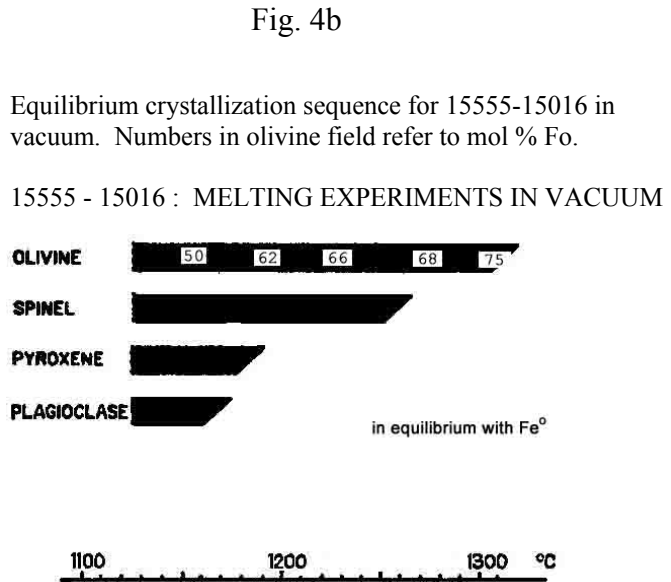
Figure 4. Low pressure experimental data
(a) Humphries et al. (1972); (b) Kesson (1977).

Barker (1974) made a study aimed at determining the composition of the gas which formed the vesicles, from analysis of gases trapped in glass inclusions released by heating. He concluded that the original gas contained 46% O, 42% C, and 12% H, and became more H_2O-rich as crystallization proceeded (similar to results from 15065). The gases released at 1200°C to 1300°C provide the best estimates of the gas composition. A peak in CO_2 at 490°C is interpreted to result from the breakdown of ~5 ppm siderite which is not a product of sample handling.

Goldberg et al. (1976) analyzed F on vesicle walls and in intervesicle areas. The thin F deposits are of lunar origin, but are thinner than occur on Apollo 15 Green Glass. The amount of F present is not enough to have caused the vesicles, but if a lot of gas escaped, HF or HF/HCl gas could have been the cause. However, Goldberg et al. (1976) consider CO a more likely phase.

Fig. 5a

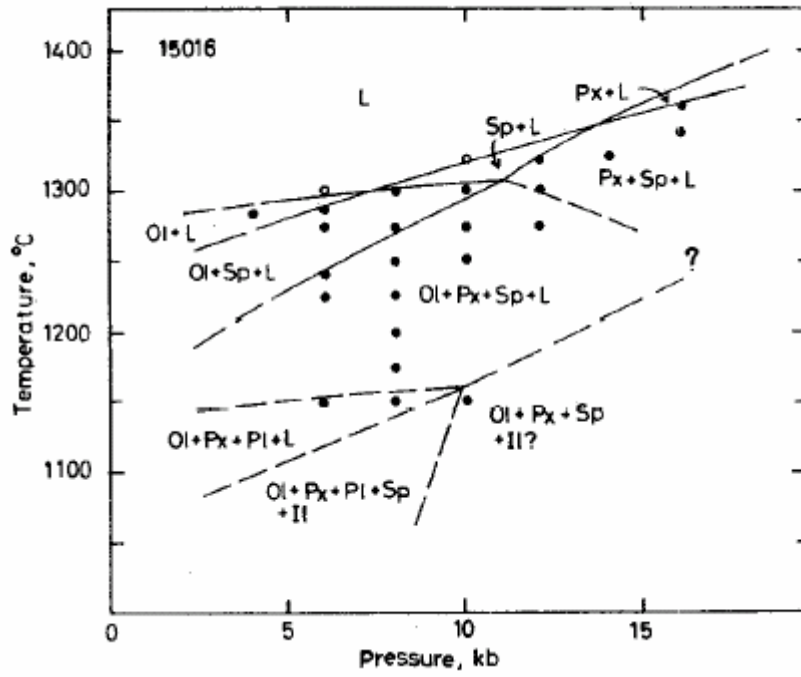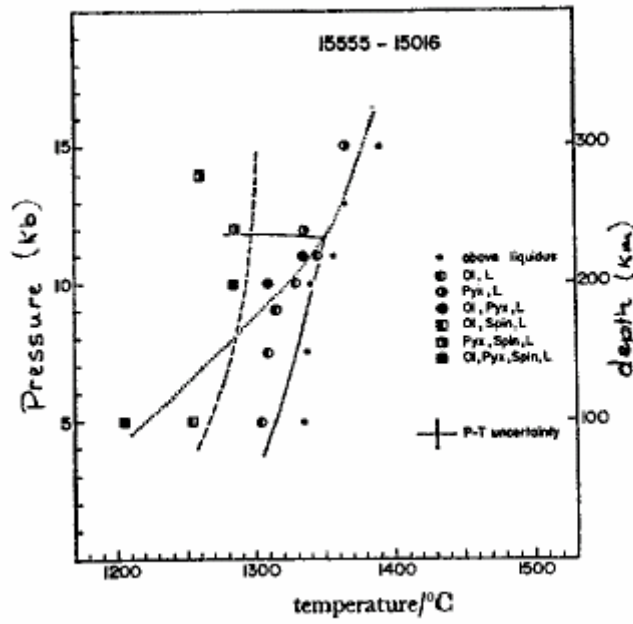Fig. 5b

