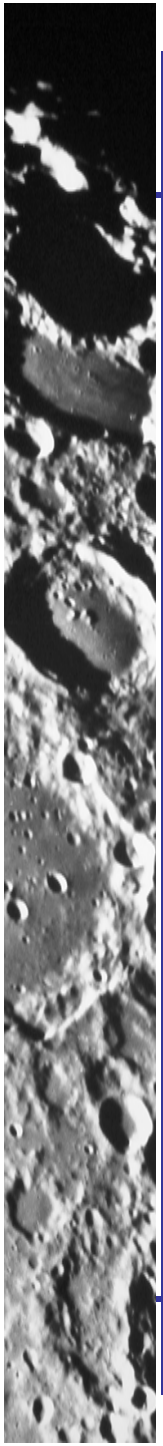
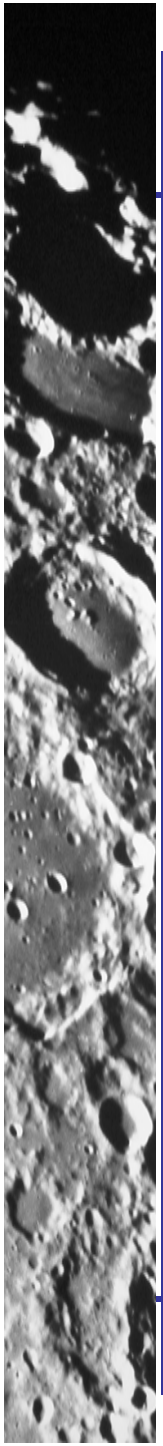




**Briefing Topic:**

# Field and Sample Guidebook to Apollo Impact Melt Breccias

**David A. Kring and Gary E. Lofgren**



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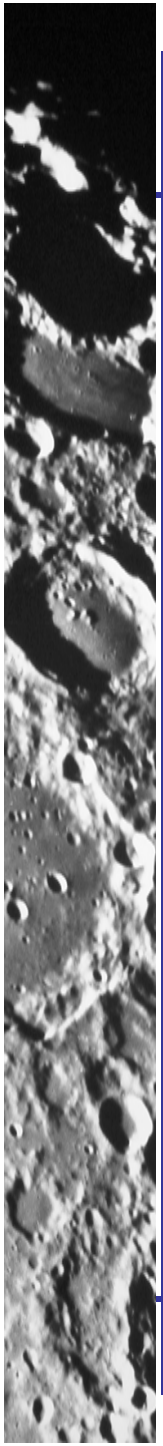
Examples of lunar impact breccias 14

- Field setting
- Rationale for collecting these specimens
- Science outcomes (including surprises)

References and other useful resources 68

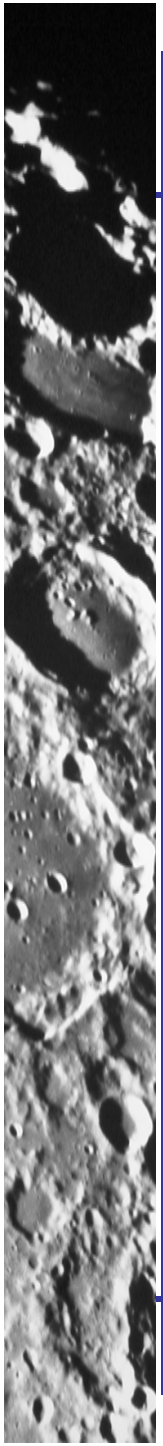


# Introduction

Lunar impact breccias are complex lithologies. When first examined in The late 1960's and early 1970's, they often vexed the community because (i) the thoroughness with which impact cratering modified the lunar surface was not commonly appreciated, (ii) few terrestrial analogues of impact breccias existed, and (iii) even fewer geologists were familiar with those terrestrial analogues and the effects of impact shock on planetary surface materials.

As scientists tried to understand the rocks, they struggled with interpretations of the textures in them and terminology. For that reason, literature descriptions of the same rock may vary considerably, confusing modern investigators who try to fathom previous results in the literature.

Fortunately, the Apollo experience was a catalyst for impact cratering studies. A more coherent use of terminology now exists. In addition, the links between petrographic properties of these rocks and the physical processes that generated them during impact events are much better understood than they were 40 years ago.



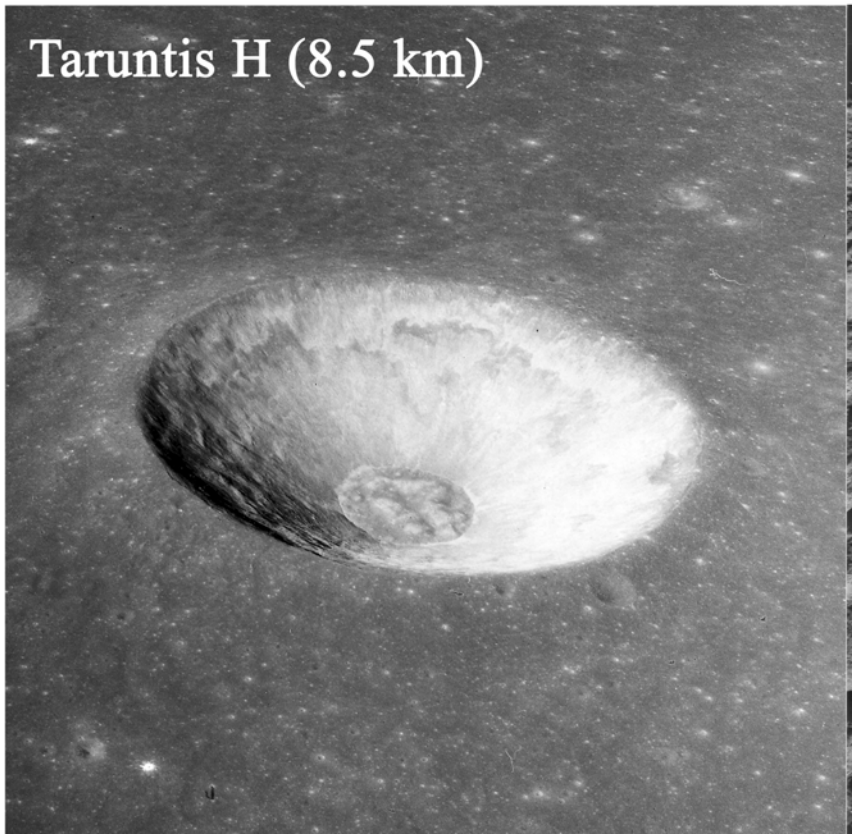
# Introduction

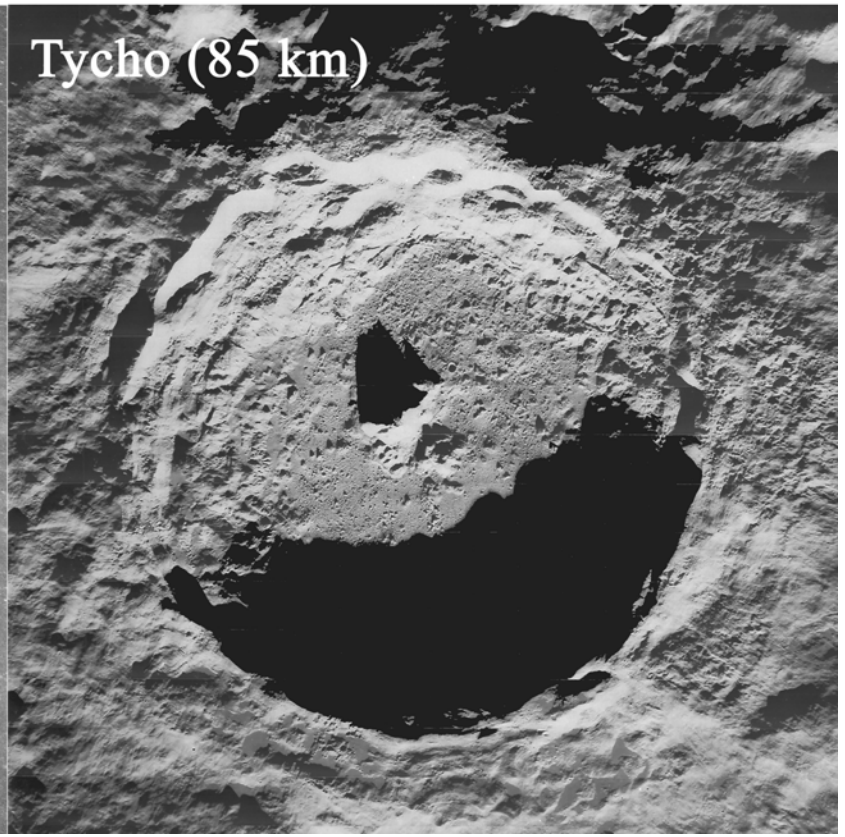
As we prepare for a new generation of lunar sample studies under the auspices of ***The Constellation Program***, we are compiling information about a few examples of lunar impact breccias. Excerpts appear below.

For the purposes of this workshop, we have designed the notes below and selected a suite of Apollo samples to:

- **Illustrate the rationale for selecting a sample of an impact melt breccia on the lunar surface, followed by the analytical results**
- **Illustrate the complexity of impact melt breccias**
- **Facilitate a discussion of interpretations of sample chronology**
- **Facilitate a discussion of sampling strategies for future crater samples selected for chronology**

# Simple and Complex Craters

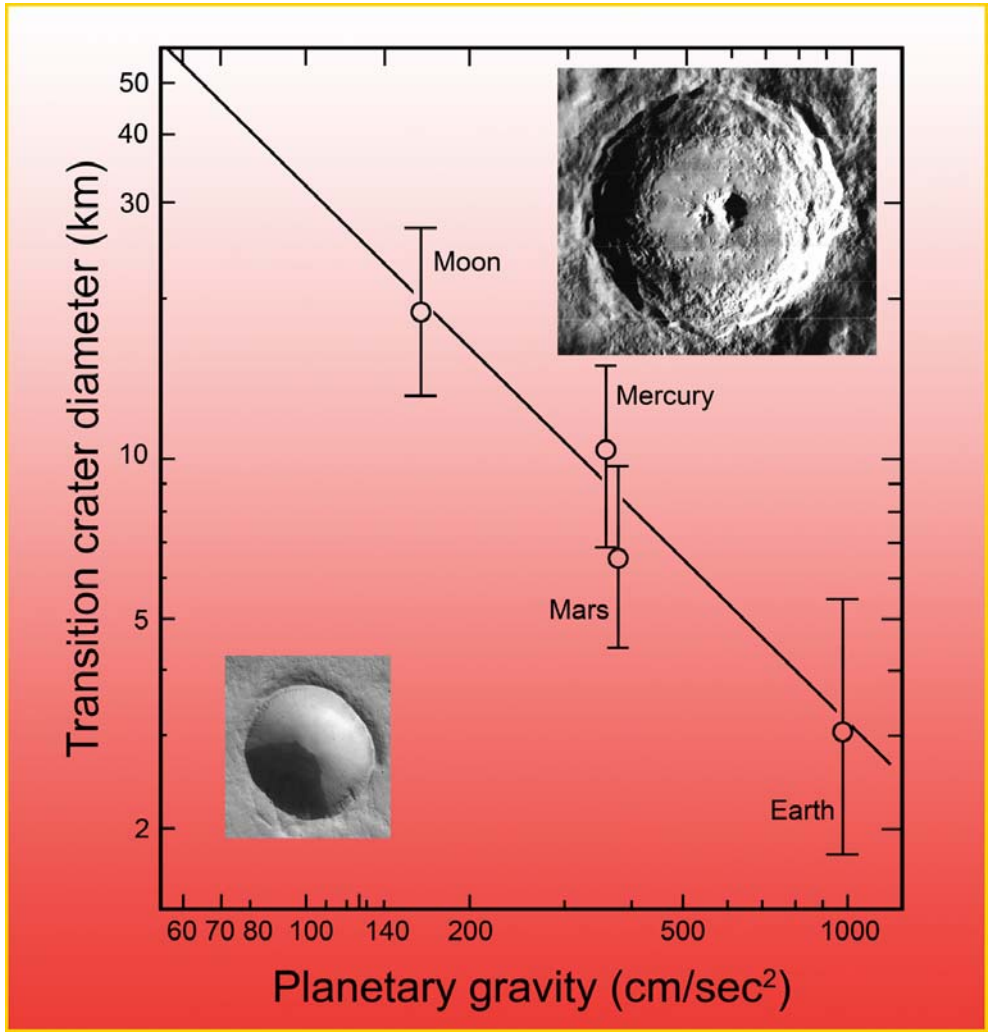





Grieve & Kring (2007)

# Simple and Complex Craters

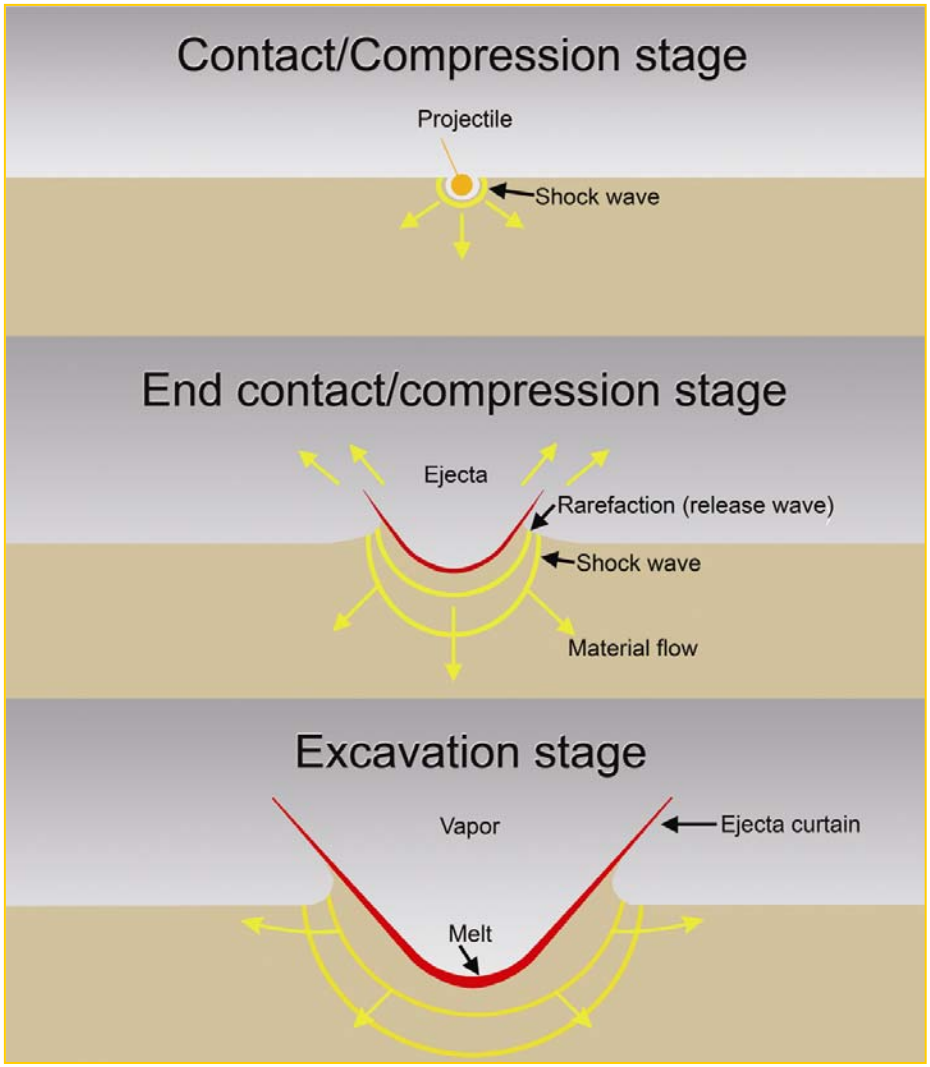



The transition diameter between simple and complex crater morphologies on the Moon is ~20 km.

The transition diameter is a function of planetary gravity.

On the Earth, the transition diameter is 2 to 4 km, depending on target lithology.

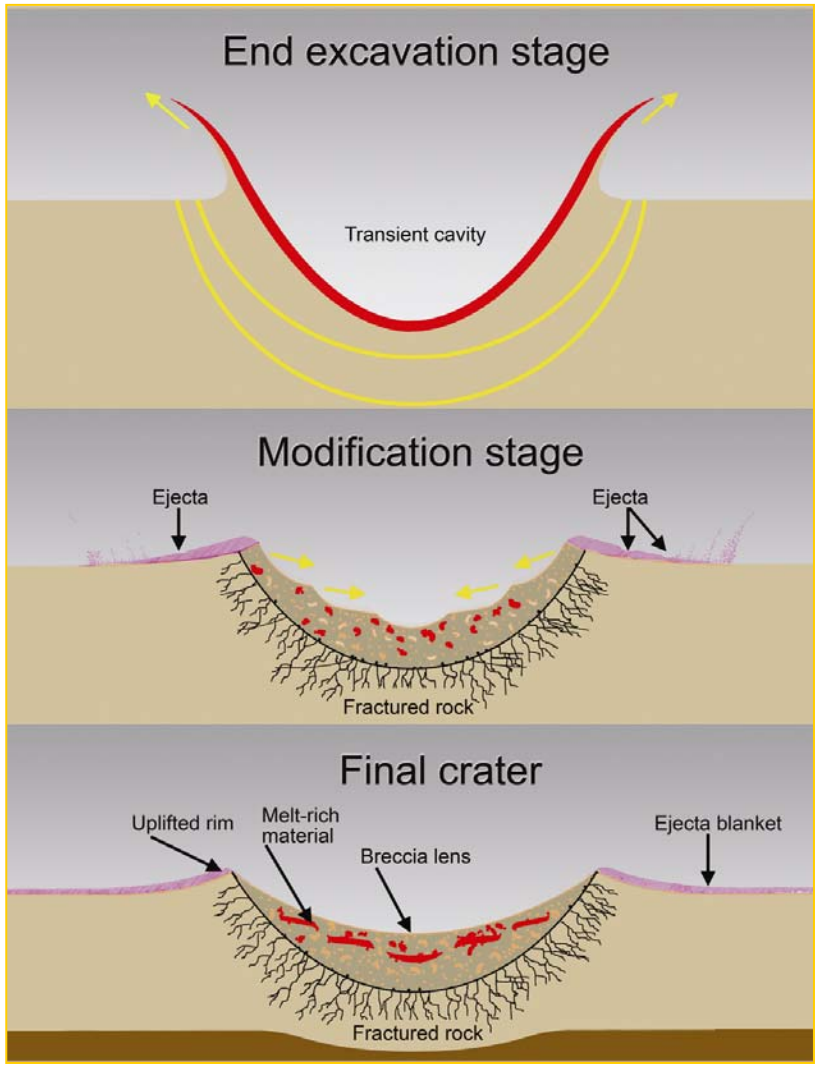
# Simple Crater Formation






Kring (2006)
See also French (1998)

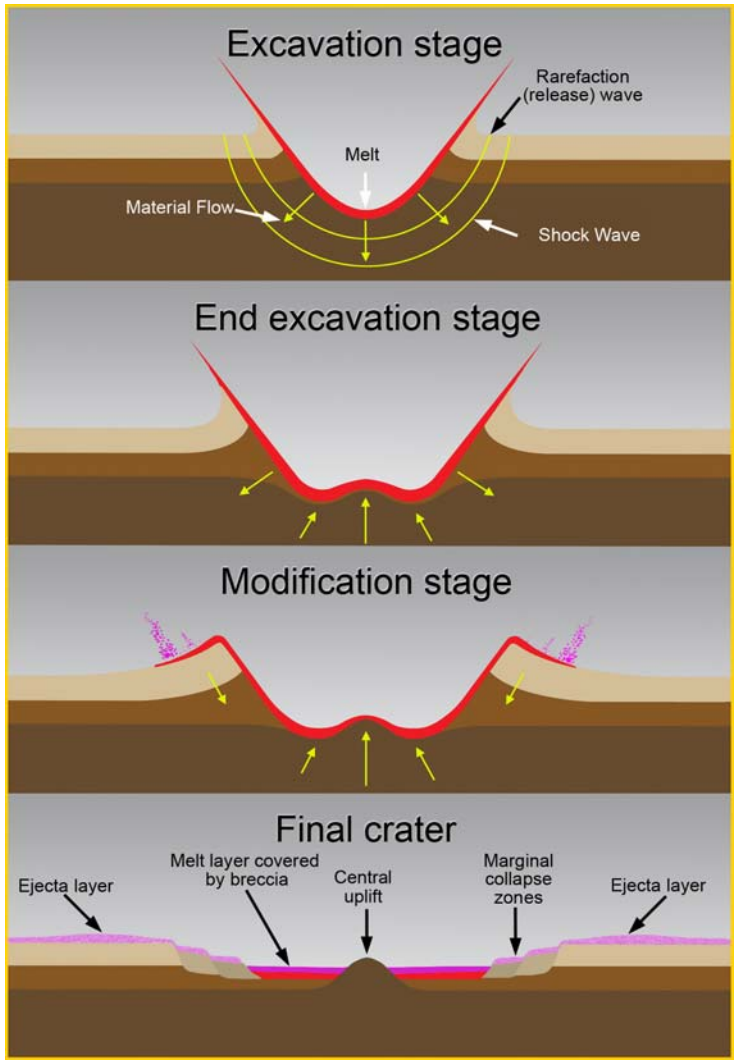
# Simple Crater Formation






Kring (2006)
See also French (1998)

