72415

Cataclastic Dunite
St. 2, 32.34 g

INTRODUCTION

72415 is a complexly cataclasized dunite that was collected, along with 72416, 72417, and 72418, to sample a 10 cm clast in the impact melt matrix of Boulder 3, Station 2 (see section on Boulder 3, Station 2, Fig. 1). It was originally a coarse-grained igneous rock consisting mainly of magnesian olivine. Pb isotopic data suggest an igneous age of between 4.37 and 4.52 Ga, in agreement with strontium isotopic analyses of paired sample 72417, which suggest that the dunite crystallized 4.45 Ga ago. It has since suffered a complex history of deformation and excavation. 72415 is a slabby sample consisting of two homogeneous matched pieces (Fig. 1), originally labelled A and B. Zap pits and a patina are prevalent on the lunar-exposed surfaces of 72415.

The two pieces of 72415 are each about 4 x 2 x 0.8 cm, and pale yellowish to greenish gray (5Y 8/1 to 5GY 8/1). Although the sample appeared to break easily in the lunar sampling, it is tough, and the ease of sampling was a result of a few penetrative fractures. Macroscopically the sample consists of about 30% pale yellow green olivines larger than a millimeter, set in a matrix (65%) of mainly similarly-colored material that is less than 1 mm (mainly less than 0.1 mm) in grain size. A few of the larger grains appear more grayish, others reddish. In thin section the sample is dominantly olivine with varied aspects of deformation, with some plagioclase, pyroxenes, and Cr-spinel.

Many but not all of the studies of 72415 were conducted under a loosely-knit consortium led by the Caltech group (e.g. Dymek et at., 1975b). Following allocation of small undocumented and documented chips, piece A, the thicker of the two, was sawn in 1974 to produce several pieces for study. Subsequently several other small pieces were taken from varied locations of both piece A and piece B.

Figure 1: Two matching pieces of 72415 prior to sampling or sawing. Clasts larger than I mm are visible. Cube has 1 cm sides. S-73-16199.

