Thermally Evolved Volatiles in Lunar Soil Simulants

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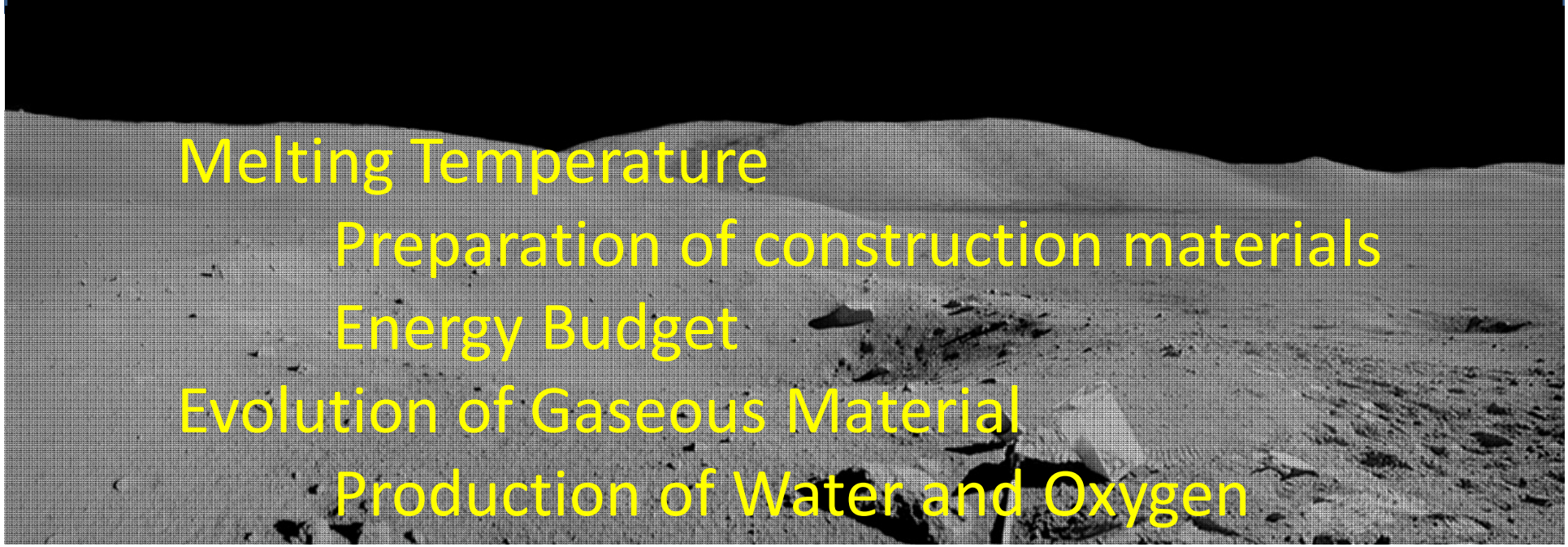
Workshop for the Lunar Applications of Mining and Mineral Beneficiation
October 5-7, 2010
Montana Tech of the University of Montana
Butte, Montana

Thermal Properties of Interest

In order to achieve a sustainable presence on the Moon (or elsewhere) it will be necessary to process materials in-situ to provide shelter, bioconsumables, etc.



Melting Temperature

- Preparation of construction materials
- Energy Budget

Evolution of Gaseous Material

- Production of Water and Oxygen

Lunar Geologic History

Initial lunar rock ~ norite.

Subsequent basaltic volcanic (& other) flows.

Hypervelocity impacts largely destroyed original rock.

Resulting broken geologic material = regolith.

Except for some outcrops in or around the mare,

All interactions with people and equipment will be with regolith!

Subsequent Geologic Processing

Particle Size -

Net result of continuing meteor bombardment.

Surface of Moon is ground mixture of fragments.

Mixture believed to be meters deep everywhere.

For Apollo mission samples
typical average particle sizes from ~ 30 to 100 um.

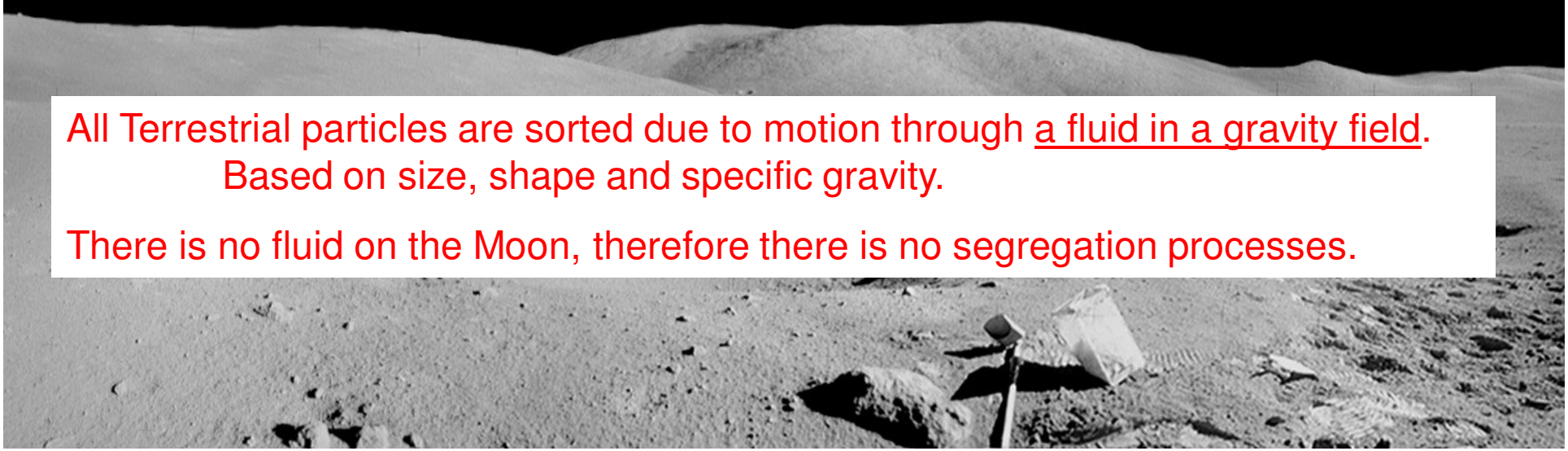
Subsequent Geologic Processing

Sorting -

All Terrestrial particles are sorted.
Based on size, shape and composition.

No Terrestrial segregation processes operate in a vacuum.

Energy input to lunar surface sufficient to cause particle motion.
Can mix but not sort.



All Terrestrial particles are sorted due to motion through a fluid in a gravity field.
Based on size, shape and specific gravity.

There is no fluid on the Moon, therefore there is no segregation processes.

So What Do We Tell Designers?

