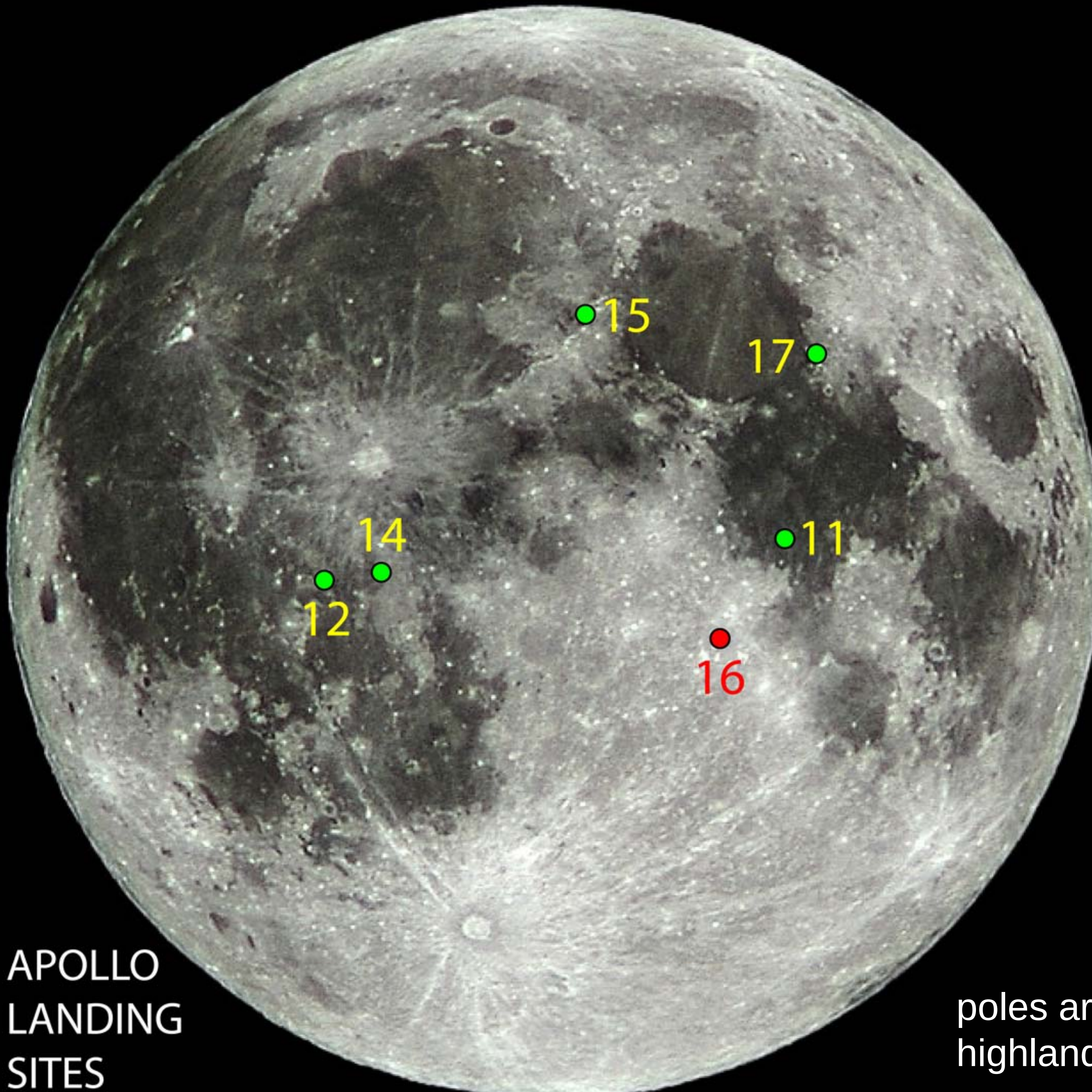
INTRODUCTION TO LUNAR REGOLITH SIMULANTS

Douglas Stoeser
U.S. Geological Survey, Denver, CO
(and the whole Simulant Project)

LUNAR SIMULANT:

"Any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and/or chemical properties of a lunar rock or soil"*

* Workshop on production and uses of simulated lunar materials: LPI Technical Report Number 91-01



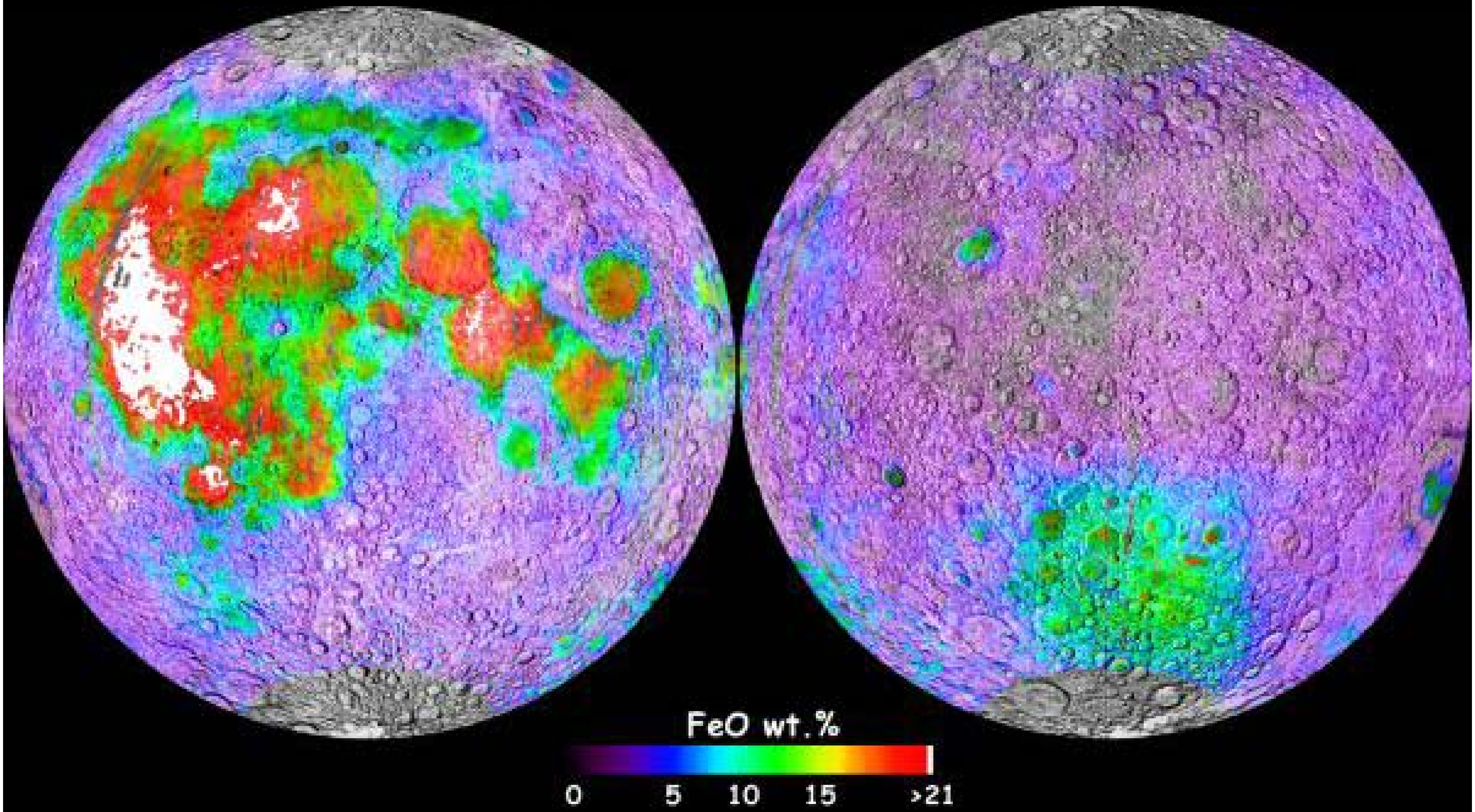
APOLLO
LANDING
SITES

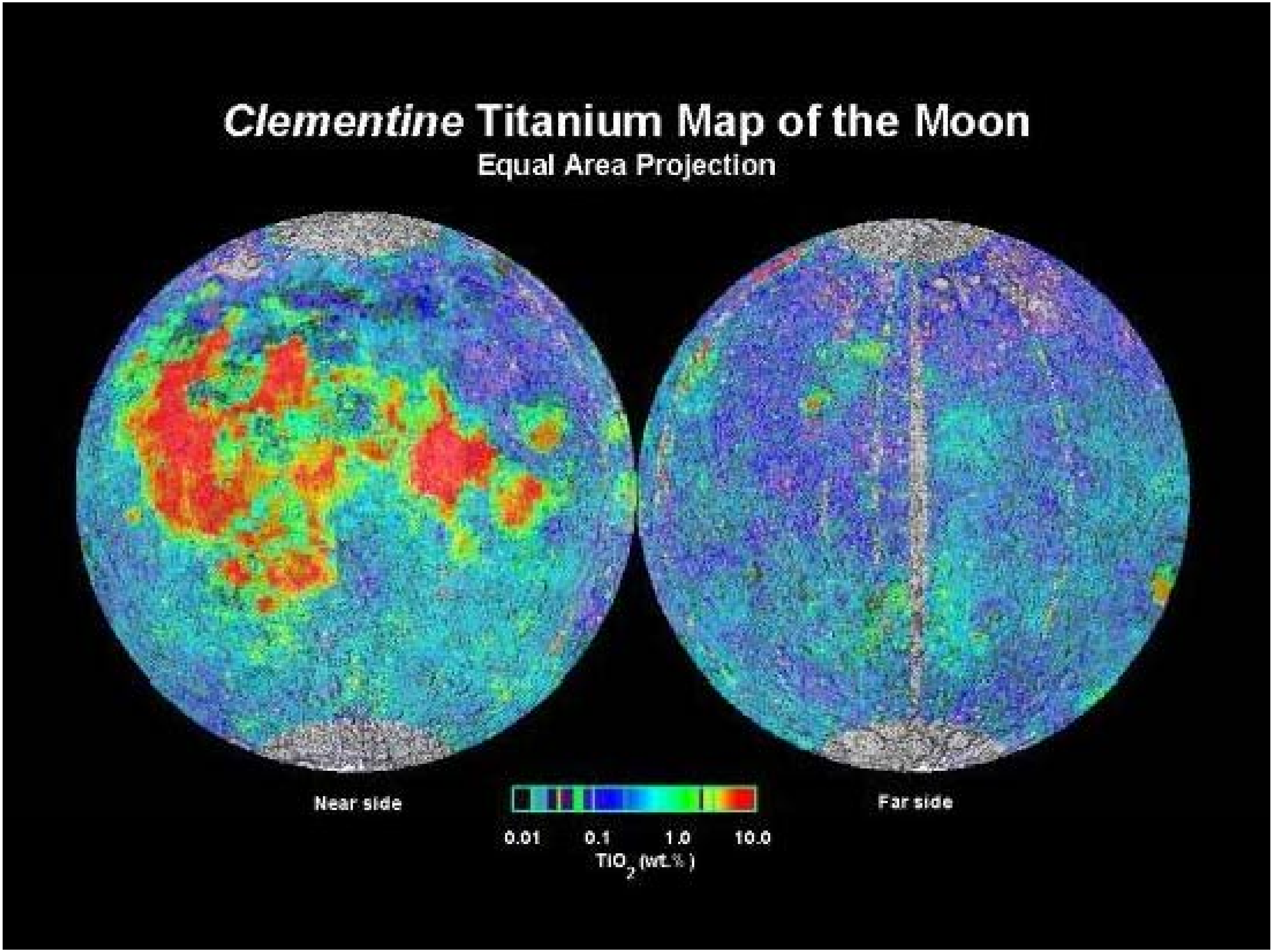
poles are ~
highlands sites

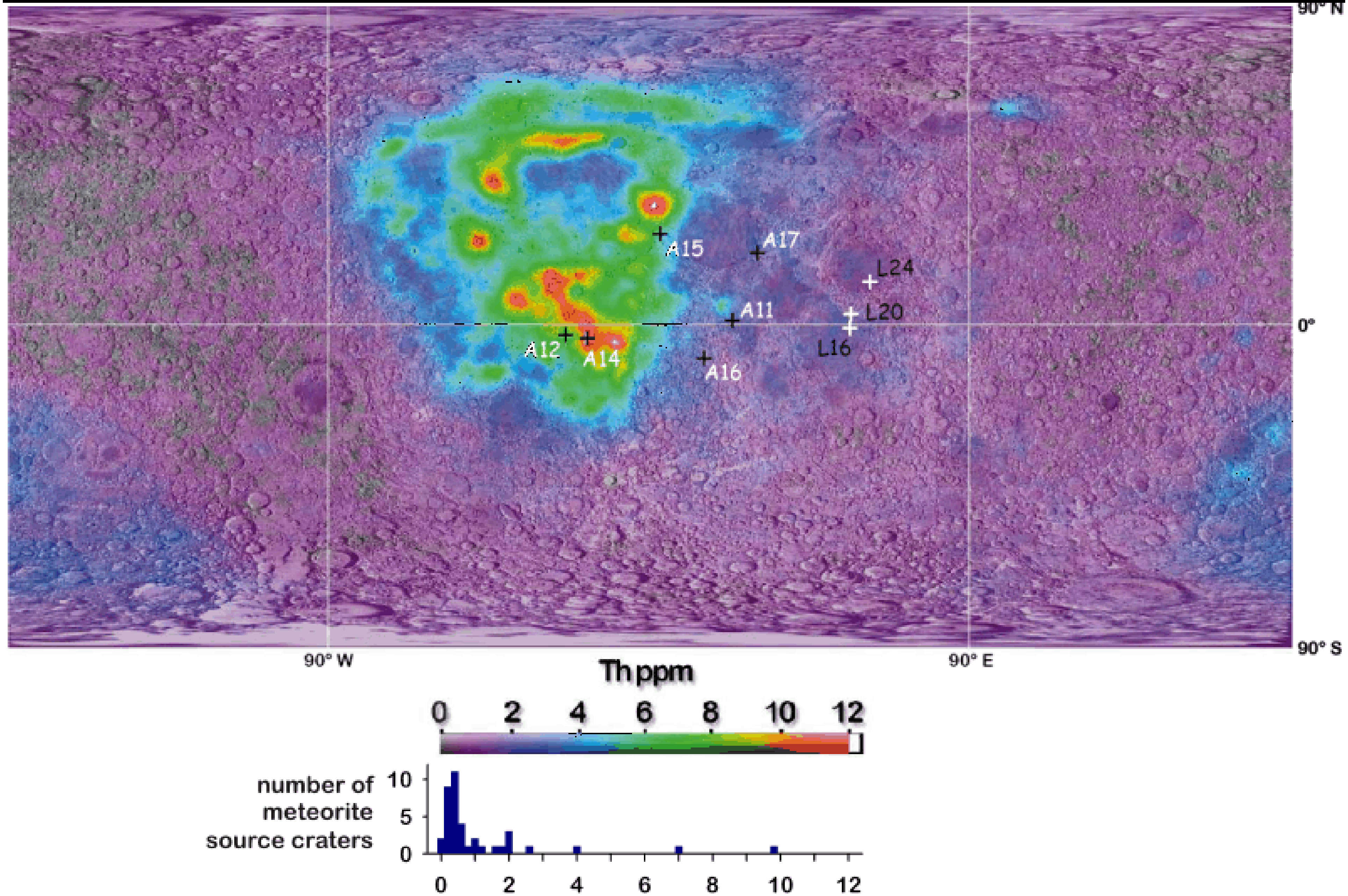
REGOLITH PROVINCES

- HIGHLANDS (UPPER LUNAR CRUST)
- MARE (LOW TO HIGH TITANIUM)
- PROCELLARUM (KREEP)
- SOUTH POLE AITKENS BASIN (LOWER LUNAR CRUST

