# 76535

Troctolite

155.5 grams


*Figure 1: Photograph of 76535 taken during PET (scale and cube are 1 cm). Photo # S-73-19425*

## Introduction

Troctolite 76535 is without doubt the most interesting sample returned from the Moon! It is a colorful, pristine, coarse-grained, plutonic rock that has had a slow cooling history. It is very old and has not been damaged by shock events. 76535 was collected as part of a rake sample at Station 6. This sample has been widely distributed, but its origin is still debated.

Figure 1 shows the main mass of 76535 before processing. The sample is friable, separating easily at the grain boundaries. Closeup photos of small pieces show the granular texture of the olivine and plagioclase (figure 2). White plagioclase grains (0.2 to 0.7 mm) are translucent to slightly milky, while lustrous olivine grains (0.2 to 0.3 mm) occur in clusters and are honey-brown in color. Plagioclase shows nice striations on flat cleavage surfaces.

## Petrography

Gooley et al. (1974) and Dymek et al. (1975) describe lunar sample 76535 as a coarse-grained, olivine-plagioclase cumulate that shows evidence of extensive annealing and re-equilibration (figure 3). This rock has a granular polygonal texture with smooth, curved

**Mineralogical Mode**

| | Gooley et al. 1974 | Dymek et al. 1975 | Warren 1993 |
|---|---|---|---|
| Olivine | 37 vol. % | 35 % | |
| Plagioclase | 58 | 60 | 50 |
| Orthopyroxene | 4 | 5 | |

grain boundaries and abundant 120 degree junctions resulting from the slow process of grain coarsening leading to a mineral fabric with minimum surface area. Stewart (1975) used the grain size of 76535 (2 to 3 mm) and various assumptions to calculate the interval of annealing (~$10^8$ y) in the temperature range 100 to 600 deg C. Steward termed this "Apollonian" metamorphism (*although the term did not stick*).

Figure 4 shows that 76535 may be considered as an end member of the Mg suite of lunar highland rocks.

Small patches of vermicular "symplectite" intergrowth of Cr-spinel+high-Ca pyroxene+/-low-Ca pyroxene are a unique feature of this rock and are generally found at grain boundaries between olivine and pyroxene (Gooley et al. 1974; Dymek et al. 1975; Bell et al. 1975). Gooley et al., Dymek et al. and Schwartz and McCallum (1999) have used to reaction relations of this mineral assemblage to calculate the depth of origin of this plutonic rock (~47 km).


*Figure 2: Photograph of small piece of 76535 (scale in mm). Note striations on plagioclase. Photo # S-73-19614*

