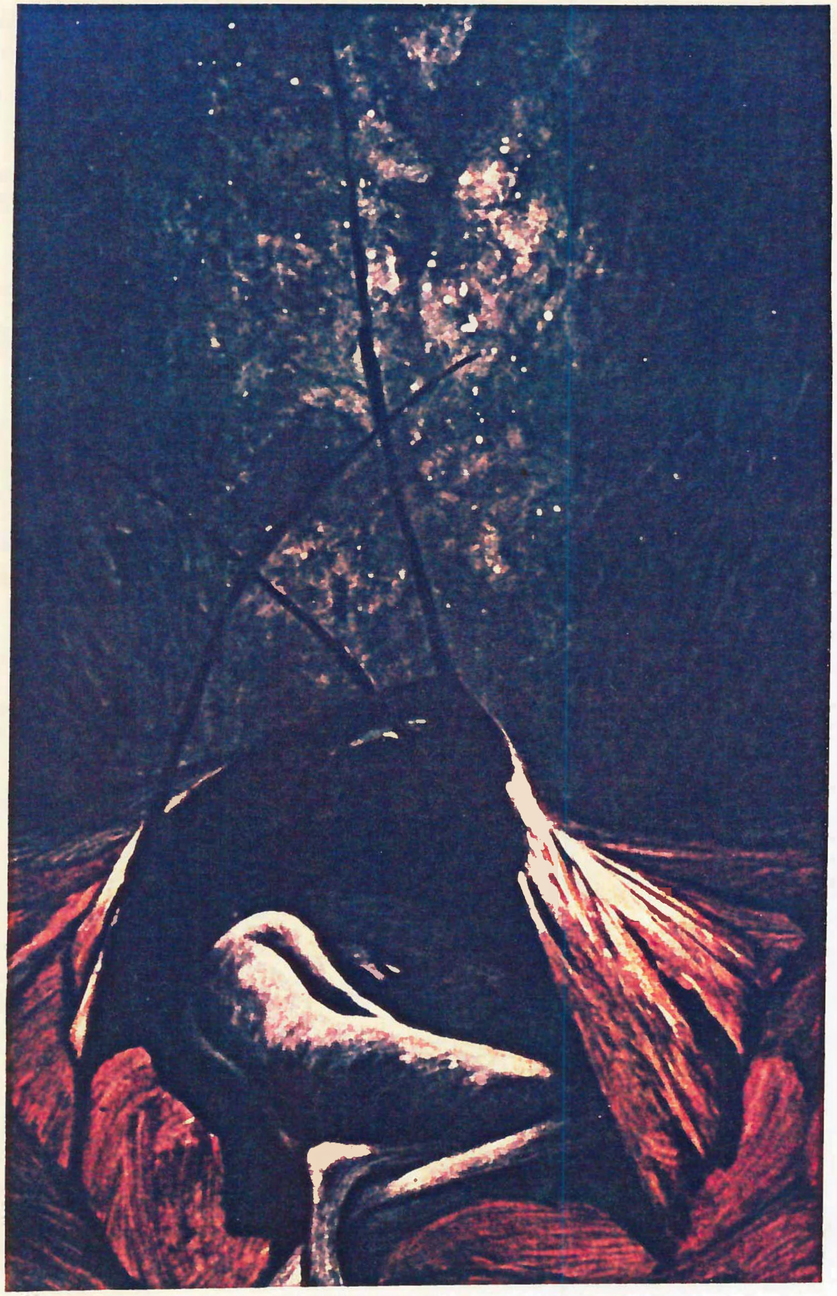

TEN YEARS OF LUNAR SCIENCE: WHAT HAVE WE LEARNED?

BRIEFING NOTES
ASTRONAUT REUNION

AUGUST 1978

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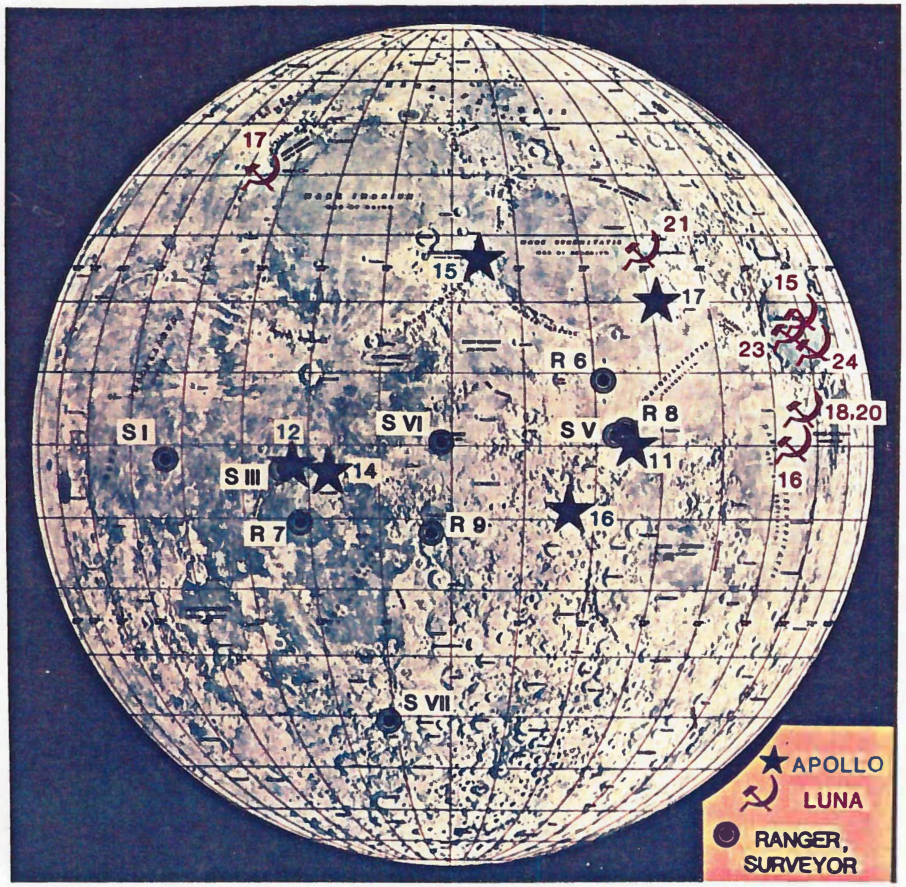
Lunar and Planetary Institute
Houston, Texas
May, 1979



THE MOON

Exploration sites of man
and his machines,
through August 1978

Apollo Landing Sites
Ranger and Surveyor Probes,
Luna Probes, and
Luna Sample Return Sites (16, 20, and 24)

LUNAR GEOLOGIC HISTORY

Apollo 11

* Mare Tranquillitatis
* Objective: sample relatively old mare surface.
* Results: Rock Type - Basalts high in Fe, Ti; H_2O absent
  Ages - Approximately 3.7 BY
* Conclusions:
  - Water not important.
  - Maria very old.
  - Maria volcanic.

Apollo 12

* Oceanus Procellarum (Mare Cognitum)
* Objective: Relatively young mare; possible ray from Copernicus.
* Results: Basalts, ∿3.15-3.35 BY
* Conclusions:
  - "Young" maria very old!
  - Copernicus may have formed approximately 0.9 BY ago.

Apollo 14

* Fra Mauro Region
* Objective: Sample Imbrium Basin ejecta blanket.
* Results: Rock Type - Variety of breccias
  Ages - Approximately 3.9 to 4.0 BY
* Conclusions:
  - Region is ejecta blanket of Imbrium basin.
  - Imbrium Basin formed approximately 3.9 to 4.0 BY ago.

Apollo 15

* Hadley/Apennine Region
* Objectives: Montes Apennius (ring of Imbrium), Hadley Sinuous Rille, Mare Imbrium.
* Results:

Rock Types	Ages
Mare: Basalts	∿3.2 BY
Apennines: Breccias	3.9-4.1 BY
Rille: Basalts (no water)	∿3.2 BY

* Conclusions:
  - Imbrium mare not produced by impact (took ∿600 MY to fill)
  - Rille related to lava flow (Collapsed tube)
  - Highlands complex in composition

Apollo 16

* Descartes Region
* Objective: Sample highland plains and volcanic-looking domes.
* Results: Impact breccias, ∿3.8-4.2 BY
* Conclusions:
  - Most flat highland areas formed by ponded impact ejecta; probably related to major multi-ringed basins.