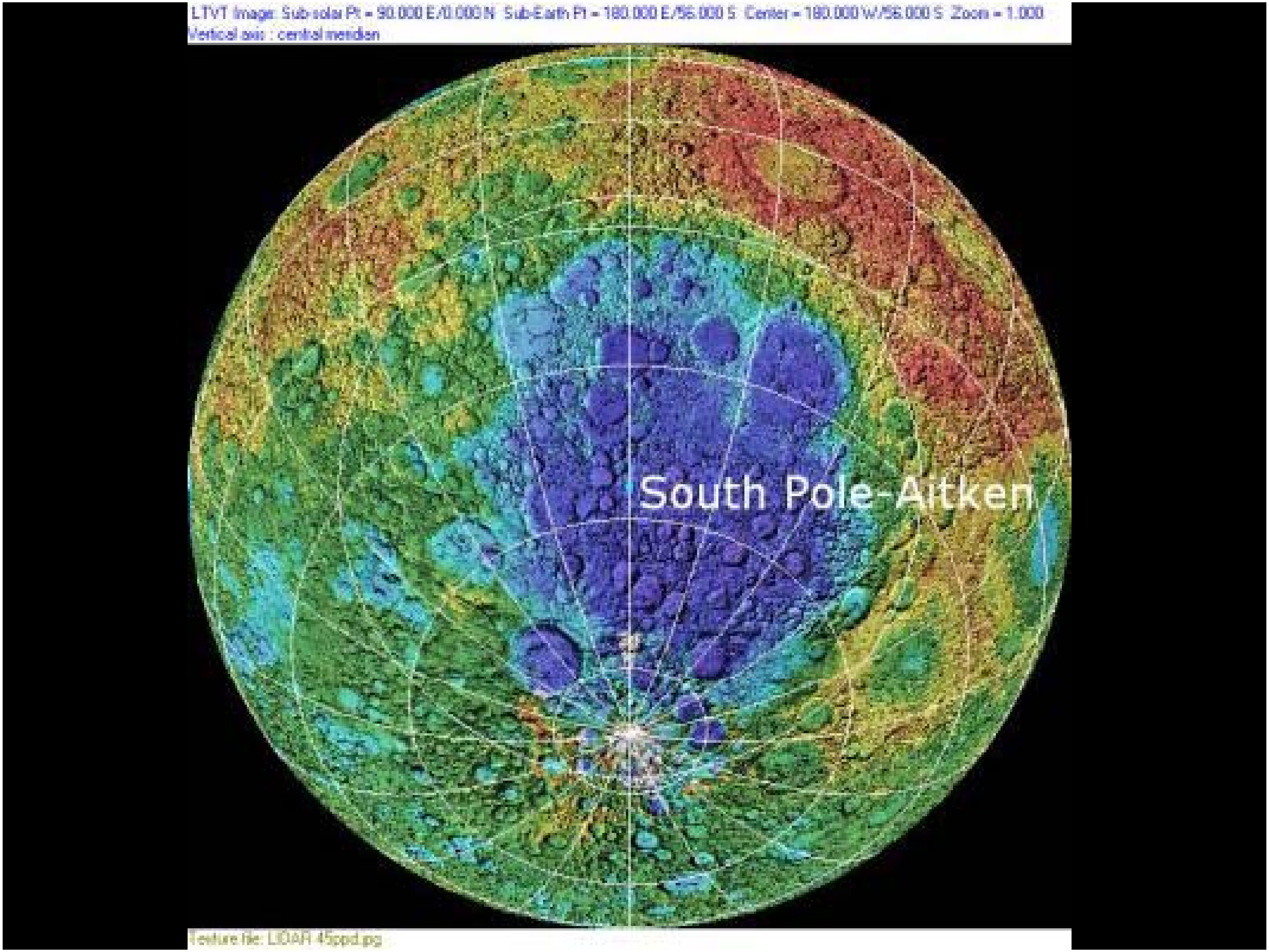
Clementine Iron Map of the Moon




Clementine Titanium Map of the Moon
Equal Area Projection
Near side
Far side
0.01
0.1
1.0
10.0
TiO2 (wt.%)

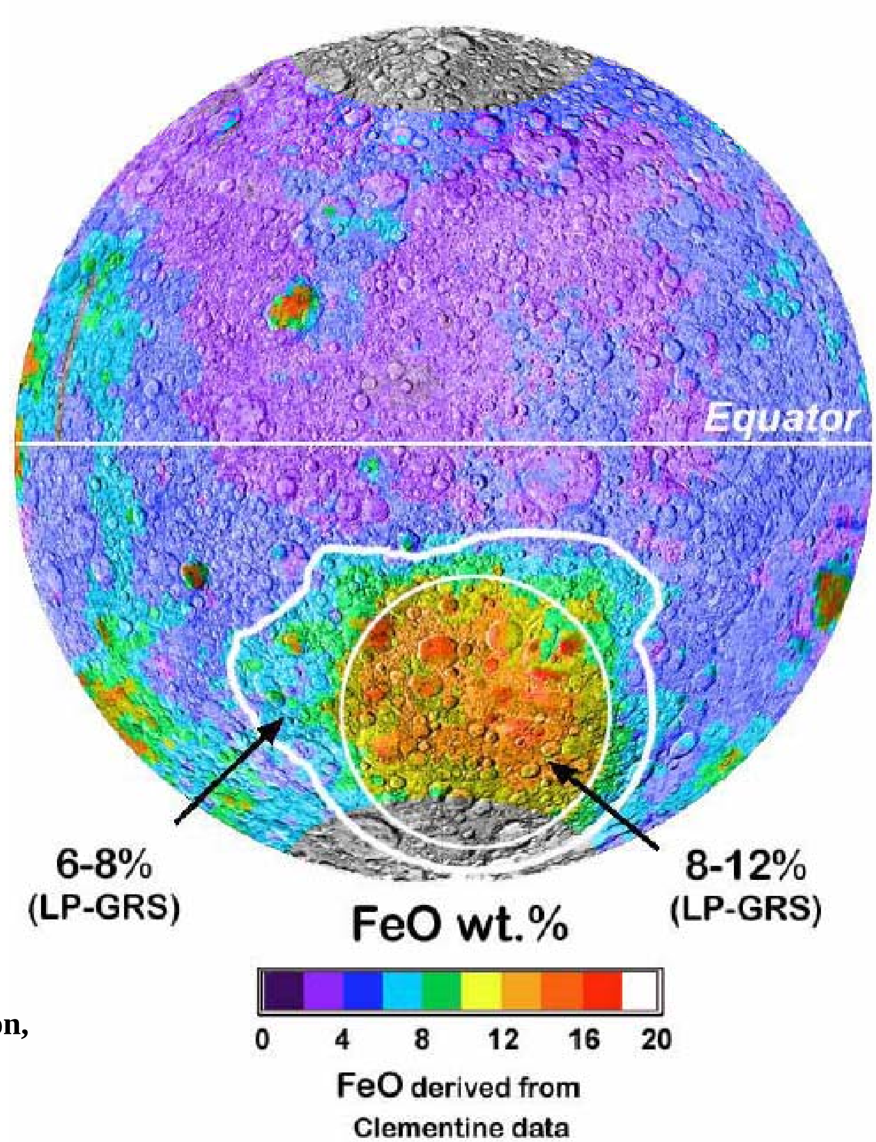


90° N
0°
90° S
90° W
90° E
A15
A17
L24
A11
L20
L16
A12
A14
A16
Th ppm
0 2 4 6 8 10 12
number of meteorite source craters
10
5
0
0 2 4 6 8 10 12


LTVT Image: Sub-solar Pt = 90.000 E/0.000 N Sub-Earth Pt = 180.000 E/56.000 S Center = 180.000 W/56.000 S Zoom = 1.000
Vertical axis : central meridian
South Pole-Aitken
Texture file: LIDAR 45ppd.jpg

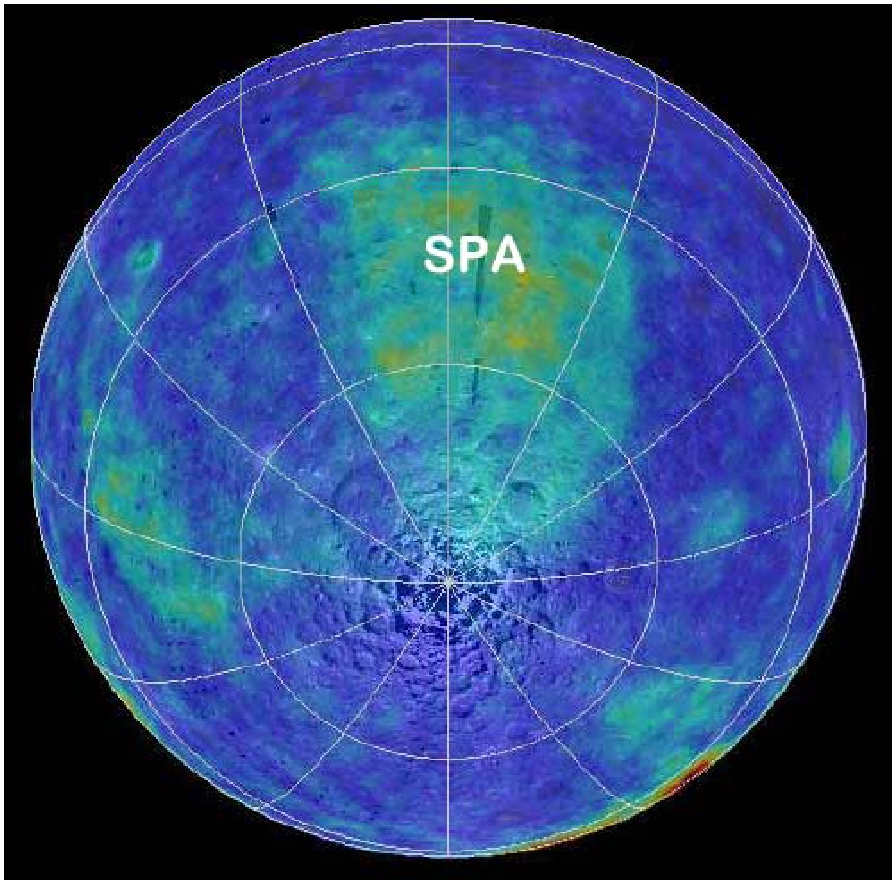
South Pole-Aitken Basin is a window to the lower crust

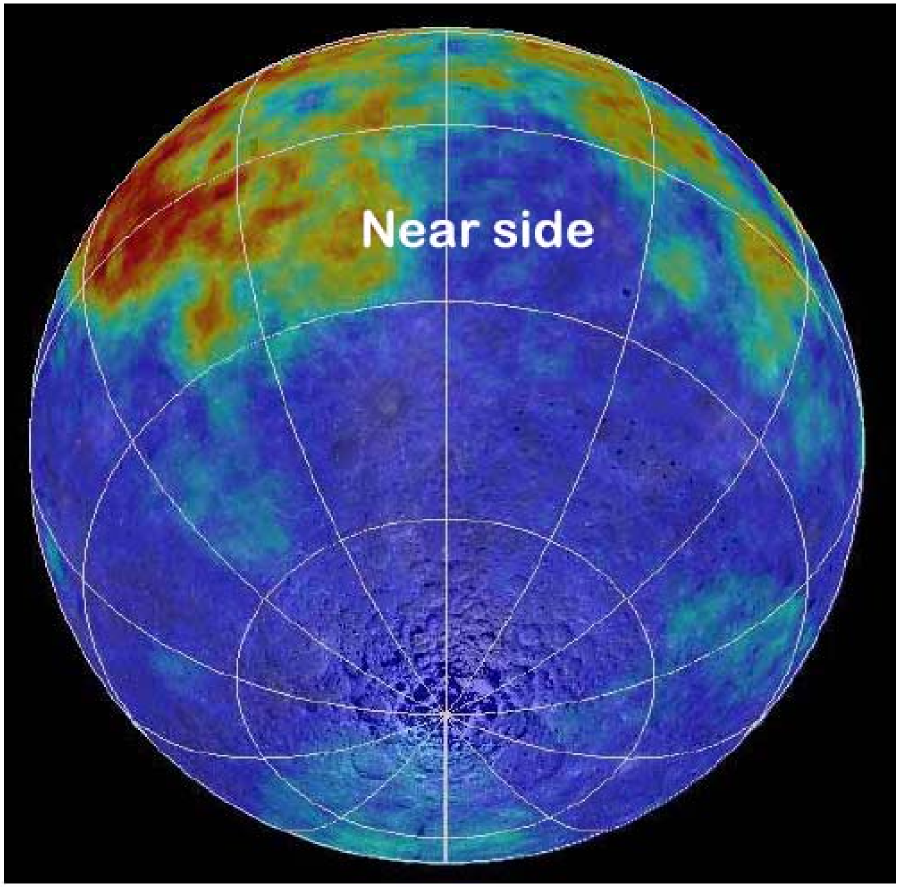
- Interior of basin is FeO-rich for the small amount of mare basalt.
- Ejecta are "intermediate" in FeO content.
- Crust appears to be 10-30 km thick beneath basin interior.



B. Jolliff, R. Korotev, and R. Zeigler, Lunar Crustal Composition, Heterogeneity, and Evolution: Implications for Exploration Workshop on Science Associated with the Lunar Exploration Architecture, Tempe, AZ Feb 27-Mar 2, 2007

South Pole is at edge of compositionally distinctive SPA basin materials.





FeO (LP-GRS)

B. Jolliff, R. Korotev, and R. Zeigler, Lunar Crustal Composition, Heterogeneity, and Evolution: Implications for Exploration Workshop on Science Associated with the Lunar Exploration Architecture, Tempe, AZ Feb 27-Mar 2, 2007

LUNAR REGOLITH SIMULANTS

User Considerations

There can't be one simulant –
the regolith isn't homogeneous and user needs vary

- Site type (mare or highlands or what?)
- General use vs specialized simulants
- Fidelity, how "good" do you need it?
- Grain size (full range, i.e. with rocks, "soil" size (<1mm), or dust?
- Maturity, how much agglutinate/glass?

