Luna:
What Did We Learn and What Should We Expect?

William T. Wallace, Ph.D.
Universities Space Research Association
NASA/Johnson Space Center
Houston, TX

Outline

- Background
  - Apollo program
  - Lunar dust info
- Activation and monitoring
- Dissolution
- Cellular toxicology

Kennedy Moon Speech

- Joint Session of Congress: May 25, 1961
- “First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth.”
- Only 20 days after first U.S. manned space flight!

Before the Moon

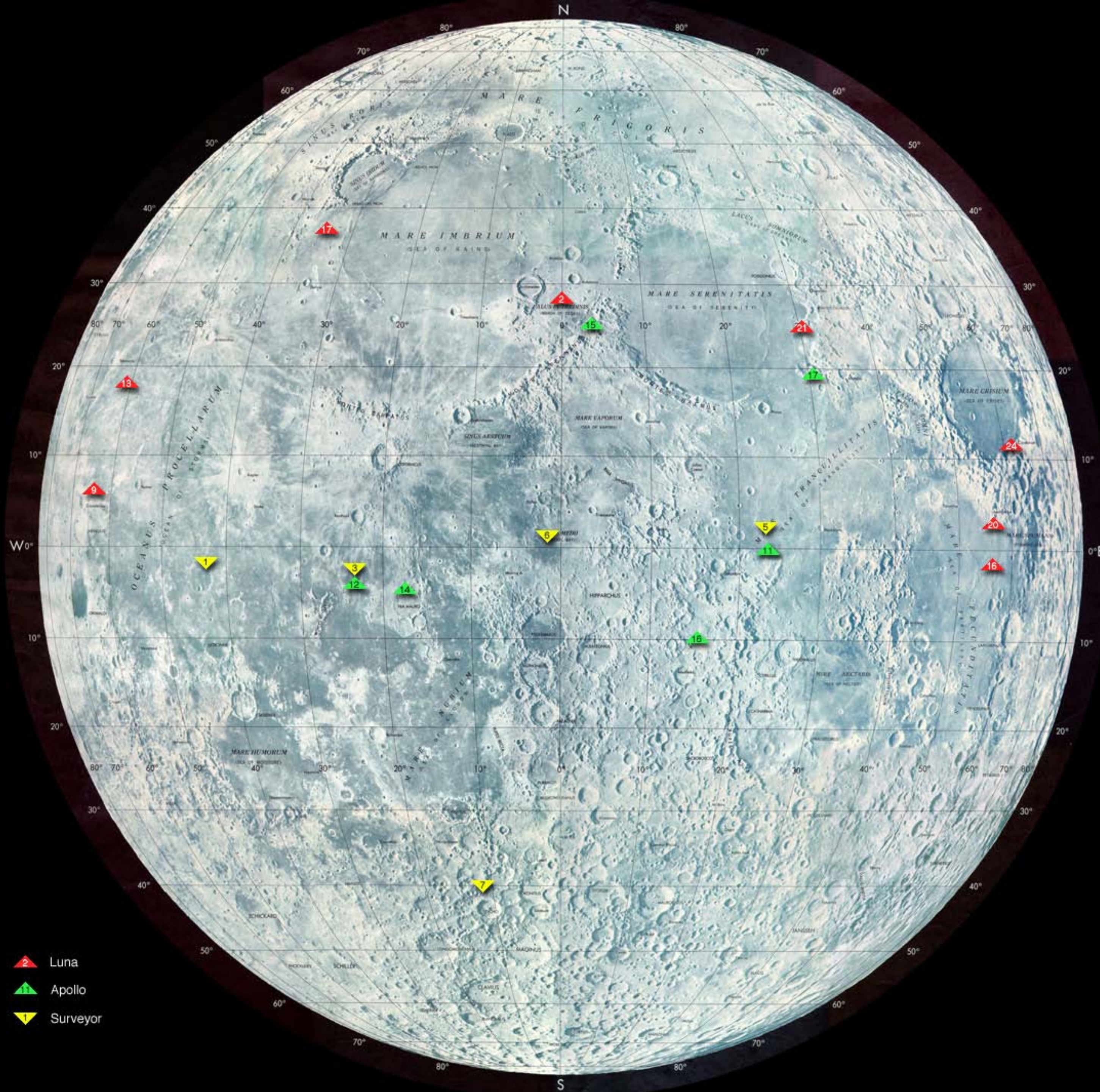
- Apollo 7 – Command module tests in low Earth orbit
- Apollo 8 – Command module to lunar orbit
- Apollo 9 – Lunar module tests in low Earth orbit
- Apollo 10 – Lunar module test in lunar orbit (down to ~ 9 miles above surface)


23

Apollo Landings

	Mission Commander	Lunar Module Pilot	Command Module Pilot	Launch	Landing Site
Apollo 11	Neil Armstrong	Buzz Aldrin	Michael Collins	07/16/69	Sea of Tranquility
Apollo 12	Pete Conrad	Alan Bean	Dick Gordon	11/14/69	Ocean of Storms
Apollo 13	Jim Lovell	Fred Haise	Jack Swigert	04/11/70	Fra Mauro*
Apollo 14	Al Shepard (first lunar golfer)	Ed Mitchell	Stu Roosa	01/31/71	Fra Mauro
Apollo 15	Dave Scott	Jim Irwin	Al Worden	07/26/71	Hadley-Apennine
Apollo 16	John Young	Charlie Duke	Tom Mattingly	04/16/72	Descartes Highlands
Apollo 17	Gene Cernan	Jack Schmitt	Ron Evans	12/07/72	Taurus-Littrow

*: Planned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MARE FRIGORIS
MARE IMBRIUM
(SEA OF RAINS)
MARE SERENITATIS
(SEA OF SERENITY)
MARE CRISIUM
MARE VAPORUM
SINUS AESTUUM
OCEANUS PROCELLARUM
MARE TRANQUILLITATIS
MARE NECTARIS
MARE HUMORUM
MARE NUBIUM
HIPPARCHUS
17
2
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16
7
Luna
Apollo
Surveyor

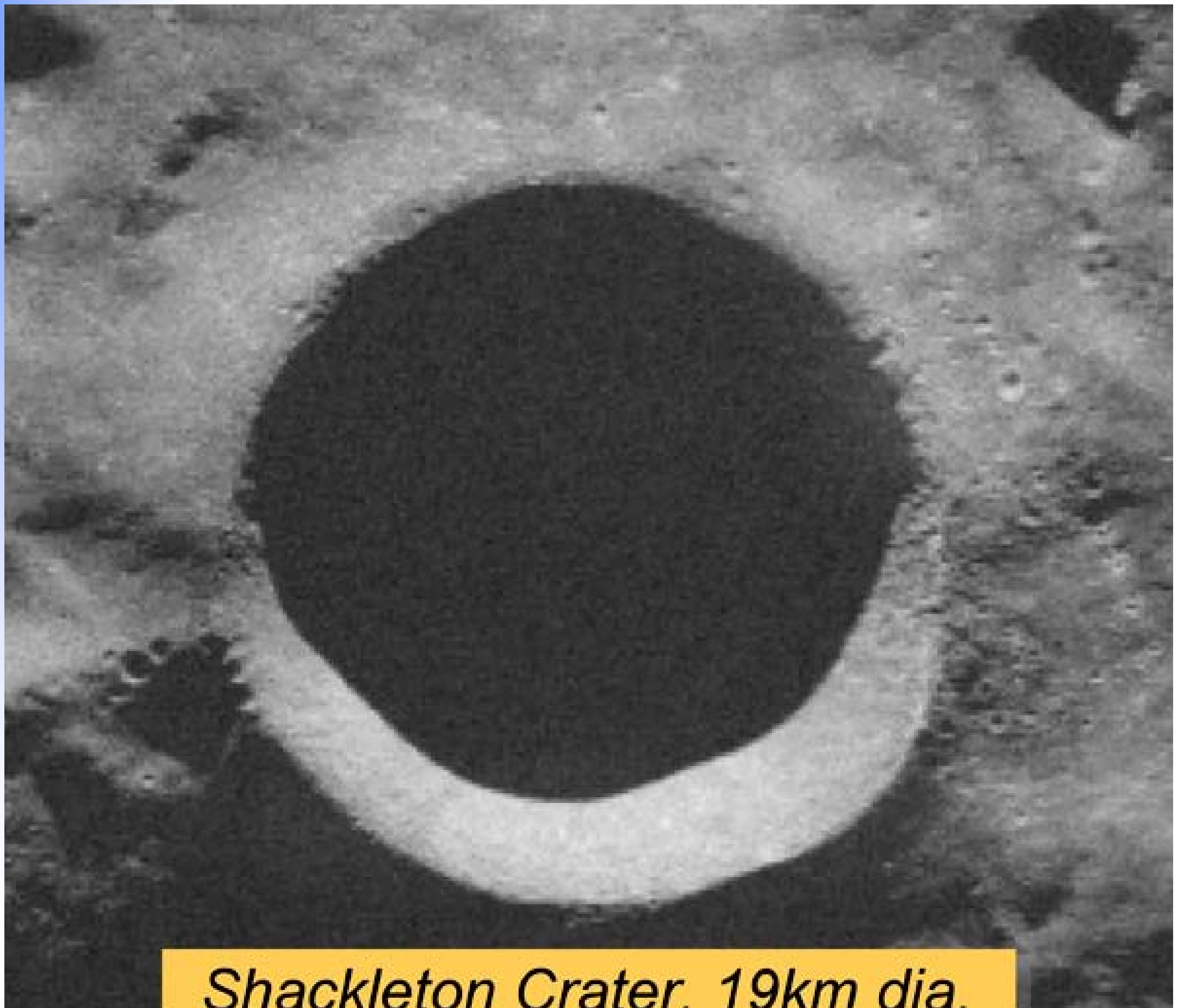
Vision for Space Exploration

"With the experience and knowledge gained on the moon, we will then be ready to take the next steps of space exploration: human missions to Mars and to worlds beyond."

- President George W. Bush

(January 14, 2004)

Possible Outpost Site



Shackleton Crater, 19km dia.
(lunar South Pole)
2005 Arecibo radar image

Why the South Pole?

- Safe
  - Thermally moderate
- Cost Effective
  - High % of sunlight
  - Allows the use of solar power
- Resources
  - Enhanced hydrogen (possibly H_2O)
  - Potentially other volatiles
  - Oxygen
- Flexibility
  - Allows incremental buildup using solar power
  - Enhanced surface daylight
  - More opportunities to launch
- Exciting
  - Not as well known as other areas
  - Offer unique, cold, dark craters

Words of Wisdom

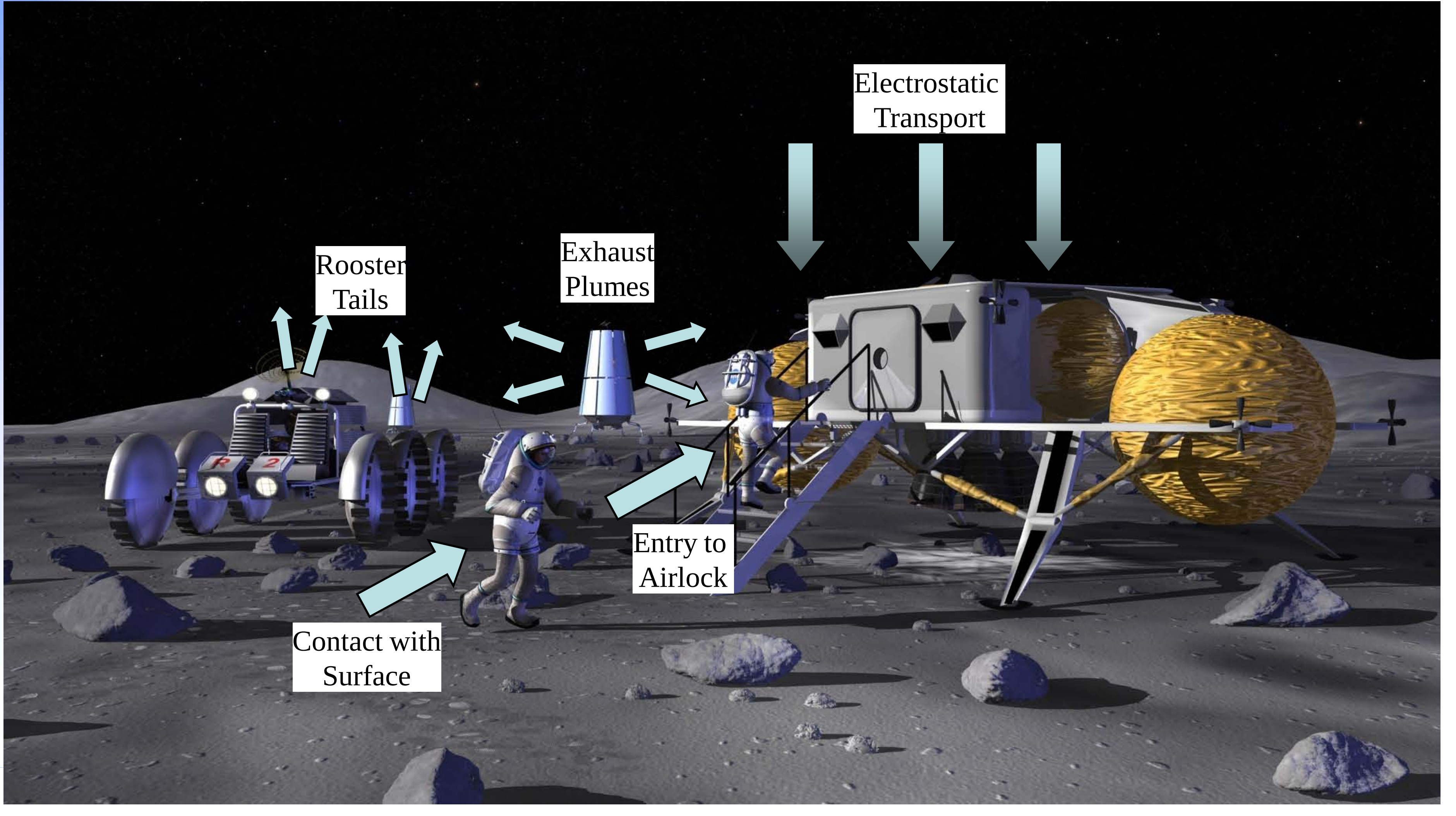
"I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust."

Gene Cernan
Apollo 17 Technical Debrief

Lunar EVA Suits

Jack Schmitt
(Apollo 17)

Dust Exposure Possibilities



J. Feighery

Problems Caused by Dust

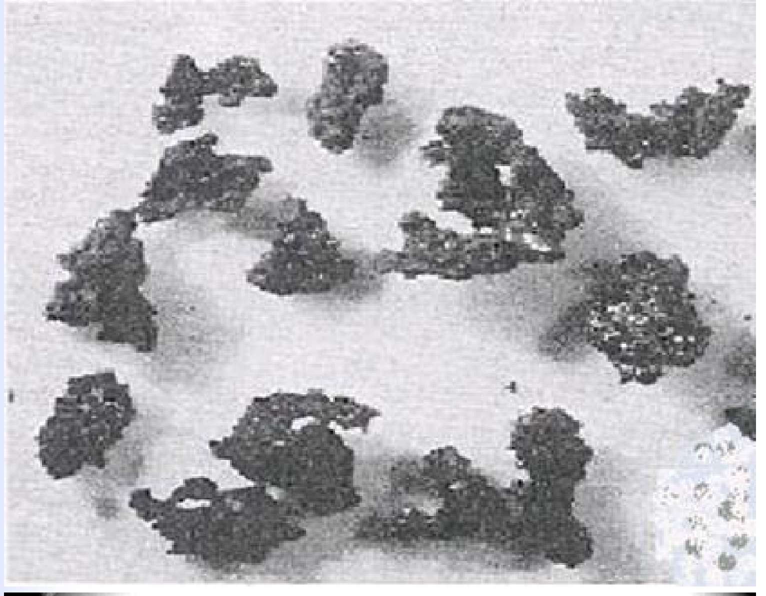
- Obscured vision
  - Apollo 15: vision completely obscured below 60 ft when landing
- Clogged equipment
  - Apollo 12: wrist and suit hose locks clogged with dust
- Coated surfaces
  - Apollo 11: T.V. cable caused tripping after dust covering
- Inhalation
  - Apollo 15: gunpowder smell
  - Apollo 17: “hay fever” symptoms
- Degraded radiators
  - Apollo 16: degraded instrument performance from overheating
- Fooled instruments
- Caused seal failure
  - Apollo 14: measurable leaking of suits
- Abraded surfaces
  - Apollo 16: gauge dials unreadable from scratching

What is lunar dust?

