15382

KREEP Basalt

3.2 grams

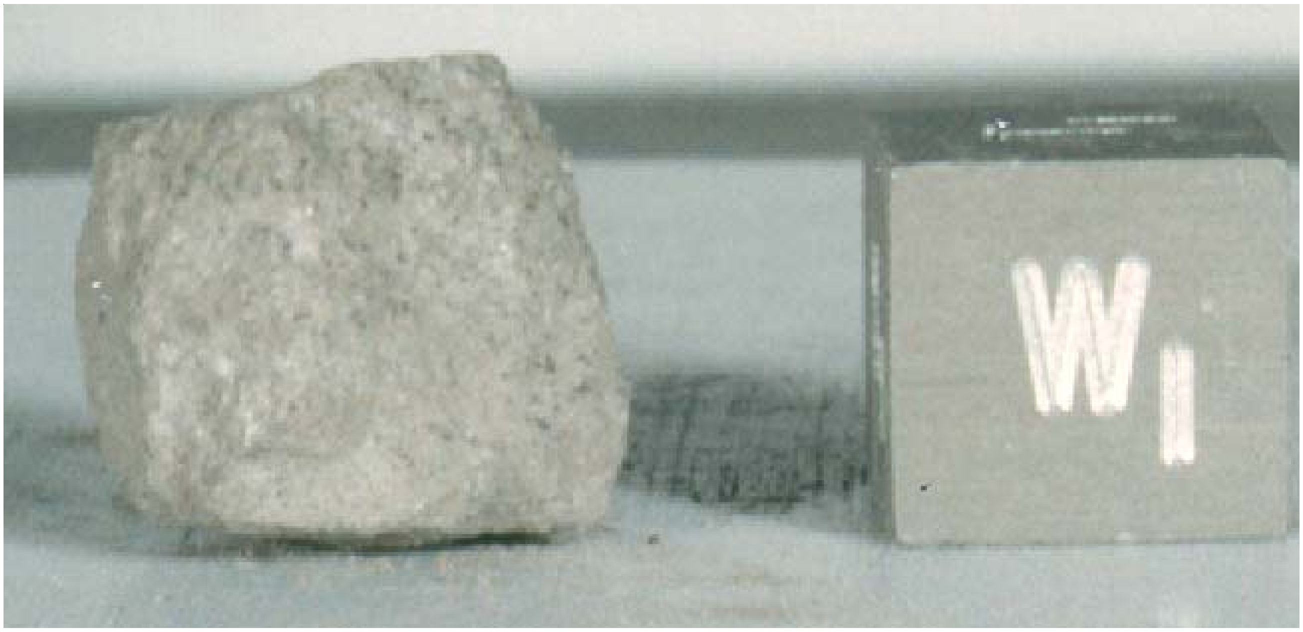

Figure 1: Photo of 15382 and one cm cube. NASA # S71-49163

Introduction

15382 is a pristine feldspathic basalt with high rare-earth-element content. Only a few pristine samples of this important rock type were returned from the moon, also including 15386 and fragments in 15434 and other Apollo 15 soils (Meyer 1972). These fragments were recognized as samples of chilled volcanic liquid and have been a source of much speculation (Meyer 1977, Ryder 1987, Papike et al. 1997). *Although 14310 was generally similar, it had high meteoritical siderophile content and is nonpristine.*

15382 was collected, along with 15386, as part of a rake sample from the soil just inside the rim of Spur Crater, Apollo 15. Meyer (1977), Warren and Wasson (1979), Ryder (1985) and Papike et al. (1998) provide reviews of what was known about KREEP basalt. Spudis (1978) and Ryder (1994) suggest that the source of the Apollo 15 KREEP basalt fragments might be the Apennine Front Formation and speculate that KREEP volcanism might have been triggered by the Imbrium impact (same age ?).

Petrography

The texture of 15382 is that of a fine-grained subophitic basalt (figure 2). Thin plagioclase laths (0.2 to 0.8 mm long) are intergrown with chemcialy zoned pyroxene (Dowty et al. 1976; Crawford and Hollister 1977). Large patches of mesostasis are present, consisting of ilmenite, high-Si glass, cristobalite, tranquillityite, armalcolite, baddeleyite, whitlockite, apatite and Cr-ulvöspinel (Nehru et al. 1974, Dowty et al. 1976).

