DRAFT

15425 – 15427
15365 – 15377

Green Glass Clods

~ 500 grams

Figure 1: Photo of green glass clods from 15426 (out of focus). The scale at the top is in cm and the edge of the cube is one inch. NASA# S71-43587.

The saga of the scientific study of a diverse collection of small green glass beads from Apollo 15 is a perfect example why, exactly, the laboratory analysis of samples returned from another planet is far superior to analysis done by remote means. The small variation in the chemistry of these beads required scientists to perfect their analytical and interpretative techniques – which can only be done with samples in hand! It has been said: Samples are like a" gift that keeps on giving."

Introduction

An abundance of small green glass spheres were found in the samples collected from around Spur Crater on the Apennine Front, Apollo 15. Two large, greenish, friable clods found at Spur Crater were placed in a documented bag and returned. When the bag was opened, these friable clods were found broken into several pieces with considerable loose "soil" partially derived from the breakup of the clods (figure 1). The surviving clods were grouped and numbered 15425, 15426 and 15427 (Butler 1971). The soil was sieved and numbered 15420 to 15424. Sample 15421 has greater than 80% green glass beads (figure 2).

Additional clods of green glass (numbered 15365-15377) were collected as part of the rake sample (bag 3/172) and the "soil" from this bag (15310 to 15314) also contained a lot of green glass fragments due to abrasion. The large soil 15300 – 4 was also found to contain numerous green glass spheres and "green glass clods". Various soils, regolith breccias and cores from this site also contain an abundance of the same, green glass beads. In general, there is more green glass in the samples on the Apennine Front than on the mare surface (Nagle 1981, Basu et al. 1981).

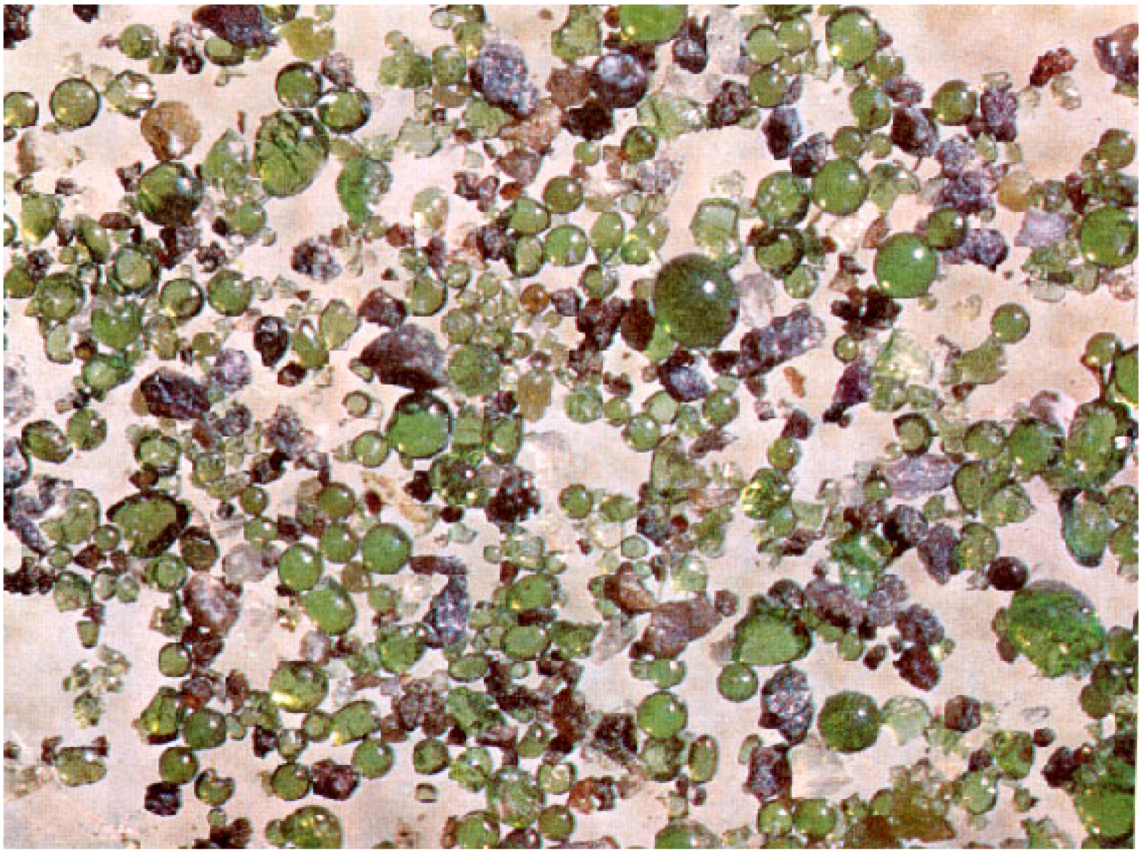


Figure 2: Example of green glass beads in 15401. Beads are 40-250 microns. From Carusi et al. (1972).

Some portions of the green glass clods are nearly pure green glass, but other portions of these clods also contain various amounts of local (gray) regolith (figure 4). In addition, various yellow impact glasses, as well as red and yellow volcanic glasses, are also found in these glass clods (Delano 1980, Delano and Livi 1981, Spangler et al. 1984, Hughes et al. 1988).

At first, the green glass from Apollo 15 was found to be rather homogeneous (Reid et al. 1972, Warner et al. 1972, Ridley et al. 1973, Agrell et al. 1973, others, see tables). However, Stolper (1974), Hlava et al. (1973) and others found slight, but significant, variation in composition. The green glass beads were eventually found to be subdivided into 7 compositional groups (Delano 1979, Ryder 1986, Galbreath et al. 1990, Steele et al. 1992) (figure 5, table 2). Hlava et al. (1973) reported analysis of 263 green glass beads from soils and rake sample 15365. Delano (1979) analyzed 416 glass particles and grouped them into five groups based on their major element composition (verified by Ryder 1986). Ma et al. (1981) analyzed 55 for trace elements, establishing 3 groups. Galbreath et al. (1990) analyzed 70 green glass particles for both major and trace

Samples with abundant Green Glass Beads

	pieces	weights		documented bag	Is/FeO
15400 - 4		153	soil	168	5.6
15420 - 4		308	soil, mixed	3/195	
15425	4	136.3	clods	3/195	
15426	3	223.6	clods	3/195	0.3
15427	numerous	115.9	clods	3/195	20-30
15310 - 4		463.4	soil from rake	3/172	
15314,1 and ,17			clods		
15365-15377	13	18	clods in rake sample	3/172	
15300 - 4		1244	soil, mixed	3/173	48
15305	1	2.9	clod	3/173	

Figure 3: Close up of 15426,26 showing that glass beads are only about ~5 % of rock, with the rest of very-fine off-white powdery material. Sample about 3 cm across. NASA S80-42656.

elements. Steele et al. (1992) analyzed 365 by INAA and selected 52 of them for major elements – they now have 7 distinct groups of green glass!

Ryder (1985) reviewed the data on the green glass clods in his Apollo 15 catalog. The section on the Orange Soil (74220) also discusses volcanic glass found on the moon.