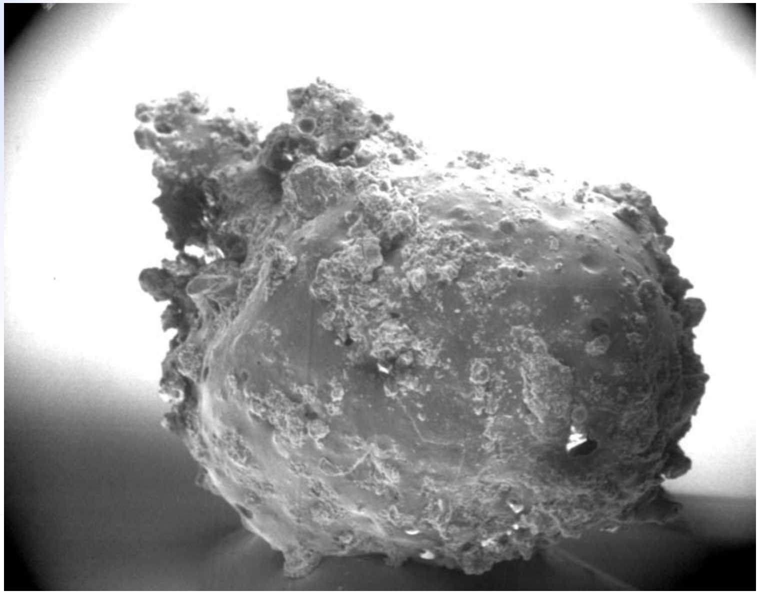
- Lunar soil is defined as the loose fragmental material with a grain size smaller than 1 cm on and near the surface of the moon. It is a subset of the lunar regolith which includes all size fragments including boulders.

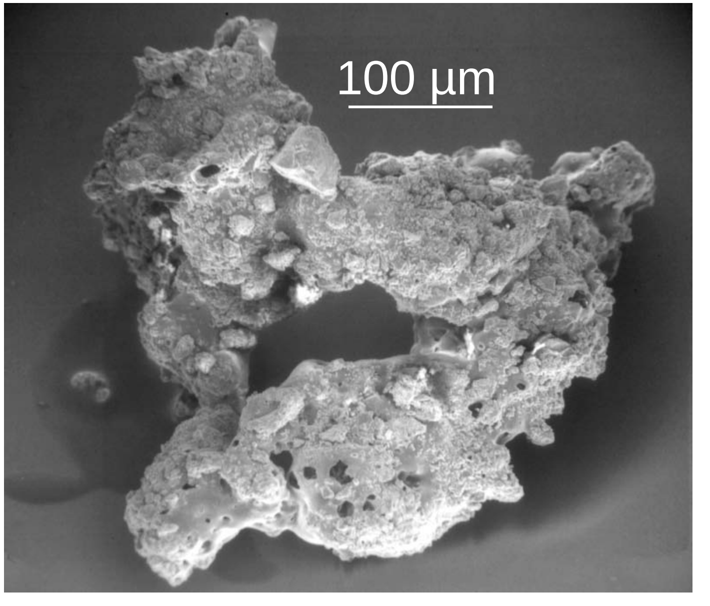
- Lunar dust is the finest size fraction of lunar soil. A working definition of lunar dust is that it is all grains smaller than 20 µm.

Lunar Dust



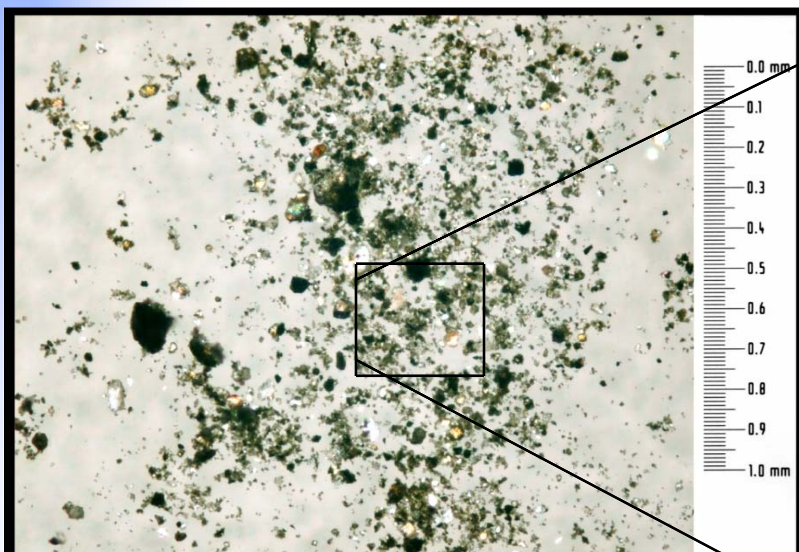
- Contains SiO_2, other oxides, and trace metals
- Magnetic
- Particles are oddly shaped, with jagged edges, and do not pack together well



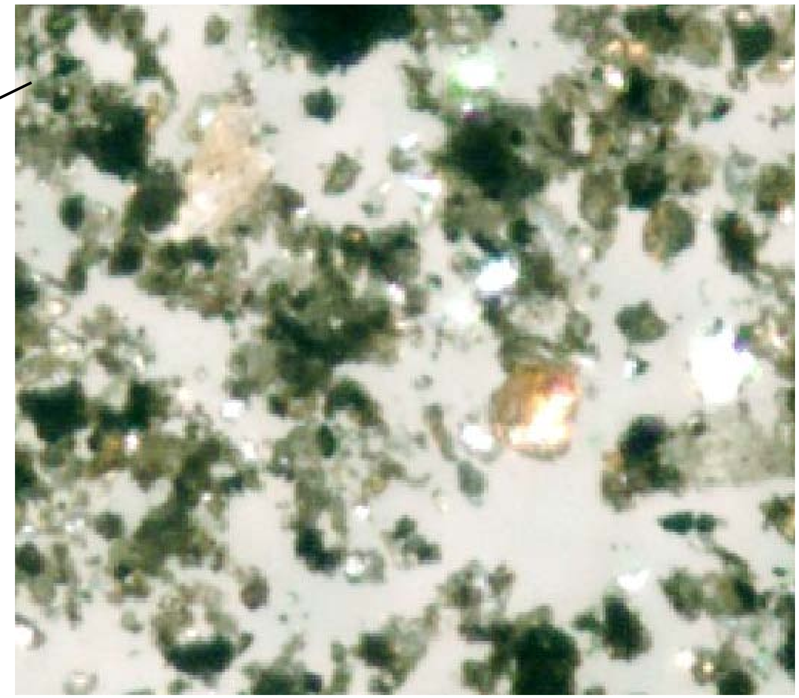


Dave McKay, JSC

Bulk Apollo 11 Soil

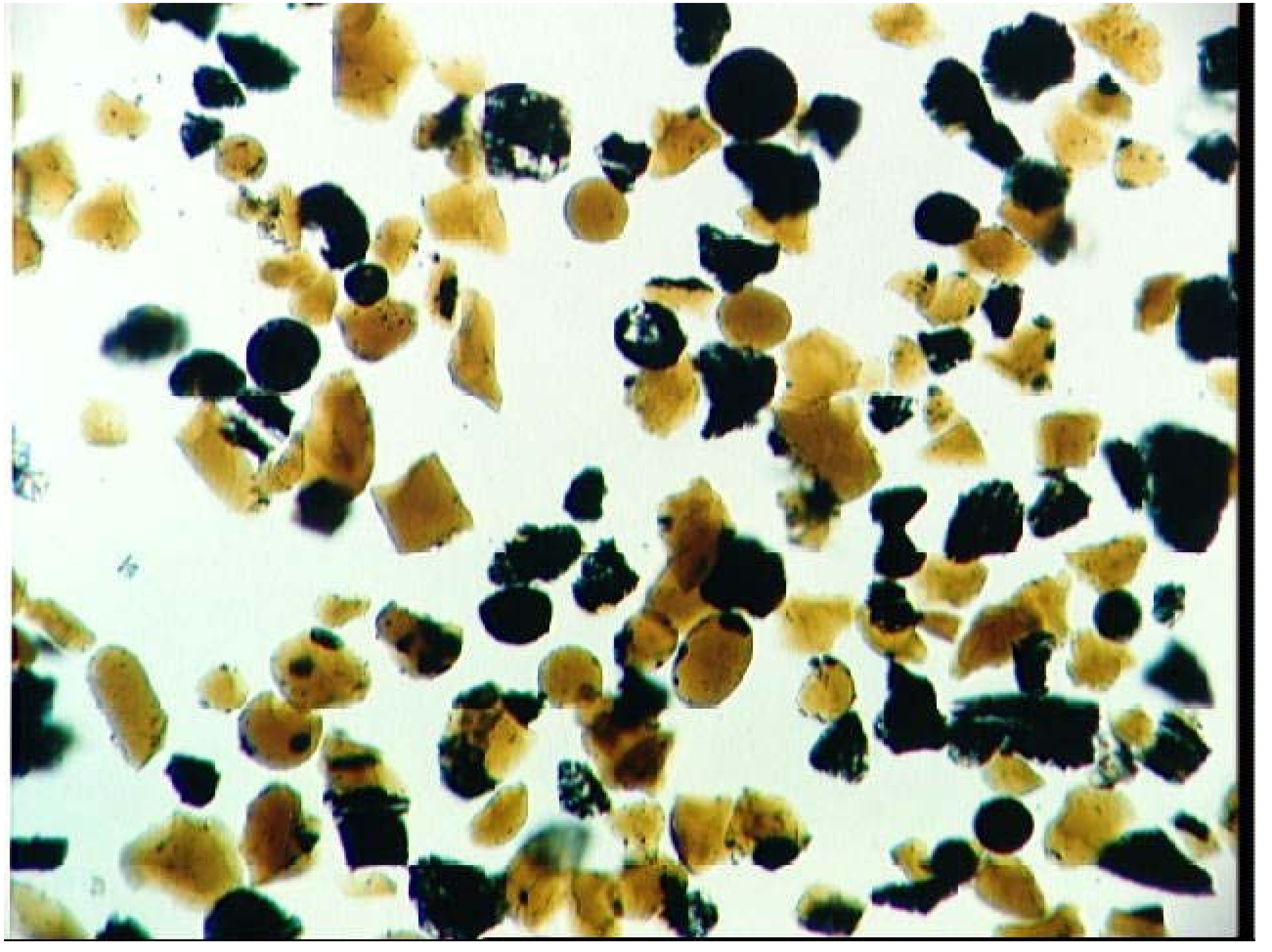


Bulk Soil (10084,1593)



20 µm

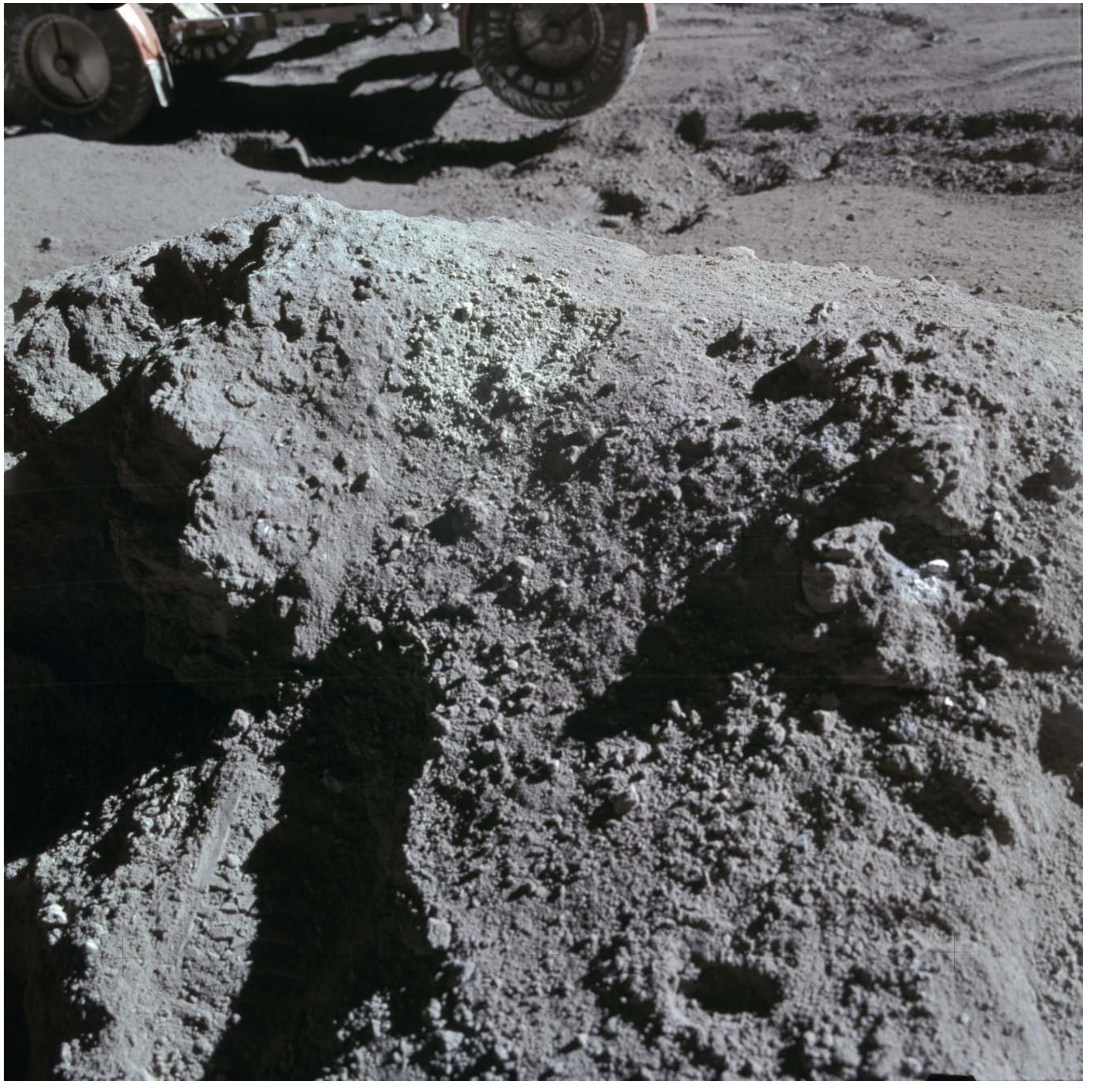
Orange Soil



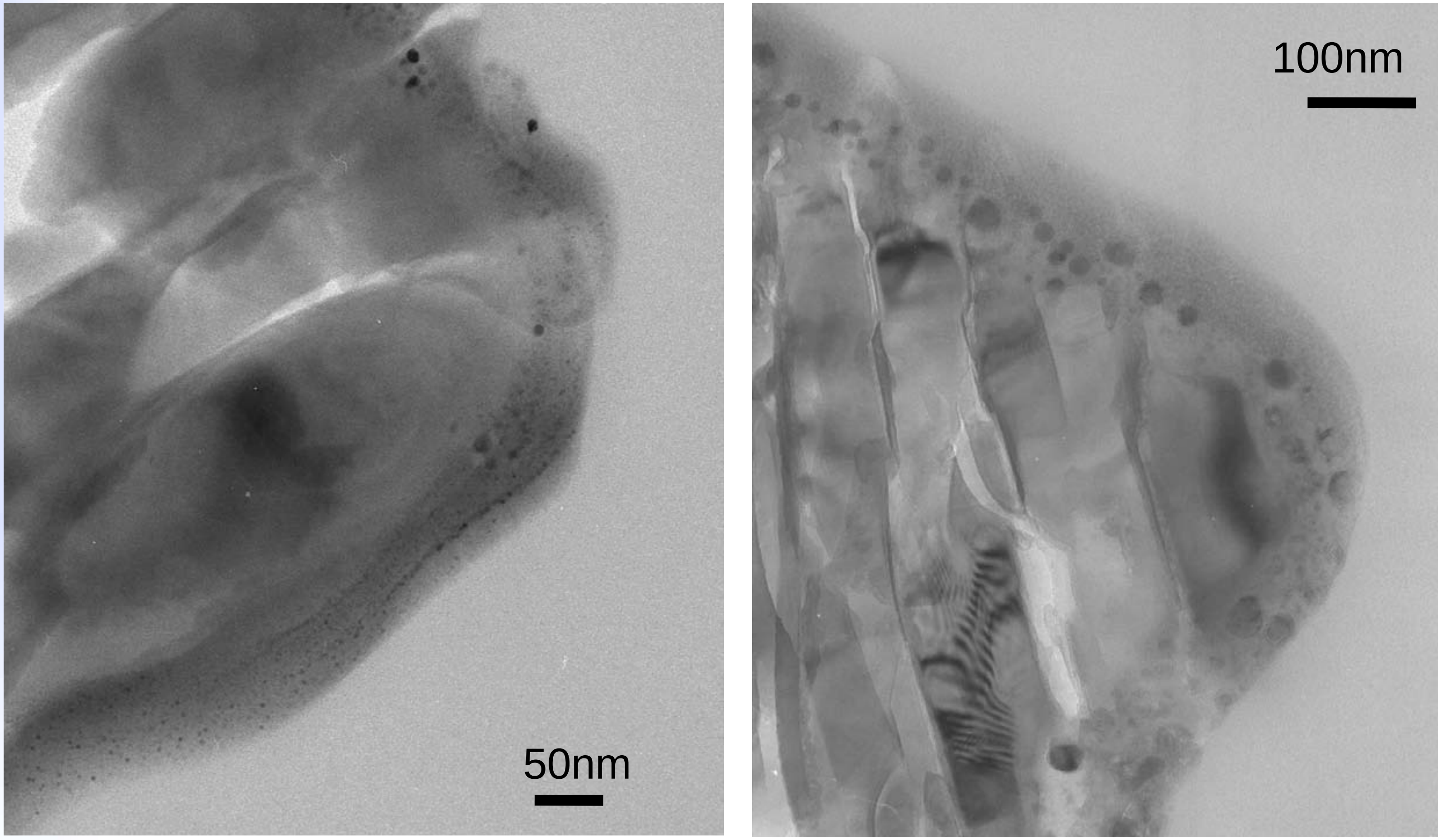
- From Taurus-Littrow (Apollo 17)
- 25-45 µm
- Produced by volcanic eruption of pyroclastic ash