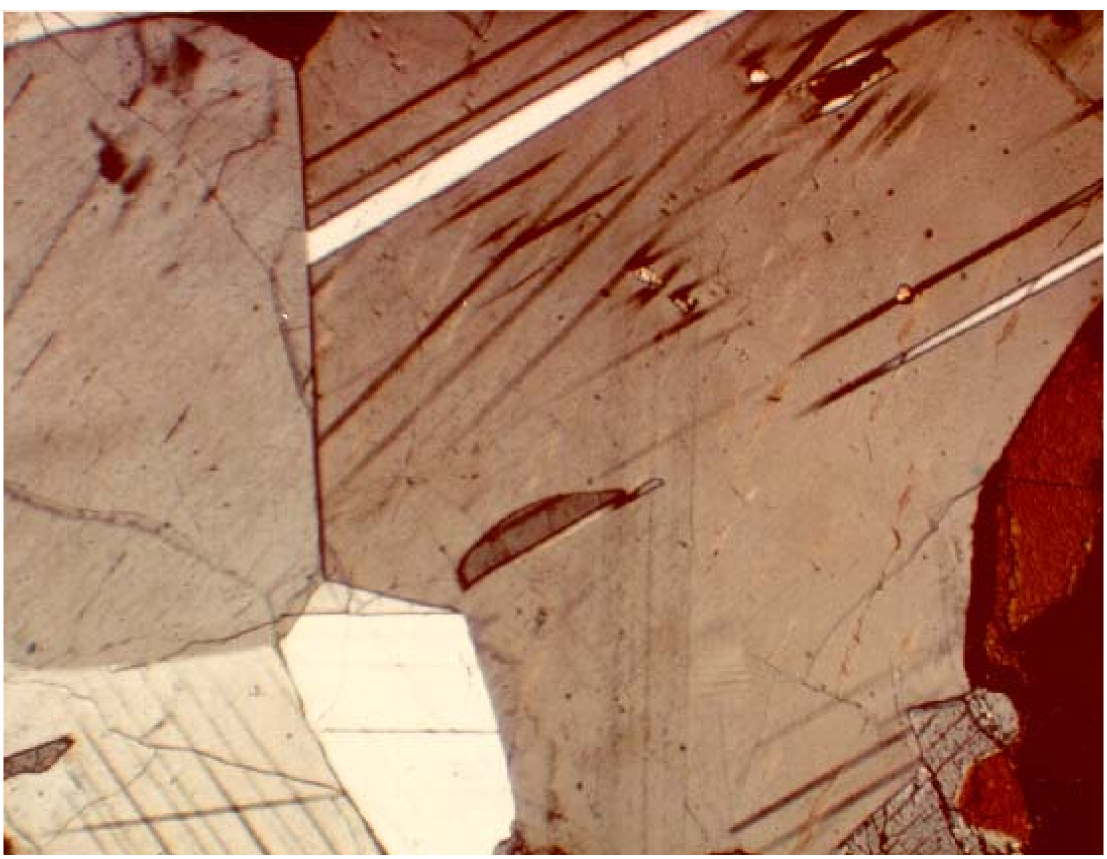


*Figure 3: Photomicrograph of thin section of 76535 (with partially crossed nicols). Photo is 3 mm across. Photo # S-76-20796.*

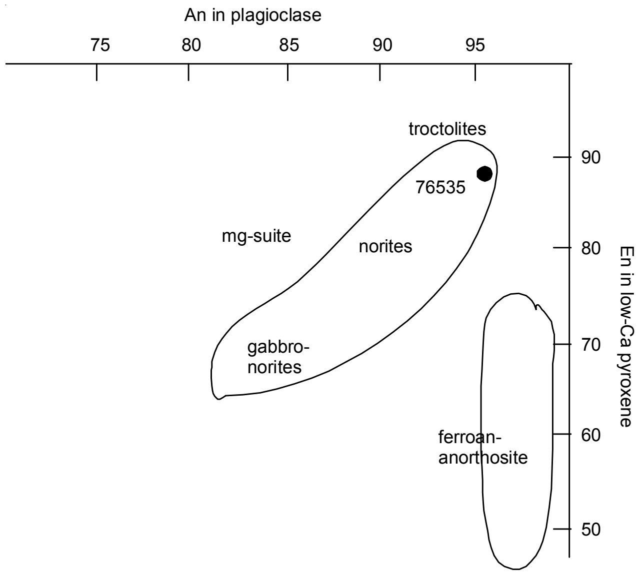



*Figure 4: Plagioclase vs. low-Ca pyroxene plot showing that 76535 is the end-member of the Mg-suite of plutonic rocks. Fields are from James and Flohr (1983) and James et al. (1989).*

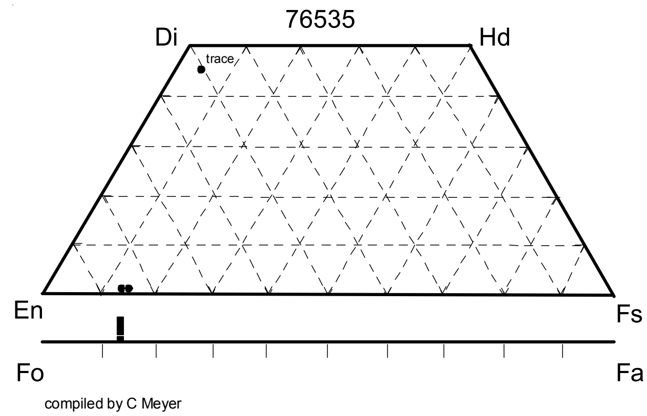



*Figure 5: Pyroxene and olivine composition of 76535. Data replotted from Dymek et al. (1975) and Gooley et al. (1974).*