Petrography

The green glass clods (15425, 15426 and 15427) are partially light-greenish-gray and partly grayish-brown – it is the greener parts that have been studied. In spite of a lot of work on these samples, there appears to be no basic description of these breccias in the literature (Ryder 1985). The clods are blocky and very friable, with average particle size less than 0.1 mm. Sample 15426,26 (figure 3) is a friable, greenish-white clod with only ~5% glass beads set in a fine white matrix of powdery material (presumably fine fragments of broken glass). The greener portions of the clods are mostly green glass beads and broken fragments of green glass, but with occasional red or yellow glass beads (figure 4). The gray portions appear to be regolith breccia, with admixed basalt fragments. Green glass clods from the rake sample (15365-15377) were cataloged by Dowty et al. (1973) (figure 5).

The green glass beads have most recently been studied by Steele (1992), Steele et al. (1992) and Galbreath (1990) who confirm the detailed analyses by Delano (1979). These authors find that there are distinct compositional groupings of glass (figure 7, table 2).

Surface features of the green glass have been studied by McKay et al. (1973), Agrell et al. (1973), Meyer et al. (1975), Butler (1978) and others. The beads generally lack hypervelocity impact craters. Some beads form composite aggregates, indicating collision while molten in the volcanic plume. Most beads have

Mineralogical Mode

See Morris et al. 1983, Wood and Ryder 1977, Basu et al. 1981

	15421	15427	15426	15301	15311
matrix (<25 ìm)		59	vol. %68	41	
glass	98	48	15	30	50
lithic	0.3	0.4	9.5	5	10
mineral	2.3	1.1	6.2	14	20

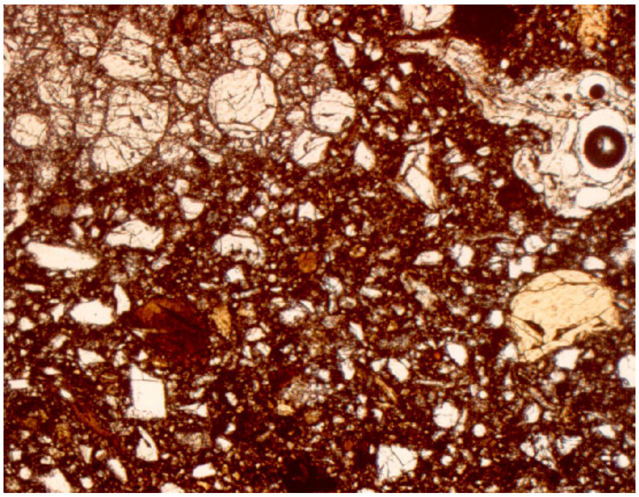


Figure 4: Photomicrograph of thin section of 15426 showing green glass spheres (clear), broken glass, orange and yellow glass as well as vesicular glass. Field of view 3.2 mm. NASA# S76-20809

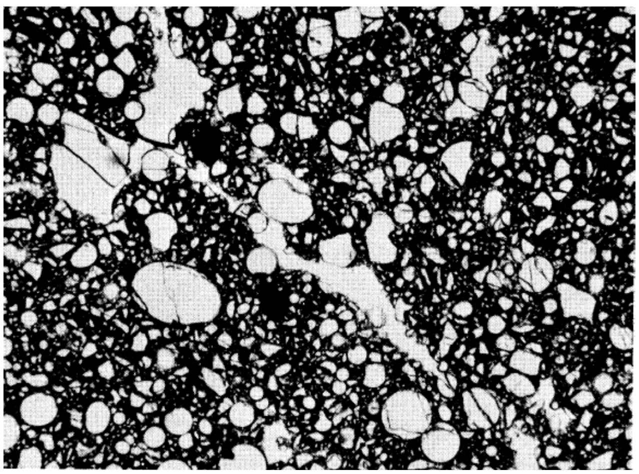


Figure 5: Photomicrograph of thin section of 15370 (from Dowty et al. 1973).

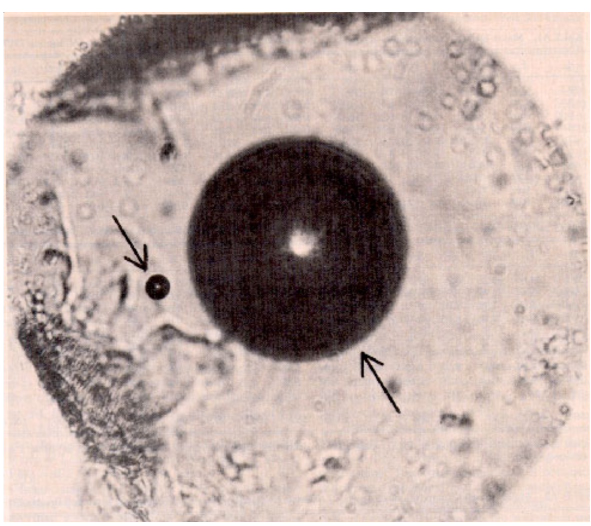


Figure 6: Vesicles in green glass from 15427 (Delano and Lindsey 1983).

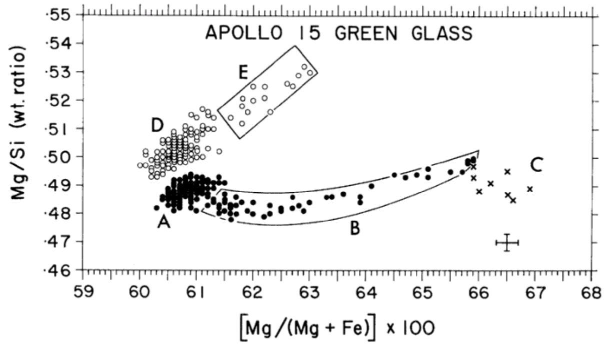


Figure 7: Composition diagram for green glass showing groupings as originally defined by Delano 1979. Averages given in table 2.

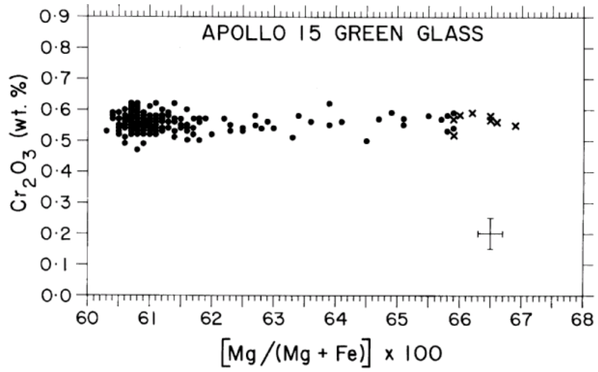


Figure 8: Cr content for Apollo 15 green glass (from Delano 1979).

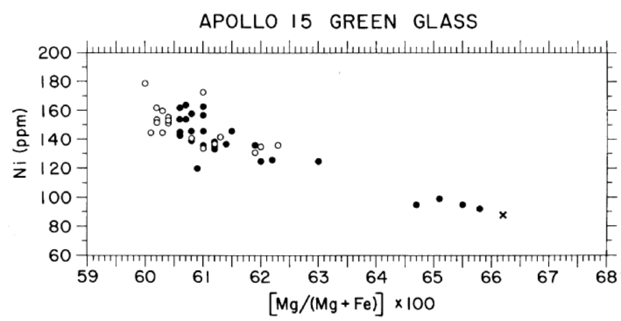


Figure 9: Ni content of Apollo 15 green glass (from Delano 1979).