What designers can expect:

for any reasonable sized sample
from top few meters
it is possible, and even probable to have:

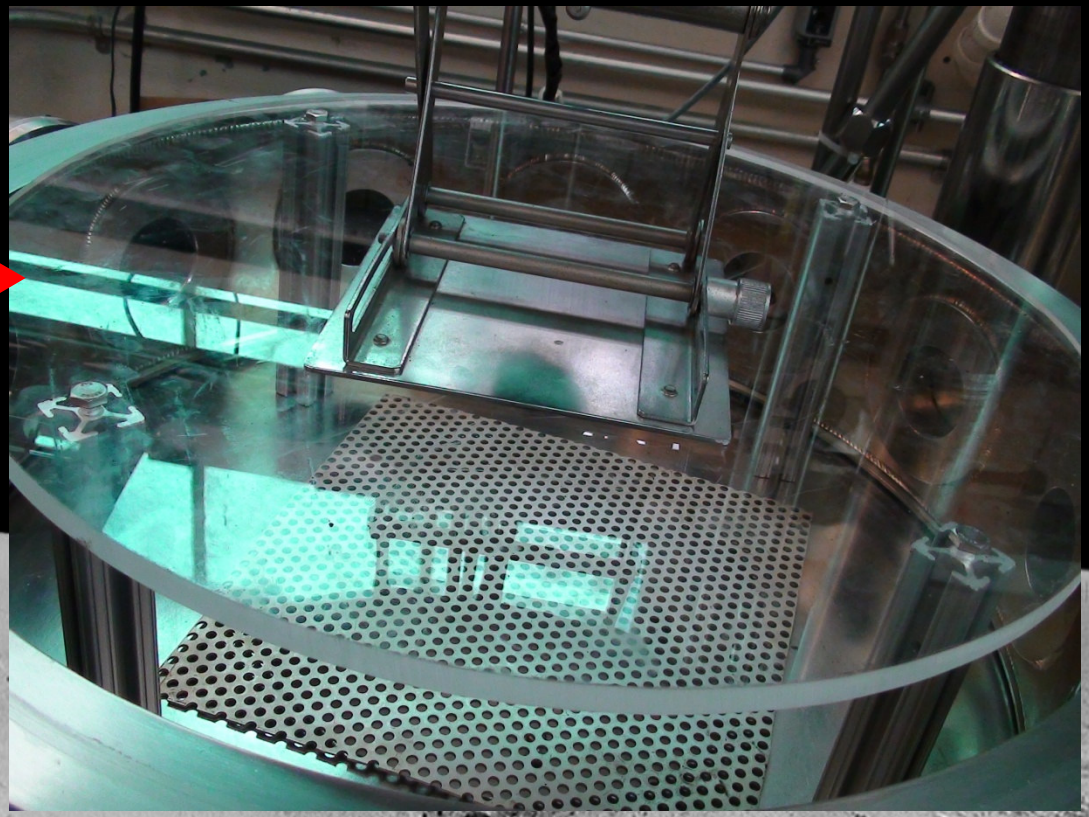
Particles of all size ranges and
Any lunar component in the sample.

To meet TRL = 6 you must test with simulant

So What Do We Tell Designers?

… And in a relevant environment!

Before →



So What Do We Tell Designers?

… And in a relevant environment!

After →

Issues with Cl, S and P

Halogens (Cl and perhaps F) produce:

$Cl \rightarrow Cl_2$ and/or HCl (Corrosive and Toxic)

Sulfur (as sulfide):

$S \rightarrow H_2S$, H_2SO_3 and or H_2SO_4 (Ditto)

S Poisons Expensive Catalysts

Phosphorus (as phosphate):

Same as Sulfur

Causes steel to become brittle

Simulant vs. Typical Regolith Composition

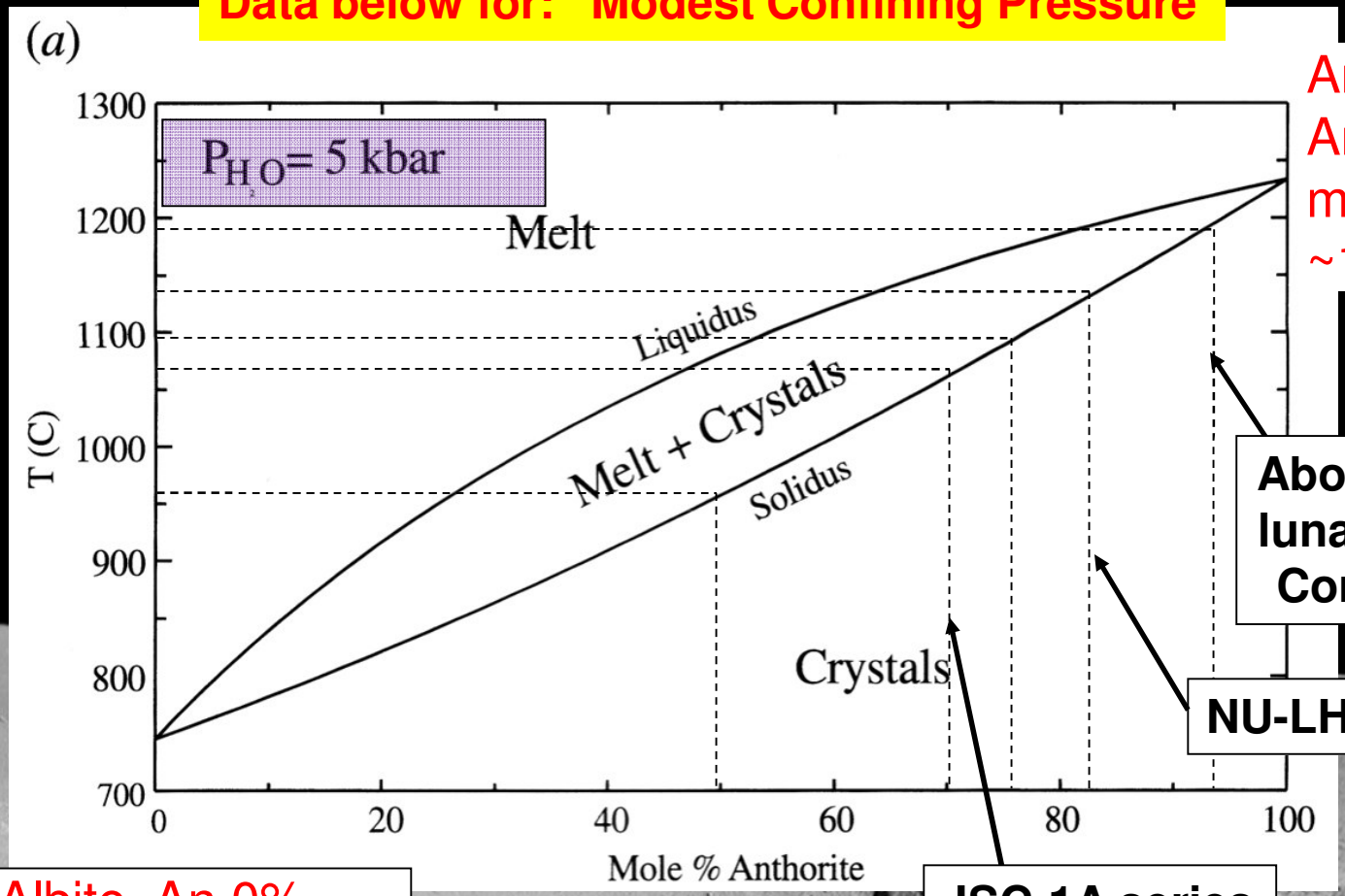
Lunar Highlands:	An >90%
NU-LHT-1M :	An 75-85%
OB-1:	An ~ 75%? (Shawmere)
Lunar Mare:	An 75-95%
JSC-1:	An 64-71% (Carpenter 2005)
JSC-1A:	An 70% (average -- Hill et al., 2007)
JSC-1AF:	An 70% (Carpenter, 2006)
MLS-1:	An 44-50% (Carpenter, 2005; Hill et al., 2007)