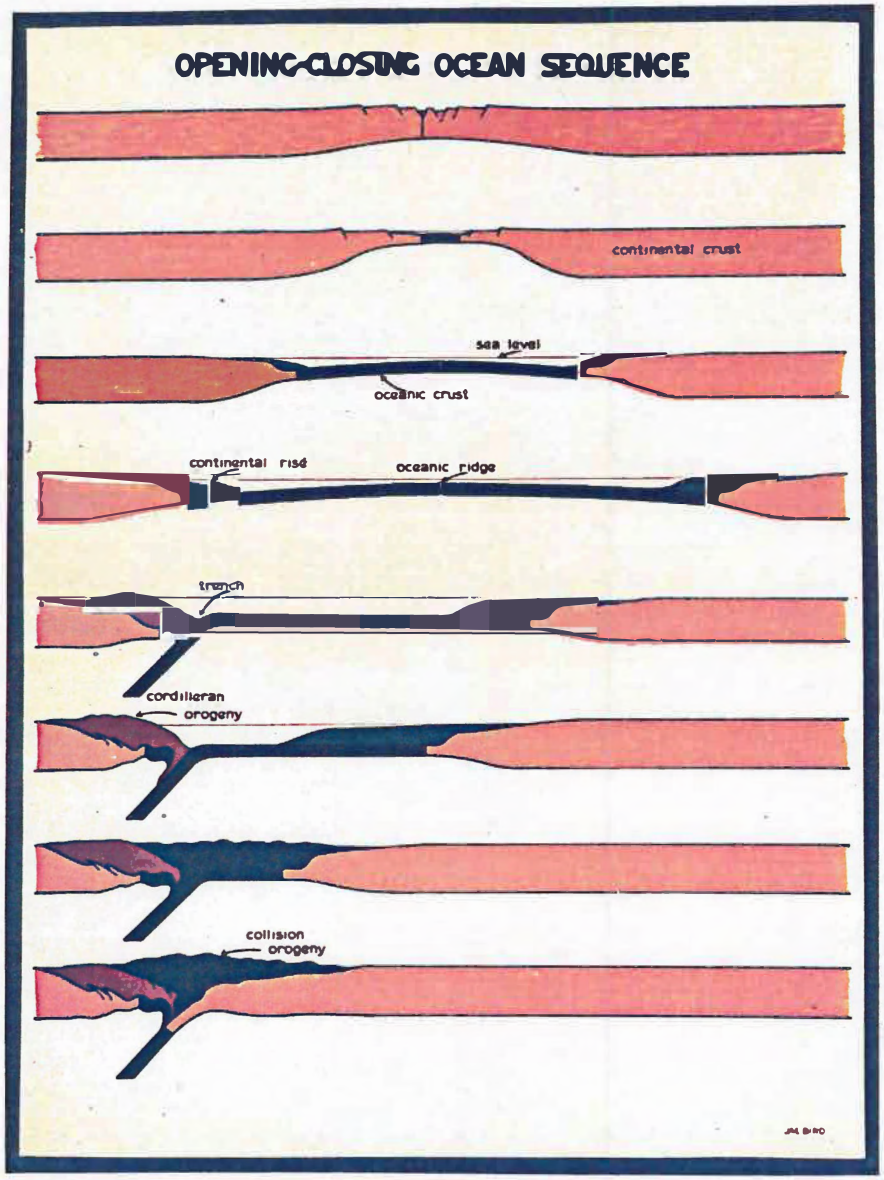
Apollo 17

* Taurus-Littrow Region
* Objectives: Mts. from older basin (Serenitatis), Flat Valley Plains between Mts., dark mantling (young volcanics?)
* Results:
  Mountains: Variety of breccias, ∿4.0 BY
  Plains: Basalts (like Apollo 11), ∿3.7 BY
  Mantle: Volcanic Glass? Regolith?, ∿3.7 BY?
* Conclusions:
  - Very young volcanism not evident.
  - Variety of breccias may represent older events.

1. Where have we been over the last ten years of lunar science?

Over the past decade there have been three major revolutions in the terrestrial and planetary sciences; two followed directly from lunar sample work:

The first is plate-tectonics -- the view that the Earth's surface consists of "plates" driven by convection which move about at rates of about 4 cm/yr and accounts for earthquakes, volcanoes and "continental drift." This model came from geophysical data obtained on the ocean floor (seismology and magnetic "stripes" due to polar reversals) and has been confirmed by deep drilling at sea. The Earth's surface has been overturned 20 to 30 times in its history -- the "oldest" ocean floor being only about 0.2 billion years old, about 4% of the age of the Earth. Most of the Earth's surface is very young, in stark contrast to the Moon whose youngest surfaces and rocks would be "ancient" by terrestrial standards.


OPENING-CLOSING OCEAN SEQUENCE
continental crust
sea level
oceanic crust
continental rise
oceanic ridge
trench
cordilleran
orogeny
collision
orogeny
JMBIRD


ATLANTIC OCEAN FLOOR
GREENLAND
EUROPE
NORTH
AMERICA
SAHARA
AFRICA
SOUTH AMERICA

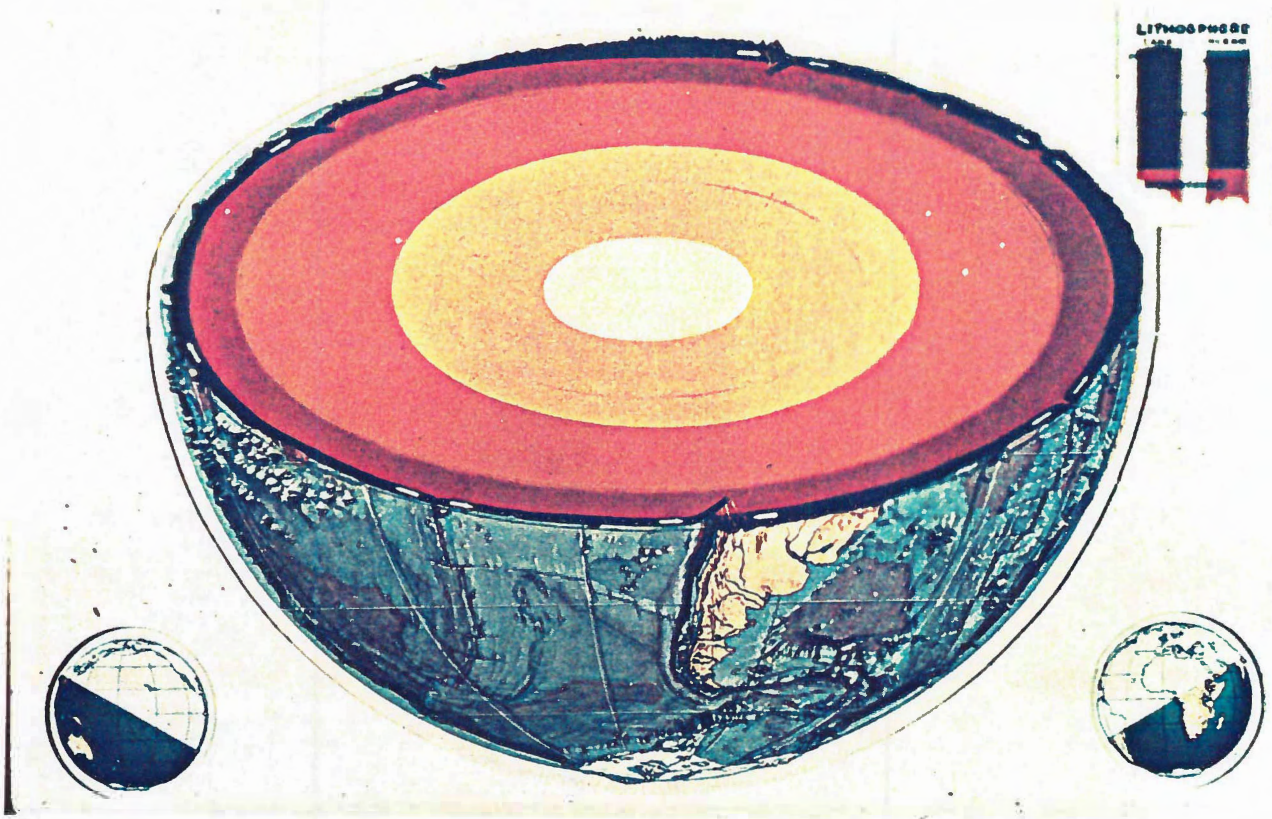


Plate motions account for:

- volcanoes
- earthquakes
- ore deposits
- continental drift

The earth's mantle is in slow convection — this is the driving force which moves the plates. The ultimate energy source is the heat of radionuclides — K^{40}, Th^{232}, $U^{235,238}$ — buried deep in the earth.

The second revolution is our view of the evolution of the Moon, especially its early history -- it's important first because it's completely different from what we imagined before Apollo (virtually all the theories of "experts" turned out to be wrong) and secondly because it has remade our view of the early Earth. Ten years ago we believed that the Earth was formed by accretion of cold particles and then very slowly heated up. We've learned from the Moon two important facts:

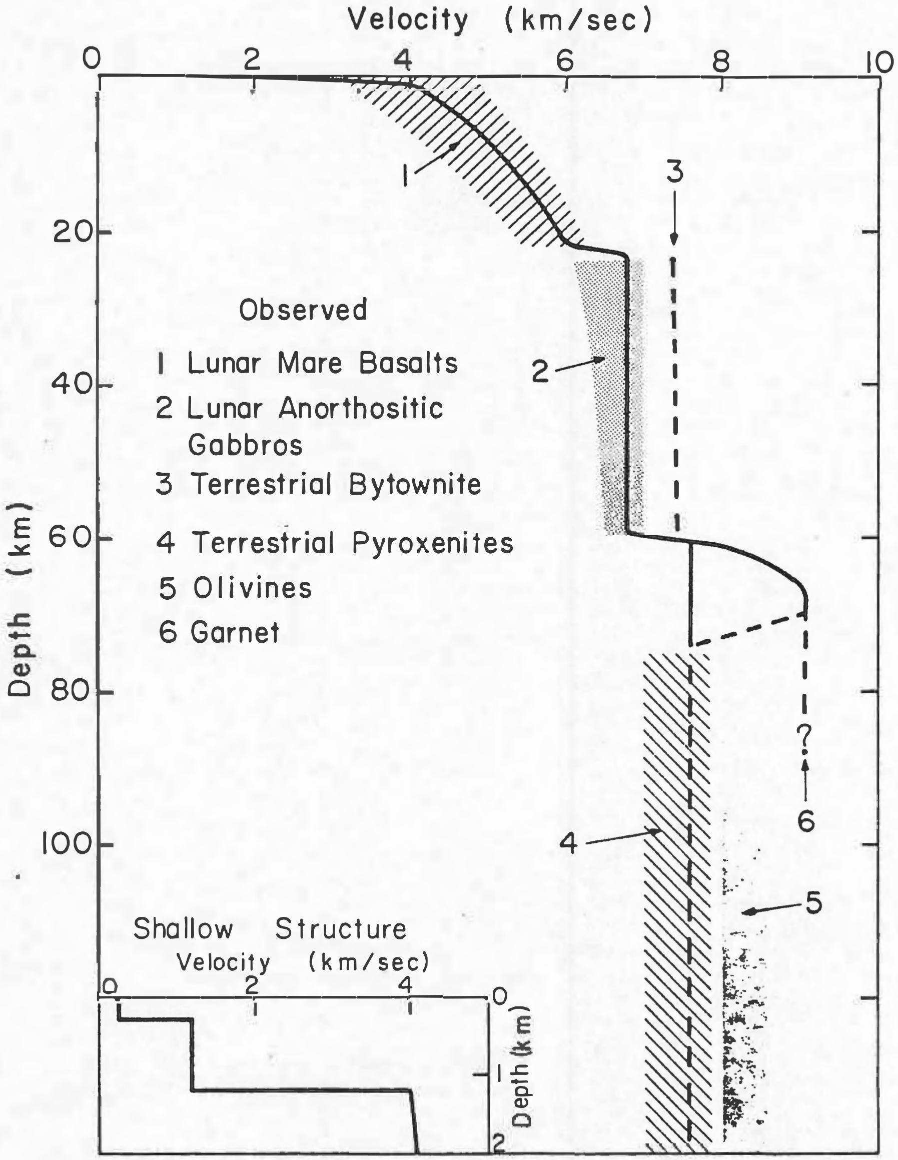
First, the Moon initially was extremely hot in its outer parts; in fact it was almost certainly molten probably to depths of 500 km or so. It was covered, in its early days, by a lava ocean. The second amazing fact was the great antiquity of the Moon, even the "young looking" surfaces (the front side mare), which were not nearly as intensely cratered as the uplands, were ancient. This was not anticipated.

