60025 CATACLASTIC ANORTHOSITE, PRISTINE 1836 g

INTRODUCTION: 60025 is a coarse-grained, moderately shocked and cataclastic ferroan anorthosite which is monomict and is free of meteoritic siderophiles (i.e. chemically pristine). A small patch of dark vesicular glass is present on one surface (Fig. 1). 60025 was collected 15 m southwest of the Lunar Module where it was perched. It is moderately coherent with some penetrative fractures. Its orientation is known and zap pits occur on all surfaces, though not equally distributed.

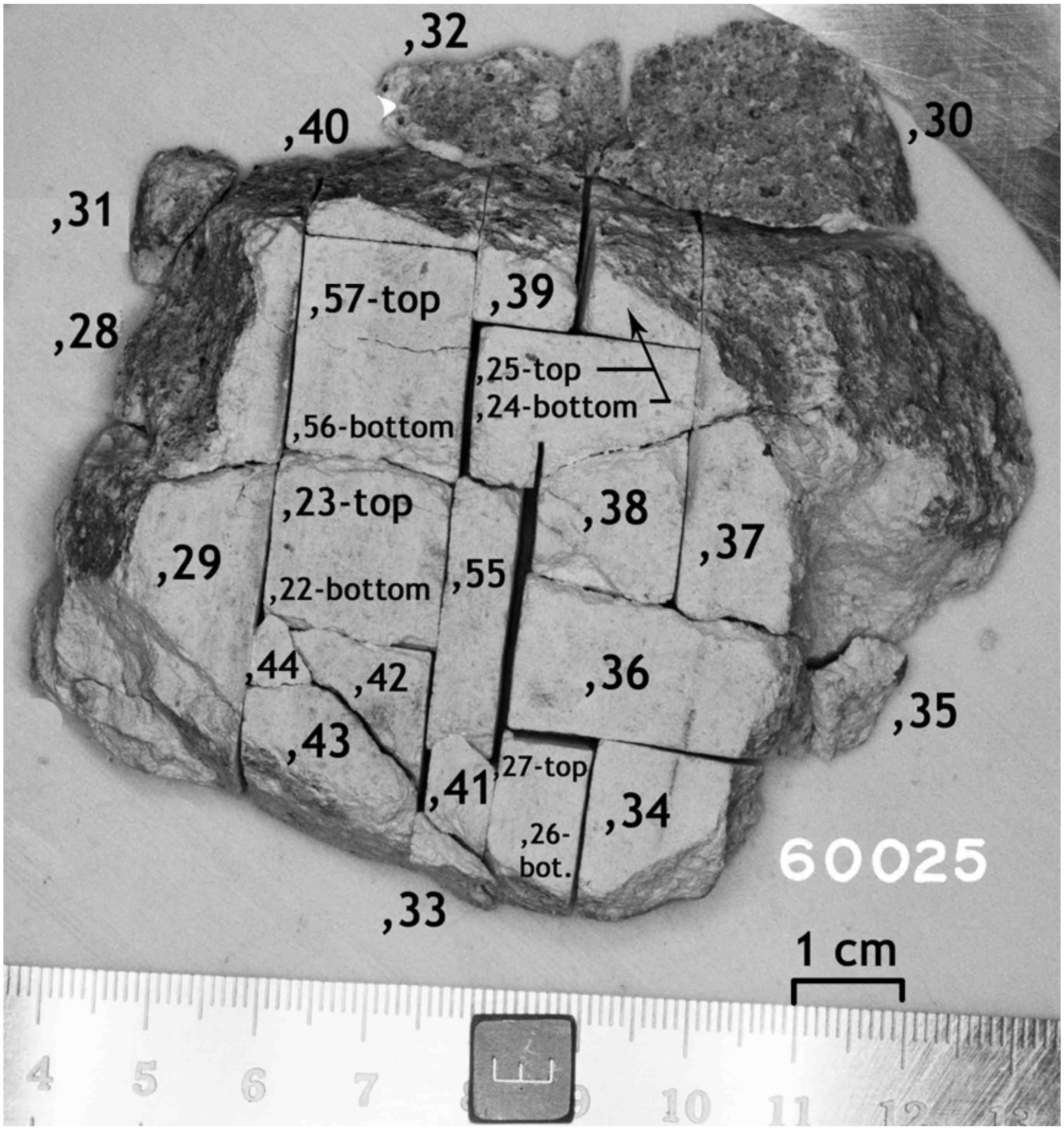


FIGURE 1. Saw-cut slab. S-72-49095.

PETROLOGY: Walker et al. (1973), Hodges and Kushiro (1973), Dixon and Papike (1975), Warren and Wasson (1978) and LSPET (1973) provide general petrographic information. Takeda et al. (1976) studied pyroxenes in detail and Longhi et al. (1976), Hansen et al (1979a) and Meyer (1979) report data on minor elements in plagioclase.

