68415 and 68416

Basaltic Impact Melt

371.2 and 179 grams

Figure 1: 68415 was chipped from top of small boulder or rim of small crater. AS16-108-17697.

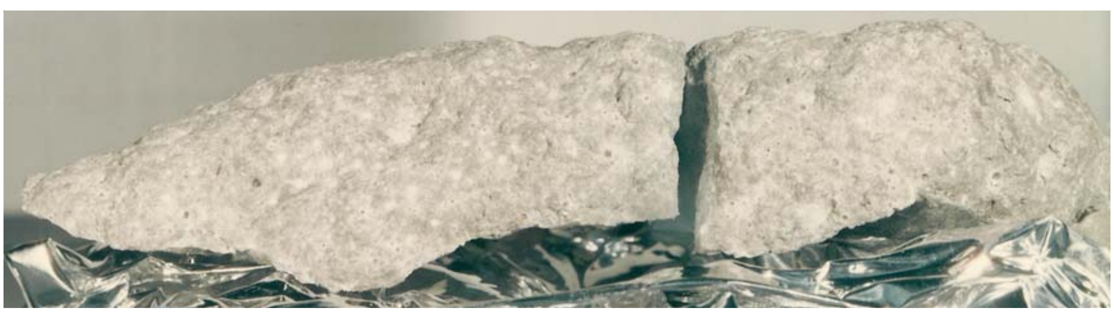


Figure 2: Photo of 68415. Sample is 15 cm long. S72-37351.

Figure 3: Photo of 68416. Sample is 7 cm across. S72-41612.

Introduction

Both 68415 and 68416 were chipped off the top of a 0.5 m boulder on the rim of a 5 m crater within a ray from South Ray Crater (figure 1). These samples were collected adjacent to each other and are found to have similar lithology and composition. The astronauts observed that additional fragments of the same material were present in the immediate area (see transcript).

These samples are highly aluminous (Al_2O_3 = 28%), with basaltic intersertal texture, contain high abundance of meteoritic siderophiles (Ir = 4-5 ppb) and are most likey crystallized impact melt. These rocks have relatively

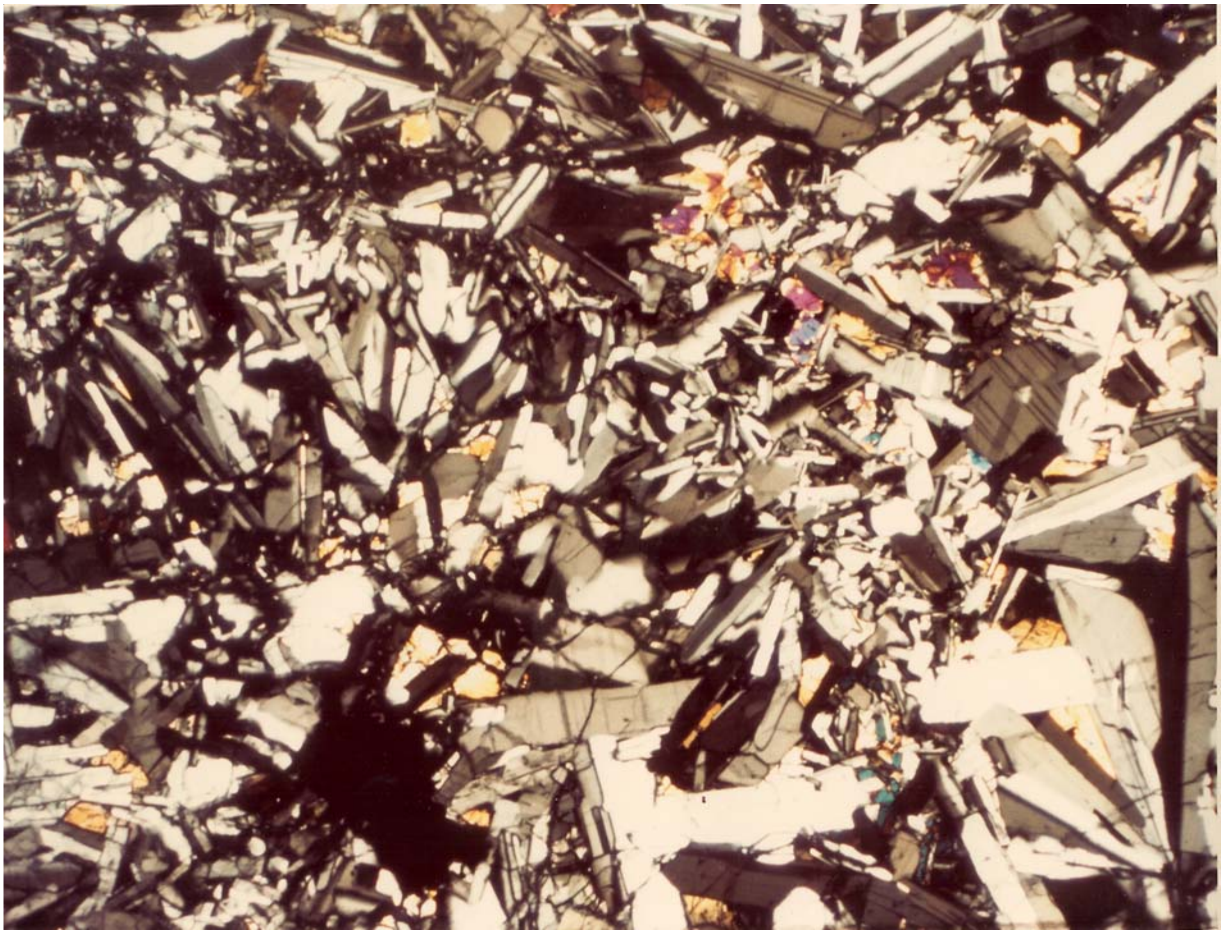


Figure 4: Photomicrograph of thin section of 68415 (crossed polarizers). S72-37351. Scale is unknown. (see also appendix)

low trace element content (Th = 1.2 ppm, Rb = 2 ppm) and very low initial $Sr^{87/86}$ ratio.