Green Soil

- Apollo 15
- Formed from same type of process as Apollo 17 orange soil

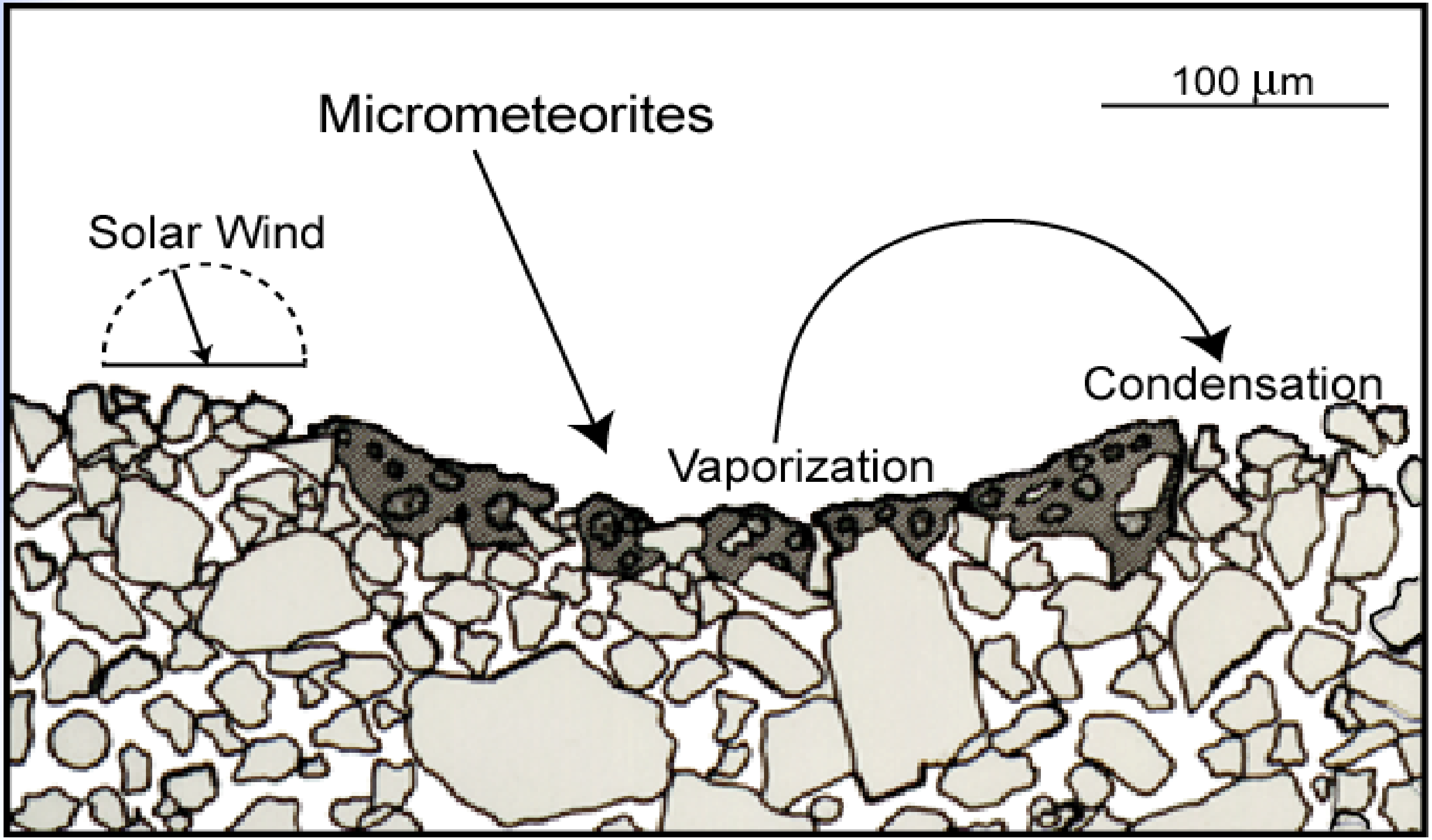


Lunar Dust Rims



Glassy rims produced by vapor/sputter deposition. Also contain ~ 10 nm Fe nanoparticles

Lunar Soil Formation



Lunar soil is formed by a combination of comminution (breaking down), agglutination (clumping together), and vapor deposition.

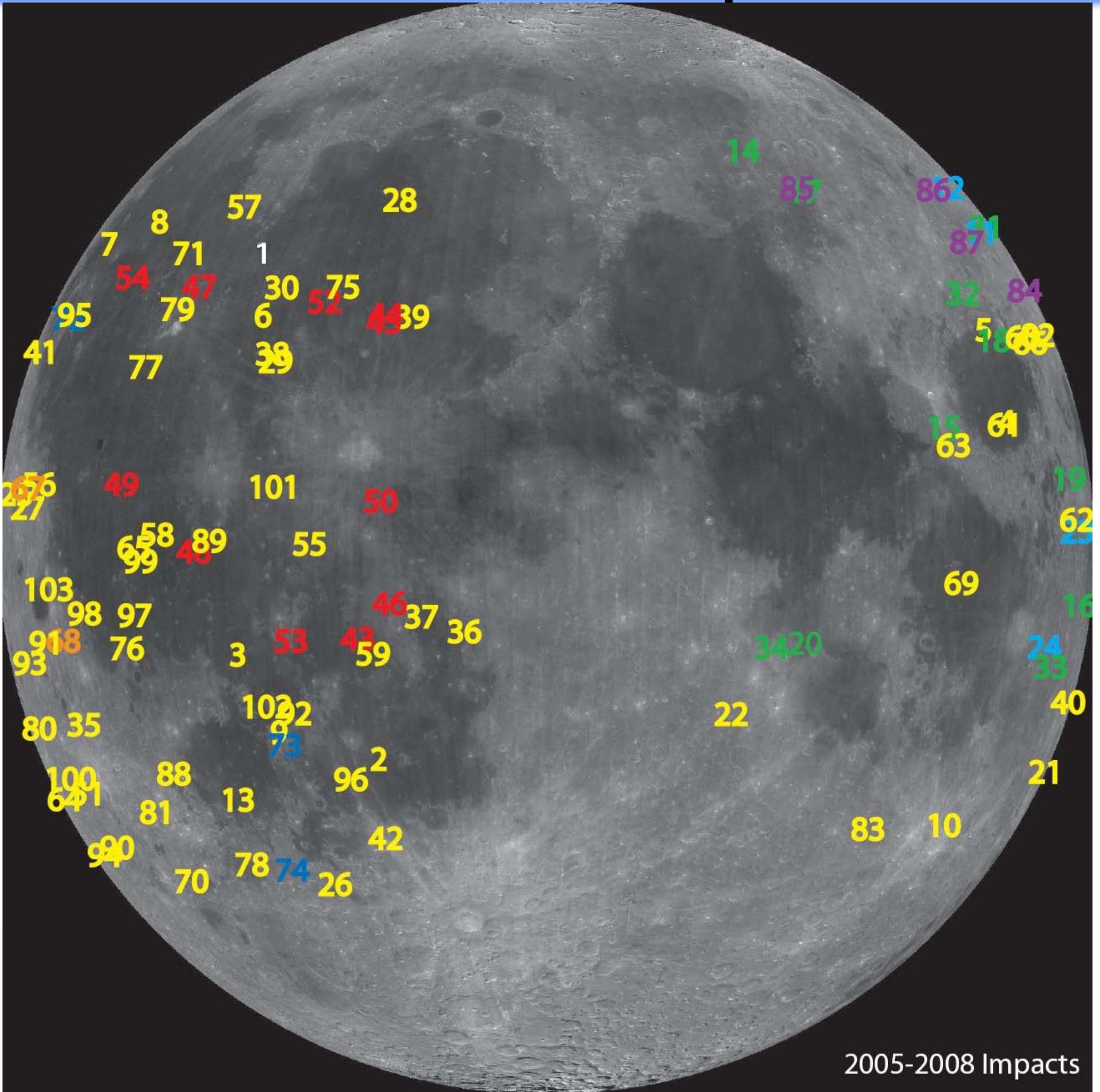
Larry Taylor, U. Tennessee

Meteorite Impact on the Moon

- 25 cm diameter meteorite traveling at 85,000 mph
- Kinetic energy of impact: 17 billion joules (equivalent to 4 tons of TNT)
- New crater: 14 meters wide by 3 meters deep
- Flash only 0.4 seconds in real-time

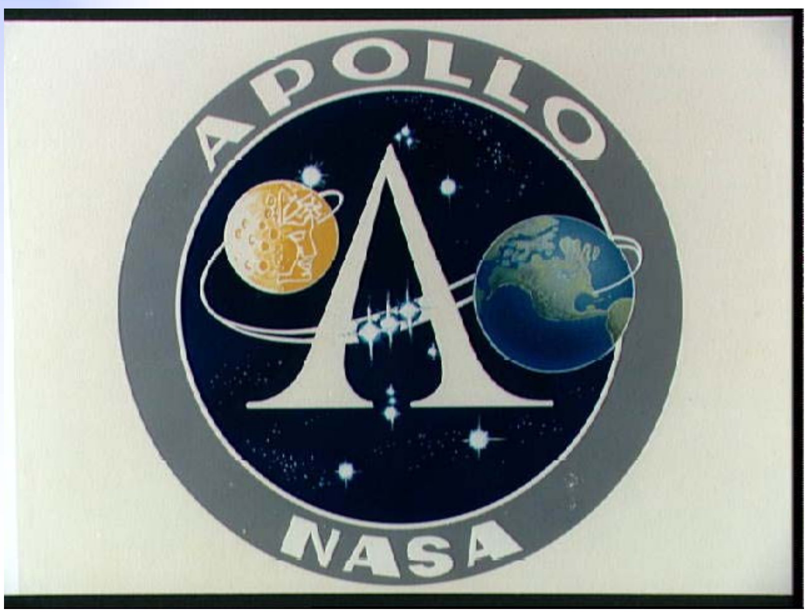
http://science.nasa.gov/headlines/y2006/13jun_lunarsporadic.htm

Recent Impacts



Further Info on Apollo

- http://www.hq.nasa.gov/alsj/main.html (Apollo Lunar Surface Journal)



Lunar Dust Simulant

Only 842 lbs of material returned from the moon! Simulant material needed for preliminary studies.

- JSC-1A-vf
- Made from volcanic ash
- 50% silicon-containing minerals
- 42-45% other oxides (Al_2O_3, FeO, MgO, CaO)
- No trace metals
- Size distribution of particles similar to samples of lunar dust
- 90% smaller than 13 µm diameter

Materials Used

Sample	SiO_2	Al_2O_3	TiO_2	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
JSC-1A-vf, % oxides	48.77	15.65	1.49	8.88 (+ 1.71% Fe_2O_3)	0.19	8.48	10.44	2.93	0.81	0.66
Apollo 16 Soil (62241), % oxides	44.65	27	0.56	5.49	0.7	5.84	15.95	0.44	0.13	0.1
Min-U-Sil Quartz, %	99.0-99.9	< 0.8	< 0.1	< 0.1 (Fe_2O_3)	0	0	0	0	0	0

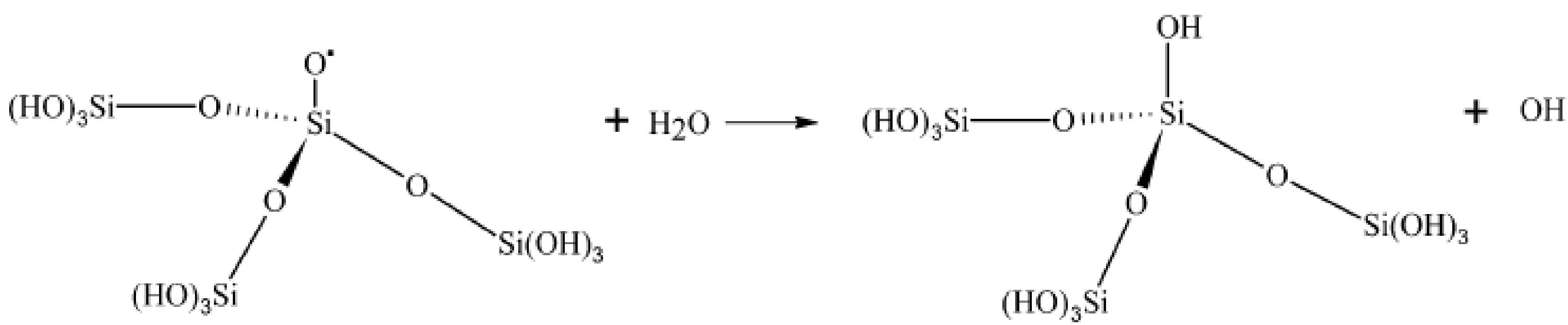
D.S. McKay, *et al.*, *LPSC XXIV* (1993) 963-964.
H.J. Rose, Jr., *et al.*, *Proc. 4th LSC* **2** (1973) 1149-1158.

Lunar Dust Activation

- Constant activation of lunar dust by meteorites, UV radiation, and elements of solar wind
- No passivating atmosphere
- Active dust could produce reactive species in the lungs
  - Freshly fractured quartz
- Must determine methods of deactivation before new lunar missions
- First, must understand how to *reactivate* dust on Earth

What Does “Activated” Mean?

- Presence of reactive sites on surface
  - Free radicals
- Ability to produce reactive species in solution

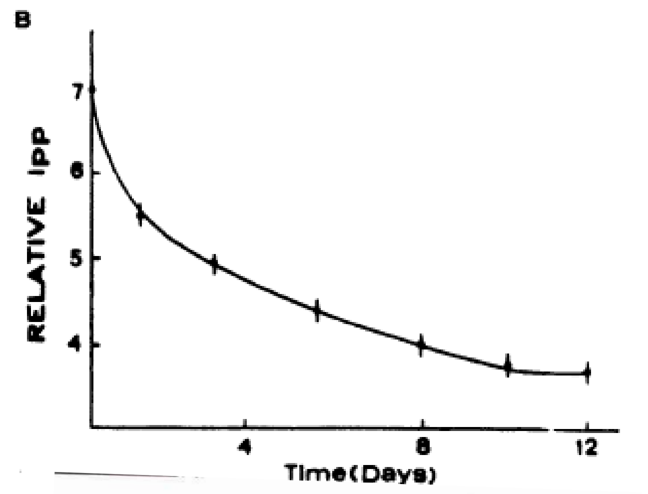


Reaction 5

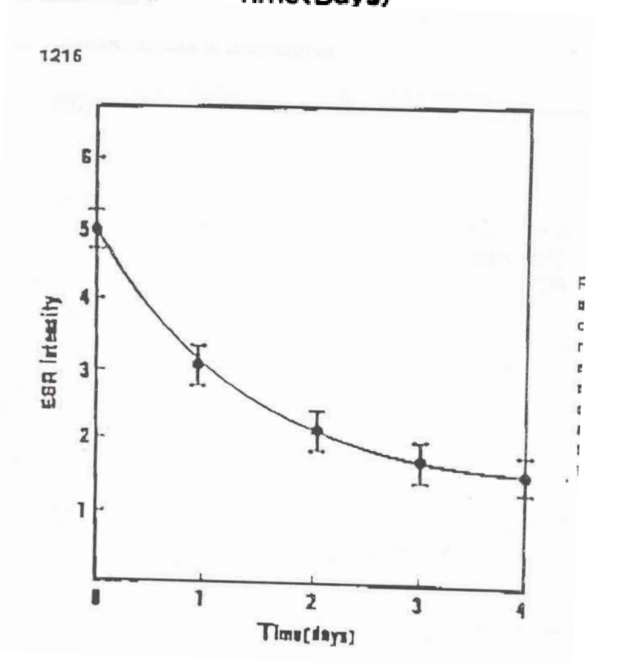
J. Narayanasamy and J.D. Kubicki, *J. Phys. Chem. B* **109** (2005) 21796-21807

Previous Studies of Quartz Activation

- Grinding quartz gives electron paramagnetic resonance (EPR) signal characteristic of Si· or Si-O· radicals
- Increased grinding time produces higher signal
- Decrease in Si-based radicals over time in air
    - Half-life of ~30 hours, with 20% of signal detectable even after 4 weeks



- Ground quartz in aqueous solution produces OH radicals
- Radical production decreases with exposure to air
    - Half life of ~ 20 hours