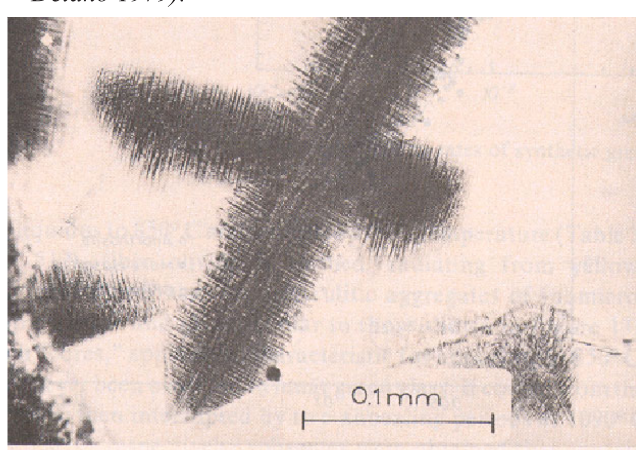


Figure 10: Olivine dendrites in 15427 (Arndt et al. 1984).

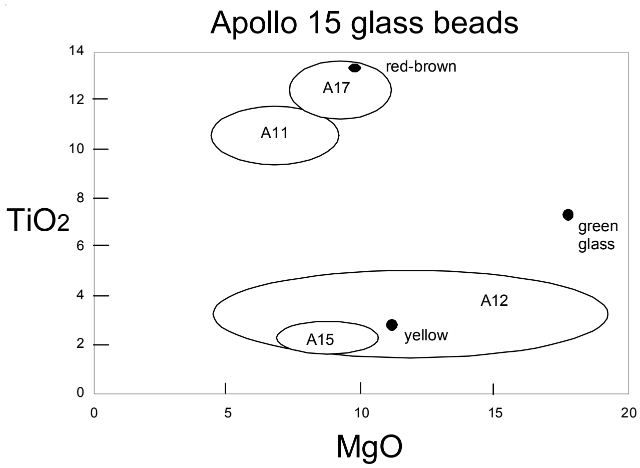


Figure 11: Composition of volcanic glass beads (clusters) in green glass clods (data from tables 2 and 3).

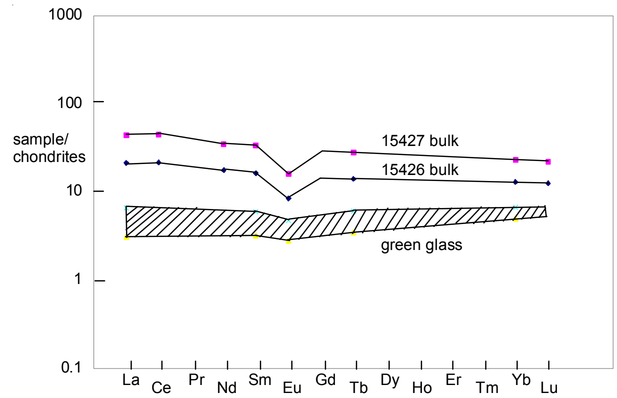


Figure 12: Normalized rare-earth-element diagram for green glass beads and green glass clods (15426 and 15427). Data from Korotev (unpublished) and table 1 and 2.

a distinct texture of micromounds due to a surface coating of condensed volatiles (figure 16, Meyer et al. 1975).

The green glass beads generally lack bubbles, but Delano and Lindsey (1983) found more than 20 vesicle-bearing volcanic glass beads in 15427 (figure 6). Steele (1992), Basu et al. (1979) and Arndt et al. (1984) studied the fine-featured olivine microlites that form during quenching the green glass. Ridley et al. (1973) and Basu et al. (1979) found that the olivine crystallites in green glass were Fo_{70-76}. Dyar (1984) studied the valence and coordination of iron in the glass during quenching experiments. All features were consistent with volcanic fire-fountaining.

The maturity index (Is/FeO) is less than 1 for 15426 (Morris 1976, McKay et al. 1984) – which is extremely low (as was the case for the Orange Soil). Stone et al. (1982) determined Is/FeO for individual glass beads, finding that it was a good discriminator for volcanic vrs. agglutinate glass.

Early on, the high Mg/Fe ratio and extremely low and flat rare-earth-element content attracted the attention of experimental petrologists whose experiments were aimed at learning the depth of origin of this primitive volcanic liquid. Green and Ringwood (1973) used previous experiments of Apollo 12 samples to predict the depth of origin (200 km) and degree of partial melting (30-60%) of the interior based on multiple saturation of orthopyroxene and olivine phases. Stolper (1974), Grove and Lindsley (1978), Grove (1981) and Longhi (1992) developed alternative models for the origin of the green glass (figure 20). Delano (1980) established the multiple saturation of phases for the red glass (figure 21) giving a depth of origin of 500 km!!

The Ni in the green glass (and other mafic volcanic glass) is substantially higher than in mare basalt (Delano 1986) and Ni abundance correlates with MgO (figure 9).

Delano (1980) studied the red volcanic glass and Hughes et al. (1988) studied yellow-brown volcanic glass from 15427 (table 4).

Stone et al. (1982) determined Is/FeO for individual glass beads, finding that 9 out of 10 green glass beads from 15401 had negligible Is/FeO.

Surface-correlated Volatiles

Meyer et al. (1975), Butler and Meyer (1976), Butler (1978), Cirlin and Housley (1979) found surface coatings of primarily ZnS on green glass beads. Morgan and Wandless (1984) found higher Cd, Zn, Se, Ag in the less than 37 micron size fraction indicating surface enrichment (figure 15). Ganapathy et al. (1973) showed that the green glass and especially the “finer matrix” of 15426 was enriched in volatile elements (Zn, Cd, Br, Se, Te, Ge, In, Tl, Bi, Ag and Sb). They also showed that Re and Ir seemed to track Zn and other volatile elements. Goldberg et al. (1975, 1976) studied F on the surfaces of green glass beads reporting up to 3000 ppm F on the surface and about 50 ppm in the interior. Jovanovic and Reed (1976) studied F, Cl, Br and I in leached and residue fractions of 15427 (but

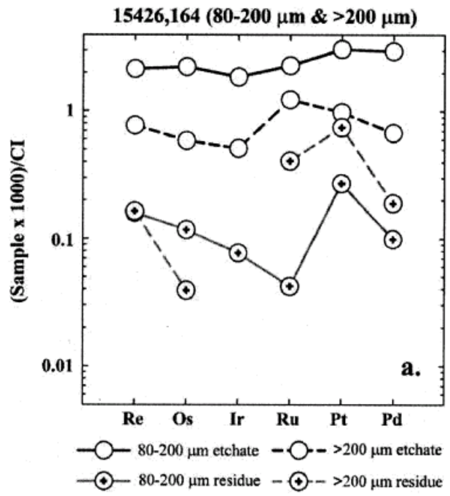


Figure 13: Concentration of highly-siderophile-elements (HSE) on and in green glass beads from 15426 (figure and data from Walker et al. 2004).

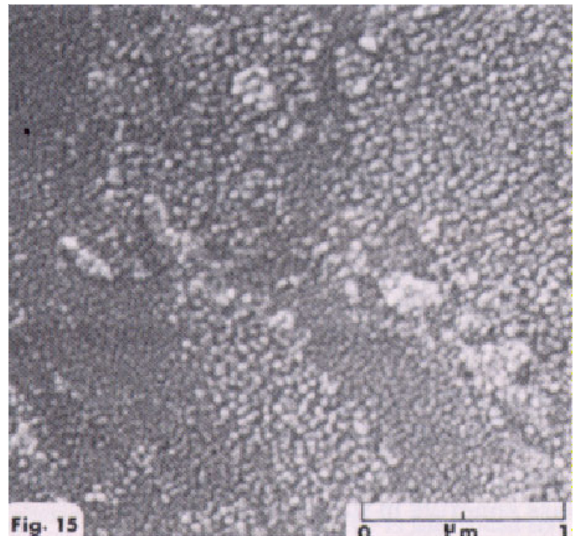


Figure 16: Micromounds on surface of green glass spheres (from McKay et al. 1973).

