NU-LHT-1M

NASA/USGS - LUNAR HIGHLANDS TYPE – v.1

MEDIUM-GRAINED (<1mm)

PILOT

HIGHLANDS SOIL SIMULANT

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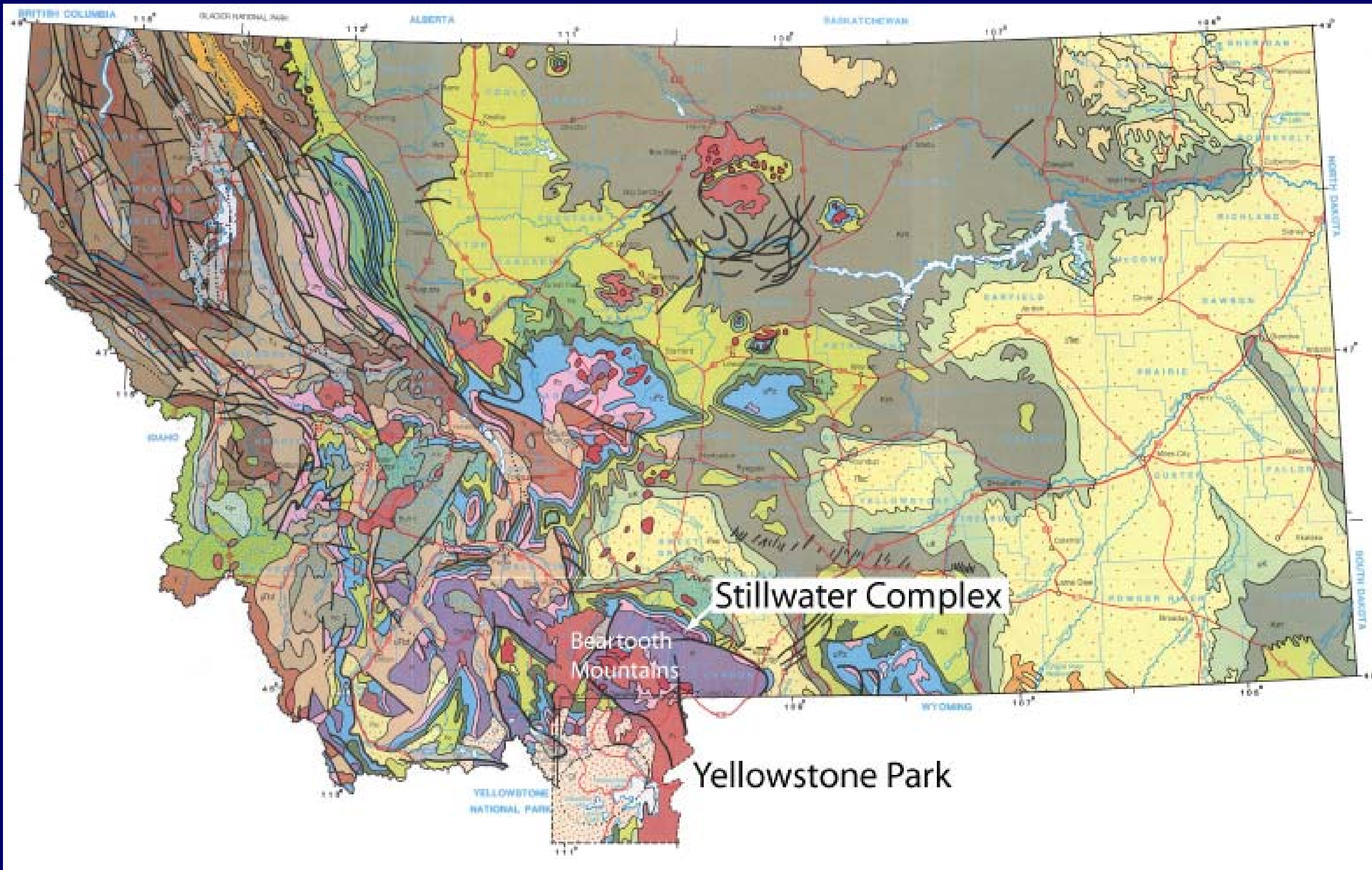
U.S. Geological Survey, Denver, CO

WHY & WHAT

- Why LHT simulants? If we put a base at the poles, the base will be on a highlands type regolith and therefore highlands regolith simulants are needed.

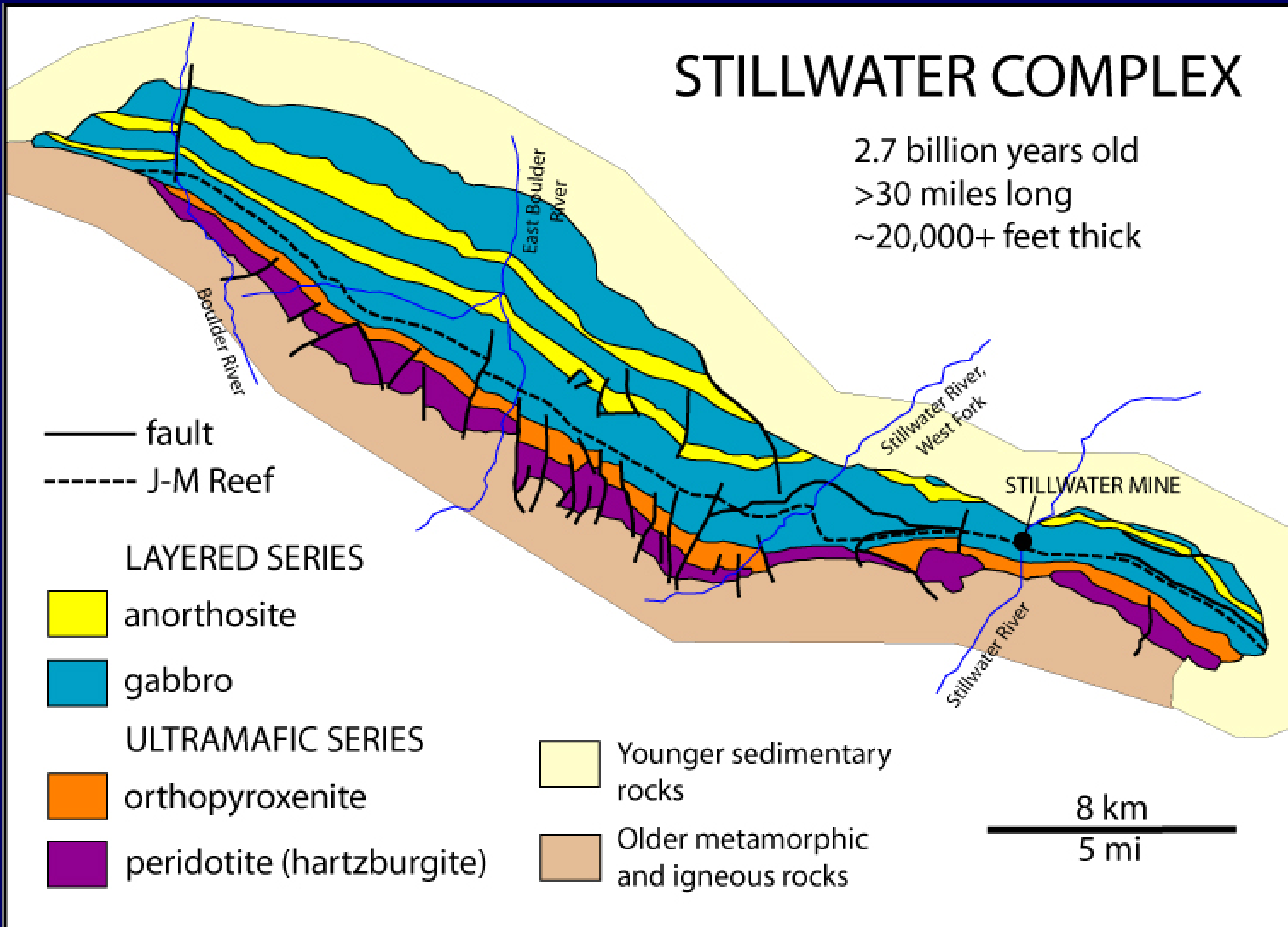
- We used an average Apollo 16 regolith target composition.