Na to Ca ratio plagioclase series is solid solution
Ca is anorthite
Na is albite

Ca/Na ratio determines An number

Why Mineral Chemistry Matters

Data below for: Modest Confining Pressure



Anorthite, An 100%, melts at ~1230°C

About average lunar highland Composition

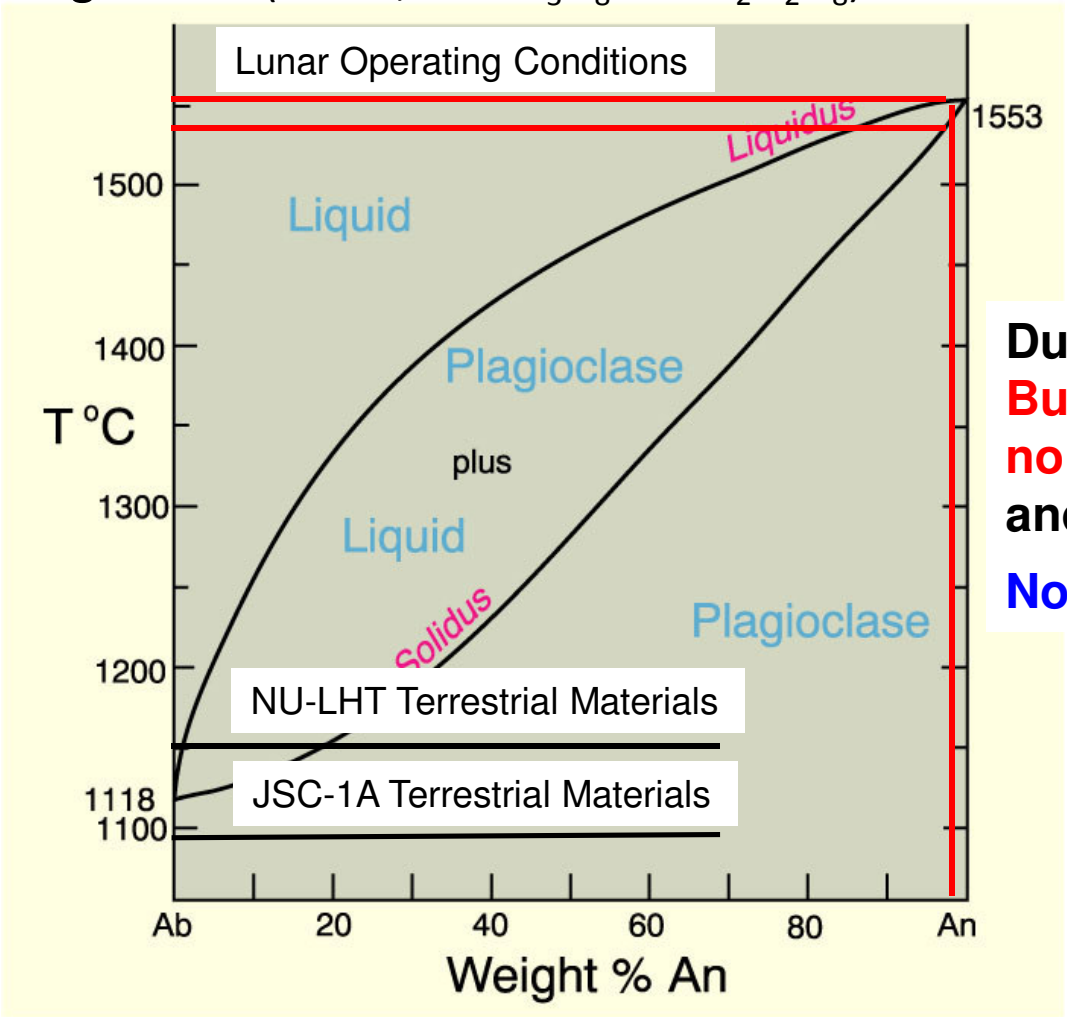
NU-LHT series

JSC-1A series

Albite, An 0%, melts at ~750°C

Systems with Complete Solid Solution

Plagioclase (Ab-An, $NaAlSi_3O_8$ - $CaAl_2Si_2O_8$)



Duplicate of prior slide
But NO Water (therefore no water alteration)
and at ambient Pressure

Note Temp increase!

Isobaric T-X phase diagram at atmospheric pressure. After Bowen (1913) Amer. J. Sci., 35, 577-599.

Experimental

Differential Thermal Analysis (DTA)

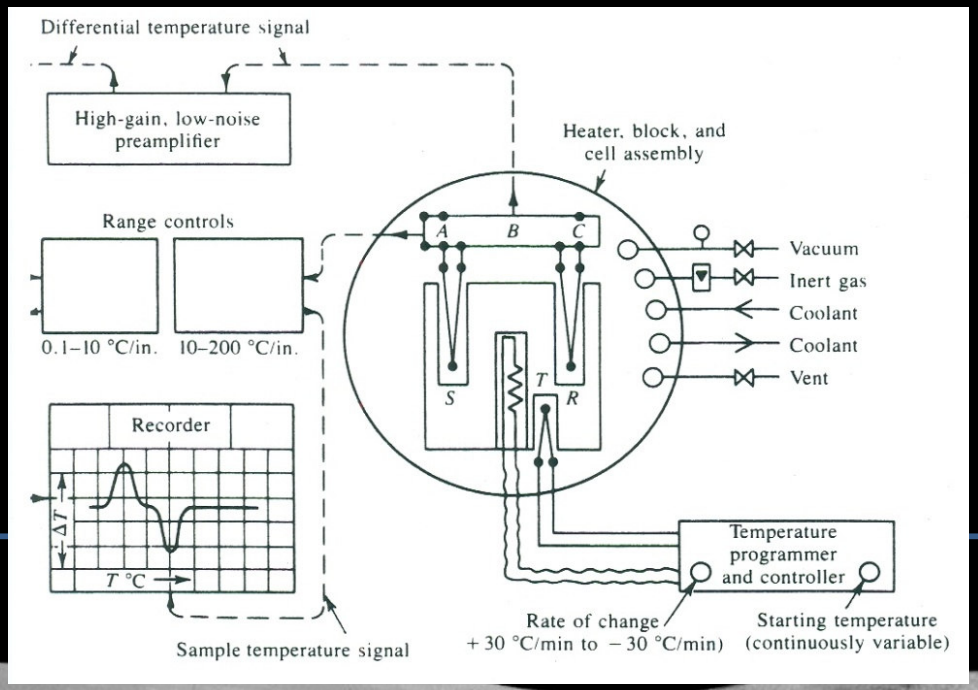
Thermo Gravimetric Analysis – Fourier Transform Infra Red Spectroscopy (TGA-FTIR)