The rock is a true anorthosite with > 90% plagioclase (An_{94-98}). Shock-twinned and fractured clasts up to 4 mm long rest in a fine-grained and often recrystallized matrix of granulated plagioclase (Fig. 2). Mafics are ferroan and irregularly distributed. Walker et al. (1973), Hodges and Kushiro (1973) and Dixon and Papike (1975) report <2% pyroxene and no olivine whereas LSPET (1973) indicates ~10% olivine, and a "mafic-rich" portion described by Warren and Wasson (1978) contains 20% olivine (Fo_{57-65}) and 10% pyroxene. A 2x2 mm optically continuous zone of pyroxene and a 4x4 mm zone of olivine attest to the coarse-grained nature of the rock prior to cataclasis (Warren and Wasson, 1978). Traces of silica, ilmenite, Cr-spinel and glassy inclusions in plagioclase are scattered throughout the rock.

FIGURE 2. 60025,130. general view, xpl. width 2 mm.

Anhedral pyroxenes (most <0.5 mm) are concentrated as discrete grains in the matrix but also occur as rods, stringers and irregular blotches along plagioclase twin planes and grain boundaries. The dominant pyroxene is orthopyroxene. Some grains show well developed exsolution lamellae of high-Ca pyroxene and were probably primary pigeonite. Augite is also present as discrete grains. Apparently three primary pyroxenes- orthopyroxene, pigeonite and augite - were present at the time of crystallization (Hodges and Kushiro, 1973). Pyroxene compositions are shown in Figure 3.

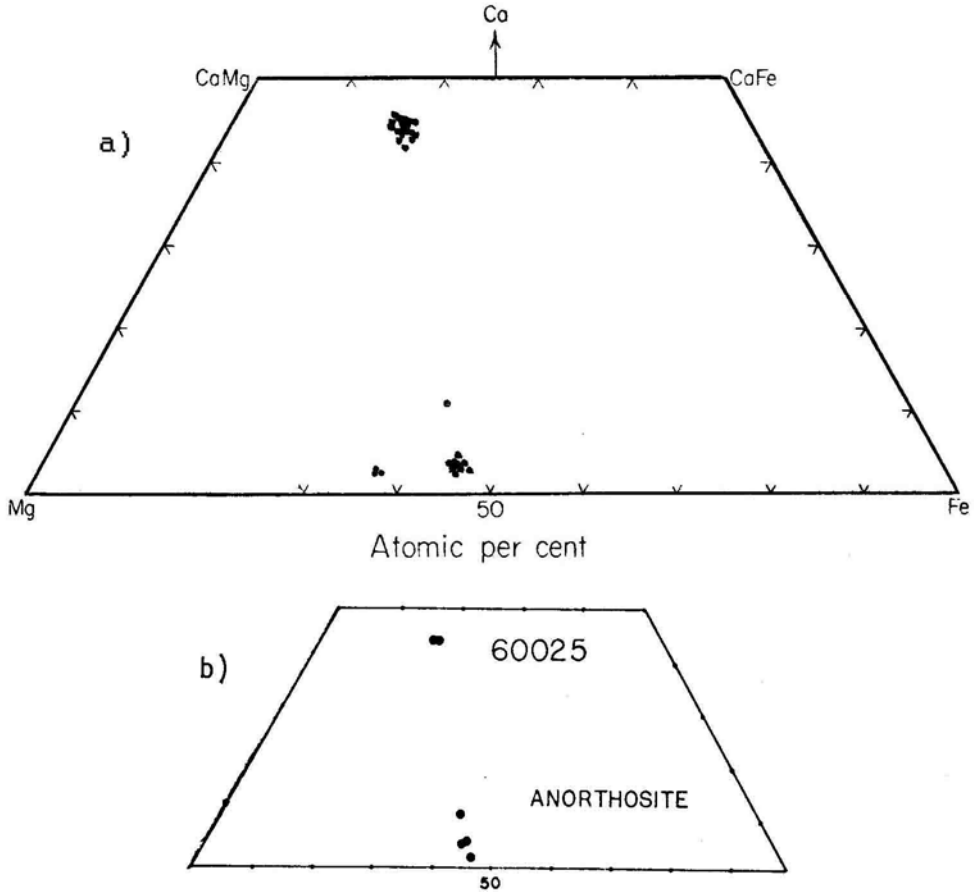


FIGURE 3. Pyroxenes.
a) from Hodges and Kushiro (1973). b) from Walker et al. (1973).

<u>EXPERIMENTAL PETROLOGY</u>: Ford et al. (1974) determined that plagioclase is the liquidus phase of a rock with the composition of 60025. The anhydrous liquidus occurs at temperatures >1370° C. Moderate water vapor pressure lowers the liquidus temperature to below 1200° C. The anhydrous solidus is ~1200° C.