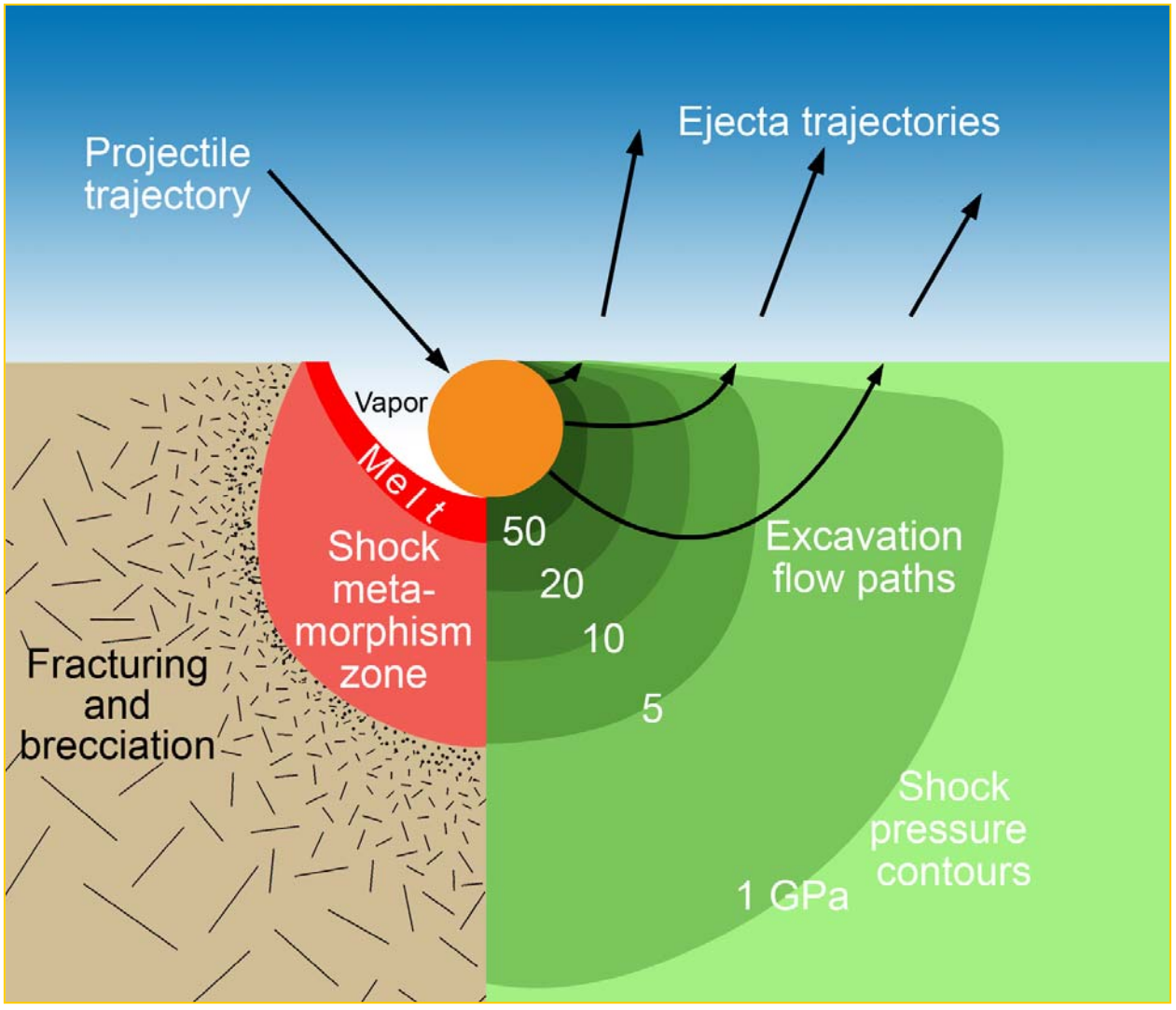
# Complex Crater Formation





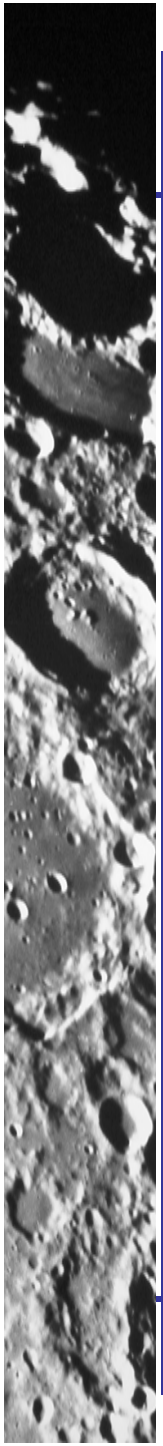

Kring (2006)
See also French (1998)

# Shock and Excavation






Kring (2006)



# Lunar Impact Breccias



TABLE 6.11. Classification, characteristics, and examples of highland polymict breccias (adapted from *Stöffler et al.*, 1980).

| Class | Main Characteristics | Examples |
|---|---|---|
| Fragmental breccia | Angular clasts in a porous, clastic matrix of rock, mineral, and rare glass debris. Some melt clasts may be cogenetic with assembly (suevite). Most are friable. | 14063, 67015, 67455 |
| Glassy melt breccia and impact glass | Coherent glassy or devitrified glass matrix with (melt breccia) or without (impact glass) clasts. | 60115, 68815, 60095, 79175 |
| Crystalline melt breccia (impact melt breccia) | Rock or mineral clasts or both in an igneous (extrusive)-textured matrix (ophitic, subophitic, poikilitic, dendritic, etc.). May be fine- or coarse-grained, and clast-rich to clast-poor. | 15455, 62295, 76015 |
| Clast-poor impact melt | Igneous (extrusive)-textured rocks but containing meteoritic siderophile contamination. Textures can be slightly more heterogeneous than igneous rocks, and rare clasts may be present. Compositions can be unlike possible igneous-generated ones. | 14310, 68415 |
| Granulitic breccia and granulite | Rock or mineral clasts or both in an equilibrated, granoblastic to poikiloblastic matrix. Clasts may not be obvious, and poikilitic textures may mimic (or even be) siderophile contamination. | 79215, 77017, 67955, 78155 |
| Dimict breccia | Veined texture of intrusive dark fine-grained crystalline melt breccia with coarser-grained light-colored breccia consisting of plutonic or metamorphic fragments or both. In some cases the dark-light relationship is mutually intrusive. | 61015, 62255, 64475 |
| Regolith (soil) breccia | Lithified regolith. Regolith fragments including impact glass and volcanic debris with a glassy matrix. Commonly retain some solar wind gases through lithification process. | 14318, 15299, 60019, ALHA 81005 |



Heiken et al. (1991)

# Lunar Impact Breccias



TABLE 6.12. Some of the more common previous names for polymict rocks (much simplified after *Stöffler et al.*, 1980).

| Present Class | Previous Names | References |
|---|---|---|
| Fragmental breccia | Light matrix breccia (LMB) | *J. Warner et al.* (1973) |
| | Feldspathic breccia | *Chao et al.* (1972a) |
| | Clastic breccia | *Stöffler et al.* (1979) |
| Glassy melt breccia | Agglutinate | *Vaniman et al.* (1976) |
| | Glassy breccia | *R. Warner et al.* (1976c) |
| | Vitric matrix breccia | *Stöffler et al.* (1979) |
| Crystalline melt breccia | Annealed Fra Mauro breccia | *Chao et al.* (1972a) |
| | Metamorphosed breccia | *J. Warner et al.* (1973) |
| | Recrystallized noritic breccia | *Vaniman et al.* (1976) |
| | Crystalline matrix breccia | *Phinney et al.* (1977) |
| | Thermally metamorphosed breccia | *James* (1977) |
| | Pyroxene poikiloblastic breccia | *Delano et al.* (1973) |
| Clast-poor impact melt | High-alumina basalt | *Kushiro et al.* (1972) |
| | Fra Mauro basalt | *Ridley et al.* (1972) |
| | Basaltic impact melt | *Ryder and Norman* (1980) |
| Granulitic breccia | Polymict metamorphic breccia | *Stöffler et al.* (1974) |
| | Granulitic impactite | *J. Warner et al.* (1977) |
| | Recrystallized ANT rocks | *R. Warner et al.* (1978a) |
| Dimict breccia | Partially molten breccia | *LSPET* (1973a) |
| | Black and white rock | *J. Warner et al.* (1973) |
| | Dike breccia | *Stöffler et al.* (1979) |
| Regolith breccia | Dark matrix breccia (DMB) | *Wilshire and Jackson* (1972) |
| | Vitric matrix breccia | *Stöffler et al.* (1974) |
| | Soil breccia | *R. Warner et al.* (1978a) |



Heiken et al. (1991)

# Lunar Impact Breccias



Complex Central Peak Crater

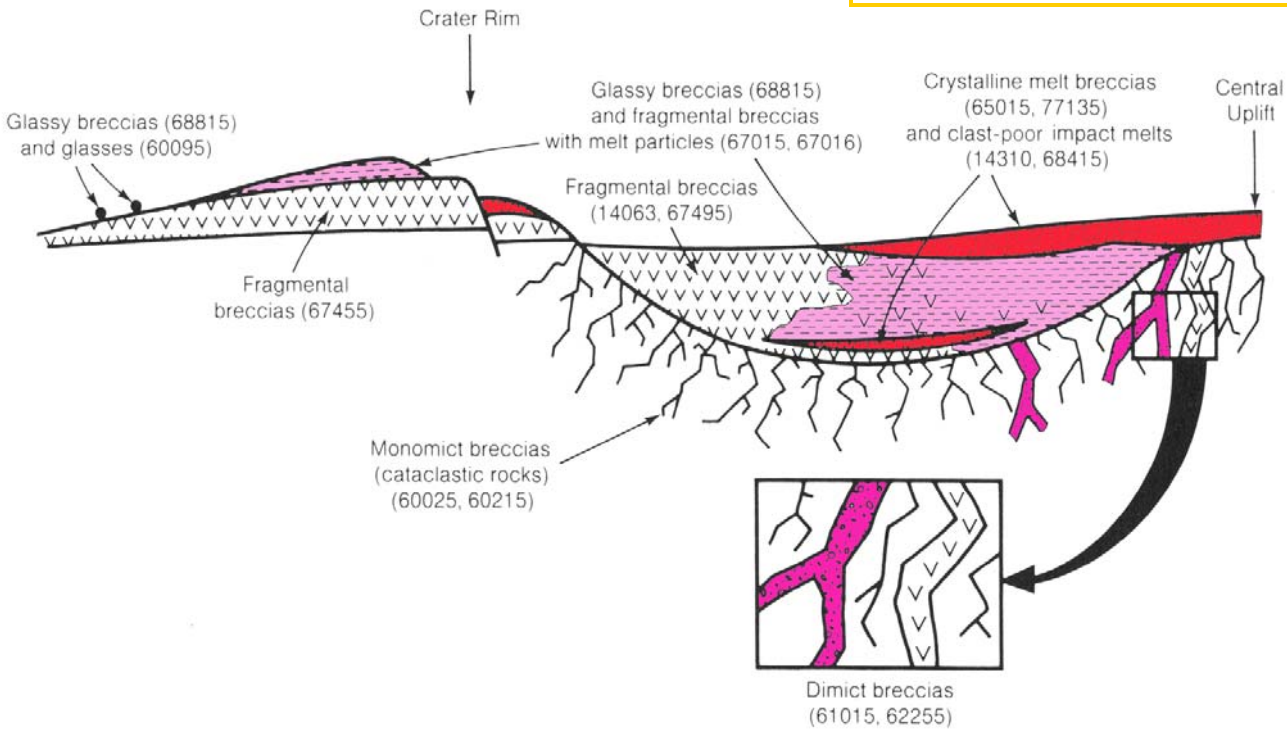
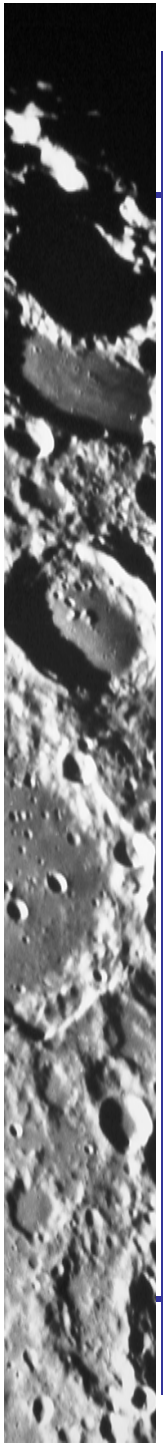



**Fig. 6.40.** Cross-section of an ideal lunar crater showing the relations of different polymict breccia types and possible monomict breccias to the geological environment of the crater (adapted from *Stöffler,* 1981). Numbers indicate actual lunar samples that are examples of the different breccia types. In reality, most lunar polymict breccias are the result of a series of impacts, and in almost all cases the target for each new breccia-producing impact is already a polymict breccia.



Heiken et al. (1991)



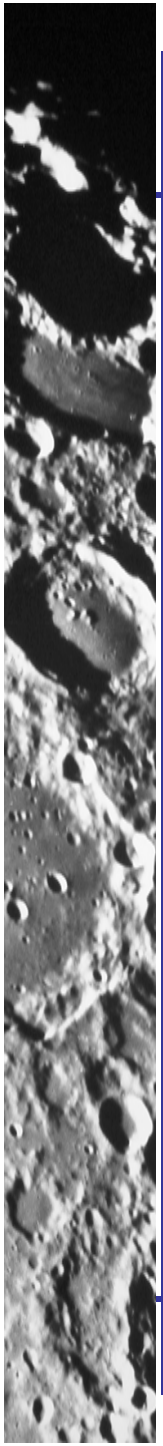
# Examples of Apollo Impact Melts

For the purposes of this tutorial, we will examine the following Apollo samples:

- Clast poor Impact Melt Breccias
  - 14310
  - 68415

- Crystalline Impact Melt Breccias
  - 15455
  - 62295
  - 65015
  - 72395 (one of the “poikilitic” impact melt breccias at Apollo 17)
  - 73215 (one of the “aphanitic” impact melt breccias at Apollo 17)
  - 73255 (one of the “aphanitic” impact melt breccias at Apollo 17)
  - 76015
  - 76215 (one of the “poikilitic” impact melt breccias at Apollo 17)

- Glassy Impact Melt Breccias
  - 60095 (impact melt spherule)
  - 60115
  - 68815
  - 79175

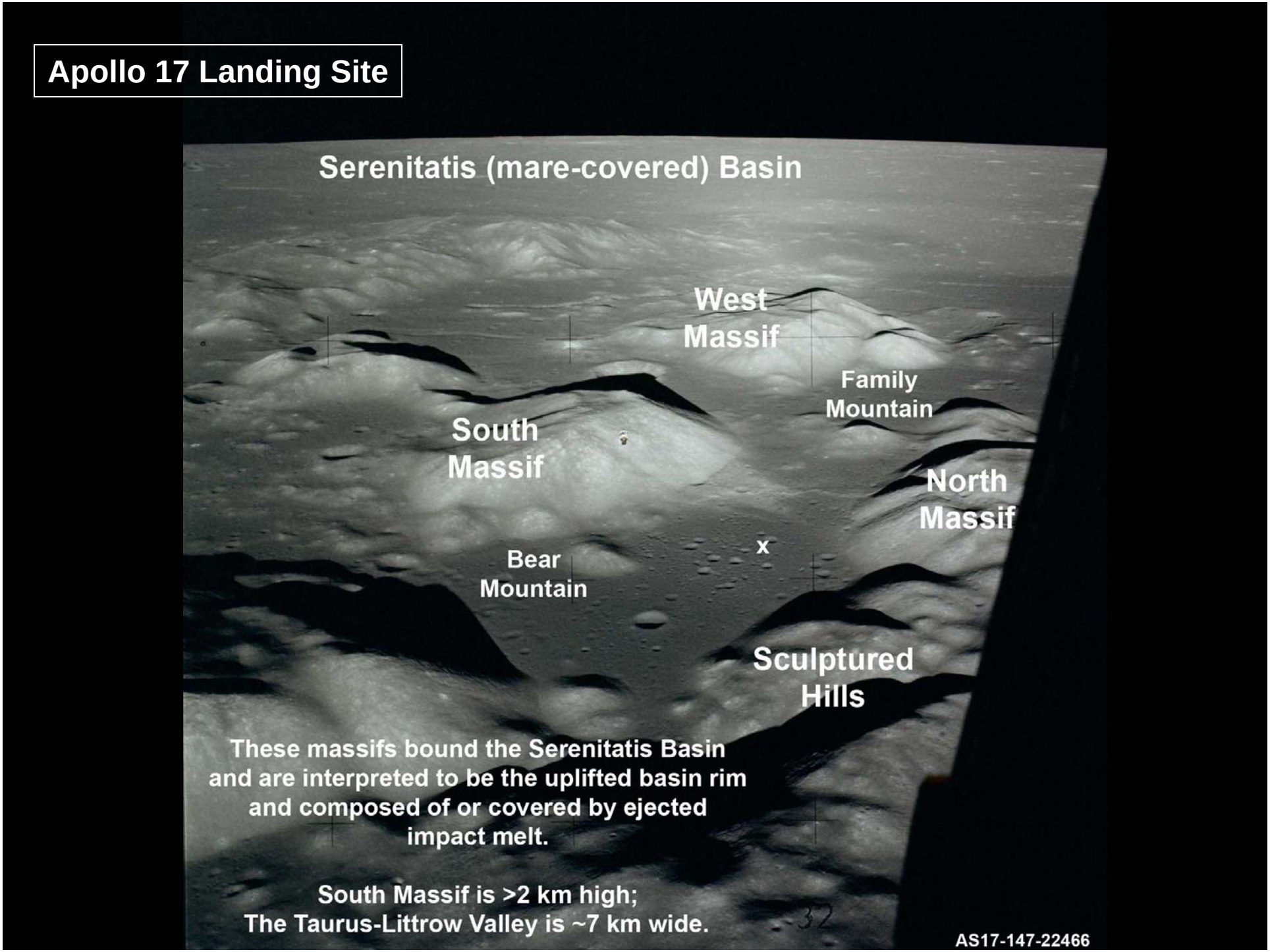


# Apollo 17 Samples

| Crystalline Impact Melt Breccias | Field Setting |
|---|---|
| • 72395 (poikilitic) | Ejected basin melt sample? |
| • 73215 (“aphanitic”) | Ejected large crater melt sample? |
| • 73255 (“aphanitic”) | Ejected large crater melt sample? |
| • 76015 | |
| • 76215 (“poikilitic”) | Ejected basin melt sample? |

| Glassy Impact Melt Breccia | |
|---|---|
| • 79175 | Ejected melt sample from Van Serg Crater |

# Apollo 17 Landing Site



Apollo 17, Station 2

Edge of Serenitatis Impact Basin

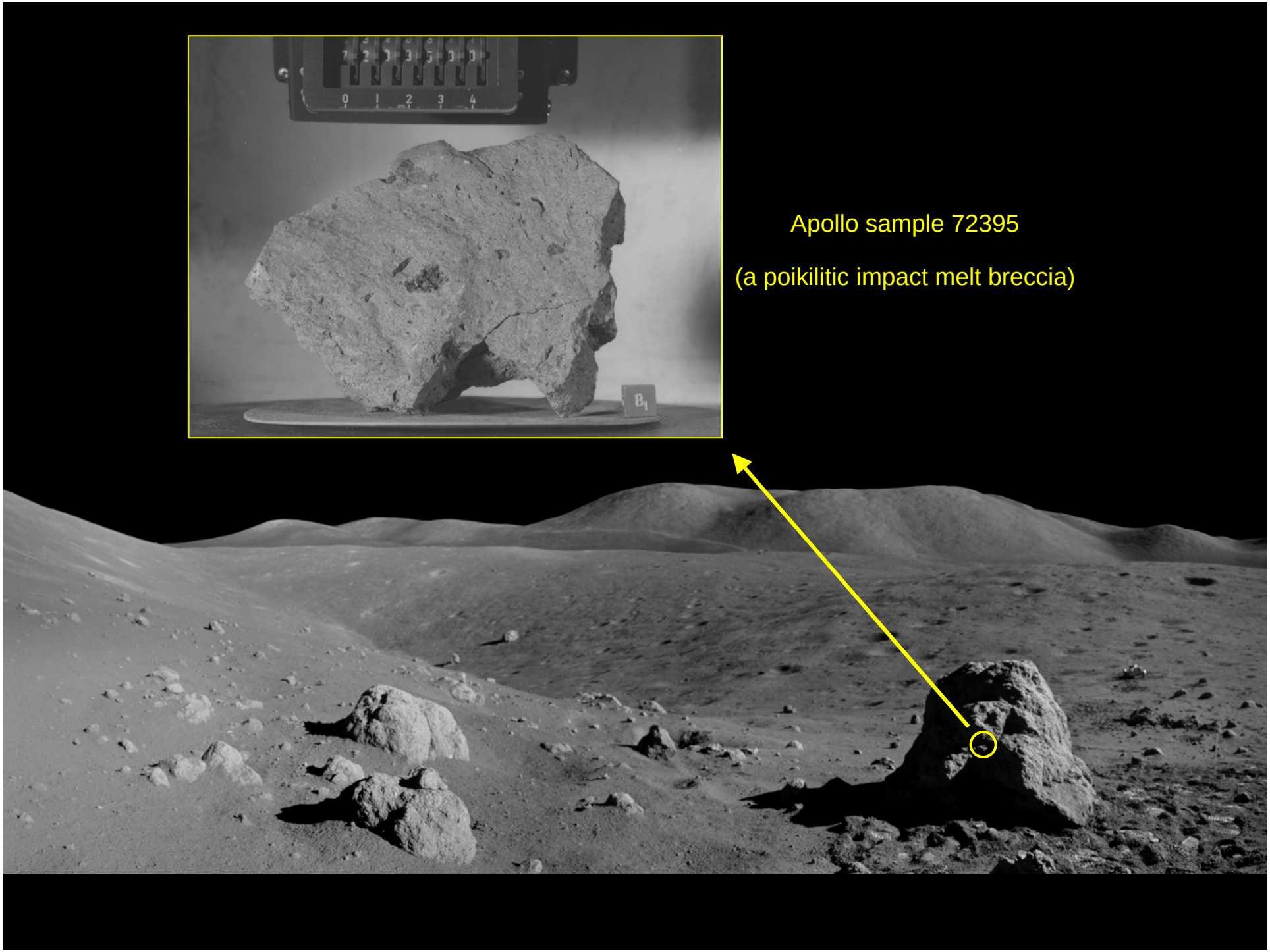
At base of the South Massif

2 meter boulder

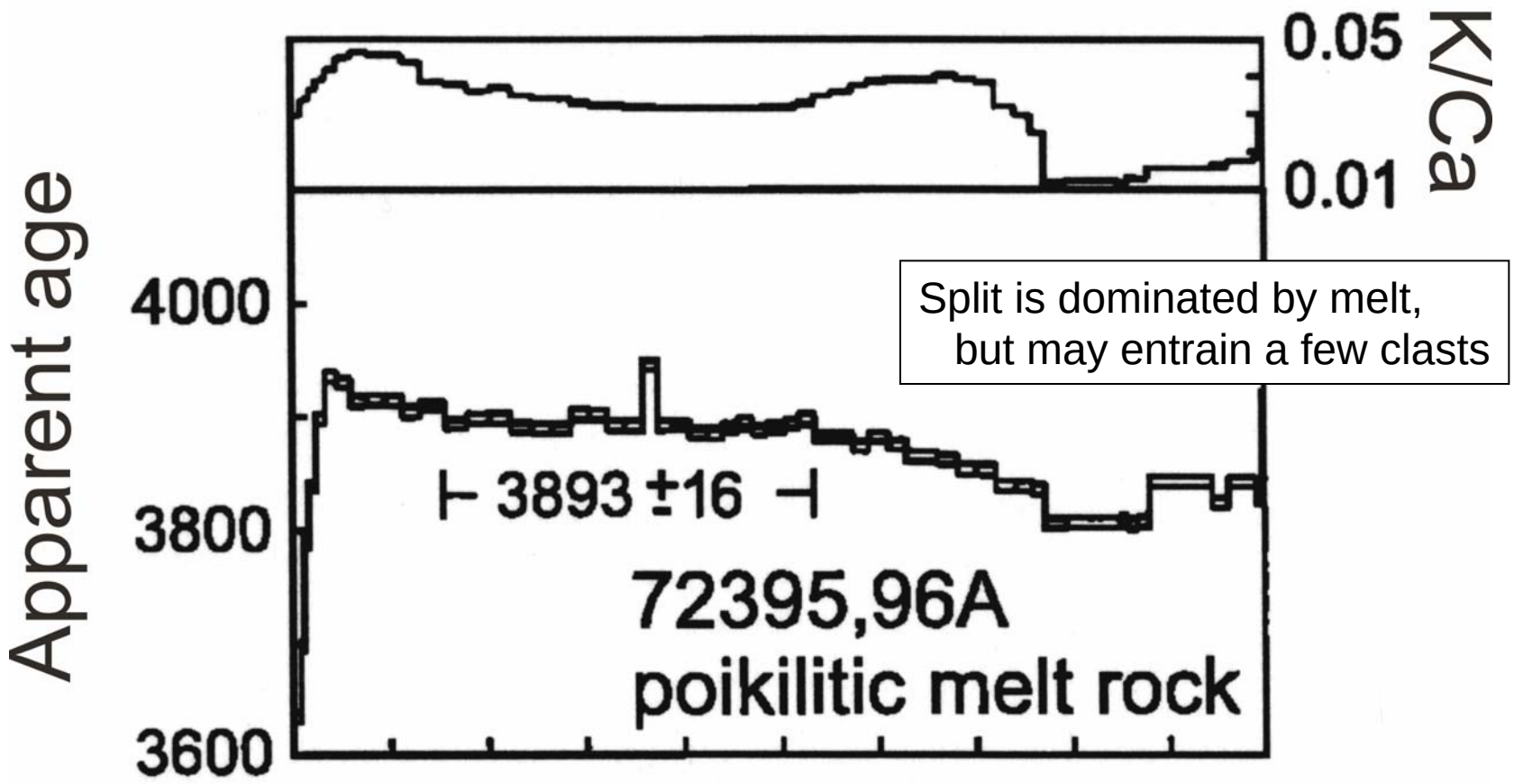
Eroded from impact melt deposit that is located higher on the massif