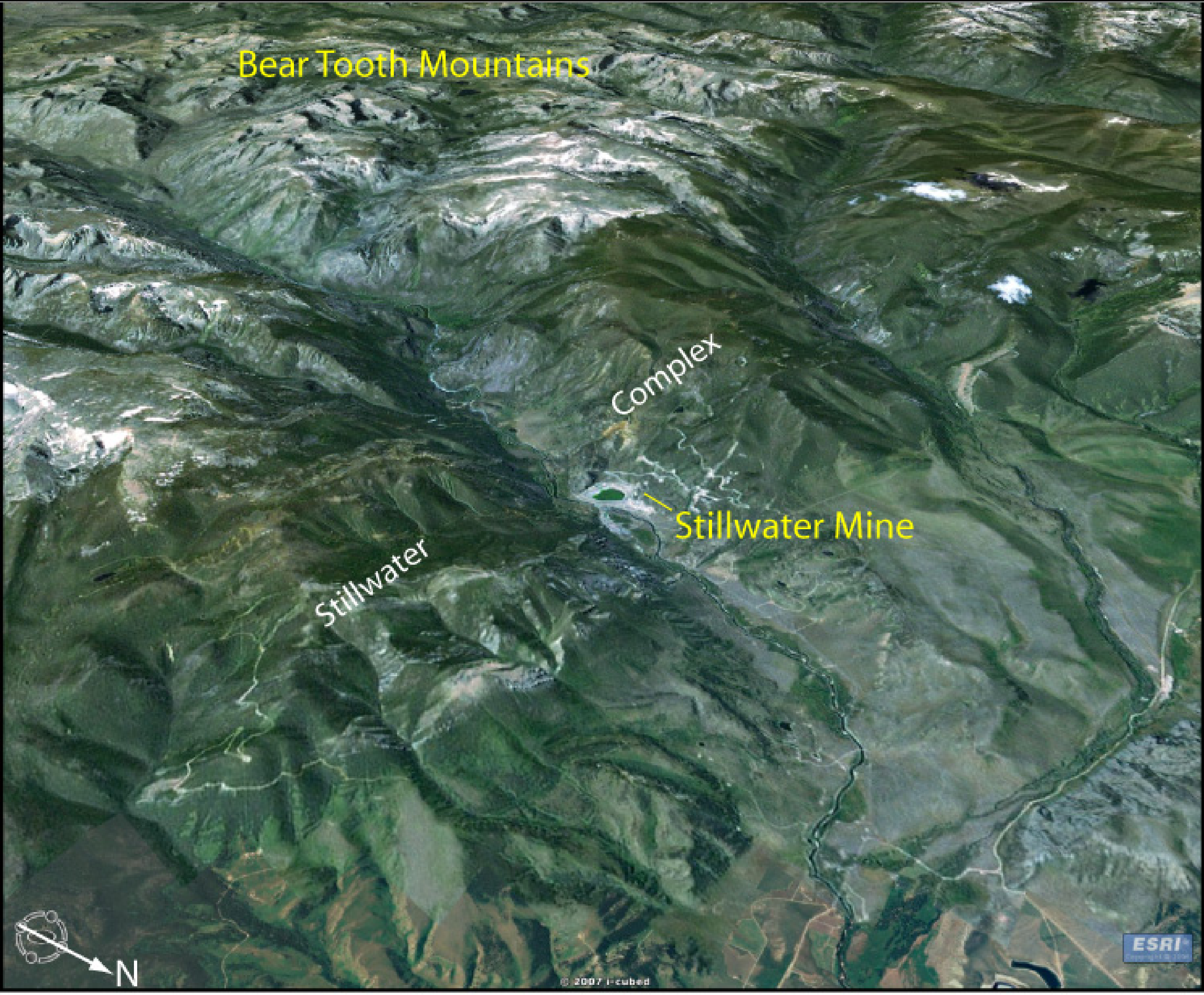
- The bulk of our material came from the Stillwater Complex in Montana which has long been proposed as a source of materials for highland simulants.

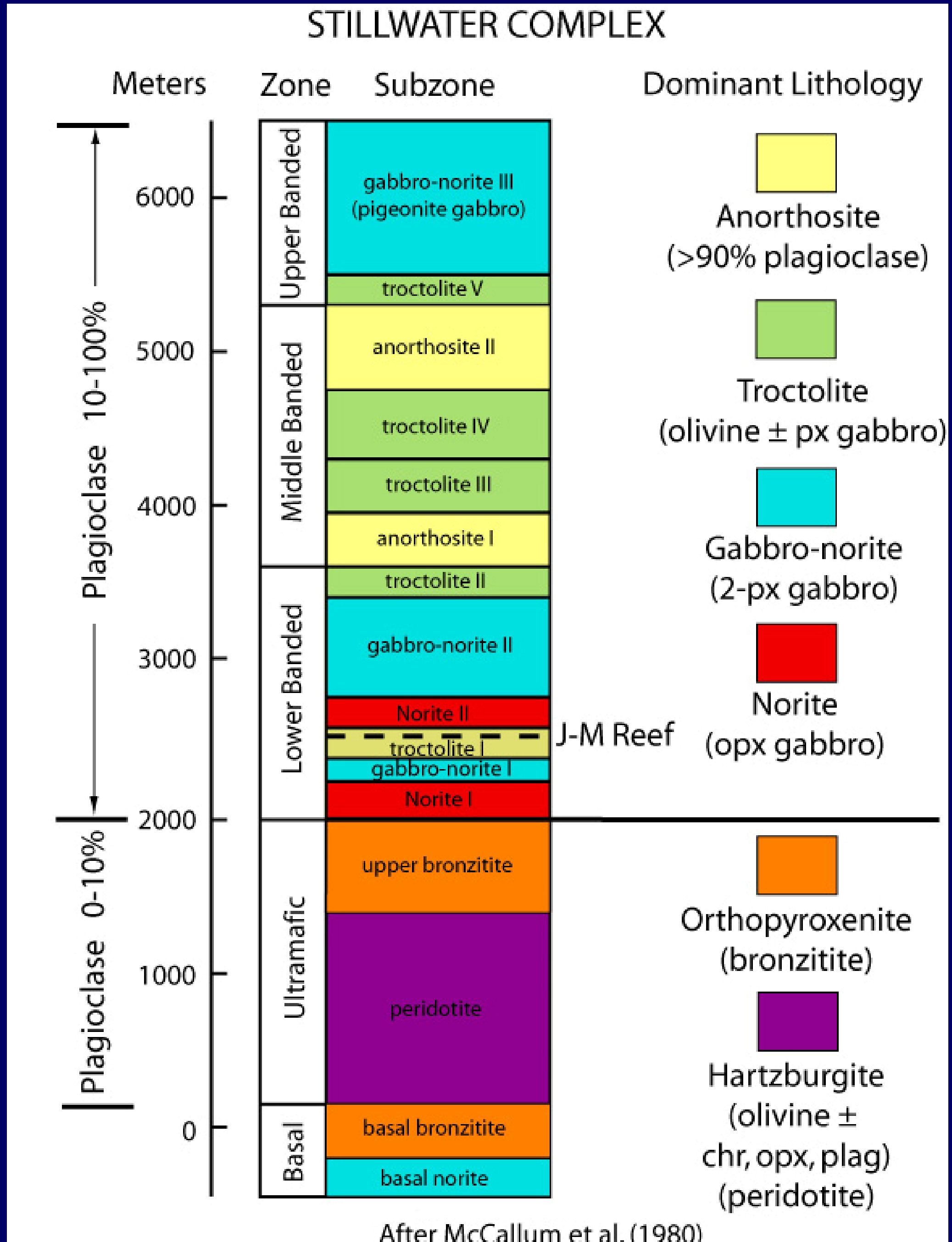

BRITISH COLUMBIA
GLACIER NATIONAL PARK
ALBERTA
SASKATCHEWAN
NORTH DAKOTA
IDAHO
SOUTH DAKOTA
WYOMING
YELLOWSTONE NATIONAL PARK
Stillwater Complex
Beartooth Mountains
Yellowstone Park