<u>CHEMISTRY</u>: Chemical studies of 60025 are listed in Table 1 and a summary Chemistry in Table 2. The splits analyzed were almost pure plagioclase (Table 2, Fig. 4); apparently none of the mafic rich portions were sampled for chemistry.

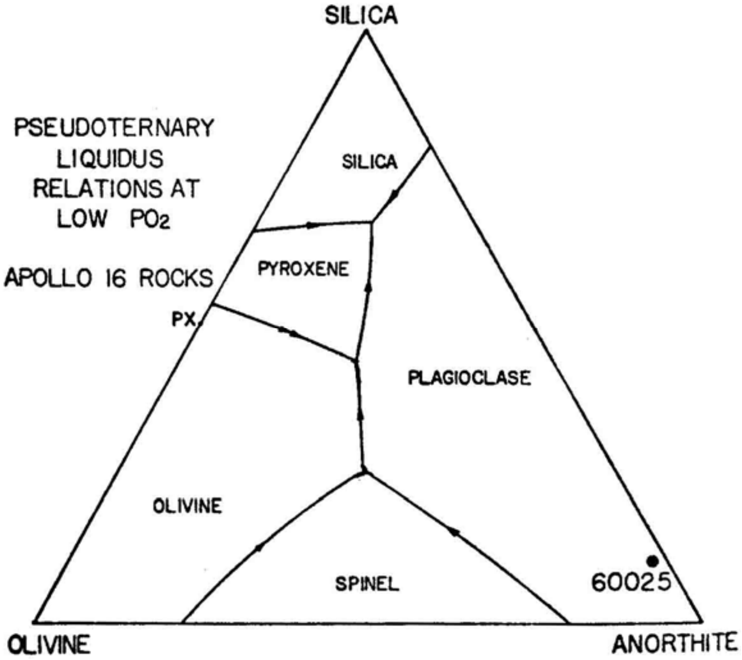


FIGURE 4. from Walker et al. (1973)

Rare earths are low with the large positive Eu anomaly typical of lunar anorthosites (Fig. 5). The REE pattern of 60025 parallels that of 15415 and 60015 but with absolute concentrations nearly twice as high. Zr and Hf and the Zr/Hf ratio are typical of lunar anorthosites and are among the lowest measured in any lunar material (Ehmann et a1.,1975; Garg and Ehmann, 1976).

60025 is also low in siderophiles indicating a lack of meteoritic contamination. Its very high volatile-to-involatile ratios (e.g. Tl/Cs and Tl/U) however suggest that a fumarolic component is present (Krahenbuhl et al., 1973). Sulfur is also enriched in 60025 relative to the other light gases (Table 2), its Fe content (Fig. 3 of Kerridge et al.,1975a) and other pristine anorthosites (e.g. 15415, 60015, 67075).

Flory et al. (1973) determined total amounts of hydrocarbons and other light gases and their release patterns upon heating. 60025 was the only rock analyzed by these authors to yield detectable methane, apparently produced by the hydrolysis of reactive, solar wind-deposited carbon.

Sato (1976) determined the oxygen fugacity of 60025 by the solid-electrolyte oxygen cell method and found it to have among the lowest fO_2 ever measured in lunar material. A self-reduction at high temperatures occurred during the first heating cycle. Reported values are given in Table 3.

STABLE ISOTOPES: Taylor and Epstein (1973) report δO^{18} and δSi^{30} values of +5.95 and -0.01 respectively for whole rock splits of 60025.

TABLE 1. Chemical studies of 60025 anorthosite.

Reference	Split #	Elements analyzed
Janghorbani et al. (1973)	,72	majors
Rose et al. (1973)	,95	majors, trace
Haskin et al. (1973)	,45	majors, REEs, other trace
Laul and Schmitt (1973)	,73	majors, REEs, other trace
Nakamura et al. (1973)	,76	majors, REEs, Ba
Walker et al. (1973)	,90	majors*
Krähenbühl et al. (1973)	,84	meteoritic sids. and vols.
Ehmann and Chyi (1974)	,72	Zr, Hf
Ehmann et al. (1975)	,72	Zr, Hf, Sc, Co, Fe, Eu
Miller et al. (1974)	,72	Fe, Sc, Co, Eu
Cripe and Moore (1974)	,82	S
Moore et al. (1973)	,82	C
Moore and Lewis (1976)	,82	N
Schaeffer and Husain (1974)	,86	K, Ca
Nyquist et al. (1975)	,26B	Rb, Sr
Papanastassiou and Wasserburg (1972b)	,65	Rb, Sr
Tera and Wasserburg (1972)	,65	U, Th, Pb
Tera et al. (1973)		
Nunes et al. (1974)	?,9003 (from ,26)	U, Th, Pb, Rb, Sr, K
Nunes et al. (1977)	,9003 (from ,26)	U, Th, Pb