One of the implications of absolute age determinations on rocks from these mare surfaces was that the surfaces could be used to determine the rate of infall of meteorites through time, because the crater-frequency differs greatly from place to place on the Moon -- a direct consequence of age and the cratering rate. Knowing the absolute ages of these surfaces permitted the problem to be worked backwards and the cratering rate to be determined. The result was fantastic, namely the impact rate on the Moon increases enormously as we go backward in time. It's not a constant impact rate at all. In fact, the rain of infalling objects was torrential early in lunar history. Beyond about 4.0 billion years, the flux was so intense that the surface was probably obliterated faster than it could form; hence the concept of a "crust" early in time (the first 20% of the age of the Moon) probably makes no sense at all.

Hence the Moon formed hot, not cold; and the impact rate was enormous early in time.

Perhaps the most important conclusion to be drawn from this is that the Earth (and all the terrestrial planets -- Mercury, Venus, Mars) probably had the same violent early childhood. Namely, through about 20% of their lifetime the planets had molten lava oceans and suffered incredible bombardment from space. This is completely different from the models we envisioned for the Earth prior to Apollo, and it came directly from work on the lunar rocks.

There are many fascinating details as well: for example, the origin of the lunar uplands -- believed to have formed by floation of light minerals from out of the lava-ocean -- may be the process responsible for the Earth's crust, a concept which would have been considered ludicrous before Apollo, and probably still would be by many Earth-locked geologists!



THE INTERIOR

— It's layered into crust (60 km thick) and mantle, like the Earth.

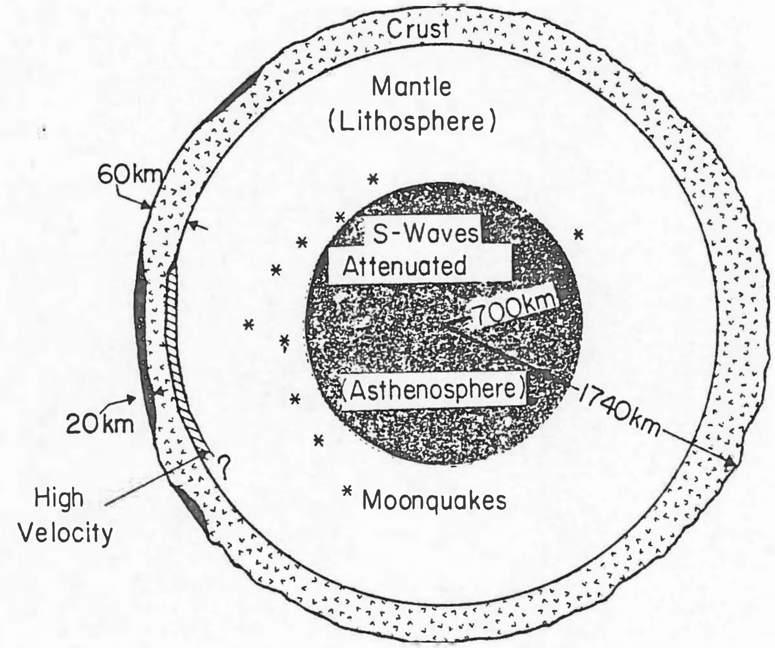
— Its heat flow is less than the Earth's, and internal temperatures are less.

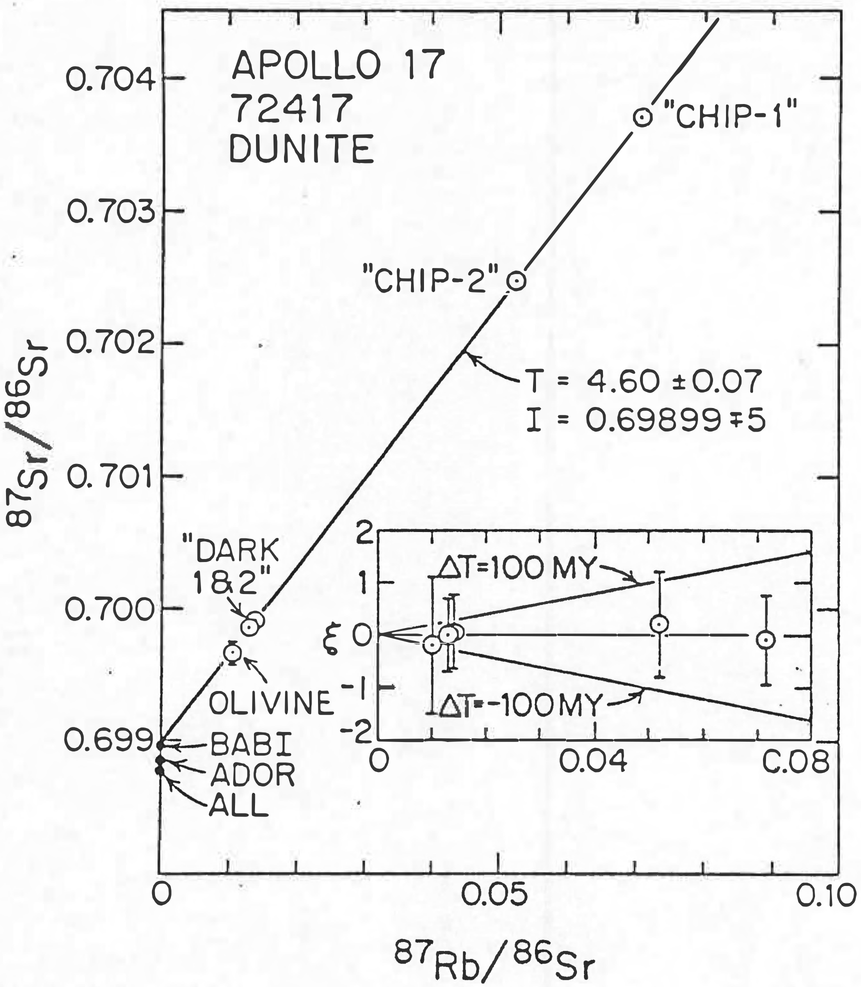
— Quakes are infrequent, deep and weak; thought to be tidally induced — <u>no</u> tectonic earthquakes.

— Existence of core is ambiguous; it's small if there is one.

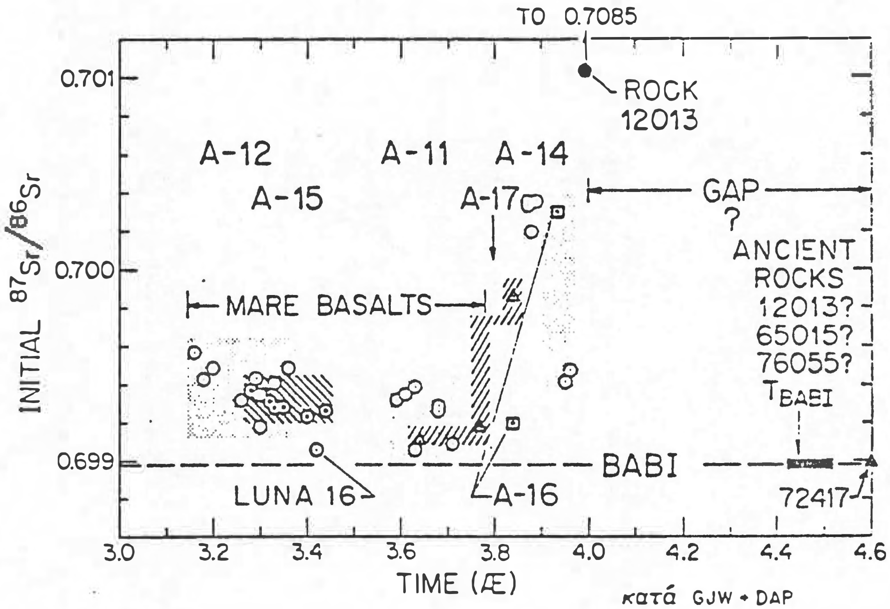
— Deep interior attenuates S waves, therefore is non-rigid.

— Crust is thicker on far-side.

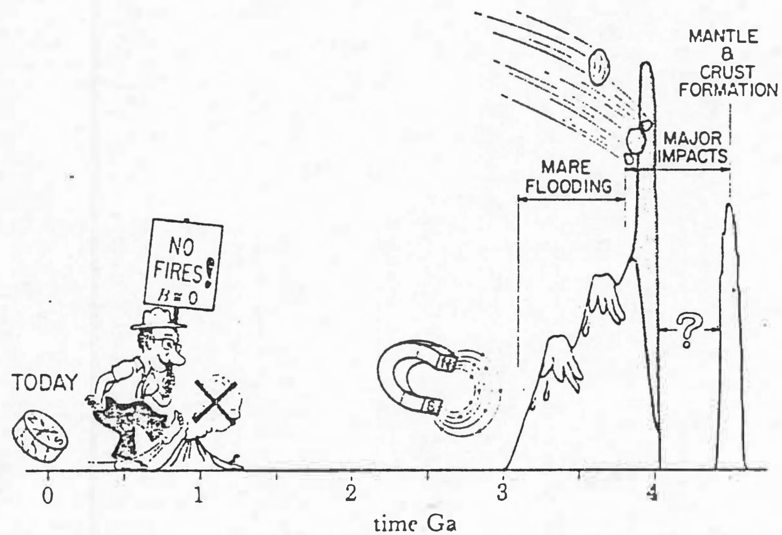




Techniques advanced immensely during Apollo; this permitted dating of small fragments with minute amounts of parent-daughter materials



Dating of lunar rocks has shown <u>all</u> the rocks are <u>very</u> old; that was a surprise.