The crystallization age of 68415 is 3.76 b.y. (corrected), making it one of the youngest highland rocks dated. It has an exposure age of about 95 m.y., which is too old for it to be from South Ray Crater.

Petrography

Lunar samples 68415 and 68416 have an igneous intersertal texture characterized by a "fret work" of plagioclase laths with interstitial olivine and pyroxene and minor occurances of opaques, phosphates, residual glass and other minerals (Helz and Appleman 1973, Gancarz et al. 1972, Walker et al. 1973, Juan et al. 1973, Brown et al. 1973 and McGee et al. 1977). Figures 2 and 3 show the rock samples, while figure 4 and 5 show the internal texture.

Although the rock appeared at first to be a "holocrystalline igneous rock" (LSPET 1972), or as recrystallized melt, it was reported to have relic xenocrysts of plagioclase (Wilshire et al. 1973) and zones of vesicular material (figure 20). The apparent plagioclase xenocrysts have undulatory extinction, anhedral shape and are Ca-rich (Helz and Appleman 1973). Thus, McGee et al. (1977) classify it as a breccia, while Ryder and Norman (1980) classify it as an impact melt.

Vaniman and Papike (1980) find that 68416 is more coarse-grained than 68415 and has slightly different pyroxene composition and zoning. Irving (1975) reported a difference in the Ni and Co content of metal grains, which are larger in size and more disperse in 68416.

Mineralogy

Plagioclase: The plagioclase in 68415 is nicely twinned and typically normally-zoned An_{98-71}. It forms a "fret work" of anhedral to euhdral laths ranging from 0.1 to several mm in length (average 0.3 mm). Rarely, large anhedral grains of Ca-rich plagiolcase xenocrysts

Figure 5: Photomicrograph of thin section of 68416,6 (crossed polarizers). S72-43652. Scale is unknown.

are found with poorly-developed twinning, with offset fracturing (Helz and Appleman 1973).

Crystallographic phenomena of anorthite in 68415 were investigated by Wenk et al. (1973) and Jagodzinski and Korekawa (1973). Meyer et al. (1974) studied the trace elements in plagioclase.

Pyroxene: Pyroxene in 68415, 68416 is found as small anhedral grains in between the feldspar laths. The chemical composition is plotted in figures 6 and 7. Sample 68416 contains orthopyroxene, while 68415 does not. Brown et al. (1973) reported more high-Ca pyroxene than low-Ca pryoxene.in 68416. Takeda (1973) reported on the lack of inverted pigeonite in 68415. Fe-rich pyroxene is found in the residual glass.

Olivine: Olivine (Fo_{70}) makes up about 2 – 5 % of the mode of 68415. It is found, along with pyroxene, in the interstitual areas.

Residual glass: Minor amounts of residual glass are found in the mesostasis between plagioclase and

CDR Now, how about that rock over yonder?
LMP That's the one I'm going for - - - look at that beauty, John! That is a crystalline rock, no breccia.
CDR A no-breccia, crystalline rock, huh?
LMP And it's whitish to gray, with a lot of zap pits in it.
CDR It even has what look to be – no, those are zap pits, aren't they?
LMP Yeah. In fact, the whole area – there's a lot of the rock here, scatter all over – scattered around.
CDR Where do you want a sample from?
LMP See that sharp corner? Right up at the top there?
\- - -
CDR Well, if that ain't pure plag, I never seen it.
LMP Don't that look like pue plag to you?
CDR I don't know what it is, though.
LMP It's pure feldspar, looks like - -
CDR Pure feldspar. Don't it look like it's been – it's so sandy looking, it could have been reworked or something.
LMP Maybe partially shocked.
CDR Shocked, yeah.
LMP But it's pure plag – it's plag, Tony. And it's in 341. Whack off – another piece right here, John. This rock is pretty predominant.
\- - -
LMP The other piece of that rock is going in 342. I see at least 10 other rocks around here that have that same appearance, so it's not completely anomalous rock.

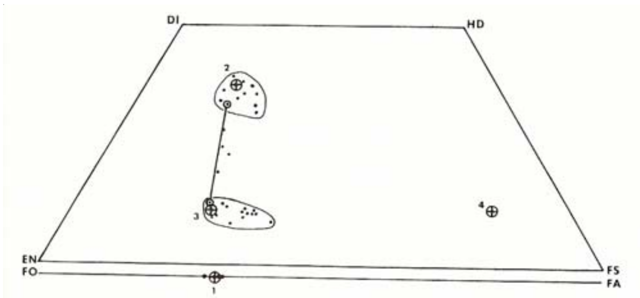


Figure 6: Pyroxene and olivine composition of 68415 (from Helz and Appleman 1973).

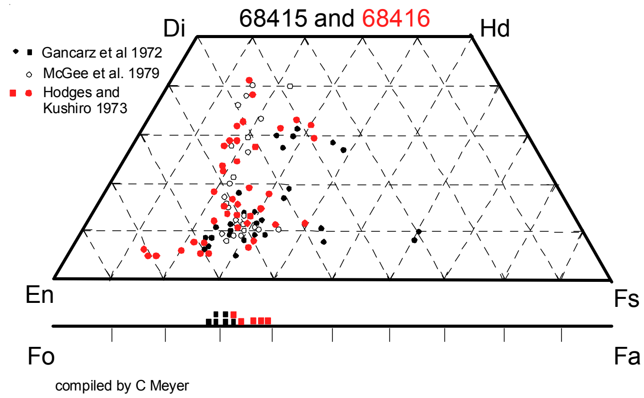


Figure 7: Pyroxene and olivine composition of 68415 (politely lifted from Gancarz, Hodges and Kushiro and McGee).

pyroxene. It is this residual glass that allows Rb/Sr dating. It is Si-rich, but not especially K-rich (Gancarz et al. 1973). A variety of minor phases are found in this residual glass including chromite, cristobalite, troilite, phosphates, armalcolite and an unidentified Y-Zr-rich phase.