It is clear from the texture of 15382, that pyroxene and plagioclase crystallized together, as along a cotectic on a phase diagram. During the crystallization, the residual liquid separated into two immiscible liquids, one Fe-rich and the other Si-rich, which are found as inclusions in plagioclase (Hollister and Crawford 1977). They find that liquid immiscibility may have occurred after only 20% of the liquid had crystallized!

Ryder (1987) discusses the petrographic evidence for nonlinear cooling rates for some of the other Apollo 15 KREEP basalt fragments, and thus, by inference, a

Figure 2: Photomicrograph of thin section of 15382 showing bent plagioclase crystals intergrown with pyroxene. NASA # S79-27741. Field of view is 2.7 mm. Photo is "off-color" because of fading of print.

volcanic origin for all of the pristine Apollo 15 KREEP basalts (including 15382 and 15386). Indeed, Dowty et al. (1976) reported one grain of plagioclase in 15382 with a relict homogeneous core (An_{95}).

Mineralogy

Pyroxene: The cores of pyroxene crystals are Mg-rich orthopyroxene, which are surrounded by zoned pigeonite (figure 3).

Plagioclase: Plagioclase is strongly zoned (An_{90-70}) and has K_2O contents ranging from 0.25% interior to 0.5% at rims. FeO and MgO are also elevated and it is clear the plagioclase formed quickly. Glass inclusions are found in the outer rims of the plagioclase laths (Hollister and Crawford 1977). Dowty et al. (1976) reported one plagioclase (0.5 x 0.2mm) with An_{95}.

Opaques: Analyses for ilmenite and Cr-ulvöspinel are reported in Nehru et al. (1974).

Glass: The intersticies between plagioclase and pyroxene contain yellow glass. The glass is potassic (6-8% K_2O) and silica-rich (70-75% SiO_2), but with exsolved blebs of Fe-rich glass (Dowty et al. 1976; Hollister and Crawford 1977).

Metal: Dowty et al. (1976) found small grains of iron metal in the mesostasis and in troilite. The metal in 15382 was found to have very low Ni content (<0.3%).

Mineralogical Mode for 15382

	Dowty et al. 1976	Crawford and Hollister 1977	Taylor et al. 1991
Pyroxene	34	42.5	41
Plagioclase	49	32.9	43
Opaques	5	6.4	6
Mesostasis	8	10.5	8
Glass		7.7	
Cristobalite	4		

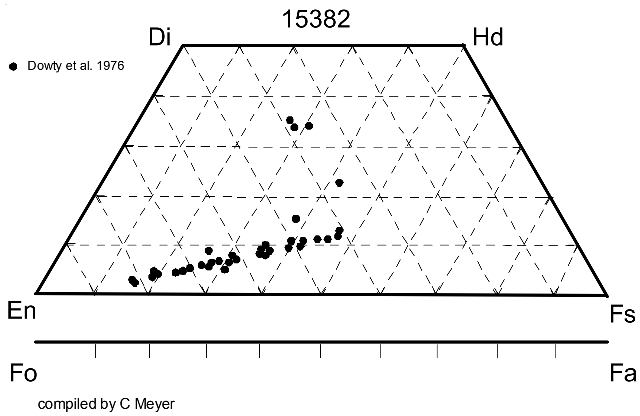

Figure 3: Pyroxene composition for 15382. Data replotted from Dowty et al. (1976).