Cartoon showing the chronology of major lunar events as presently known or surmised.

(After Wasserburg)

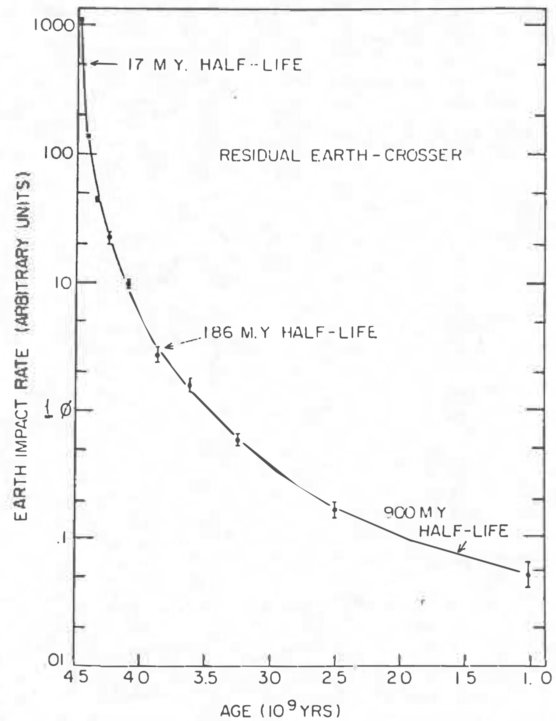
On the Moon, the show was <u>over</u> very early; but the Moon also tells us that during those early days the history was <u>violent</u>.

Principal features of the <u>early moon</u> were:

- a magma ocean, several hundred km deep
- an enormous infall rate of meteorites early in lunar history

Both of these also are true for the EARTH! and were unanticipated results.

Evolution of the earth's planetesimal swarm



Calculated Earth impact rate as a function of time for a residual Earth-crosser with initial elements $a = 0.90$, $e = 0.27$, $i = 5.7°$, and $V_G = 7.9$ km/sec. The initial rapid decay in impact rate is followed by a long-lived "tail" as a consequence of bodies being stored in Mars-crossing orbits and later returned to Earth-crossing.

(after Wetherill)

This diagram shows impact rate of meteorites as a function of time (note log scale).

Very early in time, the infall rate becomes very large; the rain of particles was torrential.

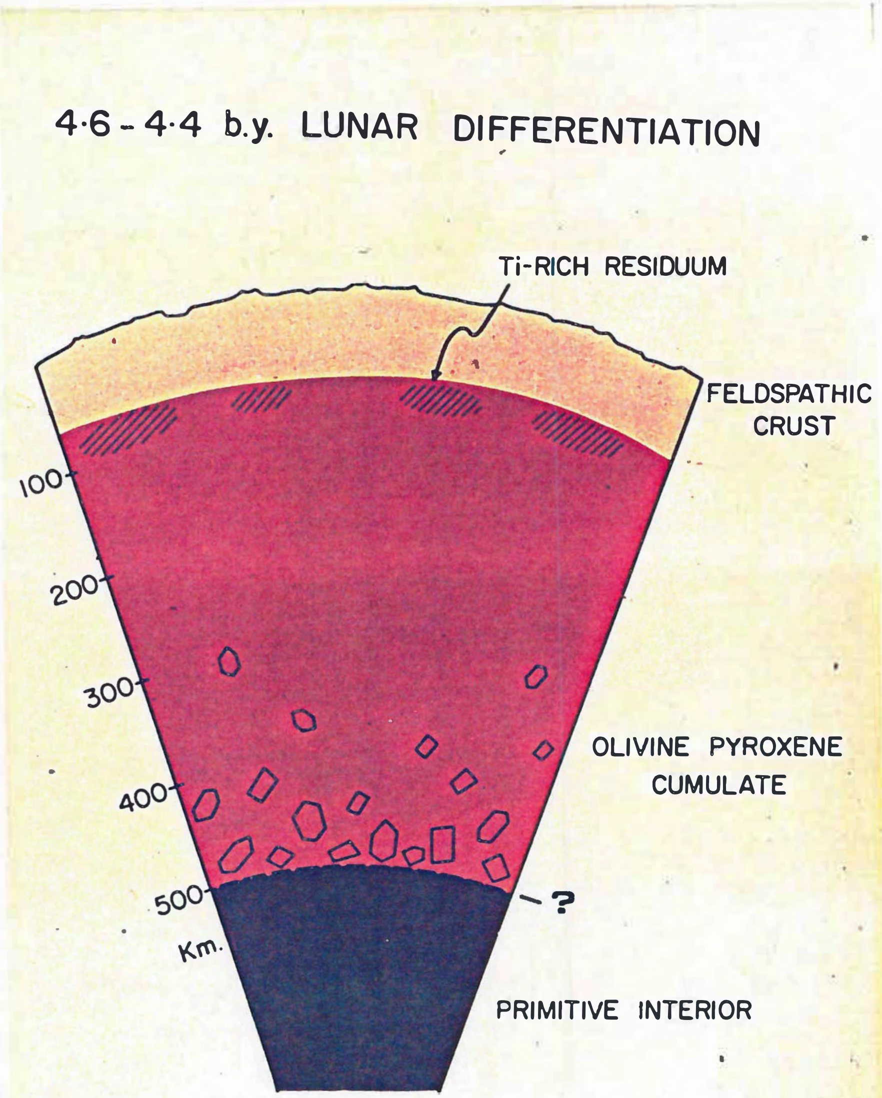
(It is now thought that this caused the intense early heating suggested by the rocks — which lead to the magma ocean, early in lunar time.

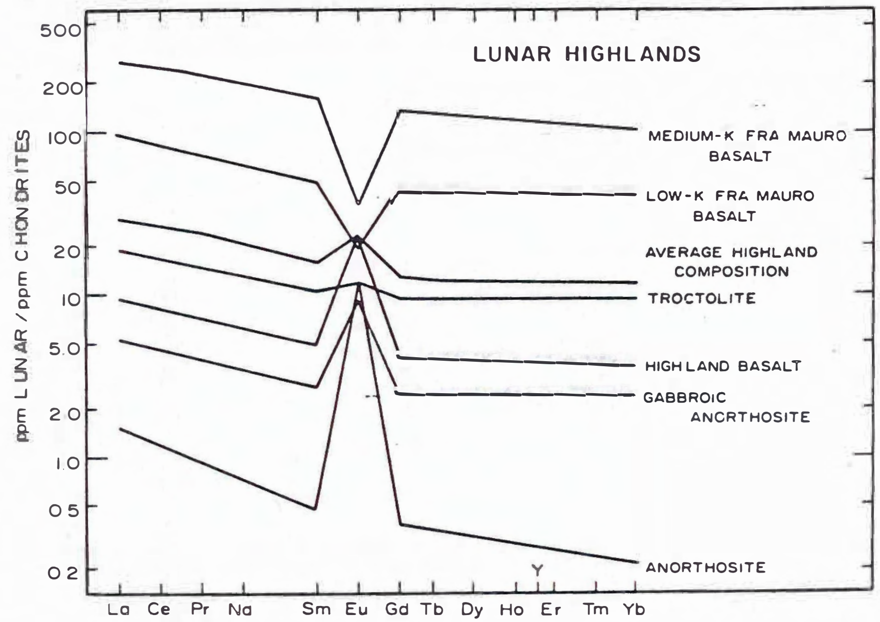
NASA
AS17-140-21497

NASA
S-71-42951

Lunar uplands rocks, sampled during Apollo 15, 16, and 17 were feldspar-rich (anorthosites) and breccia (ejecta from the basins).