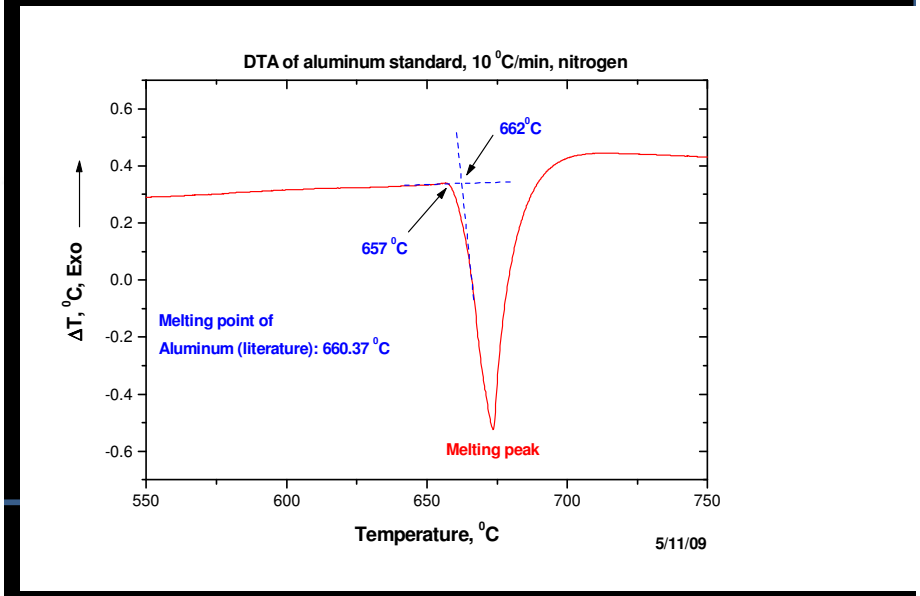
Simulants and Precursor Materials:

- JSC-1AF, NU-LHT-2M
- Dunite, Anorthosite, Norite and High Quality (HQ) Glass

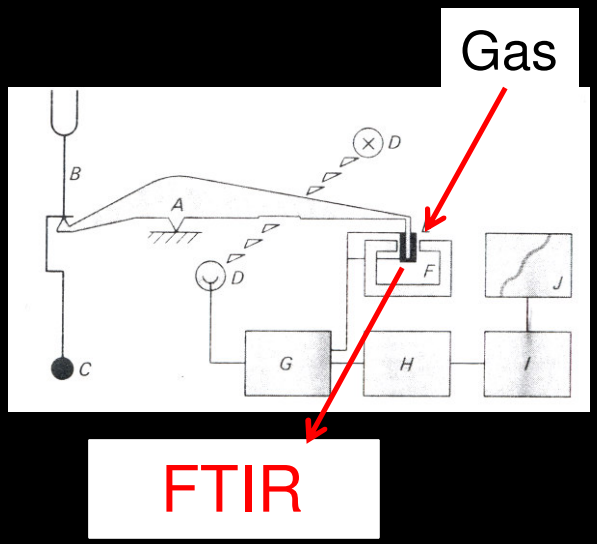
And others

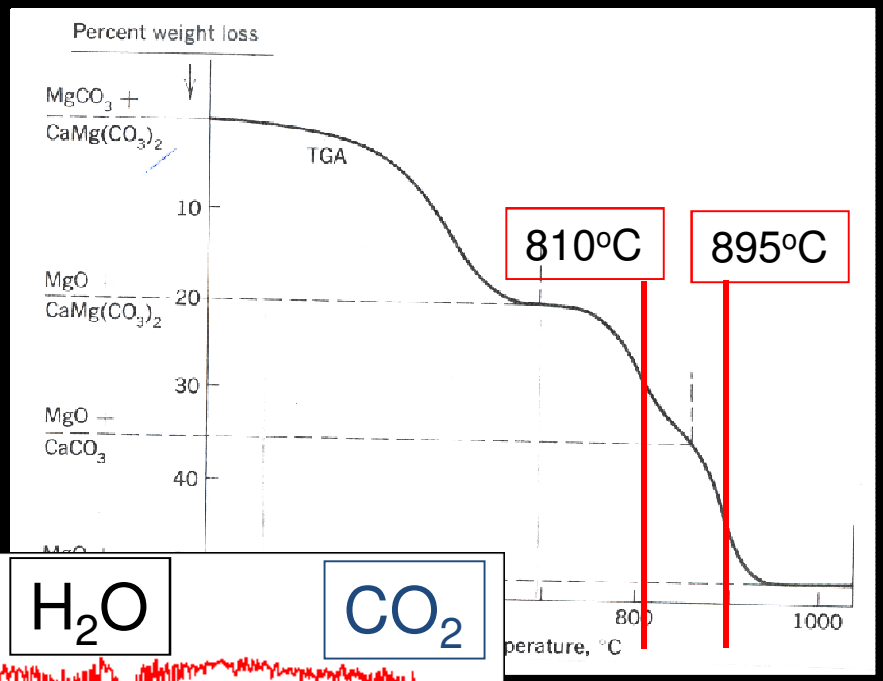
Experimental: DTA

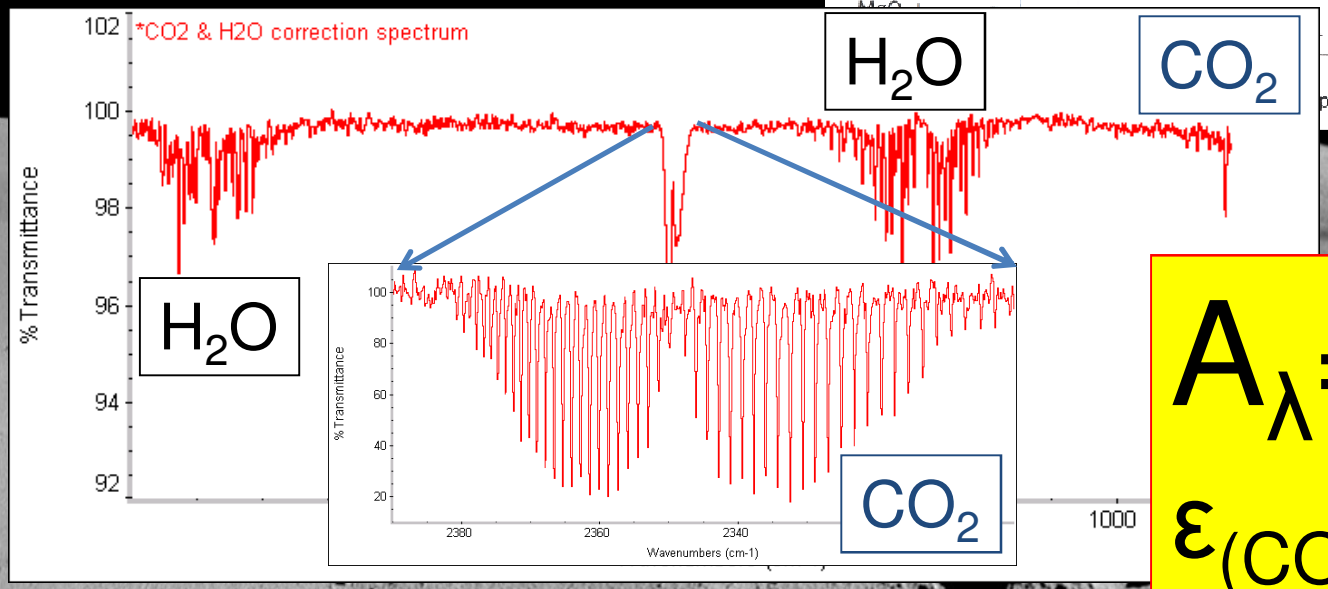




Experimental: TGA-FTIR



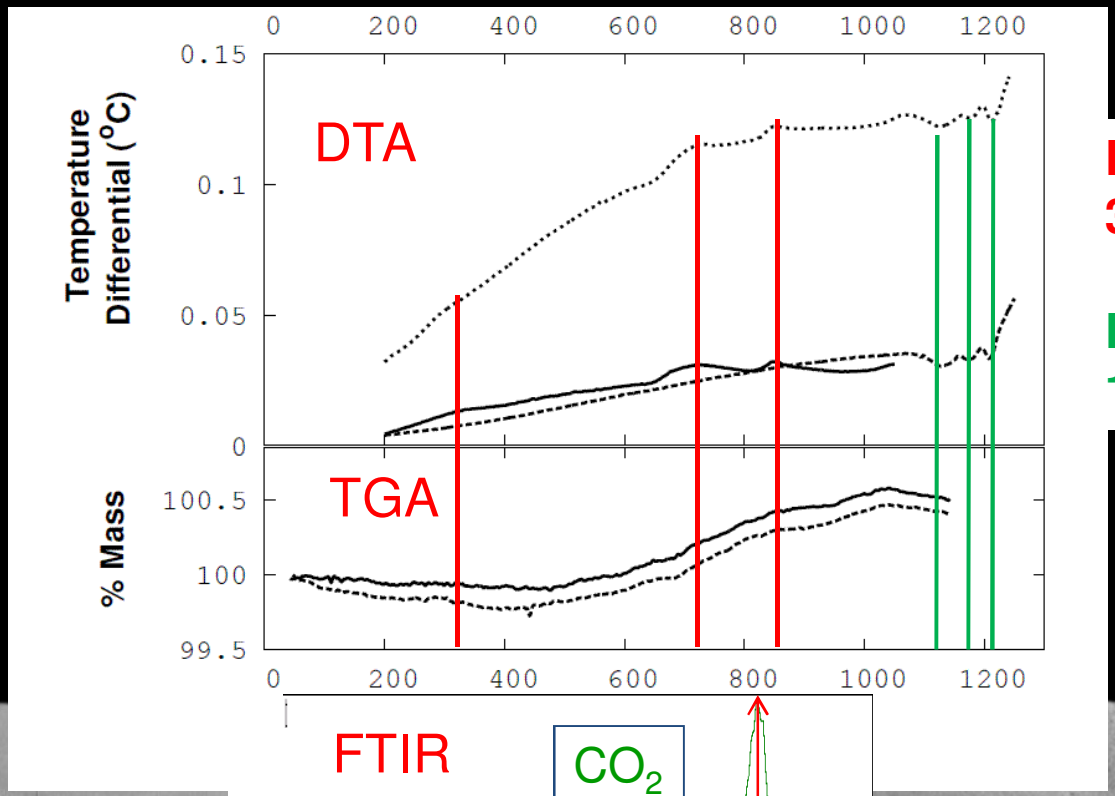


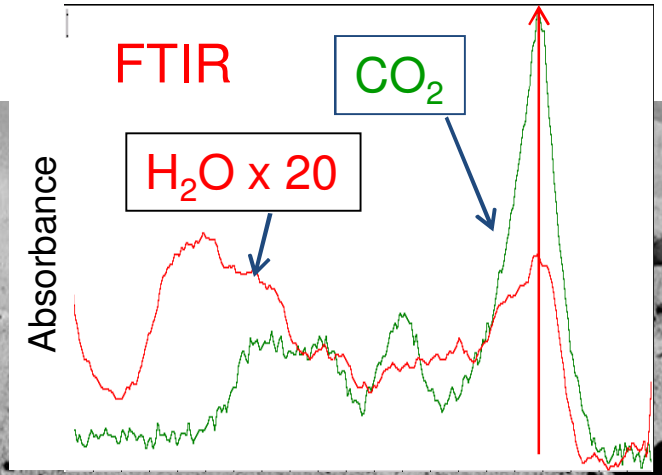


$$A_\lambda = \varepsilon_\lambda b C$$

$$\varepsilon_{(CO_2)} >> \varepsilon_{(H_2O)}$$

Results and Discussion: JSC-1AF





Exothermic Transitions:
325, 723, 849

Endothermic Transitions
1130, 1170, 1210

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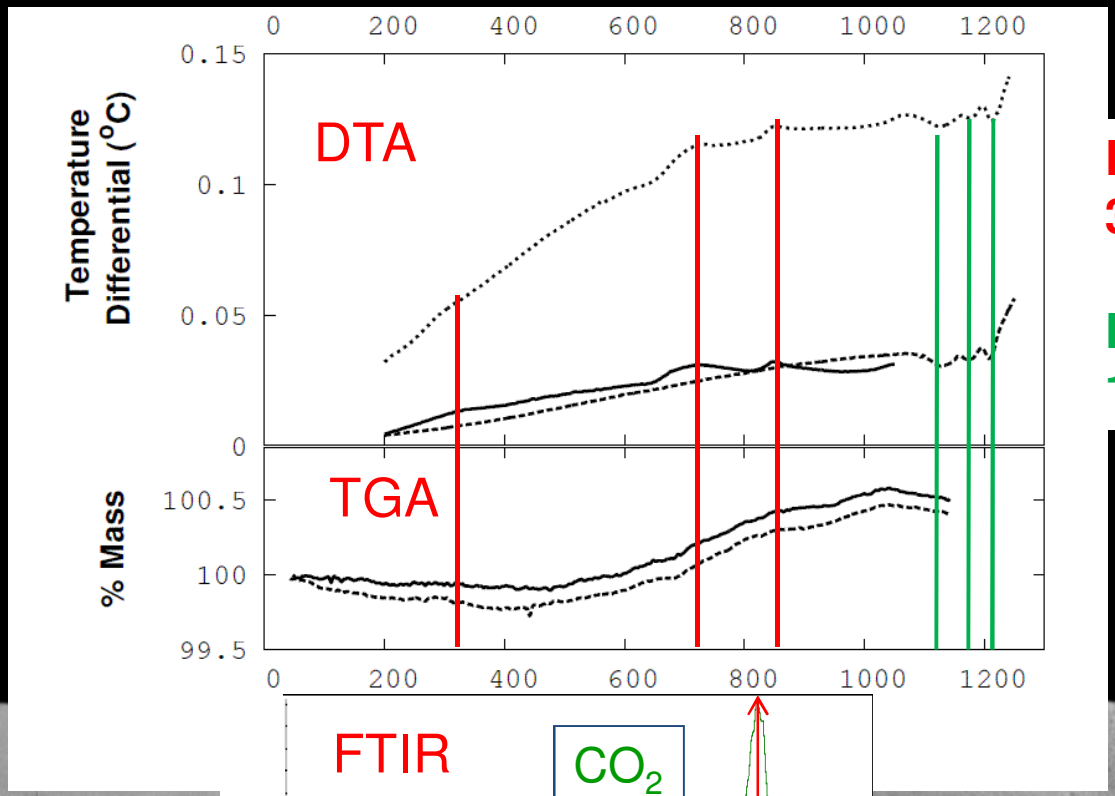