Ilmenite: Ilmenite is the main opaque phase (~1%) and occurs as irregularly-shaped grains in association with the residual glass phase.

Metallic iron: Misra and Taylor (1975) and Pearce et al. (1976) found a wide range in Ni and Co content in iron grains in 68415 (figure 8). Hewins and Goldstein (1975) explained this wide range with a fractional crystallization model (figure 9). Irving (1975) showed that the range of Ni and Co content is much wider for 68415 than 68416, probably because the iron grains in 68416 are larger. Hunter and Taylor (1981) reported no rust and only minor amounts of schreibersite in this dense, coherent rock.

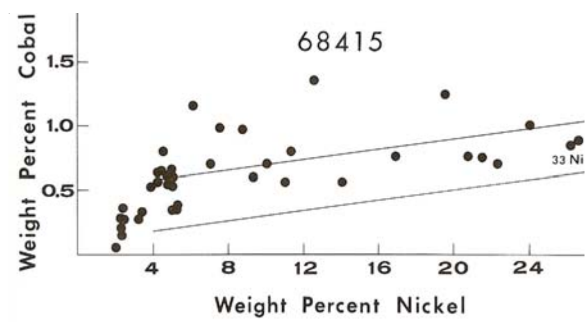


Figure 8: Composition of metallic iron in 68415 (Pearce et al. 1976).

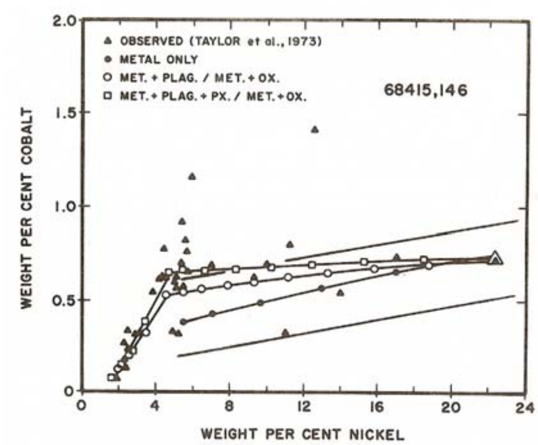


Figure 9: Crystallization path for iron grains in 68415 (Hewins and Goldstein 1975).

Chemistry

Perhaps the most telling attribute of 68415 and 68416 is that they contain significant amounts of meteoritic siderophiles (Ni = 150, Ir = 4, Au = 13), which probably means that these rocks are impact melt rocks, rather than true volcanic liquids from the lunar interior. It is also noteworthy that these rocks are very aluminous

Mineralogical Mode for 68415 (68416)

	Gancarz et al. 1972	Juan et al. 1973	Helz and and Appleman	Brown et al. 1973	Vaniman and Papike 1980
Plagioclase	82%	79	79.3	73	75.5
Pyroxene	12	16	14.7	20	16
Olivine	3	2	4.8	4.5	6.7
Ilmenite	0.1	2		2	0.1
Mesostasis	2.1	1	1		1.9
Metal	0.2				

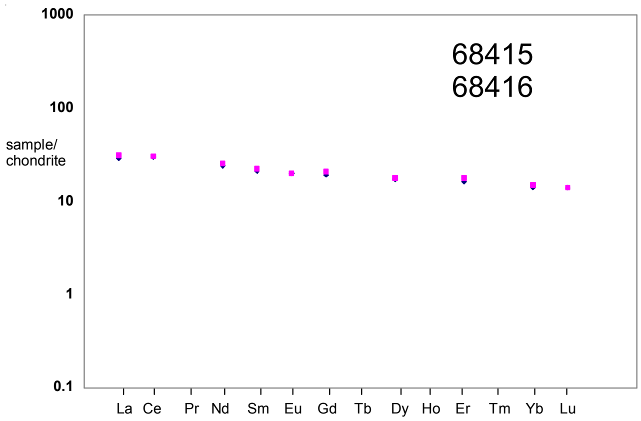


Figure 10: Normalized rare-earth-element diagram of 68415 and 68416 (data by isotope dilution mass spectroscopy, Hubbard et al. 1974).

(Al_2O_3 = 28%), and relatively low in Th (1.2 ppm) and REE (figure 10).

Rancitelli et al. (1973) determined the K, U and Th for the bulk sample (Table 1). Nava (1974), Hubbard et al. (1973), Philpotts et al. (1973), Rose et al. (1973) and Juan et al. (1973) all found consistent results (Tables 1 and 2). Krahenbuhl et al. (1973 and Wasson et al. (1975) also found reasonably consistent results. Jovanovic and Reed (1976) reported analyses for Ru and Os.

Radiogenic age dating

Sample 68415 has been precisely dated at 3.84 ± 0.01 b.y. by the internal Rb/Sr ($lamda_{Rb}$ = 1.39 x 10^{-11} yr^{-1}) isochron technique (Papanastassiou and Wasserburg 1972) and this has been confirmed by a variety of labs (figures 11-16). The initial $Sr^{87/86}$ is extremely low (0.6992).

Reimold et al. (1985) also reported Rb, Sr and Sr isotopes for 68415 and 68416 and dated another sample (67559) of basaltic impact melt at 3.76 b.y. ($lamda_{Rb}$ = 1.42 x 10^{-11} yr^{-1}).