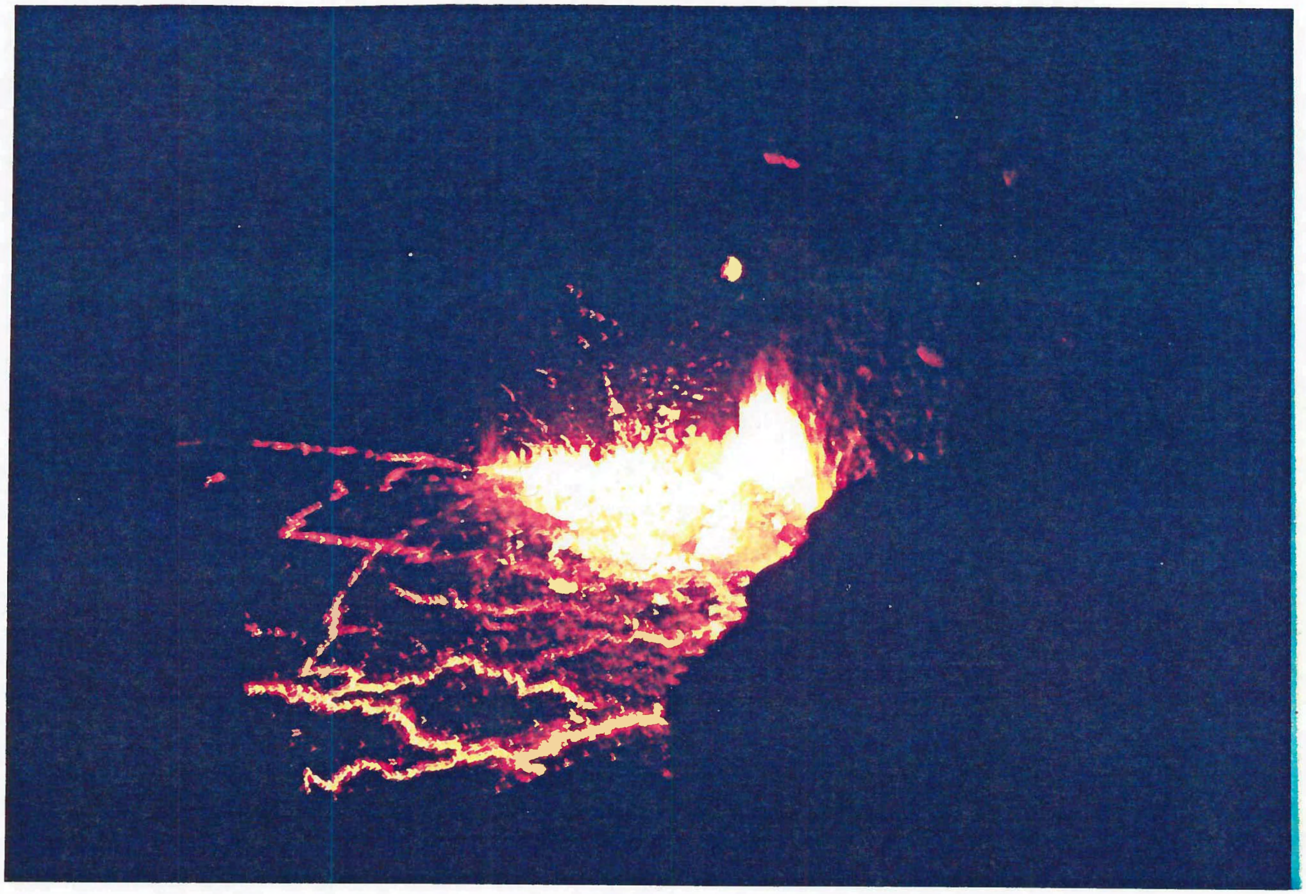
They are old and we believe....





Rare earth element (REE) abundances in highland rock types [89, 92]. Note that the average highland composition has a positive Eu anomaly. The slopes of the ~~patterns are~~ nearly parallel. The La/Yb ratio is close to 3.1 for most patterns, except for the plagioclase-rich samples, where the La/Yb ratio rises.

...the feldspar floated upward from an early magma sea which surrounded the moon before about 4.4 b.y. (The rare earth elements, particularly Eu, provide important clues about how these minerals behaved. Eu is the only REE which occurs in the plus three valence state — in which it behaves like Al. Its depletion in basalt means it was low in the source. That depletion was caused by Al-rich plagioclase floation. The material shown in the orange (at the left) is lava; the yellow material is the early feldspar-rich anorthositic crust. (Remember at this time, the infall rate of meteorites was enormous; the giant basin impacts punched holes through the crust into the melt below.)



This night-time photograph of a lava lake in Hawaii, taken during an eruption in 1973, may be a graphic approximation (in minature) of the appearance of the early lunar surface.

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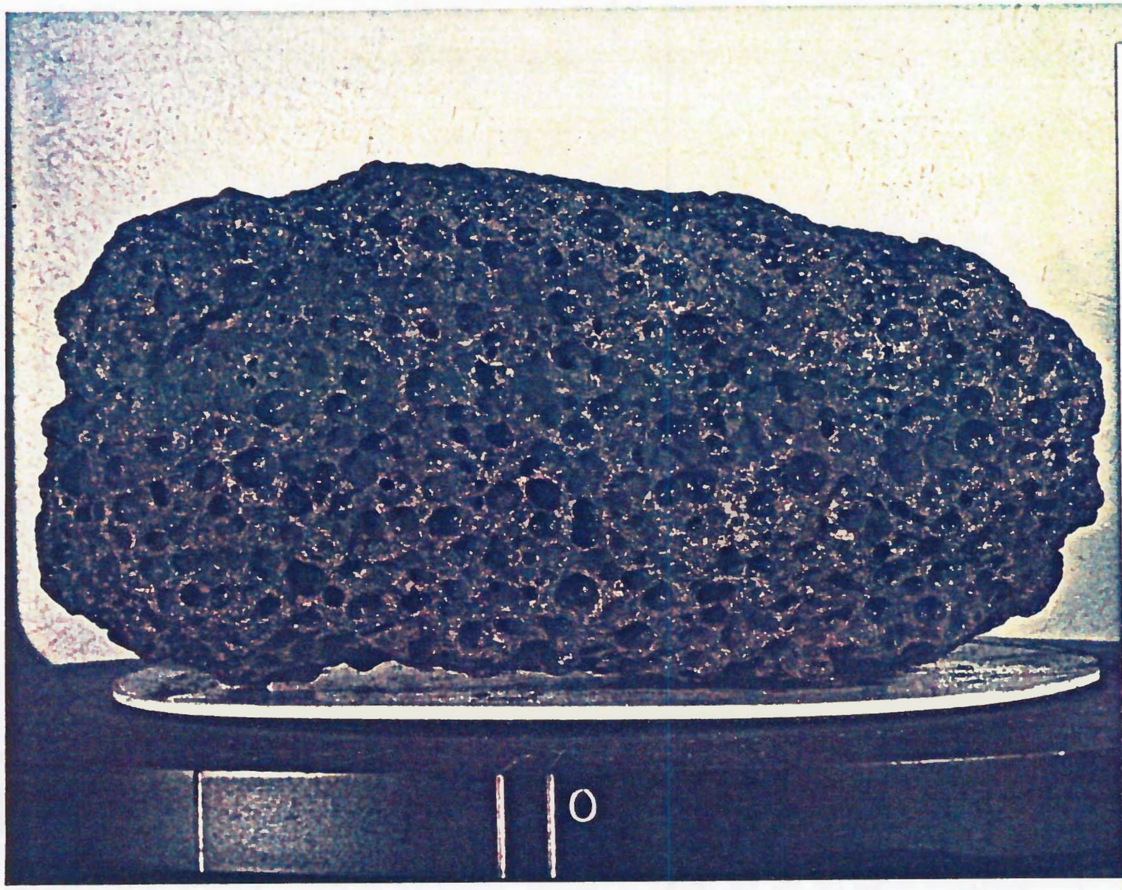


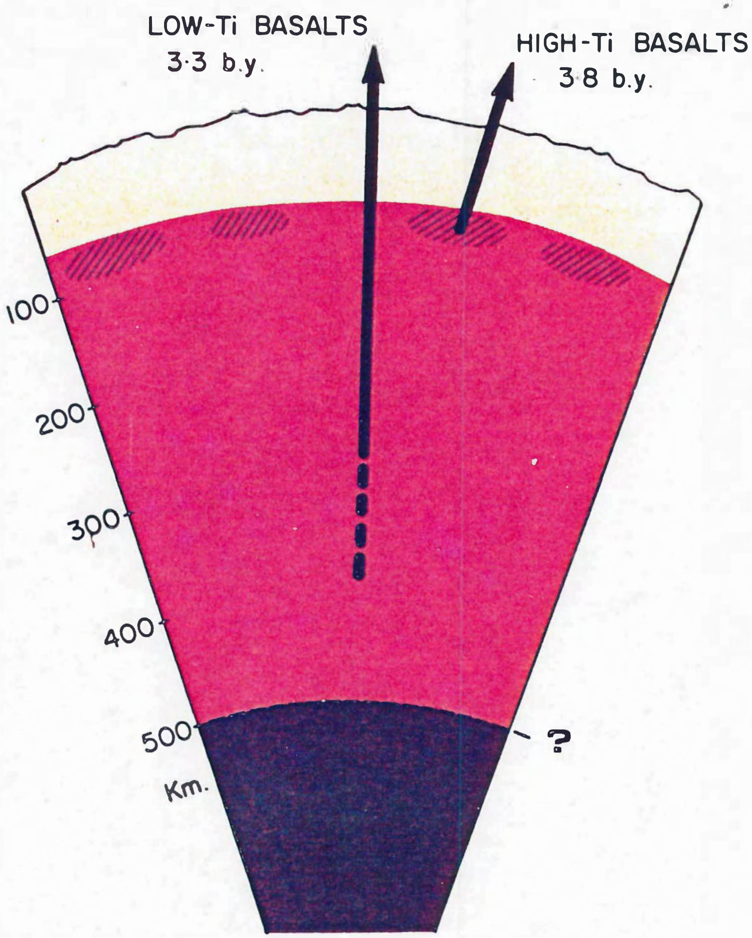
NASA
S- 76- 20797

Mare rocks are basaltic lava flows, in many respects like terrestrial basalts except that they are:

- old (all 3.1 b.y. or older)
- dry (no lunar water)
- reduced (Cr^{+2}, Ti^{+3} occur as never on Earth)

(Remote sensing data show that we've sampled only one-third of the major types of lunar basalts.)