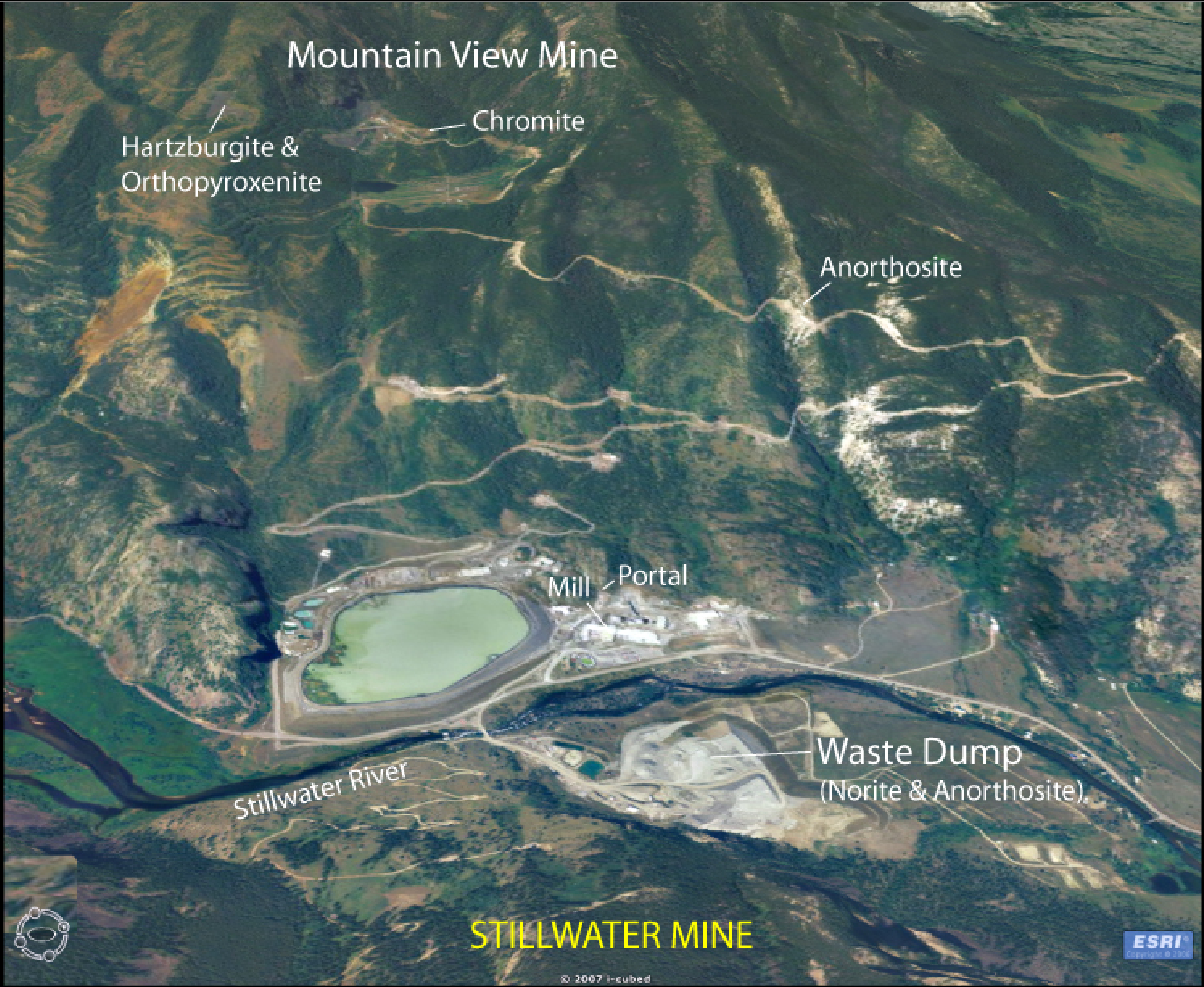
LHT-SOURCE MATERIALS

- The Stillwater Mining Company is actively supporting the simulant effort. The SMC is mining platinum and palladium from the Complex in the basal norite zone (from the "J-M Reef", 6-9 ft wide & 28 miles long).
- Both the highlands and the Stillwater are composed of the same major minerals: plagioclase (Na-Ca-Al-Silicate), pyroxenes and olivine (Fe-Mg silicates).
- The lunar highlands regolith has the overall composition of a anorthositic gabbro-norite (~75-83% calcic-plagioclase, ave. ~ An94).
- The Stillwater Complex is a mafic layered intrusion consisting of hartzburgite, orthopyroxenite, norite, gabbro-norite, gabbro, and anorthosite.
- LHT-1M is completely composed of rock materials from the Stillwater Complex, except for ilmenite obtained courtesy of Iluka Resources.
- LHT-1M glasses were made from Stillwater Mill waste.

