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Constraints on Transport and Emplacement of Labile Fractions in Lunar Cold Traps

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Genetic models are the bread-and-butter of mineral exploration. Such models must address all aspects of an ore system: source, mobilization, transport, deposition, evolution. Failure at any step suggests model failure. ALL known features must be explained.

Consider the potential ores composed of labile fractions in Cabeus Crater. In this case a complete and valid genetic model has three general attributes:

1) It explains all constituents, or calls upon a second, independent process.
2) It explains observed relative abundances.
3) It explains why other things are not present.

Note, the phases of interest are properly labiles not volatiles, they moved but did not disappear.

Current understanding of the distribution, abundance, and mechanisms of transport and emplacement of lunar labiles are very problematic [2], a point emphsized by most authors discussing lunar volatiles [3-4]. There are many speculative models about transport mechanisms and sources [5-6] though residence times are unknown [6]. Available data are either very limited (LCROSS, GRAIL, Luna 24 [8]) or ambiguous (LAMP, radar, LEND, M3).

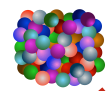
The list of known lunar labiles is intriguing [1,7,4]: H2O; Hg; ultra-light species (H2S, NH3, SO2, C2H4, CO2, CH3OH, CH4, OH, CO); Br; Ar (a true volatile); and soluble & insoluble organic matter (IOM). Although only traces of C are found in Apollo samples [10], IOM must be included as they are known as major fractions of comets [9],. Given the known molecules, additional cometary molecules should be anticipated as well [11]. The LCROSS and LAMP observations of Hg [12] suggest the possible presence of elements such as Ag, Se, Te, *etc*.

Observed	
H_2O	CH_4
H_2S	OH
NH_3	CO
SO_2	Br
C_2H_4	Hg
CO_2	Ar
CH_3OH	H_2

Genetic Models Must Explain

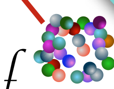
1. Source

Where did the elements / molecules come from?



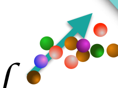
2. Mobilization f_{M_i}

How were they released from the source?



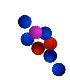
3. Transport f_{T_i}

How were they moved from source to the deposit?



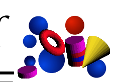
4. Deposition f_{D_i}

Why are they deposited where they are at?



5. Evolution f_{E_i}

How have they changed once in the deposit?



To transport the labiles must be mobilized. This process has fractionation coefficients per component. This is true for transport, deposition and evolution. Published concepts of mobilization are tied to source and transport.

The labiles must move at sometime, somehow, either through crustal rock, through regolith, across the lunar surface, or through space. Movement through space is the subject of much speculation and modeling, as noted above. Movement through the crust is not likely, as noted already. The crater is eroded, with subdued walls. Conceptually, light molecules outside the crater could move through fractures or the regolith blanket. However, lateral cold movement through the regolith has generally not been considered and a driving force has not been identified. Further, a mechanism of lateral movement must explain why venting to space is not significant.

Hypervelocity impact pressure waves can transmit enough energy to break down impacted rock into constituent ions. A deposit of labiles could form within the regolith where the transient conditions return to pressures and temperatures at which they re-condense. This would form a shell around the impact point, within the pores of the near-field rock and regolith. How much mass could be moved this way is unknown.

Movement under gravity would concentrate labiles at lower elevations (all else equal). However, the detection of H2O and Hg at the GRAIL impacts, on the side of a massif, strongly suggests that gravity induced movement is not the only or dominant transport process.

Current modeling of the transport of H+, OH-, H2O and "neutral" species in the solar wind, H_2O stripped from Earth, and other diffuse sources fail to explain the observed species. Nor do they explain distribution patterns. Epithermal neutron data clearly show pole-ward enhancement at scales of 10-100 km [26]. LAMP data suggest widespread water frost [27]. M3 shows polarward increases in OH concentration [16]. LEND epithermal neutron concentrations correlate with slope aspect [28]. These observations may be compatible with local deposition of Zodiacal dust mediated by surface temperature.

Solar Wind? Crustal? Comets?

The source for the labiles must be 1) within, 2) beneath, or 3) outside the crater. Labile deposition is younger than the host regolith, which is younger than the crater, which is younger than the lunar crust. Exhalation from beneath the crater of hot fluids is improbable as the expected alteration minerals are extremely rare [13]. Lunar petrology also suggests most magmas are under-saturated with H2O [14]. And the combination of labiles reported from LCROSS does not match that expected from terrestrial layered mafic intrusives [15]. If rising cold fluids are postulated there is no reason the labiles would be trapped in the regolith and not become volatiles. The observations of [16], while relevant for H2O, do not explain the presence of other molecules observed by LCROSS. [17] suggests a possible source for some but does not match the observations.

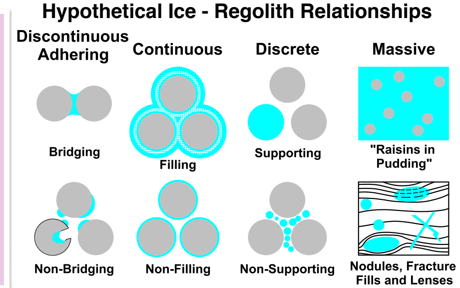
The labile material may have arrived directly from space, either as "large" masses, such as comet nuclei or Interplanetary Dust Partilces (IDP), as diffuse molecules, or as atoms recombined locally, i.e. solar wind [18]. **The zodiacal dust/micrometeorite/IDP population is known to have most if not all the species observed by LCROSS [18-20]; and its mass flux equals or exceeds the mass flux of the solar wind, 3x10-12 g/(m2 sec)** [22]. [23] is relevant to this concept.

While these can explain some of the observed species, **Hg in particular is extremely problematic to derive from any hypothesized source.** Note though, there is essentially no direct information about the Hg content of IDPs [24]. A separate source may be responsible for the Hg, and perhaps for other molecules [25].

Terrestrial? Mixture?

Molecules deposited from vacuum at low temperature may form amorphous rather than crystalline solids. The presence of other molecules may either inhibit or seed crystallization. The material might technically qualify as glass. Internal structure of the ice can be either monocrystalline or polycrystalline. In both cases crystals may be random or preferentially oriented, and may be equant or highly distorted. Crystal growth may or may not displace existing particles. Growth zonation is likely. The spatial relationships are controlled by the material's origin and history. **Unexpected compounds could form (e.g., terrestrial deposits of methane clathrate were found only recently, but are locally abundant).**

Hypothetical Ice - Regolith Relationships



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Conclusion: Problems of source, mobilization, transport, and deposition make most hypothesized models for the labile fractions observed by LCROSS very difficult to understand. Zodiacal dust or comets, appear to have the closest source composition to observed labile chemistry. Zodiacal dust can deposit the species directly into Cabeus Crater at the GRAIL impact and Luna 24 sites, where LEND, LAMP and M3 see signals. In principle this agrees with [29] though the ratio of asteroid vs. comet sources they require is problematic. An implication of this source is labile species may be more widely spread, and available than previously thought.

For any model of the labile fractions there are two major problems. Where did the Hg come from? Where did the C in the comets and zodiacal dust go to?