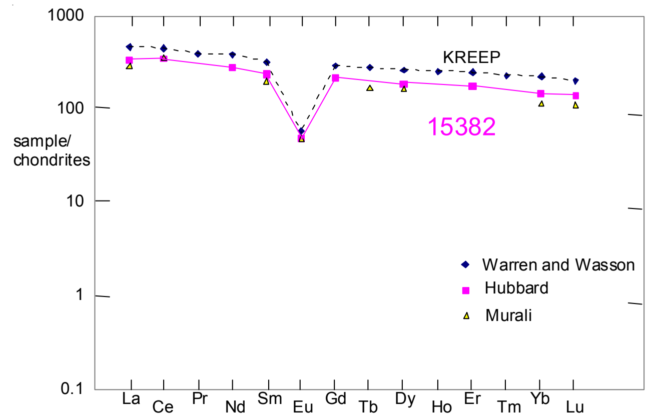

Figure 4: Normalized rare-earth-element diagram for 15382. Data from Hubbard et al. (1973) and Murali et al. (1977). "KREEP" pattern shown for comparison (see text).

Chemistry

The composition of 15382 is silica rich and high in large-ion-lithophile elements (K, Th, Zr, REE). The distinctive REE pattern is parallel to the "KREEP" pattern from other sites (Warren and Wasson 1979) (figure 4). 15382 and other KREEP basalts also have relatively high Mg/Fe ratios, such that they can not be simply derived by partial melting (McKay and Weill 1976).

Gros et al. (1976) found very low content of Ni, Ir, Au and Re in 15382, such that this pristine rock has not had an added meteoritic component *(as has been the case for most KREEP).*

Radiogenic age dating

15382 has been dated by the 39/40Ar plateau technique by Turner et al. (1973) and Stettler et al. (1973) (figures 5 and 6). Tera and Wasserburg (1976) and Papanastassiou and Wasserburg (1976, 1977) reported K, Rb, Sr and Pb isotopes on 2 mg of 15382 and have also reported a mineral isochron by Rb/Sr (see table).

Lugmair and Carlson (1978) determined the whole rock Sm and Nd isotopic composition and calculated the "whole rock" age at ~ 4.4 b.y. which is interpreted as the closure age of the initial global scale lunar differentiation (see also Carlson and Lugmair 1979).

Lee et al. (1997) determined the W isotopes in 15382 and other lunar samples.

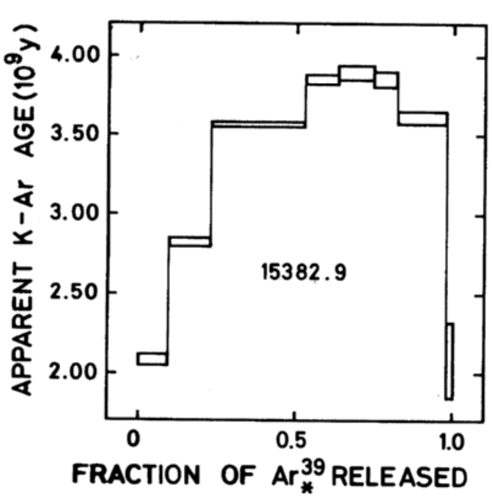

Figure 5: Ar release pattern for 15382 from Stettler et al. 1973.

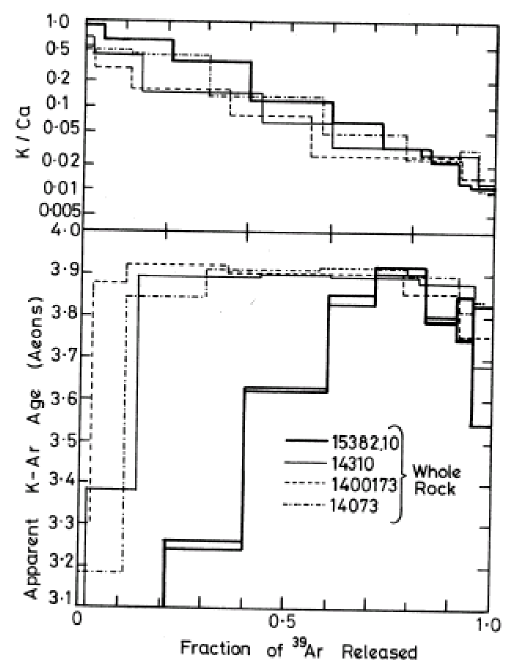

Figure 6: Ar release pattern for 15382 from Turner et al. 1973.