Nunes et al. (1973) and Tera et al. (1973 and 1974) reported U, Th and Pb isotope data (figure 16). The rock contains initial Pb as well as meteoritical Pb in addition to the radiogenic Pb, making interpretation difficult.

Nyquist (1977) discusses the origin of this rock, based on available dating. Maurer et al. (1978) and Norman et al. (2006) dated numerous other Apollo 16 rocks and find correlations of ages with chemistry. If the new decay constant is used ($lamda_{Rb}$ = 1.42 x 10^{-11} yr^{-1}), the age of 68415 is 3.76 b.y., which makes it one of the youngest rocks from the lunar highlands (figure 17)!

The Ar data for plagioclase from 68415 (figure 11) give an older age for two reasons; (a) the plagioclase separate probably included some plagioclase xenocrysts, and (b) recoil effects from adjacent K-rich phases.

Modern ion microprobe analyses of U-rich phases, at high mass resolution, and/or energy filtering should improve on the early results by Anderson and Hinthorne (1973).

Cosmogenic isotopes and exposure ages

Kirsten et al. (1973), Huneke et al. (1973) and Stettler et al. (1973) determined the cosmic ray exposure age by the ^{38}Ar method as 88 m.y, 105 m.y. and 90 m.y. respectively. Drozd et al. (1974) determined the cosmic ray exposure age by ^{81}Kr method as 92.5 ± 5.9 m.y.

Rancitelli et al. (1973) determined the cosmic-ray-induced activity of both 68415 and 68416 as ^{22}Na = 46, or 41 dpm/kg; and ^{27}Al = 156, or 160 dpm/kg, respectively, and is considered "saturated".

Other Studies

Walker et al. (1973), Ford et al. (1974) and Muan et al. (1974) reported on experiments with 68415 composition and Walker et al. produced a "phase diagram" (figure 18). The low-pressure liquidus is above 1400 deg C. But since this rock in not a true volcanic liquid, the high pressure experiments seem to have no application.

Morrison et al. (1973) and Neukum et al. (1973) reported on the density distribution of micrometeorite craters (zap pits) as function of crater size on surfaces of 68415 (figure 23). Behrmann et al. (1973) reported cosmic ray track data.

Mossbauer spectra were presented by Huffman et al. (1974), Schwerer et al. (1973) and Abu-Eid et al. (1973).

Clayton et al. (1973) reported oxygen isotopes in bulk rock and mineral seperates.

Table 1. Chemical composition of 68415.

reference	LSPET73		Bansal 72		Rose73		Philpotts73			Nava74		Krahenbuhl73		Wasson75		Rancitelli73	
weight			Hubbard74														
SiO2 %	45.4	(a)	45.4	(a)	45.3	(d)				45.9	(f)						
TiO2	0.32	(a)	0.32	(a)	0.29	(d)				0.28	(f)						
Al2O3	28.63	(a)	28.63	(a)	28.7	(d)				28.19	(f)						
FeO	4.25	(a)	4.25	(a)	4.12	(d)				4.01	(f)						
MnO	0.06	(a)	0.06		0.05	(d)				0.048	(f)						
MgO	4.38	(a)	4.38	(a)	4.35	(d)				4.41	(f)						
CaO	16.39	(a)	16.39	(a)	16.2	(d)				16.39	(f)						
Na2O	0.41	(a)	0.41	(b)	0.5	(d)				0.47	(f)						
K2O	0.068	(a)	0.068	(b)	0.09	(d)	0.06	0.06	(b)	0.06	(f)					0.11	(e)
P2O5					0.06	(d)				0.072	(f)						
S %			0.04														
sum																	
Sc ppm					8.2	(d)											
V					20	(d)											
Cr	710	(a)								479	(f)						
Co					11	(d)											
Ni	49	(a)			184	(d)						165	(c)	140	(c)		
Cu					12	(d)											
Zn					4	(d)						4.8	(c)	1.47	(c)		
Ga					2	(d)								2.99	(c)		
Ge ppb												73	(c)	98	(c)		
As																	
Se												98	(c)				
Rb	2.1	(a)	1.7	(b)	1.9	(d)	1.47	1.5	(b)			1.1	(c)				
Sr	185	(a)	182	(b)	140	(d)	180	180	(b)								
Y	23	(a)			21	(d)											
Zr	98	(a)	97.5	(b)	72	(d)		94.5	(b)								
Nb	5.6	(a)															
Mo																	
Ru																	
Rh																	
Pd ppb																	
Ag ppb												4.8	(c)				
Cd ppb												2.75	(c)	1	(c)		
In ppb														11	(c)		
Sn ppb																	
Sb ppb												0.53	(c)				
Te ppb												13.5	(c)				
Cs ppm												0.051	(c)				
Ba			76.2	(b)	70	(d)	71.6	73.4	(b)								
La			6.81	(b)													
Ce			18.3	(b)			16.3	15.7	(b)								
Pr																	
Nd			10.9	(b)			9.92	10	(b)								
Sm			3.08	(b)			2.88	2.84	(b)								
Eu			1.11	(b)			1.13	1.13	(b)								
Gd			3.78	(b)				3.27	(b)								
Tb																	
Dy			4.18	(b)			3.62	3.81	(b)								
Ho																	
Er			2.57	(b)			2.18	2.08	(b)								
Tm																	
Yb			2.29	(b)	2	(d)	2.02	1.97	(b)								
Lu			0.34	(b)			0.33		(b)								
Hf			2.4	(b)													
Ta																	
W ppb																	
Re ppb												0.434	(c)				
Os ppb																	
Ir ppb												4.58	(c)	5.6	(c)		
Pt ppb																	
Au ppb												2.65	(c)	2.8	(c)		
Th ppm	2.2	(a)	1.26	(b)												1.29	(e)
U ppm			0.32	(b)								0.175	(c)			0.32	(e)

technique: (a) XRF, (b) IDMS, (c) RNAA, (d) 'microchemical', (e) radiation counting, (f) AA and colormetric