Small patches of mesostasis (termed "mosaic assemblages") are found to contain minor minerals including: baddeleyite, low-Ca pyroxene, high-Ca pyroxene, apatite, "whitlockite", Cr-spinel, metal, K-Ba feldspar, and "pyrochlore" (Gooley et al. 1974; Dymek et al. 1975).

Oriented needles of Fe-Ni-Co metal are found in plagioclase (Bell et al. 1975).

Based on identical mineral chemistry, Warren et al. (1987) apparently found at least two additional pieces of troctolite similar to 76535 in the "coarse fines" from the soil samples (76504,12 and 76034,90).

## Mineralogy

***Olivine:*** Olivine is very homogeneous at $Fo_{87.3}$ (Dymek et al. 1975; Bersch et al. 1991).

***Pyroxene:*** Anhedral grains of orthopyroxene ($Wo_{0.9}En_{84.1}Fs_{11.3}$) up to 3 mm occur interstitial to olivine and plagioclase (Dymek et al. 1975). Figure 5 shows the composition of mafic minerals in 76535. Heavilon and Crozaz (1989) used the ion microprobe to determine the trace element content of pyroxene. Careful crystal structure refinement of single crystal X-ray study of orthopyroxene indicate closure temperature for cation ordering at about 550 deg C (Domeneghetti et al. 2001). Smyth (1975) also studied the crystal structure of opx from 76535.

***Plagioclase:*** Plagioclase is homogeneous at $An_{96.2}$ (Dymek et al. 1975). White to translucent plagioclase grains show striations due to twinning (LSPET 1973; Phinney et al. 1974; Gooley 1974). Smyth (1986) performed crystal structure refinement of anorthite using plagioclase from 76535 to determine the position of the cations in the structure. Nord (1976) studied the inclusions found in plagioclase. The trace element content of plagioclase has been reported by Haskin et al. (1975), Hansen et al. (1979), Steele et al. (1980), and Heavilon and Crozaz (1989).

***Augite:*** Small grains of augite are found in symplectite and mesostasis areas. Dymek et al. (1975) report $Wo_{43.6}En_{48.5}Fs_{4.4}$

***Spinel:*** Dymek et al. (1975) and Haggerty (1975) gives the composition of Cr-spinel, which is found intergrown with augite in symplectite.

***Baddelyite:*** Relatively large grains of $ZrO_2$ are present.

***Metal:*** Gooley et al. (1974) and Ryder et al. (1980) report the composition of metal grains in 76535.

***Phosphate:*** The composition of both apatite (F 2.95% and Cl 1.18%) and whitlockite (high REE) are given in Dymek et al. (1975).

***Troilite:*** Small grains have been reported.

***Pyrochlore:*** Reported by Dymek et al. (1975).

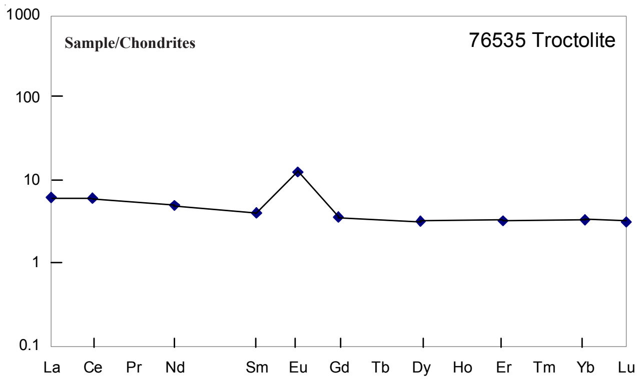



*Figure 6: Normalized rare earth element diagram for lunar troctolite 76535. Data from Haskin et al. (1975).*