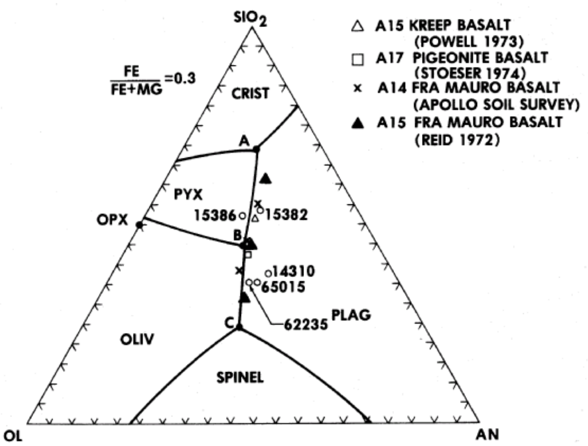

Figure 7: Projection of phase diagram for Fe/Fe+Mg = 0.3 as determined by Walker et al. (1973), showing that the compsition of 15382 is near the cotectic between pyroxene and plagioclase (figure from Meyer 1977).

The crystallization age of Apollo 15 KREEP basalts (~3.9 b.y.) is indistinguishable from the age of the Imbrium basin.

Cosmogenic isotopes and exposure ages

Stettler et al. (1973) and Turner et al. (1973) determined the exposure age of 15382 as 230 m.y. and 240 m.y. respectively by ^{38}Ar technique. O'Kelley et al. (1976) determined ^{26}Al = 74 ± 20 dpm/kg.

Other Studies

Walker et al. (1973) showed that KREEP basalt was formed by low-pressure melting (figure 7). Hess et al. (1978) studied the low pressure phase equilibria for 15382 composition and found that the liquidus occurs at 1180 deg. C with simultaneous crystallization of plagioclase (An_{85}) and low-Ca pyroxene ($Wo_5En_{76}Fs_{19}$). Ilmenite did not form until late in the crystallization sequence.

Haines and Weiss (1978) determined a fission track retention age of 3.2 b.y.

Processing

15382 was apparently sawn to yield a thin slab for thin sections. There are only 3 thin sections.

Additional material can be found in the Apollo 15 soils.

Summary of Age Data for 15382

	Ar/Ar	Rb/Sr
Turner et al. 1973	3.91 ± 0.05	
Stettler et al. 1973	3.90 ± 0.05	
Papanastassiou and Wasserburg 1976		3.90 ± 0.02

Caution: These ages have not been corrected for new decay constants.

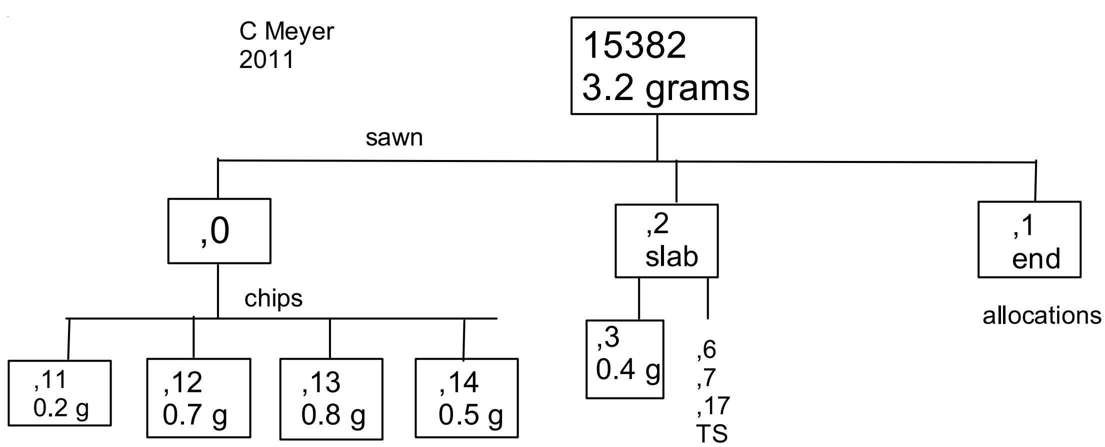

Table 1. Chemical composition of 15382.