Basic natural lithic feedstock requirements ("general use" simulant)

- 1. Must be compositionally similar to lunar (chemistry and mineralogy, i.e. include ± plagioclase, pyroxene, olivine, ilmenite, chromite, glass, etc.)
- 2. Must have little or no hydrous mineral or alteration phases
- 3. Must be available in bulk (i.e. up to thousands of tons), i.e. quarries or mines.

Types of feedstocks
(raw materials)

lithic (rock) natural

lithic synthetic

mineral natural

mineral synthetic

glass natural

glass synthetic (incl. agglutinate)

Near Term Future Feedstock Directions

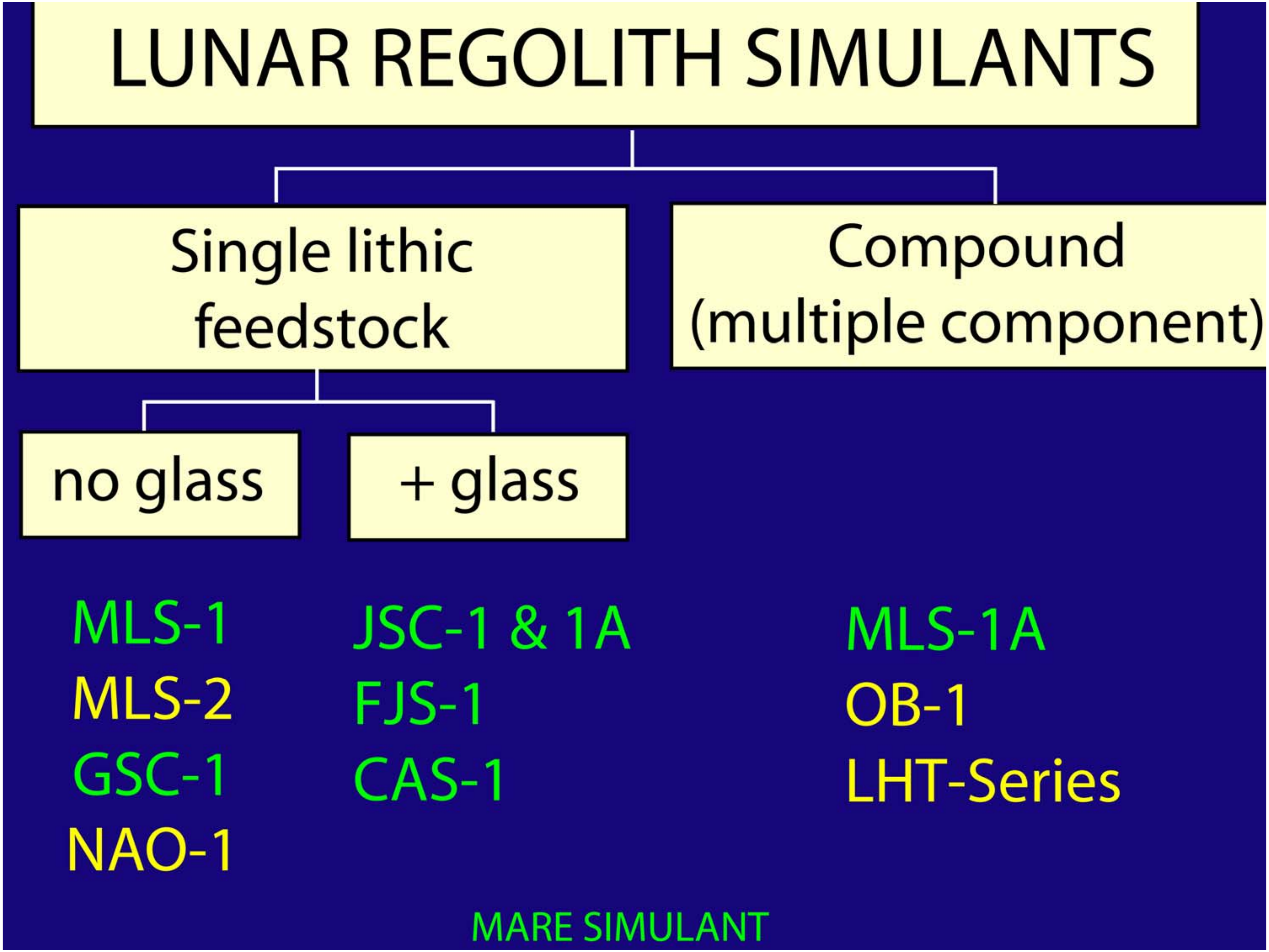
(Steve will present other future directions)

- Nanophase Fe^0 bearing agglutinate (the holy grail of simulant production) Orbitec/Zybek
- Synthetic minerals and rocks, USGS/Zybek
- Natural mineral feedstocks

Some post-Apollo regolith simulants (not an exhaustive list)

Simulant(s)	Type	Primary Reported Use	Manufacturer	Feedstock	Status
NOA-1	Highlands	General?	National Astronomical Observatories, Chinese Academy of Sciences	Gabbro (source?)	Prototype?
CAS-1	Mare, low-Ti	General?	Institute of Geochemistry, Chinese Academy of Sciences	Jinlongdingzi scoria cone	Prototype?
NU-LHT series	Highlands	General	NASA-MSFC and USGS	Stillwater mine (MT), norite, anorthosite; Twin Sisters dunite	In production and use
OB-1	Highlands	Geotechnical	NORCAT	Shawmere anorthosite, +olivine slag glass	In production and use
JSC-1 (-1A, -1AF)	Mare, low-Ti	Geotechnical and lesser chemical	Orbitec, Inc.	Basalt ash, San Francisco volcanic field (AZ)	In production and use
FJS-1	Mare, low-Ti	Geotechnical	Japanese, (JAXA, LETO)	Mt. Fuji area basalt	No longer available
MLS-1	Mare, high-Ti	Chemical	University of Minnesota	Basalt sill, Duluth complex	No longer available

Modified from C. Schrader, 08


LUNAR REGOLITH SIMULANTS
Single lithic feedstock
Compound (multiple component)
no glass
+ glass
MLS-1
MLS-2
GSC-1
NAO-1
JSC-1 & 1A
FJS-1
CAS-1
MLS-1A
OB-1
LHT-Series
MARE SIMULANT

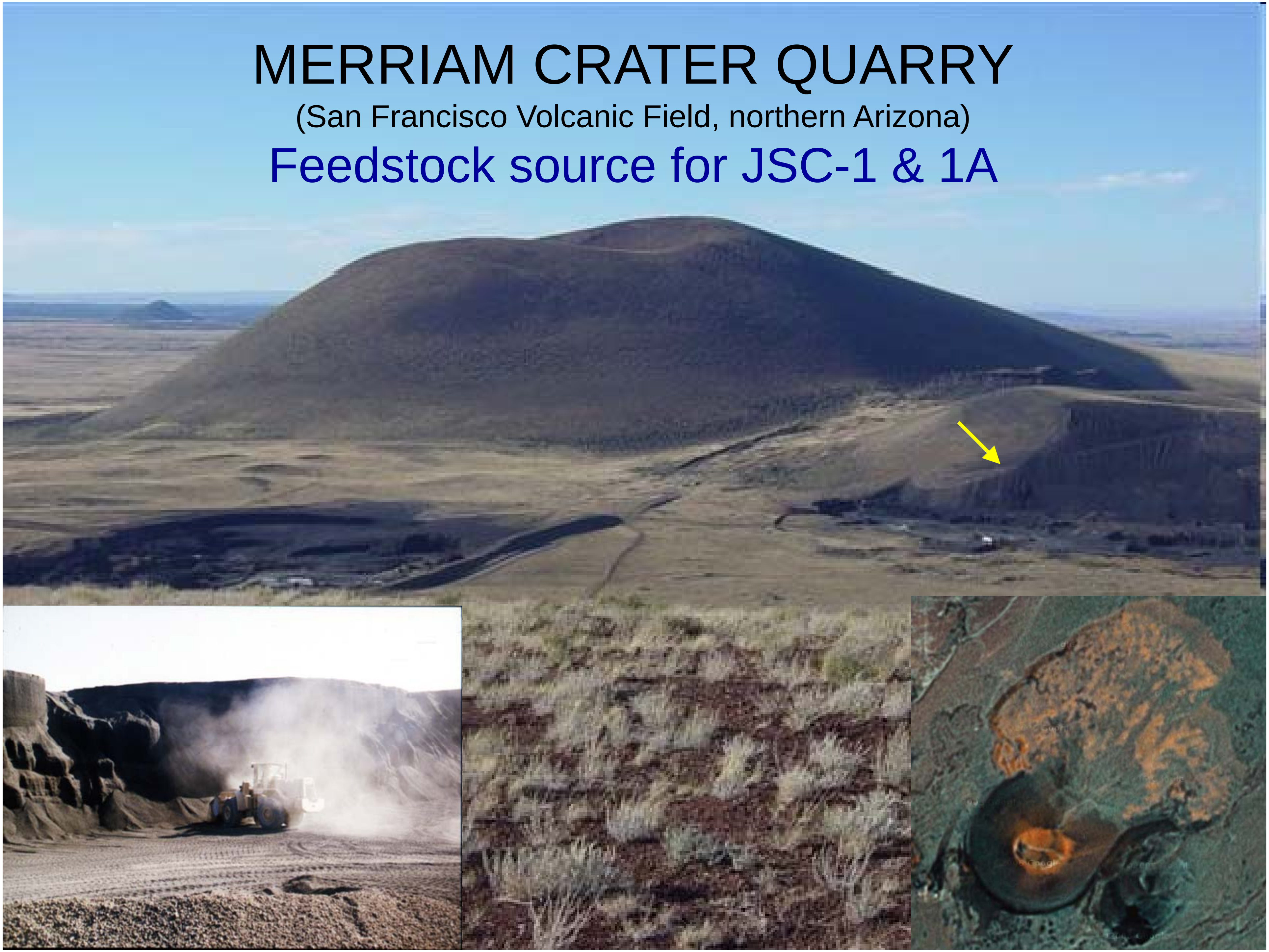
JSC-1A

A loader holds one of the one-ton bags of JSC-1A Moon regolith simulant as it is being emptied into a sandbox for NASA's 2007 Regolith Excavation Challenge. Just beyond the sandbox on the right are unopened bags of JSC-1A simulant ready to be loaded next into the sandbox. Credit: California Space Authority.

MERRIAM CRATER QUARRY

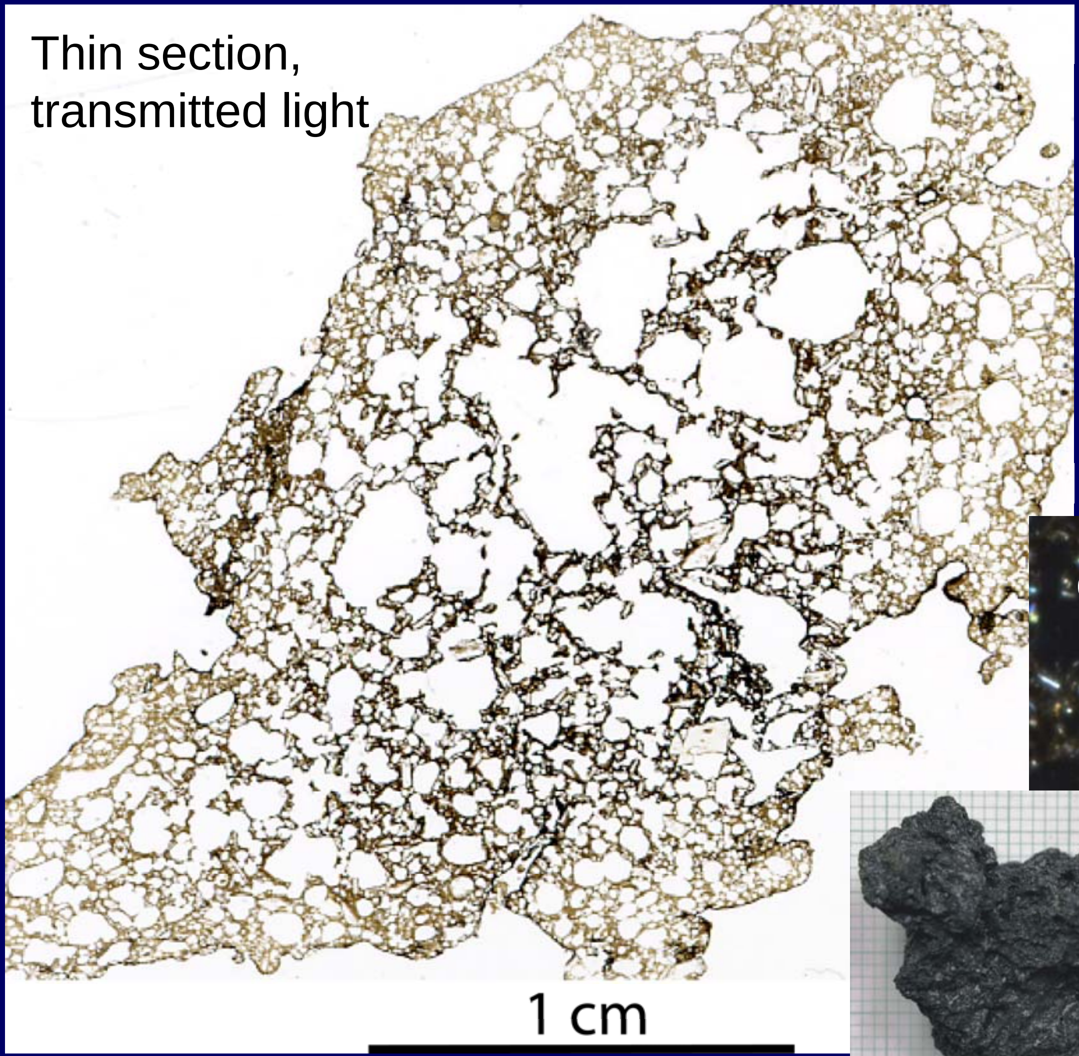
(San Francisco Volcanic Field, northern Arizona)

Feedstock source for JSC-1 & 1A

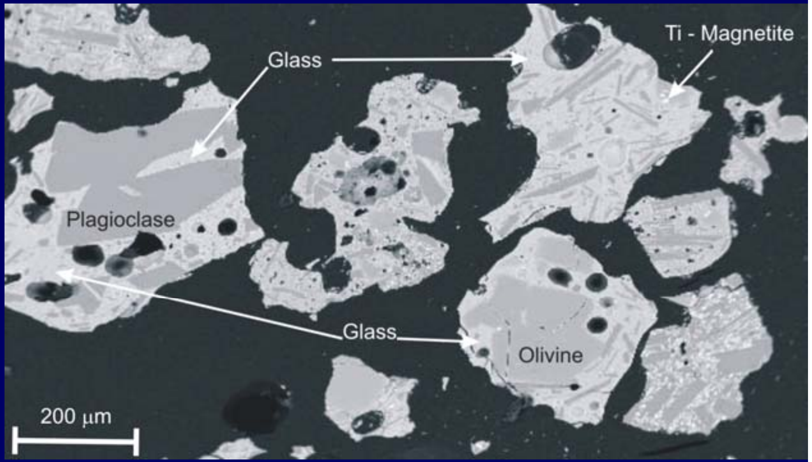


Merriam cinders

agglutinate like



SEM Backscatter (From L. Taylor)