Table 2. Chemical composition of 68416.

reference	Hubbard74		Rose73		Rancitelli73		Juan 73		68415	
weight	Wiesmann76								other	
SiO2 %	45.04	(a)	45.6	(b)			45.1	(d)		
TiO2	0.33	(a)	0.3	(b)			0.31	(d)		
Al2O3	28.75	(a)	28.4	(b)			28.5	(d)		
FeO	4.27	(a)	4.22	(b)			4.4	(d)		
MnO	0.07	(a)	0.06	(b)			0.06	(d)		
MgO	4.49	(a)	4.64	(b)			4.6	(d)		
CaO	16.31	(a)	16.32	(b)			16	(d)		
Na2O	0.34	(a)	0.44	(b)			0.48	(d)		
K2O	0.08	(a)	0.08	(b)	0.096	(c)	0.071	(d)		
P2O5	0.08	(a)	0.07	(b)						
S %	0.05	(a)								
sum										
Sc ppm			9.2	(b)						
V			21	(b)						
Cr	683	(d)					750	(d)		
Co			10	(b)			40	(d)		
Ni			205	(b)			147	(d)		
Cu			14	(b)			7	(d)		
Zn							30	(d)		
Ga			1.7	(b)						
Ge ppb										
As										
Se									Compston77	
Rb	1.7	(d)					2.4	(d)	1.61	1.43
Sr			170	(b)			190	(d)	166	147
Y			21	(b)						
Zr			80	(b)						
Nb			10	(b)						
Mo									Jovanovic76	
Ru									10	
Rh										
Pd ppb										
Ag ppb										
Cd ppb										
In ppb										
Sn ppb										
Sb ppb										
Te ppb										
Cs ppm										
Ba	78.2	(d)	76	(b)						
La	7.24	(d)								
Ce	18.4	(d)								
Pr										
Nd	11.5	(d)								
Sm	3.28	(d)								
Eu	1.11	(d)								
Gd	4.07	(d)								
Tb										
Dy	4.29	(d)								
Ho										
Er	2.86	(d)								
Tm										
Yb	2.42	(d)	1.8	(b)						
Lu										
Hf										
Ta										
W ppb										
Re ppb									Jovanovic76	
Os ppb									2.8	
Ir ppb										
Pt ppb										
Au ppb									Nunes73	
Th ppm					1.24	(c)			1.26	1.18
U ppm	0.34	(d)			0.34	(c)			0.356	0.345

technique: (a) XRF, (b) 'microchemical', (c) radiation counting, (d) AA and colormetric, (e) IDMS

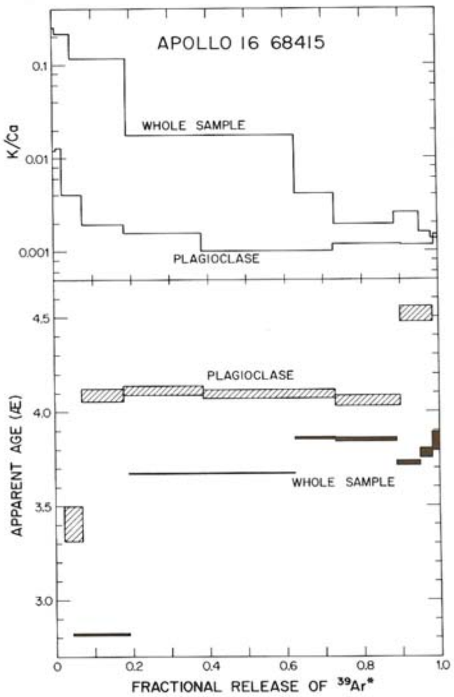


Figure 11: Ar/Ar plateau diagram for 68415 (Huenke et al. 1973).

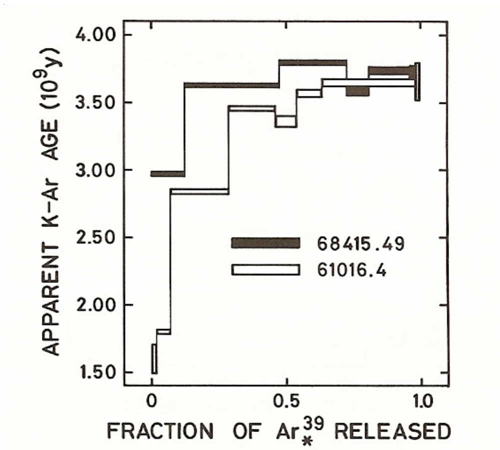


Figure 12: Ar release diagram for Apollo 16 rocks (Stettler et al. 1973).

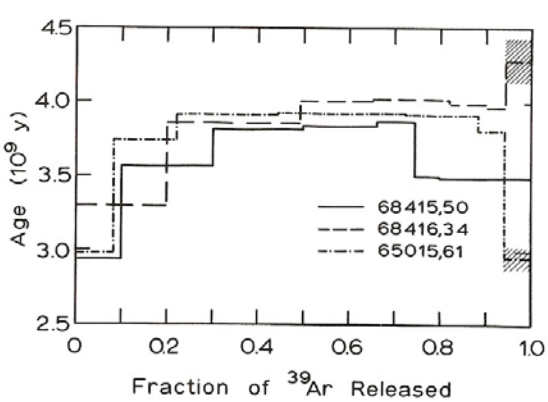


Figure 13: Ar release diagram of Apollo 16 samples (Kirsten et al. 1973).

