THE MOON AS A GIANT TAPE RECORDER FOR SOLAR SYSTEM AND SOLAR EVENTS

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A unique lunar property

The moon has a unique property compared to the terrestrial and gas giant planets of our solar system. This property consists of the ability to record and preserve evidence of both external and internal events and processes over a time span that includes most of solar system history. Every exposed surface of the moon accumulates implanted solar wind atoms, is modified by both solar flare events and cosmic rays, is exposed to solar UV which may make changes in crystal structures and composition, and is impacted by micrometeorites which create craters, melts soil, produces agglutinates, sprays melted rock, and produces vapor from highly heated silicates and oxides. The "signal" from all of these events and processes is recorded in the uppermost regolith layer, in individual soil grains, and by exposed rock surfaces. This signal consists of chemical changes, changes in morphology and texture of soil grains, implantation of atoms from the sun, radiation damage for cosmic rays and solar flare events, and other modifications driven directly by the complex interaction between solid lunar rocks and soil and the environment of the solar system. Even rare events such as nearby supernovae may have left a series of distinctive changes in lunar material. This recorded signal, if found and properly decoded, is a record of these types of events over the history of the moon.

If not covered up, this recorded signal is overwritten and destroyed by later events; the record of earlier events disappears. However, processes exist which can preserve some of this record. For example, the moon has had some endogenic surface modification over the past 4 gy. While lava flows, pyroclastic deposits, and volcanic vents are common in the mare areas, much of the moon has been modified only by external impacts during the period time since the end of the great basin-forming impact events. Surfaces covered by volcanic flows and ejecta become a reasonably permanent record of events in the early solar system. In addition, except for the smallest micrometeorites, all lunar impact events create ejecta and debris which cover exposed rock and soil. This coverage is continuous near the crater, becomes discontinuous out a few crater diameters, and may also include rays which may extend extremely long distances. As a consequence, most exposed rock and regolith surfaces are eventually covered to some degree by these impact ejecta.

The significance of geologic coverage of old material by younger material

The immediate effect of this coverage is to remove the surface material from further processing. This material becomes a time capsule preserving a record of solar system and solar processes active somewhat before and up to the time the material was buried. In the simplest case, this buried material is a layer of reworked regolith underlain by something else such as a basalt flow. How long will this buried layer be preserved? Subsequent impacts may disperse the buried material, essentially destroying its time capsule information content by mixing it with other kinds of regolith. Dusting processes also exist which can clean off rock

and regolith surfaces. Expanding vapor clouds from impacts is one example. On the other hand, subsequent nearby impacts may protect the buried material by adding additional ejecta on top of the buried layer. The ratio of preserved fossil regolith to destroyed or dispersed fossil regolith depends on the shape of the impacting flux curve, the integrated cratering time and intensity, and the probability of a large covering ejecta blanket at any one location, and the relative geometry of the new cratering event and the regolith region of interest. In general, gardening must blur and destroy the integrity of buried fossil regolith surfaces, but the stoichimetric nature of the impacting process should allow some buried regolith to escape further gardening and dispersal. The lunar regolith may therefore retain segments or fragments of fossil regolith surface layers which have escaped destruction by subsequent impacts. The probability of preservation of a specific segment of fossilized surface layer can possibly be estimated from current meteorite flux data, although past flux rates may be different.

In the ideal case, such fossil regolith layers may have a basalt flow, impact melt flow, or pyroclastic deposit either underlying or covering the deposit. Such flows or pyroclastics can be accurately age-dated and will provide the time interval and age of the preserved fossil regolith. The possibility exists that a variety of datable fossil regoliths can be located using geologic or geophysical data. Samples from such fossil regoliths can be used to determine the properties of both the impacting flux of micrometeorites and the composition of the solar wind and solar flare implanted atoms. With appropriate samples, the time scale can be accurately determined and variations can be delineated at many intervals over a period from the present back to basin-forming events, a time span of about 4gy. Such data would help us understand any variations in impacting flux objects and variations in the sun or in cosmic rays.

What should be done on the moon?