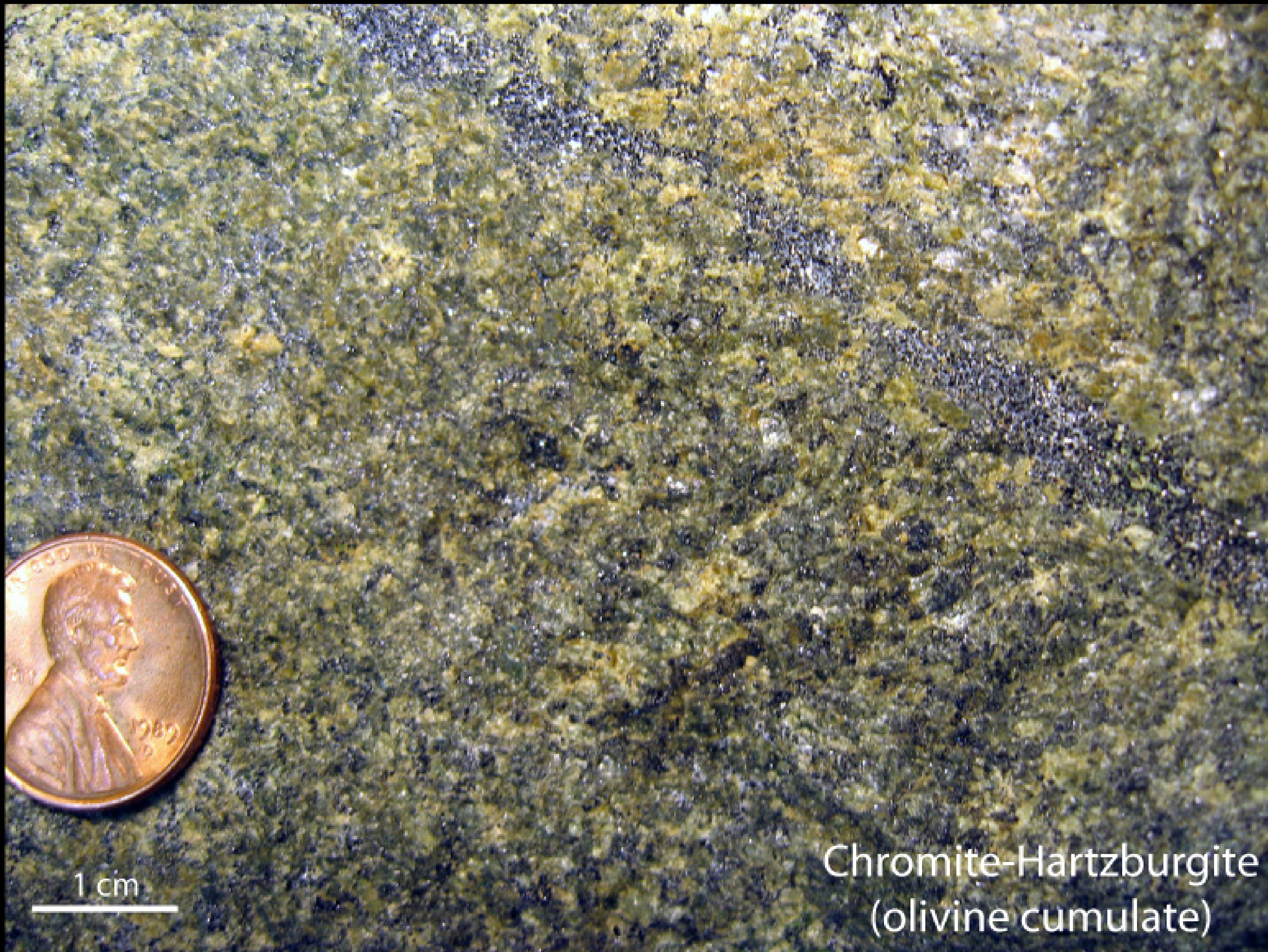

STILLWATER COMPLEX
2.7 billion years old
>30 miles long
~20,000+ feet thick
East Boulder River
Boulder River
Stillwater River, West Fork
STILLWATER MINE
Stillwater River
fault
J-M Reef
LAYERED SERIES
anorthosite
gabbro
ULTRAMAFIC SERIES
orthopyroxenite
peridotite (hartzburgite)
Younger sedimentary rocks
Older metamorphic and igneous rocks
8 km
5 mi

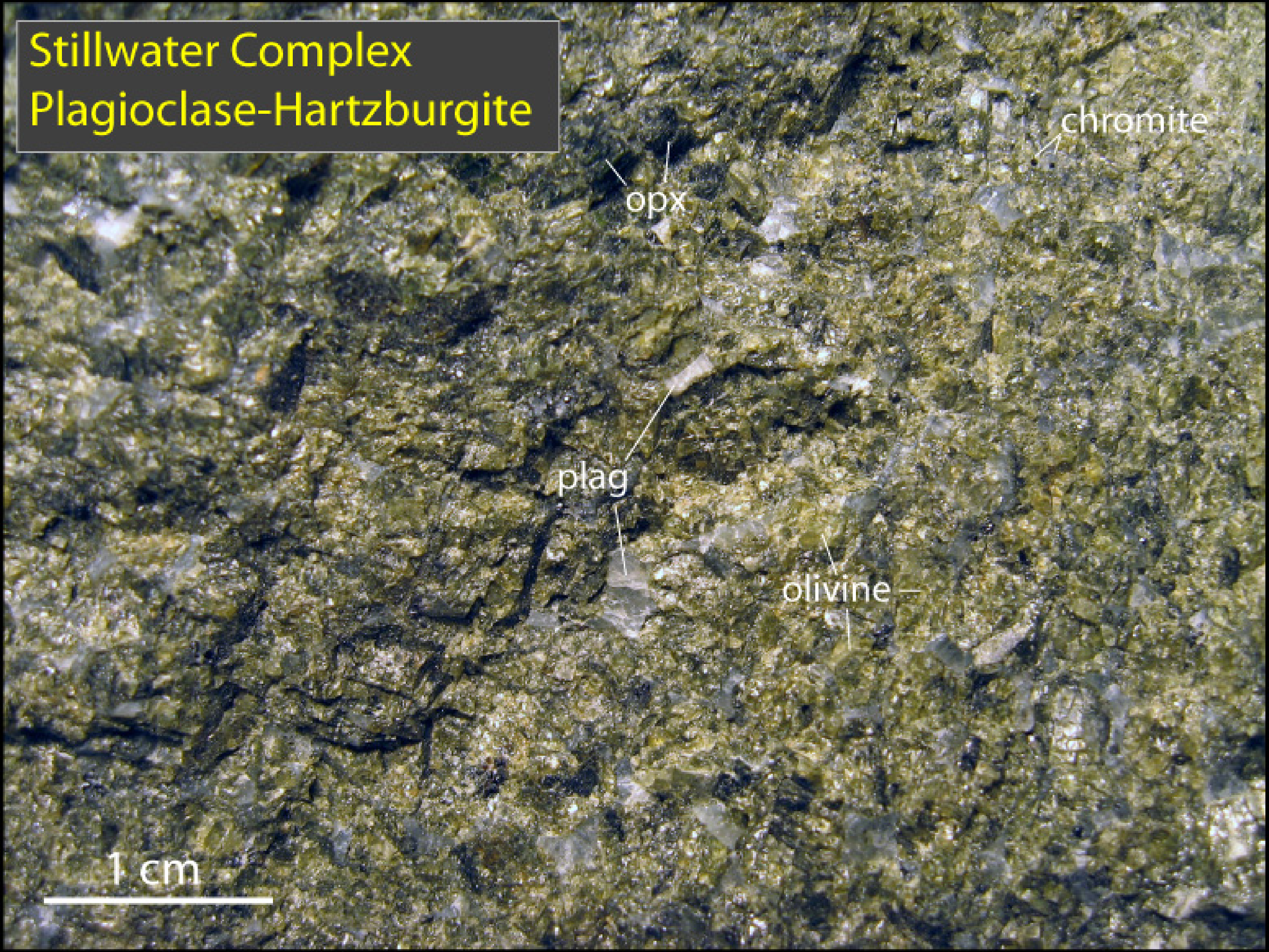

Bear Tooth Mountains
Complex
Stillwater Mine
Stillwater
N
© 2007 i-cubed
ESRI


STILLWATER COMPLEX
Meters
Zone
Subzone
Dominant Lithology
6000
5000
4000
3000
2000
1000
0
Plagioclase 10-100%
Plagioclase 0-10%
Upper Banded
Middle Banded
Lower Banded
Ultramafic
Basal
gabbro-norite III (pigeonite gabbro)
troctolite V
anorthosite II
troctolite IV
troctolite III
anorthosite I
troctolite II
gabbro-norite II
Norite II
J-M Reef
troctolite I
gabbro-norite I
Norite I
upper bronzitite
peridotite
basal bronzitite
basal norite
Anorthosite (>90% plagioclase)
Troctolite (olivine ± px gabbro)
Gabbro-norite (2-px gabbro)
Norite (opx gabbro)
Orthopyroxenite (bronzitite)
Hartzburgite (olivine ± chr, opx, plag) (peridotite)
After McCallum et al. (1980)



Mountain View Mine
Chromite
Hartzburgite &
Orthopyroxenite
Anorthosite
Portal
Mill
Waste Dump
(Norite & Anorthosite).
Stillwater River
STILLWATER MINE
ESRI
© 2007 i-cubed


1 cm
Chromite-Hartzburgite
(olivine cumulate)


Stillwater Complex
Plagioclase-Hartzburgite
chromite
opx
plag
olivine
1 cm


cpx
opx
Pl
1 cm
Stillwater
Plagioclase-Orthopyroxenite


NORITE
1 CM
PLAGIOCLASE (WHITE)
ORTHOPYROXENE (BROWN)


NORITE FEED STOCK


STILLWATER MILL "SAND" (WASTE)
Composition of plagioclase-rich gabbro-norite (69% normative plagioclase, AN82)