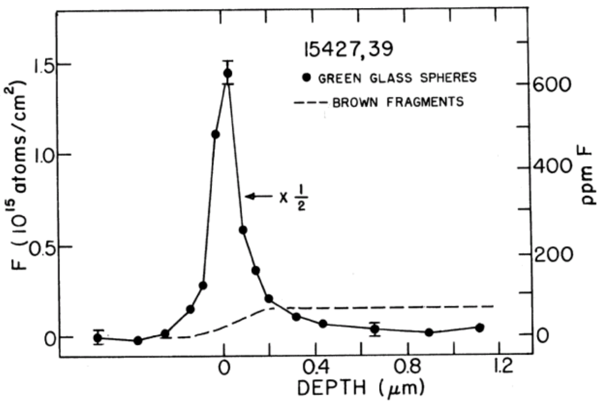


Figure 14: Depth profile for flourine (F) on green glass bead from 15427 (from Goldberg et al. 1976).

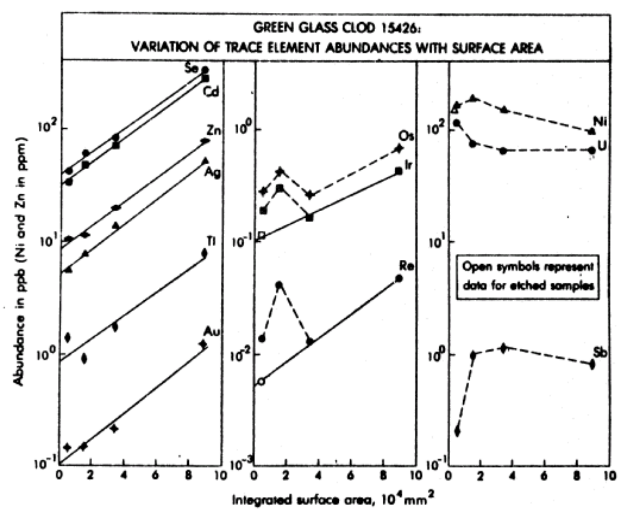


Figure 15: Concentrations of Cd, Zn, Ag, Tl, Au, Ir, Re and Os as function of grain size, showing that these elements are strongly corellated with surface area (Morgan and Wandless 1974).

did not notice anything unusual). Gibson and Andrawes (1978) reported 330 ppm S for 15427.

Recently, precise determination of highly-siderophile-element (HSE) concentrations (as etchates and residues) was reported by Walker et al. (2004) for green glass spheres from 15426 and 15421 (figure 13 and table 6). The comparatively high HSE concentrations and generally chondritic relative abundances of the etchates of 15426 suggest that the HSE in this aliquant of green glass were likely dominated by meteoritic contamination. The extremely low HSE (especially Os) in the residue is evidence that the deep interior of the moon is extremely depleted in HSE (20 times less than the terrestrial mantle).

Tatsumoto et al. (1987) did not find high ^{204}Pb in the green glass (as was the case for the Apollo 17 orange glass). However, Barnes et al. (1973) and Silver (1973) reported excess, unsupported Pb.

Chemistry

Bulk analyses of green glass samples are given in table 1 and figure 12. The green glass is very high in Mg (MgO = ~18%) and low in trace elements (U = 50 ppb) and the REE pattern is flat. The slightly elevated REE contents of the bulk samples is due to the addition of a small amount of lunar regolith.

The analyses of green glass spheres by Steele et al. (1992) are the most recent, and most comprehensive (table 2). They generally confirm the chemical groupings found by Delano (1979) and Galbreath et

al. (1990) (figure 6). Originally, Warner et al. (1972), Ridley et al. (1983) and others argued that the green glass was rather constant in composition. However, Stolper (1974), Wood and Ryder (1977) and others, explained minor variations as due to olivine separation. But the story is more complicated and apparently related to variations in deep lunar interior (Grove 1981). Although, Delano (1979) found 5 distinct groupings, in two trends (figure 7), Steele et al. (1992) show that most of the compositional characteristics of the green glasses can be explained by a model for batch equilibrium melting of a nearly homogeneous, ultramafic source region, when the complicating effects of high pressure and low oxygen fugacity are taken into account.

Schonfeld (1975) and Korotev (1987) used green glass as one of the components in their chemical mixing models for Apollo 15 soils.

Carbon and carbon compounds released by heating green glass samples have been studied by DesMarais et al. (1973), Modzeleski et al. (1972), Wszolek et al. (1972) and Simoneit et al. (1973). Simoneit et al. (1973) reported low temperature release of NO from 15426.

Walker et al. (2004) have most recently studied the highly-siderophile-element composition. They found that the "etchate" of the surfaces of the green glass contained substantially more Re, Os, Ir, Ru, Pt and Pd than the residue (figure 13, table 6). Their preferred interpretation was that this is from chondritic meteorite contamination on the surface of these glass beads. The lack of these elements in the residual glass, indicates that the lunar mantle is significantly lacking of these elements (yet there is Ni).

Radiogenic age dating

Huneke et al. (1973) and Podosek and Huenke (1973) determined the $^{39}Ar/^{40}Ar$ age of 30 mg of green glass carefully separated by Lakatos et al. (1973) (figure 18). Their age (3.38 ± 0.06 b.y.) is significantly younger

Summary of Age Data for Green Glass

	Ar/Ar	Pb/Pb
Husain 1972	3.79 ± 0.08 b.y.	
Huneke et al. 1973	3.38 ± 0.06	
Podesek and Huneke 1973	3.38 ± 0.06	
Spangler et al. 1984	3.41 ± 0.12	
	3.35 ± 0.18	
Tatsumoto et al. 1987		3.41

Note: Beware decay constant.

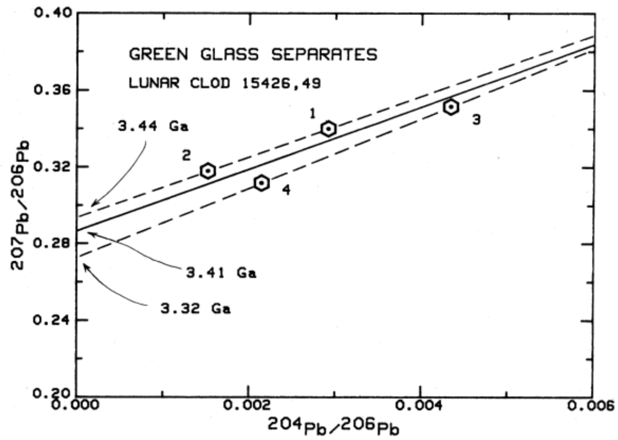


Figure 17: Pb/Pb age diagram for 15426 from Tatsumoto et al. 1987.

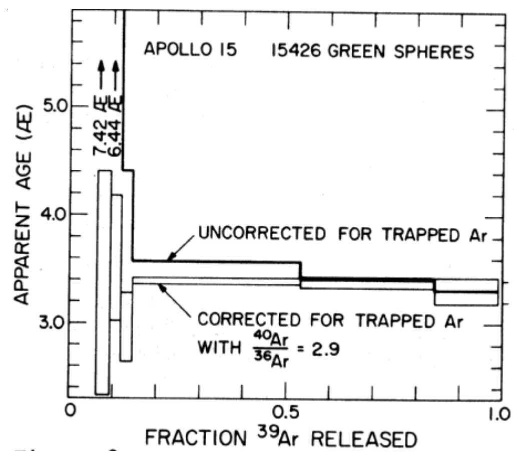


Figure 18: Ar release pattern for green glass from 15426 (Huneke et al. 1973).