*Microprobe, fused powder

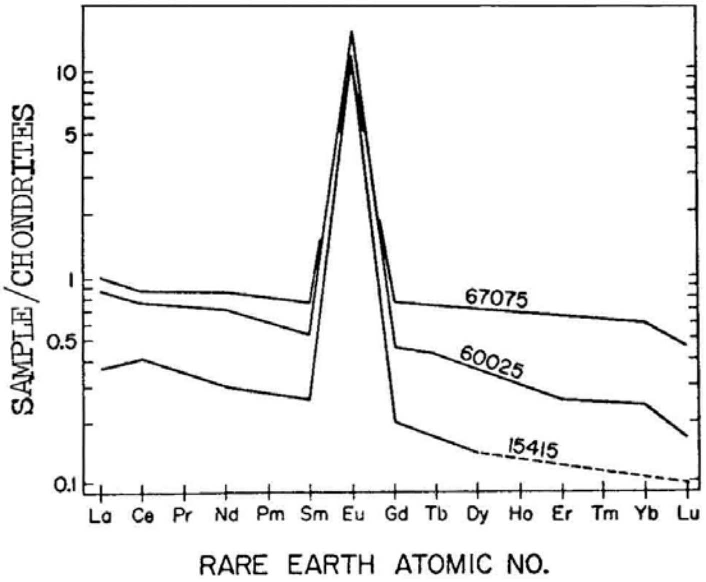


FIGURE 5. Rare earths; from Haskin et al.(1973).

TABLE 2. Summary chemistry of anorthosite 60025.

SiO_2	44.2
TiO_2	0.1
Al_2O_3	35.3
Cr_2O_3	0.02
FeO	0.6
MnO	0.014
MgO	0.2
CaO	19.0
Na_2O	0.44
K_2O	0.03
P_2O_5	0.003
Sr	218
La	0.3
Lu	0.005
Rb	0.02
Sc	0.05
Ni	∿ 1
Co	0.07
Ir ppb	0.006
Au ppb	0.007
C	35
N	56
S	240
Zn	<2(?)
Cu	8.4(?)

Oxides in wt%; others in ppm except as noted.

TABLE 3. Oxygen fugacity of 60025 (Sato, 1976).

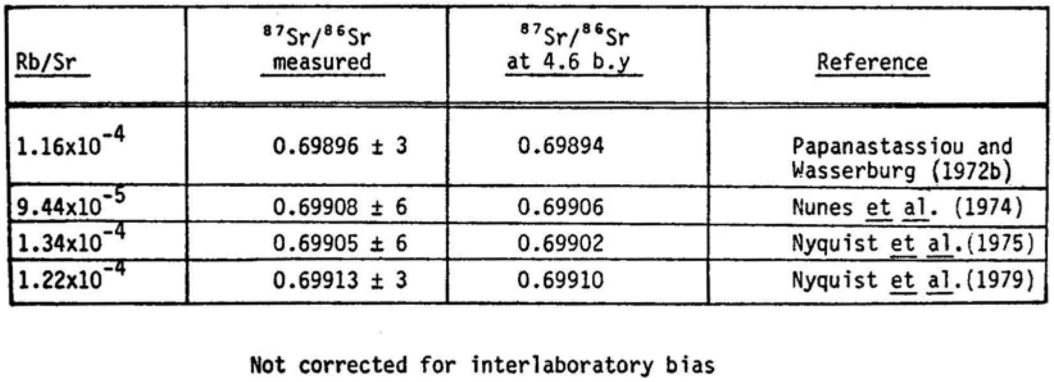
T (°C)	$-\log f_{O_2}$ (atm)
1000	16.9
1050	16.1
1100	15.4
1150	14.7
1200	14.1

RADIOGENIC ISOTOPES AND GEOCHRONOLOGY: Rb-Sr data are summarized in Table 4. The very low measured $^{87}Sr/^{86}Sr$ extrapolates to very close to BABI at 4.0 and 4.6 b.y. Only whole rock data from the anorthosite are currently available although a mineral isochron could conceivably be obtained from the mafic-rich portions of the rock. Schonfeld (1976) constructed a Rb-Sr whole rock isochron from data on lunar anorthosites which gave an apparent age of 4.6 b.y. and an initial ^{87}Sr/^{86}Sr of 0.69905. 60025 lies on this isochron.

An Ar-Ar determination yielded a well defined plateau age of 4.19 ± 0.06 b.y. (Fig. 6) (Schaeffer and Husain, 1974). There was no increase in apparent age at high temperatures (Fig. 6) indicating no relict Ar in ancient plagioclase clasts (Schaeffer and Husain, 1974).