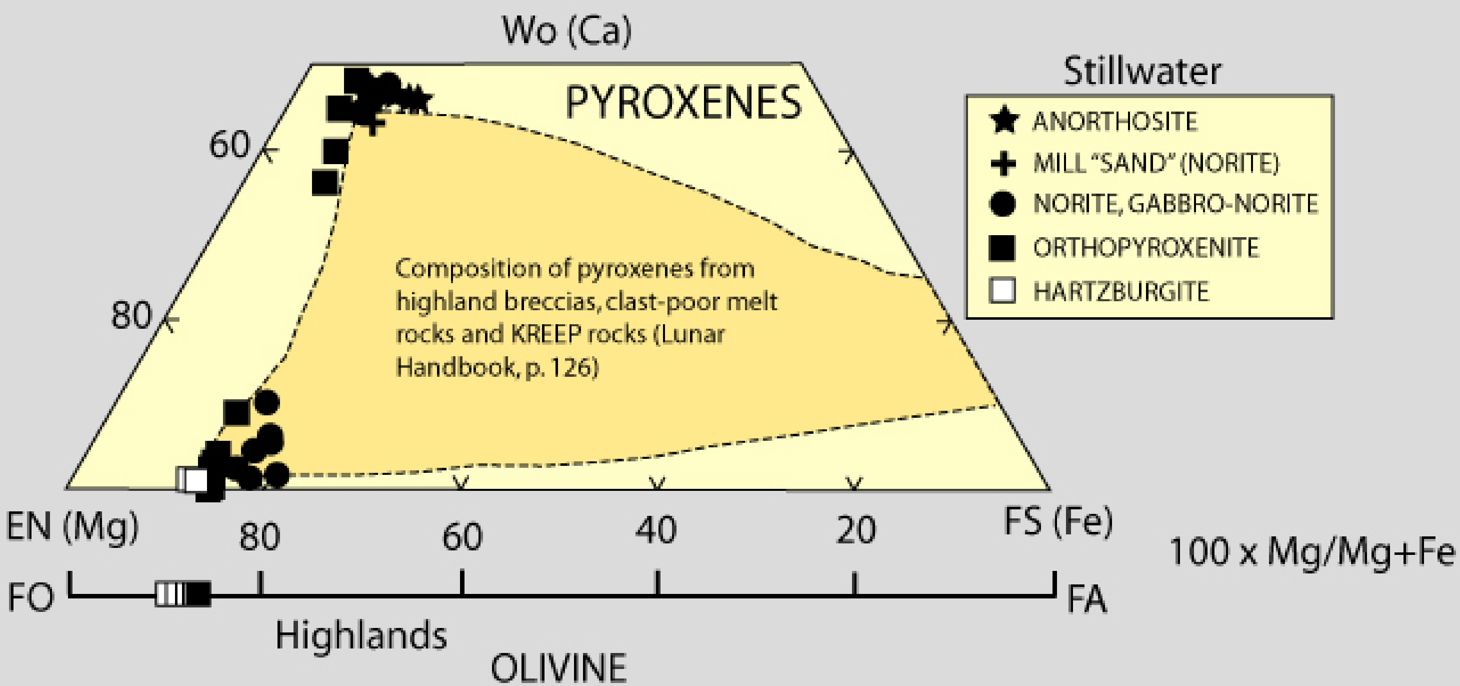

ANORTHOSITE
poikilitic
clinopyroxene
1 cm

LHT-1M Component Mineral Compositions

PLAGIOCLASE (ave. AN content & range)		
Anorthosite:	79	(62-85)
Mill Sand	83	(60-96)
Norite:	84	(78-92)
Orthopyroxene	75	(73-78)
Hartzburgite	66	(64-68)

AN = 100 x Ca/Ca+Na

Average highlands ~AN 94



Simulant requirements

- Proper Mineralogy
  - Appropriate chemical composition
  - Absence of alteration minerals
- Optimal particle size distribution
- Appropriate shape distribution
- Major glass content
  - High quality (HQ) glass
  - Agglutinate (LQ) glass

Development approach

- Target average Apollo 16 lunar soil composition
  - NASA conference pub 2255 (1982)
- Chemical analysis of starting constituents
- USGS blending program optimizes mixture
- Mixture is modified to include best mineralogical composition

USGS

Chemical composition starting materials

Sample ID	SiO_2	Al_2O_3	Fe_TO_3	MgO	CaO	Na_2O
Norite	49.4	23.72	4.07	8.17	13.6	0.84
Anorth.	48.6	30.9	1.54	1.47	15.9	1.7
Harz.	43.7	2.1	**13.1**	**38.3**	1.87	<0.2
Sand	47.7	22.1	6.2	10.5	12.5	0.9
Apollo 16	44.9	25.0	9.3	5.8	15.7	0.47

Components used

Material	Amount	% of total
Norite	38 lbs	30.0
Anorthosite	55	43.4
Hartzburgite	7.7	6.1
Ilmenite	0.92	0.73
Glass	25	**19.7**
HQ glass	5	(20)
LQ glass	20	(80)

USGS

Simulant preparation

- Starting material crushed <4 mm
  - Norite, Anorthosite, Hartzburgite,
- Grinding time experiments (ball mill)
  - Consistent size reduction
- Develop appropriate mixture of starting material
- Grind for specific time period (15, 45 min.)
- Blend as one batch
- Split using spinning riffler (200g aliquots)

USGS

LHT-1M composition

Oxide	Apollo 16	LHT-1M
SiO_2	44.9	47.6
Al_2O_3	25.0	24.4
FeO	8.4	4.3
MgO	5.8	8.5
CaO	15.7	13.1
Na_2O	0.47	1.4

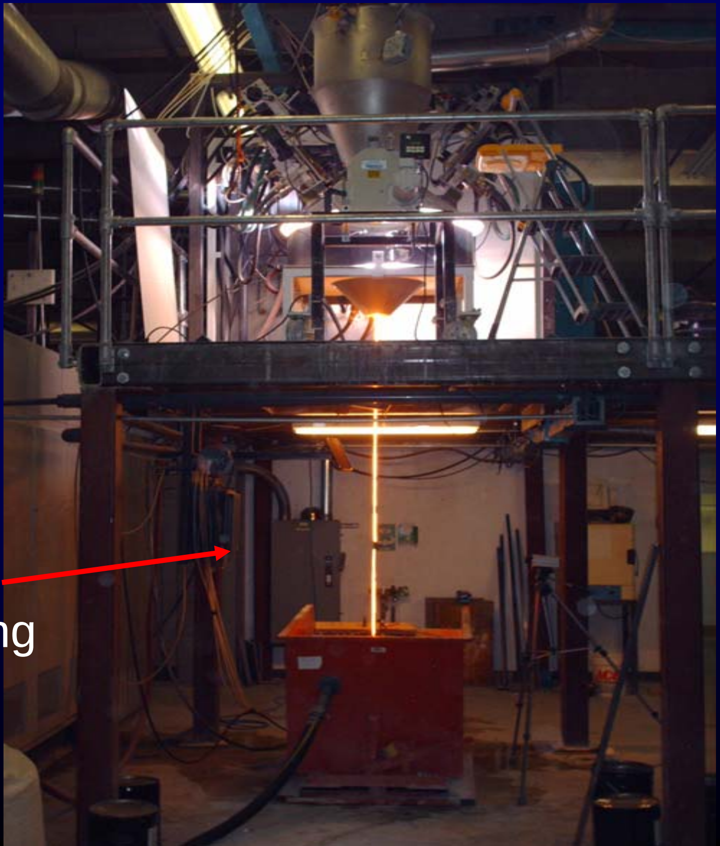
Glass production

- Need to develop technology for glass production
  - HQ glass
  - Agglutinate (LQ) glass
- High throughput 100's kg per day
- Excellent temperature control
- Able to handle geologic source material (powder)
- High temperature plasma

Plasma Technology

- Remotely-coupled transferred arcs
  - Non-conductive material rapidly heated / cooled
  - Extreme thermal gradient
  - Power density - 140 MW/m^3
- Glass exit temperatures 1,300–1,925 °C. Up to 150 kg/hr
- Plasma temperatures 13,000˚K to 21,000˚K
  - Typically run at 600 to 1,200 amps