Age = 3.893 ± 0.016 Ga (Dalrymple and Ryder, 1996)

Crew: Jack Schmitt & Gene Cernan
Panorama assembled by David Harland


Apollo sample 72395
(a poikilitic impact melt breccia)

# Crystalline Impact Melt Breccia




Split is dominated by melt,
but may entrain a few clasts



Dalrymple & Ryder (1996)

Apollo 17, Station 6

Edge of Serenitatis Impact Basin

At base of the North Massif

Group of five boulders

Rolled 440 m down the slope of the massif

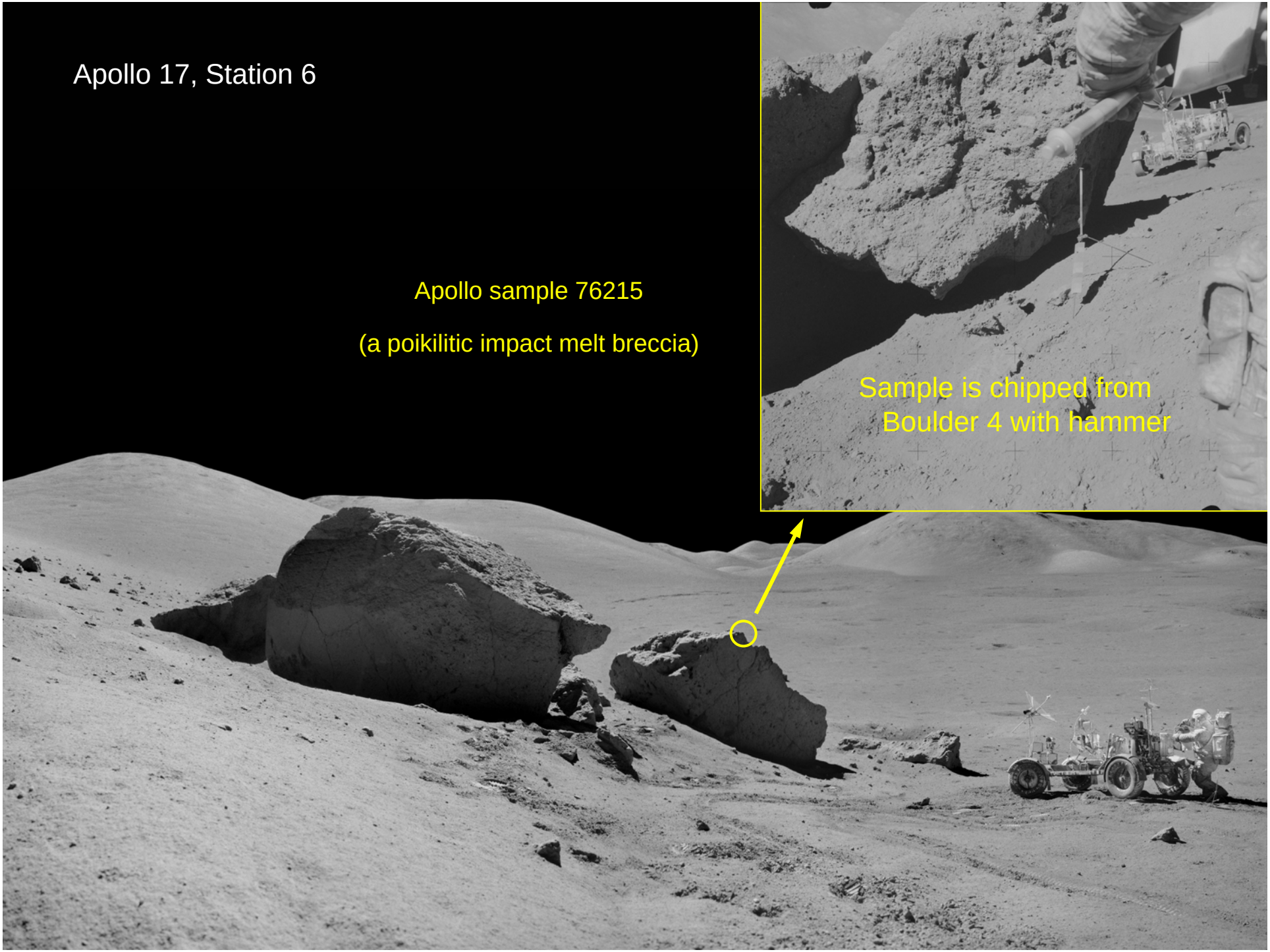
The boulders are melt breccias that differ in vesicularity, foliation, and texture

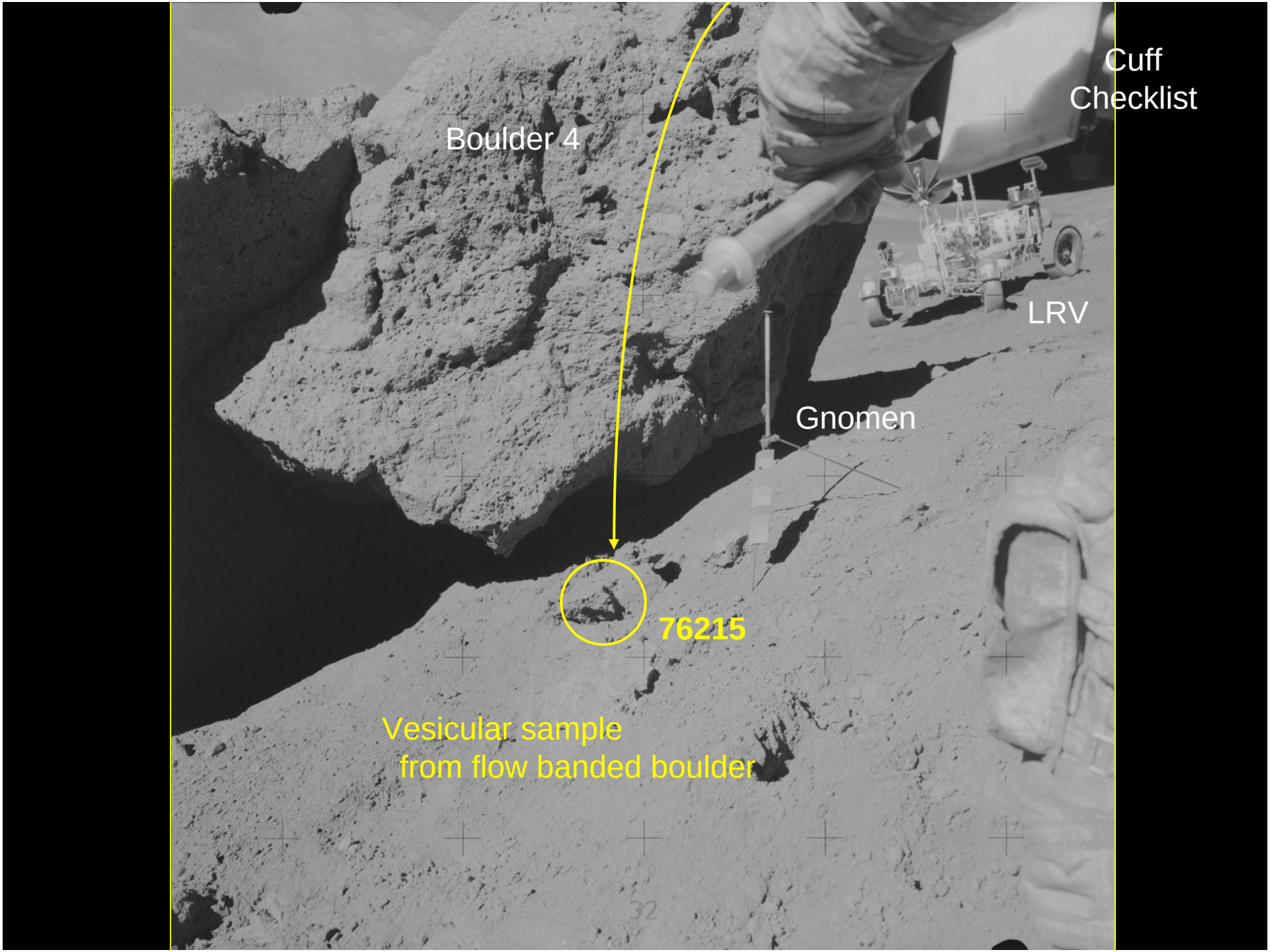
Crew: Jack Schmitt & Gene Cernan
Panorama assembled by David Harland

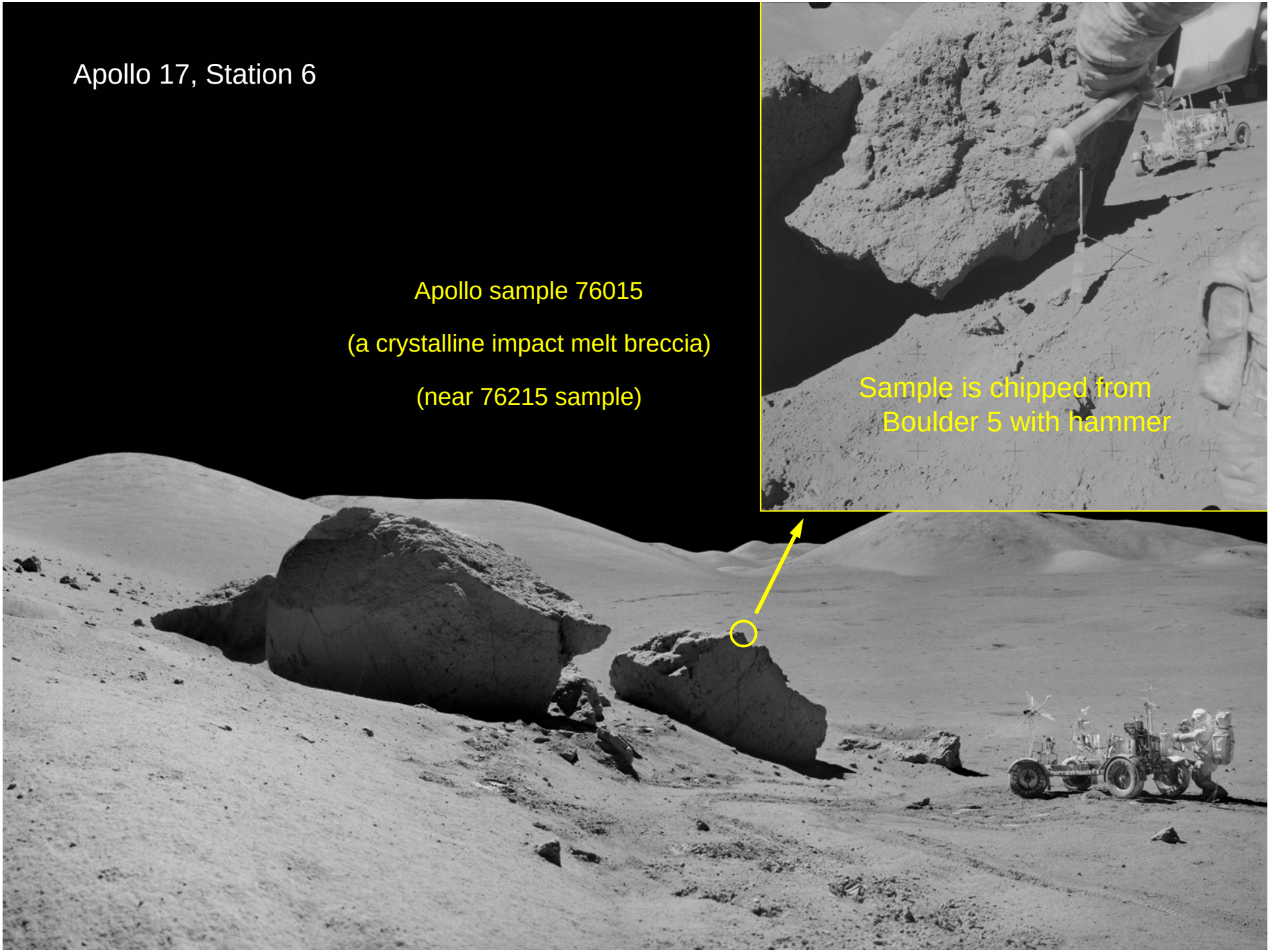
Apollo 17, Station 6

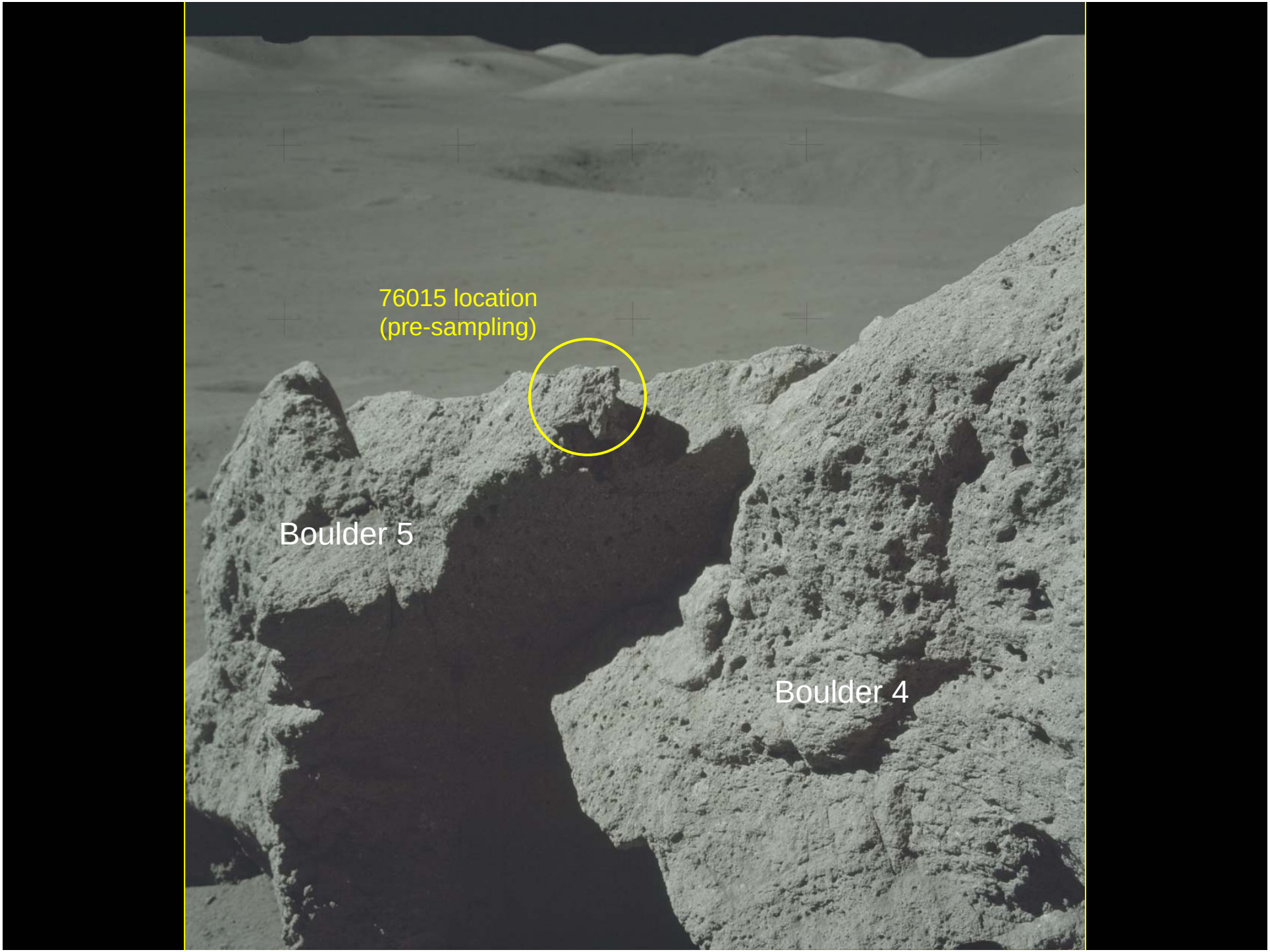
Apollo sample 76215

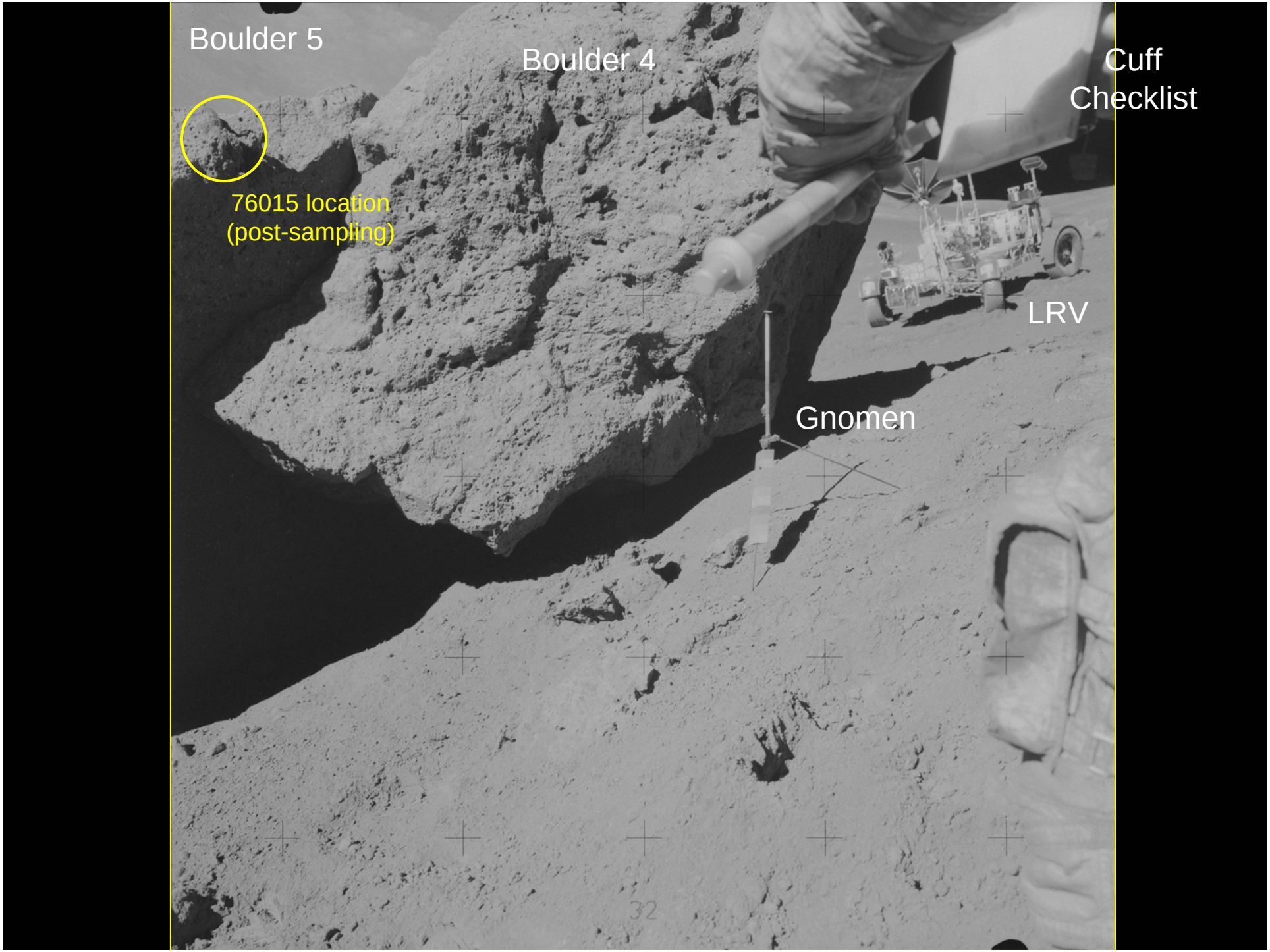
(a poikilitic impact melt breccia)