U-Th-Pb data show very low concentrations of all of these elements and essentially no initial radiogenic Pb (Tera and Wasserburg,1972; Tera et al., 1973; Nunes et al., 1974,1977). The analyses are highly discordant (Fig. 7). Lead isotopes not easily leachable and are highly evolved yielding a ^{207}Pb/^{206}Pb single stage model age of 4.64 b.y. (Tera and Wasserburg,1972). Nunes et al. (1974,1977) report serious terrestrial contamination in their samples with sawn surfaces. Interior chips without sawn surfaces do not show such contamination (Tera and Wasserburg, 1972).

TABLE 4. Summary of Rb-Sr data for anorthosite 60025.



Rb/Sr	^{87}Sr/^{86}Sr measured	^{87}Sr/^{86}Sr at 4.6 b.y	Reference
1.16×10^{-4}	0.69896 ± 3	0.69894	Papanastassiou and Wasserburg (1972b)
9.44×10^{-5}	0.69908 ± 6	0.69906	Nunes et al. (1974)
1.34×10^{-4}	0.69905 ± 6	0.69902	Nyquist et al.(1975)
1.22×10^{-4}	0.69913 ± 3	0.69910	Nyquist et al.(1979)

Not corrected for interlaboratory bias

RARE GASES/EXPOSURE AGES: Lightner and Marti (1974a) and Leich and Niemeyer (1975) provide Xe, Kr and Ar isotope data. Significant amounts of trapped Xe not of solar or cosmic origin were found. It is however isotopically indistinguishable from terrestrial Xe and is believed to represent terrestrial contamination because experiments by Niemeyer and Leich (1976) showed that unexpectedly high temperatures (>l000ºC) were required to remove known terrestrial contamination.

Marti (pers. comm., 1975, referenced in Drozd et al.,1977) calculated a single stage ^{81}Kr-Kr exposure age of 1.9 m.y., consistent with an excavation by the South Ray cratering event. Fruchter et al. (1977) and Kohl et al. (1977) report Mn and Al isotope data that confirm this 2 m.y. exposure age.

Schaeffer and Husain (1974) report Ar isotopic data and calculate ^{38}Ar-^{39}Ar exposure ages which average 8.6 m.y., considerably higher than the ^{81}Kr-Kr age which Leich and Niemeyer (1975) consider more reliable.