reference	Hubbard 73		Dowty 76		Murali 77		Gros 76		O'Kelley 76		Hollister 77		Nyquist 73	Pap 76	Lugmair 78		Lee 97	
weight					84 mg				2.24 g									
SiO2 %			*52.4*	(c)							*52.53*	(c)						
TiO2	2.17	(a)	*1.78*	(c)	2.2	(b)					*1.29*	(c)						
Al2O3	14.9	(a)	*17.8*	(c)	16.4	(b)					*18.44*	(c)						
FeO	9.2	(a)	*8.6*	(c)	10	(b)					*8.27*	(c)						
MnO			*0.1*	(c)	0.14	(b)												
MgO	7.4	(a)	*7.1*	(c)	9.8	(b)					*7.01*	(c)						
CaO	7.1	(a)	*9.9*	(c)	10.4	(b)					*10.3*	(c)						
Na2O	0.85	(a)	*0.96*	(c)	0.81	(b)												
K2O			*0.57*	(c)	0.53	(b)			0.59	(e)	*0.46*	(c)						
P2O5			*0.55*	(c)														
S %																		
sum			99.76															
Sc ppm					19	(b)												
V					60	(b)												
Cr			1437	(c)	2121	(b)												
Co					17	(b)												
Ni					28	(b)	18	(d)										
Cu																		
Zn							2.6	(d)										
Ga																		
Ge ppb							47.1	(d)										
As																		
Se							72	(d)										
Rb	16.1	(a)					16	(d)					16.1	14.1				(a)
Sr	195	(a)											195	183				(a)
Y																		
Zr	1170	(a)			966	(b)												
Nb																		
Mo																		
Ru																		
Rh																		
Pd ppb																		
Ag ppb							0.44	(d)										
Cd ppb							86.6	(d)										
In ppb							2.66	(d)										
Sn ppb																		
Sb ppb							0.17	(d)										
Te ppb							1	(d)										
Cs ppm							0.725	(d)										
Ba	793	(a)			610	(b)												
La	79.5	(a)			68.1	(b)												
Ce	212	(a)			218	(b)												
Pr																		
Nd	127	(a)													111.8	107		(a)
Sm	35.2	(a)			29.7	(b)									31.06	29.8		(a)
Eu	2.77	(a)			2.72	(b)												
Gd	42.9	(a)																
Tb					6.2	(b)												
Dy	45.7	(a)			40	(b)												
Ho																		
Er	28.1	(a)																
Tm																		
Yb	24	(a)			19.2	(b)												
Lu	3.43	(a)			2.7	(b)												
Hf	32.7	(a)			27	(b)											22.9	(a)
Ta					3.1	(b)												
W ppb																	1223	(a)
Re ppb							0.009	(d)										
Os ppb							0.018	(d)										
Ir ppb							0.013	(d)										
Pt ppb																		
Au ppb							0.003	(d)										
Th ppm					*1*	(b)			10.5	(e)								
U ppm	3.72	(a)					3.3	(d)	3.1	(e)								

technique (a) IDMS, (b) INAA, (c) broad beam e. probe, (d) RNAA, (e) radiation counting

References for 15382

Basu A., Holmberg B.B. and Molinaroli E. (1992) Origin of yellow glasses associated with Apollo 15 KREEP basalt fragments. *Proc. 22nd Lunar Planet. Sci. Conf.* 365-372. Lunar Planetary Institute, Houston.

Butler P. (1971) Lunar Sample Catalog, Apollo 15. Curators' Office, MSC 03209

Carlson R.W. and Lugmair G.W. (1979b) Sm-Nd constraints on early lunar differentiation and the evolution of KREEP. *Earth Planet. Sci. Lett.* **45**, 123-132.

Crawford M.L. and Hollister L.S. (1974) KREEP basalt: a possible partial melt from the lunar interior. *Proc. 5th Lunar Sci. Conf.* 399-419.