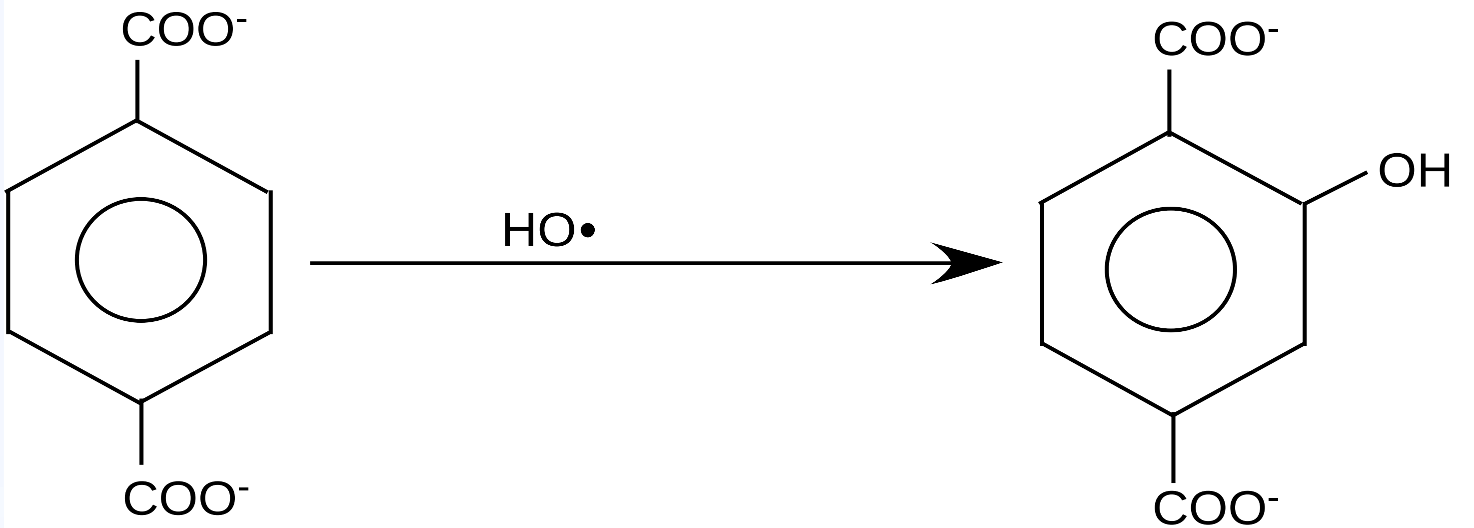
V. Castranova, *Environ. Health Perspect*. **102** (1994) 65-68.
V. Vallyathan *et al*., *Am. Rev. Respir. Dis*. **138** (1998) 1213-1219

Activation Methods Tested

- Crushing/Grinding
  - Mortar and pestle
  - Ball Mill
- UV activation

Fluorescence

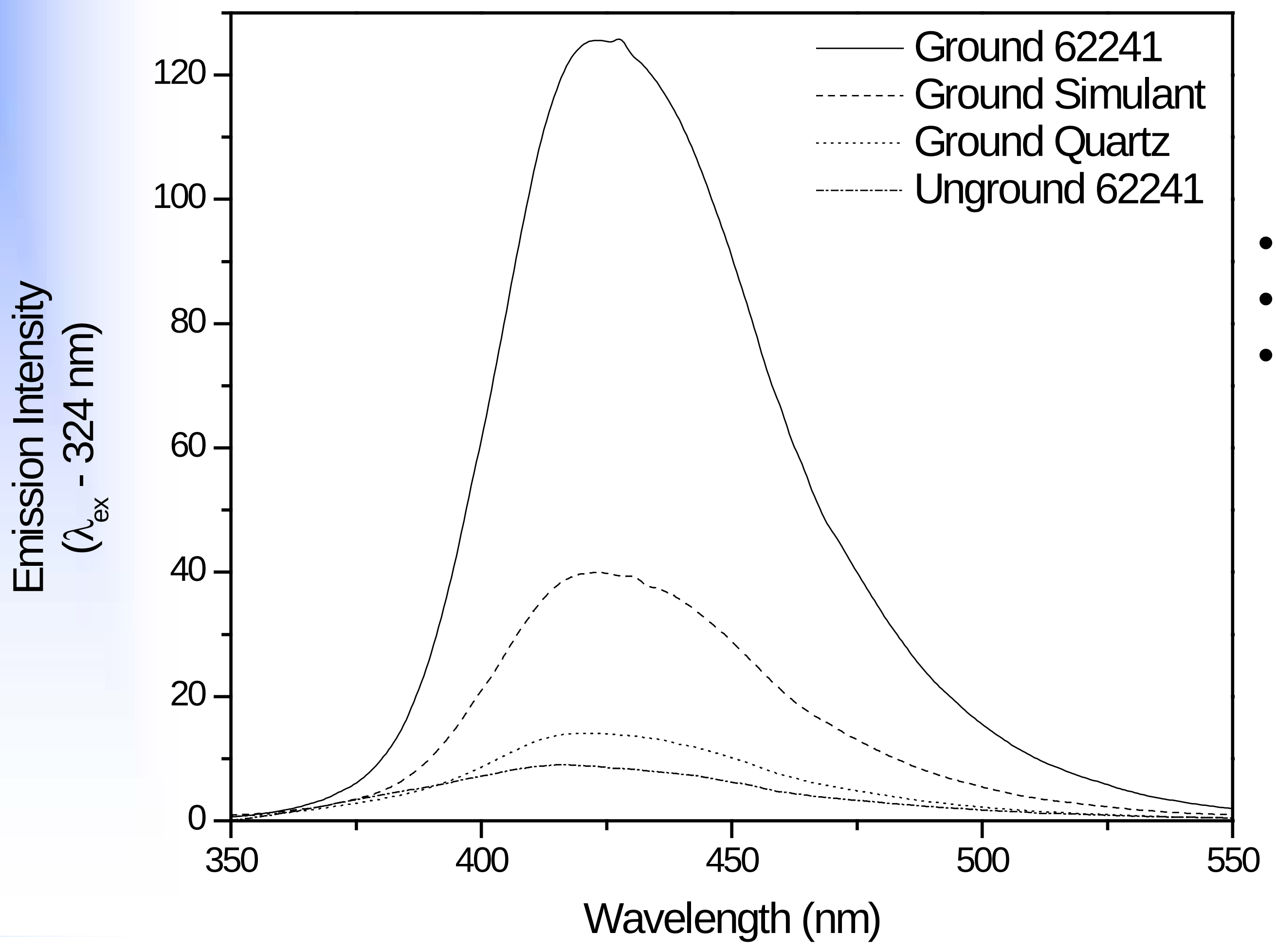
Hydroxyterephthalate as a Probe of Hydroxyl Radical Generation



Terephthalate
(non-fluorescent)

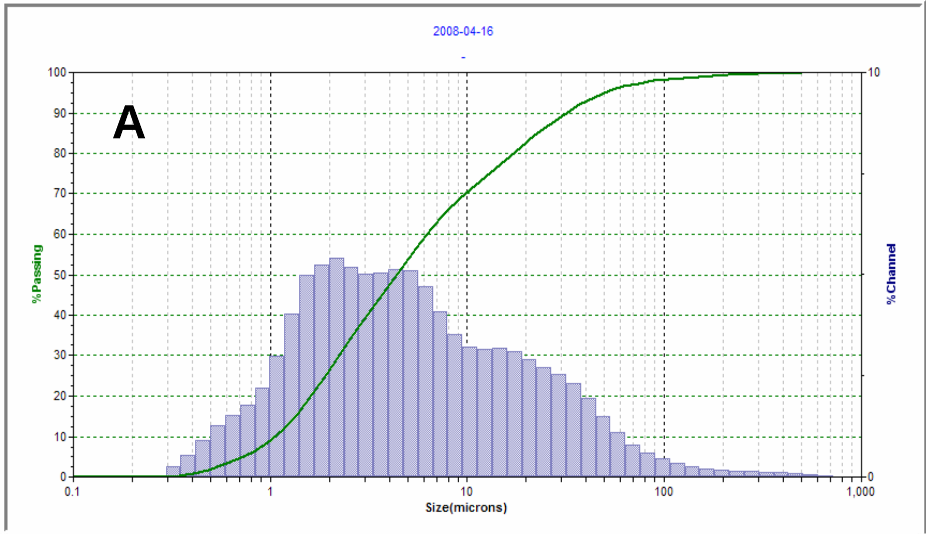
2-Hydroxyterephthalate
(fluorescent)

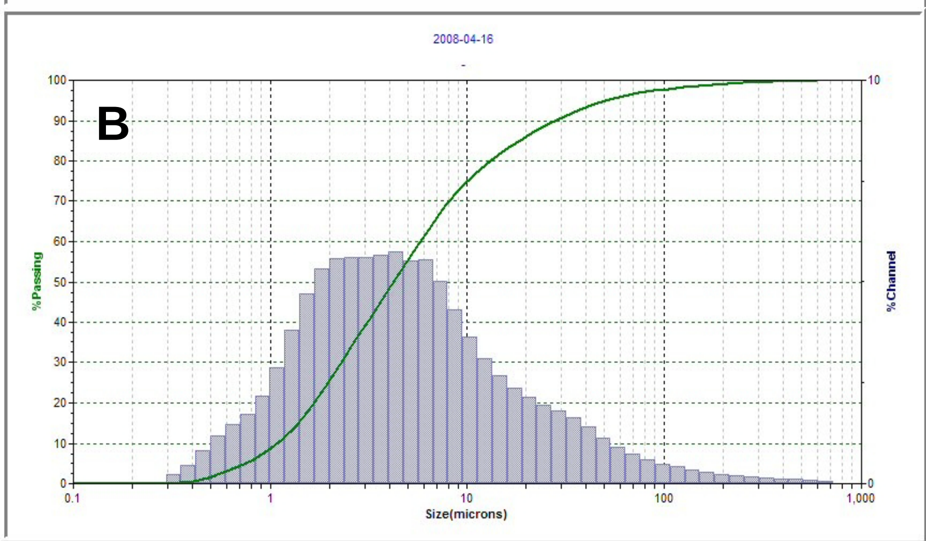
Activity Comparison of Ground Lunar Soil, Lunar Simulant, and Quartz

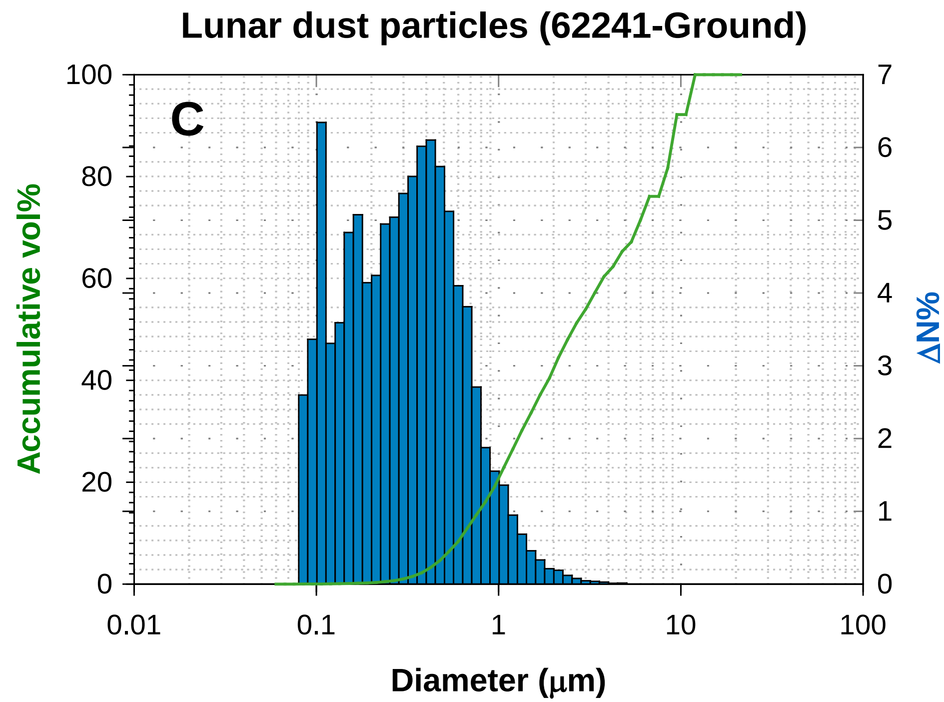


- 10 minute grinding
- 3.8 mg/mL JSC-1A-vf
- 10 mM Terephthalate

Size Distribution and Surface Area after Grinding







A: Min-U-Sil 15- 8.436 m^2/g
(unground- 3.7 m^2/g)

B: JSC-1A-vf- 5.369 m^2/g
(unground- 3.5 m^2/g)

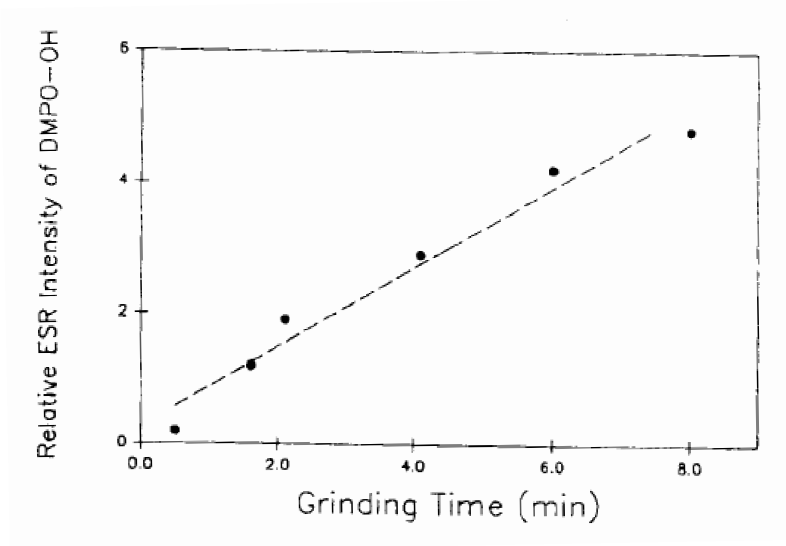
C: 62241 (Apollo 16)- 8.404 m^2/g
(unground- 1.6 m^2/g)

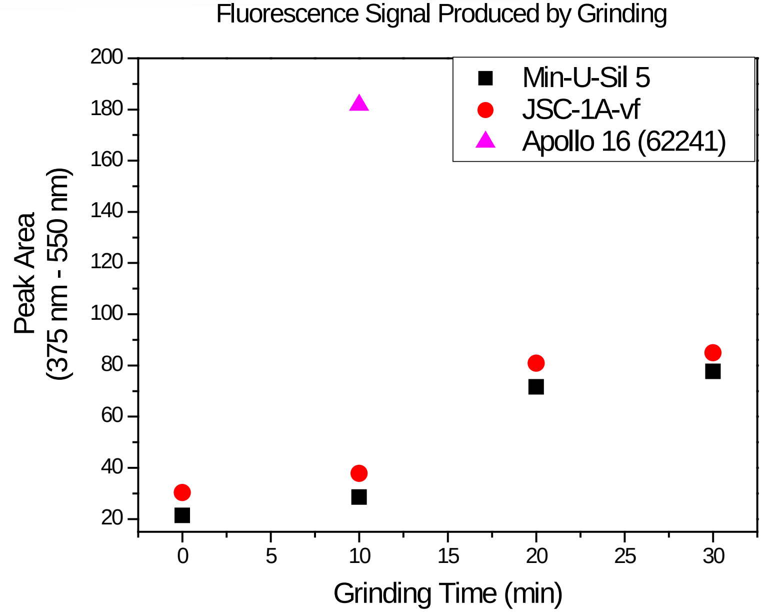
Effect of Grinding Time

• Grinding time has a direct effect on amount of hydroxyl radicals produced upon addition of ground quartz to solution

• Grinding time also shown to produce higher number of silicon-based radicals in ESR spectra

• Increase in hydroxyl production also seen for lunar simulant with increased grinding