MODEL 2



Origin of the basalts is known because from mineralogical and geochemical studies we can obtain:

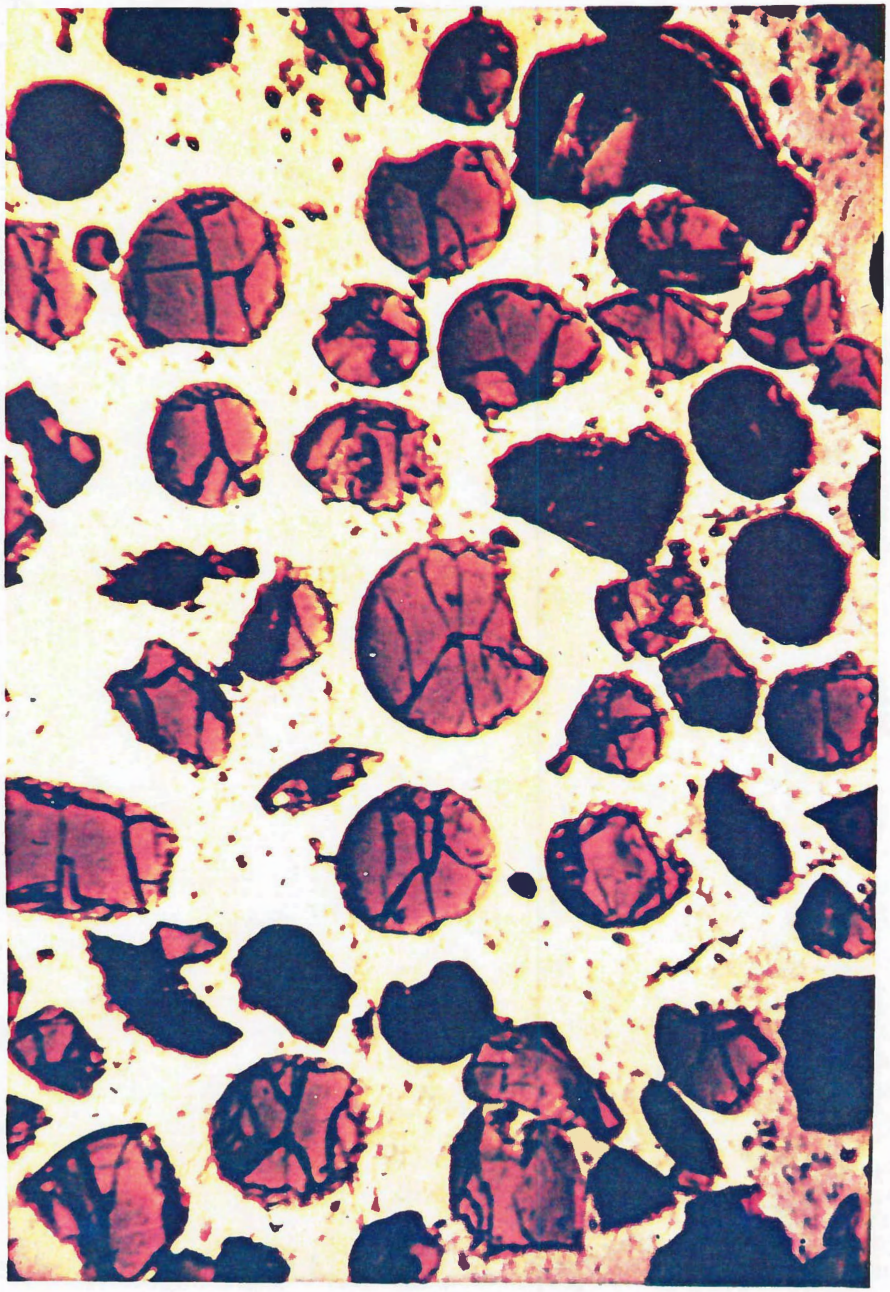
- temperature
- pressure (depth)
- age

also,

- cooling rate
- history (from textures).

The bottom line is that the basalts came from depths ranging from 100 km (early, 3.8 b.y.) and then deeper later (3.3 b.y.).

Hence, as the Moon cooled, the basalts came from progressively deeper; the youngest (yet unsampled) basalts are probably about 2.5 to 2.8 b.y. old and occur in the lunar west.

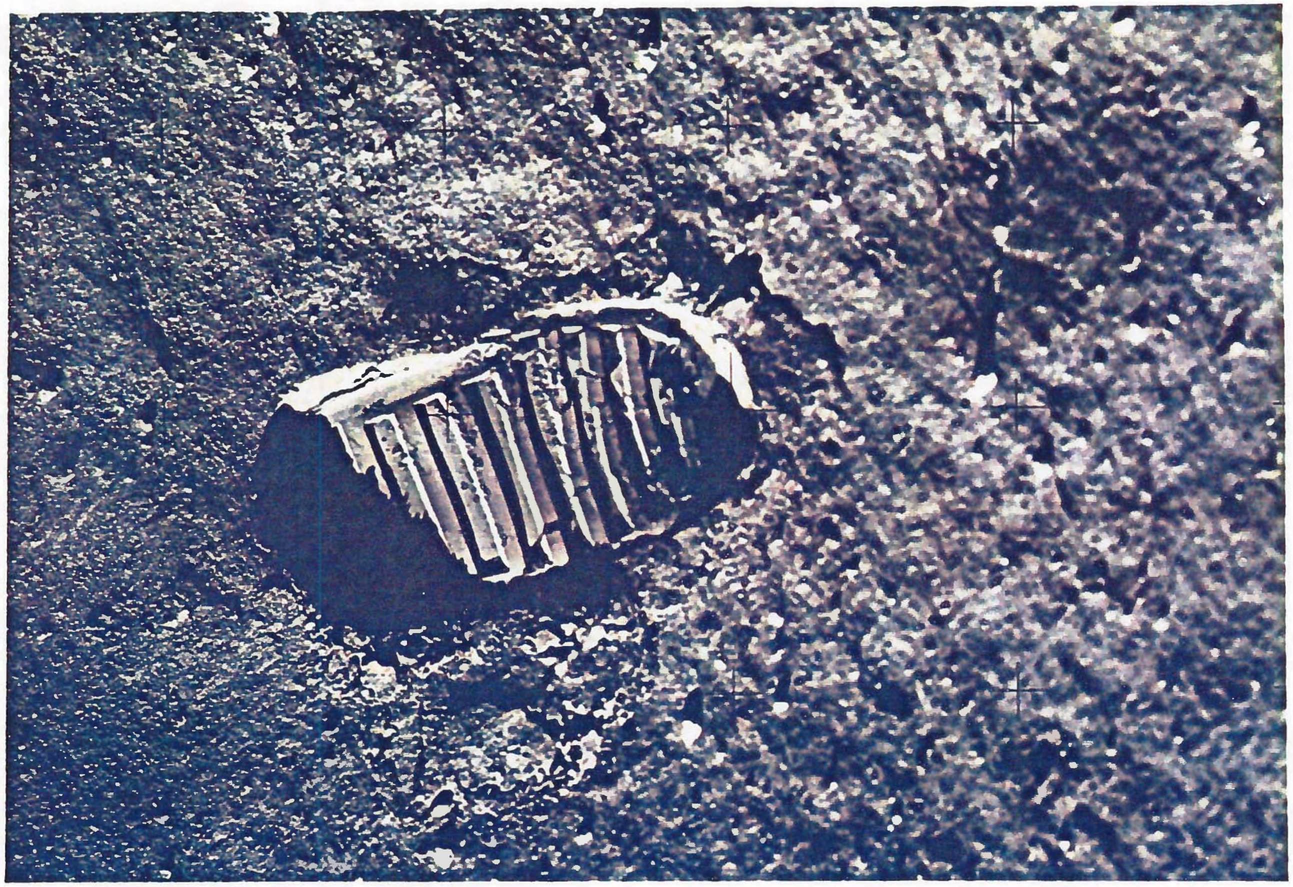


The orange soil collected during Apollo 17 contained abundant small glass spheres, certainly volcanic glass as produced in fire fountains, as in typical Hawaiian eruptions. The glass is old — pre-Mare. Such eruptions are gas driven, which is required to produce such vigorous fountaining.

The question is: What was the gas?

The gas is a clue to planetary outgassing and the origin of atmospheres. It wasn't water, but the data are unclear about what it was because gases were lost in space; what remains in the glass is in ppb amounts.

NASA
AS11-40-5877



The lunar soil

The lunar soil turned out not to be a "fairy castle" structure in which astronauts and spacecraft would sink away, rather it turned out to be much more interesting because embedded in the lunar soil are solar wind particles which contain important clues about the luminosity history of the sun.

This photograph of the Crab Nebula shows a super-nova remnant.

It is in this environment that the Solar System is now believed to have formed.

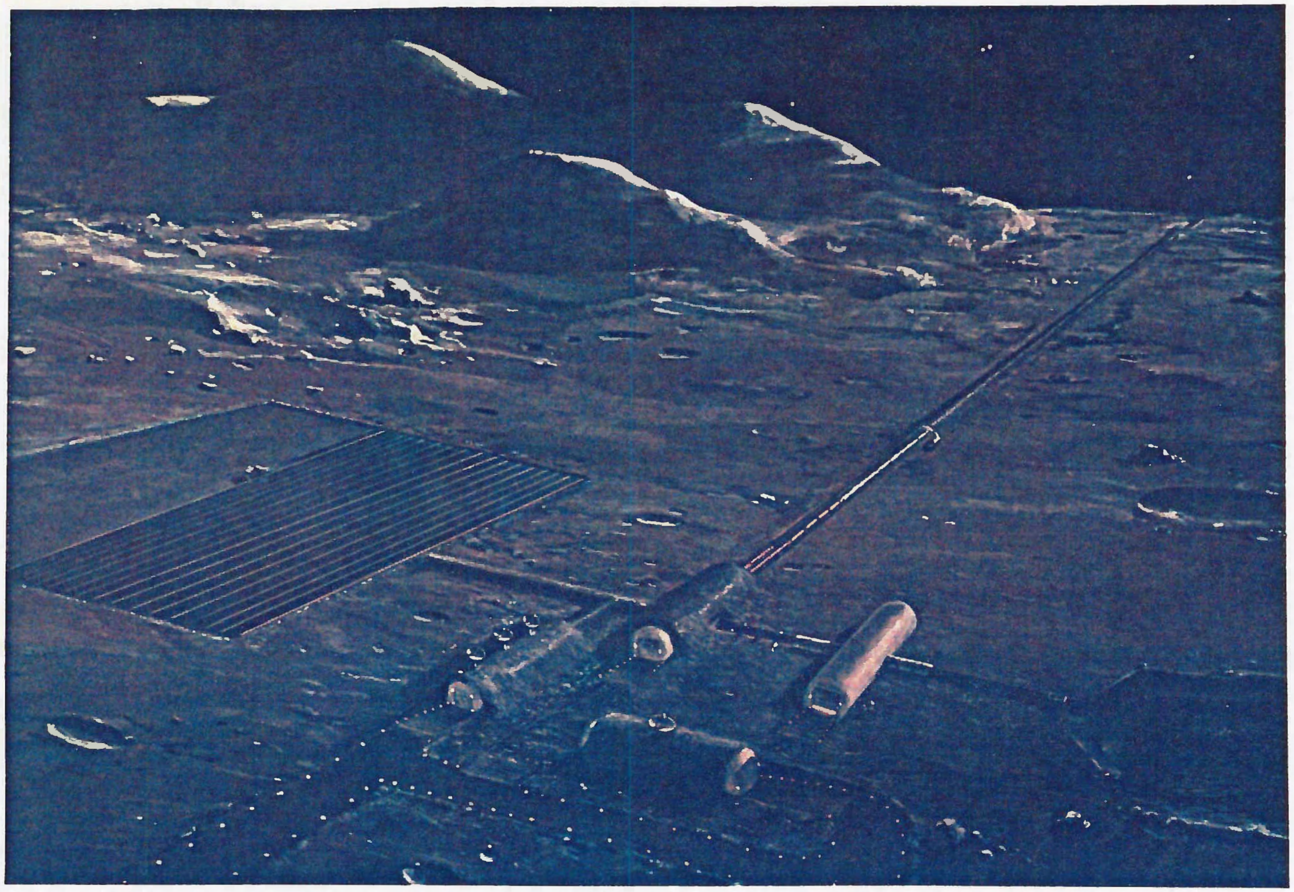
How do we know the Solar System formed this way?