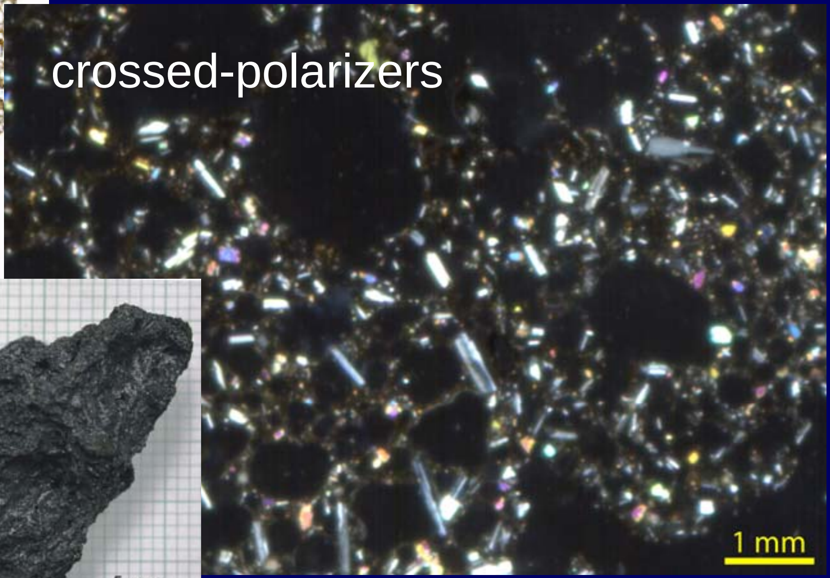


Table 1. Chemical Composition

Oxide	Merriam Crater Ash* Wt.%	Lunar Soil 14163** Wt.%
SiO_2	48.77	47.3
TiO_2	1.49	1.6
Al_2O_3	15.65	17.8
Fe_2O_3	1.71	0.0
FeO	8.88	10.5
MgO	8.48	9.6
CaO	10.44	11.4
Na_2O	2.93	0.7
K_2O	0.81	0.6
MnO	0.19	0.1
Cr_2O_3	---	0.2
P_2O_5	0.66	- - -
Total	100.01	99.8

JSC-1: A NEW LUNAR REGOLITH SIMULANT, 1993, David S. McKay, James L. Carter, Walter W. Carlton, C. Allen, and Judith H. Allton, LPSC XXIV

JSC-1 & 1A

- A very successful regolith simulant:
- JSC-1 25-27 tons
- JSC-1A 30+ tons
- 14163 px>ol

Glass	49.3
Plagioclase	37.1
Olivine	9.0
Chromite	1.1
Sulfide	1.0
Ilmenite	<0.1
Pyroxene	<0.1
Other	2.5

From Taylor, L.A. & Hill, E., 2005, JSC-1A "Exposed", petrography, mineralogy, and geochemistry.

NU-LHT-SERIES

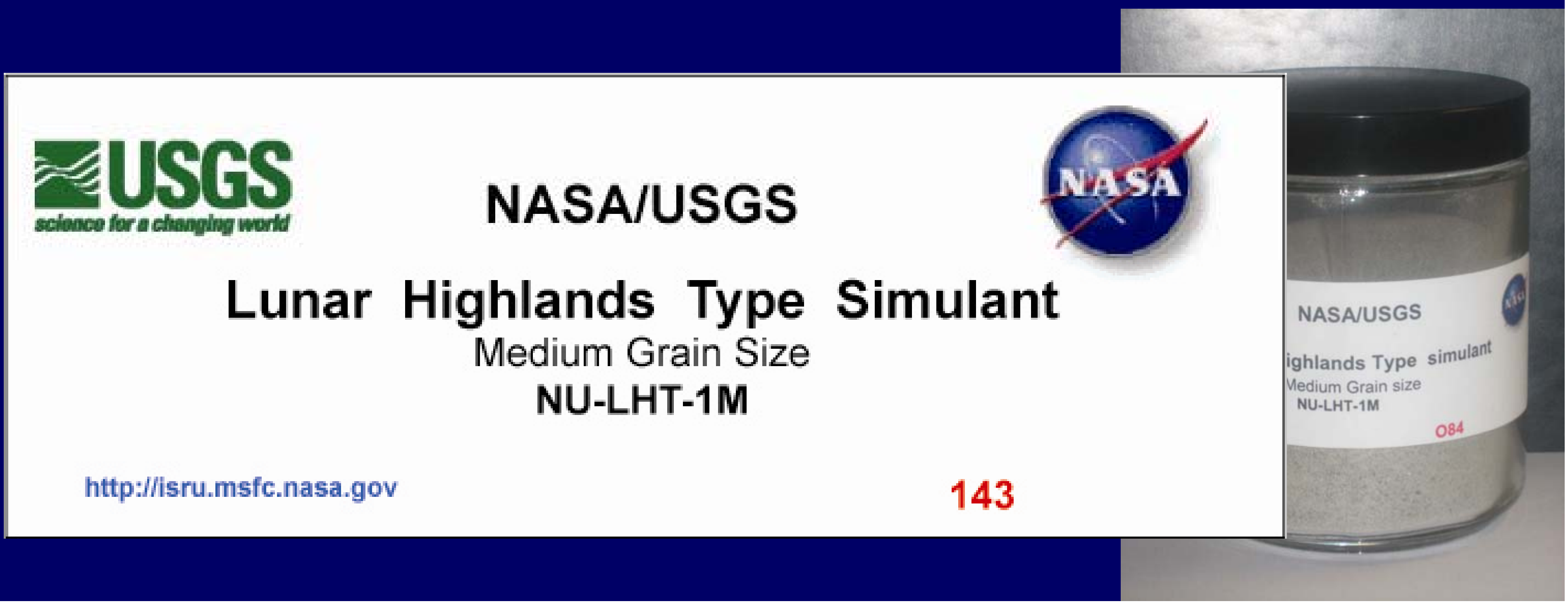
Prototypes being produced by the NASA/USGS Lunar Regolith Simulant Development “Project”

Prototypes to date:
LHT-1M, 1D
LHT-2M, 2C

NASA/USGS PROJECT SIMULANT NAMING CONVENTION

Originator - Planetary Body, Simulant Type - version & grain size indicator

NU – NASA/USGS
LHT – Lunar Highlands Type
Version – serial number (can be versioned, e.g. 1.1)
Grain size range indicator – currently: C – coarse, up to 10 cm particles, M – medium, <1mm, and D - dust, <20μm (although past usage has been up to 60μm)



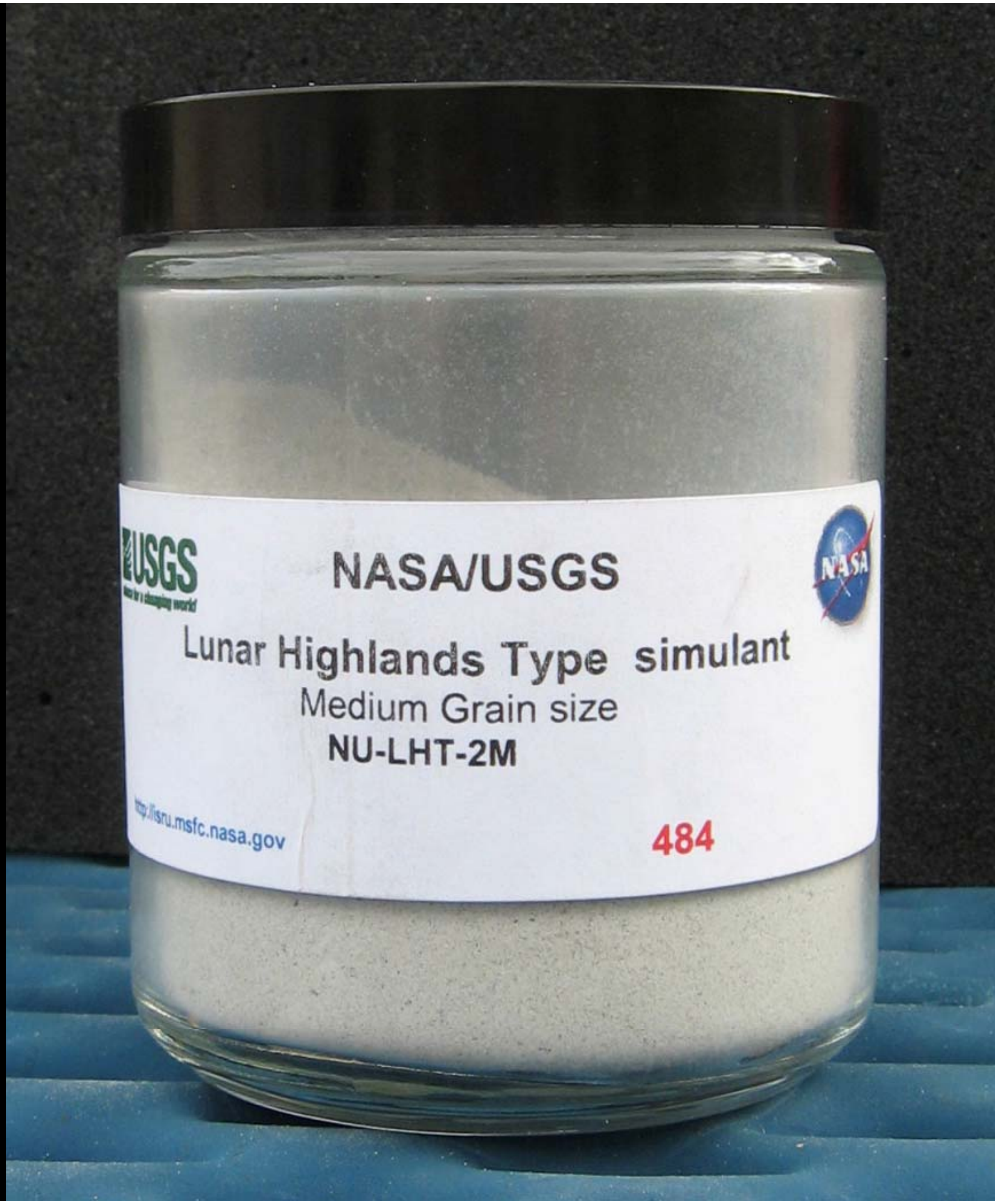
LHT DESIGN

(a "general use" simulant)

- 1. Target average Apollo 16 regolith major element chemistry
- 2. Use mixing model and cation normative mineral calculations (based on crystalline lithic components) to match overall mineralogy as closely as possible (e.g. amount of plagioclase, pyroxenes, olivine, and ilmenite)
- 3. Add synthetic agglutinate to match approximate average maturity (33%) (using Stillwater Mill "sand" as melt feedstock),
- 4. Add trace amounts mineral amounts based on amount of phosphorus and sulfur (normative cation amounts)
- 5. Match typical lunar grain size distribution

