POTENTIAL RESOURCES OF THE MOON
LUNAR RESOURCE ACCESSIBILITY

MAJOR FACTORS

• ORIGINAL ROCK COMPOSITION

• REGOLITH FORMATION

• IGNEOUS CRYSTAL SETTLING

• ABSENCE OF FLUID WATER
REGOLITH MATURATION

• BEGINS WITH SURFACE STABILIZATION
  – MODIFICATION BY:
    • PRIMARY IMPACTS
    • SECONDARY IMPACTS
    • HYDROGEN REDUCTION OF FEO
    • SPACE RADIATION
    • INTERNAL VOLATILE MIGRATION

• SPACE RADIATION
  – COSMIC RAYS
  – SOLAR-WIND IONS
REGOLITH SUMMARY - 1

- REGOLITH (mantle of fragmental, unconsolidated material overlying bedrock)
  - >6M DEEP ON 3.8 BY OLD SURFACES
- CONSTITUENTS:
  - ROCK FRAGMENTS
  - AGGLUTINATES (IMPACT GLASS WELDING TOGETHER ROCK AND MINERAL FRAGMENTS)
  - MINERAL FRAGMENTS
  - VOLCANIC GLASS SPHERES AND FRAGMENTS
  - METEORITIC CONTAMINATION (<0.3%)
  - ADSORBED SOLAR WIND VOLATILES (H₂ AND HE)
  - PRODUCTS OF SOLAR AND COSMIC RADIATION
REGOLITH SUMMARY - 2

- LATERAL MIXING RATE
  - ON THE ORDER OF 10S OF METERS PER 100 MY
  - ~100S OF METERS PER BILLION YEARS

- VERTICAL MIXING IRREGULAR
  - 3M DRILL CORES INDICATE TEXTURAL LAYERING BUT NO SIGNIFICANT CHEMICAL CHANGE WITH DEPTH
REGOLITH SUMMARY - 3

- GEOTECHNICAL PARAMETERS
  - DENSITY ~1.9 GM/CM³
  - HIGH BEARING STRENGTH
  - MODERATE COHESION
  - >60% PARTICLES <100m (THAT IS, PENETRATING DUST!!!!!!)
  - HIGHLY ABRASIVE (THAT IS, RELIABLE SEALS REQUIRED!!!!)
  - DISSEMINATED, FINE GRAIN NATIVE IRON
  - DISSEMINATED, FINE GRAIN IRON SULFIDE
  - HIGHLY REDUCING (HYDROGEN)
LUNAR CONSTRUCTION
NON-METALLIC MATERIALS

• REGOLITH
  – INSULATION
  – RADIATION PROTECTION
• COARSE REGOLITH FRACTION
  – ROAD AGGREGATE
  – CONCRETE
• FINE REGOLITH FRACTION
  – COMPACTED “BRICK”
  – SINTERED “BRICK”
  – REGOLITH/METAL COMPOSITES
  – SOLAR PHOTOVOLTAIC CELLS
The Surface of the Moon is Slightly Richer in Fe, Ca, and Mg Compared to the Earth's Crust
LUNAR MANUFACTURING
METALLIC MATERIALS
(HIGH TI BASALTS)

• FINE REGOLITH FRACTION/MAJOR ELEMENTS
  – IRON IN IRON-TITANIUM OXIDE (22 WT % FEO AND 1 WT % NATIVE IRON)
  – TITANIUM IN IRON-TITANIUM OXIDE (11 WT % TIO₂ IN ILMENITE)
  – MAGNESIUM IN MAGNESIUM-IRON SILICATES (7 WT % MGO)
  – ALUMINUM IN CALCIUM-ALUMINUM SILICATES (9 WT % AL₂O₃)
  – SILICON IN CALCIUM-ALUMINUM SILICATES (40 WT % SIO₂)

• FINE REGOLITH FRACTION/MINOR ELEMENTS
  – PLATINUM GROUP IN METEORITIC DEBRIS
  – CHROMIUM IN CHROMIUM-IRON OXIDE

• PYROCLASTIC GLASSES
  – MAGNESIUM (16 WT % MGO)

• GRAVITY CONCENTRATIONS IN BASALT FLOWS
  – TITANIUM (ILMENITE)
  – ALUMINUM/SILICON (PLAGIOCLASE)
  – CHROMIUM (CHROMITE)
  – IRON/SULFUR (TROILITE)
Clementine Titanium Map of the Moon
Equal Area Projection