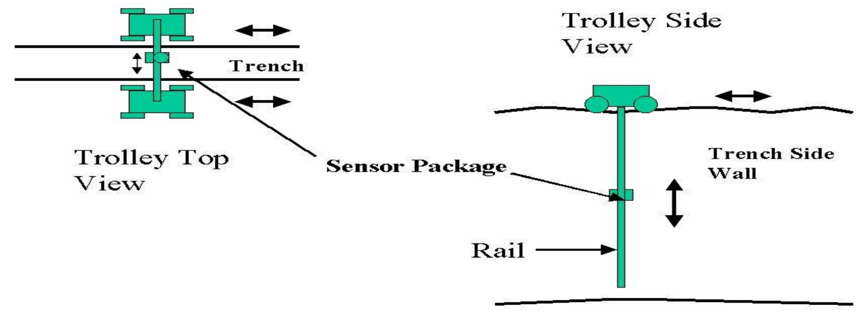
Outcrops preserving lunar stratigraphy should be sought. Careful sampling of material from identifiable layers may contain the desired fossil regolith. Layers sandwiched between lava flows or between melt flows would be the most useful because of the potential for accurate age-dating. One example is the apparent regolith in the Apollo 15 rille which appears to be capped or sandwiched by a basalt flow. Other examples may be found in crater walls. In addition to preserved layers of buried or sandwiched fossil regolith, it is also possible that marker beds from major impacts may be formed and preserved. Such marker beds, while gardened and dispersed in many places, may also be preserved by burial by younger ejecta material. An example of a possible marker bed (somewhat disrupted) is the ropy glass concentration at the Apollo 12 site. Is this ropy glass, most concentrated in sample 12033, part of a buried marker bed from a major lunar cratering event? Age dating of the ropy glass has provided a good age data point for impact that formed the source crater. the A key component of scientific information needed from future lunar missions is the discovery, documentation, sampling, and return of fossil regolith samples.

Are marker beds from larger cratering events common on the moon? Examination of the lunar cores and drive tubes from Apollo did not reveal any stratigraphic horizon that could be traced between even nearby adjacent cores at the same site. It may be that the regolith layers are mostly too fragmented by impact to be reliably traceable from core to core. Consequently, the Apollo lunar cores and drive tubes have revealed little information on the fine-scale stratigraphy of the lunar regolith, and almost no information on the lateral variation over meters and 10s of meters. ***The location and sampling of clear fossil regoliths and the subsequent analysis and documentation of their exposure age and formation age are arguably the most important scientific activities that humans can do on the moon.***

The advantages of trenching

This frustration with retrieving stratigraphic information from cores leads to alternative approach to understanding the regolith: digging trenches. A trench creates "road cuts," and access to the trench walls allow the entire two dimensional regolith can be examined along the length and depth of the trench. Soil mechanic considerations suggest that the sidewall of a trench will likely remain standing and intact to a up to 3 meters. Deeper trenches can be made by offsetting the wall in steps of by successive passes in which the trenching device is placed in the trench and then proceeds to dig a deeper trench. A trench would reveal fragments of continuous layers, unconformities, and marker beds even if not all were present at any one point. In contrast, a single random core may completely miss some layers or may misleadingly show layers which are only of local extent, but which look major in the core section. Trenches provide a 2-dimensional view of the regolith whereas cores provide only a one dimensional view. Intersecting trenches even provide the ability to construct a 3-dimensional view. On human missions, where possible, a trench should be dug into the regolith extending down as deep as is practical, but at least a few meters. Automated trenching can be done and concepts for such devices exist (see below).

Trench lengths of at least 5-10 meters would be very useful, and trench lengths of ~100m would be ideal. At mare sites it might even be practical to trench to the base of the regolith (3-6m). Careful analysis and sampling of the trench wall should occur soon after the trenching operation. Proper documentation may reveal segments of continuous layers which have been covered up by impact ejecta from a single event so as to preserve their fossil information. The documentation of trench walls can be automated with a device that maps using spectral data, and x-ray florescence from either x-ray sources or electron beams, and other techniques on a pixel-by-pixel basis much like a scaled-up automated electron microprobe. : The approach is to design and test a prototype lunar "tape reader." The playback mechanism consist of devices to make vertical "roadcuts" 10s of meters in length by trenching the regolith followed by detailed imaging and pixel-by-pixel chemical analysis of the trench wall using an x-y matrix instrument carrier. and a variety of sensors (digital cameras for visible, IR, UV, pixel-by-pixel mineralogy by micro-raman, chemistry by LIBS, laser mass spectrometry, x-ray emission).



Such mapping would likely reveal any continuous layers, determine their extent, and document their thickness. Automated instrumented systems would provide chemistry, mineralogy, and soil maturity. Sampling of each major layer or unit could be done by the crew or by an automated system that uses a side-wall core or a small scoop. Pixel-by-pixel automated mapping would also uncover buried rocks. Such rocks have the potential that their outer surfaces may have been exposed to microcratering and solar particle implantation during a specific time interval in the past. Consequently, these rocks constitute time capsules buried at different depths and different times within the regolith section revealed by the trench. Apollo experience has shown that, while technically part of the regolith sequence, rock surfaces may accumulate both micrometeorite impact craters and solar particles for much longer times compared to individual small soil grains. Well-documented buried rocks may prove to be the best approach to detailed sampling and analysis for solar system and solar history over time.