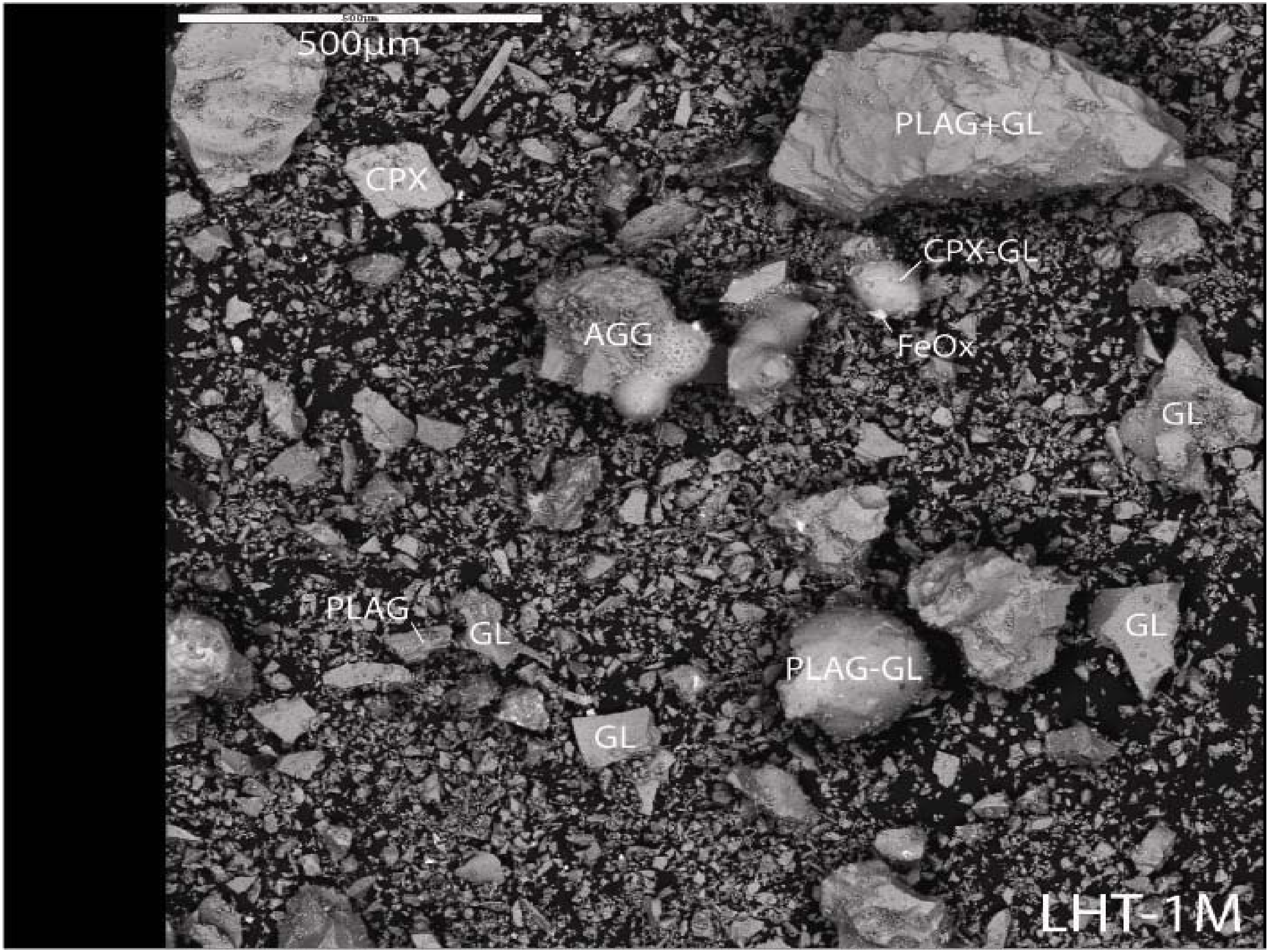
LHT PROTOTYPES

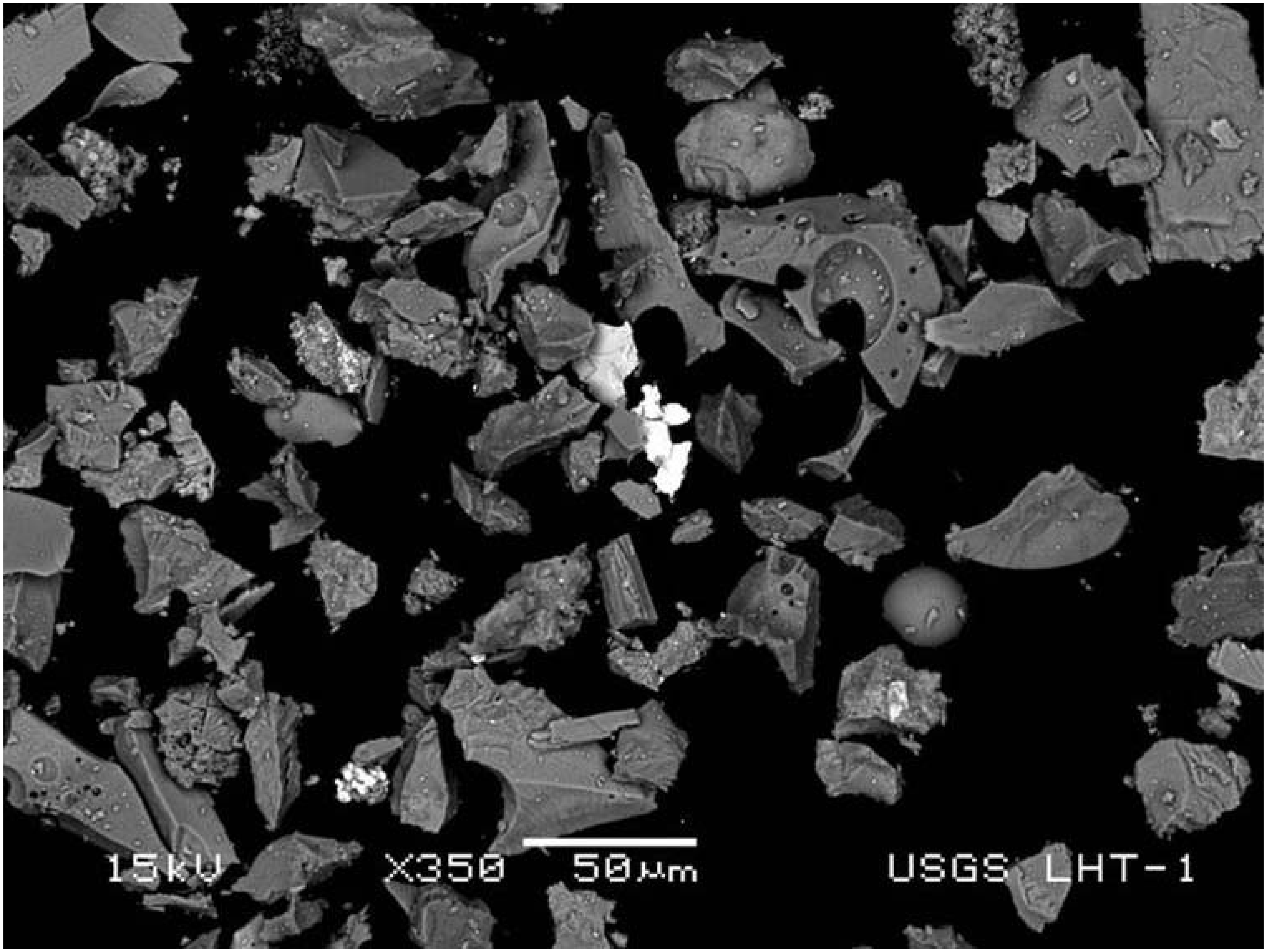
1M	1D	2M	2C
Stillwater norite (plag, opx, cpx), anorthosite (plag, cpx), hartzburgite (ol, chr, opx), syn-agglutinate, glass	1M ground to <60μm	Stillwater norite, anorthosite, Twin Sisters dunite (ol, chr), syn-agglutinate, glass, trace minerals: ilmenite, β-TCP, fluorapatite, pyrite	2M plus syn-impact melt breccia particles up to 10 cm

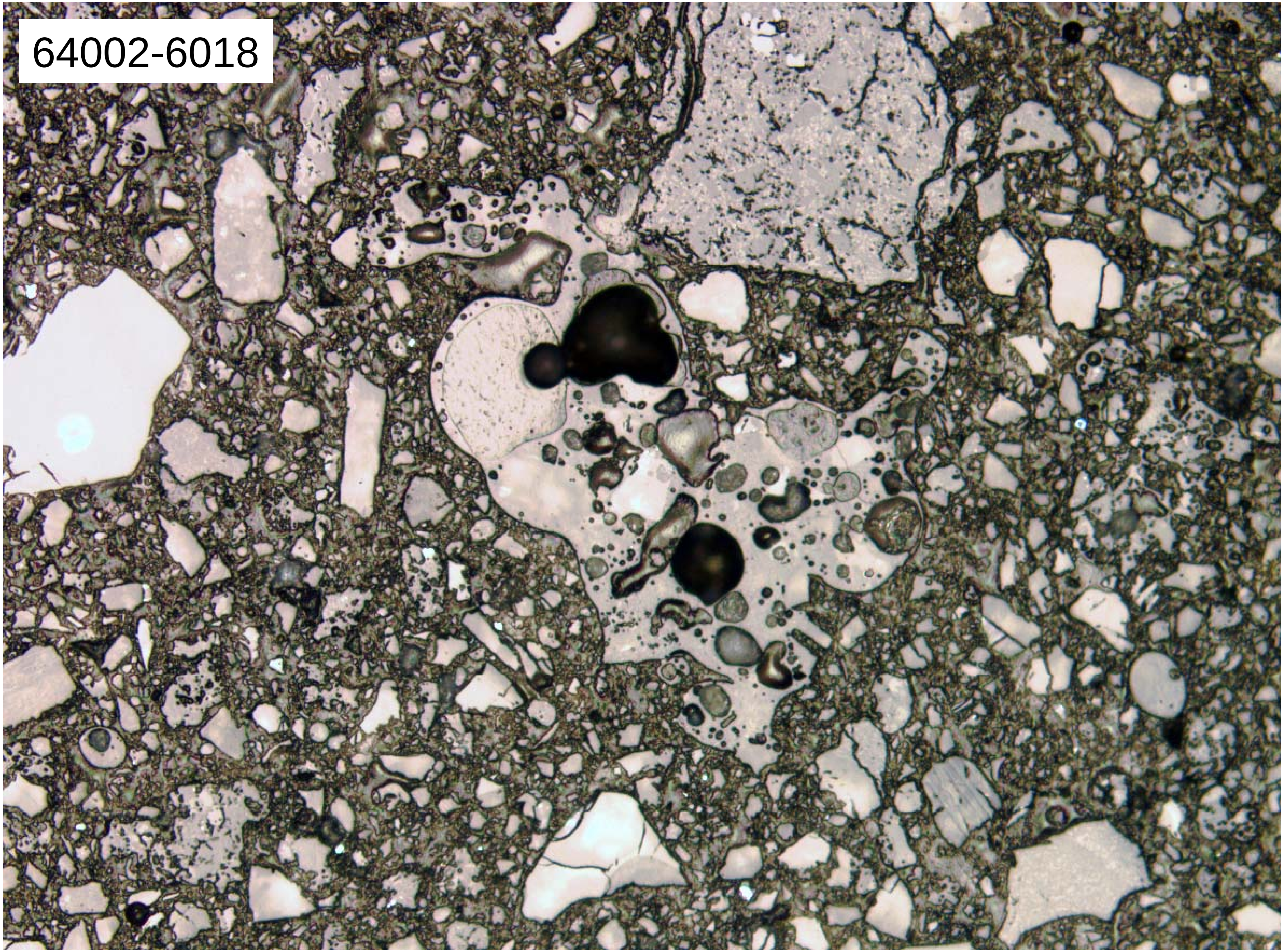


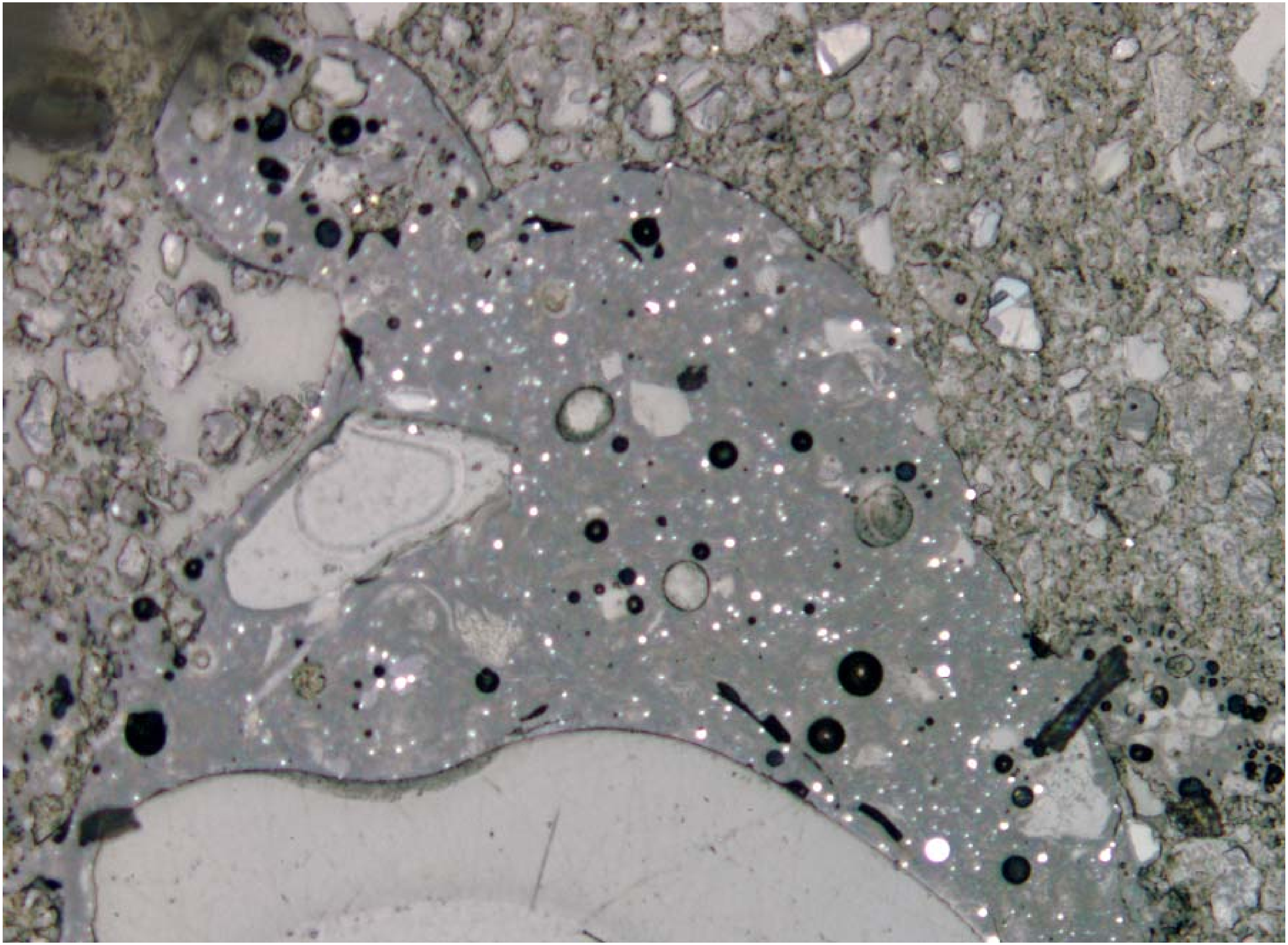
Stoeser has
bottle #666

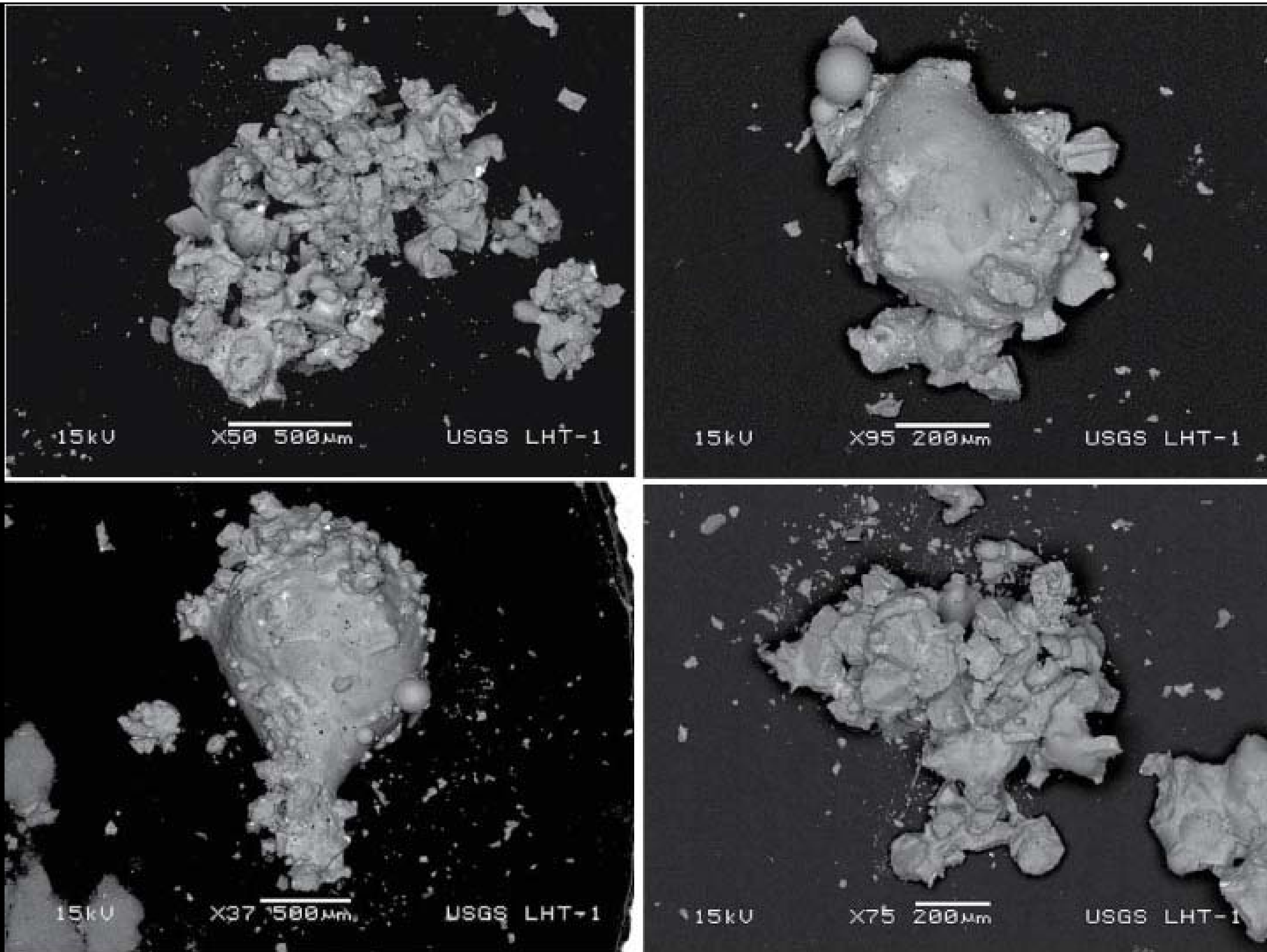
LHT-2C (and the 2007 project mug)