Near side

Far side

$\text{TiO}_2$ (wt.%)
LUNAR SPECIAL COMPOUNDS

• LUNAR KREEP (NOT NORMALLY ASSOCIATED WITH BASALTIC REGOLITH)
  – PHOSPHATE (P$_2$O$_5$)
  – POTASH (K$_2$O)
  – SODA (Na$_2$O)
INDIGENOUS LUNAR VOLATILES

• FROM PYROCLASTIC GLASSES
  – OXYGEN (ELECTROLYSIS OF H₂O PRODUCED BY HYDROGEN REDUCTION)

• ADSORBED ON PYROCLASTIC GLASSES (LARGE VOLUME PROCESSING)
  – FLUORINE
  – CHLORINE
  – VOLATILE METALS (COPPER, ZINC, LEAD)

• FROM REGOLITH (LARGE VOLUME PROCESSING)
  – SULFUR (IRON SULFIDE)
SOLAR WIND VOLATILES
REGOLITH FINES

• HYDROGEN
  – 96% OF SOLAR WIND IONS
  – 30 PPM AVE.
    • HIGHER IN REGOLITH DERIVED FROM TITANIUM-RICH BASALTS AND ANORTHOSITE
  – UP TO ALMOST 150 PPM IN SOME APOLLO 16 SAMPLES

• HELIUM
  – 4% OF SOLAR WIND IONS
  – UP TO 70 PPM IN REGOLITH DERIVED FROM TITANIUM-RICH BASALTS
    • UP TO 30 PPB $^3$HE

• NITROGEN
• CARBON
• TRACE NOBLE GASES (KR, XE, AR)
Inferred Titanium Content of Regolith of Mare Tranquillitatis

- **+7.5%**
- **6.0 - 7.5%**
- **3.0 - 6.0%**

~300 km
# Minable Regolith and Helium Content of Mare Tranquillitatis

<table>
<thead>
<tr>
<th>Regolith Category</th>
<th>Area, km²</th>
<th>Avg. He Content, wppm</th>
<th>Regolith Minable, tonnes</th>
<th>He, tonnes</th>
<th>He3, tonnes</th>
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<tbody>
<tr>
<td>A</td>
<td>84,000</td>
<td>38</td>
<td>252x10⁹</td>
<td>9.58x10⁶</td>
<td>3,635</td>
</tr>
<tr>
<td>B</td>
<td>195,000</td>
<td>25</td>
<td>598x10⁹</td>
<td>14.96x10⁶</td>
<td>5,754</td>
</tr>
<tr>
<td>Totals</td>
<td>279,000</td>
<td></td>
<td>850x10⁹</td>
<td>24.54x10⁶</td>
<td>9,439</td>
</tr>
</tbody>
</table>

Note: He-3 content based on He/He-3 = 2600.
Average depth of regolith = 3 m.
COMETARY VOLATILES
POLAR DEPOSITS?

• HYDROGEN REGIONAL AVE. INCREASES TO 150 PPM
  – LUNAR PROSPECTOR EPITHERMAL NEUTRON SPECTRA

• VERY HIGH CONCENTRATIONS OF HYDROGEN IN THREE SOUTH POLE CRATERS
  – ASSUMED TO BE WATER-ICE BY PROSPECTOR TEAM
  – FAST NEUTRON SPECTRA CONFIRM?
  – CLEMENTINE BI-STATIC RADAR CONFIRM?

• HYDROCARBONS?
COMETARY VOLATILES
DATA SOURCES

- EPITHERMAL NEUTRON DATA (FELDMAN)
  - AVERAGE ~50 wppm HYDROGEN
  - ~150 wppm IN POLAR REGIONS
  - 1500 ± 800 wppm IN DEEP POLAR CRATERS
- CLEMENTINE 750nm ALBEDO VS. NEUTRON DATA (DING)
  - 36 wppm NEARSIDE VS. 28 wppm FARSIDE
- CLEMENTINE BI-STATIC RADAR (NOZETTE)
  - CONTROVERSIAL INTERPRETATION OF ICE
INTERPRETATION?