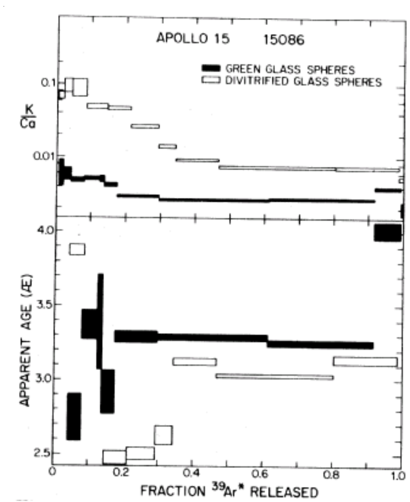


Figure 19: Ar release pattern for green glass from breccia 15086 (Huneke et al. 1974).

Other studies Green Glass

Magnetics

Pearce et al. 1973	
Morris 1976	Is/FeO
Stone et al. 1982	Is/FeO
Griscom et al. 1973, 1975	esr/fmr
Friebele et al. 1974	fmr

Spectra

Burns and Dyar 1983	mossbauer
Dyar 1984	mossbauer
Perry et al. 1972	raman spec.
Greegor and Lytle 1983	XANES

Tracks

Fleischer and Hart 1973, 1974	
Storzer et al. 1973	U = 0.049 ppm
Bhandari et al. 1972, 1973	
MacDougall et al. 1973	

Experimental

Arndt et al. 1984	devitrification rate
Fang et al. 1983	cooling rate
Grove and Lindsley 1978	400 km, batch
Grove 1981	
Grove and Vaniman 1978	
Delano 1979, 1980	500 km
Longhi 1987, 1992	polybaric
Green and Ringwood 1973	200 km

Isotopes

Clayton et al. 1972, 1973	Oxygen
Clayton and Mayeda 1975	
Barnes et al. 1973	K
Lugmair and Marti 1978	Nd
Lakatos et al. 1973	
Heymann 1975	
Bogard and Nyquist 1972	15923
Megrue 1972, 1973	
Barraclough and Marti 1985	

Gas release

Simoneit et al. 1973	NO ?!?
DesMarais et al. 1973	C

than that obtained by Husain (1972) and more precise than that determined by laser probe (Spangler et al. 1984) on individual glass beads. This result seems also seems to be confirmed by Pb/Pb (Tatusmoto et al. 1987, figure 17). The mare basalt flows at Apollo 15 are also about 3.4 b.y.

In addition, Spangler et al. (1984) determined 3.62 ± 0.07 b.y. for yellow volcanic glass in 15426-7. Spangler and Delano (1984) also determined 3.35 ± 0.05 b.y. for the *yellow impact* glass mixed in the green glass clods. Finally, Huneke et al. (1974) reported an age of

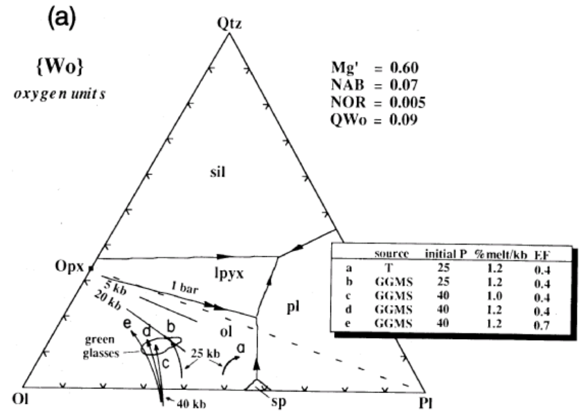


Figure 20: Summary of experimental work on green glass composition (from Longhi 1992).

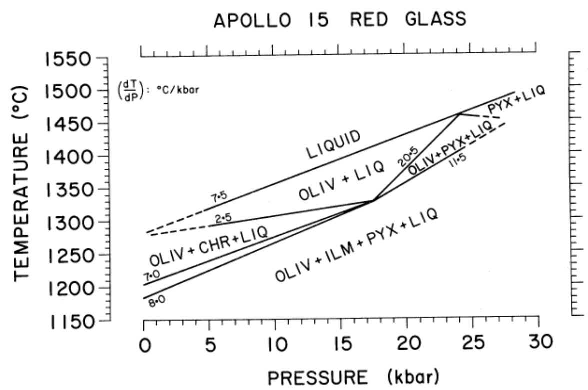


Figure 21: Experimental phase diagram for red glass from Apollo 15 (from Delano 1980).

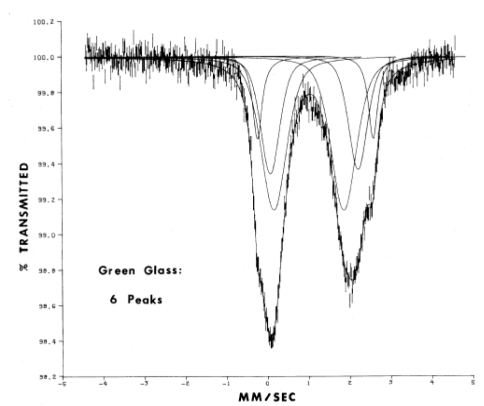


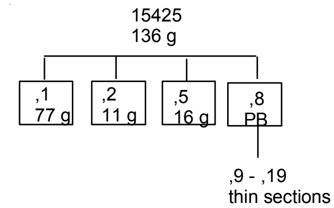
Figure 22: Mossbauer spectra of green glass from 15426 (from Burns and Dyar 1983).

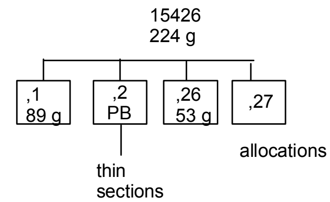
3.29 ± 0.06 b.y. for green glass spheres hand-picked from breccia 15086 (figure 19).

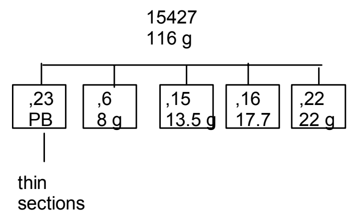
Lugmair and Marti (1978) modeled the Nd-Sm evolution of the green glass and determined a a model age of 3.8 b.y. Since this nearly coincides with the true age, the source region for the green glass must

Rake Samples with Green Glass

	weight	thin sections
15365	2.9 g	,4 ,5 ,6
15366	3.3	,3 ,6
15367	1.1	
15368	0.4	
15369	2.5	,7 ,8
15370	2.9	,3 ,5 ,6
15371	0.5	,12 ,13
15372	0.8	
15373	0.6	
15374	1.0	
15375	0.4	
15376	1.0	,3 ,4 ,5 ,6 ,7 ,8 ,9
15377	0.5	
15378	3.3	
15305	2.9	
15326	2.5	
Coarse-fines with Green Glass		
15314,1	0.16	
15314,17		,90 TS







also have a very low and unfractionated REE pattern (i.e. primitive).