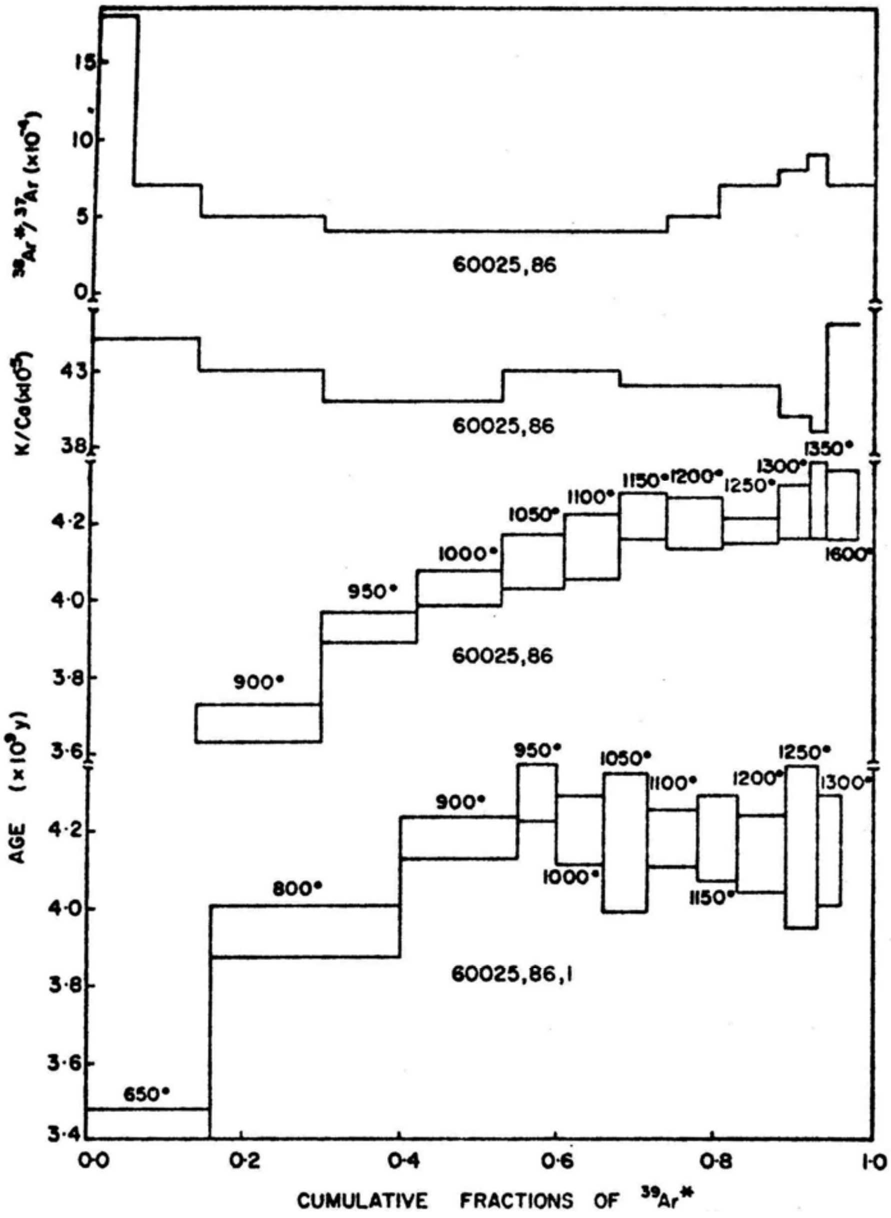


FIGURE 6. Ar release;
from Schaeffer and Husain (1974).

<u>PHYSICAL PROPERTIES</u>: Limited magnetic information is provided by Cisowski et al. (1976) who found that 60025 possesses high saturation isothermal remanent magnetization (IRMs) comparable to soil breccias and well above that of other cataclastic anorthosites (see their Fig. 6).

Katsube and Collett (1973a,b) and Gold et al.(1976b) report electrical characteristics of the anorthosite (Fig. 8).

Sondergeld et al. (1979) measured compressional wave velocities on three perpendicular surfaces of a slab of the anorthosite. Measured velocities were all <1 km/sec and deviated up to 29% from the mean value of the three directions (0.66 km/sec). Neither variation in temperature (up to 90º C) nor vacuum (down to 10^{-6} µm Hg) had any detectable effect on the velocities. These data agree well with seismic wave data from the lunar surface at the Apollo 16 site.