Trenching has the potential of producing far better data on the nature and sampling technique should provide far better carefully chosen samples. Samples would be returned to Earth for detailed analysis. Particularly with limited return cargo capacity, pre-screening samples will likely be necessary, and the trench approach offers superior access to targeted sample selection compared to random cores. A combination of field geology, unconformity identification, intelligent sampling of outcrops, coupled with trenching and sample return and analysis will provide a powerful and realistic approach to reading the tape of the preserved fossil regoliths on the moon. Because of the potential of enormous added value to samples chosen from well-documented regolith stratigraphy, I strongly recommend that trenches be dug and sampled on each human lunar mission as the top priority scientific activity at each site.

I have personally studied nearly every opened core in the Apollo collection as well as samples from two cores from the Russian Luna collection. While we learned much from these cores, we were never able to correlate stratigraphy between cores even at the same station, we could not tell whether variations were totally local or represented site-wide, regional or even global events, and we had great difficulty determining even relative ages of various core units. The elaborate detailed drawings and description in the many core catalogs contain little or no useful information and were seldom referenced in the scientific literature. Except on robotic missions, I concluded that taking cores is a waste of crew time on future lunar missions and also wastes considerable sample return payload mass; much of the mass consists of the core hardware and redundant samples that provide little new information. The return of carefully chosen samples from a mapped "roadcut" should be far superior in useful information content compared to a few cores. (However, if trenching and roadcut mapping are not practical, coring is still preferable to no depth data at all).

If we were able to sample outcrops or produce trenches to collect well-documented fossil regolith samples, what types of data and questions could they address?

- **Record of large solar flare events over time**
- **Record of long term changes in chemical and isotopic composition of solar wind to provide a basis for interpreting the evolution of the sun over time**
- **Possible record of cosmic ray variations including major rare intense cosmic ray events and implications for climate change, global warming and cooling, and life on Earth**
- **Possible record of nearby supernovae and implications for life on Earth and climate change**
- **Record of possible periodic intense micrometeorite bombardment from concentrated dusty regions of our galaxy and a determination of whether passing of the solar system through dusty parts of our galaxy leaves a record in the lunar regolith**
- **Record of occasional asteroid and comet breakup with short term but intense bombardment of the moon and Earth**

  - **Record of occasional large asteroid or comet impacts on the Earth with subsequent ejection of a large number of rock fragments to the moon (in the form of concentrated meteorite layers or marker beds)**
  - **Possible record of early (before ~3.5by) major impacts on Earth in the form of meteorite concentrations or marker beds on the moon (could even include fossil traces of early life on Earth or even pre-biological organic chemistry; Earth rocks could readily be recognized by their high Na content and the ratio of Na to other elements—an automated "roadcut" mapping system could easily detect high Na pixels at a ppm or possibly a ppb level compared to the number of low-Na pixels)**
  - **Record (in the form of concentrated meteorite layers or marker beds) of major impact events on Venus, Mercury, Mars, or the satellites of Saturn and Jupiter, assuming rocks from these bodies have distinctive chemistry, isotopic ratios, or trapped gas/atmosphere content. Just as the martian and lunar meteorites on Earth have been a "poor man's" sample return, meteorites found in the lunar regolith may be a way to sample other planetary bodies.**

Summary

The moon offers a unique opportunity to find samples that may have recorded major solar events and major solar system events, and possibly even major galaxy events over geologic time. It should be possible to locate appropriate lunar samples ranging from recent back to the end of the cataclysm. In some cases, the exposure time and interval for these samples can be accurately determined. Collection of appropriate fossil regolith samples and rocks can be greatly facilitated by a trenching device followed by an automated pixel-by-pixel mapper, analyzer, and sample collection operation. The potential value of such well documented fossil regolith samples would be immense. They preserve a record of a variety of events in the past ~4gy of solar system history and the history of the sun. The implications of decoding this information would be immense and might change our basic concepts of the evolution of the solar system, the sun, the Earth's climate, and the origin and evolution of life on Earth. Documentation of this record preserved in the lunar regolith may turn out to be the single most useful scientific task for human visits to the moon, and could justify the entire program in the eyes of the public, Congress, and the Administration,