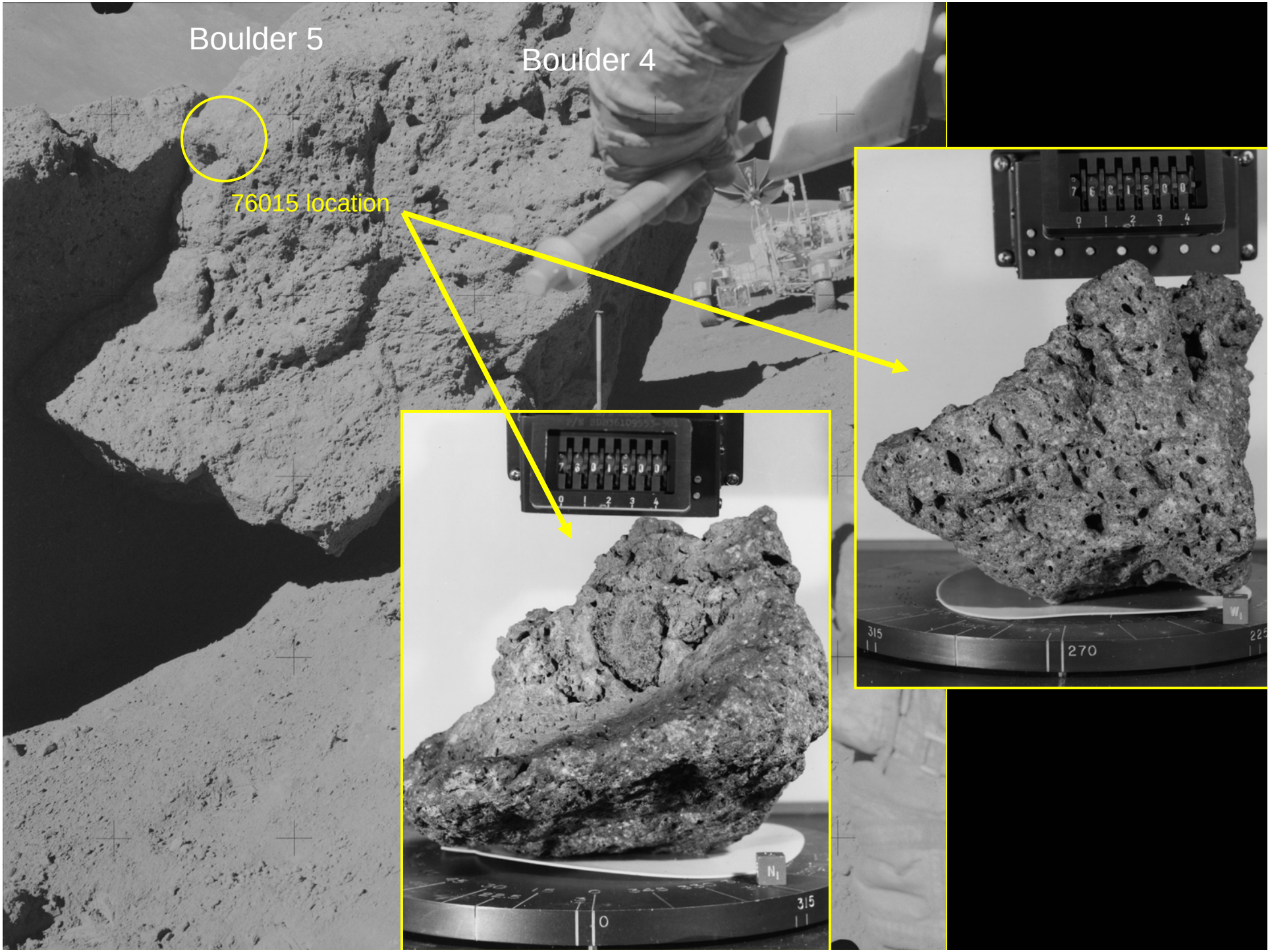

Apollo 17, Station 6
Apollo sample 76215
(a poikilitic impact melt breccia)
Sample is chipped from
Boulder 4 with hammer


Cuff
Checklist
Boulder 4
LRV
Gnomen
76215
Vesicular sample
from flow banded boulder

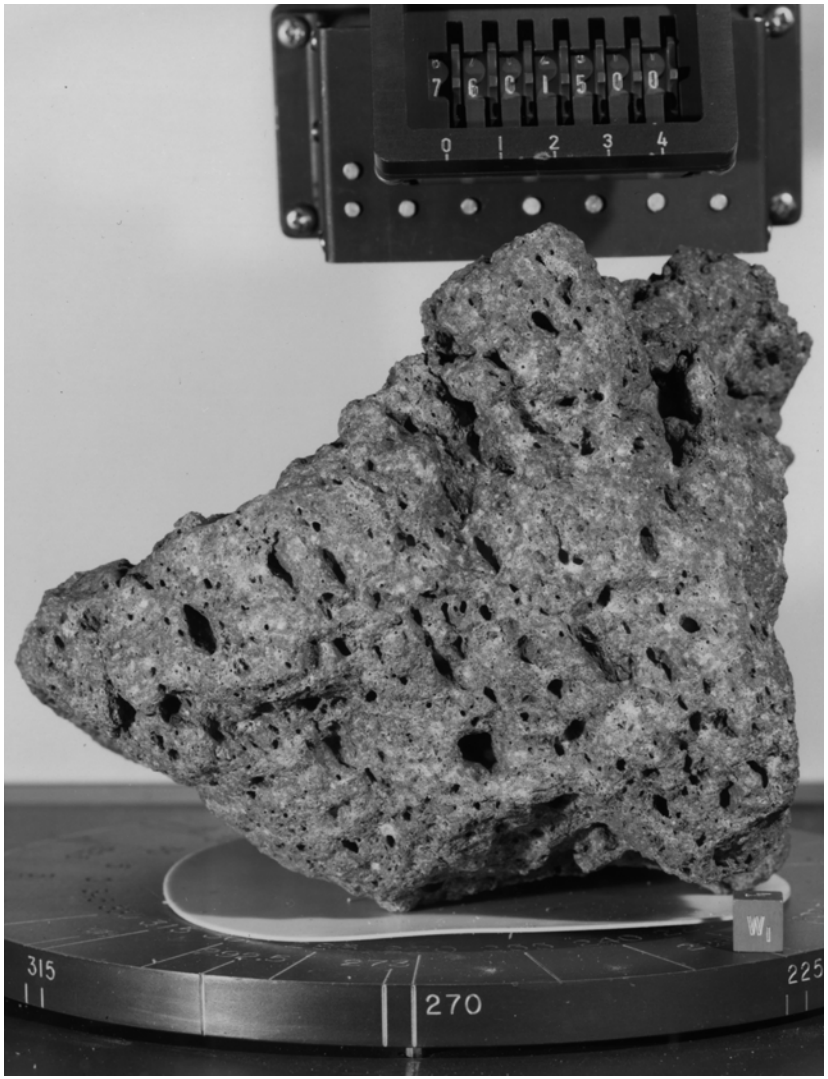

Apollo 17, Station 6
Apollo sample 76015
(a crystalline impact melt breccia)
(near 76215 sample)
Sample is chipped from
Boulder 5 with hammer


76015 location
(pre-sampling)
Boulder 5
Boulder 4


Boulder 5
Boulder 4
Cuff
Checklist
76015 location
(post-sampling)
LRV
Gnomen


Boulder 5
Boulder 4
76015 location
315
270
225
315
0

# Crystalline Impact Melt Breccia




76015

A vesicular “poikilitic” impact melt at the Apollo 17 landing site.

Matrix of sample has an Ar-Ar age of 3.93 ± 0.04 Ga (Cadogan & Turner, 1976).

# Crystalline Impact Melt Breccia

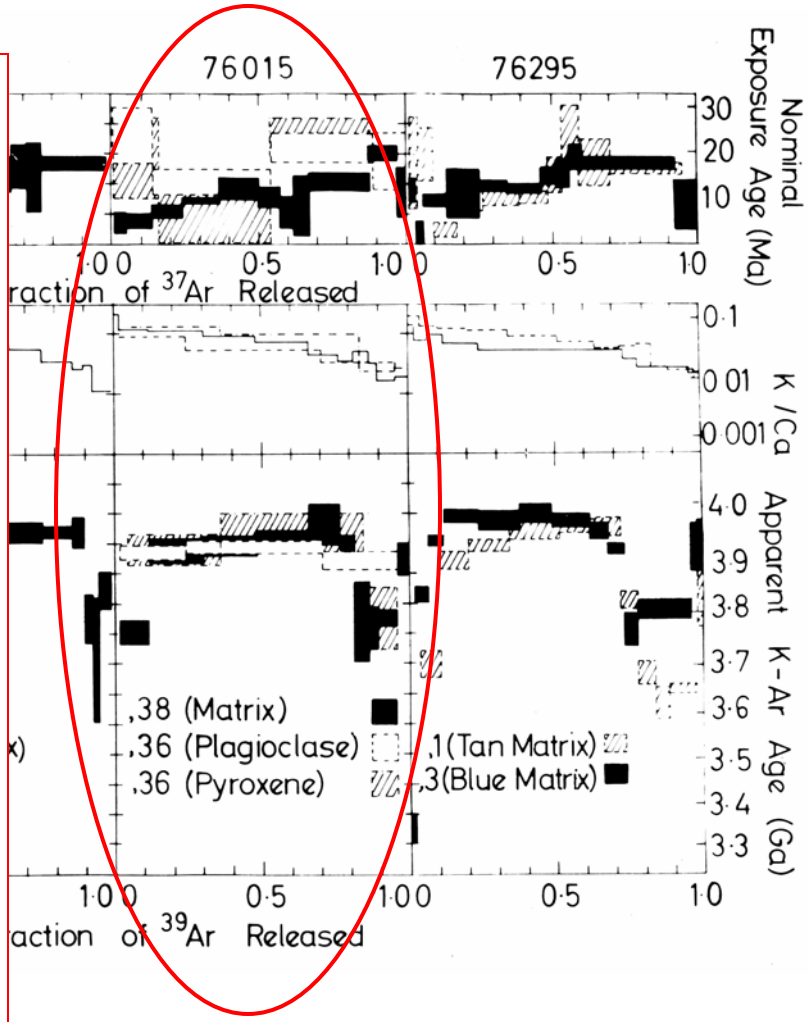
76015

Inferred Ar-Ar age is
3.93 ± 04 Ga, based on a "matrix" split.

Pyroxene separate has
a plateau of 3.92 ± 04 Ga, while

Plagioclase separate has
a plateau of 3.96 ± 06 Ga

Cardogan & Turner (1976)



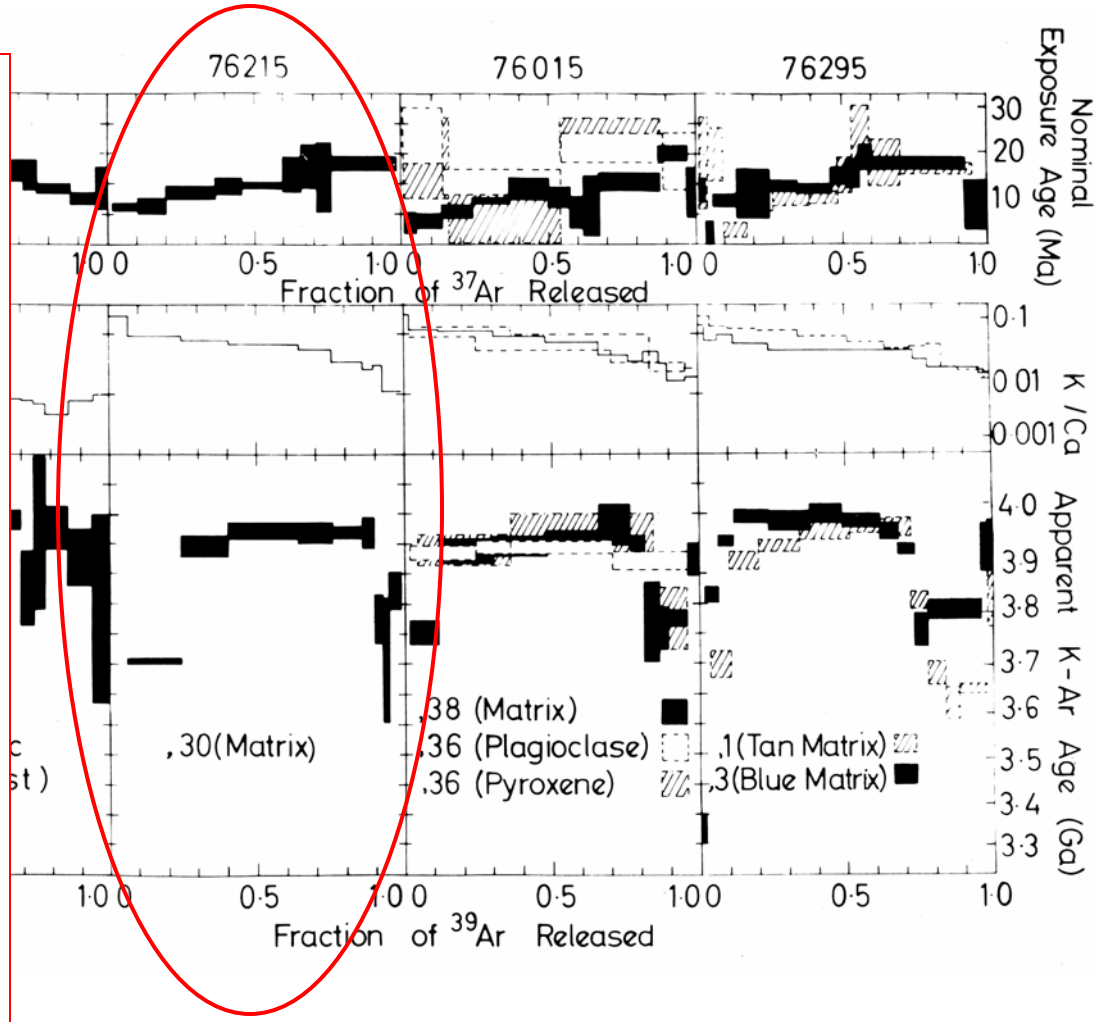
# Crystalline Impact Melt Breccia

76215

Inferred Ar-Ar ages is 3.94 ± 04 Ga.

Sample is described as being composed of matrix and clasts.

Cardogan & Turner (1976)



Apollo 17, Station 3

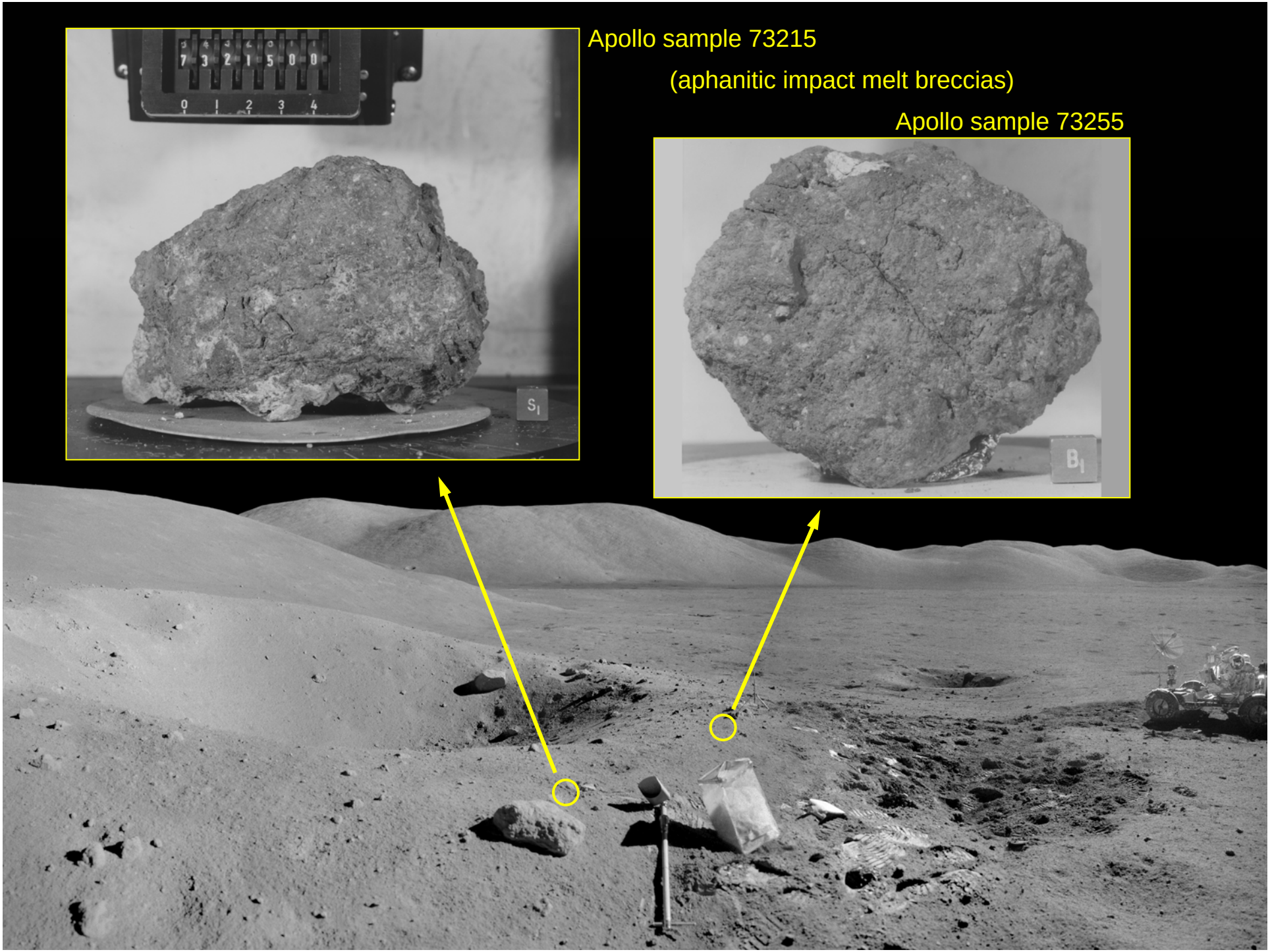
Edge of Serenitatis Impact Basin

At base of the South Massif

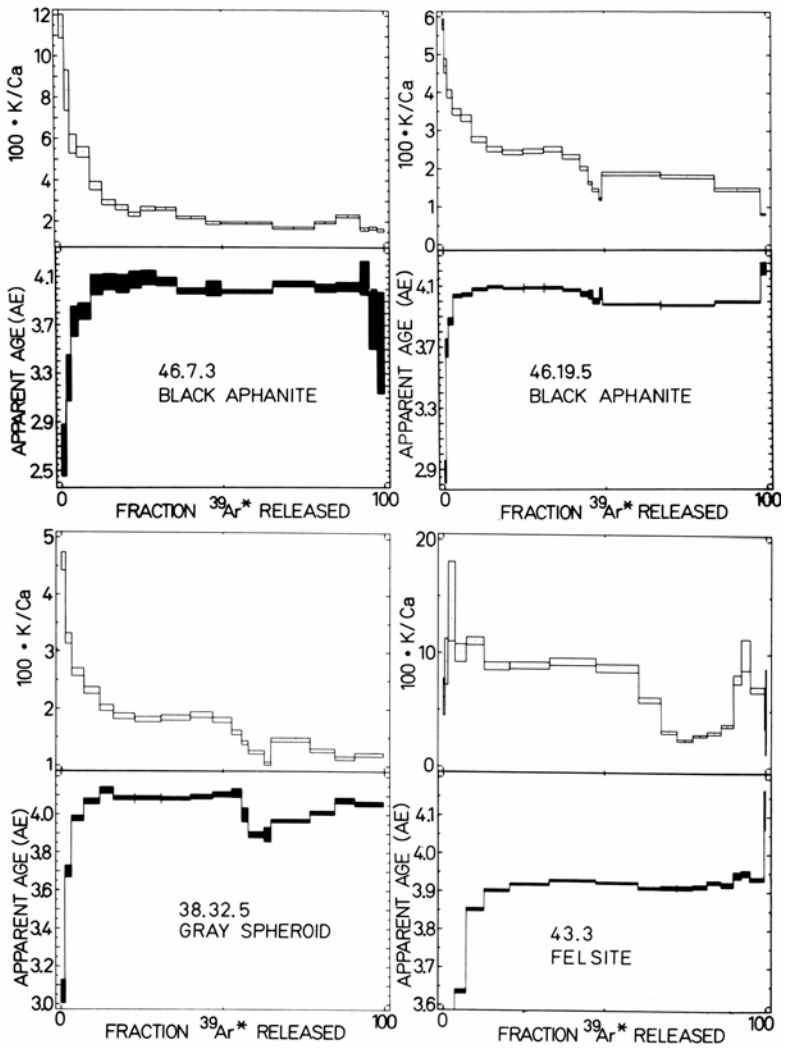
In mantle of light-colored material,
believed to be a landslide off of the South Massif

12 m crater excavated rocks from light mantle unit

Crew: Jack Schmitt & Gene Cernan
Panorama assembled by David Harland


Apollo sample 73215
(aphanitic impact melt breccias)
Apollo sample 73255

# Crystalline Impact Melt Breccia




73215

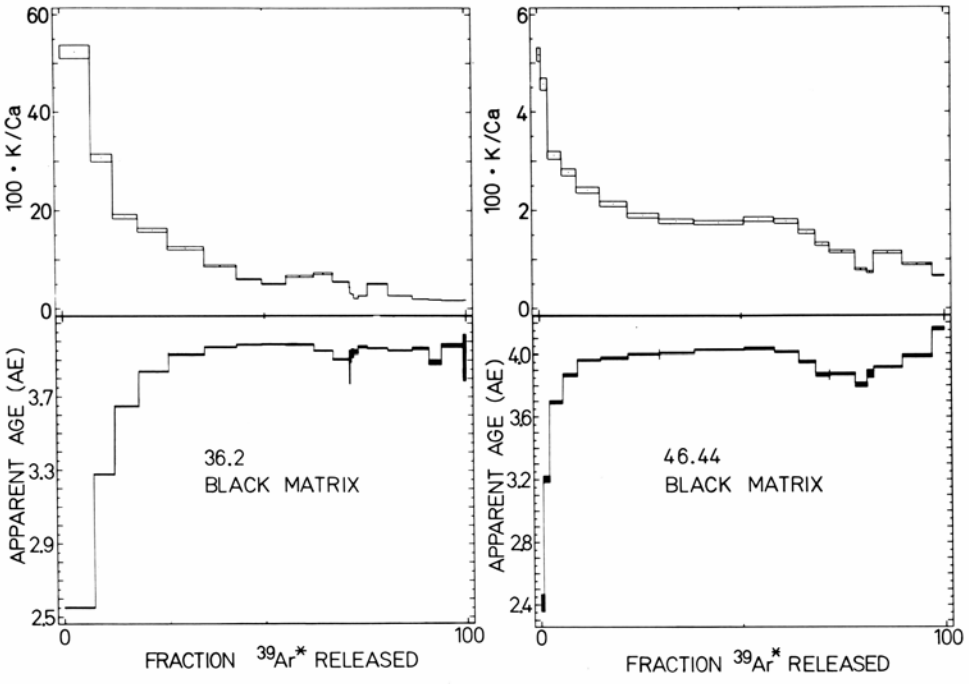
Several splits were separated from the breccia.

Black aphanite splits produced ages of 4.02 & 4.08 ± 01 Ga.

A “felsite” split produced an age of 3.92 ± 01 Ga.