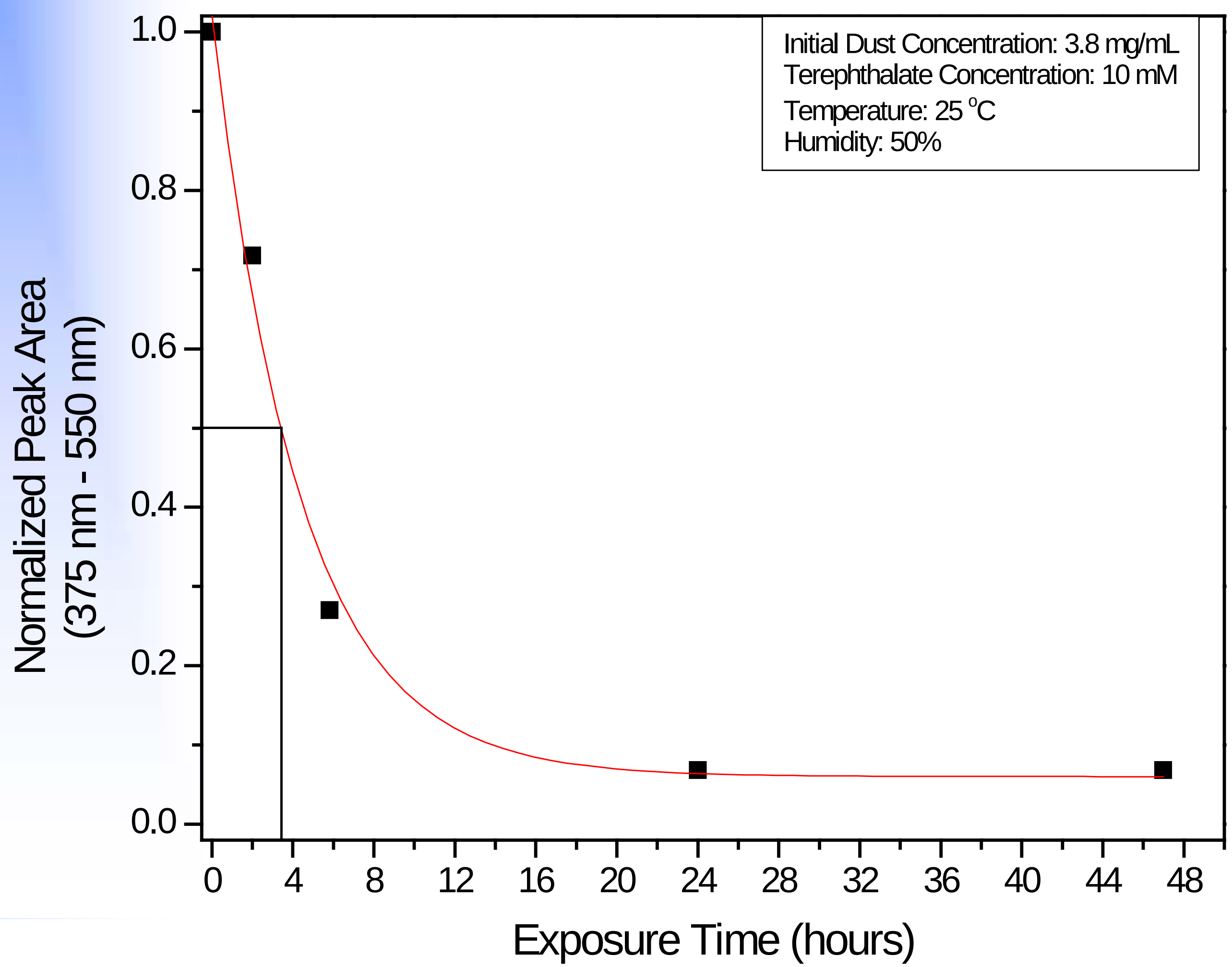




N.S. Dalal, X. Shi, and V. Vallyathan, *Free Rad. Res. Comms.* **9** (1990) 259-266.

Deactivation after Grinding

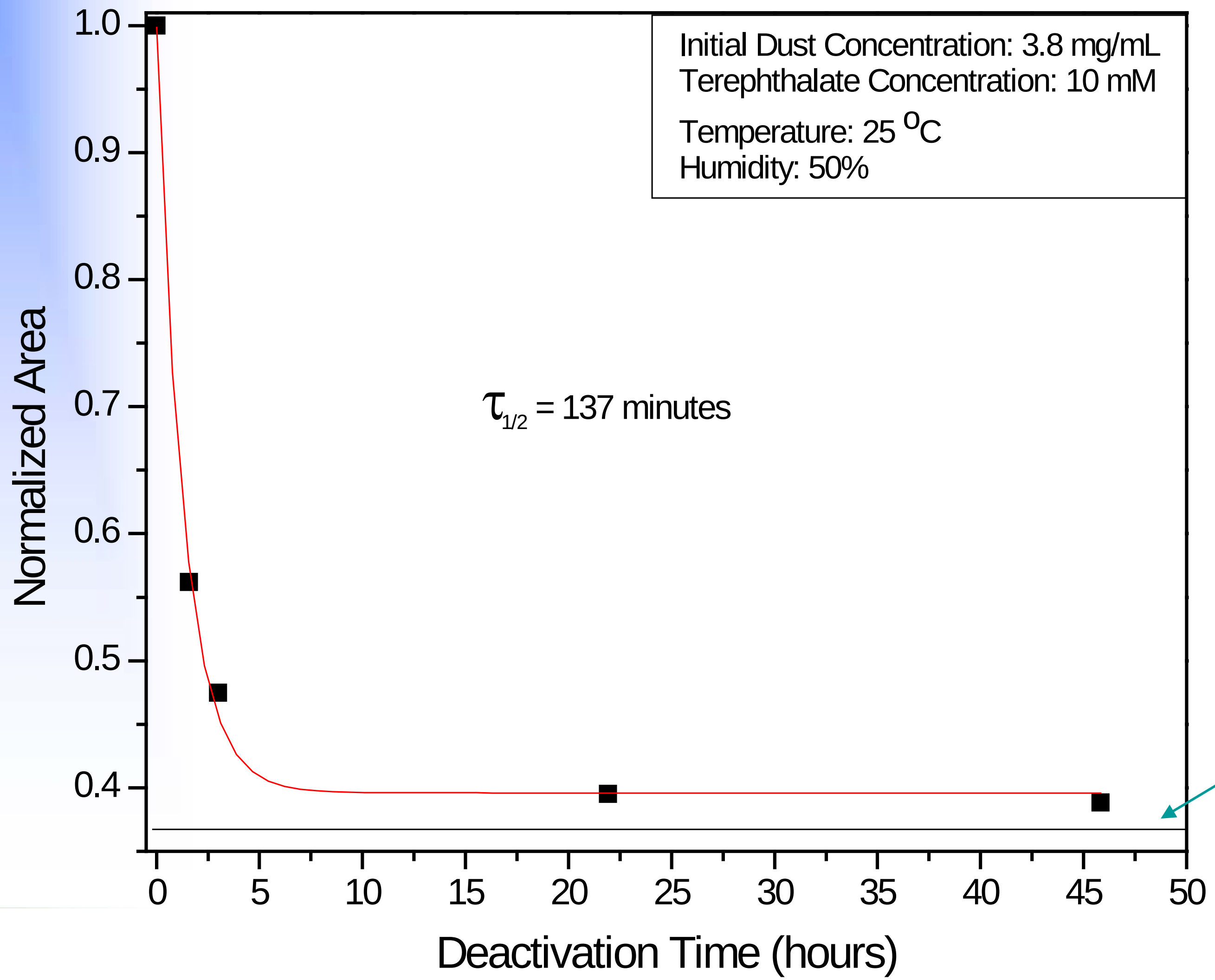
Deactivation of Freshly Ground Lunar Simulant (JSC-1A-vf)



- Activity of freshly ground simulant can be reduced by exposure to humid environment.

- Multiple sets of deactivation experiments show simulant half life to be ~ 3 hours with activity approaching unground levels at ~ 24 hours.

Deactivation of Freshly Ground Quartz

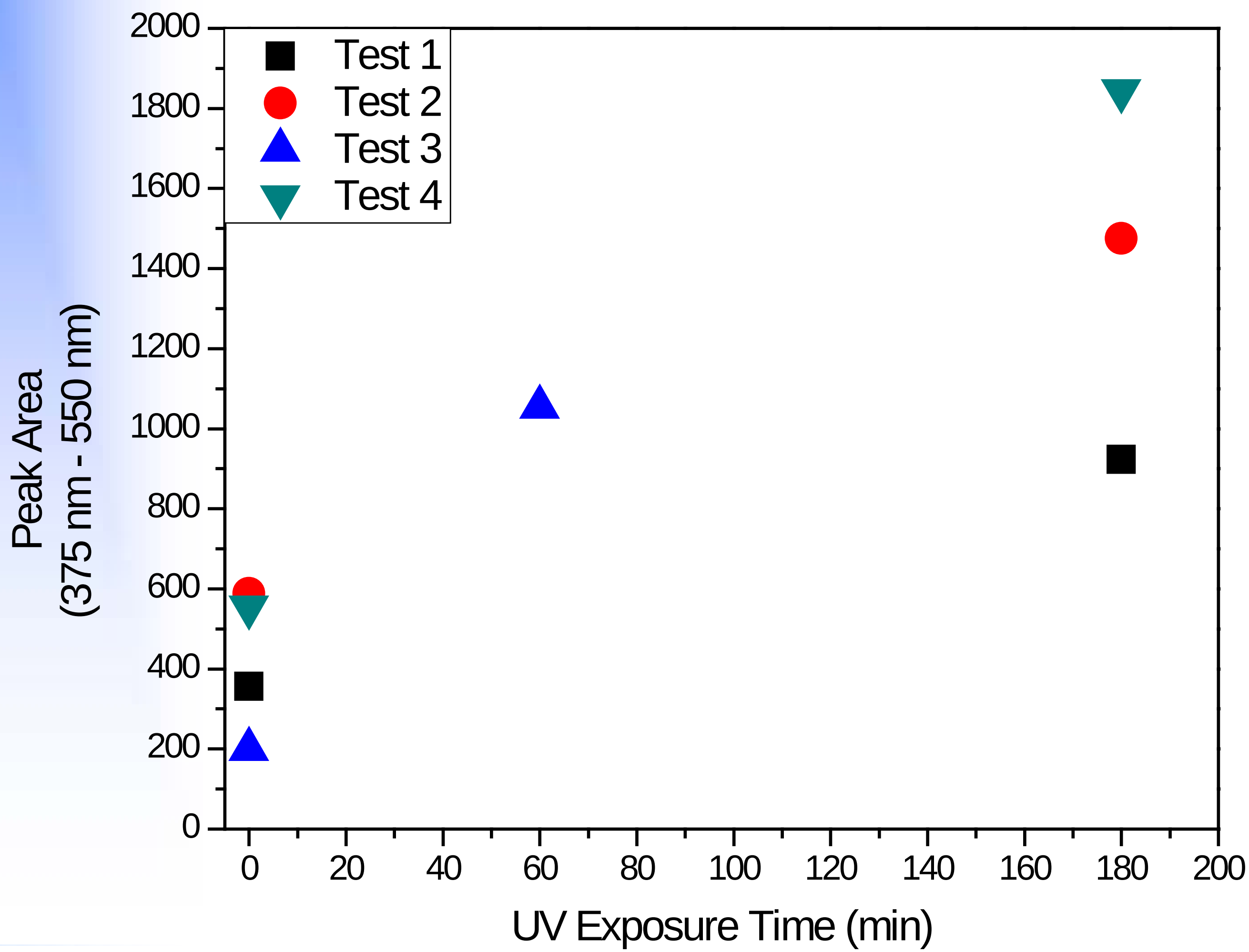


Much faster deactivation of quartz, especially with respect to approach of unground activity.

Activity of unground quartz (close to zero intensity; normalized to freshly ground)

Activation by UV Exposure and Heating

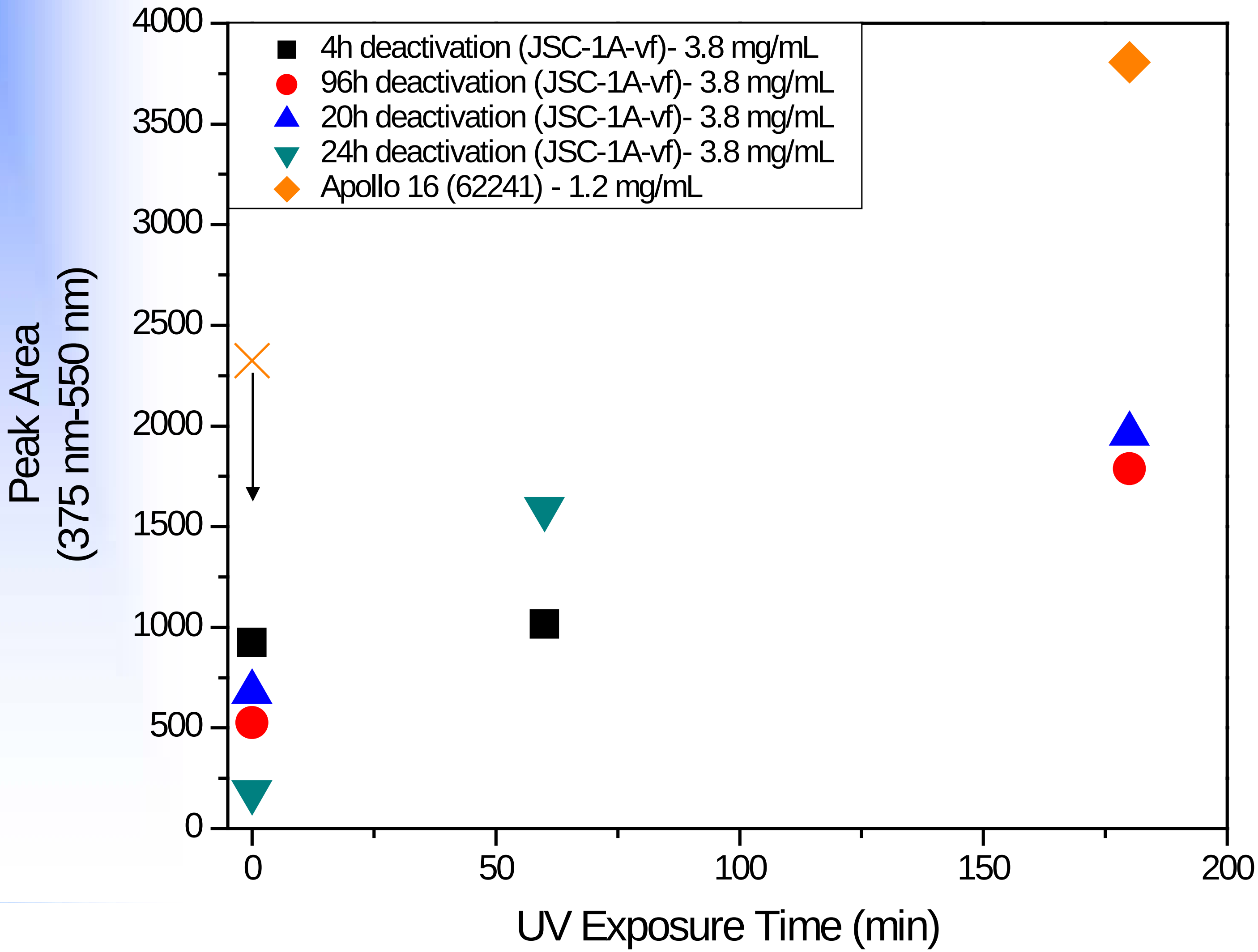
UV Activation of Unground Lunar Simulant



- 3.8 mg/mL JSC-1A-vf
- 10 mM Terephthalate
- 800 W UV (initial setting)
- ~ 5 X 10^{-4} Torr

Exposure of unground simulant to UV radiation under vacuum leads to the production of hydroxyl radicals by the simulant when placed in solution.

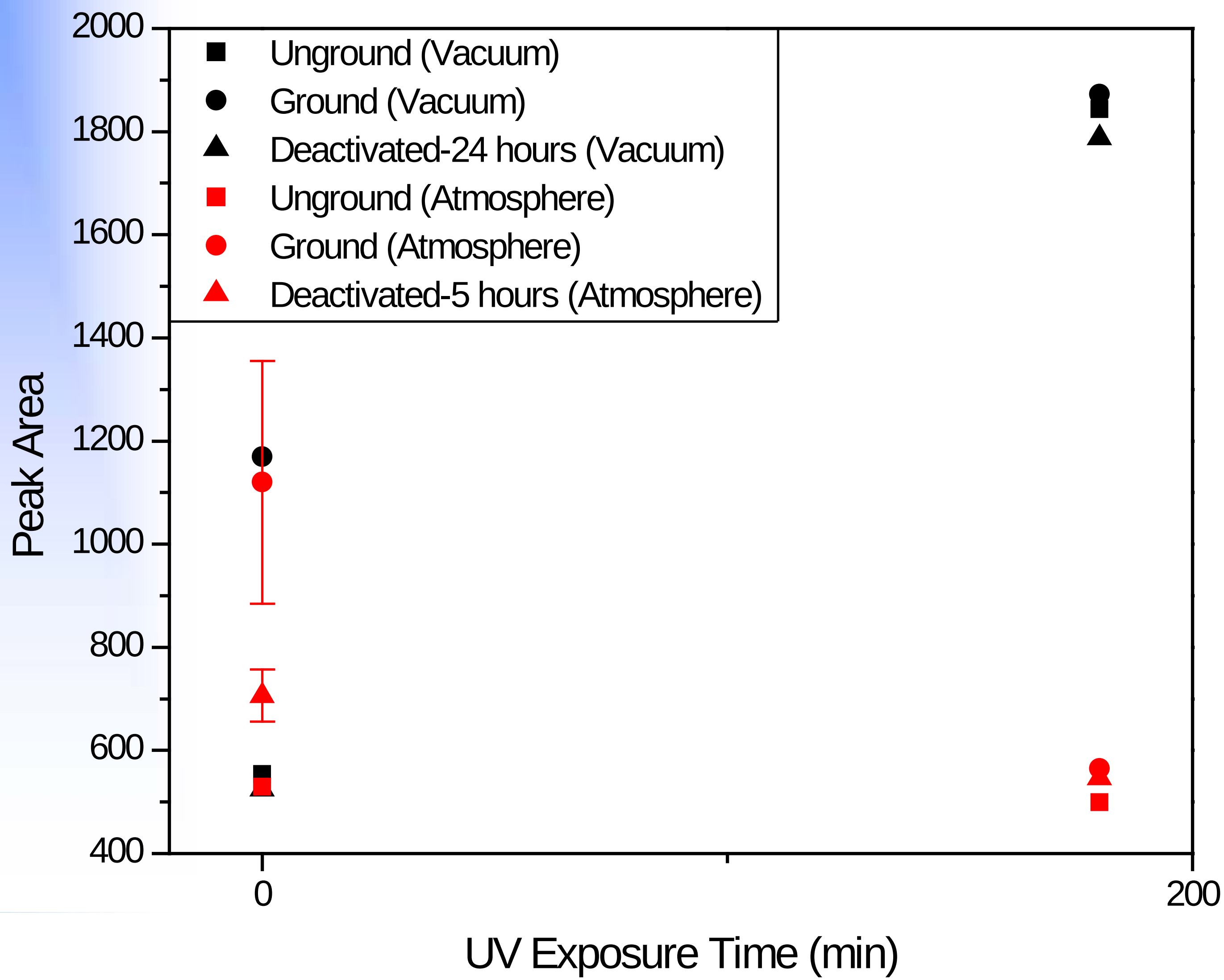
UV Reactivation of Ground, Deactivated Lunar Dust and Simulant



Final deactivation point from initial lunar dust testing (> 1 month further deactivation; upper limit for activity)

Deactivated (50% RH, 25 °C) lunar simulant and lunar dust can be reactivated by exposure to UV radiation under vacuum.