Figure 5. High pressure experimental data
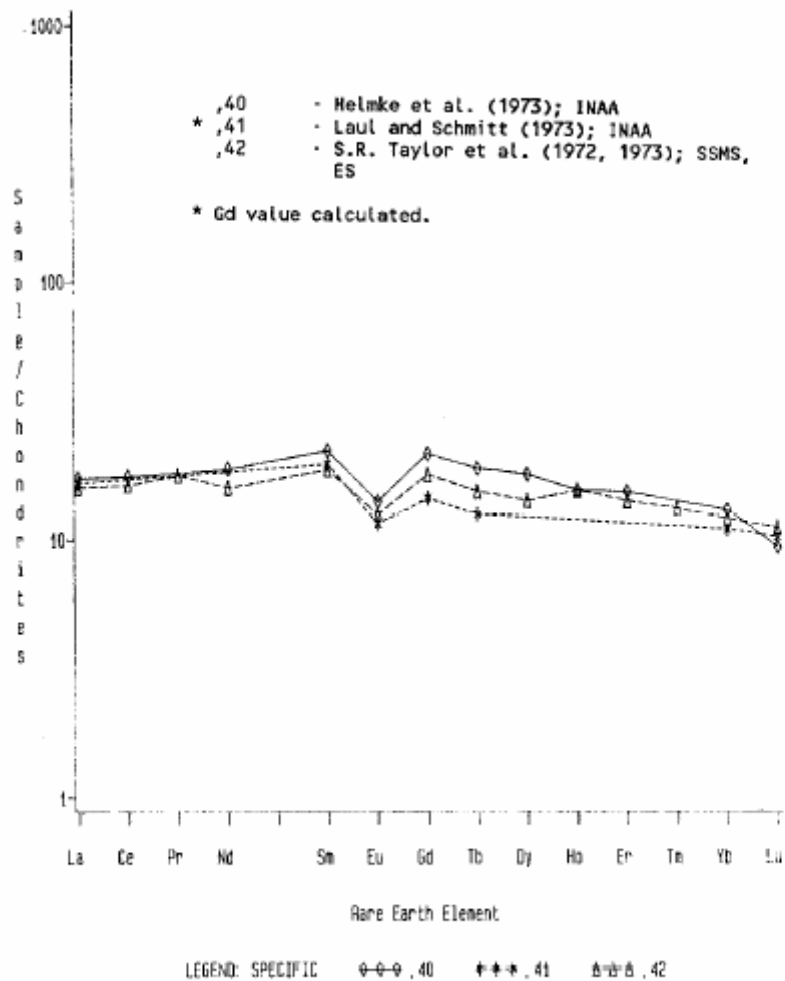(a) Kushiro (1972); (b) Kesson (1977).