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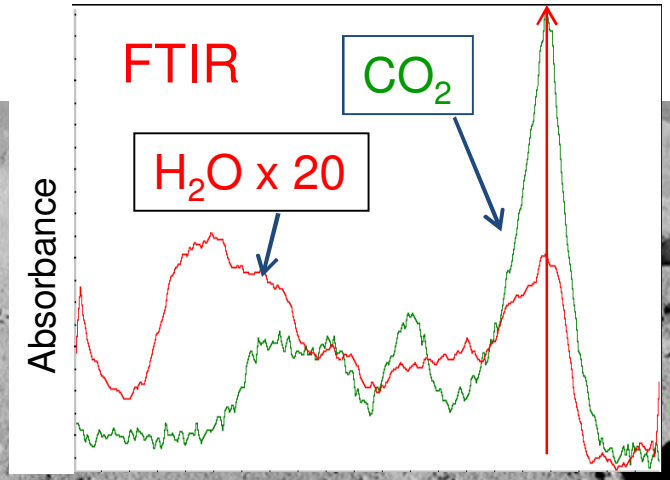
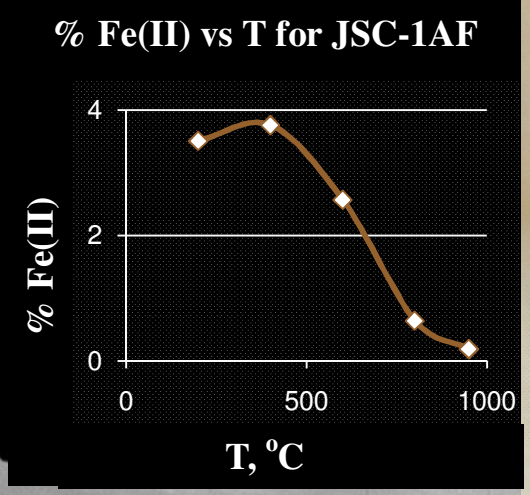


While the 810°C CO_2 evolution does correspond to a dolomite type of decomposition, there is yet another explanation…

Results and Discussion: Inert Heating



Results and Discussion: NU-LHT-2M

Major Crystalline Lithics (Rock)

- Anorthosite + Norite (50-55)
- Dunite (9)

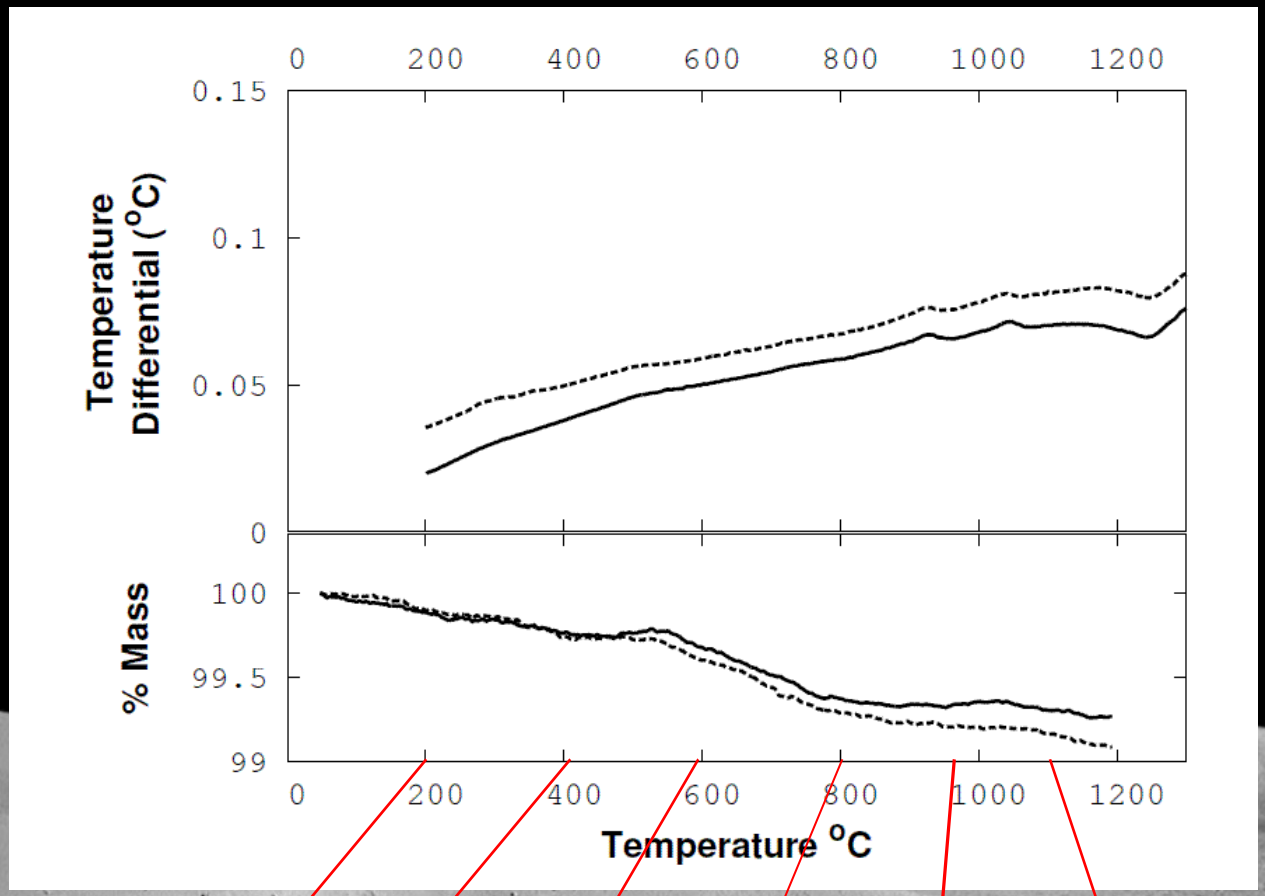
Trace Minerals (<1% each) (Under Investigation)