Dowty E., Conrad G.H., Green J.A., Hlava P.F., Keil K., Moore R.B., Nehru C.E. and Prinz M. (1973a) Catalog of Apollo 15 rake samples from stations 2 (St. George), 7 (Spur Crater) and 9a (Hadley Rille). Inst. Meteoritics Spec. Publ. No 11, 51-73. Univ. New Mex. ABQ.

Dowty E., Keil K., Prinz M., Gros J. and Takahashi H. (1976) Meteorite-free Apollo 15 crystalline KREEP. *Proc. 7th Lunar Sci. Conf.* 1833-1844.

Gros J., Takahashi H., Hertogen J., Morgan J.W. and Anders E. (1976) Composition of the projectiles that bombarded the lunar highlands. *Proc. 7th Lunar Sci. Conf.* 2403-2425.

Haines E.L. and Weiss J.R. (1978) KREEP fission track ages from Hadley Delta (abs). *Lunar Sci.* **IX**,, 448-450.

Hess P.C., Rutherford M.J. and Campbell H.W. (1978) Ilmenite crystallization in nonmare basalt: Genesis of KREEP and high-Ti mare basalt. *Proc. 9th Lunar Planet. Sci. Conf.* 705-724.

Hlava P.F., Green J.A., Prinz M., Keil K., Dowty E. and Bunch T.E. (1973) Apollo 15 rake samples, microbreccias and non-mare rocks: Bulk rock, mineral and glass electron microprobe analyses. Inst. Meteoritics Spec. Publ. No 11, 51-73. Univ. New Mex. ABQ

Hollister L.S. and Crawford M.L. (1977) Melt immiscibility in Apollo 15 KREEP: Origin of the Fe-rich mare basalts. *Proc. 8th Lunar Sci. Conf.* 2419-2432.

Hubbard N.J., Gast P.W., Rhodes J.M., Bansal B.M., Wiesmann H. and Church S.E. (1972a) Nonmare basalts: Part II. *Proc. 3rd Lunar Sci. Conf.* 1161-1179.

Hubbard N.J., Rhodes J.M., Gast P.W., Bansal B.M., Shih C.-Y., Wiesmann H. and Nyquist L.E. (1973b) Lunar rock types: The role of plagioclase in non-mare and highland rock types. *Proc. 4th Lunar Sci. Conf.* 1297-1312.

Lee D-C., Halliday A.N., Snyder G.A. and Taylor L.A. (1997) Age and origin of the Moon. *Science* **278**, 1098-1103.

LSPET (1972a) The Apollo 15 lunar samples: A preliminary description. *Science* **175**, 363-375.

LSPET (1972b) Preliminary examination of lunar samples. Apollo 15 Preliminary Science Report. NASA SP-289, 6-1—6-28.

Lugmair G.W. and Carlson R.W. (1978) The Sm-Nd history of KREEP. *Proc. 9th Lunar Planet. Sci. Conf.* 689-704.

McKay G.A. and Weill D. (1976) The petrogenesis of KREEP. *Proc. 7th Lunar Sci. Conf.* 2427-2447.

McKay G.A. and Weill D. (1977) KREEP petrogenesis revisited. *Proc. 8th Lunar Science Conf.* 2339-2355.

Meyer C. (1972) Mineral assemblages and the origin of non-mare lunar rock types (abs). *Lunar Sci.* **III,** 542-544. Lunar Planetary Institute, Houston.

Meyer C. (1977) Petrology, mineralogy and chemistry of KREEP basalt. *Physics and Chemistry of the Earth* **10**, 239-260. (Ahrens and Runcorn , eds)

Murali A.V., Ma M.-S., Laul J.C. and Schmitt R.A. (1977a) Chemical composition of breccias, feldspathic basalt and anorthosites from Apollo 15 (15308, 15359,15382, and 15362), Apollo 16 (60618 and 65785), Apollo 17 (72434, 72536, 72559, 72735, 72738, 78526, and 78527) and Luna 20 (22012 and 22013) (abs). *Lunar Sci.* **VIII**, 700-702. Lunar Planetary Institute, Houston.

Neal C.R. and Kramer G.Y (2003) The composition of KREEP: A detailed study of KREEP basalt 15386 (abs#1665). *Lunar Planet. Sci.* **XXXIV,** Lunar Planetary Institute, Houston.