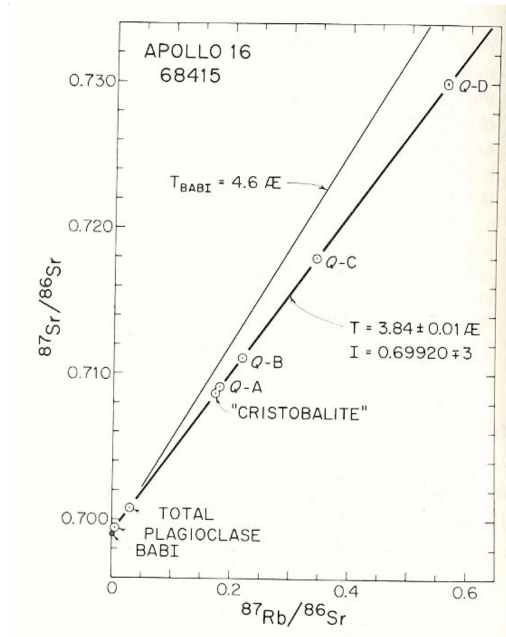


Figure 14: Internal Rb/Sr isochron diagram for 68415 (Papanastassiou and Wasserburg 1972).

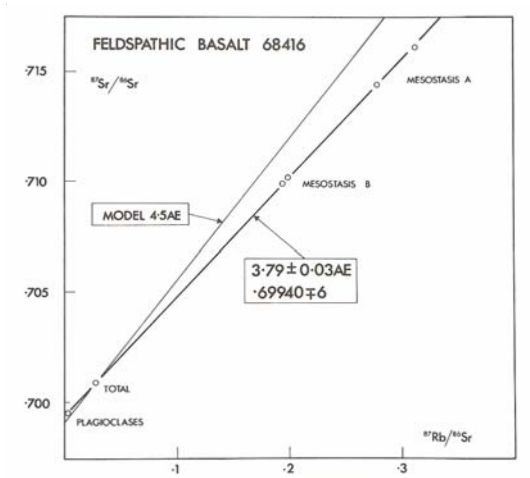


Figure 15: Internal Rb/Sr isochron diagram for 68416 (Compston et al. 1977).

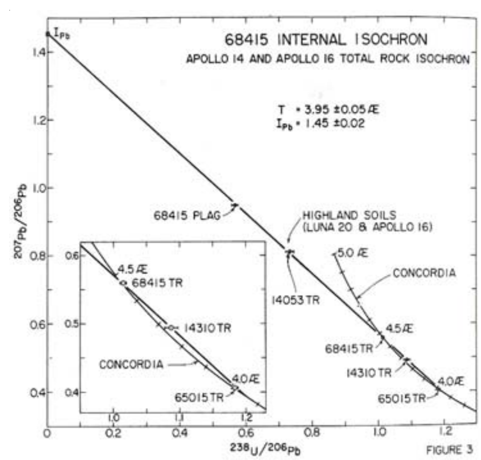


Figure 16: Internal U/Pb isochron diagram for 68415 (Tera et al. 1973).

Summary of Age Data for 68415 and 68416

	Ar/Ar	Rb/Sr	U/Pb	Pb/Pb
Huneke et al. 1973	3.85 ± 0.04 b.y.			
Huneke et al. 1973 (plag)	4.09			
Kirsten et al. 1973	3.85 ± 0.06			
Stettler et al. 1973	3.80 ± 0.04			
Papanastassiou and Wasserburg 1972		3.84 ± 0.01		
Tera et al. 1973			3.95 ± 0.05	
Anderson and Hinthorne 1973		phosphate		3.96 ± 0.18
		Zr-phase		3.96 ± 0.28

Caution: Beware change in decay constants.

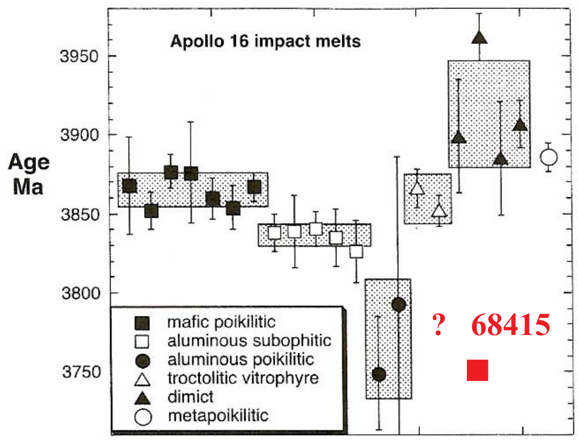


Figure 17: Age of 68415 plotted on summary diagram of Norman et al. 2006 (68415 corrected for modern decay constants)..

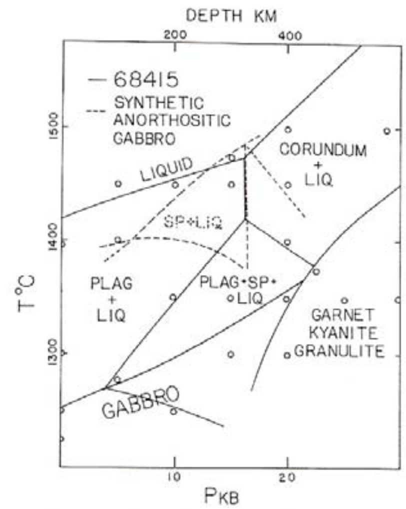


Figure 18: Experimental phase diagram for 68415 (Walker et al. 1973).

Collinson et al. (1973), Nagata et al. (1973), Pearce et al. (1973), Stephenson et al. (1974) and Brecker (1977) reported on magnetic experiments and remanent magnetism.