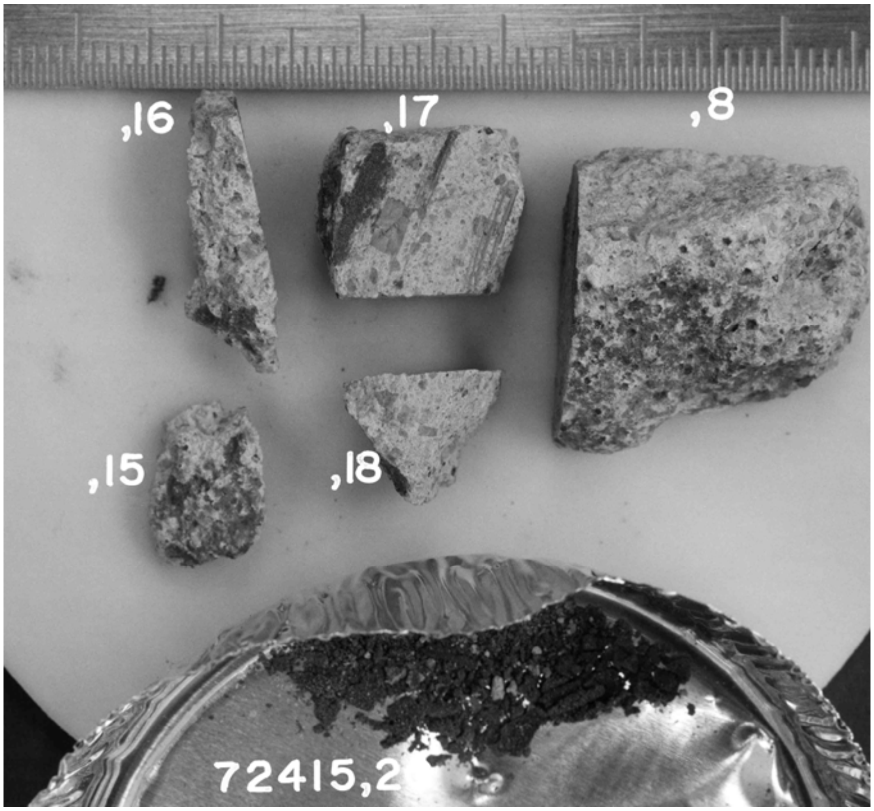


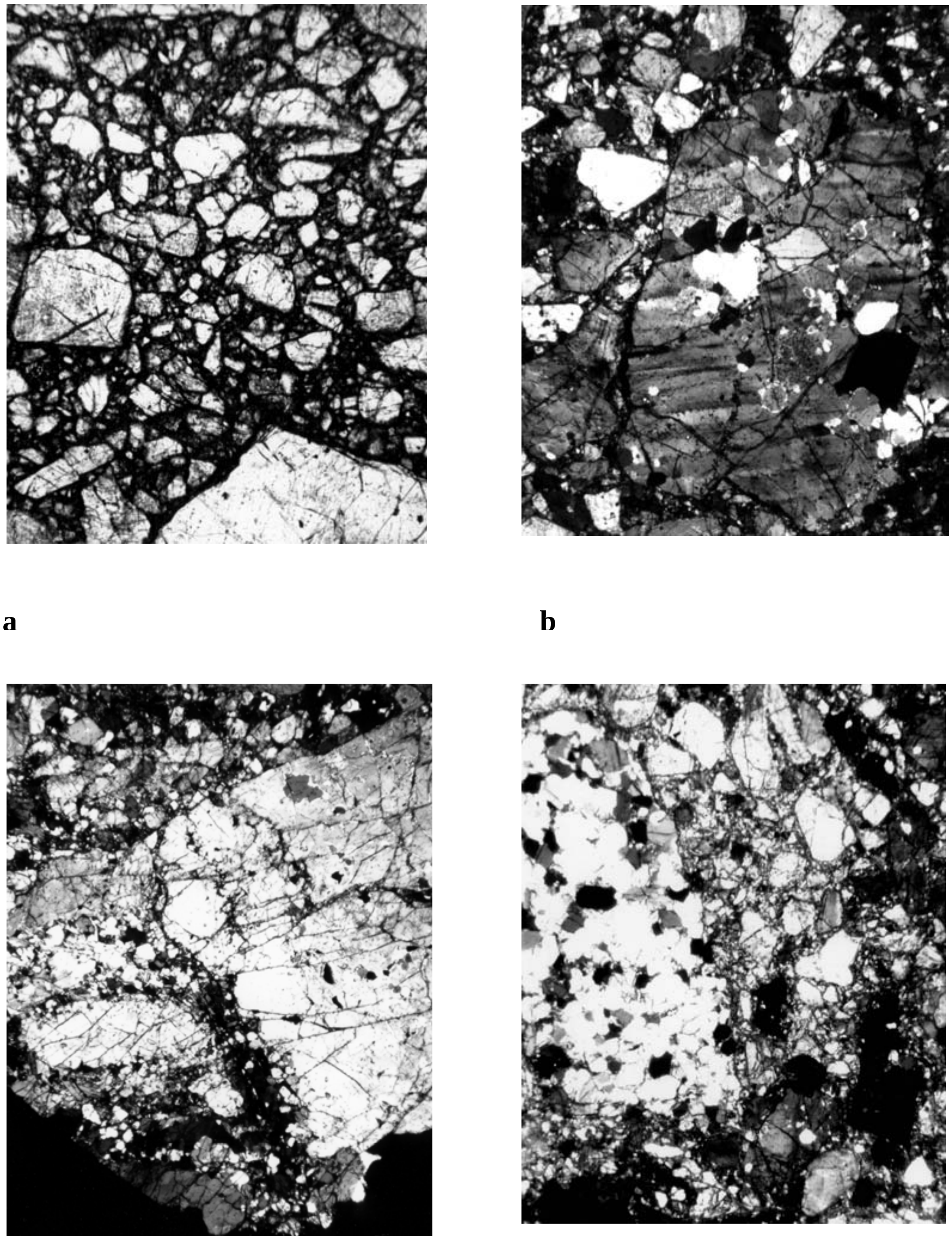
Figure 2: Sawing of one of the main pieces of 72415. An end piece was sawn first, and divided to give, 15 and, 16. A second cut produced a slab that was sawn across to produce, 17 and, 18; the latter was made into thin sections. S74-19014.

PETROGRAPHY

72415 is a cataclasized dunite (LSPET,1973; Albee et al., 1974a, 1975; Simonds et al., 1974; Stoffler et al., 1979; Ryder 1992x). The Caltech consortium described the petrography of 72415 and 72417 in detail (Albee et al., 1974a, 1975; Dymek et al., 1975b), providing photomicrographs and microprobe data. Because the two samples appear to be virtually identical, the descriptions do not always distinguish them. Most of the thin sections were from 72415 and show a complex history of deformation following original crystallization (Fig. 3).