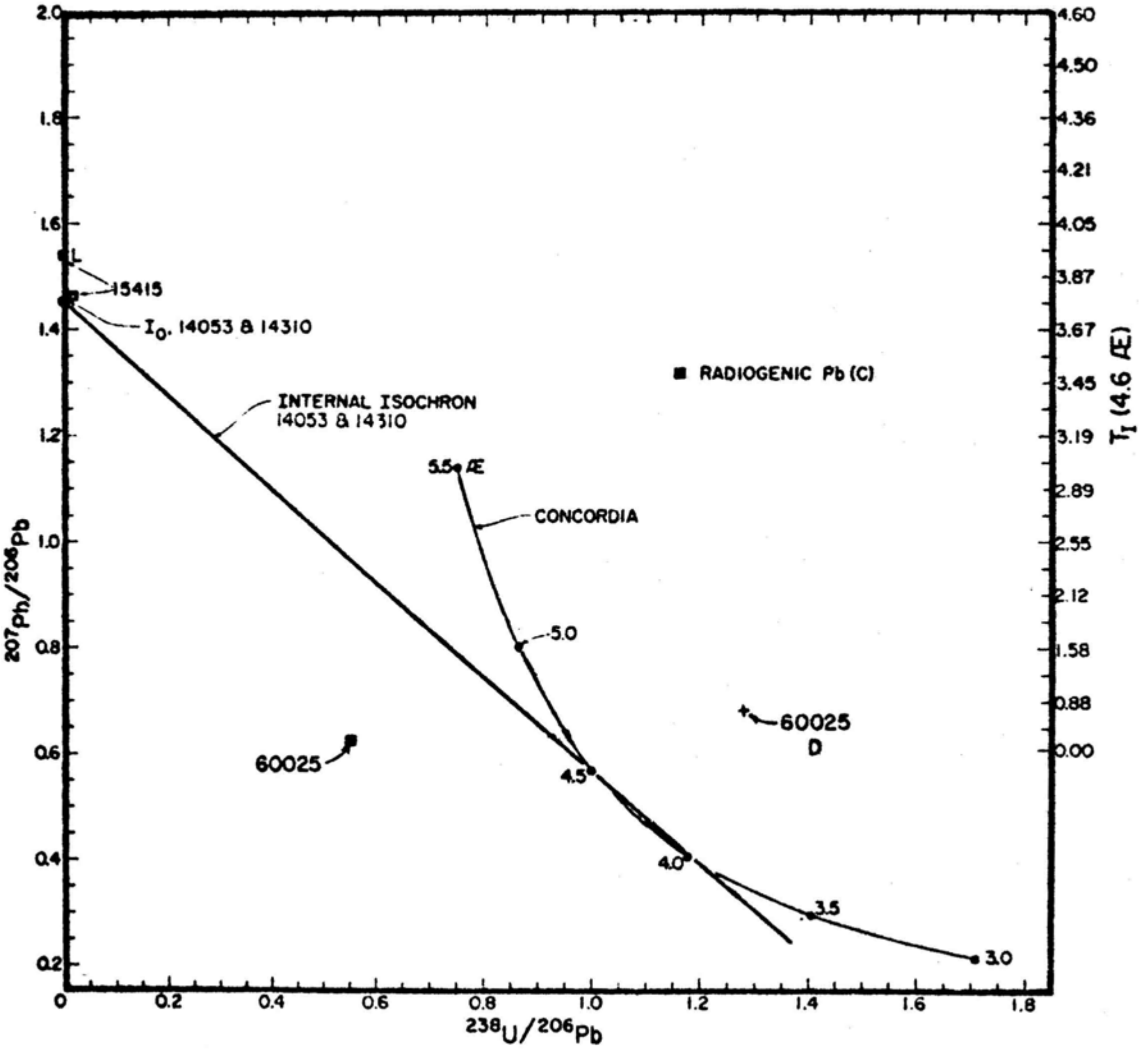


FIGURE 7. U-Pb evolution diagram;
from Tera and Wasserburg (1972).

Jeanloz and Ahrens (1978) determined shock wave, equation of state data for the anorthosite over the pressure range 400-1000 kbar (Fig. 9). Porosity in the rock (average ~18%) induces smaller peak pressures and greater temperatures than experienced by non-porous rocks subjected to similar shock conditions. Jeanloz and Ahrens (1979) extended the shock wave experiments to higher and lower pressures (1160 and 270 kbar).

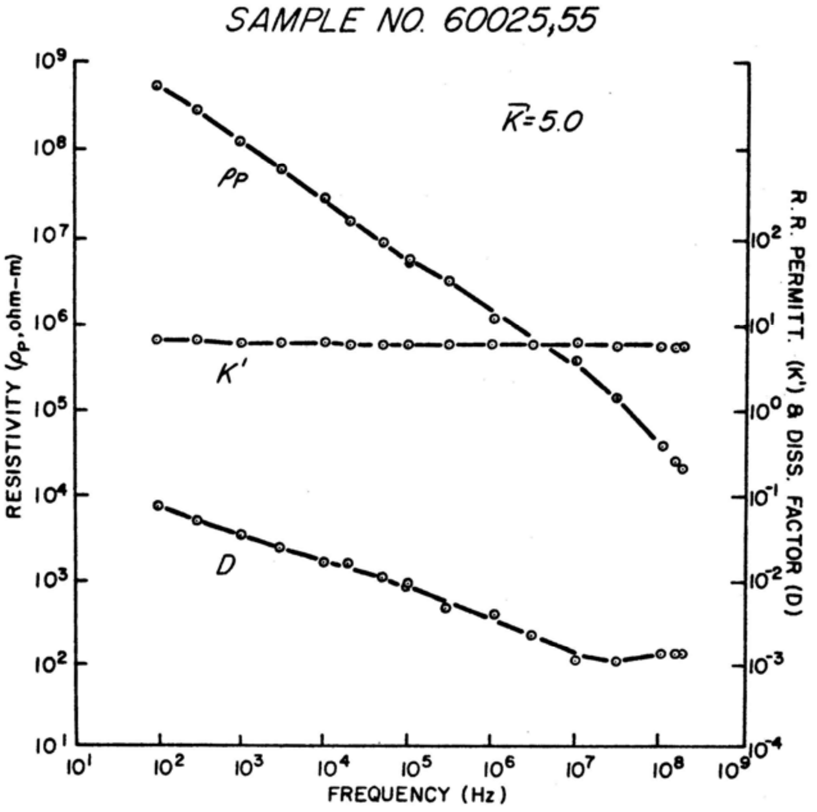


FIGURE 8. Electrical properties; from Katsube and Collett (1973b).