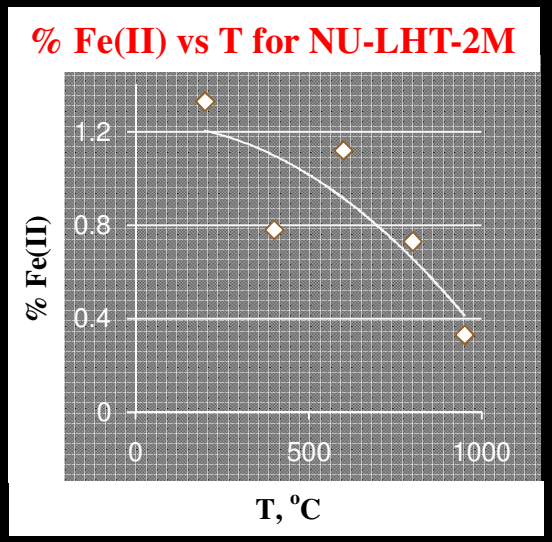
- Ilmenite
- Whitlockite (synthetic)
- Fluor-apatite
- Pyrite

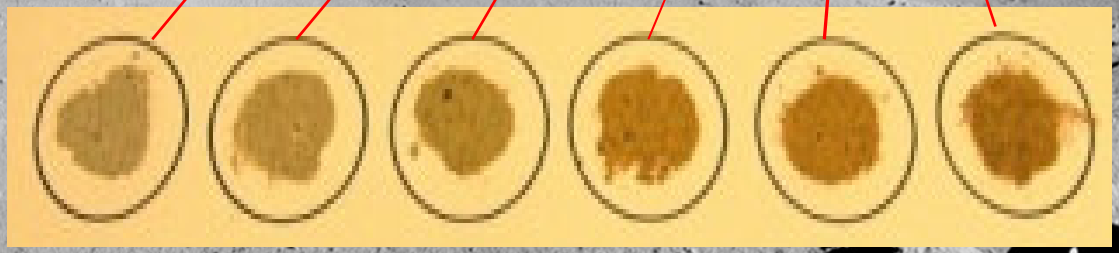
Glassy Components

- HQ Glass (5)
- Agglutinate (30) (Not Studied)