Effects of Vacuum on UV Activation/Deactivation of Lunar Simulant



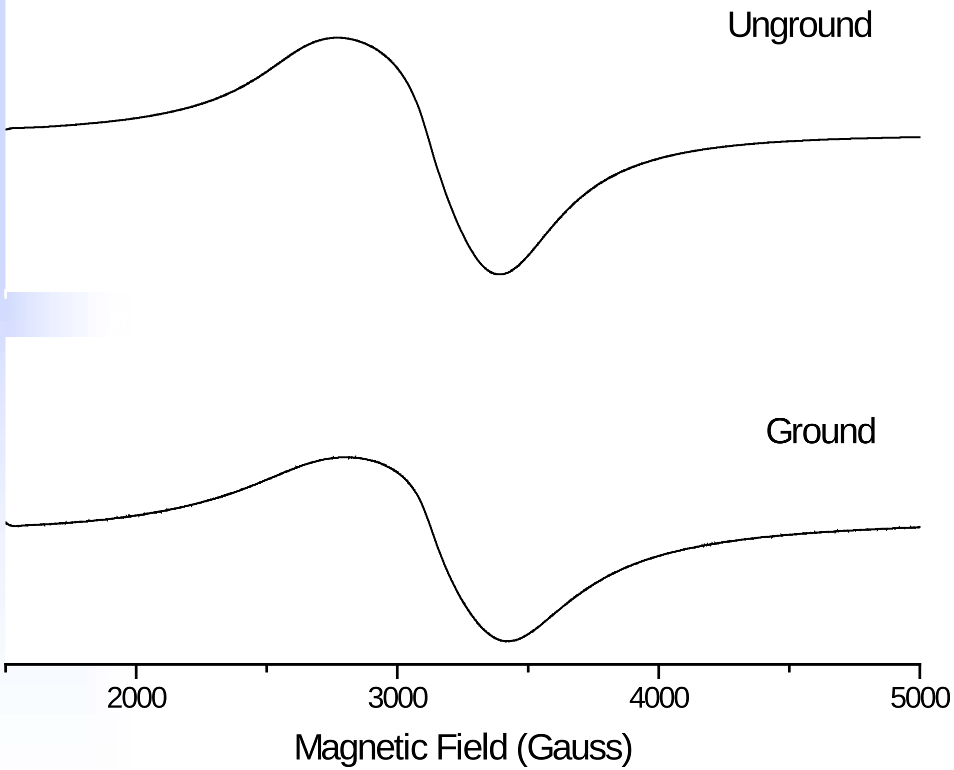
- 3.8 mg/mL
- 10 mM Terephthalate
- 800 W UV (initial setting)

- Error bars for deactivated and ground simulant account for activities prior to and at conclusion of UV exposure.

Exposure of active simulant to UV in air leads to deactivation!

EPR

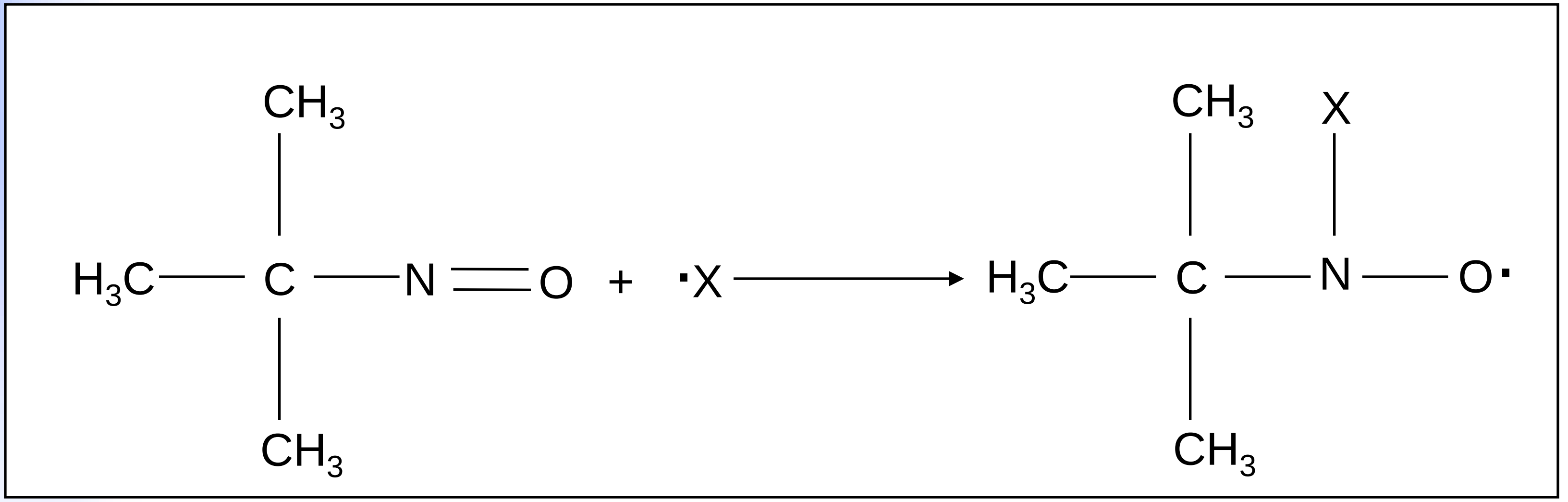
EPR Spectra of Apollo 62241



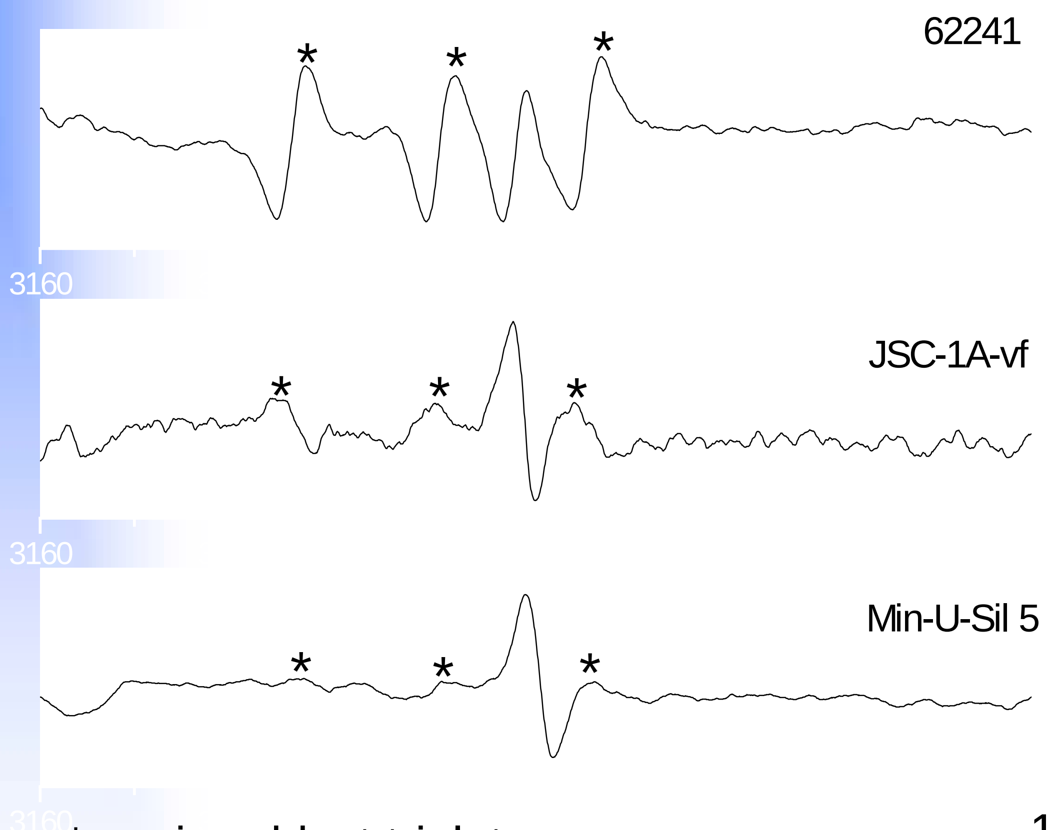
- Broad peaks: no determination of silicon- or oxygen-based radicals
- Change in g-values from 2.11 (unground) to 2.09 (ground)
- Similar downward shifts and g-values seen previously by Haneman and Miller*

*: D. Haneman and D.J. Miller, *Proc. Second Lunar Sci. Conf.* **3** (1971) 2529-2541.

MNP Spin-adduct Reaction



Spin-trapping of Radicals



10 minute grinding

10 minute grinding

30 minute grinding

* : spin-adduct triplet

100 mM MNP/acetonitrile

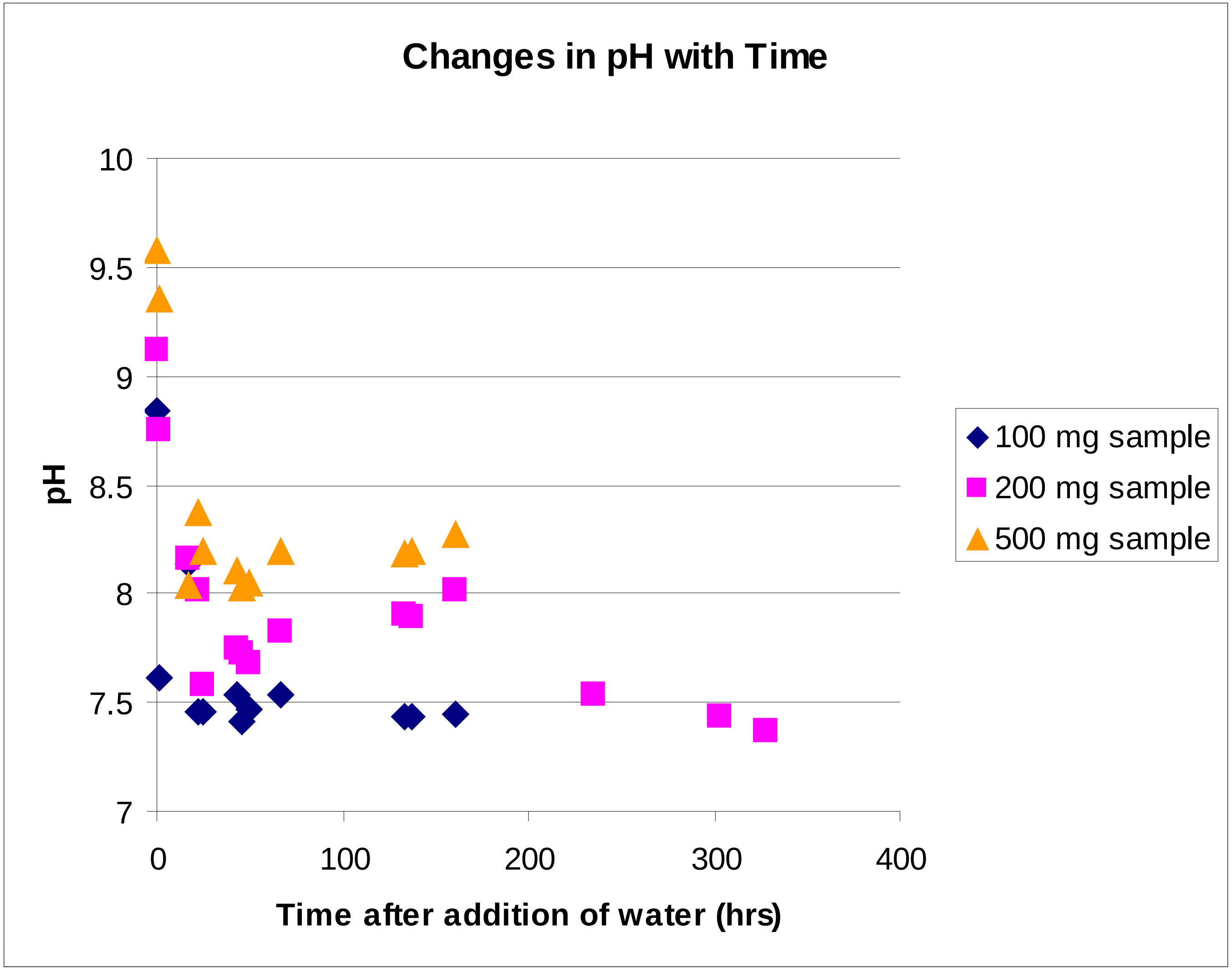
- Level of activity increases in the order: quartz < lunar dust simulant < lunar dust
- Peak-to-peak splitting corresponds to radical containing no hydrogen
    - Activated species likely interacting with acetonitrile to produce radicals
- Future testing to include hydroxyl radical trap in water

Solubility

Technique

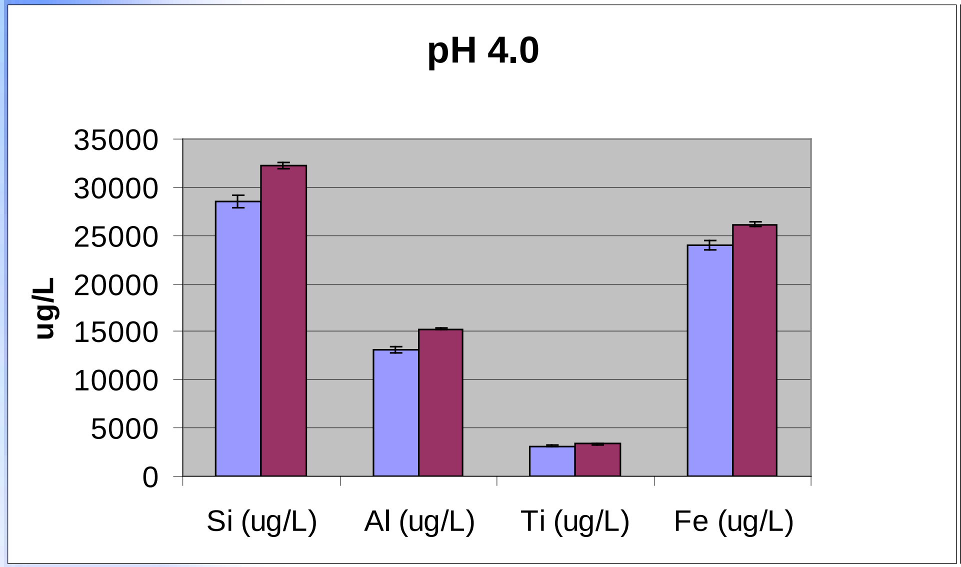
- Place 10 mg JSC-1A-vf in 20 mL of buffer solution in 50 mL centrifuge tube
- Rotate tubes for 72 hours under ambient conditions (23-25 ^{o}C, 30-50% RH)
- Flush syringes and 0.2 µm syringe filters with distilled water
- Filter solutions
- Measure concentrations using ICP-MS