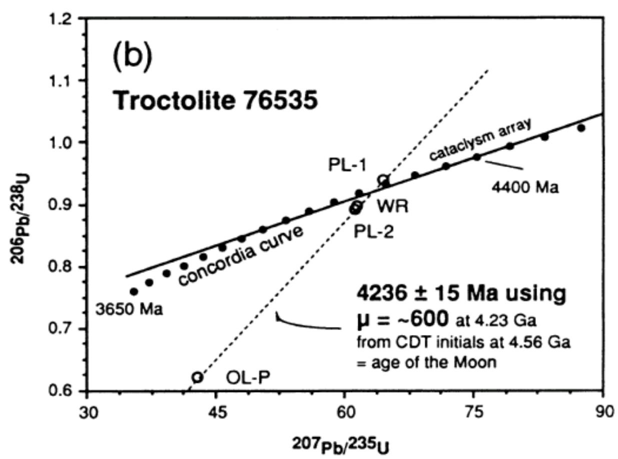



*Figure 7: U-Pb concordia diagram for 76535. From Premo and Tatsumoto (1992).*

## Chemistry

Rhodes et al. (1974), Haskin et al. (1974) and Wiesmann and Hubbard (1975) reported the bulk chemical composition of 76535 (table 1 and figure 6). Morgan et al. (1974) and Wolf et al. (1979) reported the trace siderophile and volatile elements.

Haskin et al. used the whole-rock composition and known distribution coefficients to calculate the probable parent liquid. They concluded that the rock may have had ~16% trapped liquid when it originally crystallized from the melt.

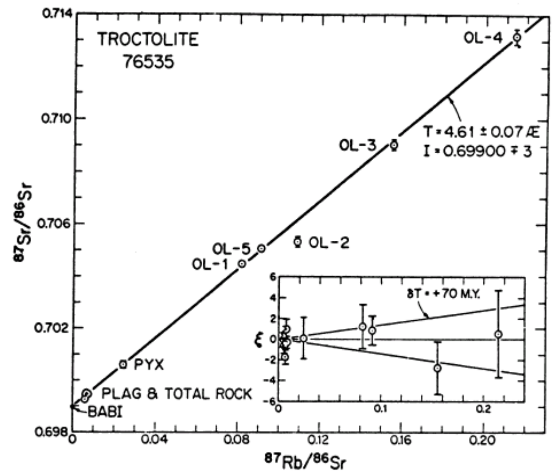



*Figure 8: Rb-Sr isochron diagram for 76535. From Papanastassiou and Wasserburg (1976).*

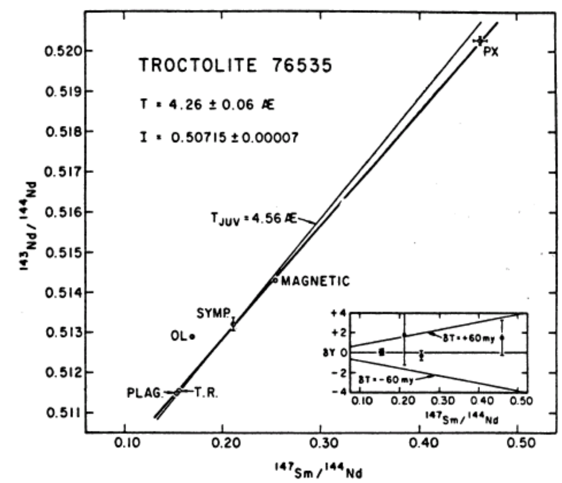



*Figure 9: Sm-Nd isochron for 76535 troctolite. From Lugmair et al. (1976).*

## Radiogenic age dating

Heroic efforts have been made to age date troctolite 76535 and the data from different decay schemes seem to be at odds (see Summary). Most recently, Premo and Tatsumoto (1992) have carefully considered the age of 76535 and concluded that it was formed between 4.23 and 4.26 b.y. (figure 7).