Todd et al. (1973) and Wang et al. (1973) studied the sound velocity and importance of microcracks.

Tsay and Live (1976) and Tsay and Bauman (1977) used electron spin resonance to identify Fe^{3+} in plagioclase.

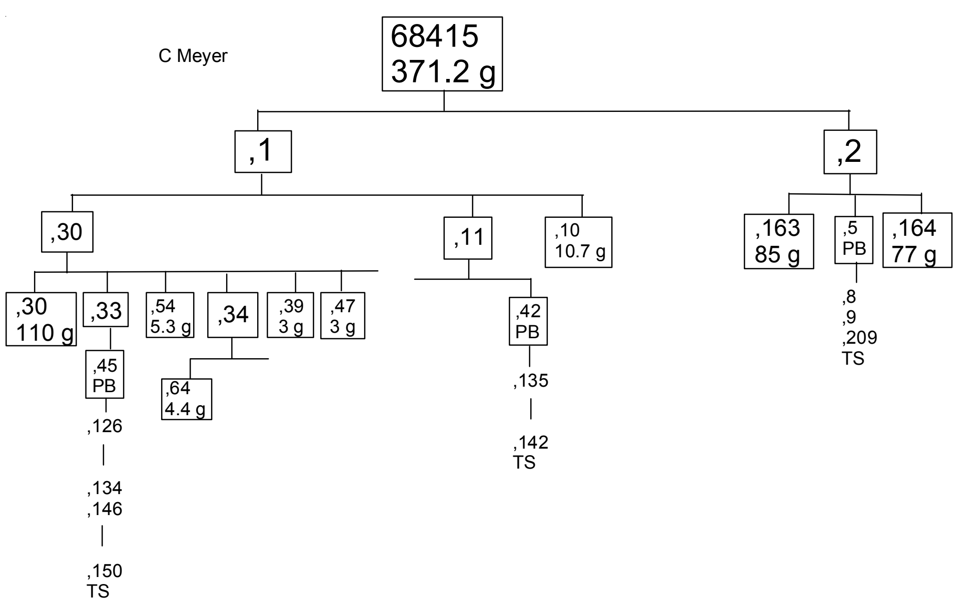


Figure 19: Location of saw cut in 68415,2. S75-32781. Cube is 1 inch.

Figure 20: Sawn surface of 68415,2. S75-32778. Sample is about 5 cm across.

Processing

Although the lunar orientation of these samples is well known by surface photography, they have apparently not be used for cosmic ray depth profiles (they aren't very thick).

68415 was returned as two pieces (figure 2). Part 1 of 68415 was cut into columns, while part 2 was cut in half (figures 19 and 20). 68416 was also sawn in half and one half (,9) was broken into many pieces (figure 21). There are 26 thin sections of 68415 and 13 sections of 68416.

Ryder and Norman (1980) and Taylor et al. (1991) give lenghty reviews of all the data on 68415 and 68416 (*not a lot of work has been done since)*. Four large pieces, each about 100 grams, and numerous small pieces, are still available for research. Additional samples of other highly aluminous impact melt are also available.

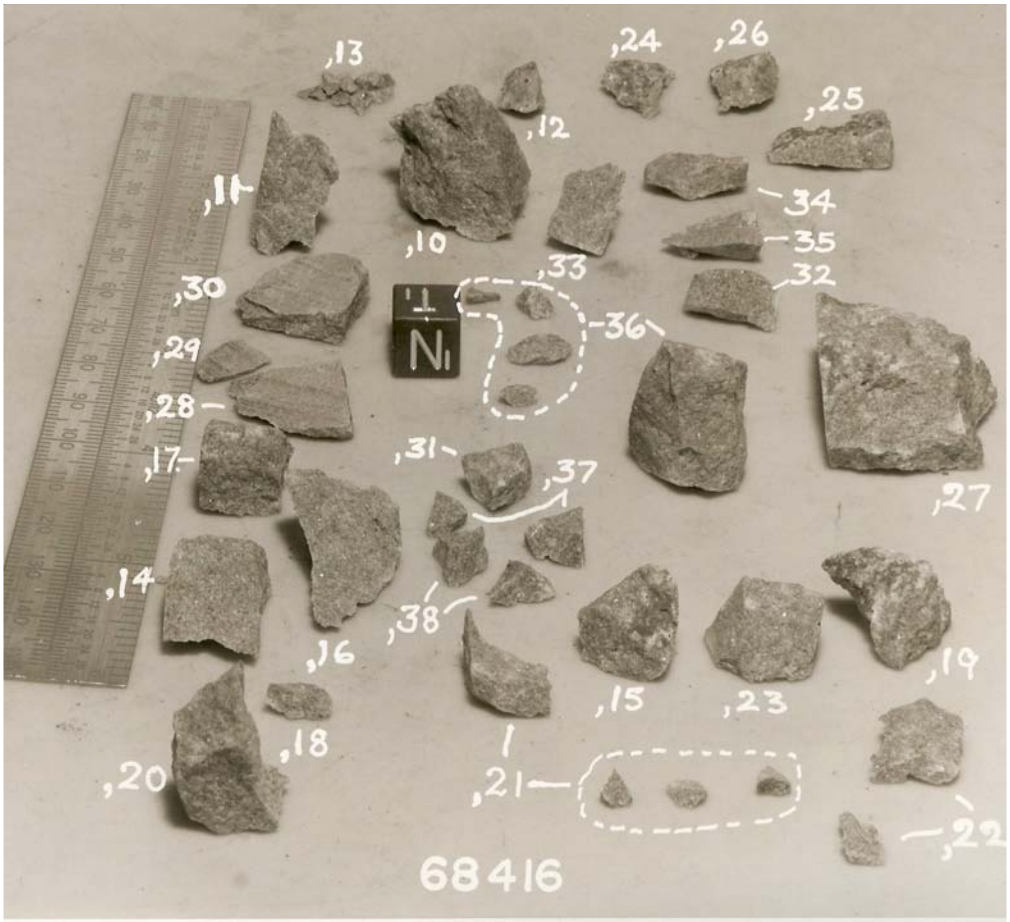
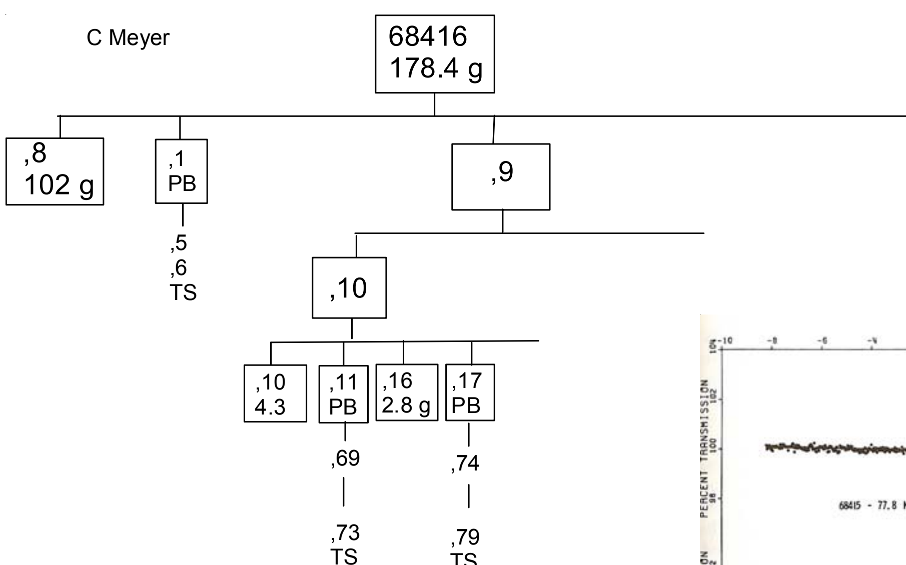