Figure 6. Rare earths in rock 15016

TABLE 15016-1

	,37	,41	,33		,42	,38	,31	,39d		,46	
Wt % SiO2	43.78	43.97	44.30				43.9	43.9			
TiO2	2.28	2.31	2.27	2.1			1.77	3.0			
Al2O3	8.17	8.43	8.39	8.8			15.8	8.3			
FeO	22.50	22.58	22.95	21.8			16.53	21.7			
MgO	11.58	11.14	11.65	11	11.12		9.16	11.4			
CaO	9.06	9.40	9.20	9.0	9.05		10.9				
Na2O	0.24	0.21	0.32	0.251	0.2510b		0.32				
K2O	0.04	0.03	0.05	0.041	0.0410	0.0451					0.0405
P2O5	0.25	0.07	0.06		0.0410						
(ppm) Sc			32	36			25.0				
V			200	250			140				
Cr	7530		4500	5860			4100				
Mn	2600	2600	2200	2000			2550,1200	1680			
Co			65	53			56.0				
Ni			86				74.0			85	
Rb			<1		1.0		0.83	0.73,0.81,0.65			0.670
Sr		83	80		99			89.7,91.4,93.3			90.7
Y			21				26.0				
Zr		95	69	150			94.0				
Nb			<10				6.2				
Hf				2.5			2.04				
Ba			30	70	132		61.0				
Th						0.52	0.5				
U					0.51	0.15	0.12				
Pb							0.56				
La			<10	5.5	13		5.3				
Ce							14.4				
Pr							2.0				
Nd							9.6				
Sm				3.6			3.42				
Eu				0.80			0.87				
Gd							4.5				
Tb				0.59			0.73				
Dy							4.55				
Ho							1.1				
Er							2.86				
Tm							0.40				
Yb			4.2	2.2			2.42				
Lu				0.35			0.38				
Li			4.6		7.5						
Be			1.0								
B											
C											
N											
S	1900	700c									
F											
Cl											
Br											
Cu			11a				10.0				
Zn											1.8
(ppb) I											
At											
Ga			4600				4400	3600			
Ge											28
As											
Se											
Mo											
Tc											
Ru											
Rh											
Pd											
Ag											
Cd										2.0	
In										0.36	
Sn							190				
Sb											
Te											
Cs					40						
Ta				400							
W											
Re											
Os											
Ir										0.12	
Pt											
Au										0.27	
He											
Tl											
Bi											
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)

TABLE 15016-1 ctd.

|		,31	,41	,44	,78		,40	,32	,33
Wt %	SiO2				44.26				
	TiO2				2.29				
	Al2O3				8.52				
	FeO				22.93				
	MgO				10.84				
	CaO				9.43			7.1	8.3
	Na2O				0.32				
	K2O				0.05			0.0340	0.036
	P2O5				0.08				
(ppm)	Sc						39.1		
	V								
	Cr				5500		6400		
	Mn				2400				
	Co						54		
	Ni				68				
	Rb			0.879	0.65				
	Sr				93.3				
	Y						23		
	Zr	94.7d,a					86		
	Nb						7		
	Hf	2.53d					2.6		
	Ba								
	Th								
	U			0.160					
	Pb								
	La						5.77		
	Ce						15.6		
	Pr								
	Nd						11.4		
	Sm						4.05		
	Eu						0.970		
	Gd						5.4		
	Tb						0.90		
	Dy						5.74		
	Ho						1.1		
	Er						3.1		
	Tm								
	Yb						2.62		
	Lu						0.321		
	Li								
	Be								
	B								
	C			11					
	N			<2					
	S		860e	790e	400				
	F								
	Cl								
	Br								
	Cu								
	Zn			1.05			<4		
(ppb)	I								
	At								
	Ga					2700	3200		
	Ge			4.38					
	As								
	Se			114					
	Mo								
	Tc								
	Ru								
	Rh								
	Pd			<0.33					
	Ag			0.84					
	Cd			2.05					
	In			0.34					
	Sn			<60					
	Sb			3.8					
	Te			2.4					
	Cs			33.5			29		
	Ta								
	W								
	Re			0.033					
	Os			<0.01					
	Ir			0.018					
	Pt								
	Au			0.025					
	Hg								
	Tl			0.32					
	Bi			0.36					
		(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)

References to Table 15016-1.

References and methods:

(1) Kushiro et al. (1972) conventional
(2) PET (1972), Rhodes and Hubbard (1973) XRF, AAS
(3) Christian et al. (1972); Cuttitta et al. (1973) XRF, etc.
(4) Laul and Schmitt (1973) INAA
(5) Muller (1972,1975) INAA, AAS
(6) O'Kelley et al. (1972a,b,c) GRS
(7) S.R. Taylor et al. (1972,1973) SSMS, ES
(8) Compston et al. (1972) ID, XRF
(9) Janghorbani et al. (1973) NAA
(10) Baedecker et al. (1973) RNAA
(11) Evensen et al. (1973) IDMS
(12) Ehmann and Chyi (1974); Garg and Ehmann (1976) RNAA
(13) Gibson et al. (1975) combustion
(14) Kaplan et al. (1976) combustion
(15) Wolf et al. (1979) RNAA
(16) Chappell et al. (1973) XRF
(17) Helmke et al. (1973) INAA
(18) Husain et al. (1974) from argon isotopes
(19) Kirsten et al. (1973) from argon isotopes
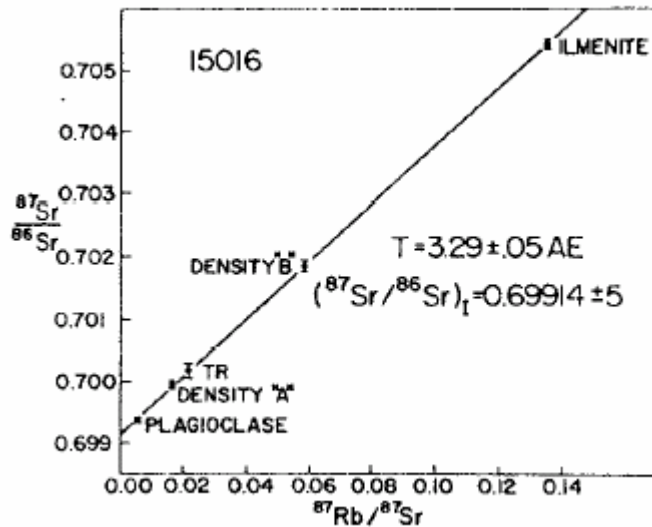
Rb-Sr internal isochron for 15016. TR = total rock;
density "A" = $2.89 < \rho < 2.96$; density "B" = $324 < \rho < 4.1$;
Errors for $^{87}Rb/^{86}Sr$ are $\pm 2\%$; Errors for $^{87}Sr/^{86}Sr$ are notedin Table 1.
Best fit line obtainedby York (1966) type of weighted regression analysis, with 2σ errors.

Figure 7. Rb-Sr isochron (Evensen et al., 1973).

RADIOGENIC ISOTOPES AND GEOCHRONOLOGY: Evensen et al. (1973) measured Rb and Sr isotopes on total rock and mineral separates from 15016, finding an internal isochron age of 3.29 ± 0.05 b.y. and initial $^{87}Sr/^{80}Sr$ of 0.69914 ± 0.0005 (Fig. 7). The whole rock data corresponds with T_{BABI} of 4.27 b.y. after adjusting for inter-laboratory bias (Nyquist et al. (1977). Compston et al. (1972) also measured Rb and Sr isotopes in whole rock samples, finding substantially higher $^{87}Sr/^{86}Sr$ ratios (Table 2) (even when adjusted for inter-laboratory bias). These higher values give substantially older T_{BABI} ages (Nyquist 1977). The duplicate whole rock analyses spread along a 3.3 b.y. isochron.

Kirsten et al. (1973) found a ^{40}Ar-^{39}Ar plateau age of 3.38 ± 0.08 b.y., but no details are given. Husain (1974) on the other hand did not find any consistent plateau from his tabulated data, and 19% of the radiogenic ^{40}Ar was lost (Husain 1972). A K-Ar age of 2.90 ± 0.04 b.y. (Husain 1974) reflects this Ar loss.

Anderson and Hinthorne used an ion probe to measure Pb isotopes on a phosphate, determining an age of 3.75 ± 0.27 b.y.

EXPOSURE: Kirsten et al. (1972) and Husain (1974) determined ^{38}Ar exposure ages of 285 m.y. and 315 m.y. respectively. Eldridge et al. (1972) studied cosmogenic radionuclides; according to Yokoyama et al. (1974) the ^{26}Al is at saturated values, indicating an exposure of at least 2 m.y.

PHYSICAL PROPERTIES: Gose et al. (1972) and Pearce et al. (1973) studied and tabulated the basic magnetic properties (from room temperature hysteresis loops) and NRM of chips of 15016. 15016,28 demagnetized systematically and a stable magnetization is indicated (Fig. 8) but ,29, although it contained no soft component, showed a random scatter of direction. The magnetization gives a low field estimate (e.g., Cisowski et al., 1975).

Charette and Adams (1975) depict a reflectance spectra in the 0.5 to 2.5 micron region which is similar to that for 15555.