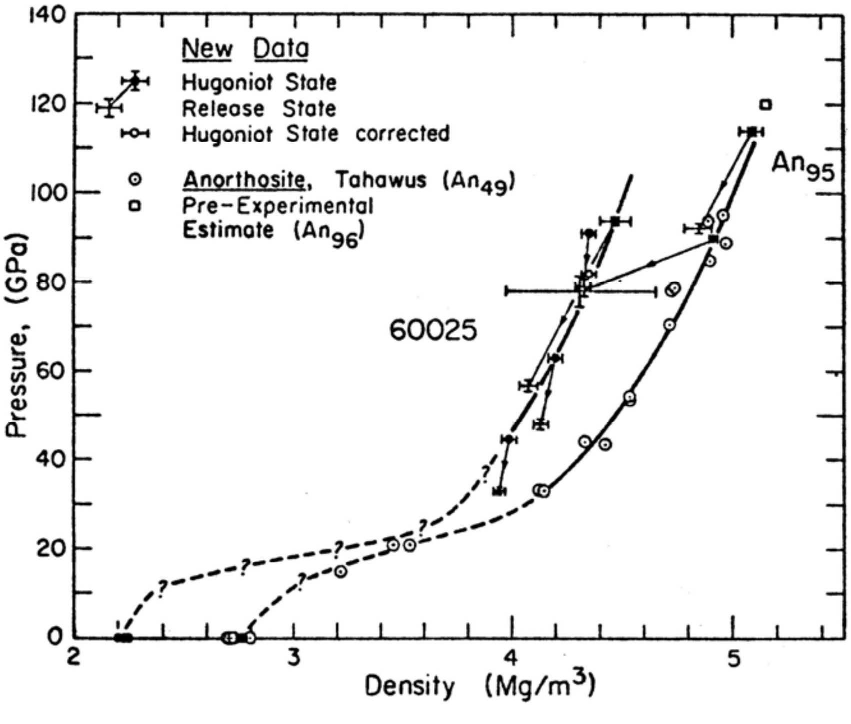


FIGURE 9. Hugoniot equation of state data; from Jeanloz and Ahrens (1978).

Microcracks were studied by Simmons et al. (1975) who found two sets of shock induced cracks, possibly indicating separate shock events.

Hapke et al. (1978) provide ultraviolet reflectance data.

<u>PROCESSING AND SUBDIVISIONS</u>: In 1972, 60025 was sawn into three main pieces (Fig. 10). The slab and the E butt end were extensively subdivided and allocated. The mafic-rich thin sections described by LSPET (1973) and Warren and Wasson (1978) are from an undocumented chip (60025,9) which is now a potted butt. Processing notes in the data pack indicates that mafic-rich clumps may be present on the N surface.

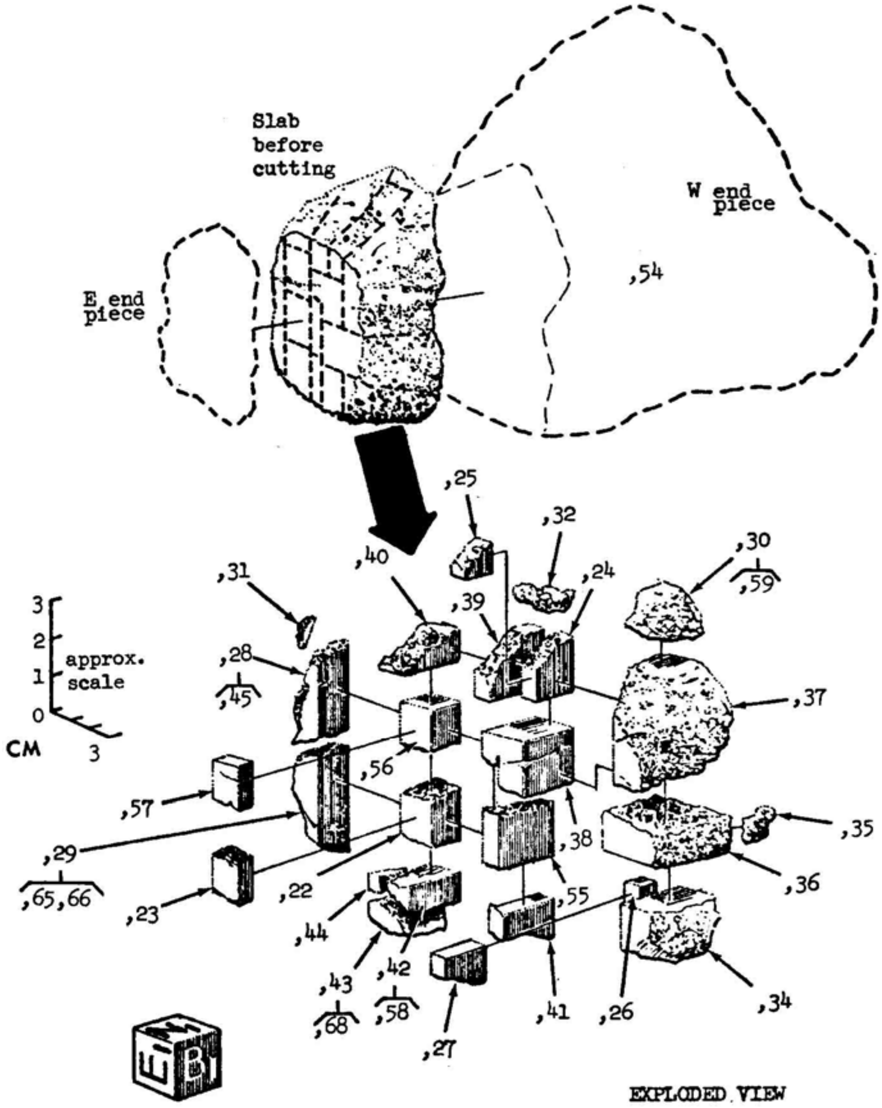


FIGURE 10. Cutting diagram.