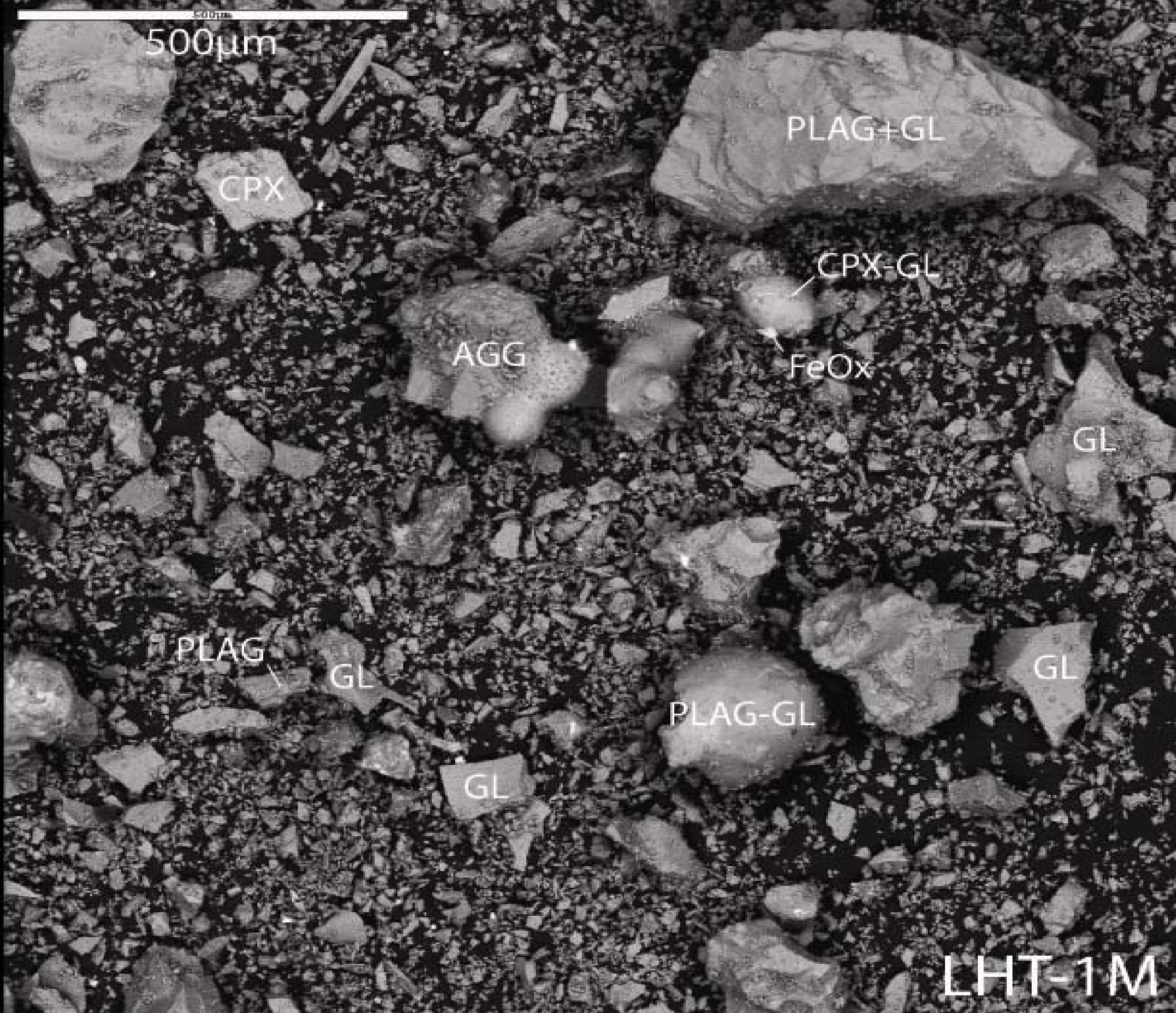
LHT glass manufacturing



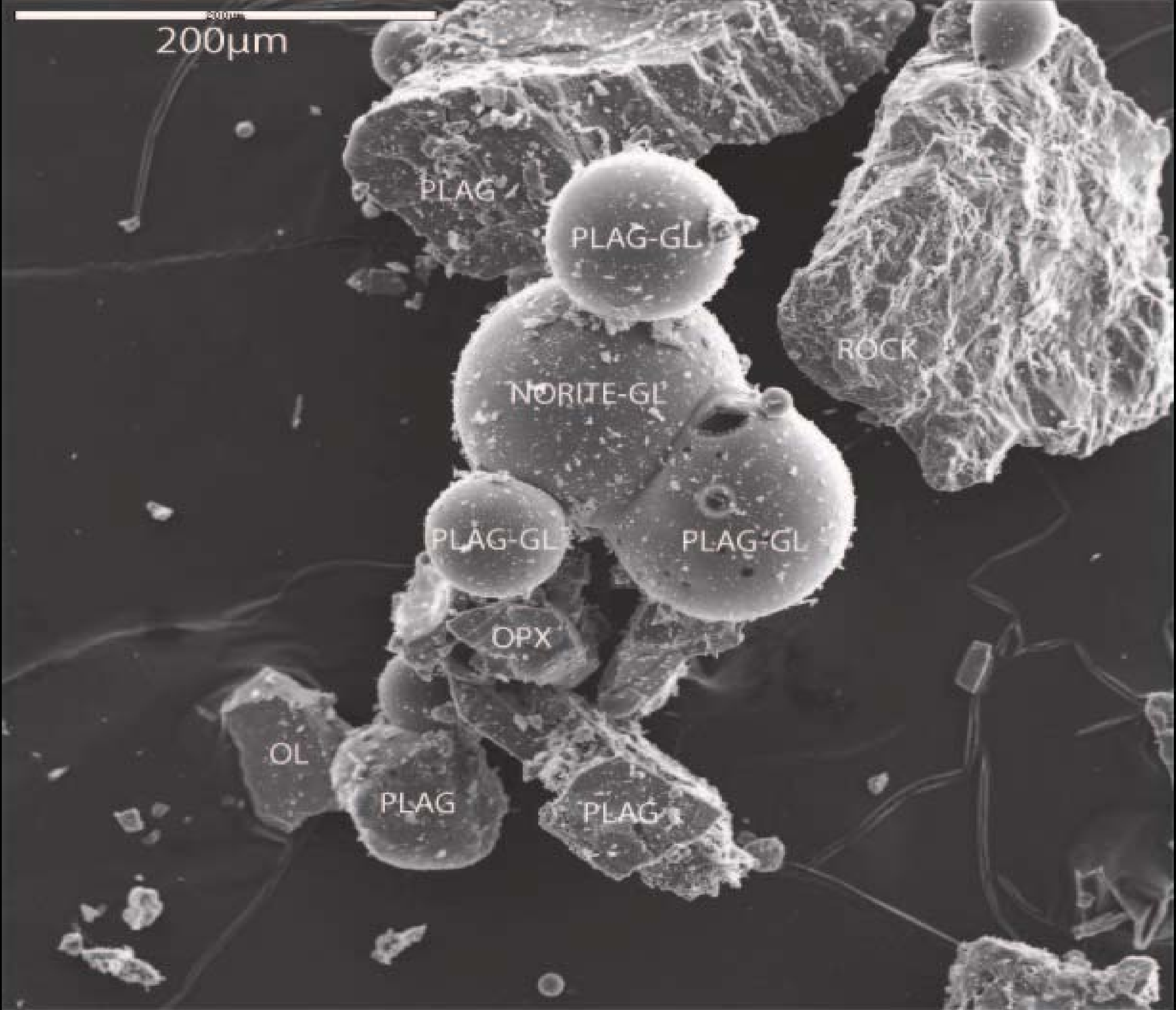
Agglutinate production

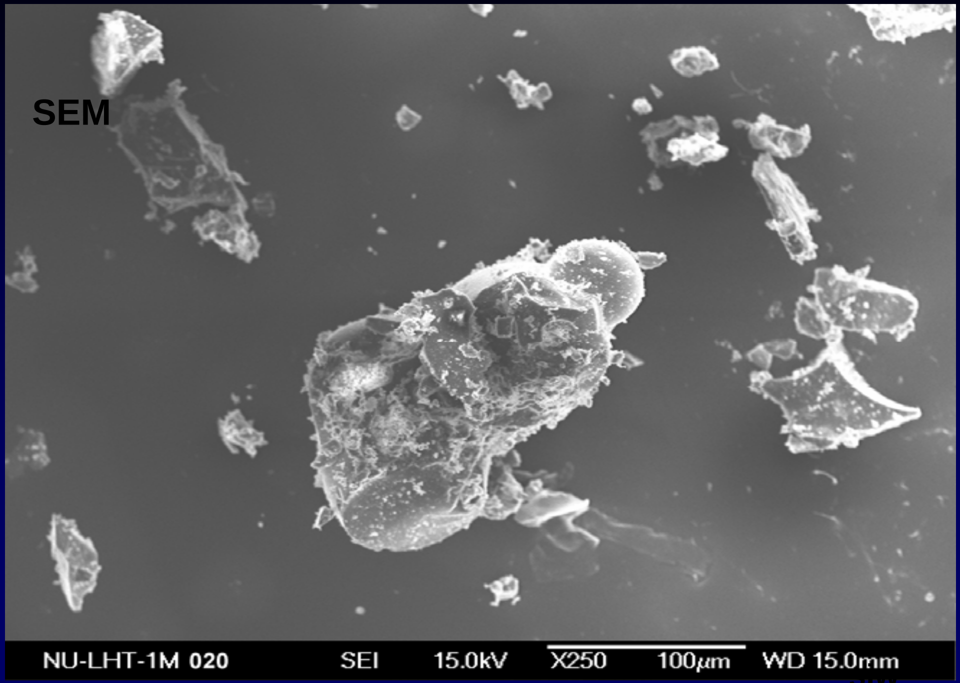
- Partially melted material
- Irregular internal structure, vesicles
- Very friable
- Production rates at 50+ kg (110+ lbs) per day

Movie clip

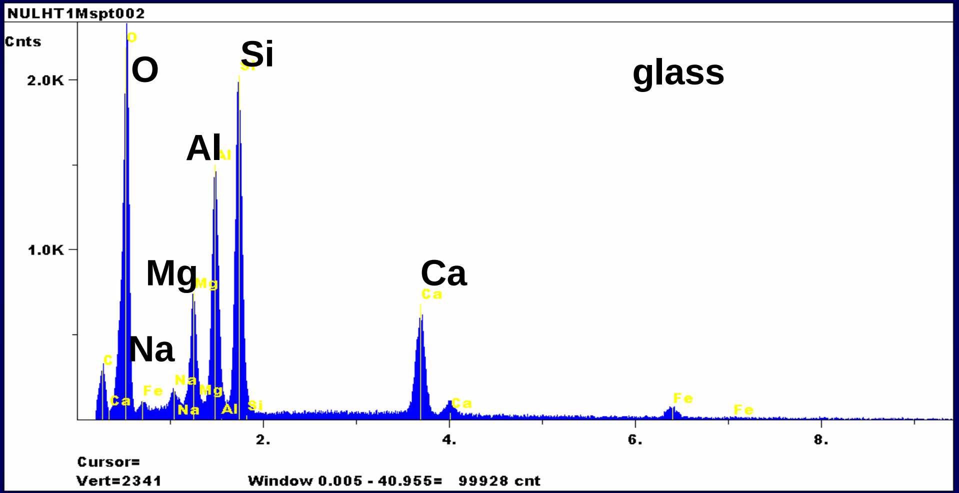

500μm
PLAG+GL
CPX
CPX-GL
AGG
FeOx
GL
PLAG
GL
PLAG-GL
GL
GL
LHT-1M

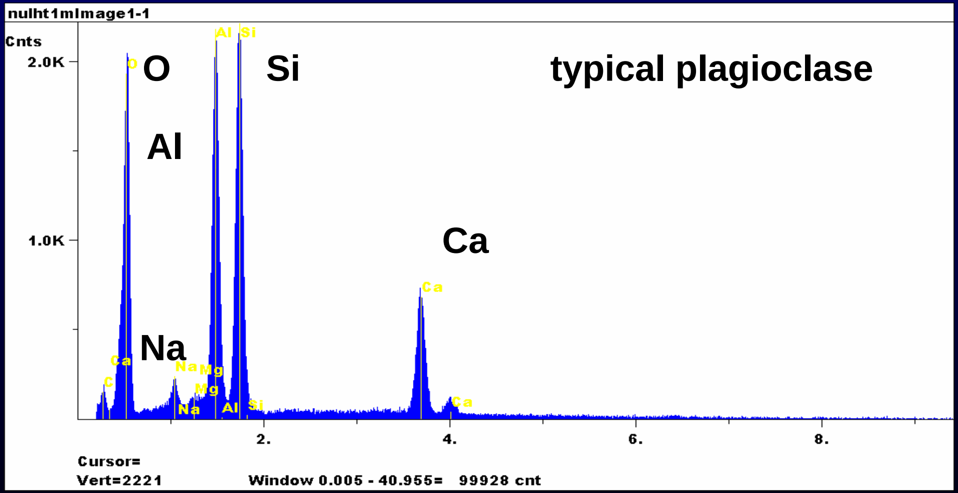

15kV
X37 500µm
USGS LHT-1


200μm
PLAG
PLAG-GL
ROCK
NORITE-GL
PLAG-GL
PLAG-GL
OPX
OL
PLAG
PLAG



Glass spherules are rare to isolated. This one is firmly attached to larger vesicular glass.