**Summary of age data for 76535**

| | | |
|---|---|---|
| 4.19 ± 0.02 | K-Ar | Husain and Schaeffer (1975) |
| 4.16 ± 0.04 | K-Ar | Huneke and Wasserburg (1975) |
| 4.27 ± 0.08 | K-Ar | Bogard et al. (1975) |
| 4.61 ± 0.07 | Rb-Sr | Papanastassiou and Wasserburg (1976) |
| 4.26 ± 0.02 | Sm-Nd | Lugmair et al. (1976) |
| 4.330 ± 0.064 | Sm-Nd | Premo and Tatsumoto (1992) |
| 4.27 ± 0.03 | Pb-Pb | Hinthorne et al. (1975) |
| 4.236 ± 0.015 | U-Pb | Premo and Tatsumoto (1992) |

## Table 1. Chemical composition of 76535.

| *reference* | Rhodes 74 | | Haskin 74 | | Wiesmann 75 | | Morgan 74 | | Kieth 74 | |
|---|---|---|---|---|---|---|---|---|---|---|
| *weight* | 1.3 g | | | | | | 151 mg | | 155 g | |
| SiO2 % | 42.88 | (a) | | | | | | | | |
| TiO2 | 0.05 | (a) | | | | | | | | |
| Al2O3 | 20.73 | (a) | | | | | | | | |
| FeO | 4.99 | (a) | | | | | | | | |
| MnO | 0.07 | (a) | | | | | | | | |
| MgO | 19.09 | (a) | | | | | | | | |
| CaO | 11.41 | (a) | | | | | | | | |
| Na2O | 0.23 | (d) | | | | | | | | |
| K2O | 0.03 | (a) | 0.028 | (c ) | | | | | 0.0283 | (f) |
| P2O5 | 0.03 | (a) | | | | | | | | |
| S % | 0 | (a) | | | | | | | | |
| *sum* | | | | | | | | | | |
| | | | | | | | | | | |
| Sc ppm | | | | | | | | | | |
| V | | | | | | | | | | |
| Cr | 753 | (a) | | | | | | | | |
| Co | | | | | | | | | | |
| Ni | 25 | (a) | | | | | 44 | (e) | | |
| Cu | | | | | | | | | | |
| Zn | 1 | | | | | | 1.2 | (e) | | |
| Ga | | | | | | | | | | |
| Ge | | | | | | | 0.0017 | (e) | | |
| As | | | | | | | | | | |
| Se | | | | | | | 0.0041 | (e) | | |
| Rb | 0.2 | | 0.24 | (c ) | | | 0.2 | (e) | | |
| Sr | 111 | | 114 | (c ) | | | | | | |
| Y | 4.4 | | | | | | | | | |
| Zr | 12 | | 23.6 | (c ) | | | | | | |
| Nb | 1.2 | | | | | | | | | |
| Mo | | | | | | | | | | |
| Ru | | | | | | | | | | |
| Rh | | | | | | | | | | |
| Pd ppb | | | | | | | | | | |
| Ag ppb | | | | | | | 0.12 | (e) | | |
| Cd ppb | | | | | | | | | | |
| In ppb | | | | | | | | | | |
| Sn ppb | | | | | | | | | | |
| Sb ppb | | | | | | | 0.014 | (e) | | |
| Te ppb | | | | | | | 0.28 | (e) | | |
| Cs ppm | | | | | | | 0.014 | (e) | | |
| Ba | | | 33 | (c ) | | | | | | |
| La | | | 1.51 | (c ) | | | | | | |
| Ce | | | 3.8 | (c ) | | | | | | |
| Pr | | | | | | | | | | |
| Nd | | | 2.3 | (c ) | | | | | | |
| Sm | | | 0.61 | (c ) | | | | | | |
| Eu | | | 0.73 | (c ) | | | | | | |
| Gd | | | 0.73 | (c ) | | | | | | |
| Tb | | | | | | | | | | |
| Dy | | | 0.8 | (c ) | | | | | | |
| Ho | | | | | | | | | | |
| Er | | | 0.53 | (c ) | | | | | | |
| Tm | | | | | | | | | | |
| Yb | | | 0.56 | (c ) | | | | | | |
| Lu | | | 0.079 | (c ) | | | | | | |
| Hf | | | 0.52 | (c ) | | | | | | |
| Ta | | | | | | | | | | |
| W ppb | | | | | | | | | | |
| Re ppb | | | | | | | 0.0012 | (e) | | |
| Os ppb | | | | | | | | | | |
| Ir ppb | | | | | | | 0.0054 | (e) | | |
| Pt ppb | | | | | | | | | | |
| Au ppb | | | | | | | 0.0025 | (e) | | |
| Th ppm | | | | | | | | | 0.19 | (f) |
| U ppm | | | | | | | 0.0194 | (e) | 0.054 | (f) |