The mineralogy of the sample was summarized by Dymek et al. (1975b) (Table 1). It consists of 93% olivine, with small amounts of other silicates, and trace amounts of Cr-spinel and metal; there is also extremely rare troilite, whitlockite, and Cr-Zr armalcolite. The abundance of plagioclase varies significantly among thin sections. The dunite is about 60% angular to subangular clasts of single crystals of olivine up to 10 mm across in a fine-grained matrix that is dominantly olivine (Fig. 3a).The existing texture results mainly from cataclastic crushing, and not from recrystallization at the microscopic scale. Many clasts show subgrains and strain bands (Figs. 3b,c), and many show inclusions that give a cloudy appearance. Some clasts are poygonalized olivine (Fig. 3d). Sparse symplectites consist mainly of chromite and pyroxenes. Fairly common veinlets cutting olivines contain plagioclases as well as olivines. Inclusions, microsymplectites, shock and recrystallization features of olivines, strain bands, and relict grain boundaries are truncated by the cataclasis, showing that they existed prior to that event. On the basis of the mineralogy, James and Flohr (1982) and James et al. (1982) suggested that the sample was related to Mg-norites rather than Mg-gabbronorites, but the evidence was not conclusive. The injection of feldspar-rich material of uncertain source was a factor contributing to the problem.

The compositions of silicate and oxide minerals in 72415 and 72417 are shown in Figure 4, and metal compositions in Figure 5 (Dymek et al., 1975b). The olivines show a small range in composition from F086-89, with no systematic variation with petrography. This range was confirmed by Bell et al. (1975). LSPEf (1973) gave a range of F0SS-90 but this is not confirmed by others. Ryder (1984, 1992x) showed that that individual grains were different and zoned over distances of two to three millimeters, and that the range was wider than in dunites from terrestrial plutonic cumulates, the Marjalahti pallasite, or troctolite



a **b** **c** **d**

Figure 3: Photomicrographs of 72415,28 (a,d) and 72415,25 (b,c). All about 1 mm width of view, all crossed polarizers except a) plane transmitted light. a) General view of cataclastic matrix, with olivine clasts in an olivine matrix. Olivines show inclusions and cloudiness, subangular shapes, and varied sizes. b) larger olivine clad showing presence of subgrains and deformation bands. c) larger olivine clast showing subgrains and a veinlet system (mainly lathy plagioclase + olivine). d) general matrix showing lithic class to left of polygonalized olivine.

76535 (Figs. 6 and 7). He also showed that the calcium in olivines had a substantial range and was higher than in 76535. The zoning is concluded to be an original igneous feature, not a deformation-related one. These data suggest a cooling rate faster than is consistent with deep plutonic processes i.e. shallow cumulate processes.

Ryder (1983) and Bersch (1990) analyzed Ni in the olivines, showing a range from 220-70 ppm, and higher than in 76535 olivines. Bersch (1990) also analyzed precisely for other minor elements in olivines.

The composition of plagioclases varies with petrography, with felty plagioclases tending to be the most calcic (An_{94-97}), laths zoned from An_{94-95}, and plagioclase associated with symplectites the most sodic (An_{91-89})(Fig. 4). That associated with recrystallized olivines covers a wide range (An_{95-89})• The pyroxene also varies with petrography (Fig. 4). Those with higher Ca abundances are probably real, not mixtures. The chrome-spinel has a restricted composition (Fig. 4), but that in symplectites is more iron-rich. The metal grains contain high Ni and Cc (Fig. 5; data also presented in Dymek et al.,1976a); Ryder et al.. (1980a) obtained even higher Ni abundances of 36 to 370. Analyses of silicate phases by Richter et al (1976a) are similar to those of Dymek et al. (1975b).

The symplectites consist of mainly of Cr-spinel and high-Ca pyroxene; low-Ca pyroxene, olivine, plagioclase, and metal are present in some (Dymek et al., 1975b). Their textures range from granular to vermicular. Albee et al. (1974a, 1975) and Dymek et al. (1975b) interpret these intergrowths as late-stage magmatic products, not solid-state reaction products. Bell and Mao (1975) and Bell et al. (1975) described these symplectites as rosettes, and tabulated bulk compositions derived from microprobe data (Table 2). They