Remnant fragments found in meteorites have:

- high temperature of formation.
- great age (predating the Sun).
- odd isotopic compositions (suggestive of high neutron flux)

The third revolution is very recent and suggests the birth of the solar system was even more violent. Data from analysis of meteorite fragments suggest that the solar system is debris left over from exploding stars and that the interstellar shock waves were responsible for the condensation of the Solar System itself. The Sun and Solar System may have been born as the direct consequence of super-nova explosions in the early solar neighborhood. Within certain stony meteorites, such as Allende which fell in Mexico in 1969, there are small rather innocuous looking mineral grains. The analysis of these grains has led to a completely new view of the earliest days of the solar system, perhaps before the Sun itself existed.

There are three remarkable facts about these grains: (1) they consist of very high temperature minerals (such as perovskite, a titanium magnesium oxide); (2) they are very old; they yield ages which predate other meteorites and the oldest lunar rocks, and (3) they contain elements whose isotopic abundances are unlike anything found in nature; similar to what you would expect of material exposed to an intense neutron flux -- much as you would get by putting a rock into an atomic pile. These three intriguing facts, along with the textural setting of the fragments within their parent meteorite (namely a complicated but not undecipherable mineralogical mess) presented an astro-geophysical jig-saw puzzle whose solution was to shake our view of the birth of our world. It did. The dialogue is intense and involves mineralogists, nuclear chemists and astrophysicists. The current view is that (1) the fragments contain heavy elements certainly produced within stars, (2) the high temperatures and intense neutron flux had to be produced in some event (or events) very early in the solar system's history; very likely these events were the explosion of massive stars which evolved very quickly, expended their nuclear fuel at an enormous rate, became unstable (when their light elements were burned), and collapsed under their own gravity. This collapse produced enormous heat and pressure and a collossal blast resulted. A shock wave was propagated into the interstellar medium and following behind the shock were the blast products from the dying star. The interstellar medium is not homogeneous, rather it contains clouds of dust and gas. The interaction of strong shocks with matter such as these clouds has been carefully calculated (for military reasons) and the effects are known, namely intense heating and collapse. The collapse of such a gas cloud may have led to the condensation processes which created the Sun and the planets, by processes long theorized. Hence, the marriage of three very different disciplines (geochemistry, astrophysics, and shock wave physics) has led to a new view of the birth of the solar system; the view is violent and involves nearby supernova explosions and suggests that the solar system grew up in a very rough stellar neighborhood. (It is noteworthy that the machines which produced the measurements of the isotope anomalies found in Allende and other meteorites were developed specifically for lunar sample analysis. These laboratories, at CalTech, Chicago and NASA, are concurrently studying lunar samples and meteorites in a two-pronged attack on the related problems of the earliest history of the Moon, the Earth, the Sun and the Solar System. The experimental techniques required to produce the precise measurements on these materials did not exist a decade ago, and were developed during and by the Apollo project; in a very direct sense, Apollo resulted in a new solar system cosmology -- in a way which could not have been predicted. That frontier-of-the-mind continues to vigorously expand to this very day, almost a decade since the landing of Apollo 11.)



The Moon and the Future

The return to the Moon is likely to be for practical reasons — to use our knowledge of its resources, perhaps for construction in earth orbit.

Lunar resources are well defined:

— the regolith may be used for shielding or to make glass or fiberglass

— ilmenite (mare soils) contains abundant titanium, iron, and oxygen

— plagioclase (upland soils and rocks) contains calcium, aluminum, silicon and oxygen

and

— "other" — hydrogen (from the solar wind) occurs in trace amounts on soil particles) and perhaps there are some surprises awaiting us in as yet unexplored geological settings, such as volcanoes or central peaks of large craters.

2. The View Ahead -- What next and so what? It is clear that the scientific payoff of the Apollo commitment was enormous and it is crucial to realize:

A. The scientific results from Apollo are still rolling in. (Most of the major results were unanticipated; new exciting problems continue to appear which bear on the Earth, the Sun and the early Solar System.)

B. The next important scientific stop is Mars. (We believe that Apollo amply demonstrated that remote automatic missions provide all the right questions, but the answers to these fundamental questions come from samples and in-situ science. Mars is next!)

C. We are keenly interested in seeing the Apollo results used for practical purposes. (This will be accomplished both on the Earth and also in the return to the Moon for very practical purposes, as well as science.)

These three statements might be rephrased into the simple question, "What's in it all for the man-on-the-street?"

A short list follows:

I. First, the Apollo project was a demonstration of national will and technological ability -- in some sense, a substitute for war! In this context, the science was a secondary, although important activity. However, the scientific payoff has been spectacularly successful and continues to be -- the differential cost of the science may be one of the greatest bargains of all time, in terms of important new data about the universe, our origins and the Earth. For an investment of several billion dollars over a decade, we've shown that nearly everything we thought about the Moon and the Earth was wrong, and furthermore these erroneous views have been replaced with ones which are not only more interesting but more valuable in terms of practical applications.

II. The Moon has proved to be the source of new data on important problems in ways we didn't (or couldn't) guess prior to return of the rocks. Some examples are:

-- the history of the Sun, its luminosity history and its effect on our climate are being addressed by studies of the lunar soil.

-- our view of the origin of the Earth's crust has been profoundly changed by the origin of the lunar uplands.

-- the origin of the Earth's atmosphere is still a mystery; part of the solution may be locked in the orange volcanic glass sampled at Apollo 17.

3. There are 27 large volumes (and 32,000 pages) devoted to lunar science (the Proceedings of the annual Lunar and Planetary Science Conference). The wealth of analytical data and descriptions comprises the handbook on near-earth resources! We know for example that some of the lunar mare rocks and soils contain high abundances of titanium and iron (and oxygen). The upland rocks and soils are aluminum and calcium rich. The lunar soil contains small amounts of hydrogen helium and noble gases -- of solar wind origin. At some point in the future, these materials will be used for practical purposes. Because of the high launch energies required to place objects into Earth orbit relative to the Moon (a ratio of about 20 to 1), extraterrestrial raw materials will become more economical than materials launched from the Earth. In this sense, the lunar program is part of the resource assessment of near-earth space, quite analogous to geological reconnaissance of Alaska's north slope 30 years ago. This "payoff" probably is in the future at least several decades, but it is certain.

4. Other payoffs of lunar science include:

-- new instrumentation -- such as the precise mass spectrometers developed for Apollo and applied to the meteorite fragments -- is being applied to the solution of terrestrial geological problems every day.

-- new experimental methods, such as extremely clean laboratories developed for contamination control (keeping the ficticious moon-bugs out) also meant that the samples were also exceedingly clean; these procedures permitted measurements to be made with extremely low "backgrounds", never before achieved. Applications are many, such as in blood chemistry, where precision of lead measurements have been much improved using lunar methods. Micro-sample techniques developed in Apollo are now applied to many earth sciences problems, including microparticle analysis collected by aircraft.

-- a generation of young scientists have been trained as graduate students and post-doctoral fellows in Apollo; the demands of the lunar program were intense and the standards uniquely high. These young scientists are rising to assume important positions of scientific leadership in many fields; the Apollo experience is paying off in areas of energy and mineral resources and national security as well as space, as these young scientists assume responsible research and administrative roles in various mission agencies and throughout industry. In these cases, perhaps the most important benefit of the Apollo experience is an attitude -- one of delivering high quality results, under intense competitive pressure and on a tight timeline. (The nation certainly faces future challenges in energy and mineral resources which will draw on these traits.)

5. Aren't we through with the Moon?

Any planetary scientist could make a list of a dozen sites to visit to answer an important question. (See attached list). For example:

A. At the lunar poles, there may be gases trapped in permanently shaded areas, such as steep crater walls -- this material would contain important clues about primitive planetary atmospheres (and also might be rocket fuel).

B. We know (from earth-based telescopic observations) that we have sampled only one third of the mare basalts; we would like to get to the rest; especially since they contain an important part of the volcanic history of the Moon.

C. Central peaks of large craters should contain rocks from great depth; perhaps below the crust of the Moon. We have not sampled this material.

D. We've not sampled the upland rocks of the lunar backside; these "continental" areas of the Moon are probably like upland samples from the frontside, but we don't know this.