*technique (a) XRF, (b) INAA, (c ) IDMS, (d) AA, (e) RNAA, (f) counting*

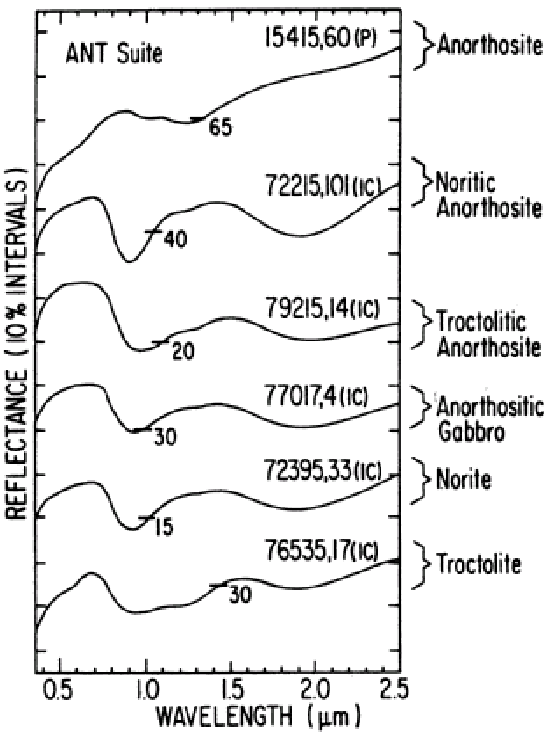



*Figure 10: Reflectance spectra of Apollo 17 rocks including troctolite 76535. From Charette and Adams (1977).*

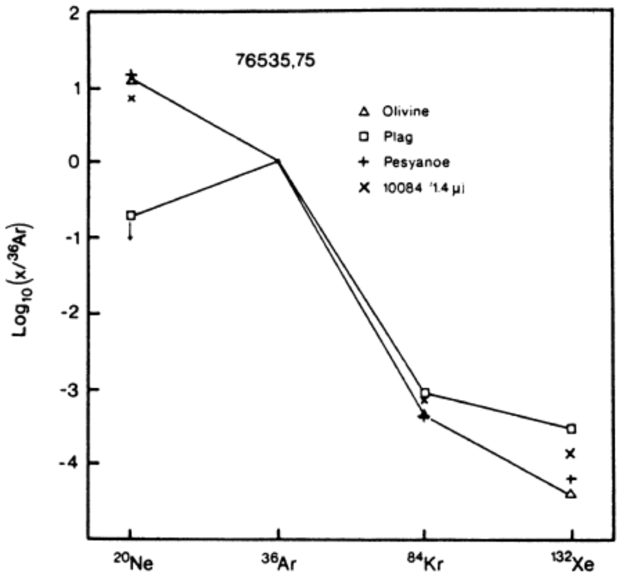



*Figure 11: Relative abundance of trapped rare gases in 76535. From Chaffee et al. (1981).*