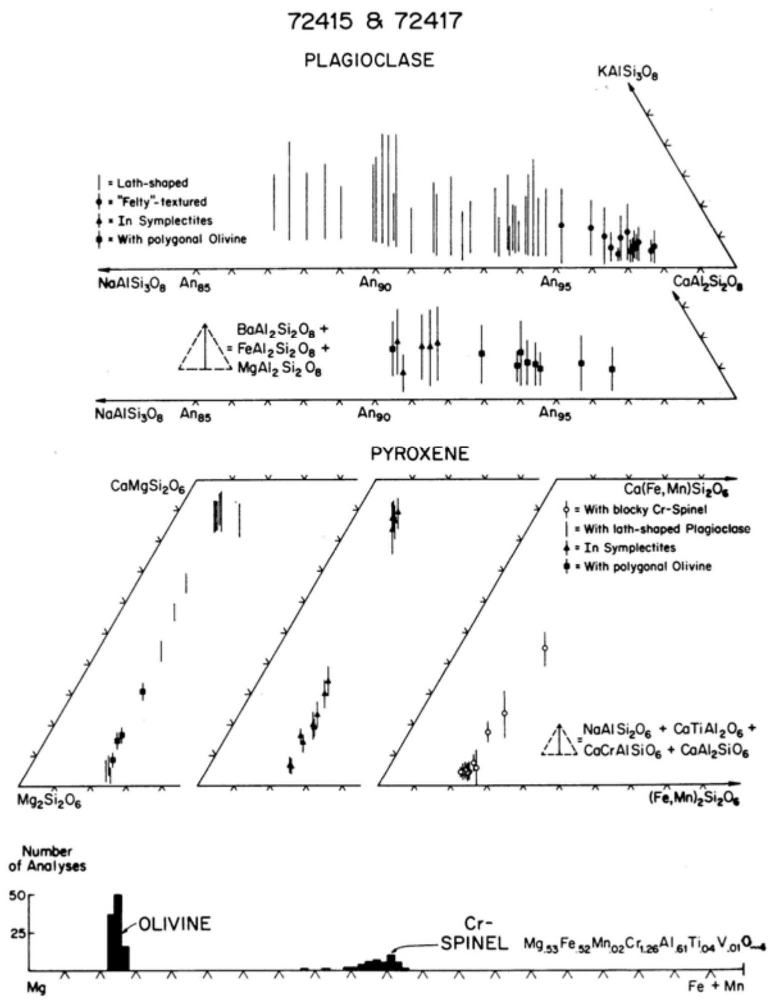


Figure 4: Compositions of silicate minerals and chrome-spinel in 72415 and 72417 (Dymek et al., 1975b).

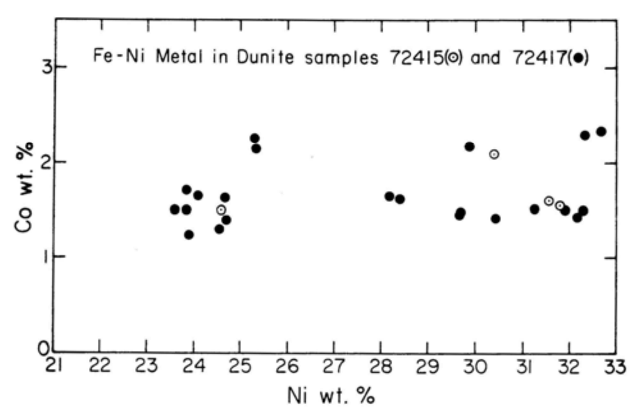


Figure 5: Ni and Co in metal grains in 72415 and 72417 (Dymek et al., 1975b).

Table 1: Phase abundances, "average" phase compositions, and bulk chemical composition, derived from microprobe point counts, of 72415 and 72417 (Dymek et al., 1975b).

	Plag.	Low-Ca pyx	High-Ca pyx	Olivine	Cr-spinel	Metal*	Bulk composition	
Vol.%	4.0_3	2.1_8	1.0_2	92.5_2	0.1_9	0.0_7	Calculated	LSPET,
Wt.%	3.3_5	2.1_7	1.0_0	93.0_4	0.2_6	0.1_7	(4641 Points)	1973
SiO_2	44.79	56.05	54.13	40.24	0.04	0.05	40.70	39.93
TiO_2	< 0.01	0.28	0.11	0.02	1.05	< 0.01	0.03	0.03
Al_2O_3	35.00	0.96	1.22	< 0.01	16.71	n.a.	1.25	1.53
Cr_2O_3	n.a.	0.26	1.11	0.04	51.81	0.54	0.19	0.34
MgO	0.23	32.29	18.40	47.65	10.60	0.01	45.24	43.61
FeO	0.14	6.94	2.71	12.29	19.27	67.65	11.82	11.34
MnO	n.a.	0.15	0.11	0.13	0.58	0.02	0.13	0.13
CaO	19.25	2.24	22.50	0.13	n.a.	0.01	1.04	1.14
Na_2O	0.62	0.01	0.05	n.a.	n.a.	n.a.	0.02	< 0.02
K_2O	0.09	n.a.	n.a.	n.a.	n.a.	n.a.	0.00_3	0.00
BaO	0.04	n.a.	n.a.	n.a.	n.a.	n.a.	< 0.01	—
ZrO_2	n.a.	n.a.	n.a.	n.a.	< 0.01	n.a.	< 0.01	< 0.01
V_2O_3	n.a.	n.a.	n.a.	n.a.	0.37	n.a.	< 0.01	—
Nb_2O_5	n.a.	n.a.	n.a.	n.a.	0.05	n.a.	< 0.01	< 0.01
NiO	n.a.	n.a.	n.a.	< 0.01	n.a.	30.42	0.07	0.02
Co	n.a.	n.a.	n.a.	n.a.	n.a.	1.42	< 0.01	—
Total	100.16	99.18	100.34	100.50	100.48	100.14†	100.49	98.07
	An 92.0	Wo 3.0	Wo 41.7	Fo 87.2				
	Ab 5.4	En 84.2	En 49.7	Fa 21.8				
	Or 0.5	Fs 10.4	Fs 4.3					
	Others 2.1	2.4	4.3					

*Elemental abundances, converted to oxides for bulk-composition calculation.
†Includes 0.02 wt.% P.
n.a. = not analyzed.