PROCESSING AND SUBDIVISIONS: A few small chips were taken, (including ,3 for a potted butt to make thin sections ,5 to ,14) prior to substantial sawing of the rock (Fig. 9). ,0 remains as 601.8 g; ,16 (80.3 g) is in remote storage; and ,20 (64.7 g) was encapsulated for display. Most subsequent splits and allocations were from the two central sawn pieces ,17 and ,19 (Fig. 9). More thin sections were made from ,22 (thin sections ,140 to ,150), and three P.I. made thin sections were from ,47 (thin sections ,157 to ,159).

TABLE 15016-2. Whole Rock Rb-Sr Isotopic Data

Reference	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	I $^{87}Sr/^{86}Sr$
Evensen et al. (1973)	0.0214	0.70016 ± 13	0.69914a
Compston et al. (1972)	0.0233	0.70064 ± 10	0.69954b
Compston et al. (1972)	0.0255	0.70083 ± 10	0.69963b

(a) from isochron
(b) assuming 3.3 b.y. age
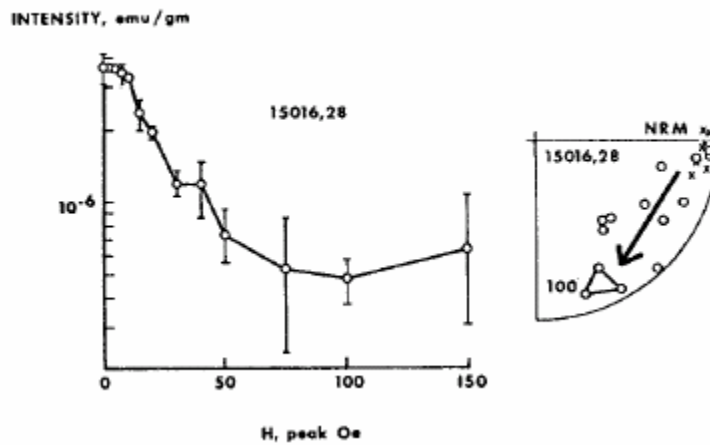
AF demagnetization of 15016.
Arrows show change in direction upon demagnetization.

Figure 8. AF demagnetization (Pearce et al., 1973).
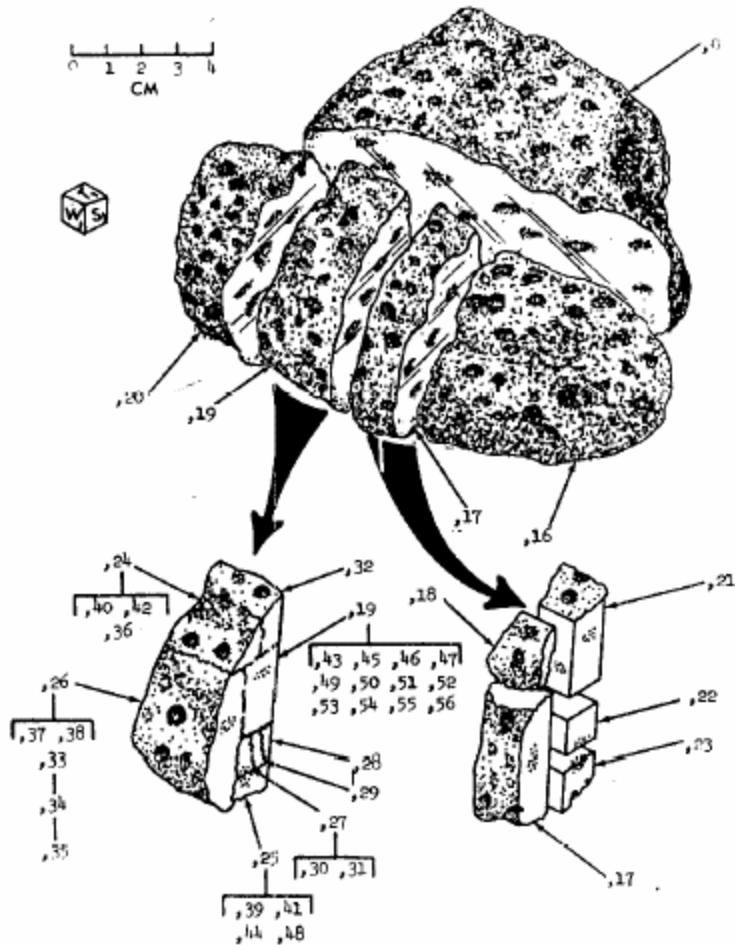
B₁ WORK ORIENTATION (LRL "MUG" PHOTOGRAPHY)

Figure 9. Main sawing and subsplits of 15016.