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

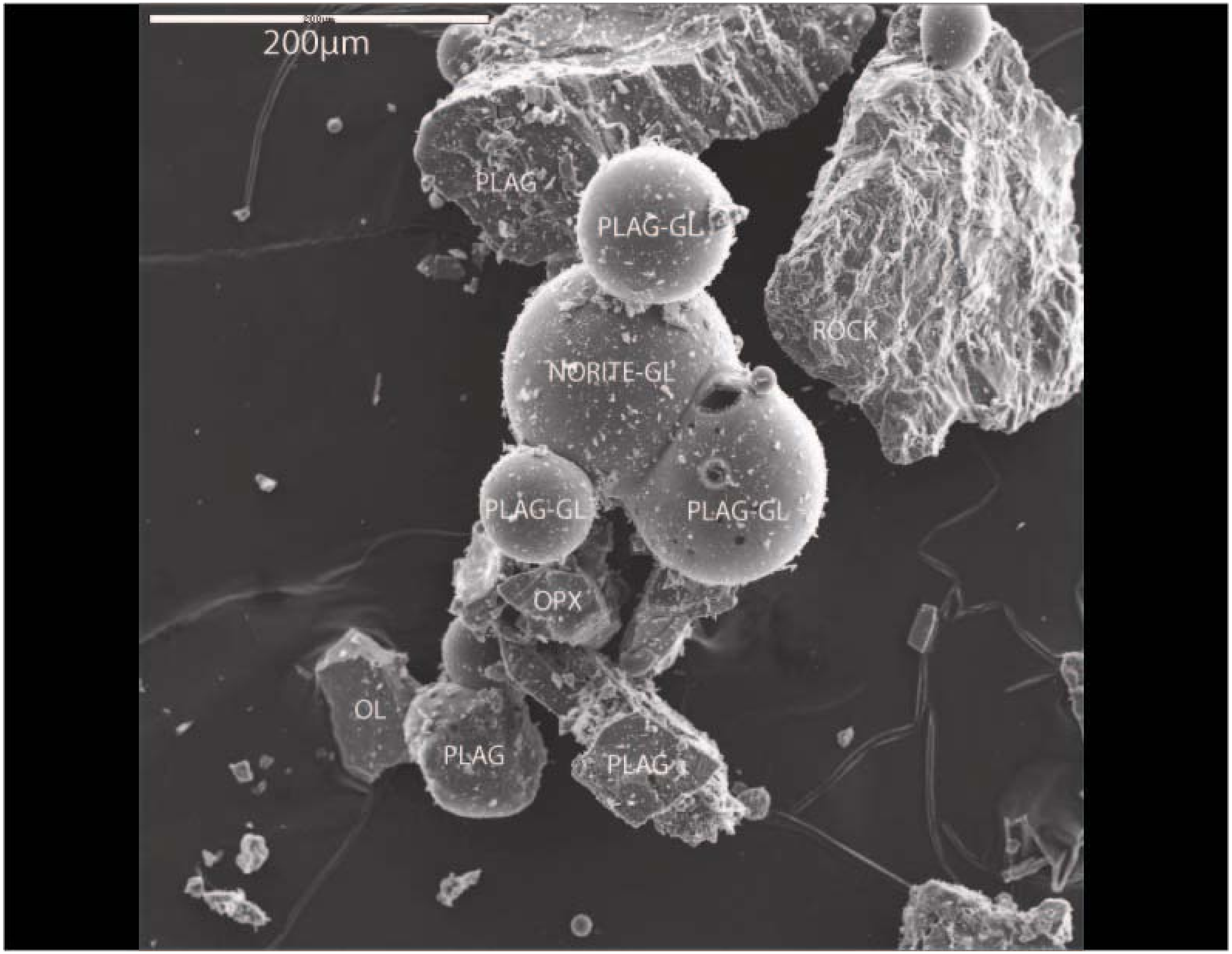

15kV
X350
50µm
USGS LHT-1

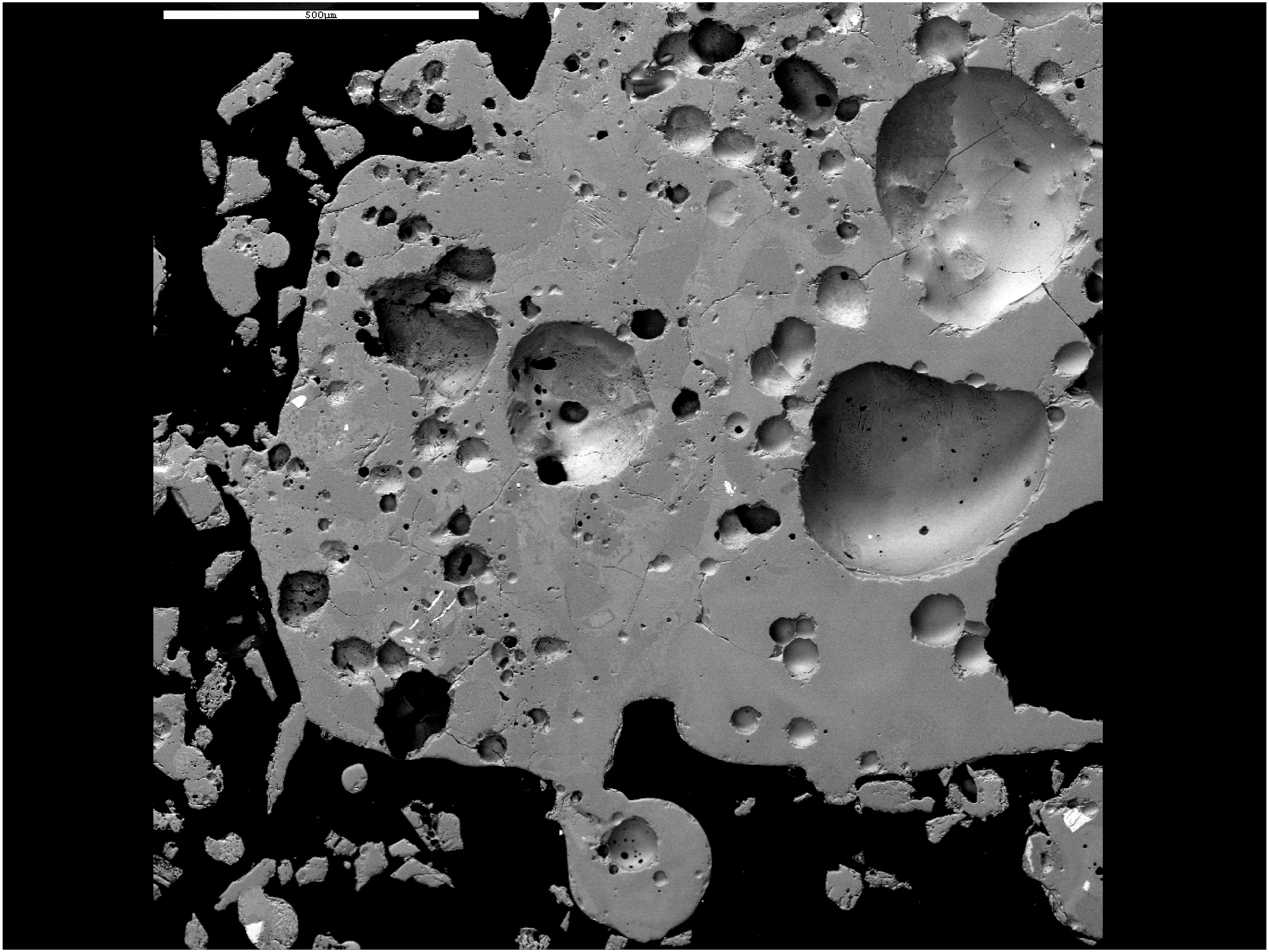

64002-6018





EXAMPLES OF LARGE PSEUDO-AGGLUTINATE PARTICLES FROM NU-LHT-1M PILOT


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


500µm

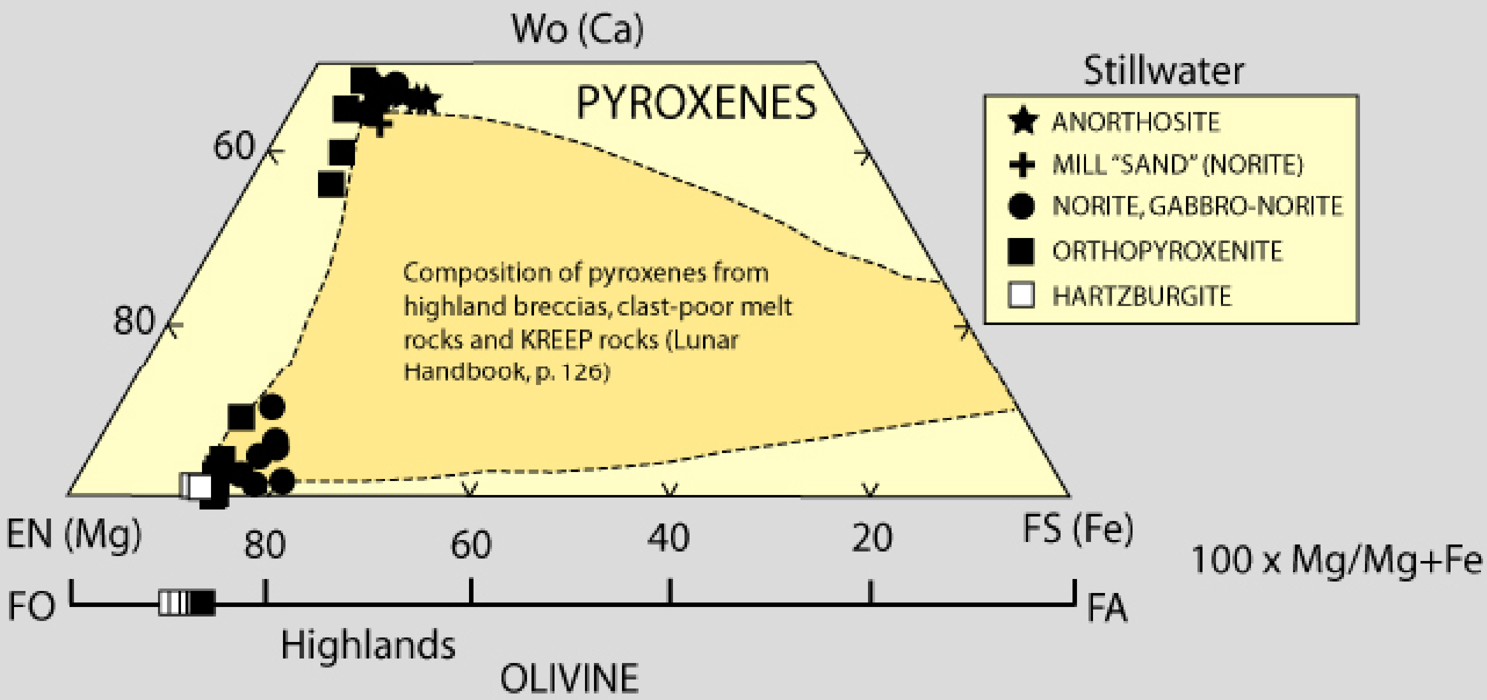
LHT-1M Component Mineral Compositions

PLAGIOCLASE (ave. AN content & range)

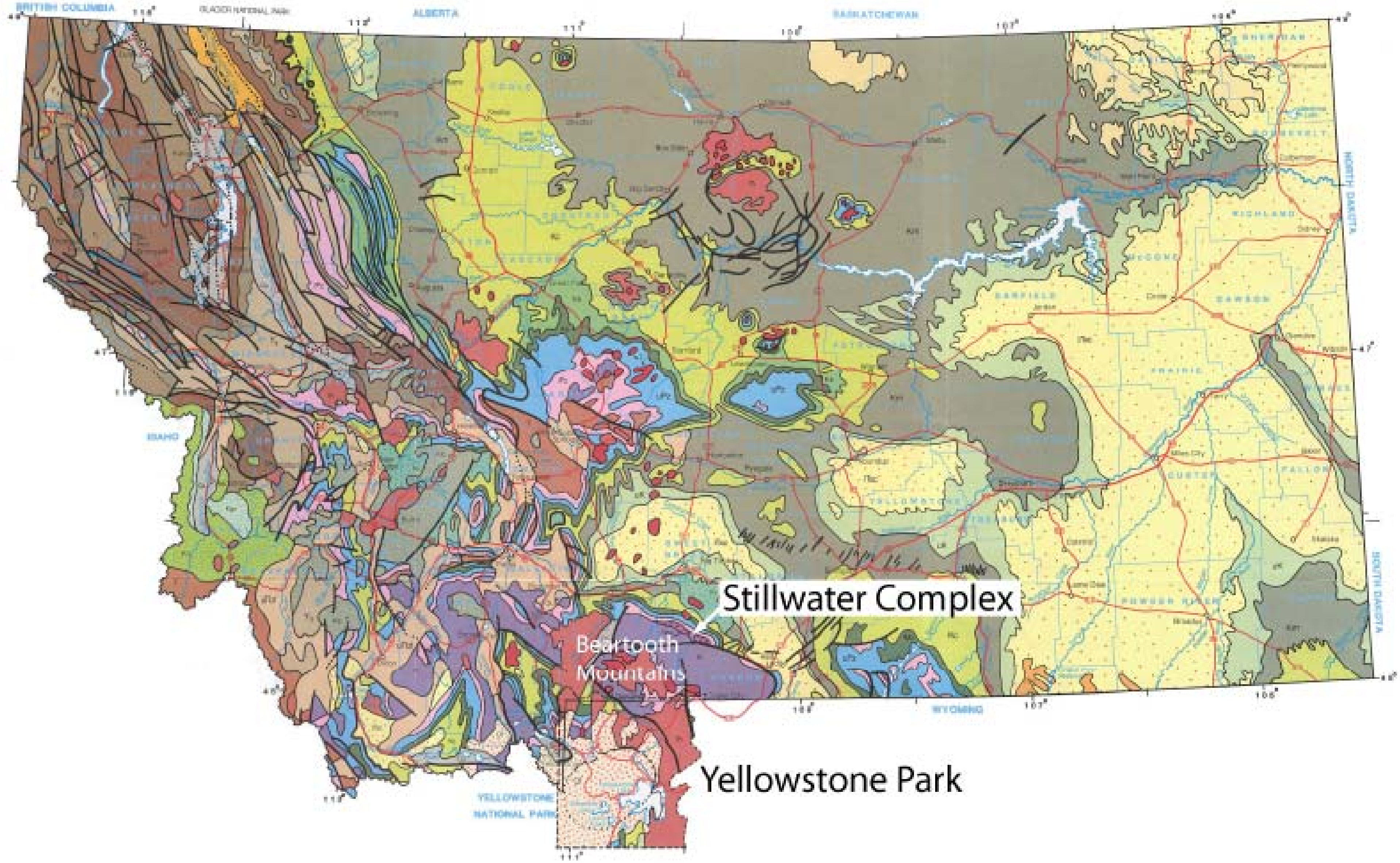
Anorthosite:	79	(62-85)
Mill Sand	83	(60-96)
Norite:	84	(78-92)
Orthopyroxene	75	(73-78)
Hartzburgite	66	(64-68)