- **PROSPECTOR TEAM**
  - LARGE QUANTITIES OF POLAR ICE WITH SOME SOLAR-WIND HYDROGEN
  - LATER, ICE ONLY IN 3 SOUTH POLE CRATERS
  - MORE RECENTLY, ICE ALSO IN REGOLITH

- **ALTERNATIVE**
  - LARGELY COLD TRAPPED SOLAR-WIND HYDROGEN
SOLAR-WIND IONS

• HYDROGEN (PROTONS)
  – ~96% OF THE SOLAR-WIND
  – INITIALLY IMBEDDED IN MINERAL AND GLASS CONSTITUENTS
  – PARTIALLY RELEASED AS PICKUP IONS
    • MICROMETEOROID IMPACT
    • DIURNAL HEATING
  – RETAINED BY BURIAL
CONDITIONS AT THE POLES

• **PERMANENT SHADOW** - ~230°C

• **OUTSIDE PERMANENT SHADOW**
  – AVERAGE SURFACE TEMPERATURE INCREASES WITH DECREASING LATITUDE

• **MAXIMUM CONTRAST BETWEEN EQUATOR AND PERMANENT SHADOW**
  – ~350°C
PICKUP IONS

• RELEASED REGOLITH VOLATILES
  – IONIZED AND ENTRAINED IN SOLAR-WIND
  – LOST ENTIRELY OR RE-IMPLANTED

• DEFINITIVE MODEL OF HISTORY OF PICKUP IONS NOT YET AVAILABLE
  – APOLLO, CLEMENTINE AND PROSPECTOR DATA DEFINE ~STEADY-STATE IN REGOLITH
    • SANTARIUS AND STUDENTS HAVE BEGUN TO MODEL OVER-ALL PROCESS
STEADY-STATE HYDROGEN CONCENTRATION

• APOLLO SAMPLES: 100 ± 50 wppm
  – MAY BE LOW DUE TO HANDLING LOSSES

• PROSPECTOR DATA FOR REGIONS WITH PERMANENT SHADOW
  – ~150 wppm (HIGH END OF APOLLO DATA)
  – X3 THAT SEEN FOR LOWER LATITUDES
  – GRADUAL CHANGE ACROSS PERMANENT SHADOW BOUNDARIES
  – 1500 ± 800 wppm IN DEEP POLAR CRATERS
HYDROGEN RETENTION

• PLAGIOCLASE FELDSPAR \((\text{Ca, Na})_2\text{Al}_2\text{Si}_2\text{O}_8\)
  – KNOWN TO ASSUME A CATION POSITION IN FELDSPAR - SODIUM SUBSTITUTE?
    • NOTE TRANSIENT LUNAR SODIUM ATMOSPHERE
  – SUPPORTED BY INHANCEMENT NEAR LARGE, YOUNG HIGHLAND CRATERS WHERE FRESH PLAGIOCLASE IS EXPOSED

• ILMENITE \((\text{FeTiO}_3)\)
  – CLEMENTINE-PROSPECTOR COMPARISON BY DING
Medium Energy Neutron Distribution
Lunar Prospector

Near-Side & North Pole

Epithermal Neutrons (counts)

518.
511.
504.
497.
490.
483.
476.
469.
462.
455.
448.

Far-Side & South Pole

Los Alamos National Laboratory
POLAR SOLAR-WIND CONSIDERATIONS

- VARIABLES AFFECTING ADDITIONS AND LOSSES OF HYDROGEN NEAR THE POLES
  - SOLAR-WIND FLUX VS. LATITUDE AND LONGITUDE
  - TILT OF MOON’S AXIS RELATIVE TO ECLIPTIC
  - NON-ECLIPTIC COMPONENT OF SOLAR-WIND
  - DIURNAL TEMPERATURE VARIATION VS. LATITUDE AND LONGITUDE
  - PICKUP-ION REDEPOSITION RATES VS. LATITUDE AND LONGITUDE
  - ABUNDANCES OF RETENTIVE MINERALS
  - MOON’S INTERACTION WITH THE MAGNETOSPHERE
  - FLUX OF MICRO-METEORITES IMPACTING THE MOON
EROSION OF WATER ICE BY MICROMETEOROIDS

• REGOLITH TURNOVER (GARDENING)
  – FEW CM EVERY 10 MILLION YEARS

• BLANKET OF COMETARY ICE WOULD ERODE AT COMPARABLE RATE
  – SPUTTERING DUE TO SOLAR-WIND WOULD ADD TO EROSION RATE
  – SOME PROTECTION POSSIBLE IN DEEP CRATERS OR BY FORTUITOUS EJECTA
SCIENCE CONCLUSIONS

• THE HYDROGEN SIGNAL IN POLAR REGIONS IS LARGELY A CONCENTRATION OF SOLAR-WIND HYDROGEN BY COLD-TRAPPING
  – WATER ICE MAY BE PRESENT IN DEEP CRATERS WHERE PARTIALLY PROTECTED FROM EROSION
  – WATER ICE MAY BE LOCALLY MIXED INTO REGOLITH WHERE INITIALLY PROTECTED FROM EROSION BY IMPACT EJECTA