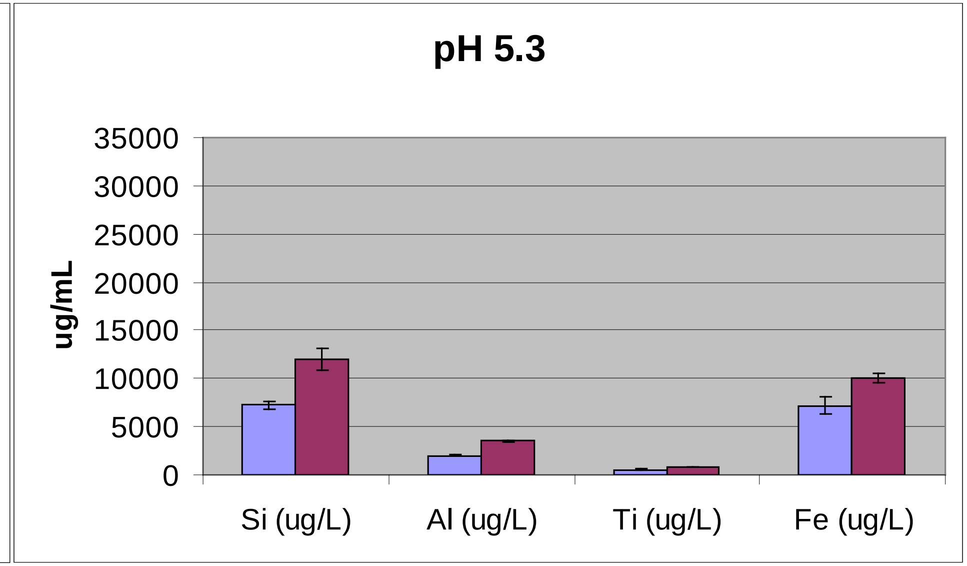
pH Effects

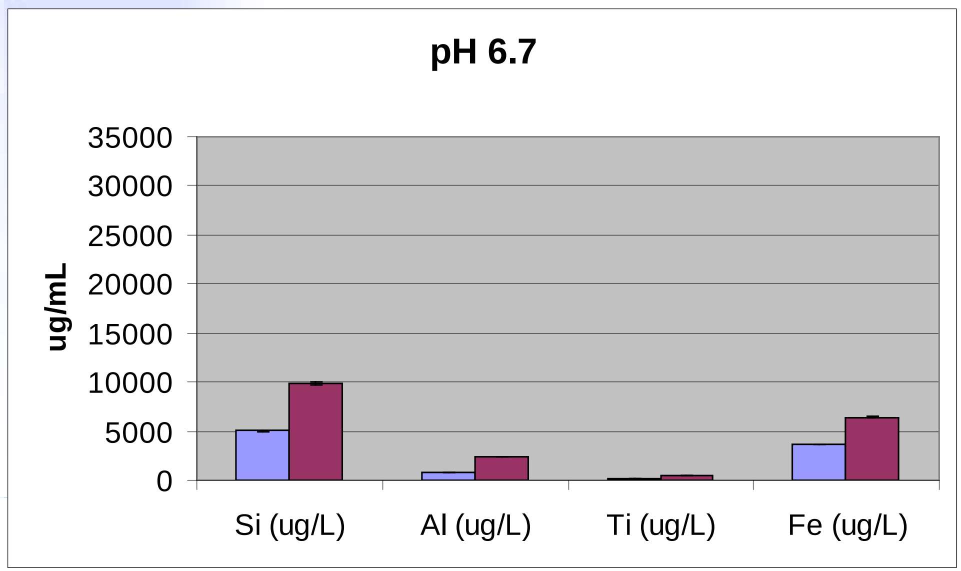


Changes in pH with Time
10
9.5
9
8.5
8
7.5
7
pH
0
100
200
300
400
Time after addition of water (hrs)
100 mg sample
200 mg sample
500 mg sample

Effect of pH on Leaching

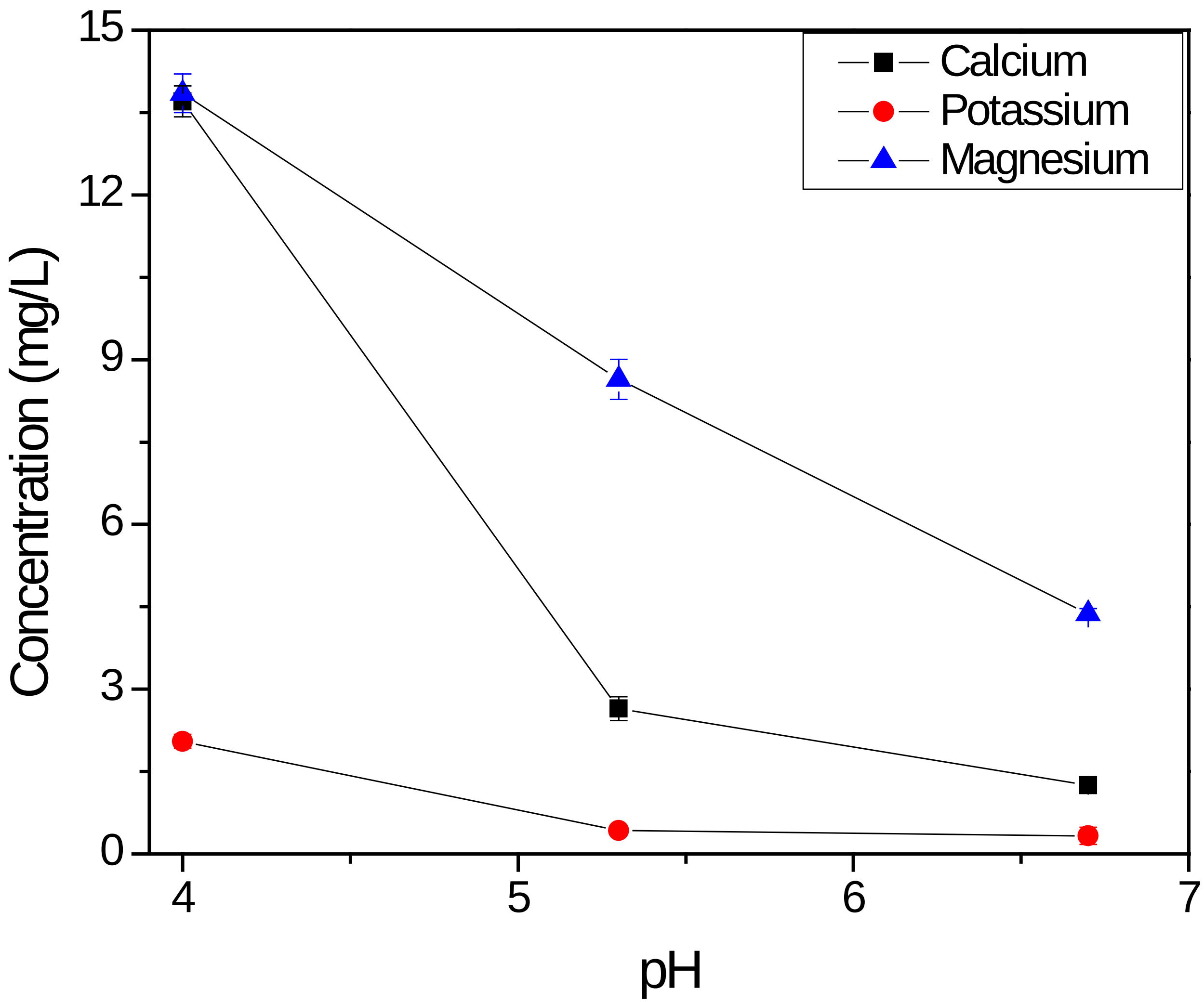




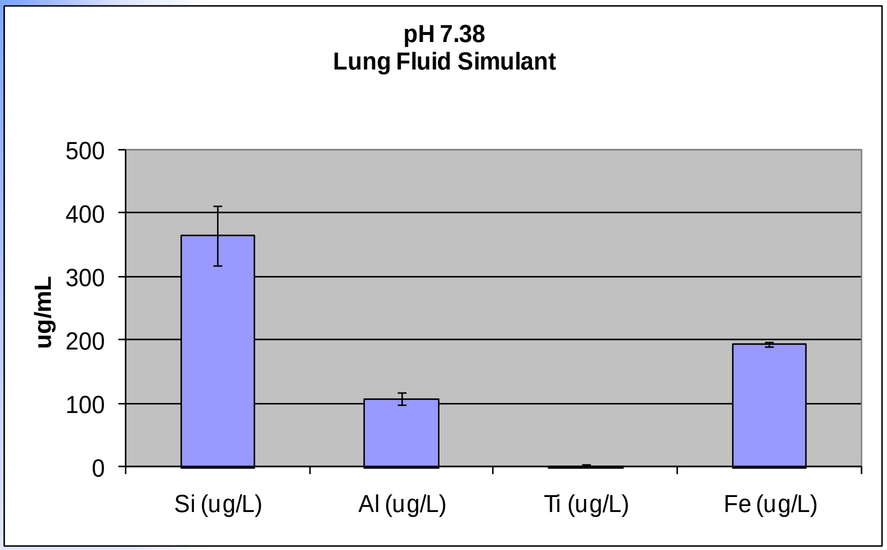


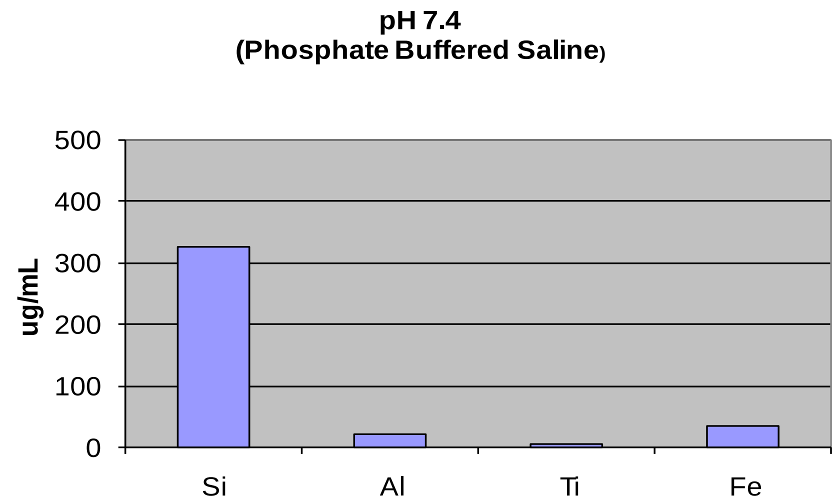
Blue: Unground
Maroon: Ground

Effect of pH on Leaching



Lung Fluid Simulant





Tyrode's solution modified to approximate Gamble's solution*

1.8 mM $CaCl_2 \cdot 2H_2O$, 1.12 mM $MgCl_2$, 2.68 mM KCl, 11.9 mM $NaHCO_3$, 136.89 mM NaCl, 0.42 mM NaH_2PO_4, 5.55 mM D-Glucose, 10 mM NH_4Cl, 0.2 mM trisodium citrate, 6 mM glycine, 0.5 mM Na_2SO_4

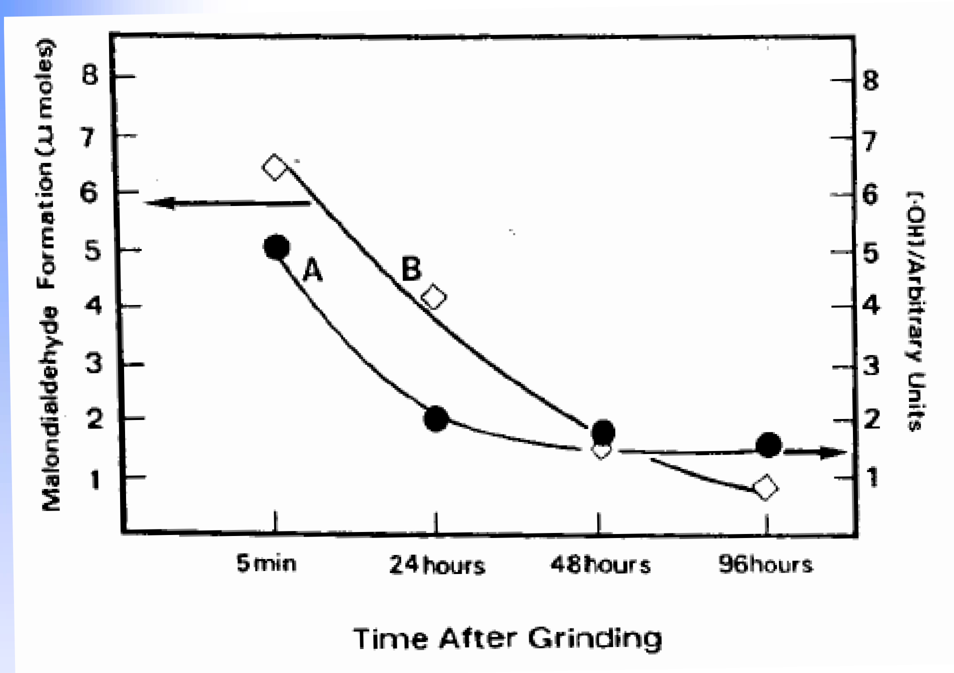
*: G.M. Kanapilly *et al*., *Health Physics* **24** (1973) 497-507.

Solubility Summary

- Grinding of lunar dust simulant leads to increased dissolution in buffers of different pH
- Decreases in pH lead to increased leaching from lunar simulant
- Use of lung fluid simulant does not lead to significant increase in leaching
- Where to go from here?
  - Different time points?
  - Lunar dust?
- Thanks to Mike Kuo for ICP-MS measurements

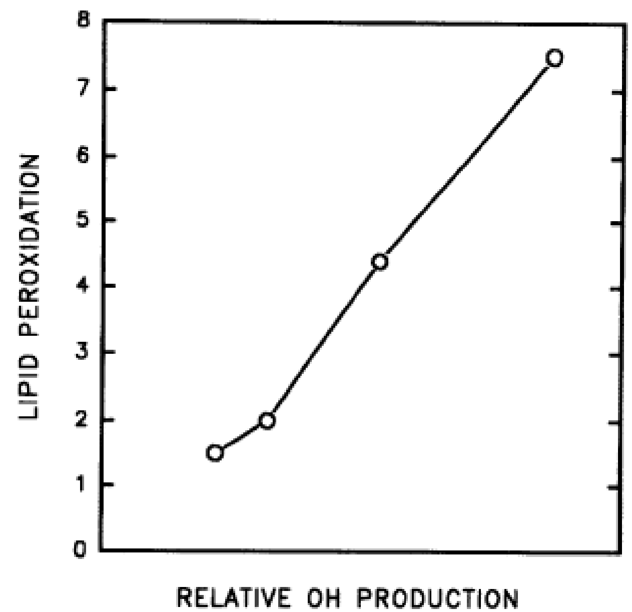
Cell Culture

Direct Toxicity of Quartz



Parameter	Aged Si	Fresh Si
Hemolysis[b]	2 ± 1%	39 ± 1%
Membrane leakiness[c]	15 ± 2%	58 ± 8%
Lipid peroxidation[d]	1.5 ± 0.4 μmol mal	7.5 ± 0.6 μmol mal

- Grinding of quartz also leads to direct toxicity *in vitro*
- Ability of ground silica to oxidize lipids is directly correlated to the number of radicals produced in solution and "freshness" of silica



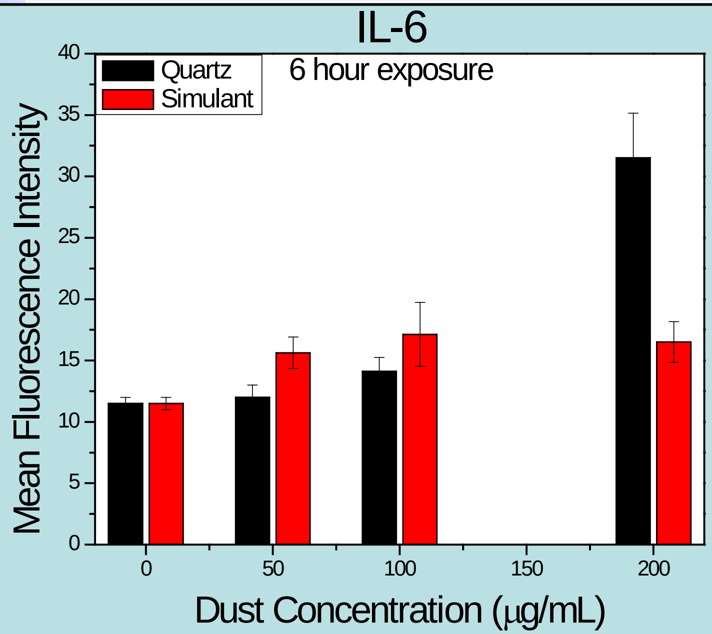
V. Castranova, *Environ. Health Perspect*. **102** (1994) 65-68.
N.S. Dalal, X. Shi, and V. Vallyathan, *Free Rad. Res. Comms.* **9** (1990) 259-266.