Table 2: Microprobe analyses in weight % of symplectites in 72415 (Bell et al., 1975). Each analysis is the average of four or five separate analyses made within single symplectites that average 30 microns diameter.

	No.	1	2	8	9	10	12	13	Host olivine
R^{1+}	Na_2O	0.16	0.01	0.00	0.00	0.05	0.01	0.00	0.00
R^{2+}	MgO	16.06	24.72	24.30	19.07	17.80	17.95	21.68	47.52
	FeO	8.17	9.83	9.32	8.29	7.84	8.10	8.21	11.48
	NiO	0.00	0.00	0.00	0.02	0.04	0.04	0.03	0.00
	CaO	14.75	5.36	6.90	12.91	14.55	12.22	12.61	0.12
	MnO	0.21	0.11	0.12	0.13	0.09	0.11	0.04	0.12
R^{3+}	Cr_2O_3	18.02	15.95	15.48	15.90	16.12	17.04	14.23	0.08
	Al_2O_3	4.61	3.97	4.16	4.48	4.13	5.36	3.80	0.00
R^{4+}	SiO_2	37.13	39.59	39.39	38.12	38.05	38.45	38.39	40.71
	TiO_2	0.46	0.30	0.41	0.34	0.32	0.22	0.17	0.01
	Arithmetic total	99.58	99.83	100.09	99.26	98.99	99.50	99.14	100.04

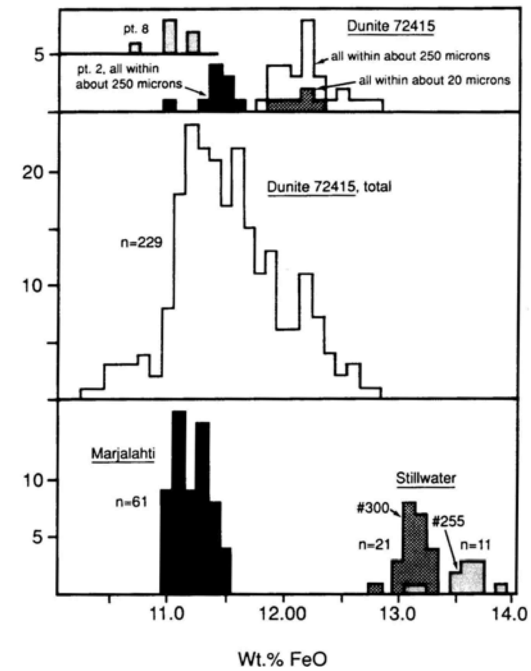


Figure 6: Variation in olivine compositions expressed as FeO wt% in samples of dunite 72415, two Stillwater troctolites, and Marjalahti. Ryder (1992a).

described their detailed occurrences. Bell and Mao (1975) concluded that the bulk compositions of symplectites were equivalent to garnet, and that the symplectites (and the dunite) had formed at high-pressure. Bell et al. (1975) included authors with differing interpretations, although all disagreed with the Dymek et al. (1975b) interpretation of late-stage magmatic products. Two authors continued to prefer the garnet hypothesis, comparing the observations with high-pressure experimental products; two preferred an origin from the diffusion of elements from olivine.

Dymek et al. (1975b) outlined the history of the dunite on the basis of the deformation features and superposition. The isotopic data (for 72417) suggest an early igneous origin, with little subsequent disturbance of the isotopic system. Nonetheless, petrographically the sample underwent a complex history. The primary differentiation produced a coarse plutonic cumulate, with olivine and Cr-spinel crystallizing prior to plagioclase, then Cr-spinel, pyroxenes, plagioclase, and metal crystallized from trapped interstitial