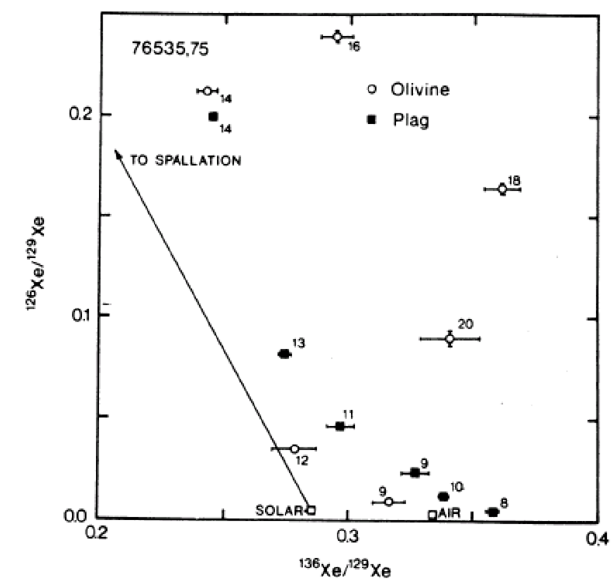



*Figure 12: Xenon isotopic data for olivine and plagioclase separetes from 76535. From Chaffee et al. (1981).*

The various age dating studies of troctolite 76535 may provide an interesting study in the preservation of radiogenic information through the coarse of major metamorphic change. Careful study of Rb-Sr, Sm-Nd, U-Pb and $^{40}Ar/^{39}Ar$ systematics has yielded a broad range of apparent isotopic closure ages; 4.61 to 4.16 b.y. (see Summary). The Rb-Sr isochron (figure 8) is based on Rb-rich inclusions in olivine, whereas the Sm-Nd isochron (figure 9) is based on REE included in pyroxene, plagioclase and accessory phases, exclusive of olivine.

Domeneghetti et al. (2001) and Nord (1976) note that this apparent age discrepancy is consistent with what is known about cation ordering in orthopyroxene and subsolidus exsolution of inclusions found in plagioclase. The Rb-Sr isochron presumably dates the isolation of Rb-rich inclusions in olivine (?) and is apparently insensitive to the metamorphism that produced the texture of the rock, while the Sm-Nd, U-Pb and $^{40}Ar/^{39}Ar$ ages involve lower temperature mineral phases that are more sensitive to subsequent metamorphism and closure to movement of radiogenic elements at a later time. The study of rare gases by Chaffee et al. (1981) also shows that the different minerals in 76535 have different, mineral-specific, isotopic closure ages.

## Cosmogenic isotopes and exposure ages

Bogard et al. (1975), Crozaz et al. (1974) and Lugmair et al. (1976) reported cosmic ray exposure ages of 195 ± 10 m.y., 211 ± 7 m.y., and 233 ± 16 m.y., respectively.

Premo and Tatsumoto (1992) show a hint of a lower intercept age at 62 ± 32 m.y., suggesting Pb disturbance at the time of excavation.

Kieth et al. (1974) reported the cosmic ray induced activity of 76535.

## Other Studies

Charette and Adams (1977) have recorded the spectral reflectance of 76535 (figure 10). Braddy et al. (1975) reported a fission track age of 4.07 b.y.