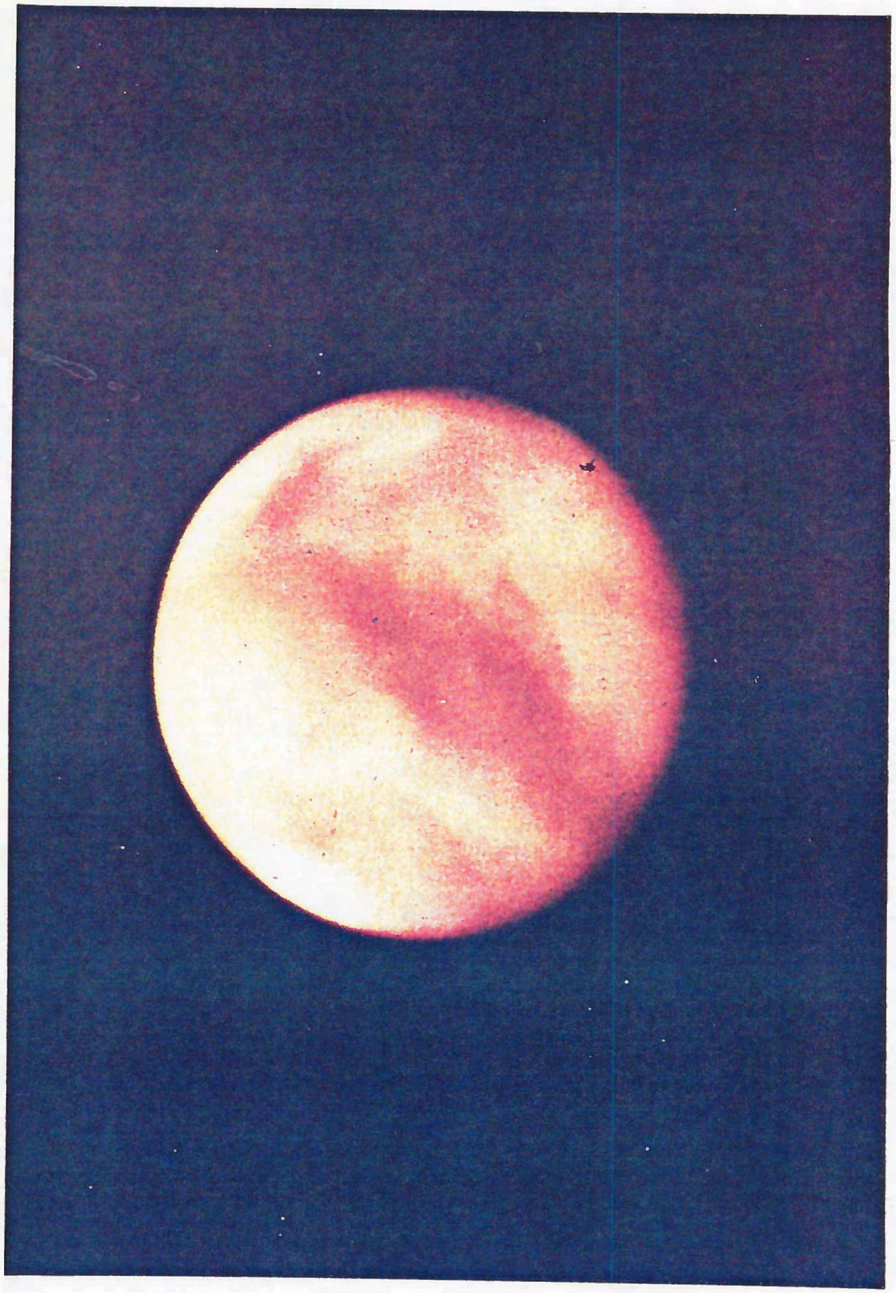
E. There are crater chains on the Moon which are almost certainly volcanoes similar in many respects to terrestrial kimberlite pipes; while we don't expect them to contain diamonds as they do on the Earth, they may contain an abundance of deep-seated fragments sampled off the walls during the violent eruptions responsible for these features. These volcanoes are free drill holes, perhaps several hundred kilometers deep.

6. <u>Origin of the Moon</u>

We still have not resolved the "origin of the Moon" -- why not, after all these years? The reason is: the violent and hot early days of the Moon (and Earth); only rare fragments survived from the magma oceans and the intense early bombardment. There's no trace of the original Moon left; many clues, but the evidence is all circumstantial.

We do know that the Earth and Moon are very closely related chemically (and isotopically) but the Moon is depleted in everything volatile. It's dry.

It appears unlikely that the Moon was captured; it is too closely related to the Earth chemically. It could have formed by simultaneous accretion, by condensation from an early hot atmosphere around the Earth, or by fission as the Earth formed its core.



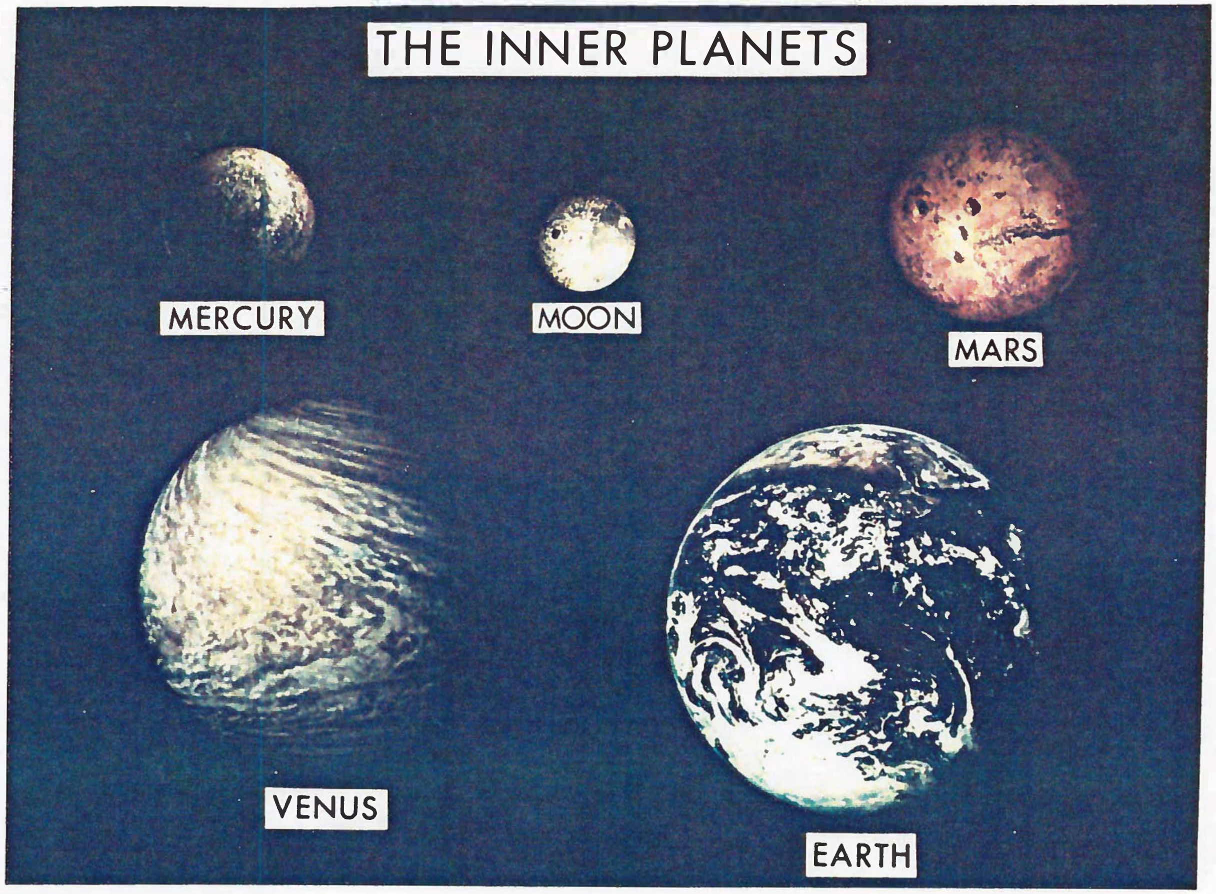
7. Where next?

Where Next? Mars?

The unmanned planetary exploration program continues to provide us with a steady stream of new facts about the solar system. During the next half a dozen years exciting new misisons are planned for Venus (VOIR), Jupiter and its satellites (JOP-Galileo) and a comet. The two spectacularly successful Viking missions, each with a soft lander and orbiter, have provided us with our first close look at Mars. Viking was rather like the pre-Apollo, Surveyor and Orbiter missions to the Moon combined. As with the lunar predecessors, these missions have provided as many more exciting new questions as they have provided answers. Mars fascinates us for many reasons, but primarily because it appears to fit in between the Earth and Moon in many respects. For example, Mars may be in an incipient stage of development of plate tectonics, intermediate between the dead Moon and the hyperactive Earth. Perhaps even more fascinating to us are the many unique features observed on Mars -- the enormous volcanoes, the largest known in the solar system; polar caps, layers of ice and dust certainly containing the history of martian climate; huge rift valleys, which dwarf the Grand Canyon.

In brief, we are at a stage in our knowledge of the planets which is rather like astronomy in 1910, just before the creation of the famous diagram of Hertzsprung and Russell. The array of observational facts is growing and it is being synthesized, and people are thinking. The observational facts will fall into some order -- which demands explanation (and perhaps suggest applications).

Mars is the next point for a focused effort; meanwhile the unmanned planetary exploration program continues to provide crucial new data in a balanced way.


THE INNER PLANETS
MERCURY
MOON
MARS
VENUS
EARTH

TO SUM UP

Question 1

What has happened in the last ten years (while you astronauts were off becoming senators and running companies)?

Answer 1

Apollo science has remade our "creation myths"! Since 1968 there have been major overhauls in our view of the origin of the Moon, the Earth and the formation of the Solar System; we're now using lunar rocks and data to work on the history of the Sun, the origin of the Earth's crust, and the origin of the Earth's atmosphere. Lunar techniques are being applied to study the origin of the elements, the earliest history of the solar system and many very practical problems, such as element distribution and migration in the Earth's crust, the origin of ore deposits, environmental problems of nuclear waste management, and many others.

Question 2

What next (and so what)?

Answer 2

On to Mars -- we think it may turn out to be even more interesting than the Moon! (Viking provided an excellent list of questions; samples, in situ instruments (and men?) will provide the answers. (We hope this will be done by Americans, not entirely by our Soviet colleagues. Luna 24 was OK, but Apollo was infinitely better!) Also, let's use all this lunar information. The use of lunar materials is being studied, and practical methods for its use are defined. For example, the first manned Mars rocketship could be built of titanium from the Moon.