Figure 21: Exploded parts diagram for 68416,9. NASA S72-53520. Cube is 1 cm.



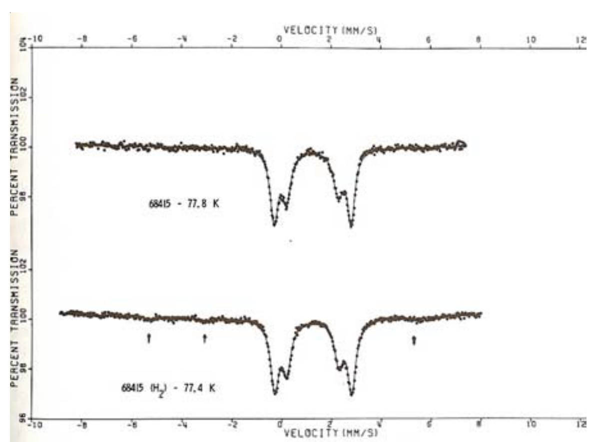


Figure 22: Mossbauer spectra of 68415 (from Schwerer et al. 1973).

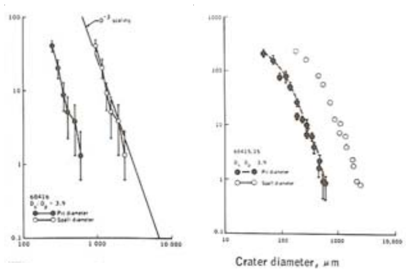


Figure 23: Crater density curves for zap pits on 68416 and 68415 (Morrison et al. 1973).

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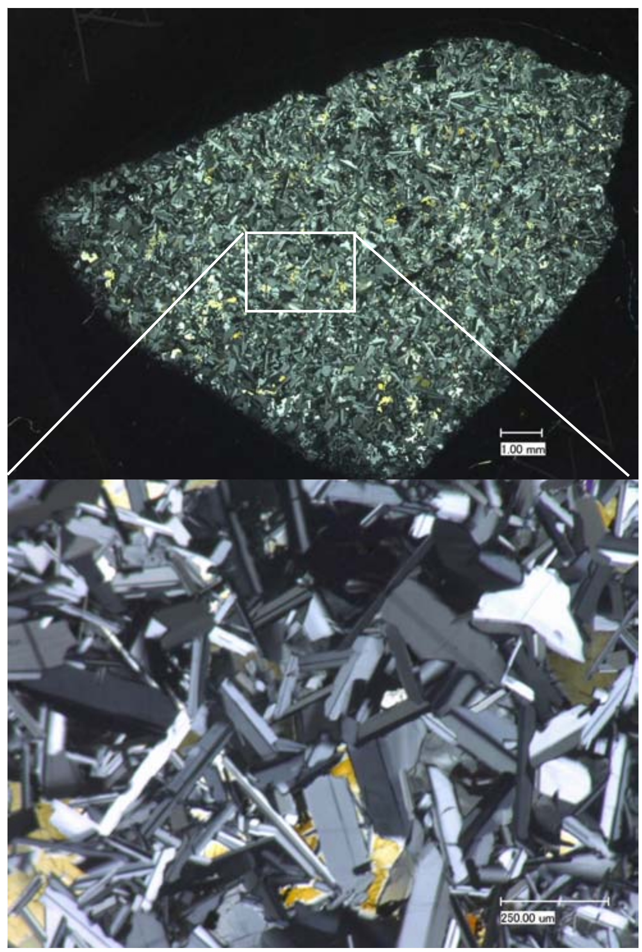

Apendix: Photomicrographs with cross nicols of thin section 68415,127 takne by C Meyer @20x and 200x.