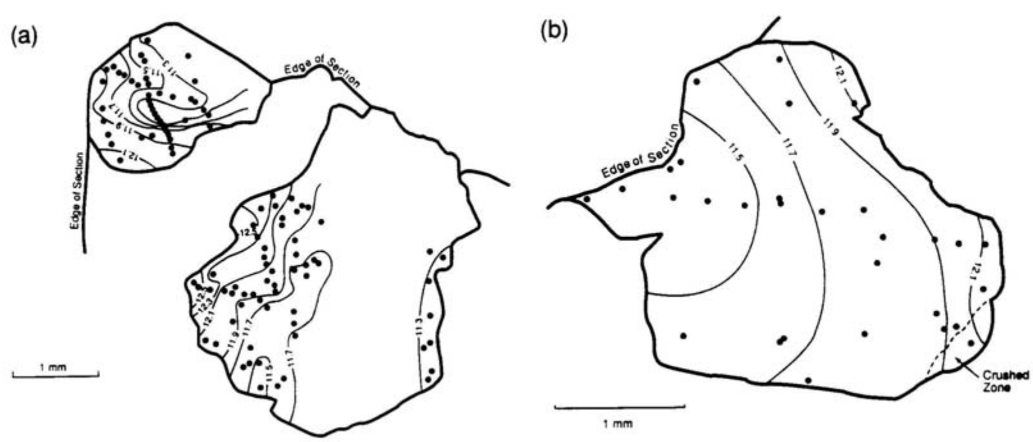


Figure 7. Sketches of zoning in larger olivines in 72415 samples, expressed as contours of FeO wt %. Dots are analytical locations. a) grains in 72415,27, the smaller grain shows a very steep gradient. b) grain in 72415,28. Ryder (1992a).

magma. None of the plagioclase appears to be cumulate. The sample was then shocked to about 330 Kb or more (according to work of Snee and Ahrens, 1975 a,b; see below), consistent with an excavation depth of 50 to 150 km, producing maskelynite and a silicic melt from the intercumulus material. However, there are unshocked plagioclases laths that crystallized from that melt. Some recrystallization then took place. A second shock event produced the present observed Cataclasis; this took place prior to the incorporation of the clast into the 72435 host melt (although perhaps only seconds before).

Snee and Ahrens (1975a,b) studied the shock-induced deformation features of 72415 and compared them with the products of experiments. 72415 shows varied shock features, including irregular fractures, planar fractures (single planes and sets), well-defined deformation bands, planar elements, isolated mosaicism, and a few completely recrystallized grains. The orientation of the planar fractures are similar to those observed in experiments of shock from 330 to 440 Kb. Some bipyramid orientations in the sample are not present in the experiment products; similarly, the experimental products do not include recrystallization features.

Richter et al. (1976a,b) made a detailed study of the deformation features in 72415, using SEM as well as microscopic and microprobe techniques, concentrating on the microcracks and micropores. The microstructures show a diverse complex history that is different from any other rocks studied. Healed and sealed cracks are abundant, but open ones are rare. The healed cracks are planes of solid phases and pores; some of the solids are Fe-metal. Symplectites tend to be on or near to microcracks, suggesting a genetic link; microprobe analyses show that Al and Cr are concentrated along cracks even where symplectites are not present. Cracks in olivine are commonly sealed by plagioclase, some of which may be injected shock melt. Others contain abundant micropores (0.1 to 0.4 microns); the micropores have irregular subspherical shapes. Some form subparallel strings, others are random. The open cracks are unlike any others described from lunar rocks, being narrow (0.1 microns) with isolated terminations. The

Table 3: Summary of events in the deformation history of 72415 (Richter et al., 1976a)

Crystallization—igneous prehistory
Tectonic cracking
Microcrack annealing, Development of symplectite
Major shock (330–440 kbar—probably confined)
Plagioclase sealed cracks
Annealing
Cataclasis by tectonic process
Excavation by shock
Sintering

matrix is cataclastic, and most of its plagioclase is free of shock effects. In contrast with the Dymek et al. (1985b) interpretation, Richter et al. (1976a) note that there is definite sintering (as revealed by the SEM) that produced a highly porous spongy mass in the matrix, with delicate necks preserved. The history as derived by Richter et al (1976a) is shown as Table 3. Whileconsistent with that of Dymek et al. (1975b) it is more detailed. A stage of tectonic deformation followed by slow annealing of cracks and then the development of symplectites took place after igneous crystallization. The major shock deformation that followed was in turn followed by some recovery before the latest Cataclasis and some sintering.

Using the mineral chemical data for pyroxenes of Dymek et al. (1975b) and an orthopyroxene-augite geothermometer, Ishii et al. (1976) derived a temperature of 1120 degrees C for the last equilibration of pyroxenes. Herzberg (1979) estimated a pressure of crystallization of 0 +/- 0.5 Kb using the alumina content of the pyroxenes in the of+2px+plag assemblage, and assuming a temperature of equilibration of 1000 +/- 50 degrees C estimated from the pyroxene quadrilateral locations. Finnerty and Rigden (1981) in contrast used olivine barometry (from the Ca-content) to derive a pressure of 6.4 to 11.6 Kb (for a temperature estimate of 948-988 degrees C), which they claim is consistent with the depth estimate made by Snee and Ahrens (1975a). However, in the same study they derived a depth estimate for 76535 of 600 km, which seems wholly unrealistic. Clearly these temperature and pressure estimates are inconsistent and unreliable, presumably at least in part because the original igneous crystallization did not produce a totally equilibrated assemblage, and because of the complex history following crystallization.