Nehru C.E., Prinz M., Dowty E. and Keil K. (1973) Electron microprobe analyses of spinel group minerals and ilmenite in Apollo 15 rake samples of igneous origin. Spec. Pub. Num. 10, UNM Inst. Meteor. ABQ

Nehru C.E., Prinz M., Dowty E. and Keil K. (1974) Spinel-group minerals and ilmenite in Apollo 15 rake samples. *Am. Mineral.* **59**, 1220-1235.

Nyquist L.E., Hubbard N.J., Gast P.W., Bansal B.M., Wiesmann H. and Jahn B-M. (1973) Rb-Sr systematics for chemically defined Apollo 15 and 16 materials. *Proc. 4th Lunar Sci. Conf.* 1823-1846.

O'Kelley G.D., Eldridge J.S., Northcutt K.J. and Schonfeld E. (1976) Radionuclide concentrations of KREEP basalt samples 15382 and 15386 (abs). *Lunar Sci.* **VII**, 651-652.

Papanastassiou D.A. and Wasserburg G.J. (1976b) Early lunar differentiates and lunar initial $^{87}Sr/^{86}Sr$ (abs). *Lunar Sci.* **VII**, 665-667. Lunar Planetary Institute, Houston.

Papanastassiou D.A., DePaolo D.J., Tera F. and Wasserburg G.J. (1976c) An isotopic triptych on mare basalts: Rb-Sr, Sm-Nd, U-Pb. *Lunar Science* **VIII**, 750-752. Lunar Planetary Institute, Houston.

Ryder G. (1985) Catalog of Apollo 15 Rocks (three volumes). Curatoial Branch Pub. # 72, JSC#20787

Ryder G. (1987) Petrographic evidence for nonlinear cooling rates and a volcanic origin for Apollo 15 KREEP basalt. *Proc. 17th Lunar Planet. Sci. Conf.* in J. Geophys. Res. **92**, E331-E339.

Ryder G. (1988) Quenching and disruption of lunar KREEP lava flows by impacts. *Nature* **336**, 751-754.

Shih C.-Y. (1977) Origins of KREEP basalts. *Proc. 8th Lunar Sci. Conf.* 2375-2401.

Simonds C.H., Warner J.L. and Phinney W.C. (1975b) The petrology of the Apennine Front revisited. *Lunar Sci.* **VI**, 744-746.

Spudis P.D. (1978) Composition and origin of the Apennine Bench Formation. *Proc. 9th Lunar Planet. Sci. Conf.* 3379-3394.

Stettler A., Eberhardt P., Geiss J., Grogler N. and Maurer P. (1973) Ar^{39}-Ar^{40} ages and Ar^{37}-Ar^{38} exposure ages of lunar rocks. *Proc. 4th Lunar Sci. Conf.* 1865-1888.

Swann G.A., Hait M.H., Schaber G.C., Freeman V.L., Ulrich G.E., Wolfe E.W., Reed V.S. and Sutton R.L. (1971b) Preliminary description of Apollo 15 sample environments. U.S.G.S. Interagency report: 36. pp219 with maps

Swann G.A., Bailey N.G., Batson R.M., Freeman V.L., Hait M.H., Head J.W., Holt H.E., Howard K.A., Irwin J.B., Larson K.B., Muehlberger W.R., Reed V.S., Rennilson J.J., Schaber G.G., Scott D.R., Silver L.T., Sutton R.L., Ulrich G.E., Wilshire H.G. and Wolfe E.W. (1972) 5. Preliminary Geologic Investigation of the Apollo 15 landing site. In Apollo 15 Preliminary Science Rpt. NASA SP-289. pages 5-1-112.

Walker D., Grove T.L., Longhi J., Stopler E.M. and Hays J.F. (1973a) Origin of lunar feldspathic rocks. *Earth Planet. Sci. Lett*. **20**, 325-336.

Warren P.H. and Wasson J.T. (1978) Compositional-petrographic investigation of pristine nonmare rocks. *Proc. 9th Lunar Planet. Sci. Conf.* 185-217.