Cosmogenic isotopes and exposure ages

Results of radiation counting of 125.7 grams of 15426 ^{26}Al (59 dpm/kg), ^{22}Na (38 dpm/kg) are reported in LSPET 1972.

Huneke et al. (1973) reported the exposure age as 300 m.y. and Spangler et al. (1984) determined exposure ages between 300 and 275 m.y. Lakatos et al. (1973) carefully determined the He, Ne and Ar in green glass beads separated from 15426.

Fleischer and Hart (1973) determined a track exposure age of 0.5 m.y. for the green glass in 15427.

Processing

Obviously, each sample bag or container that held these friable breccias was found to contain numerous glass beads in the residue. This has been the source of many of the glass beads studied.

The rake sample collected at Spur Crater (15310 to 15392) also contained a few green glass clods – listed in table (Bunch et al. 1972, Cameron et al. 1972, Carusi et al. 1972, Cavaretta et al. 1972, Dowty et al. 1972, Ryder 1972, Ryder and Sherman 1989, Steele et al. 1972).

Table 1a. Chemical composition of Green Glass Samples.

	bulk		bulk	bulk	bulk		hand picked	green clod				glass		composite	
reference	LSPET 72		LSPET 72	Korotev	Korotev	(e)	Wiesmann 75				Taylor 73			Ma 81	
weight	15426		15427	15426	15427		15301,76	15303		15401,27	15421,24	15426,38		15426	
SiO2 %			45.18							45.3	45.5	45.6			
TiO2			1.14	0.5		(d)	0.43	0.45	(a)	0.4	0.32	0.29		0.33	(d)
Al2O3			15.06	9.75		(d)				7.52	7.64	7.67		7.7	(d)
FeO			13.72	17.9	14.4	(d)				20	19.6	19.7		20.1	(d)
MnO			0.18							0.22	0.2	0.21			
MgO			12.14	15.1		(d)	16.9		(a)	17.1	16.7	16.6		18	(d)
CaO			11.11	8.5	9.9	(d)	8.4		(a)	8.43	8.68	8.72		8.1	(d)
Na2O			0.36	0.22	0.37	(d)	0.2	0.17	(a)	0.13	0.13	0.12		0.144	(d)
K2O	0.099	(c)	0.11				0.018	0.017	(a)	<0.06	<0.06	<0.06		0.018	(d)
P2O5			0.09												
S %			0.06												
sum															
Sc ppm				33.5	27.7	(d)				30	46	43	(b)	39	(d)
V				124		(d)				160	170	150	(b)	170	(d)
Cr			2737	3360	2580	(d)				3000	2700	2800	(b)	3852	(d)
Co				69.6	50.2	(d)				72	70	72	(b)	80	(d)
Ni				210	191	(d)				185	180	170	(b)		
Cu										6.8	6	3.5	(b)		
Zn															
Ga										4.7	4.7	4.7	(b)		
Ge ppb															
As															
Se															
Rb			2.7				0.253	0.329	(a)	0.41	0.23	0.34	(b)		
Sr			111	60	100	(d)	28.6	27.8	(a)						
Y			39							9.5	9.5	7.2	(b)		
Zr			152	70	170	(d)		21.5	(a)	28	31	22	(b)		
Nb			10							2.1	1.9	1.5	(b)		
Mo															
Ru															
Rh															
Pd ppb															
Ag ppb															
Cd ppb															
In ppb															
Sn ppb										110	160	120	(b)		
Sb ppb															
Te ppb															
Cs ppm					0.11	(d)									
Ba				59	103	(d)	15.9	15.6	(a)	20	20	17	(b)		
La				4.99	10.2	(d)	0.8	1.24	(a)	1.42	1.65	1.4	(b)	1.25	(d)
Ce				13	27	(d)		3.74	(a)	3.9	5.1	3.8	(b)		
Pr										0.51	0.69	0.53	(b)		
Nd				8	16	(d)	2.65	2.5	(a)	2.1	2.65	2.2	(b)		
Sm				2.43	5.05	(d)	0.866	0.818	(a)	0.8	0.81	0.76	(b)	0.78	(d)
Eu				0.478	0.919	(d)	0.27	0.246	(a)	0.26	0.23	0.21	(b)	0.24	(d)
Gd							1.44	1.2	(a)	0.99	1.1	0.91	(b)		
Tb				0.51	1.03	(d)				0.16	0.17	0.15	(b)	0.18	(d)
Dy							1.61	1.52	(a)	1.1	1.35	1.1	(b)		
Ho										0.28	0.32	0.27	(b)		
Er							0.87	1.02	(a)	0.85	0.9	0.8	(b)		
Tm										0.14	0.17	0.15	(b)		
Yb				2.1	3.83	(d)	1.04	0.995	(a)	0.81	1	0.93	(b)	0.92	(d)
Lu				0.304	0.54	(d)	0.164	0.15	(a)	0.13	0.16	0.14	(b)	0.16	(d)
Hf				2	3.9	(d)		0.7	(a)		0.53	0.42	(b)	0.7	(d)
Ta				0.27	0.55	(d)									
W ppb												0.14	(b)		
Re ppb															
Os ppb															
Ir ppb				<2	3.3	(d)									
Pt ppb															
Au ppb				<2	2.5	(d)									
Th ppm	1.9	(c)		0.9	1.7	(d)				0.21	0.18	0.08	(b)		
U ppm	0.43	(c)		0.23	0.42	(d)	0.063	0.088	(a)			0.02	(b)		

technique (a) IDMS, (b) Spark Source MS, (c) radiation counting, (d) INAA, (e) unpublished

Table 1b. Chemical composition of Green Glass Samples.

	glass	glass	matrix	bulk	bulk	bulk			av. 32	av. 28	av. 11		av. 5	187	
reference	Ganapathy 73			Morgan 84					Best 72	Ridley 73		Agell 73		Warner 72	
weight	15426 gg	brown	15426	15426	repeat	15426	<37 microns			15101	15427	15427	15425	all soils	
SiO2 %									45.7	45.21	45.38	45.23	45.26	45.4	(g)
TiO2									0.41	0.43	0.39	0.35	0.41	0.42	(g)
Al2O3									7.2	7.63	7.34	7.73	7.51	7.72	(g)
FeO									19.3	19.73	19.44	19.77	19.77	19.6	(g)
MnO									0.17			0.31	0.33		(g)
MgO									16.9	17.69	17.29	16.66	17	17.5	(g)
CaO									8.3	8.14	8.49	8.42	7.95	8.34	(g)
Na2O									0.15	0.13	0.13	0.22	0.13	0.12	(g)
K2O									0.18	0	0.02	0.07	0.07	0.01	(g)
P2O5									0.07			0.02	0.02		(g)
S %												0.03			(g)
sum															
Sc ppm															
V															
Cr									3558	3010	3010	3421	3489	2942	(g)
Co	77	60	48					(f)							
Ni				116	163		96	(f)	tr.						
Cu															
Zn	19	18	80	26	24	51	80	(f)							
Ga															
Ge ppb	37	64	196					(f)							
As															
Se	69	101	174	109	106	125	334	(f)							
Rb	0.46	2	0.47					(f)							
Sr															
Y															
Zr															
Nb															
Mo															
Ru															
Rh															
Pd ppb															
Ag ppb	8.9	8	39	21	14	25	53	(f)							
Cd ppb	46	48	183	110	89	118	283	(f)							
In ppb	1.3	1.2	9.3					(f)							
Sn ppb															
Sb ppb	0.12	0.3	1.58	2.9	0.9	0.89	0.83	(f)							
Te ppb	3.3	12	16					(f)							
Cs ppm	0.024	0.174	0.027					(f)							
Ba															
La															
Ce															
Pr															
Nd															
Sm															
Eu															
Gd															
Tb															
Dy															
Ho															
Er															
Tm															
Yb															
Lu															
Hf															
Ta															
W ppb															
Re ppb	0.02	0.029	0.047	0.031	0.032	0.034	0.048	(f)							
Os ppb				0.42	0.41		0.68	(f)							
Ir ppb	0.22	0.38	0.41	0.32	0.28	0.32	0.43	(f)							
Pt ppb															
Au ppb				0.52	0.34		1.23	(f)							
Th ppm															
U ppm	0.12	0.915	0.095	0.061	0.081	0.125	0.066	(f)							

technique (f) RNAA, (g) electron microprobe

Table 2. Chemical composition (averages) of green glass groups.