CHEMISTRY

Chemical analyses are listed in Table 4. The analyses correspond with a magnesian dunite with low abundances of incompatible elements and those compatible with feldspars. There are no analyses for

Table 4: Chemical analyses of bulk rock for 72415

Split	,2	,10	,2	,10b	,31	,33a	,33b
wt %							
SiO_2	39.93						
TiO_2	0.03						
Al_2O_3	1.53						
Cr_2O_3	0.34						
FeO	11.34						
MnO	0.13						
MgO	43.61						
CaO	1.14						
Na_2O	<0.02						
K_2O	0.00						
P_2O_5	0.04						
ppm							
Sc							
V							
Co							
Ni	173	149					
Rb	<0.2	0.045					
Sr	11						
Y	1.1						
Zr	2.6						
Nb	0.3						
Hf							
Ba							
Th							
U		0.0062					
Cs		0.0142					
Ta							
Pb							
La							
Ce							
Pr							
Nd							
Sm							
Eu							
Gd							
Tb							
Dy							
Ho							
Er							
Tm							
Yb							
Lu							
Li							
Be							
B							
C							
N							
S			44				
F							
Cl							
Br		0.0084					
Cu							
Zn	4	2.1		2.4(a)	2.4(a)	2.3(a)	4.1(a)
ppb							
Au		0.255		2.0	0.19	0.35	2.4
Ir		0.0052		2.4	0.023	0.022	0.105
I							
At							
Ga							
Ge		29.8		250	30	71	320
As							
Se		4.9		10	10	5.0	12
Mo							
Tc							
Ru							
Rh							
Pd							
Ag		0.25					
Cd		0.37					
In							
Sn							
Sb		0.47					
Te		<0.036					
W							
Re		0.0048		0.158	<0.04	<0.06	<0.07
Os							
Pt							
Hg							
Tl		0.049					
Bi		0.41					
	(1)	(2)	(3)	(4)	(4)	(4)	(4)

(1) LSPET (1973), Rhodes (1973); XRF
(2) Higuchi and Morgan (1975a,b); RNAA.
(3) Gibson and Moore (1974a,b); combustion.
(4) Morgan and Wandless (1988); RNAA

Notes:
(a) erroneously tabulated by authors as ppb

the rare earths. In addition to the tabulated data, Gibson et al. (1977) published a hydrogen abundance of 9.4 ppm without discussion. This abundance is higher than in mare basalts and about twice as high as in impact melts.

The major element analyses are fairly consistent with those for 72417. However, within the Caltech consortium, 72415 appears to have been considered as "normal" and 72417 as comparatively "alkali-rich" (Higuchi and Morgan, 1975a); the tabulated analyses do not support such a distinction, with Higuchi and Morgan (1975a) noting that their "alkali-rich" sample had lower Rb than their "normal" sample. While siderophiles (Ni, Ir, and some others) and some volatiles are high in some subsamples, Higuchi and Morgan (1975a) and Morgan and Wandless (1979) noted that they were not in meteoritic proportions and considered them to be indigenous. Morgan and Wandless (1988) analyzed for siderophile and volatile elements in further small subsamples that were randomly chosen but cannot be considered to be representative whole rocks because of their sizes. The data confirm an indigenous origin for these elements, and suggest a source magma that contained about 6x as high volatile abundances as mare basalts. They also noted that 3 of their subsamples were lower in volatiles and siderophiles than one other in 72415 and than the 72417 subsamples similarly analyzed.

Delano (1980) used the published data for compatible elements to place constraints on their abundance in the parental magma of the dunite.

RADIOGENIC ISOTOPES

Premo and Tatsumoto (1993) reported preliminary Pb-Pb and U-Pb isotopic data for four separates from 72415 (two "whole-rock," one olivine, and one magnetically removed mixture that is mainly pyroxenes and spinet), summarized in Figure 8. The separates were treated with water-alcohol and very dilute acids to remove secondary Pb components. The Pb from all the separates is very radiogenic (olivine the most radiogenic), but very little Pb is in them so laboratory blank is a significant component in all. With a best guess blank correction, the magnetic and olivine separates give a minimum age of 4.37 ± 0.23 Ga applicable to the dunite as a whole. The two whole-rocks do not plot together and suggest that WR-2 contains some uncorrected non-radiogenic Pb (above blank). Olivine and WR-1 are most reliable and indicate an age of 4.52 ± 0.06 Ga, older but within error limits of the Rb-Sr age of 72147 (4.45 ± 01 Ga). Corrections to align the whole rock and the magnetic separates with olivine are too great to be explained by laboratory chemistry, and suggest pre-preparation contamination, possibly meteoritic. Regardless, the Pb-Pb age is constrained between about 4.37 and 4.52 Ga, assuming the olivine data is unmovable. The data clearly indicates derivation from a high-μ source (>500), similar to results from norite 78235 and 76535 by the same laboratory.