Jessberger et al. (1977)

# Crystalline Impact Melt Breccia



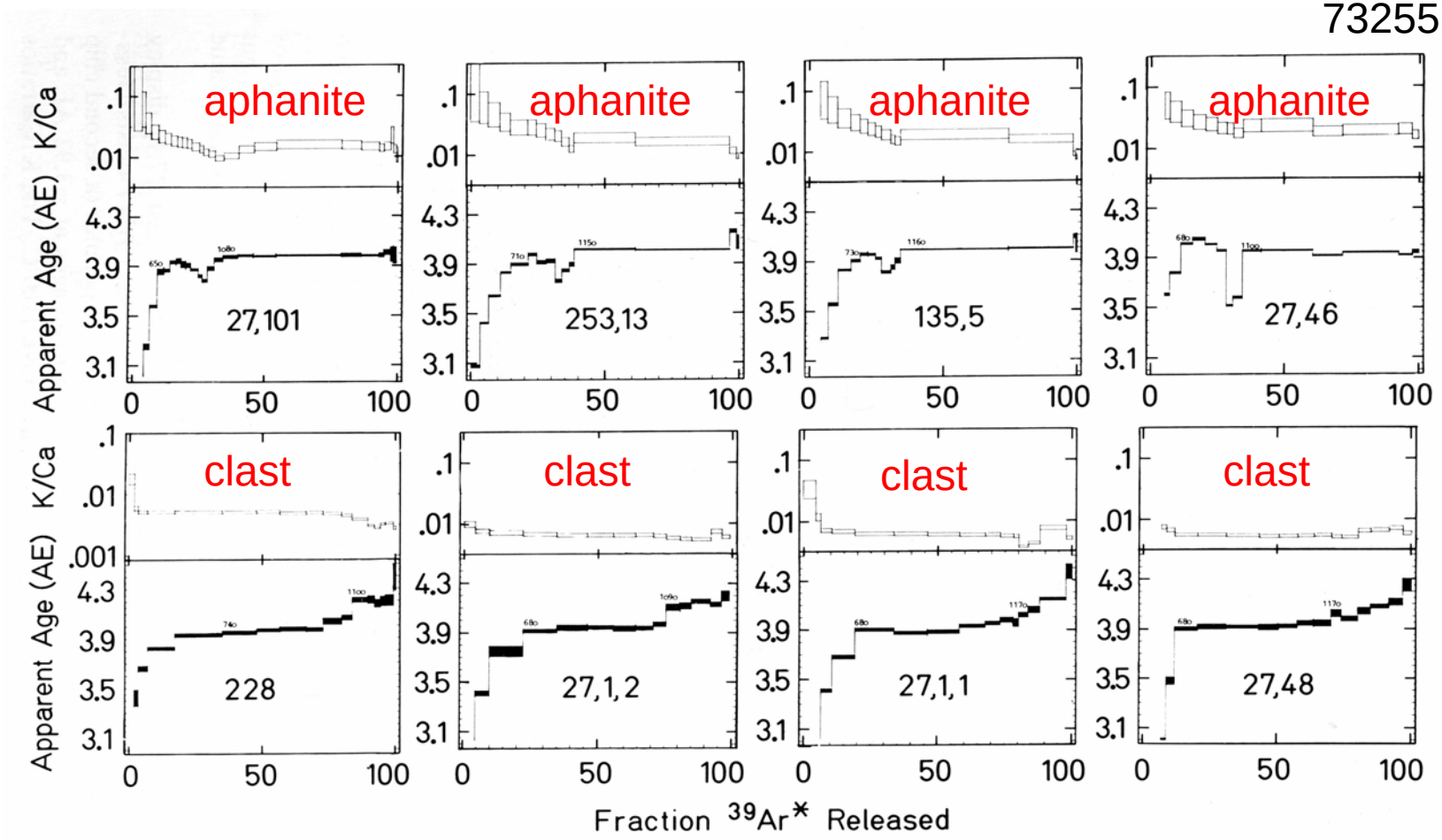

73215

Black matrix splits produced ages of 3.98 ± 01 & 4.04 ± 03 Ga.

Jessberger et al. (1977)

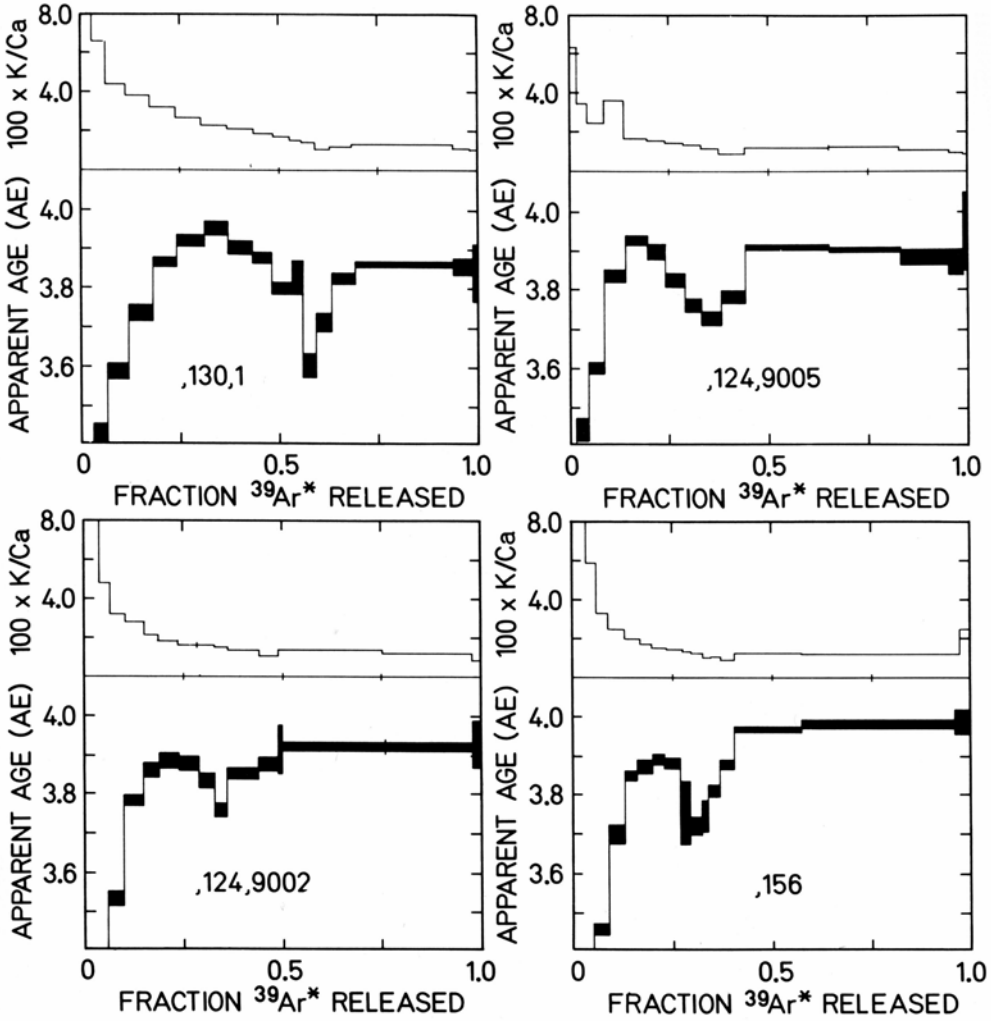
# Crystalline Impact Melt Breccia

73255




- Aphanite age of 3.89 ± 02 to 3.92 ± 02 Ga is inferred for 73255 (Staudacher et al., 1978)

# Crystalline Impact Melt Breccia

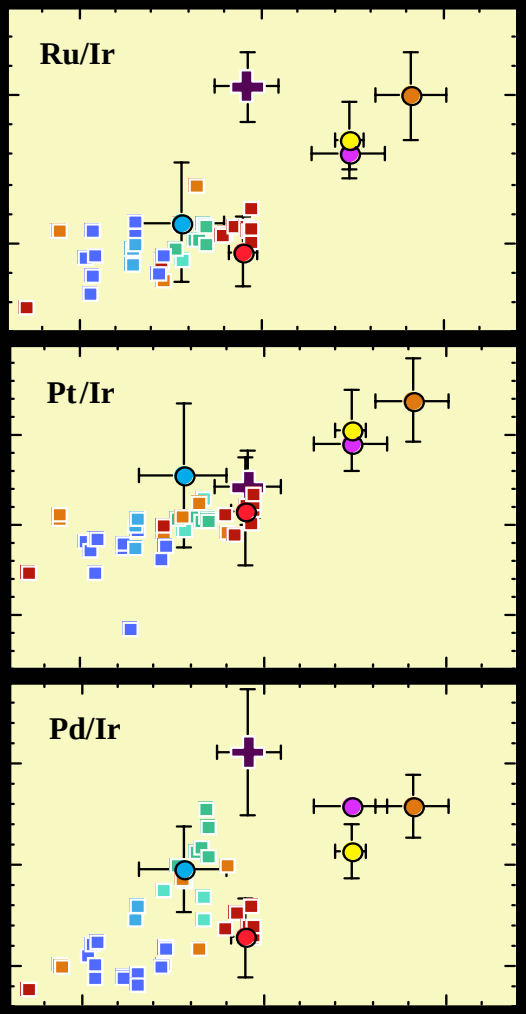



73225

The sample is matrix-rich, with much of the entrained plagioclase and lithic clasts removed with tweezers and drill.

Inferred the matrix-forming event occurred 3.88 ± 02 Ga.

Jessberger et al. (1976)




Puchtel, Walker, James, & Kring (2008)

## Apollo samples

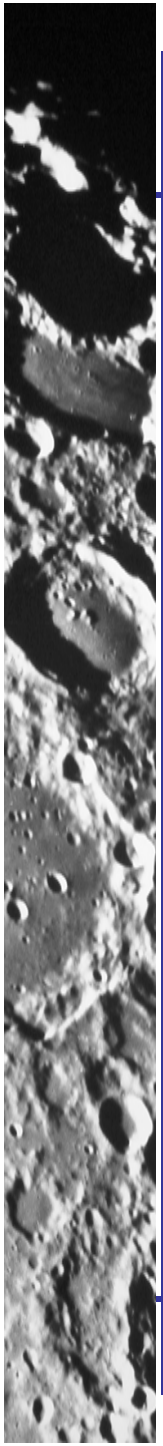
| | | | |
|---|---|---|---|
| 73215 | A | SM | Ordinary chondrite affinities |
| 73255 | A | SM | Ordinary chondrite affinities |
| 14321 | - | - | New type of projectile |
| 72395 | P | SM | New type of projectile |
| 76215 | P | NM | New type of projectile |

- Not all Apollo 17 impact melt breccias are produced by the the same impact event
- Aphanitic samples have HSE signatures dominated by granulite clasts; thus, the results reveal the projectiles that affected granulite precursors, not the projectile that produced the aphanitic melts
- Our inventory of asteroid compositions is still incomplete

## Lunar Meteorite

| | |
|---|---|
| NWA 482 | Enstatite (and marginally ordinary) chondrite affinities |

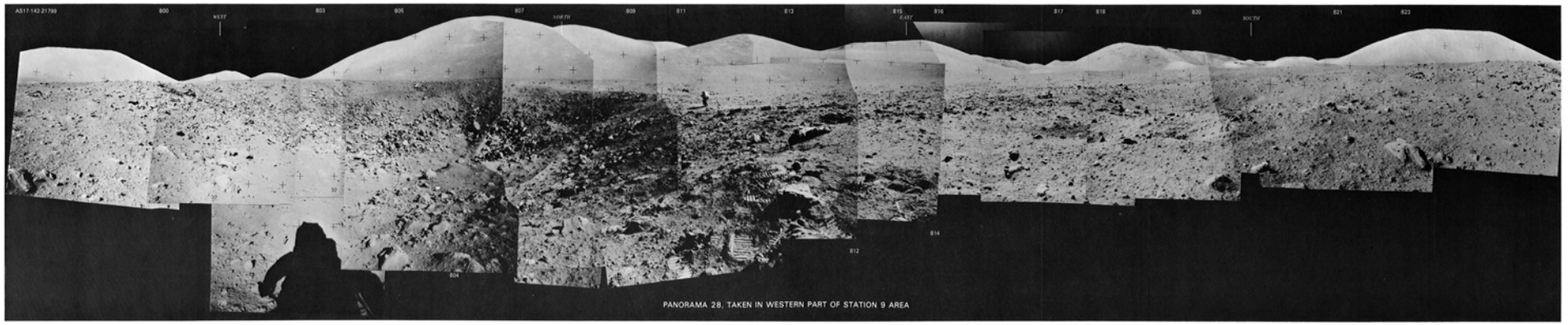
These data also suggest the dominant source of projectiles hitting the Moon and early Earth are asteroidal, not cometary.



# Summary of Apollo 17 Boulders

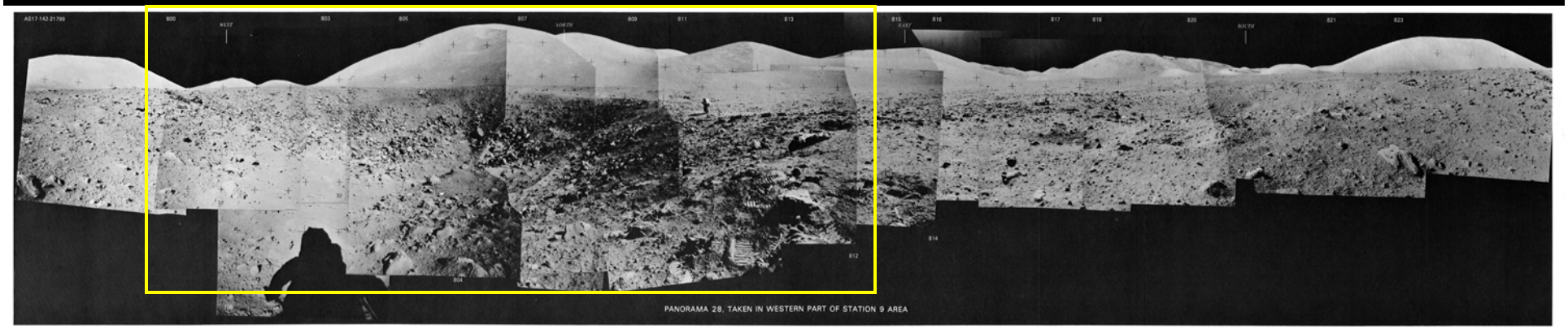
| Sample | Classification | Texture | Age (Ga) | Projectile Affinities |
|---|---|---|---|---|
| 72395 | X'alline IMB | Poikilitic | 3.893 ± 16 | new type of projectile |
| 76215 | X'alline IMB | Poikilitic | 3.94 ± 04 | new type of projectile |
| 76015 | X'alline IMB | Poikilitic | 3.93 ± 04 | not analyzed |
| 73215 | X'alline IMB | Aphanitic | 3.99 to 4.04 | ordinary chondrite |
| 73255 | X'alline IMB | Aphanitic | 3.88 ± 02 | ordinary chondrite |

Apollo 17, Station 9
Panorama 28



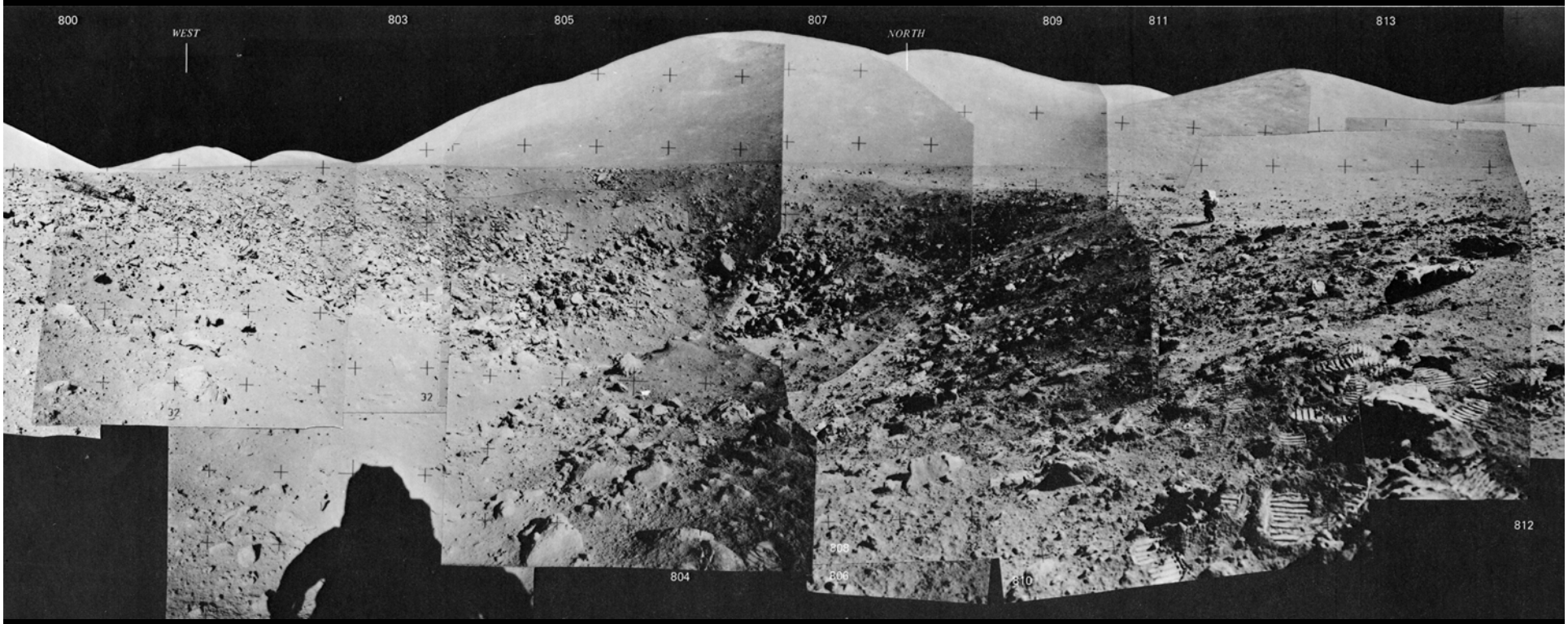

Van Serg Crater

Apollo 17, Station 9
Panorama 28




Van Serg Crater

Apollo 17, Station 9
Panorama 28

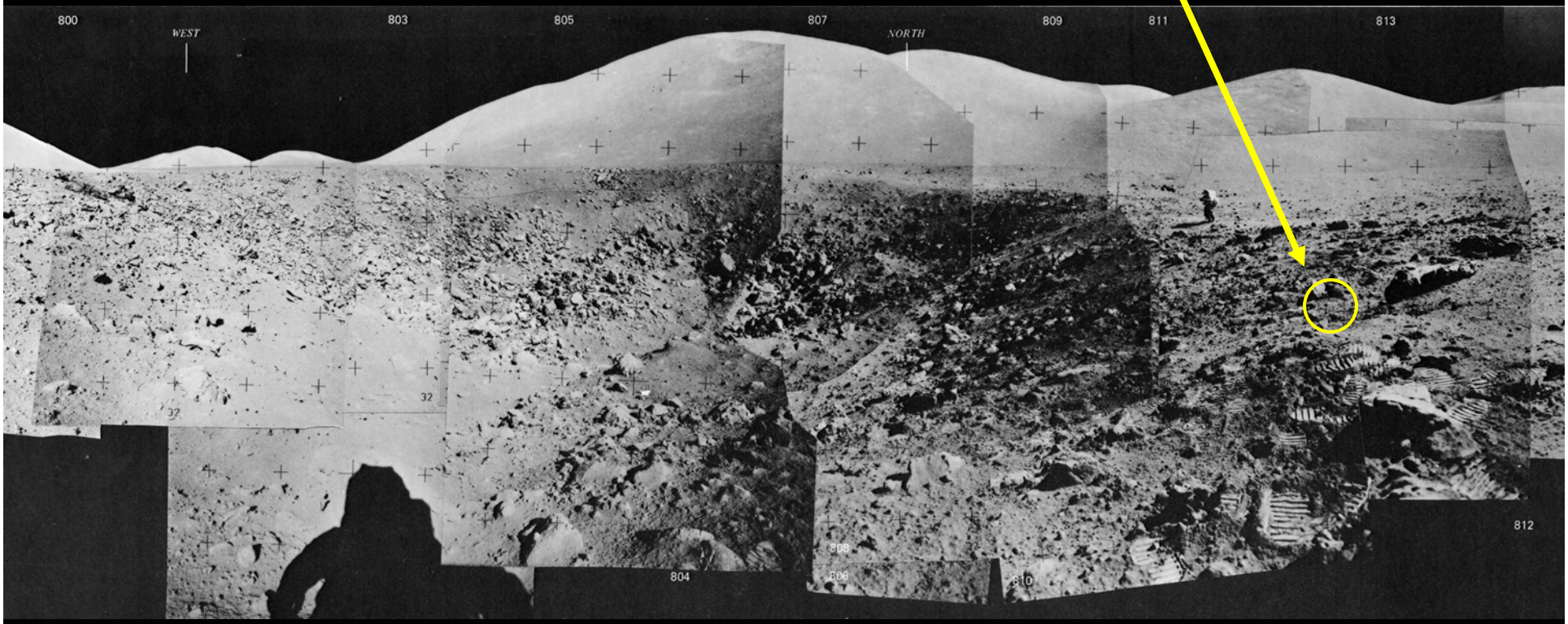



Van Serg Crater →

90 m diameter crater
w/ blocky central mound ~30 m in diameter
Discontinuous benches on crater walls
Raised blocky rim
Blocky ejecta blanket