reference	Steele 1992							Delano 1986						Galbreath 90					
group	C	hB	IB	hA	IA	D		C	A	B	D	E		A	B	C	D	E	
SiO2 %	48.12	46.17	47.2	45.64	45.46	45.15	(a)	48	45.5	46	45.1	45.2	(a)	45.6	45.8	48.1	45.3	45.3	(a)
TiO2	0.26	0.4	0.35	0.39	0.39	0.42	(a)	0.26	0.38	0.4	0.41	0.43	(a)	0.4	0.42	0.24	0.45	0.45	(a)
Al2O3	7.94	8.13	8.08	7.96	7.83	7.62	(a)	7.74	7.75	7.92	7.43	7.44	(a)	7.6	7.8	7.45	7.3	7.2	(a)
FeO	16.29	18.62	17.2	19.54	19.78	20.1	(a)	16.5	19.7	19.1	20.3	19.8	(a)	19.8	18.3	16.3	20.3	19	(a)
MnO	0.24	0.27	0.26	0.27	0.27	0.26	(a)	0.19	0.22		0.22	0.22	(a)	0.3	0.3	0.32	0.29	0.22	(a)
MgO	17.95	17.09	17.8	16.94	17.11	17.59	(a)	18.2	17.2	17.2	17.6	18.3	(a)	17.6	17.8	18.6	18.1	18.5	(a)
CaO	8.67	8.82	8.65	8.72	8.65	8.38	(a)	8.57	8.65	8.75	8.43	8.15	(a)	8.4	8.4	8.23	8.2	8	(a)
Na2O														0.13	0.17	0.18	0.16	0.18	(a)
K2O																			
P2O5																			
S %																			
sum																			
Sc ppm	35.8	36.2	36	36.6	37.1	35.3	(a)							38	37.1	36.5	36.9	36.5	(c)
V														163	157	157	159	162	(c)
Cr	3790	3674	3729	3695	3756	3667	(a)	3900	3831	3763	3763	3695	(a)	3230	3200	3340	3170	3200	(c)
Co	56.3	71.7	63.7	75.8	77.5	79	(a)							68	58	44	67	58	(c)
Ni	118	158	126	164	172	164	(a)	90	170	150		170	(a)						
Cu																			
Zn																			
Ga																			
Ge ppb																			
As																			
Se																			
Rb																			
Sr														22	21	11	22	27	(c)
Y																			
Zr														20	23	11	19	22	(c)
Nb																			
Mo																			
Ru																			
Rh																			
Pd ppb																			
Ag ppb																			
Cd ppb																			
In ppb																			
Sn ppb																			
Sb ppb																			
Te ppb																			
Cs ppm																			
Ba														13	15	7	13	16	(c)
La	0.72	1.54	1.15	1.18	0.92	1.16	(b)							1.1	1.4	0.7	1	1.4	(c)
Ce														2.9	3.5	1.8	2.8	3.7	(c)
Pr																			
Nd														1.6	1.9	1	1.5	2.1	(c)
Sm	0.47	0.891	0.71	0.736	0.62	0.74	(b)							0.5	0.6	0.3	0.5	0.8	(c)
Eu	0.159	0.27	0.22	0.235	0.22	0.284	(b)							0.14	0.16	0.08	0.16	0.19	(c)
Gd																			
Tb	0.127	0.222	0.19	0.194	0.18	0.202	(b)												
Dy														0.9	0.9	0.6	0.8	1.1	(c)
Ho																			
Er														0.5	0.6	0.4	0.6	0.76	(c)
Tm																			
Yb	0.8	1.093	0.96	0.96	0.93	0.94	(b)							0.7	0.7	0.5	0.7	0.8	(c)
Lu	0.125	0.165	0.14	0.141	0.146	0.145	(b)												
Hf																			
Ta																			
W ppb																			
Re ppb																			
Os ppb																			
Ir ppb																			
Pt ppb																			
Au ppb																			
Th ppm																			
U ppm																			

technique (a) electon probe, (b) INAA, (c) ion microprobe

Table 3. Chemical composition of Individual Glass Beads (examples).

	15301 (green)					15301 (yellow)				15426 (green)	brown	green	green	green		
reference	Hughes 90					Hughes 90				Ma 81		Steele 92		Galbreath 90		
weight (a)	8	10.5	30.5	37.5	6.3	21.5	74.8	1.3		average 55	average 5	C	E	1	4	
SiO2 %	44.8	45	44.4	44.9	42.3	48	43	42.8	(c)			48.26	45.38	45.9	46.1	(c)
TiO2	0.44	0.45	0.47	0.46	3.75	3.42	3.55	3.69	(c)	0.38	3.7	0.24	0.45	0.37	0.45	(c)
Al2O3	7.8	7.5	7.5	7.4	8.7	9.5	9.1	8.9	(c)	7.5	8.5	7.88	7.76	7.88	7.73	(c)
FeO	20.1	20	20.7	20.7	22.3	20	22.1	22.7	(c)	20	23.2	16.09	19.38	19.9	19.6	(c)
MnO	0.31	0.31	0.32	0.27	0.34	0.26	0.3	0.31	(c)	0.26	0.273	0.25	0.251	0.17	0.4	(c)
MgO	17.2	17.9	17.2	17.1	12.8	7.5	12.2	11.5	(c)	17.5	12.5	18.19	18.12	17.7	17.6	(c)
CaO	8.7	8.1	8.6	8.5	8.7	10.6	8.7	9.1	(c)	8.5	9	8.59	8.17	8.46	8.56	(c)
Na2O	0.15	0.17	0.17	0.19	0.48	0.44	0.57	0.54	(b)	0.133	0.4	0.125	0.147	0.14	0.05	(c)
K2O	0.02	0.02	0.02	0.02	0.07	0.06	0.08	0.08	(b)		0.09					
P2O5																
S %																
sum																
Sc ppm	37.3	33.6	37.3	35.4	43.2	56.6	47.8	43.4	(b)	37.5	43.5	36.2	33.1	39.2	38	(d)
V										165	116			172	161	(d)
Cr	3626	3489	3626	3489	3968	5063	3832	4447	(b)	3654	3777	3934	3489	3434	3178	(d)
Co	75	77	77	77	67	34	73	65	(b)	74.8	65.2	53	72.9	69	66.3	(d)
Ni	155	159	163	191	162	64	72	72	(b)	153		95	131			
Cu																
Zn																
Ga																
Ge ppb																
As																
Se																
Rb																
Sr	30	40	20	20	160	110	170	320	(b)					23.6	20.7	(d)
Y																
Zr	20		15		260	250	190	200	(b)					21.3	18.8	(d)
Nb																
Mo																
Ru																
Rh																
Pd ppb																
Ag ppb																
Cd ppb																
In ppb																
Sn ppb																
Sb ppb																
Te ppb																
Cs ppm		0.05	0.04	0.03	0.24	0.09	0.15	0.08	(b)							
Ba	38	26	8	39	142	116	173	129	(b)					15.4	13.1	(d)
La	1.3	1.7	1.5	1.3	8.7	11.7	8.9	10	(b)	1.2	9.6	0.656	1.696		1.31	(d)
Ce	4.9	3.6	3.4	3.4	25.6	36.2	25.5	25.6	(b)					3.49	3.4	(d)
Pr																
Nd	3.3	2.9	2.4	3.5	18.6	23.3	18	16	(b)					1.73	1.73	(d)
Sm	0.77	0.79	0.81	0.84	6.4	9	7.1	6.7	(b)	0.83	6.8	0.429	0.97	0.55	0.56	(d)
Eu	0.26	0.26	0.26	0.29	1.61	1.68	1.89	1.6	(b)	0.24	1.51	0.161	0.312	0.09	0.1	(d)
Gd																
Tb	0.16	0.2	0.21	0.22	1.58	2.02	1.64	1.58	(b)	0.21	1.4	0.121	0.234	0.94	0.99	(d)
Dy																
Ho																
Er														0.62	0.6	(d)
Tm																
Yb	0.88	0.91	0.85	1.01	4.2	7.3	4	4.6	(b)	0.97	4.5	0.777	1.033	0.71	0.81	(d)
Lu	0.14	0.13	0.16	0.17	0.49	0.93	0.59	0.55	(b)	0.14	0.62	0.141	0.152			
Hf	0.51	0.5	0.59	0.48	4.7	5.5	5.4	4.7	(b)	0.57	5.1					
Ta	0.14	0.21	0.13	0.15	0.85	1	1	0.85	(b)		0.7					
W ppb																
Re ppb																
Os ppb																
Ir ppb																
Pt ppb																
Au ppb																
Th ppm	0.1	0.13	0.2	0.16	1.11	0.86	1.11	0.95	(b)							
U ppm		0.11			0.34	0.37	0.25	0.26	(b)							