Glass has Mg-rich highlands composition regardless of shape, and is homogeneous.
No inclusions have been identified in glass.
Nothing found in sample that looks like agglutinate.
Found isolated ilmenite(?), a Zr-rich grain, and a grain consisting of Si, Al, C, and O.





Glass constituents (in order of decreasing peak height, which qualitatively correlates to abundance): O, Si, Al, Mg, Ca, Na, Fe.

Composition is excellent approximation to those of many lunar highland impact glasses .

USGS

System overview

Bruker AXS X-ray detectors

Carl Zeiss custom SEM

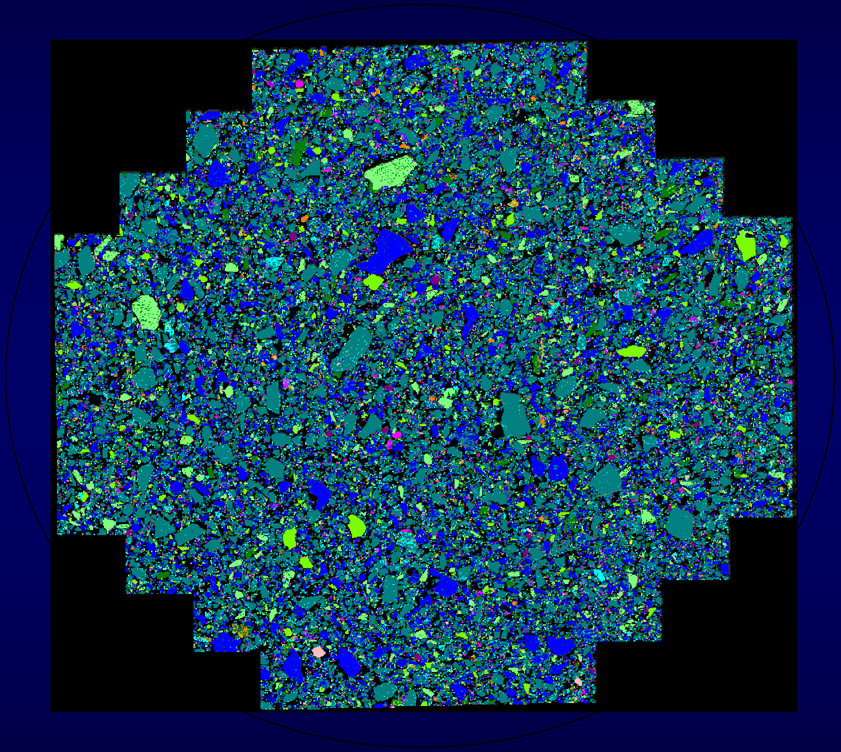
Intellection iDiscover™ analytic software suite