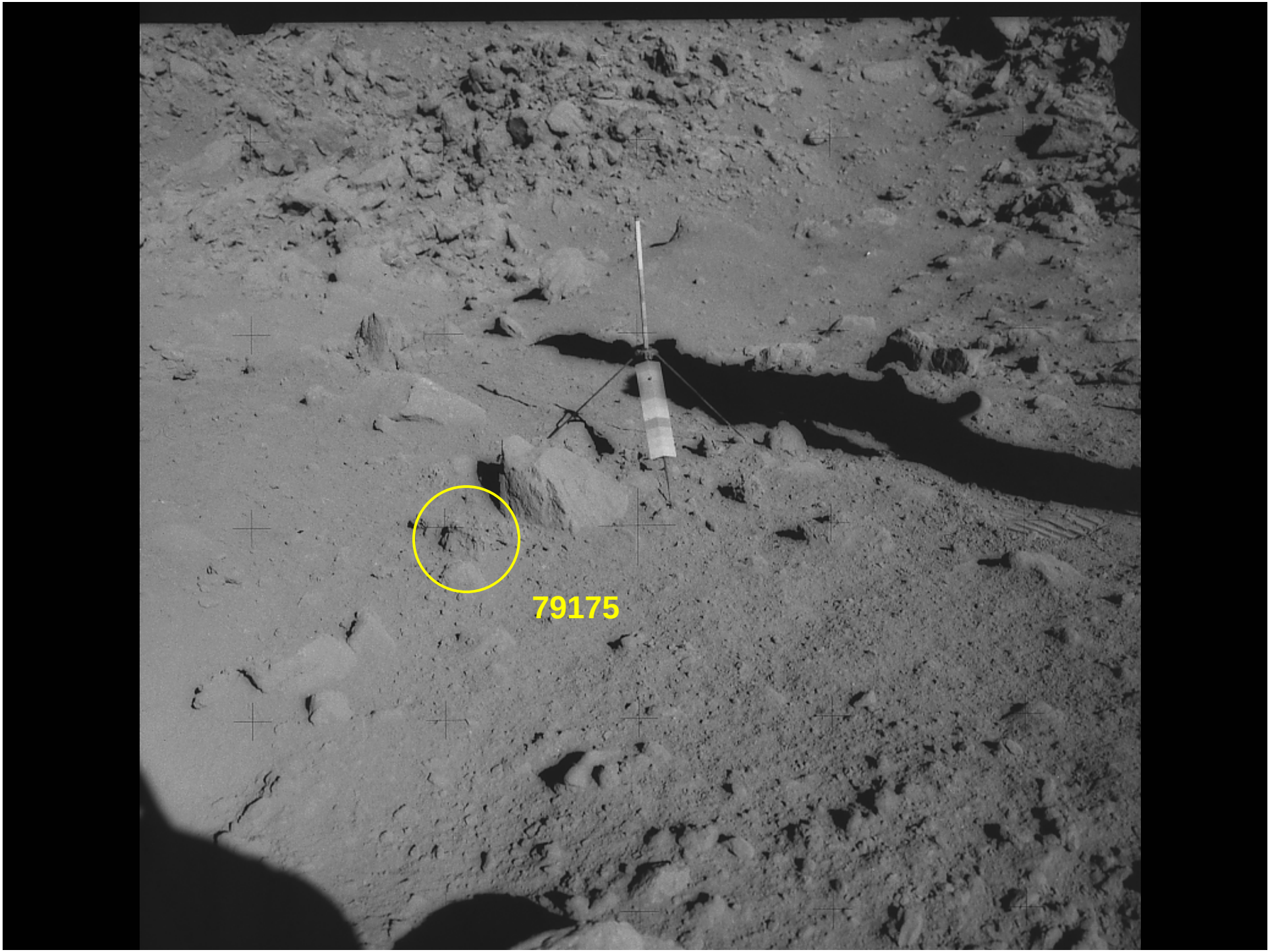
Apollo 17, Station 9
Panorama 28

79175
Ejected melt from Van Serg Crater

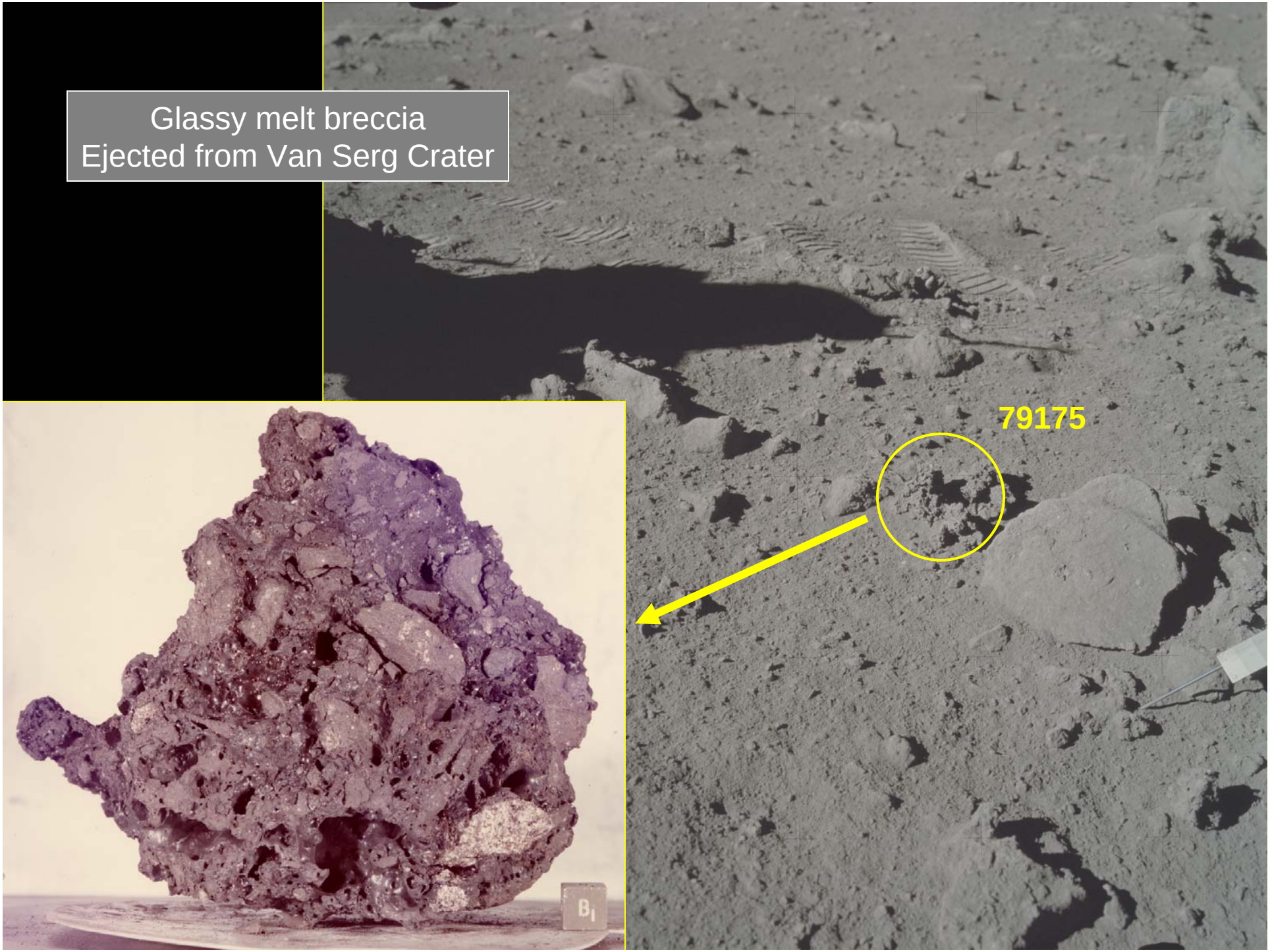


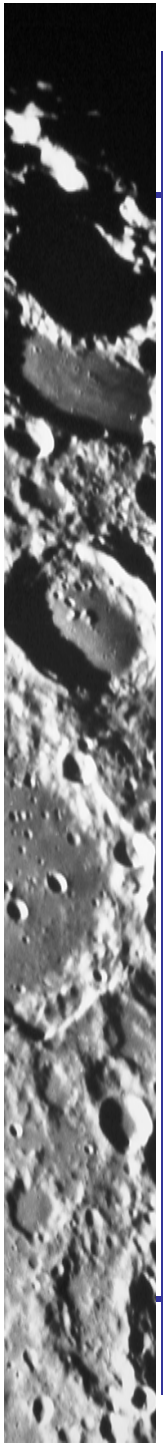

Van Serg Crater →

90 m diameter crater
w/ blocky central mound ~30 m in diameter
Discontinuous benches on crater walls
Raised blocky rim
Blocky ejecta blanket


79175

Glassy melt breccia
Ejected from Van Serg Crater





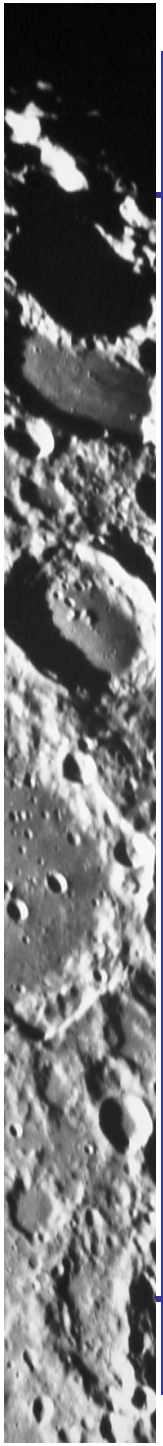
# Glassy Impact Melt Breccia

79175

Once the samples were returned to Houston, this particular sample was not used to determine age of Van Serg Crater.

A neighboring sample (79155) has an exposure age of 575 ± 60 Ma (Kirsten & Horn, 1974) and another (79215) has an exposure age of 3.7 Ma (Bhandari et al., 1976). In addition, a trench sample (79221) has an approximate age of 1.5 Ma (Yokoyama et al., 1976).

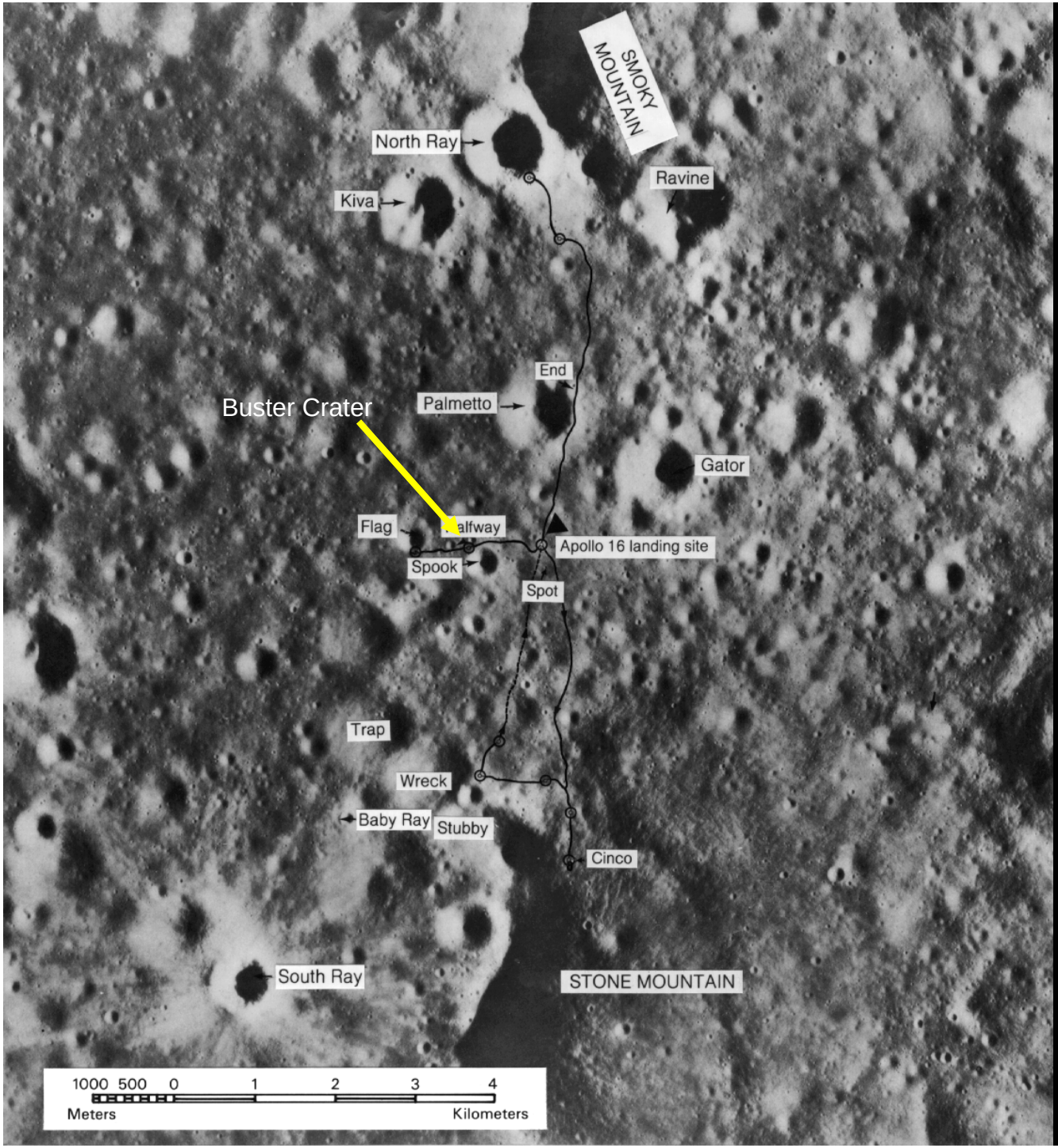
The morphology of Van Serg, when compared to that of the 10 to 30 Ma Shorty Crater, suggests the younger exposure ages (1.5 to 3.7 Ma) reflect the approximate age of the Van Serg impact (Wolfe et al., 1981).

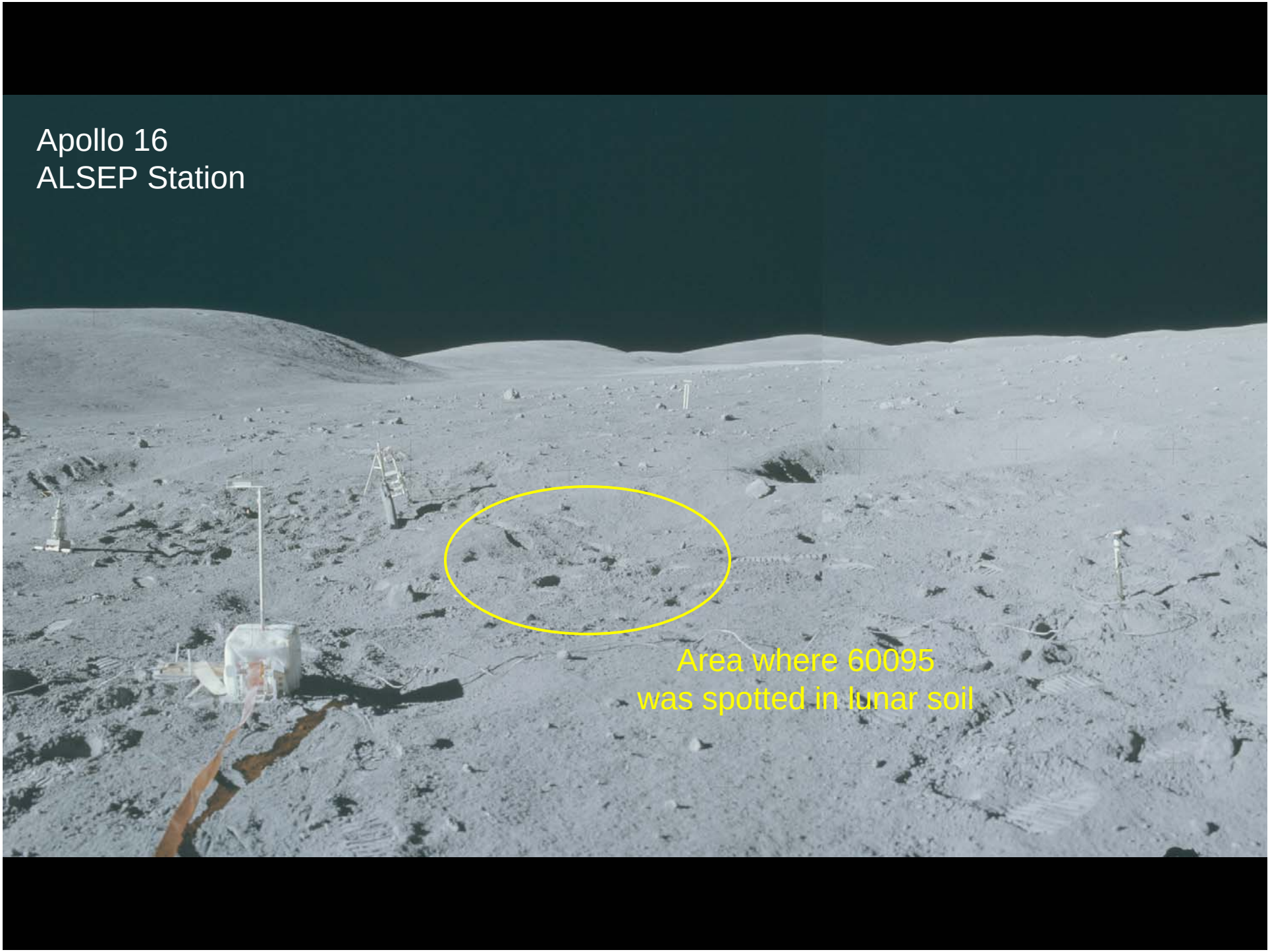


# Apollo 16 Samples

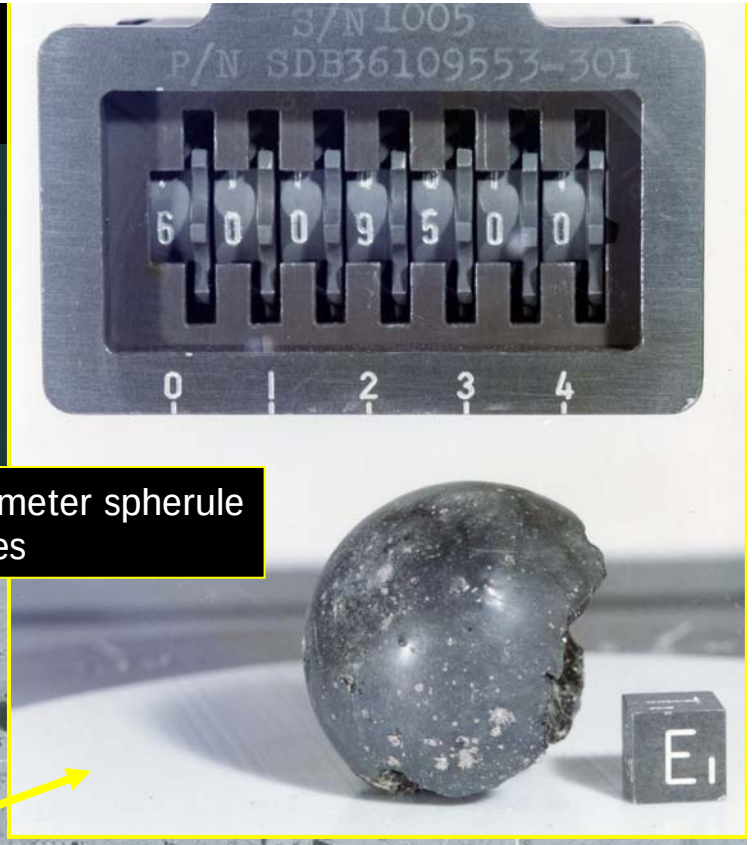
| Glassy Impact Melts and Melt Breccias | Field Setting |
|---|---|
| • 60095<br>• 60115<br>• 68815 | Glassy impact melt spherule in soil |
| **Clast-poor Impact Melt Breccia** | |
| • 68415 | |
| **Crystalline Impact Melt Breccia** | |
| • 62295 | Ejected from Buster Crater |