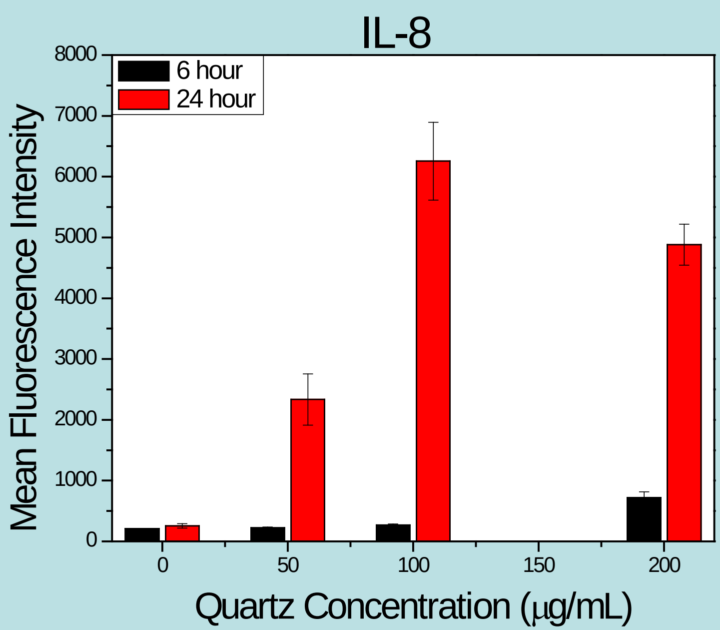
Techniques

- A549 alveolar epithelial cells or BEAS-2B bronchial epithelial cells grown 72 hours
- Treatment media prepared by adding 10 mg of sample to 10 mL media w/o FBS (A549: F12K, BEAS-2B: GTSF-2)
    - Dilutions prepared (200, 100, and 50 µg/mL) from stock
    - Growth media removed from cells and 1 mL treatment media added
    - Cells incubated in treatment media for 6, 24, or 72 hours
- Media removed and centrifuged (5 min, 6000 rpm) to remove dust or cellular debris
- Supernatants tested for inflammatory mediators (IL-8, IL-6, and TNF-α)
- MTT toxicity testing also performed (mitochondrial activity)

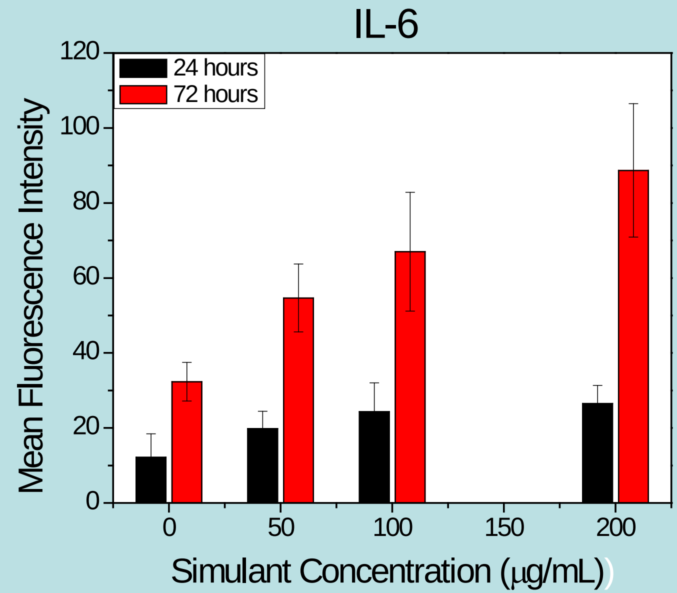
Cytokine Production

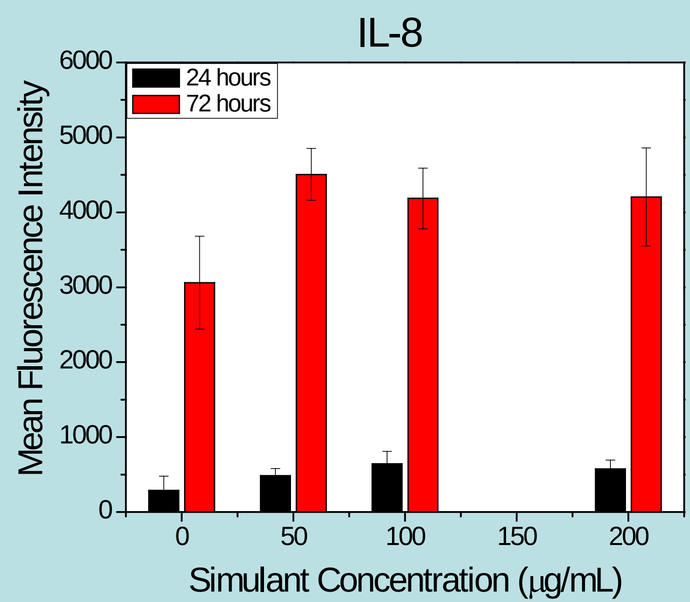
Unground JSC-1A-vf & Min-U-Sil 5



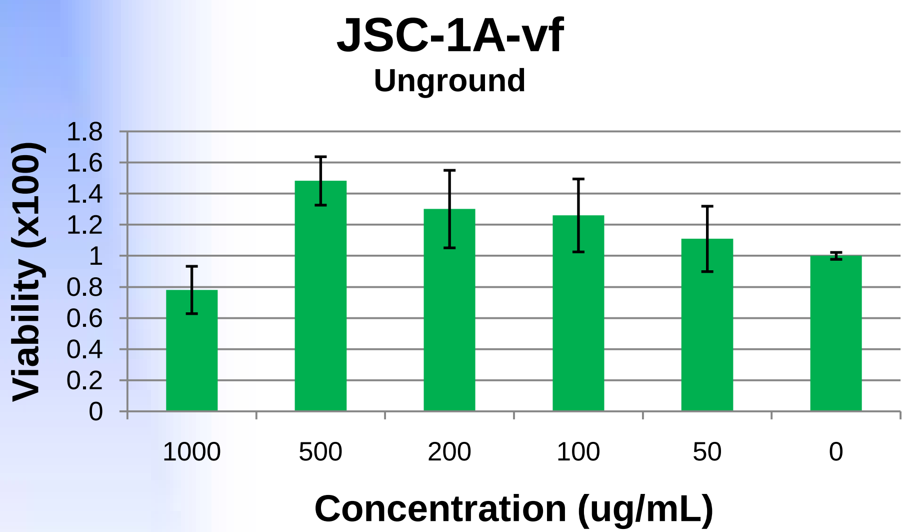


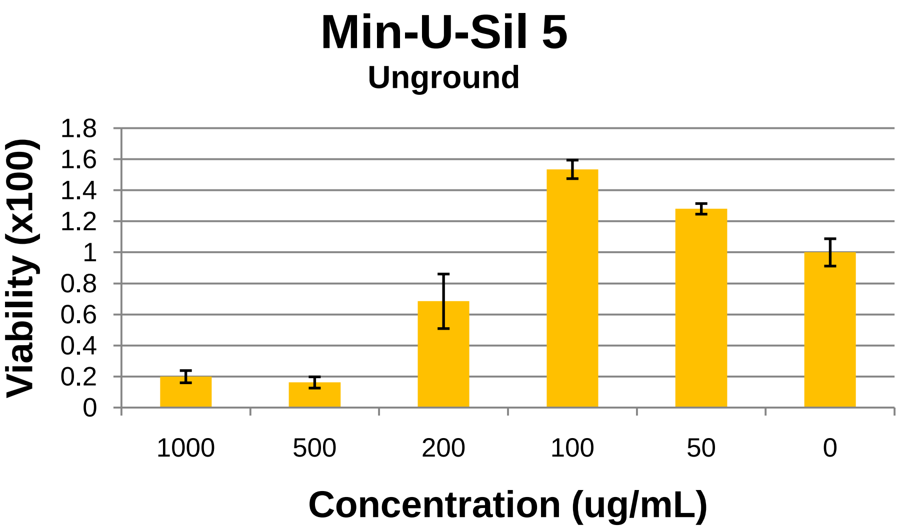
Ground JSC-1A-vf





A549 Viability



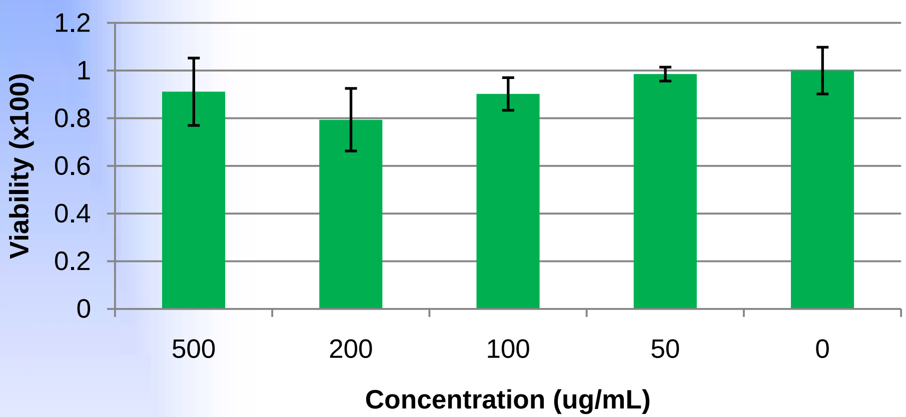


- Only highest concentration of simulant shows toxic effects; could be due to blockage of light by the dust
- Quartz is more toxic at lower concentrations

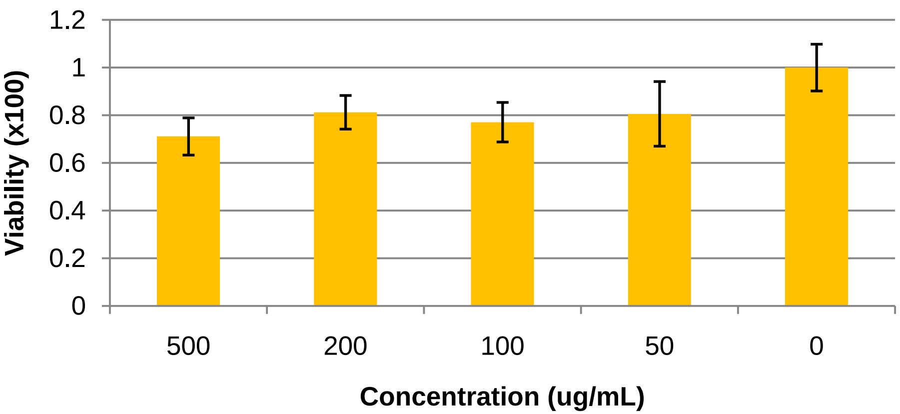
58

A549 Viability

JSC-1A-vf
Ground

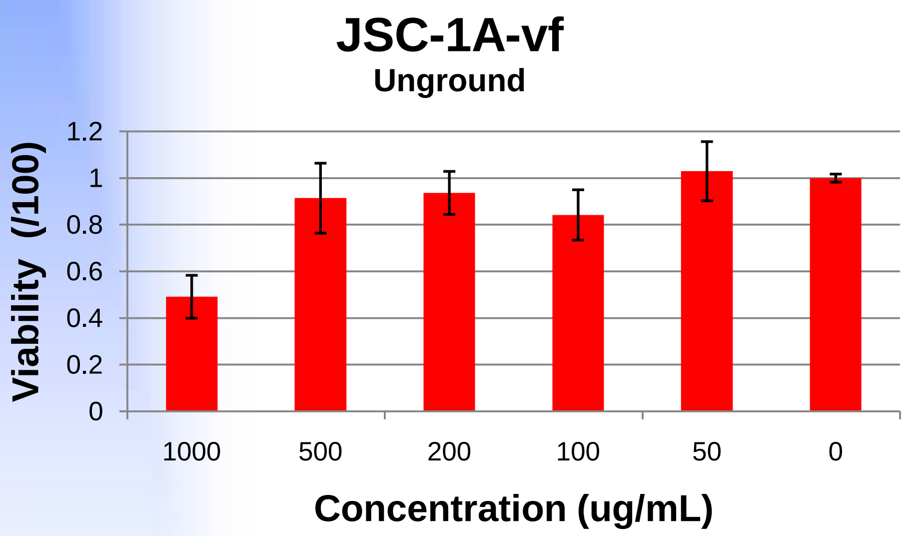


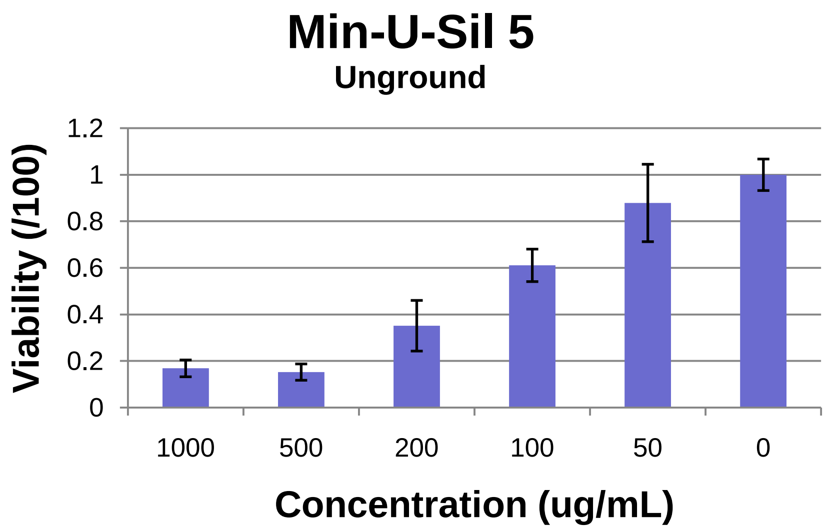
Min-U-Sil 15
Ground



59

BEAS-2B Viability

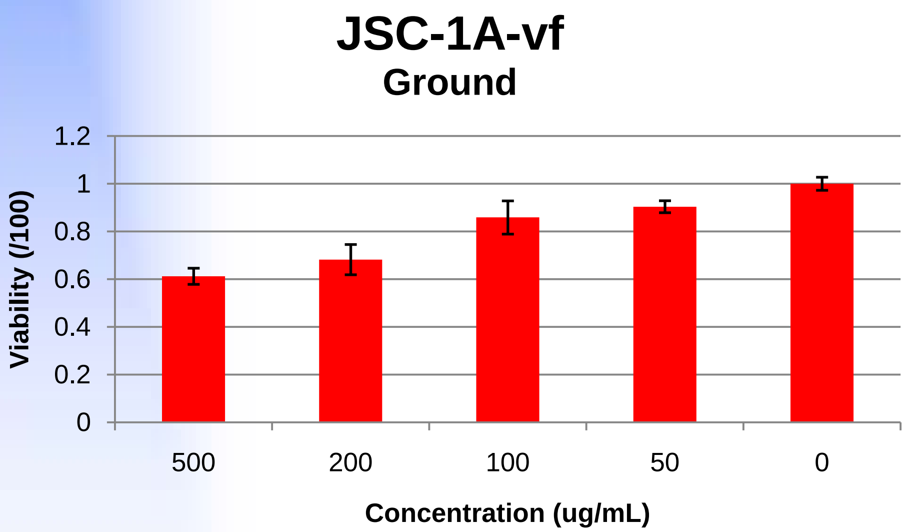


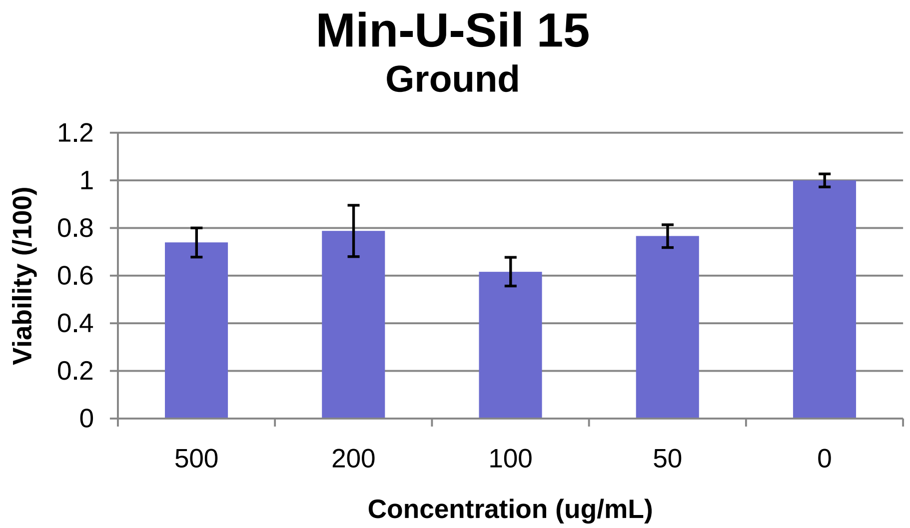


- Little toxicity seen for JSC-1A-vf
- Quartz shows relatively high toxicity even at low concentrations

60

BEAS-2B Viability





Cell Culture Conclusions

- Unground quartz causes an increase in IL-6 and IL-8 levels in A549 cells
  - Time dependence seen for IL-8 increase
- Unground JSC-1A-vf only causes noticeable IL-6 increase at highest concentration tested
- Ground JSC-1A-vf also produces IL-6 and IL-8 in A549
- Unground quartz is toxic to both A549 and BEAS-2B cells
  - Higher concentration required in A549
- Unground simulant only shows toxicity at highest concentration tested (1 mg/mL)

62

Acknowledgements

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