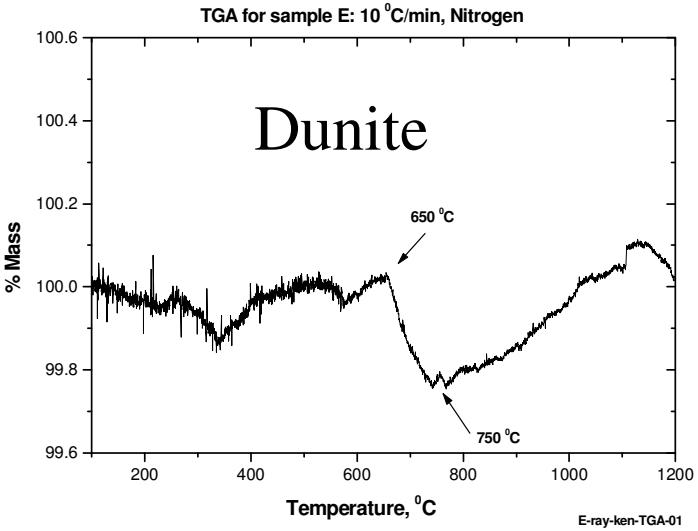
Results and Discussion: NU-LHT-2M

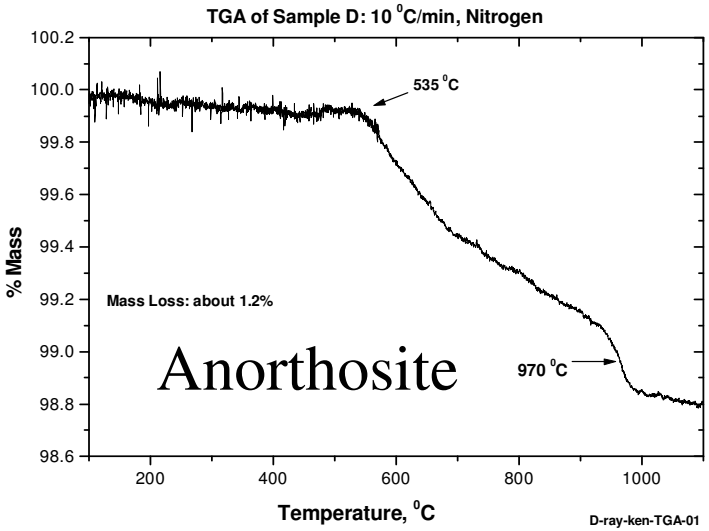


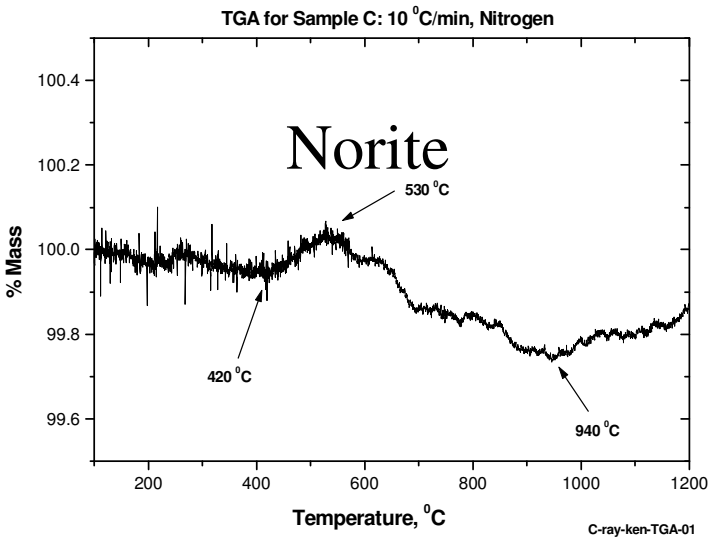


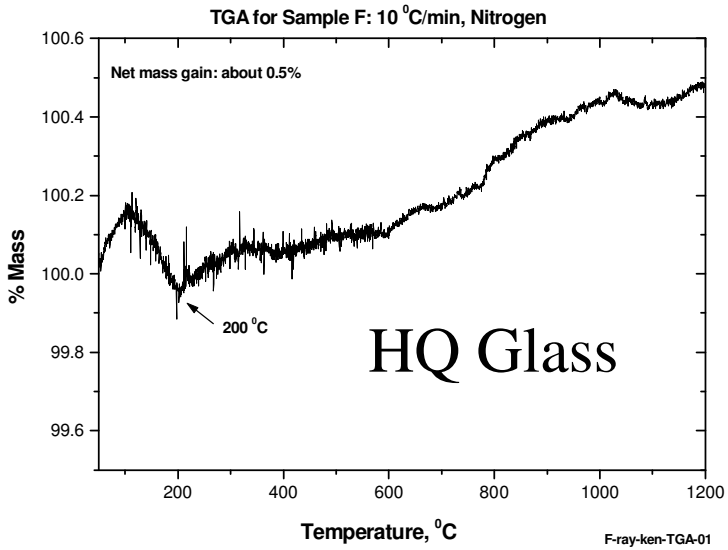


Results and Discussion: NU-LHT Components

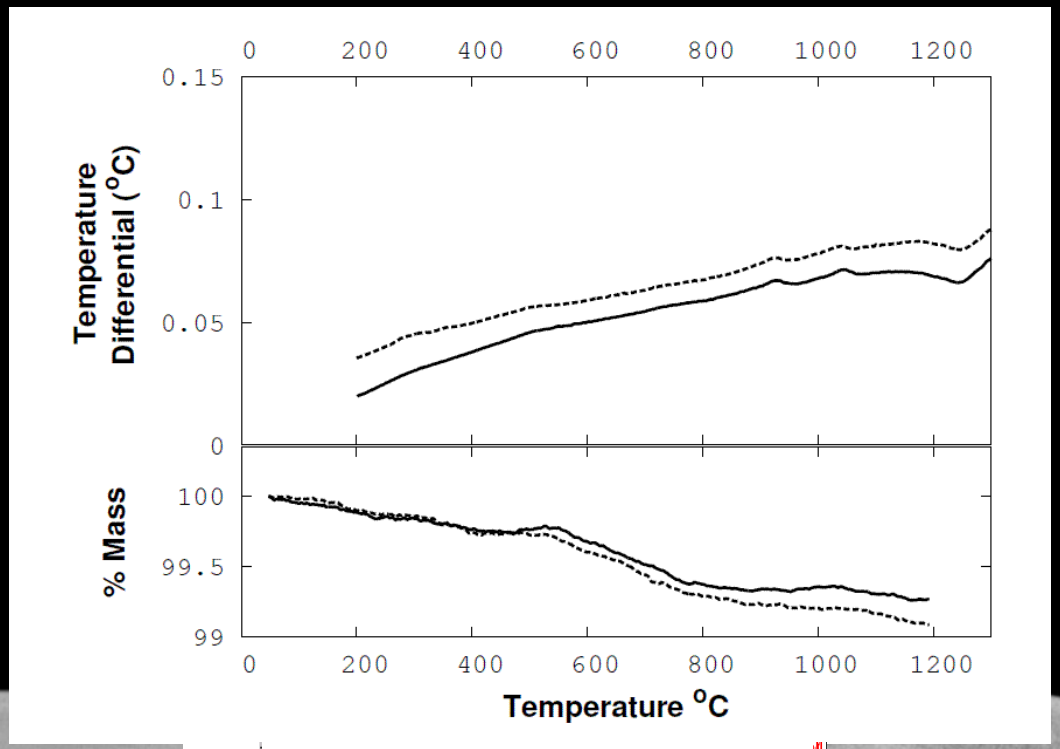


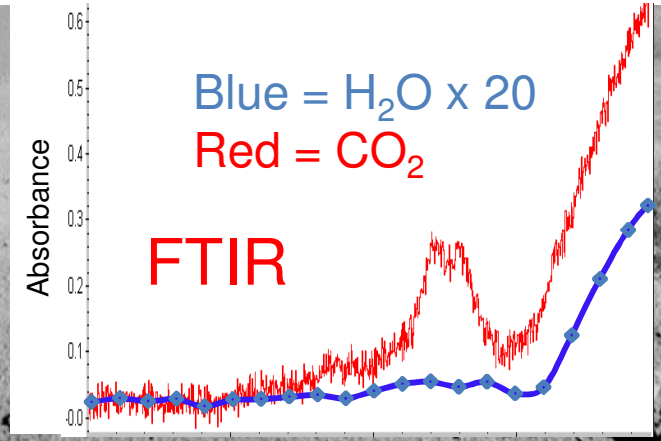






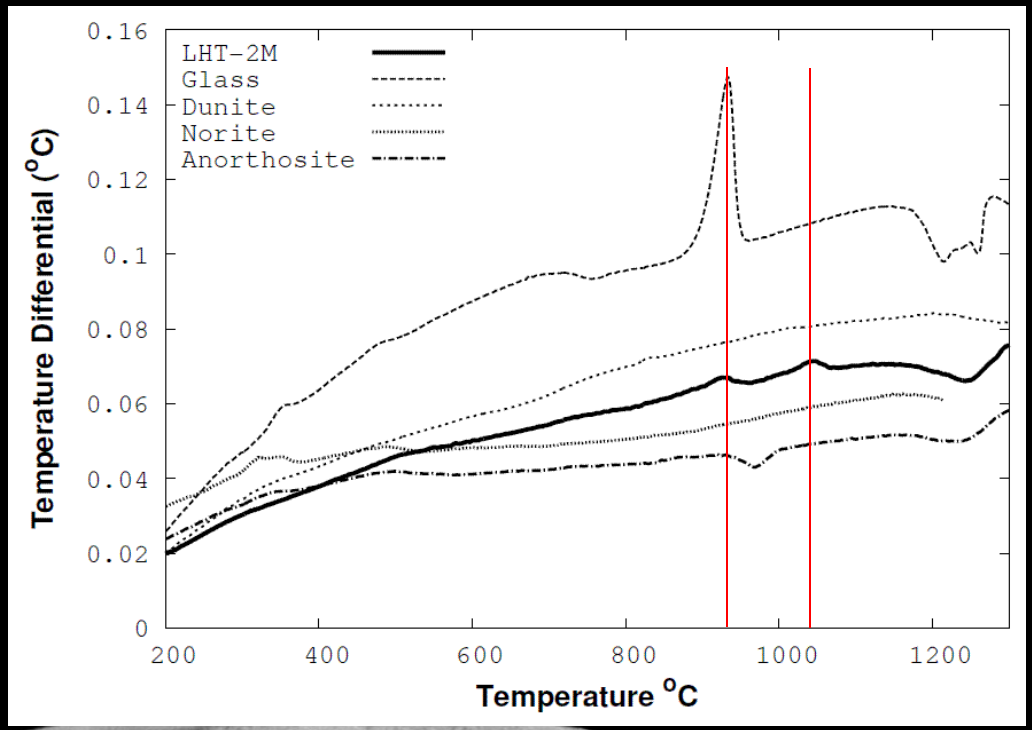
Results and Discussion: NU-LHT-2M





NOT Caliche!

Results and Discussion: NU-LHT Components



2M	290	500	740	924	1048	1244	
An	355	490		970			
Dun	310						>1350
Nor	425	455 488					
HQ	359	482	756	934		1215 1231	1318

Red = Exothermic
Green Endothermic

Conclusions

Simulants evolve H_2O and CO_2 at multiple temperatures and in amounts specific to each

Significant differences yield false operational information:

- Elevated temperature operation
- Differences in vacuum testing
- Evolution of spurious volatiles

Be Careful of how you dry your samples!

Significant follow-on work required:

- Oxygen free DTA and TGA data
- Thermal properties of other constituents
- Routine quality control procedure development
  (Broad utility, e.g. Mars Simulants, etc.)

Acknowledgements

Stillwater Mining Co.
Generous assistance and access to their rocks

William Betts
For countless hours spent making figures

Thank You!
Any Questions?