# Apollo 16 Landing Site




Apollo 16
ALSEP Station
Area where 60095
was spotted in lunar soil

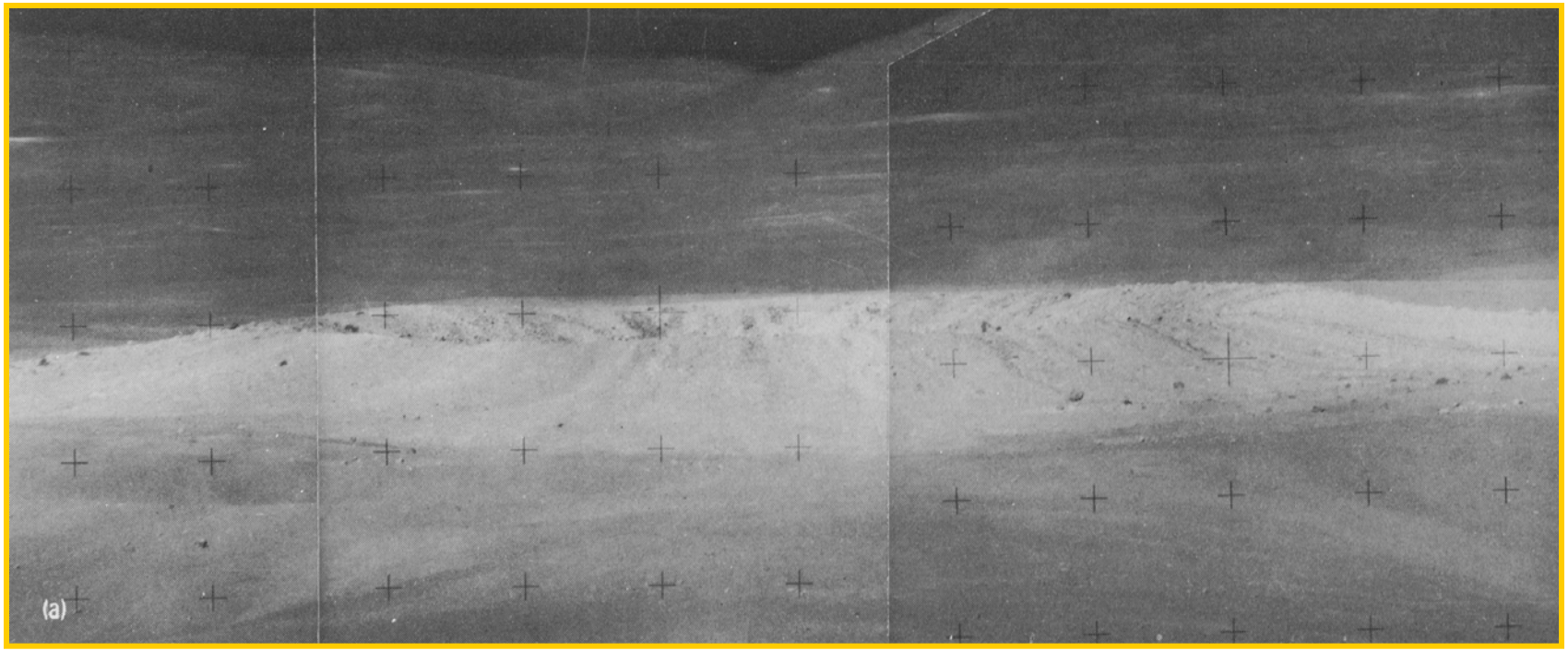
Apollo 16
ALSEP Station




2.6 cm diameter spherule
w/ vesicles

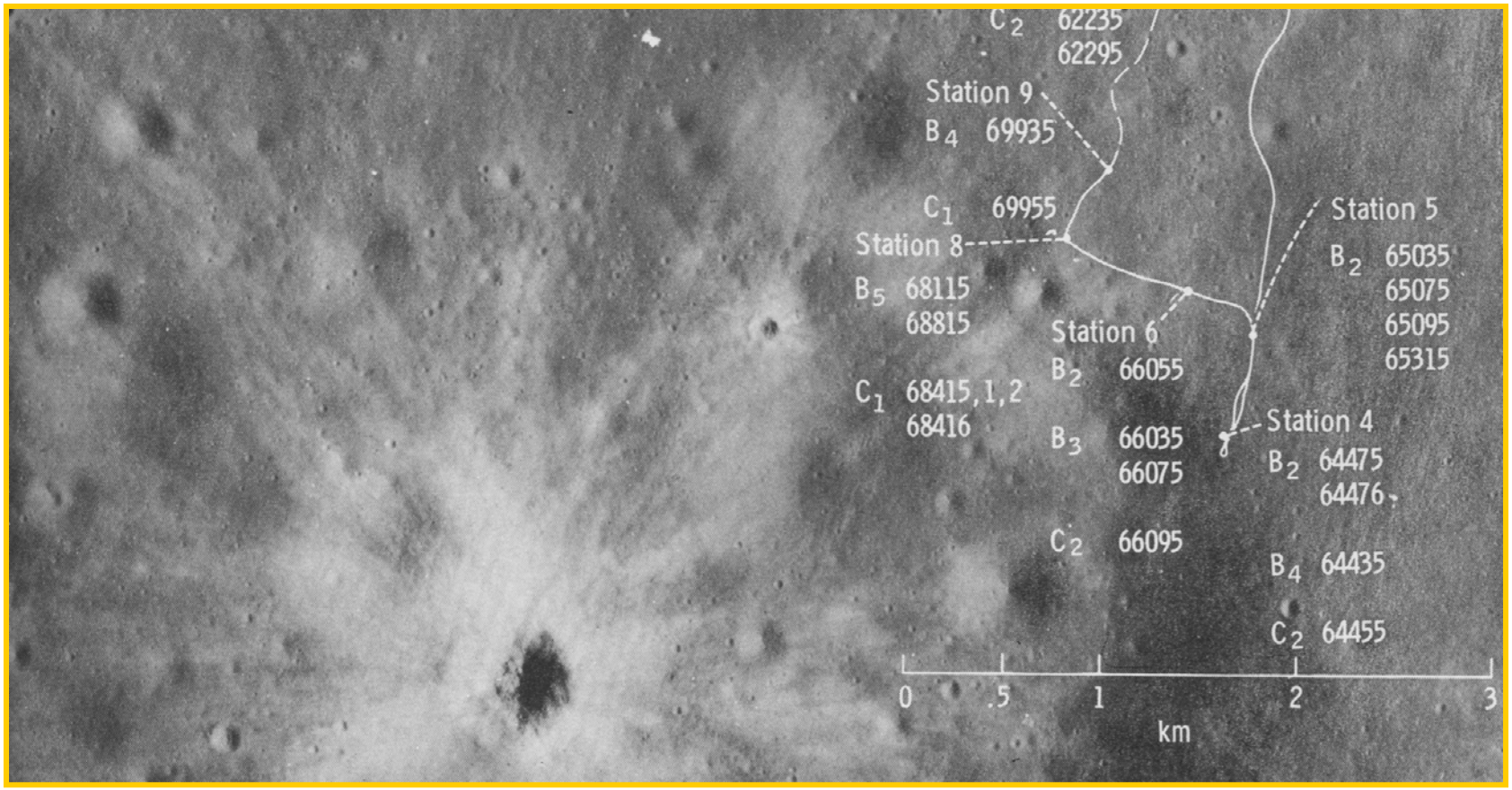
Area where 60095
was spotted in lunar soil

# South Ray Crater (Apollo 16)




- **Oblique “aerial” view from *Orion* (LM)**
- **Uplifted rim with ejecta blanket**
- **680 m diameter crater**

# South Ray Crater (Apollo 16)




- **Astronauts did not reach South Ray Crater, so ejected debris deposited far from the crater was sampled instead**

Apollo 16, Station 8
Boulder C
One of several boulders in ejecta blanket
of South Ray Crater
Collected in hopes of determining age of crater

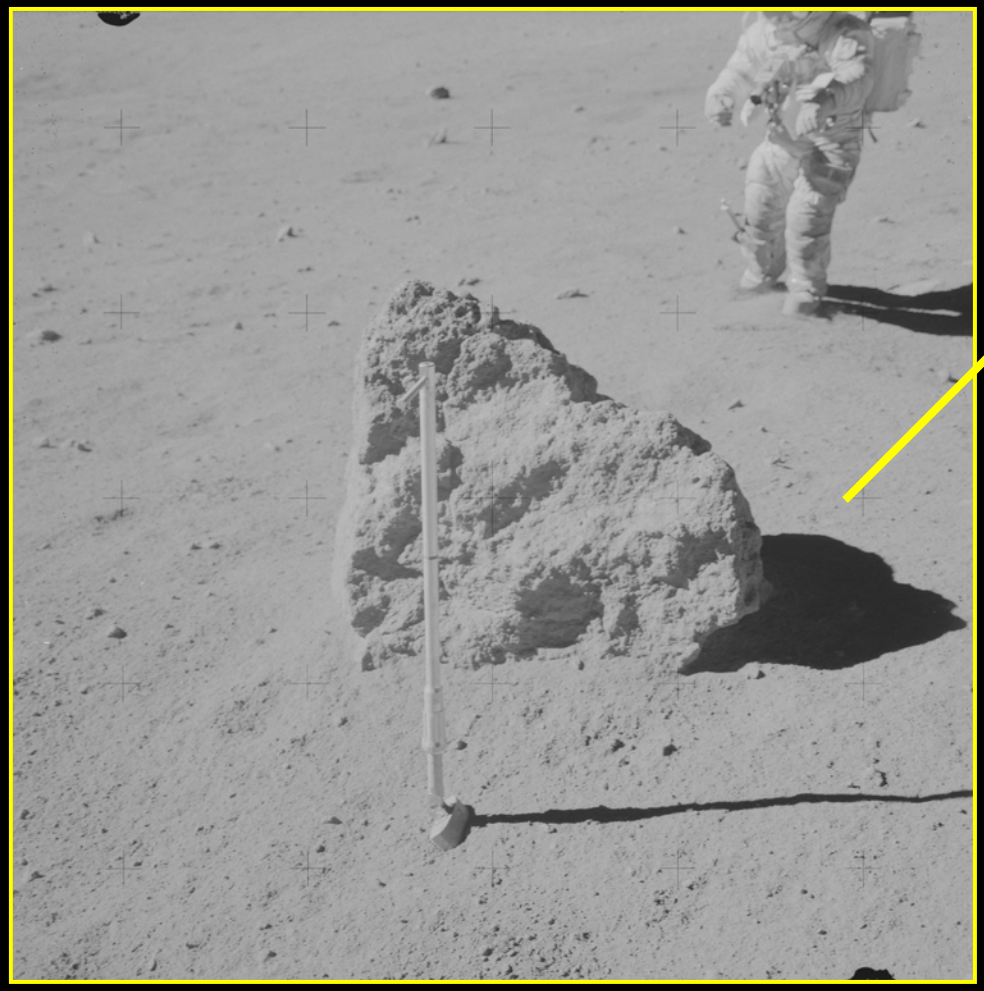
Apollo 16, Station 8
Boulder C
One of several boulders in ejecta blanket
of South Ray Crater
Collected in hopes of determining age of crater → We now know that this was a fruitless exercise.

Such a small crater was not going to produce such large blocks of melt with representative ages and eject them to such far distances.

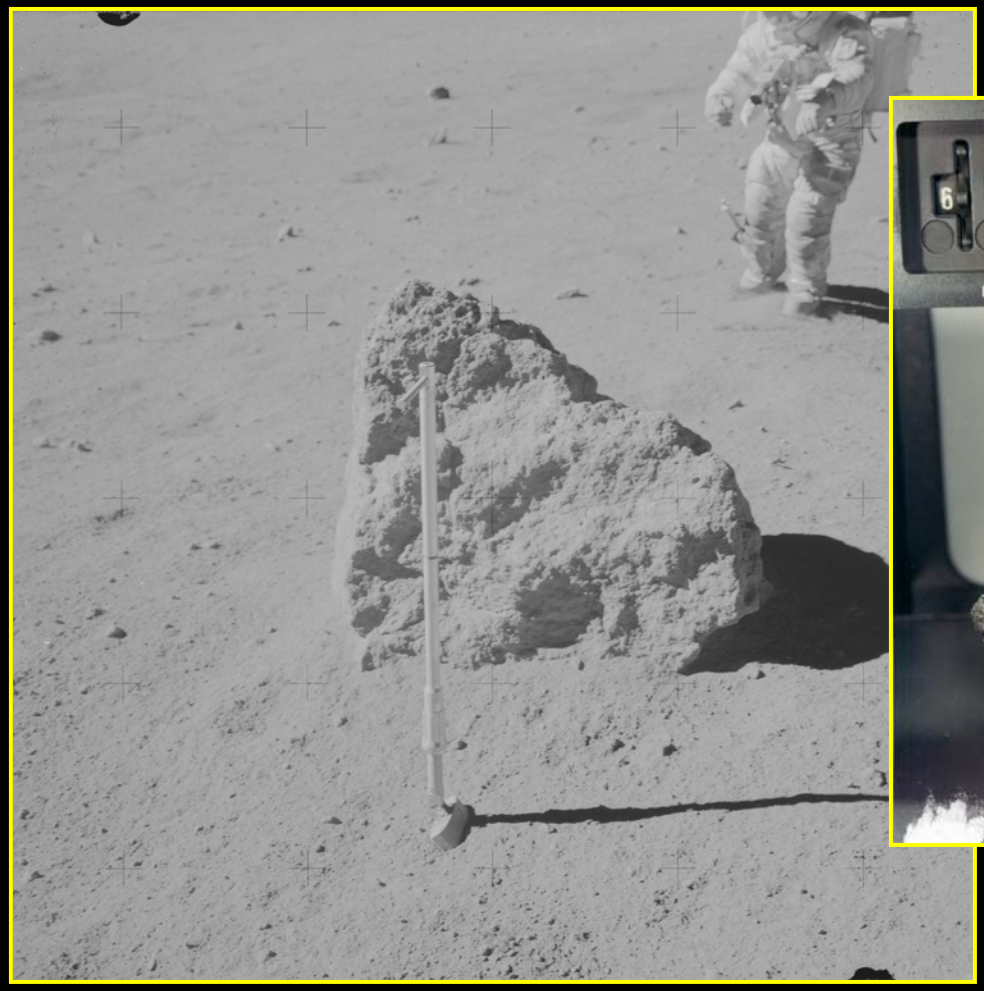
Samples of impact melt in these localities were produced by older impact events & excavated by the South Ray event.

Thus, the sample has an age that is older than that of the South Ray Crater event.

Apollo 16, Station 8
Boulder C
One of several boulders in ejecta blanket
of South Ray Crater
Collected in hopes of determining age of crater



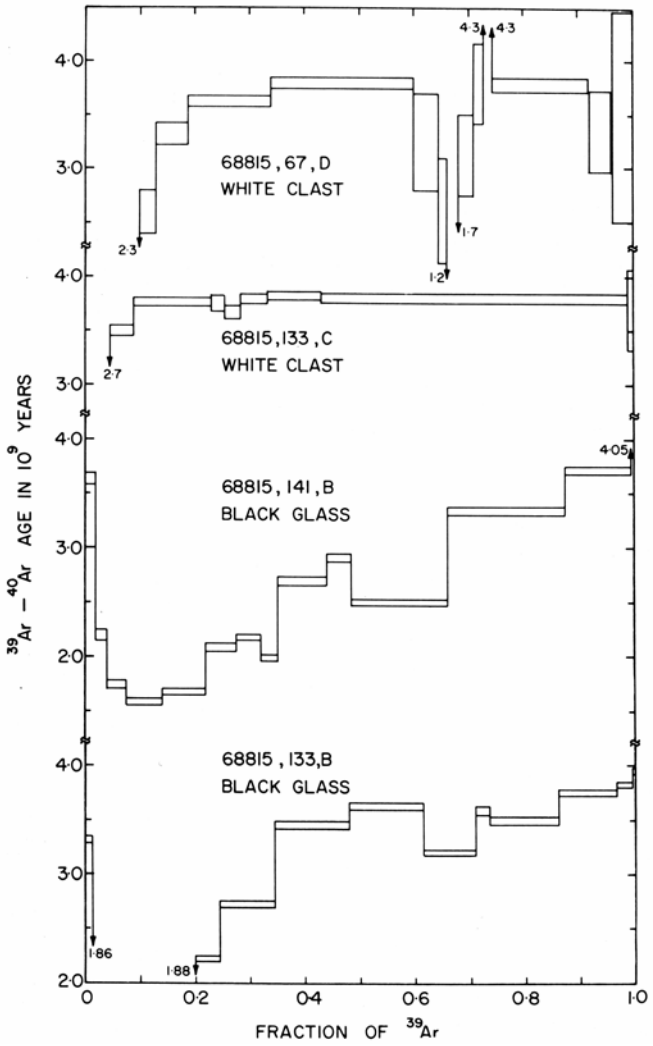
Apollo 16, Station 8
Boulder C
One of several boulders in ejecta blanket
of South Ray Crater
Collected in hopes of determining age of crater



68815

In thin-section, the sample has multiple flow structures and glass

# Glassy Melt Breccia




68815

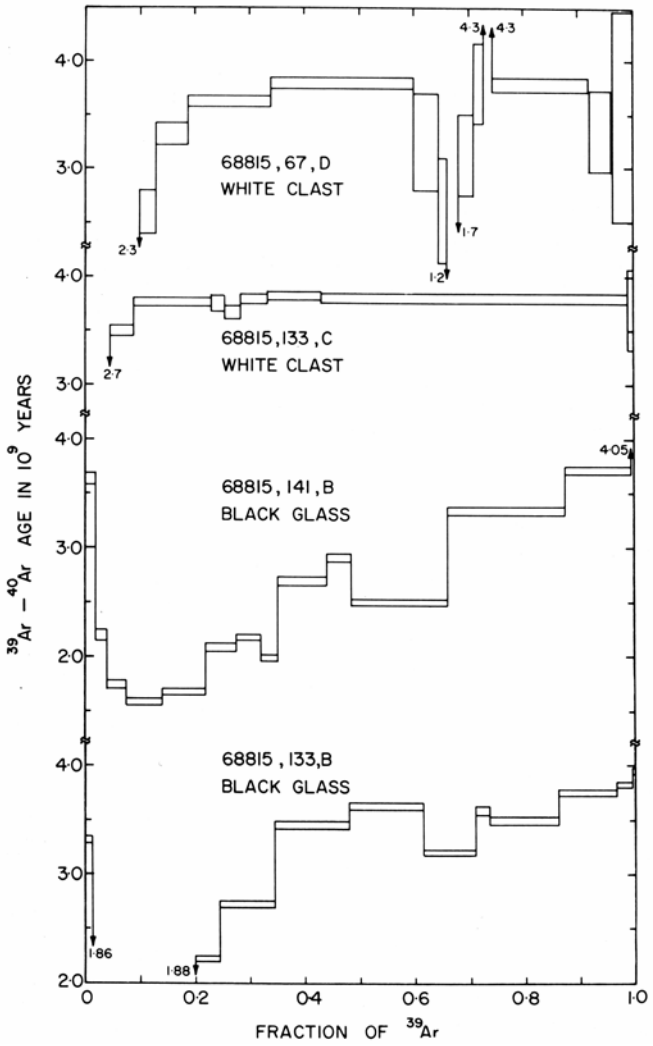
A 3.81 Ga age was inferred for these two clasts

A 3.76 Ga age was inferred for these two splits of melt



Schaeffer & Schaeffer (1977)

# Glassy Melt Breccia




68815

A 3.81 Ga age was inferred for these two clasts

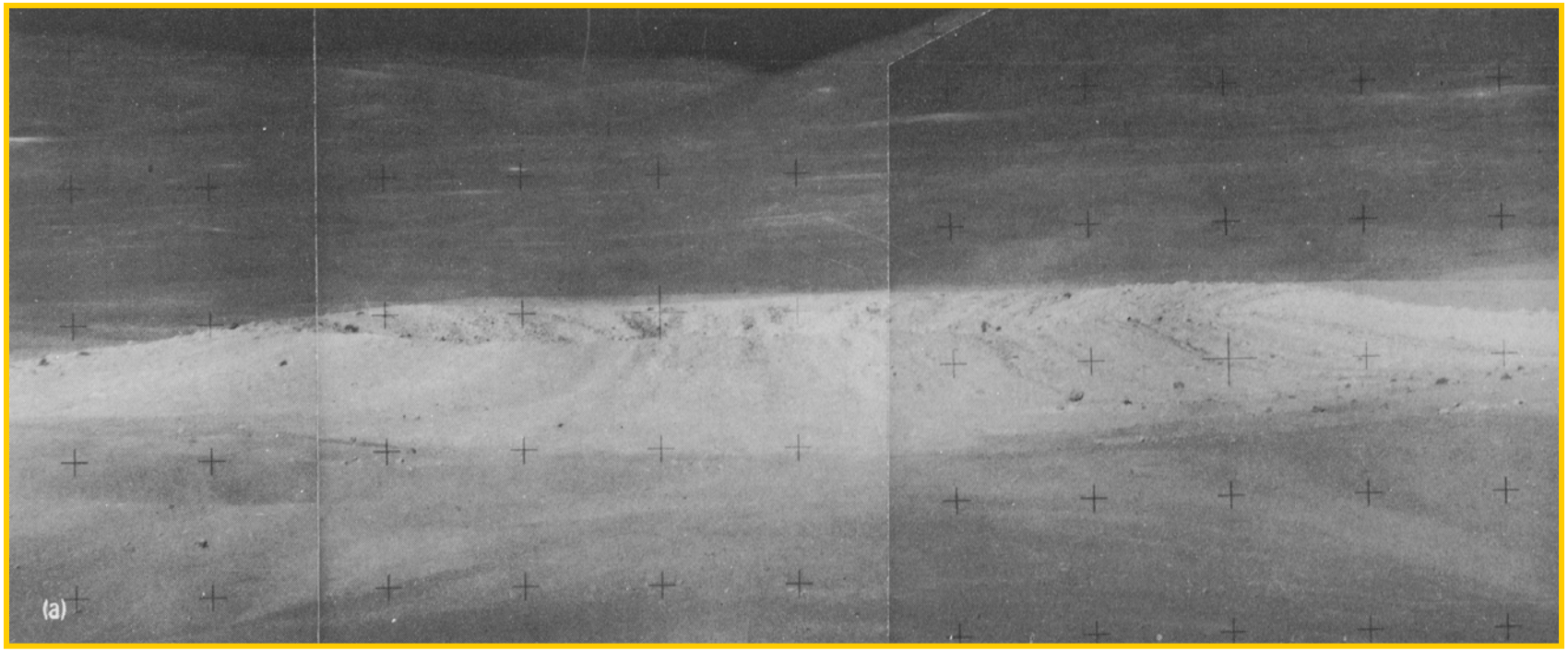
A 3.76 Ga age was inferred for these two splits of melt

The 3.7-3.8 Ga age is too old to represent Buster Crater; rather, 68815 is an older impact lithology that was excavated by the Buster event.



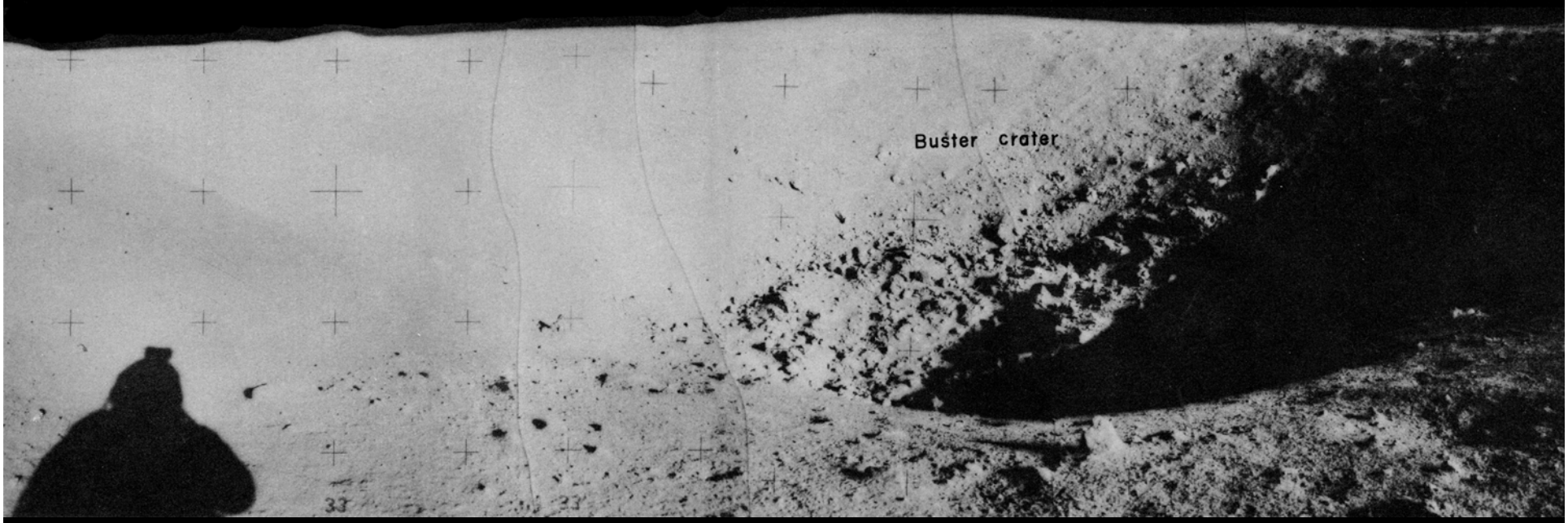
Schaeffer & Schaeffer (1977)

# South Ray Crater (Apollo 16)




- South Ray Crater is 2 million years old (Arvidson et al., 1975), based on exposure age techniques
- Sample 68815 (like many large boulders in ejecta) were originally produced by much older impact events. In this case, an impact event that occurred during the lunar cataclysm, ~3.9 Ga.