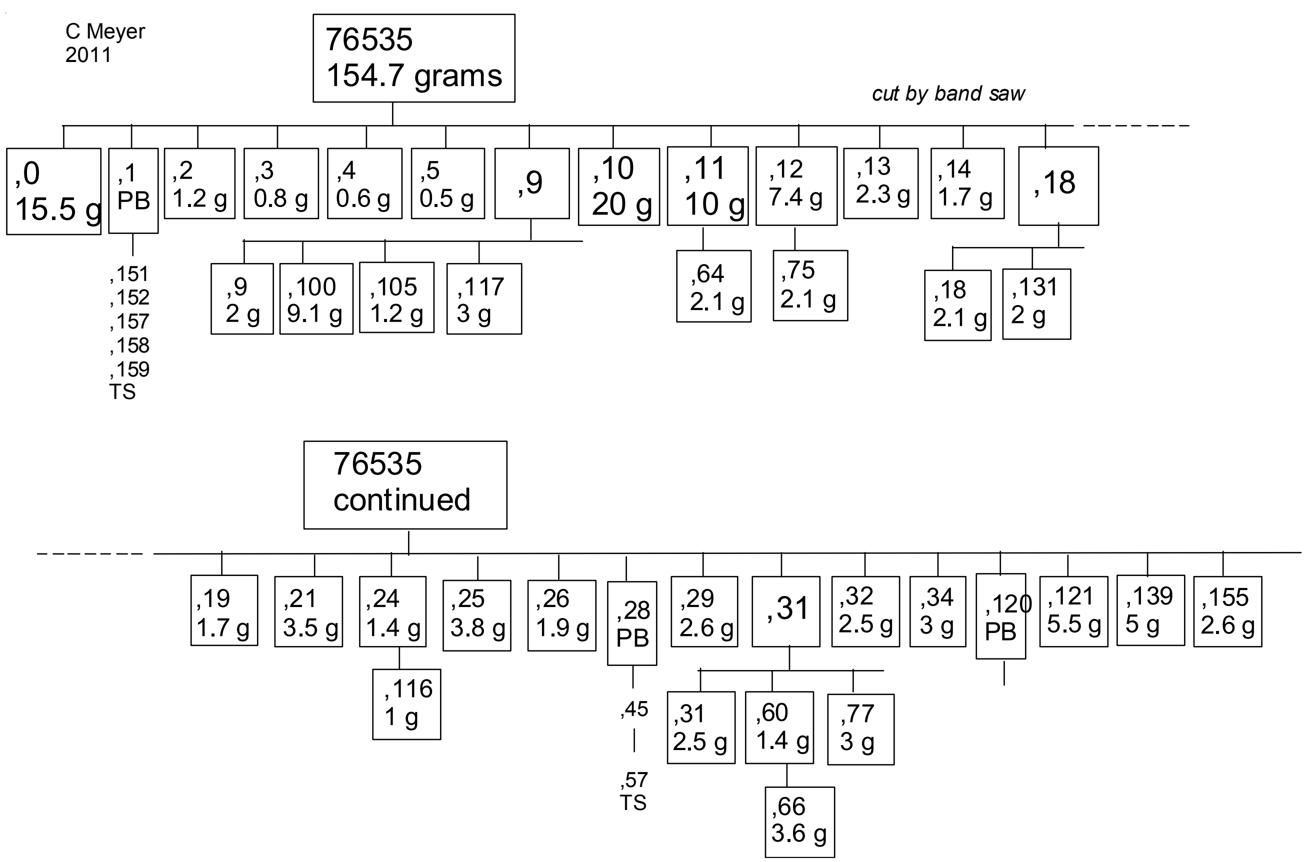
Hohenberg et al. (1980) and Chaffee et al. (1981) have carefully studied “excess” fission xenon and trapped solar wind noble gases in troctolite 76535 (figures 11, 12). Stepwise heating of separated olivine and plagioclase showed evidence for *in-situ* decay of $^{244}$Pu leading to fission Xe ages of 4.50 b.y. and 4.25 b.y. respectively (consistent with Rb-Sr and Sm-Nd ages above).

## Processing

Two 2 gram pieces of 76535 were used by Rhodes et al. (1994) and Haskin et al. (1994) to obtain the chemical composition.

The sample is very friable and broke up during initial sawing. There are probably other pieces of this sample in the residue of the collection bag (76530).

Photo Numbers
S73-19425
S73-19458
S73-19459
S73-19601
S73-19614
S73-19622
S73-20409B
S76-20796



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