technique (a) micrograms, (b) INAA, (c) elec. Probe, (d) ion probe

Table 4. Chemical composition of red and yellow glass (in green glass clods).

	red-brown	yellow	red	red	red	yellow	brown	yellow	yellow-brown		ave 41	
reference	Ridley 73		Delano 80			Delano 81	Butler 78	Delano 86	Hughes 88	Ma 81	Hughes 88	
weight	15427	15427	A	B	C	indiviual	15425,26		15427			
SiO2 %	36.16	42.47	35.6	36	36.5	44	42.86	42.9				
TiO2	13.48	3.96	13.8	13.8	13.6	4.67	3.58	3.48	3.5	3.7	3.7	(a)
Al2O3	8.54	9.01	7.15	7.7	8.46	10.4	8.48	8.3	8.2	8.5	8.3	(a)
FeO	20.48	21.78	21.9	21.5	20.9	20	21.97	22.1	22.2	23.2	22.8	(a)
MnO			0.25	0.24	0.24	0.22	0.32	0.27	0.28	0.273	0.28	(a)
MgO	10.65	12.39	12.1	11.1	10.3	9.79	12.63	13.5	12.1	12.5	12.9	(a)
CaO	8.89	9.23	7.89	8.3	8.7	9.92	8.4	8.5	9	9	8.4	(a)
Na2O	0.64	0.53	0.49	0.58	0.61	0.61	0.36	0.45	0.4	0.4	0.51	(a)
K2O	0.5	0.45	0.12	0.14	0.15	0.17	0.09		0.08	0.09		
P2O5												
S %												
sum												
Sc ppm									42	43.5		
V									118	116		
Cr	3968	3900	5268	4516	3763	1916	4310	4037	4174	3763	4926	(a)
Co									69	65		
Ni			<50					85				
Cu												
Zn												
Ga												
Ge ppb												
As												
Se												
Rb												
Sr												
Y												
Zr												
Nb												
Mo												
Ru												
Rh												
Pd ppb												
Ag ppb												
Cd ppb												
In ppb												
Sn ppb												
Sb ppb												
Te ppb												
Cs ppm												
Ba												
La									8.6	9.4	(b)	
Ce									24.5		(b)	
Pr												
Nd									14.8		(b)	
Sm									6.4	6.8	(b)	
Eu									1.45	1.51	(b)	
Gd												
Tb										1.4	(b)	
Dy												
Ho									1.74		(b)	
Er												
Tm									0.74		(b)	
Yb									4.3	4.6	(b)	
Lu									0.48	0.62	(b)	
Hf									5.3	5	(b)	
Ta									0.58	0.69	(b)	
W ppb												
Re ppb												
Os ppb												
Ir ppb												
Pt ppb												
Au ppb												
Th ppm												
U ppm												
technique	*(a) elec. Probe, (b) INAA*											

Table 5. Chemical composition of rake samples.

	15365	15366	15370	15376	
reference	Bunch 72	Steele 72	Bunch 72	Bunch 72	
weight	bulk	green gl.	bulk	bulk	
SiO2 %	43.8	46.4	43.2	43.6	(a)
TiO2	0.44	0.4	0.4	0.43	(a)
Al2O3	7.7	7.5	7.1	7	(a)
FeO	21.4	20.3	21	21.5	(a)
MnO	0.3		0.21	0.23	(a)
MgO	15.7	18.1	18.5	18.7	(a)
CaO	8.6	8.1	8.2	8.3	(a)
Na2O	0.12	0.1	0.07	0.08	(a)
K2O	<0.02	0.07	<0.02	<0.02	(a)
P2O5	0.02		0.03	0.03	(a)
S %					
sum					
Sc ppm					
V					
Cr	3200	3500	3600	3500	(a)

Table 6: Highly Siderophile Elements in 15426.

	80 - 200 microns		> 200 micron	
Figure				
	etchate	residue	etchate	residue
Ru	1.48	0.027	0.8	0.264
Pd	1.67	0.056	0.38	0.107
Re	0.082	0.0061	0.03	0.0063
Os	1.02	0.035	0.268	0.0181
Ir	0.845	0.035	0.232	
Pt	2.642	0.234	0.842	0.642

(ppb from Walker et al. 2004)

Table 7: Additional compositional data for green glass.

		U ppm	Th ppm	K2O %	Rb ppm	Sr ppm	Nd ppm	Sm ppm	technique
Keith et al. 1972	15426	0.41	1.89	0.09					counting
Barnes et al. 1973	15426	0.1134	0.4203		0.584	40.59			IDMS
Tatsumoto et al. 1987	15426	0.1134	0.633						IDMS
	15426	0.072	0.275						IDMS
	residue gg	0.0475	0.1642						IDMS
	residue gg	0.0396	0.1394						IDMS
	residue gg	0.0339	0.1258						IDMS
Lugmair and Marti 1978	15426 gg								IDMS
Fleischer and Hart 1974	15401 gg	0.044							tracks
	15426	~0.05							tracks
MacDougall et al. 1973									
Storzer et al. 1973	green glass	0.049							tracks
Bhandari et al. 1973									
Wiesmann 75	15303 clod	0.088		0.12	0.329	27.8	2.5	0.818	IDMS
	15301 gg	0.063		0.12	0.253	28.6	2.65	0.866	IDMS

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