Intellection QEM*SEM® integrated control hardware

QEMSCAN® uses advanced e-beam technology from Carl Zeiss and combines this with high resolution BSE and SE imaging, and state-of-the-art Energy Dispersive Spectrometers. It integrates these using iDiscover software to provide a solution capable of identifying most rock-forming minerals in just milliseconds

QEMSCAN® Results

Digital photograph of a 30mm diameter polished block



QEMSCAN® false-coloured, digital particle mineral map montage of a polished block

Modal Composition and Repeatability

	NU-LHT-1M: C	NU-LHT-1M: B
CaMgFe Glass	26.0	26.8
MgFeAl Silicate	0.5	0.5
Ca Al Silicate Glass	1.7	2.2
Mg Silicates	1.3	1.4
Olivine	3.5	3.6
Orthopyroxene	7.6	6.8
Clinopyroxene	8.3	8.2
K Feldspar	0.1	0.1
Plagioclase (An60-An100)	45.6	44.6
Plagioclase (Ab-An60)	4.1	4.1
Quartz	0.2	0.2
Ilmenite	0.6	0.4
Chromite	0.1	0.1
Magnetite	0.1	0.3
Iron	0.0	0.5
Others	0.3	0.4
Total	100	100

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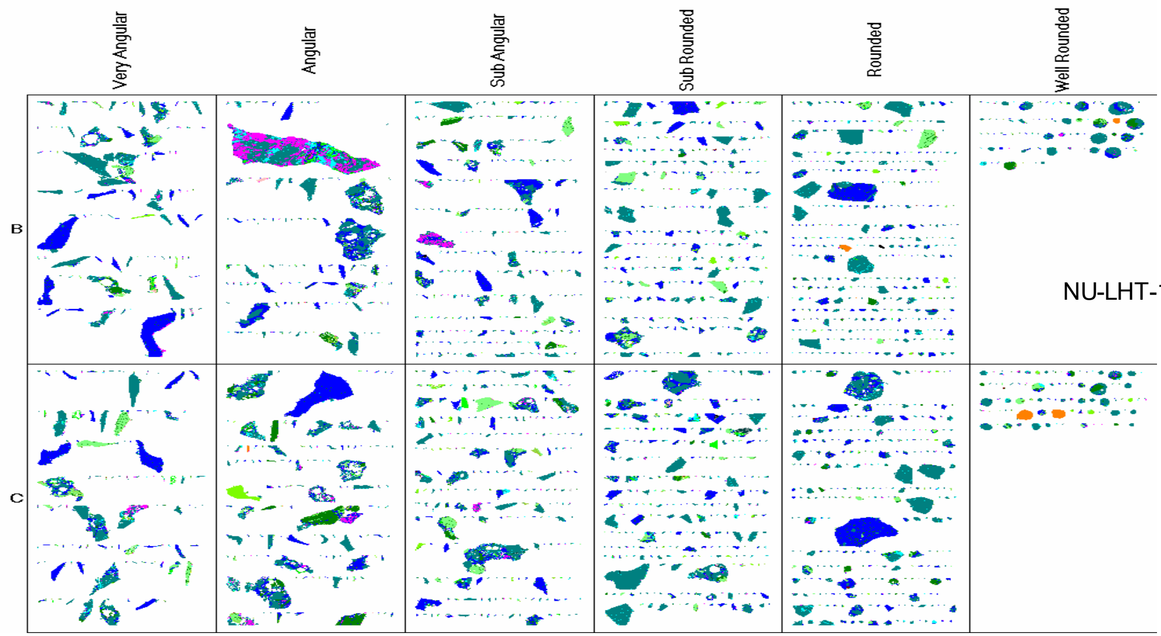
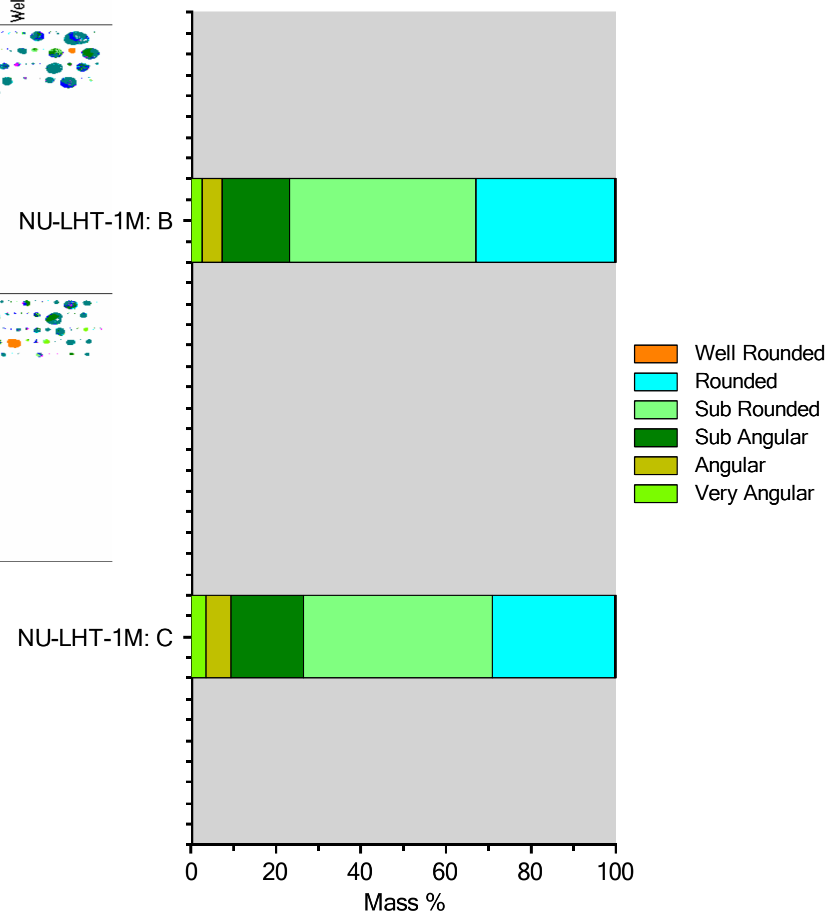
Simulant Particle Shape - Quantified



	NU-LHT-1M: C	NU-LHT-1M: B
Very Angular	3.5	2.5
Angular	5.8	4.8
Sub Angular	17.2	15.9
Sub Rounded	44.3	44.0
Rounded	29.1	32.6
Well Rounded	0.2	0.2
Total	100	100



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Production plans

- Create a prototype material NU-LHT-2M
  - Improvements from LHT-1M effort
  - Addition of minor minerals - fidelity
  - Nanophase iron in agglutinate?
  - More spheroids
- 900 – 1000 pounds
- Expected completion date 1-1-08

U.S. Geological Survey
National Aeronautical and Space Administration
Certificate of Analysis
Lunar Highlands Type simulant (Pilot)
NU-LHT-1M

Material used in the preparation of this pilot simulant material was collected under the direction of the USGS in 2007 from the Stillwater Mining Company, located near Nye, Montana. A variety of samples from the mining operations and locations adjacent to the mine were obtained which are believed to represent the various geologic rock types found in the highlands region of the moon. The USGS performed a basic separation of the starting material by visual inspection, followed by blending of selected aliquots based on chemical and mineralogical considerations. Glass and agglutinate production using material from the Stillwater mine was performed at Zybeck Technologies Inc. using a high temperature plasma melter. Glass and mafic components were then combined, processed and bottled at the USGS. Information presented below is based on analyses preformed at the USGS, Bureau of Reclamation, and Horiba Instruments Inc.

Element	Mean	s.d.	Oxide	Mean	s.d.
Al, %	12.9	1.0	Al_2O_3, %	24.4	3.5
Ca	9.38	0.40	CaO	13.1	0.56
Fe (II)	2.55	0.01	FeO	3.30	0.012

Acknowledgements

- Stillwater Mining company - Dave Ryckman
- JSC collaborators

  John Lindsay, Sara Nobel, Susan Wentworth
- Horiba instruments, shape/size analysis
- Zybeck Advance Products – Mike Weinstein
- Intellection - Alan Butcher

USGS