EXPOSURE

Keith et al. (1974a,b) tabulated disintegration counts for cosmogenic radionuclides in 72415, without discussion. Yokoyama et al. (1974) used the $^{26}A1$ and ^{22}Na data to state that the sample was saturated in ^{26}AL hence exposed for at least a few million years.

PHYSICAL PROPERTIES

Pearce et al. (1974a, b) tabulated magnetic properties of 72415 (Table 5) with little specific discussion. The metal content is exceptionally low.

Brecher (1975, 1976a) described magnetic anisotropy (high-field saturation and remanence) in 72415 as reflecting the petrographic texture of the sample. Some features with a preferential orientation produced by shock, such as metal decorating planar structures, would certainly produce a magnetic anisotropy. (However, it is not obvious in any petrographic description that there are preferred orientations within 72415; most planar features appear to predate the last cataclasis. This puts Brecher's hypothesis in some doubt in this particular case).

PROCESSING

72415 was created from two pieces that matched (Fig. 1), termed A and B. The first subdivisions were a loose undocumented chip (, 1, thin sections); two combined pieces from opposite ends of piece A (, 2, chemistry, magnetic); small chips and fragments (, 4, unallocated); and an undocumented chip (, 6, tracks, no published data). Subsequently piece A was sawn as shown in Figure 2. Sample, 18 was consumed making thin sections. , 17 (4.5 g); and, 16 (1.4 g) remain intact. Small pieces for chemistry, radiogenic isotopes, and thin sections were later taken from, 8, 15; and, 10 (small chips from piece B), and other small chips allocated for spectral reflectance studies. Piece B (now, 9, 12.3 g) is virtually intact and stored at Brooks. Sample, 8 is now 4.4 g.

Table 5: Some magnetic properties of 72415 (Pearce et al., 1977a).

Sample	J_s (emu/g)	X_p (emu/g Oe) $\times 10^6$	X_0 (emu/g Oe) $\times 10^4$	J_{rs}/J_s	H_c (Oe)	H_{rc} (Oe)	Equiv. wt.% Fe°	Equiv. wt.% Fe^{++}	$\frac{Fe^\circ}{Fe^{++}}$
Dunite clast 72415,2	.064	19.3	.35	—	—	—	.03	8.85	.0033

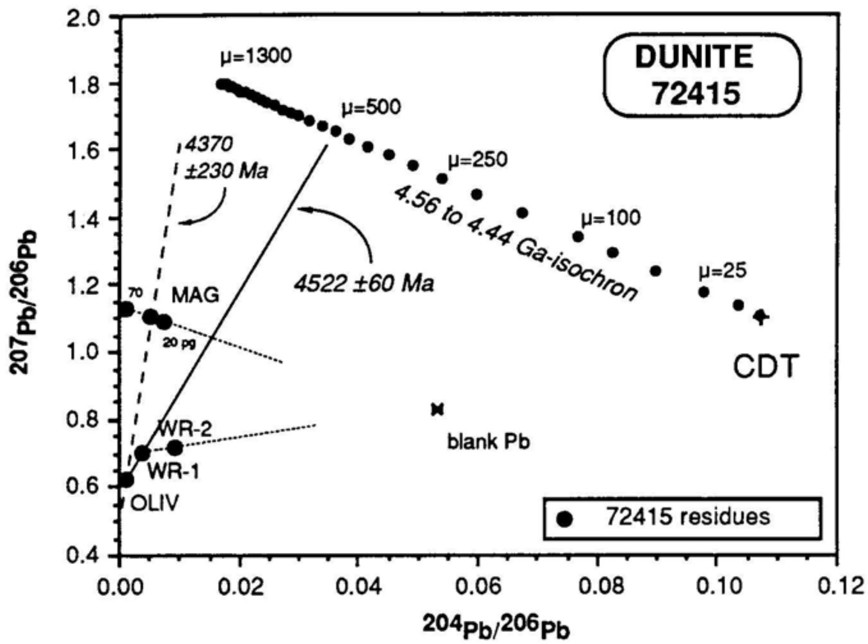


Figure 8. Pb-Pb correlation diagram for lunar dunite 72415 separates WR-I and WR-2 are whole-rock samples, OLIV is the olivine separate, and MAG is a magnetic separate consisting mainly of pyroxene and spinet. CDT is Canyon Diablo troilite.