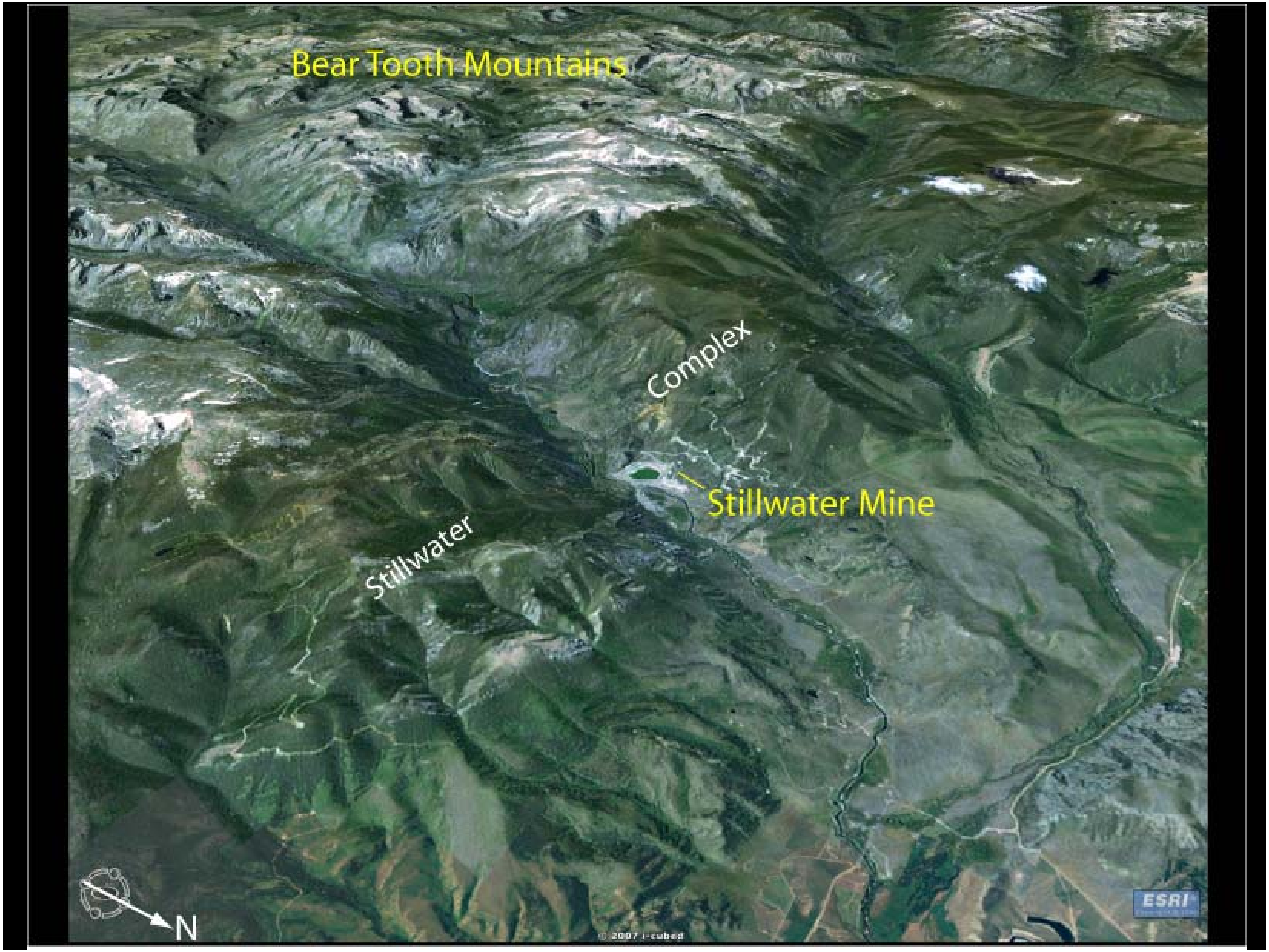
AN = 100 x Ca/Ca+Na

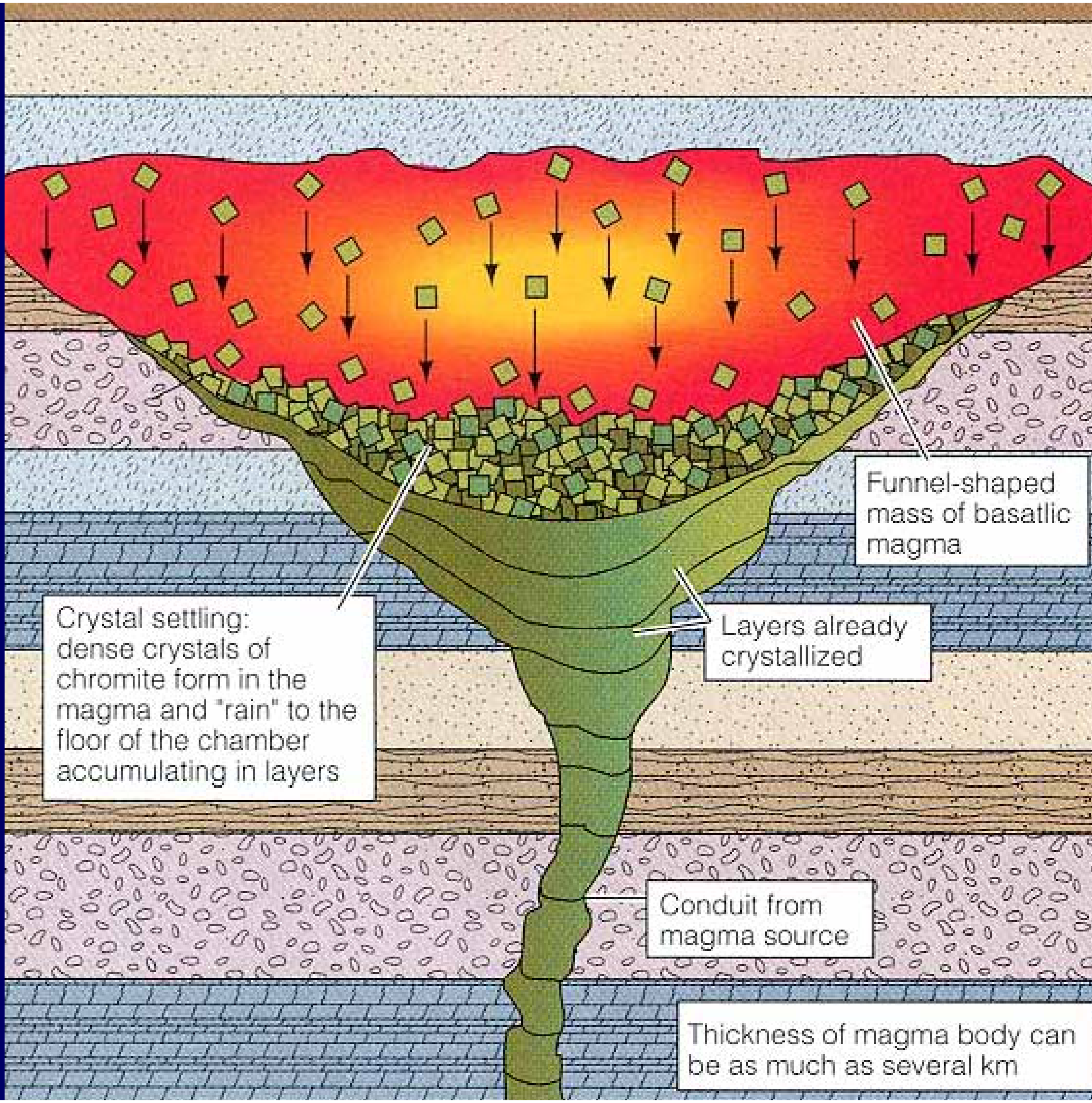
Average highlands ~AN 94

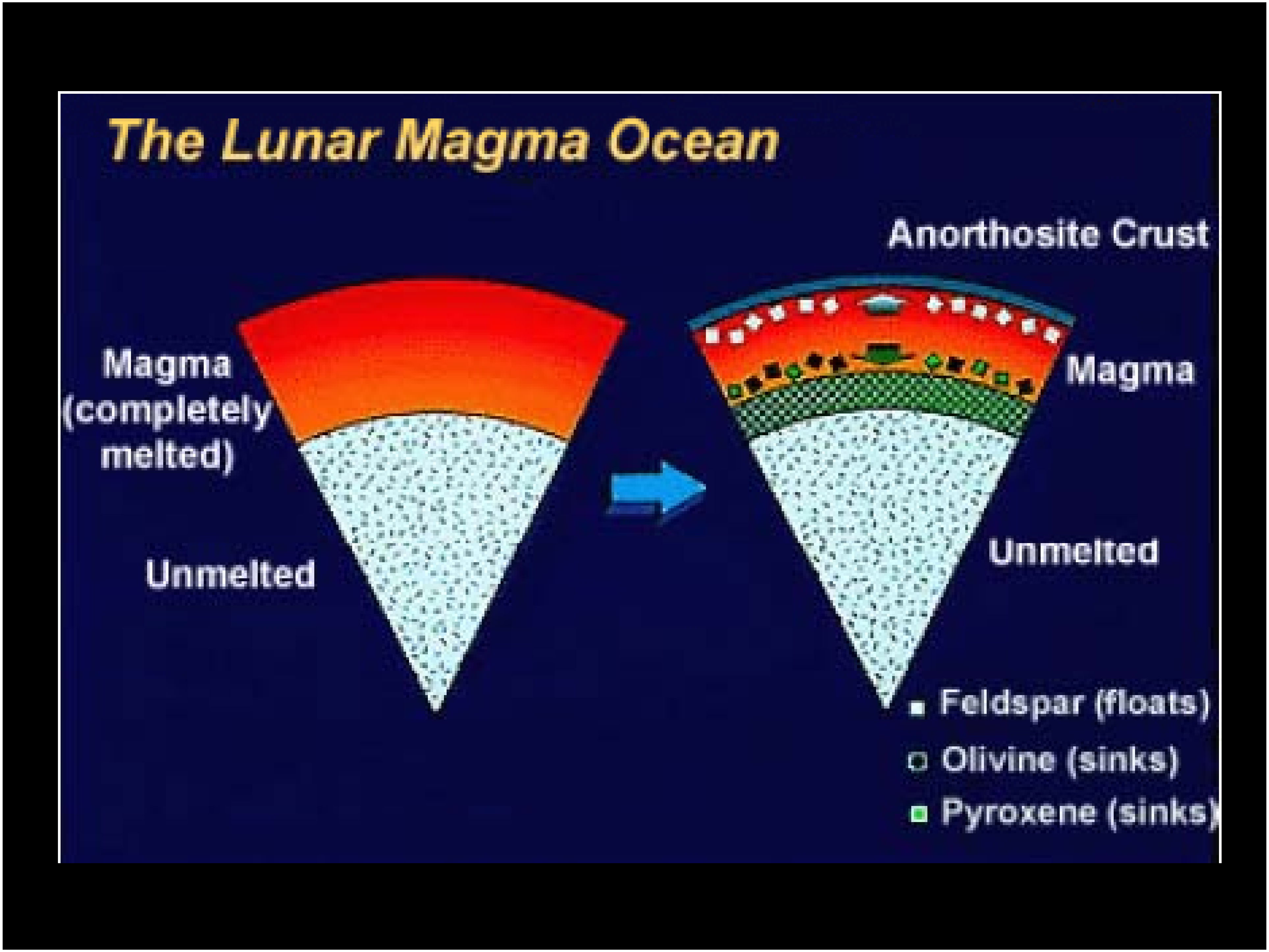



STILLWATER
MINING COMPANY
STILLWATER MINE


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

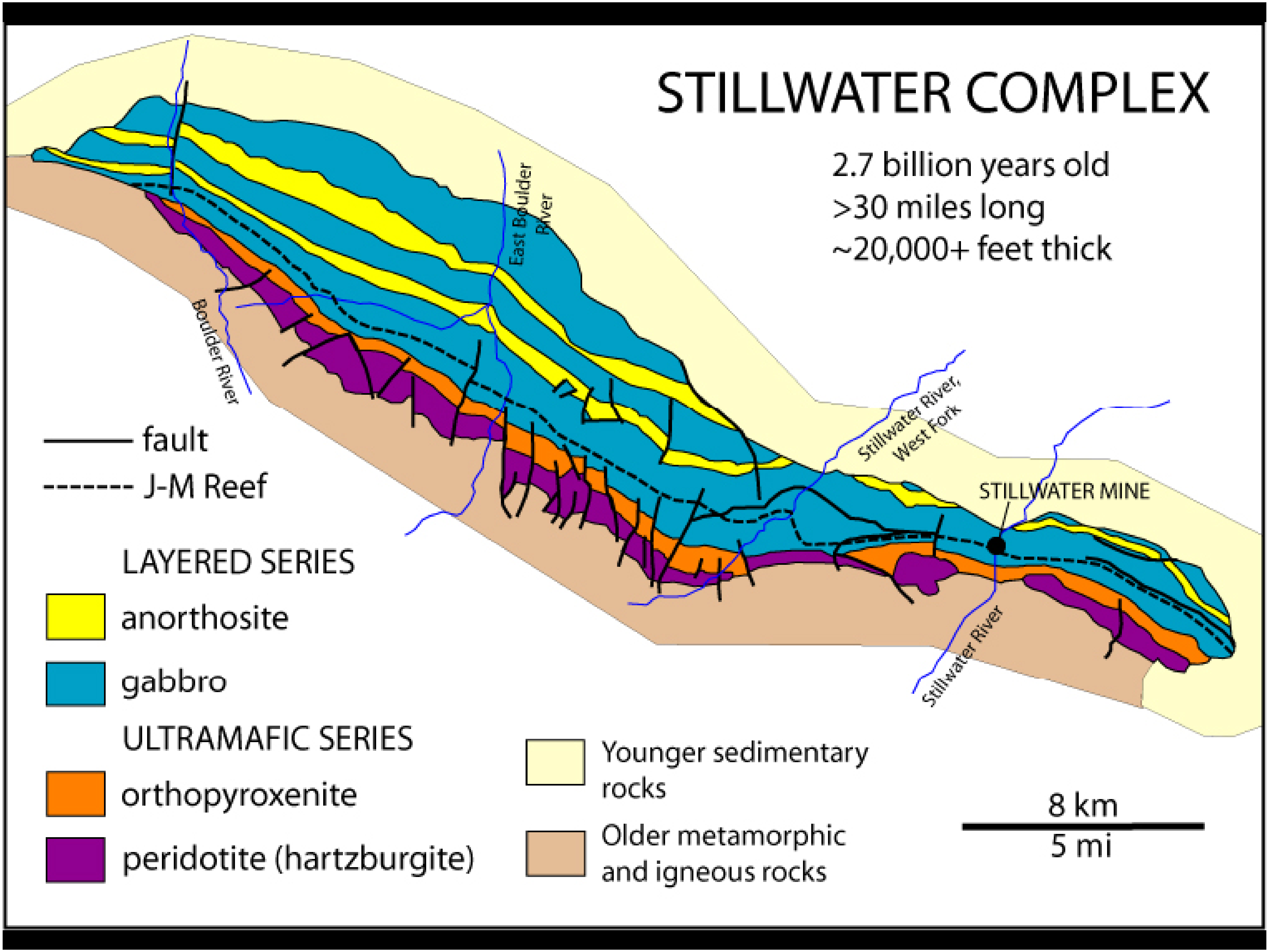

Bear Tooth Mountains
Complex
Stillwater Mine
Stillwater
N
ESRI
© 2007 i-cubed


Funnel-shaped mass of basatlic magma
Crystal settling: dense crystals of chromite form in the magma and "rain" to the floor of the chamber accumulating in layers
Layers already crystallized
Conduit from magma source
Thickness of magma body can be as much as several km

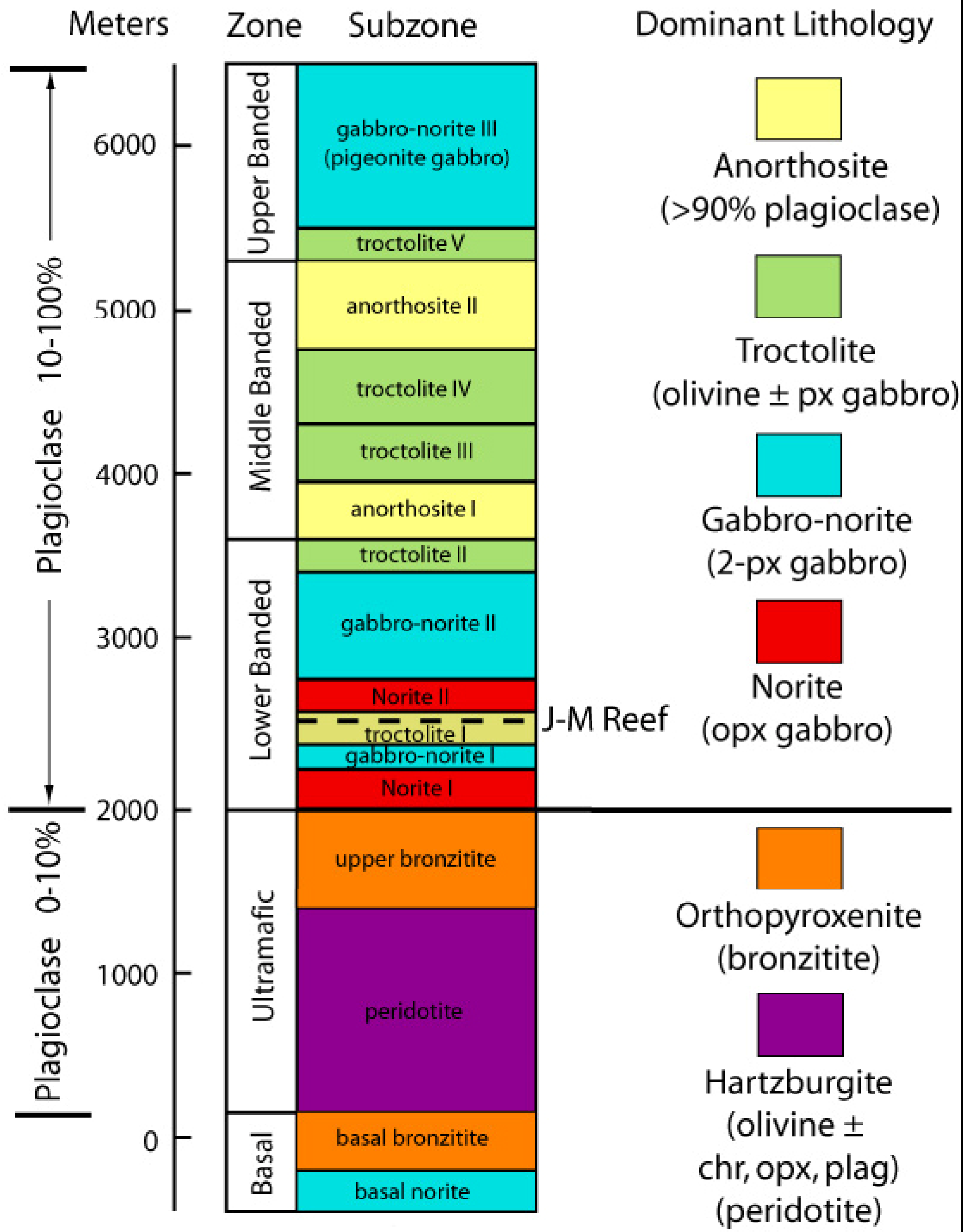

The Lunar Magma Ocean
Anorthosite Crust
Magma
(completely
melted)
Magma
Unmelted
Unmelted
Feldspar (floats)
Olivine (sinks)