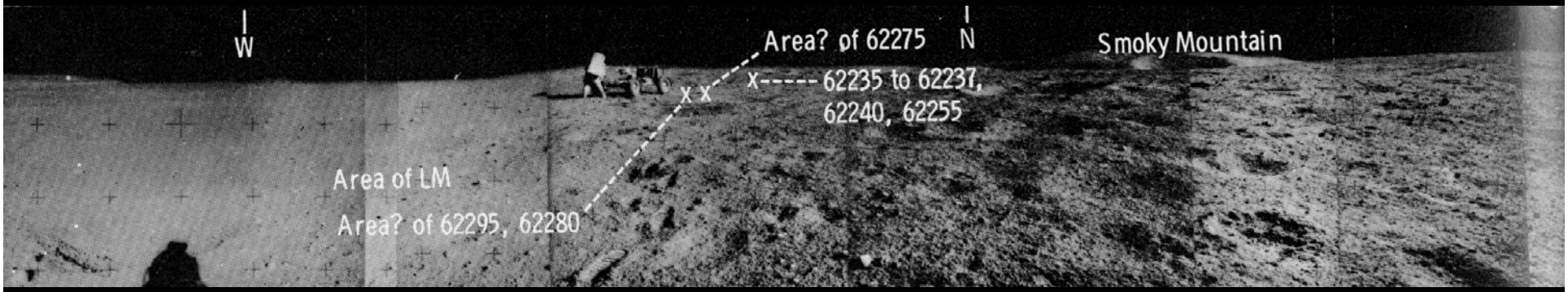
Apollo 16
Station 2
(Partial view of Panorama 7)




Buster Crater

- ~90 m in diameter
- Six samples (including 62295) were collected from ejecta on the crater rim and beyond to determine the age of Buster Crater. (This strategy is now known to be flawed, because that type of sample was not reset by the impact event.)

Apollo 16
Station 2
(Partial view of Panorama 7)

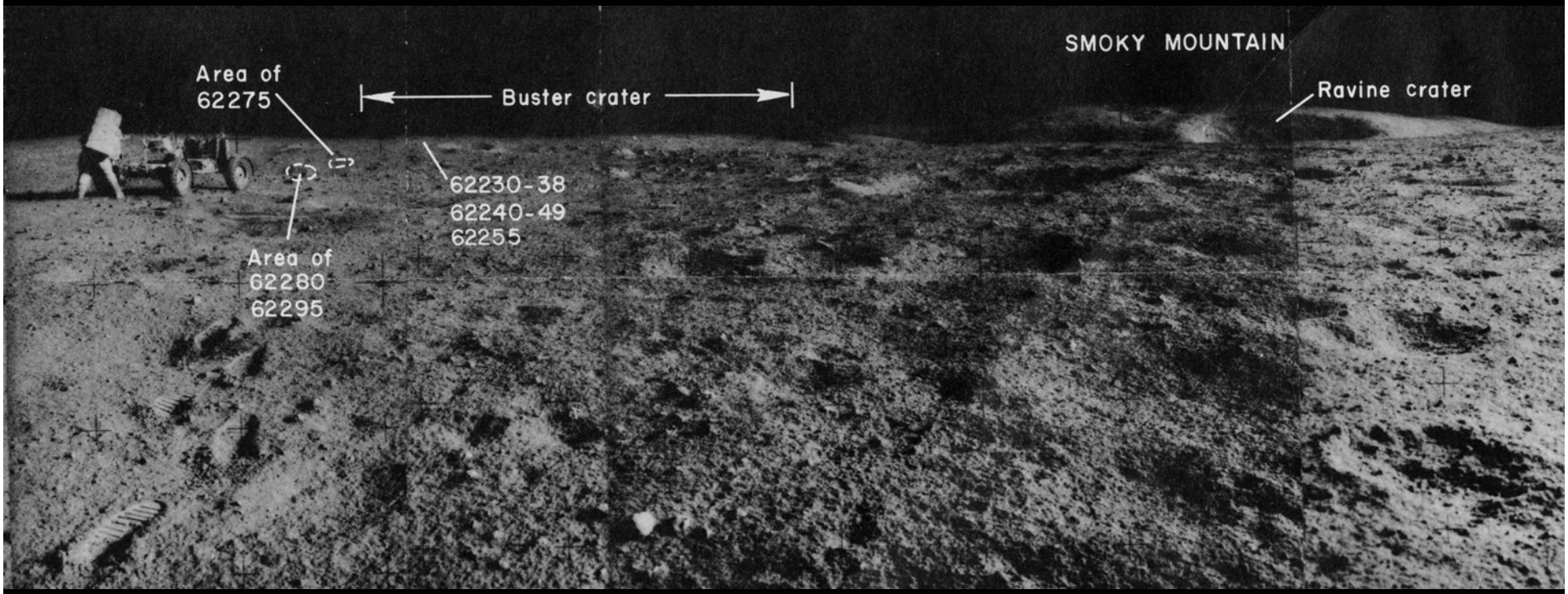



Buster Crater

~90 m in diameter

Six samples (including 62295) were collected from ejecta on the crater rim and beyond to determine the age of Buster Crater. (This strategy is now known to be flawed, because that type of sample was not reset by the impact event.)

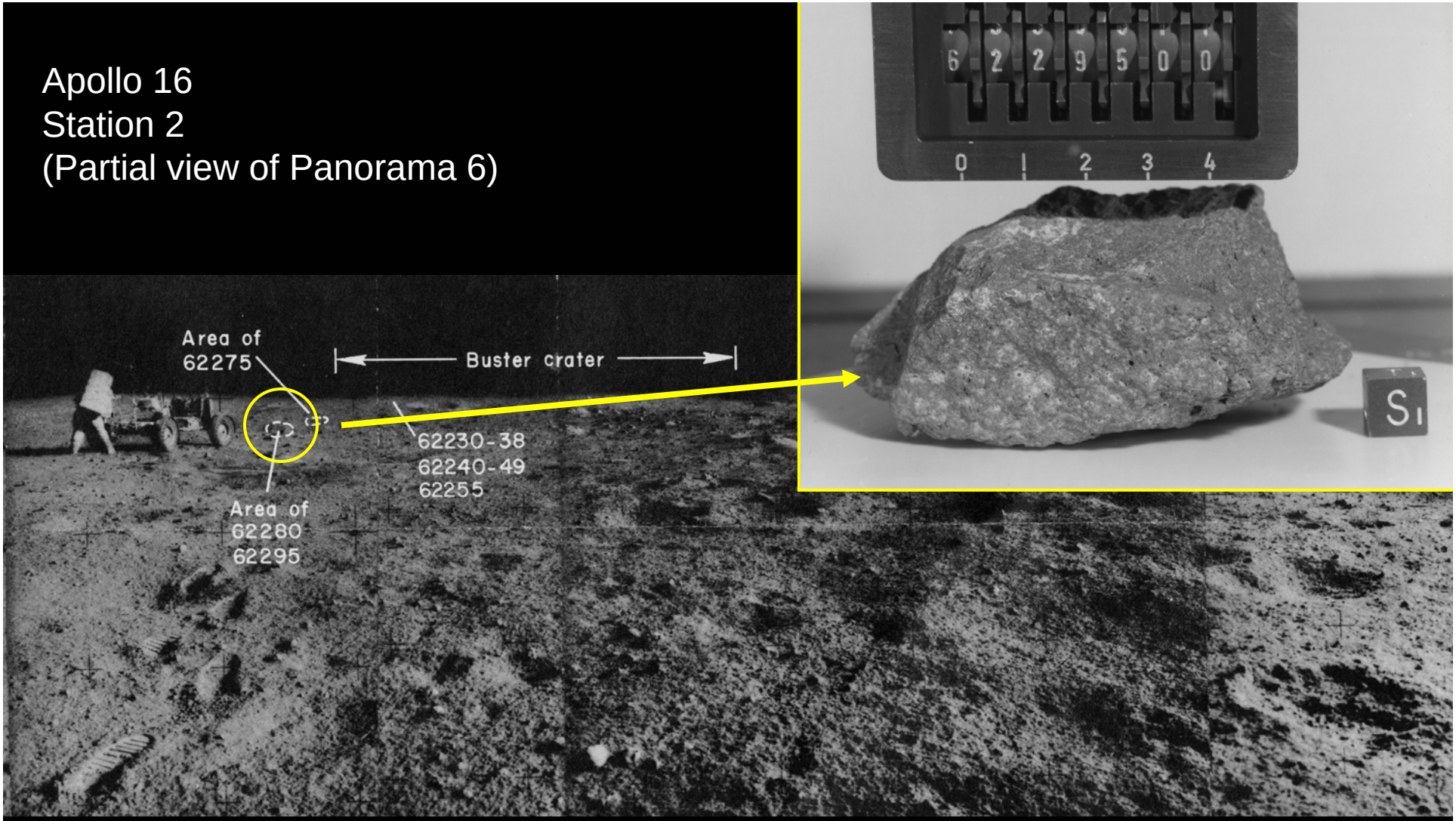
Apollo 16
Station 2
(Partial view of Panorama 6)




Buster Crater

- ~90 m in diameter
- Six samples (including 62295) were collected from ejecta on the crater rim and beyond to determine the age of Buster Crater. (This strategy is now known to be flawed, because that type of sample was not reset by the impact event.)

Apollo 16
Station 2
(Partial view of Panorama 6)

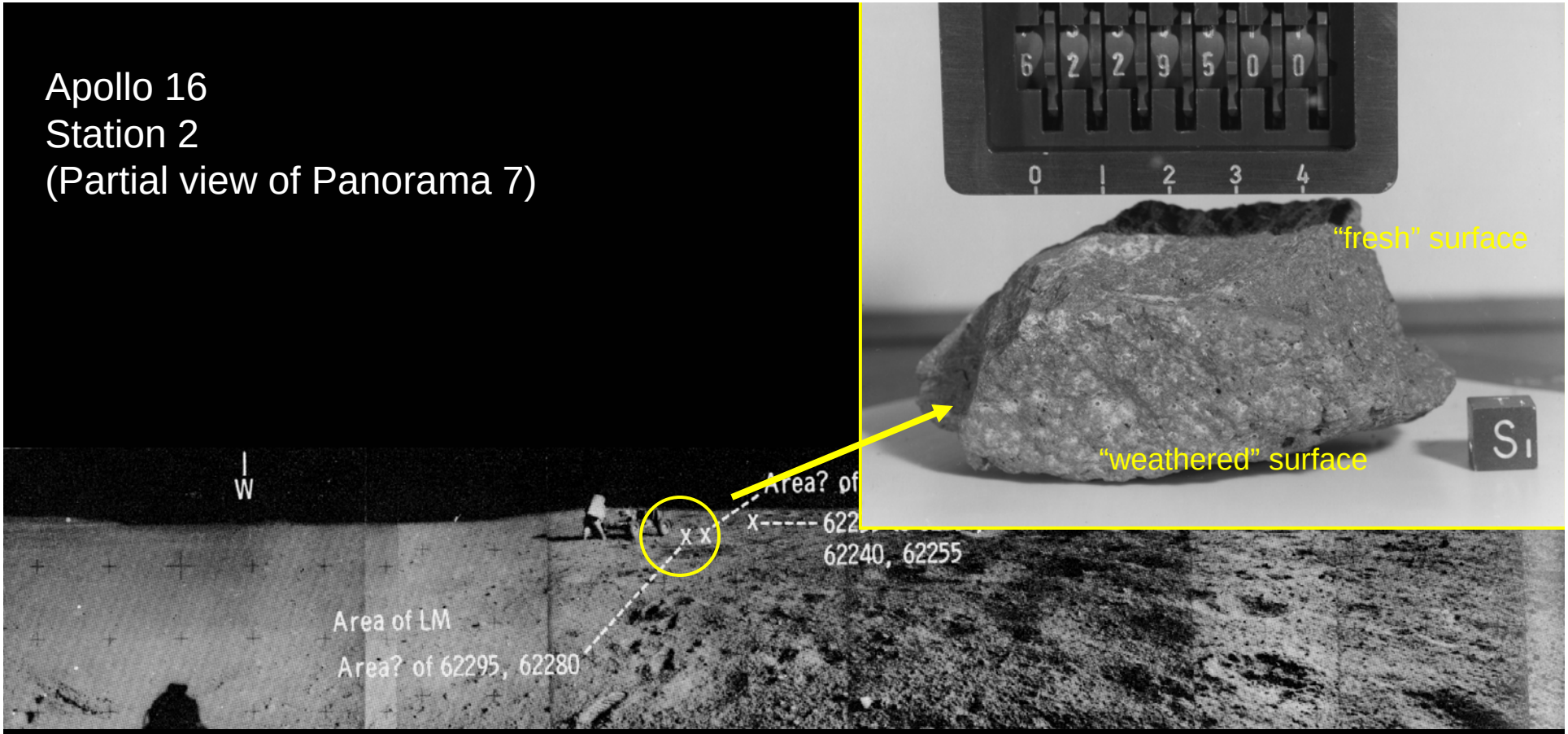



Buster Crater

~90 m in diameter

Six samples (including 62295) were collected from ejecta on the crater rim and beyond to determine the age of Buster Crater. (This strategy is now known to be flawed, because that type of sample was not reset by the impact event.)

Apollo 16
Station 2
(Partial view of Panorama 7)



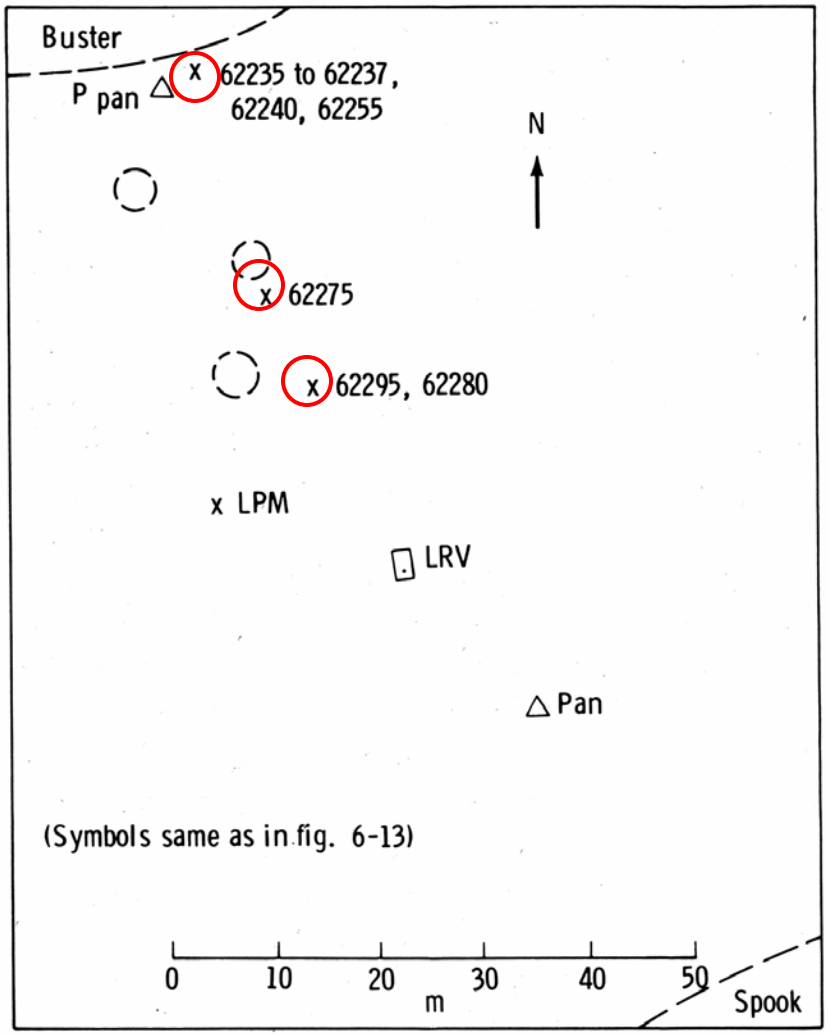

Another perspective of the sample site

Buster Crater

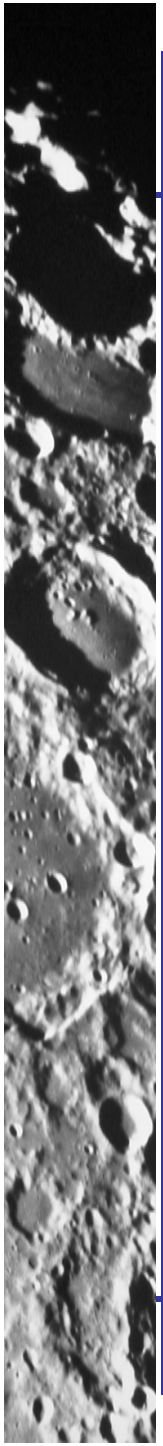
~90 m in diameter

Six samples (including 62295) were collected from ejecta on the crater rim and beyond to determine the age of Buster Crater. (This strategy is now known to be flawed, because that type of sample was not reset by the impact event.)

# Buster Crater Ejecta

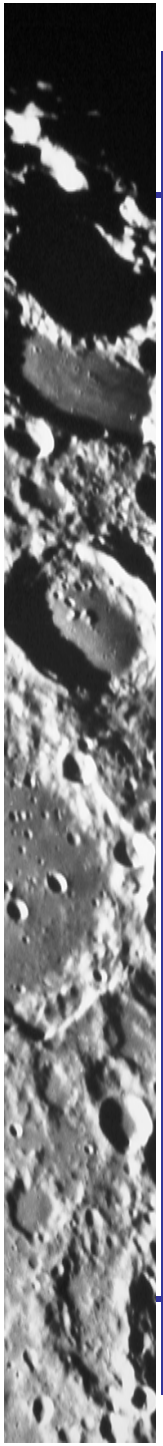



62295 was one of six samples collected from a radial transect beyond the rim of Buster Crater in an attempt to find an appropriate ejected melt sample to determine the age of the impact event.



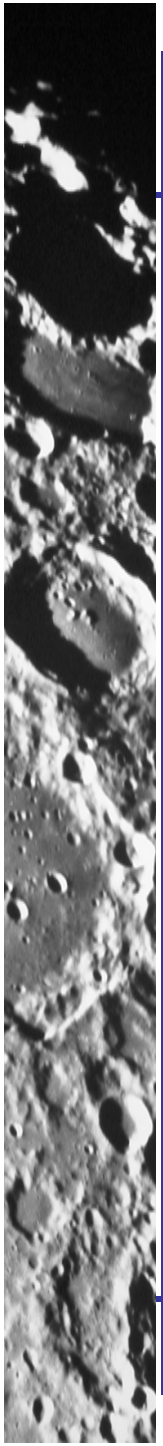
# Some Lessons Learned

- The geologic structure and/or stratigraphy of basin massifs is poorly understood and will need to be investigated by crew during future missions.
- Basin massifs may contain melt produced by parent basin, but melt that is linked to that specific basin may be difficult to identify.
- Massifs contain melt from other impact events.
- Small impact events do not “shock” reset the ages of ejected debris. Samples can be ejected and/or shock-metamorphosed, but not have reset ages.
- Samples can be “disturbed” and have partially reset radiometric ages.
- Impact melt or impact melt breccias need to be heated to sufficiently high temperatures for sufficiently long time for degassing to reset radiometric clocks.
- Impact melt breccias are complex lithologies that must be subdivided (at a minimum into clast and melt fractions) to obtain reliable ages.



# Some Lessons Learned

- Melts with the same ages can be produced by multiple impact events. Other criteria, however, may reveal different events:
  - geochemical variations in melt composition that imply different target materials
  - geochemical fingerprints indicating distinct impactors
  - isotopic fingerprints indicating distinct impactors
  - different melt textures, although this criteria should be used cautiously



# Acknowledgements

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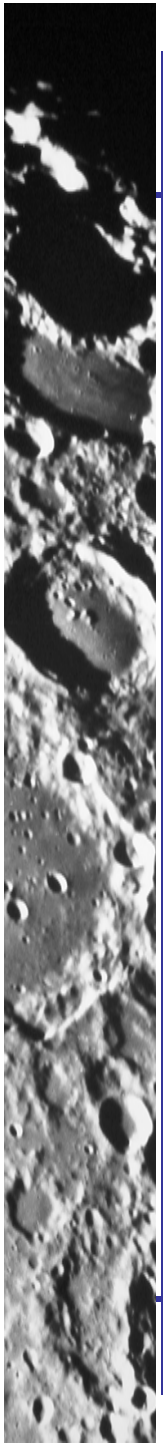

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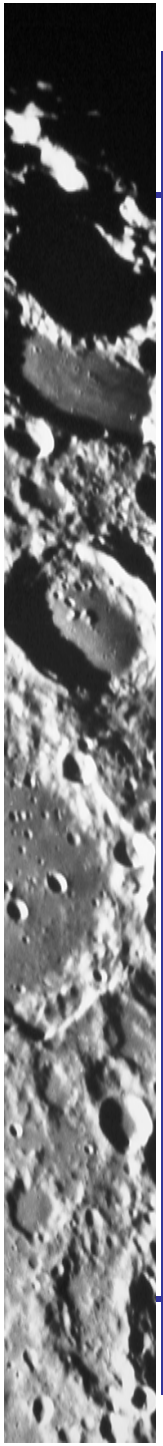

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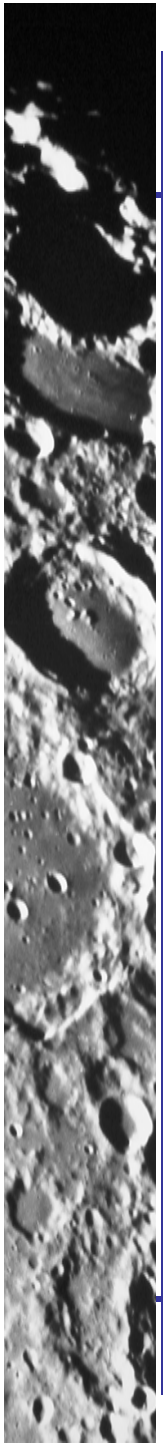

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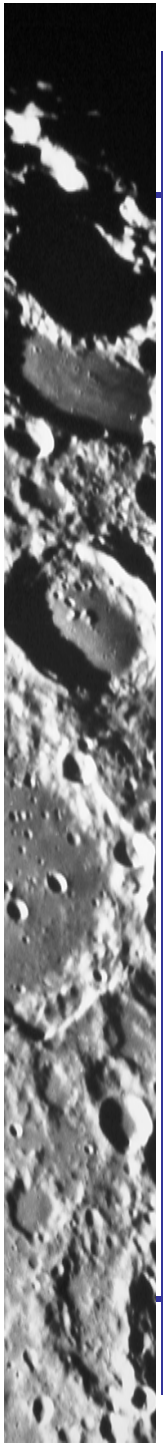

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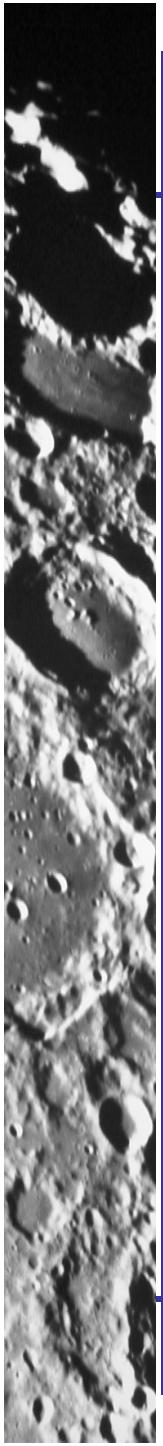

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