Pyroxene (sinks)

LAYERED MAFIC INTRUSIONS

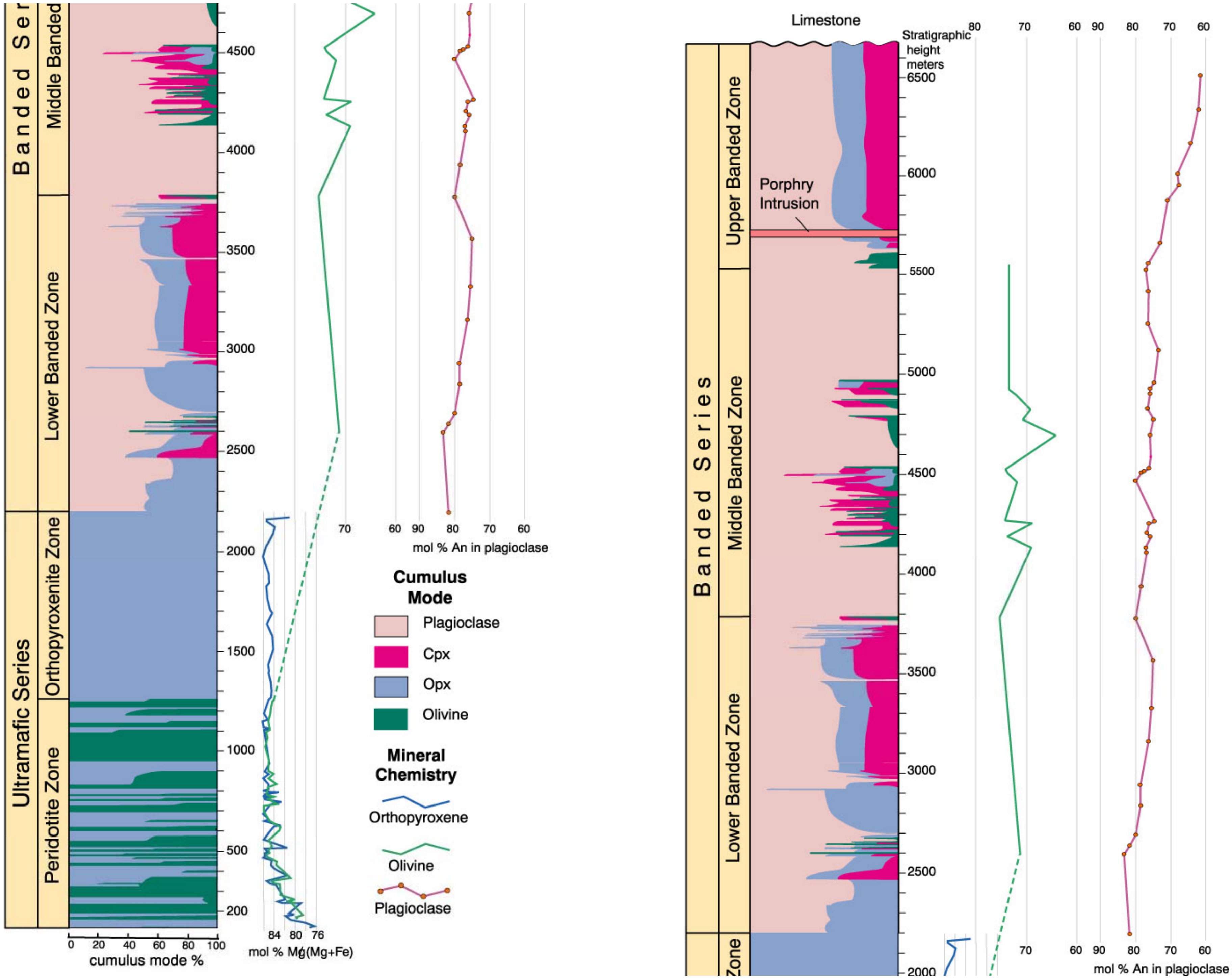
Name	Age	Location	Area (km^2)
Bushveld	Precambrian	S. Africa	66,000
Dufek	Jurassic	Antarctica	50,000
Duluth	Precambrian	Minnesota, USA	4,700
Stillwater	Precambrian	Montana, USA	4,400
Muskox	Precambrian	NW Terr. Canada	3,500
Great Dike	Precambrian	Zimbabwe	3,300
Kiglapait	Precambrian	Labrador	560
Skaergård	Eocene	East Greenland	100

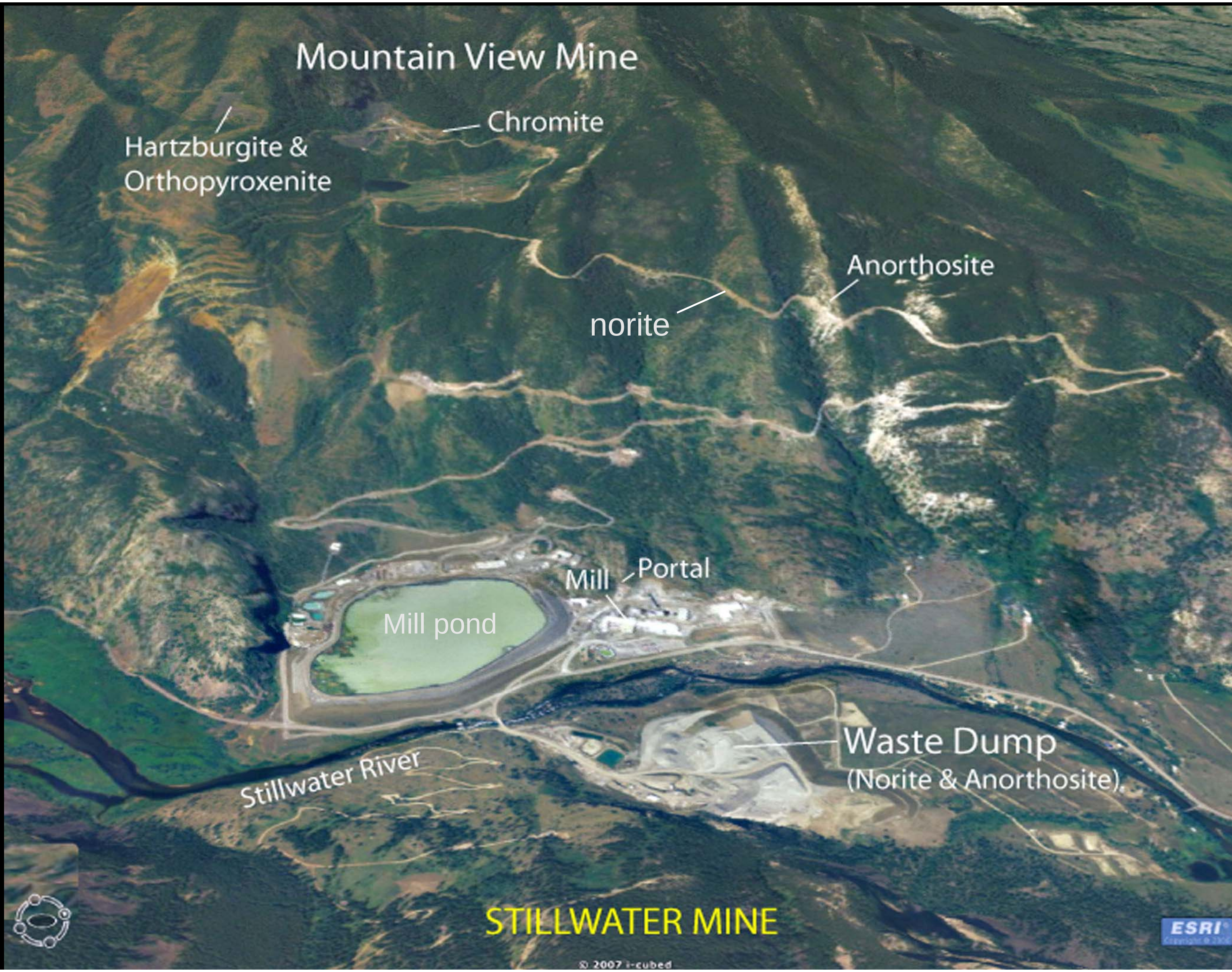

STILLWATER COMPLEX
2.7 billion years old
>30 miles long
~20,000+ feet thick
East Boulder River
Boulder River
Stillwater River, West Fork
STILLWATER MINE
Stillwater River
fault
J-M Reef
LAYERED SERIES
anorthosite
gabbro
ULTRAMAFIC SERIES
orthopyroxenite
peridotite (hartzburgite)
Younger sedimentary rocks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

STILLWATER COMPLEX



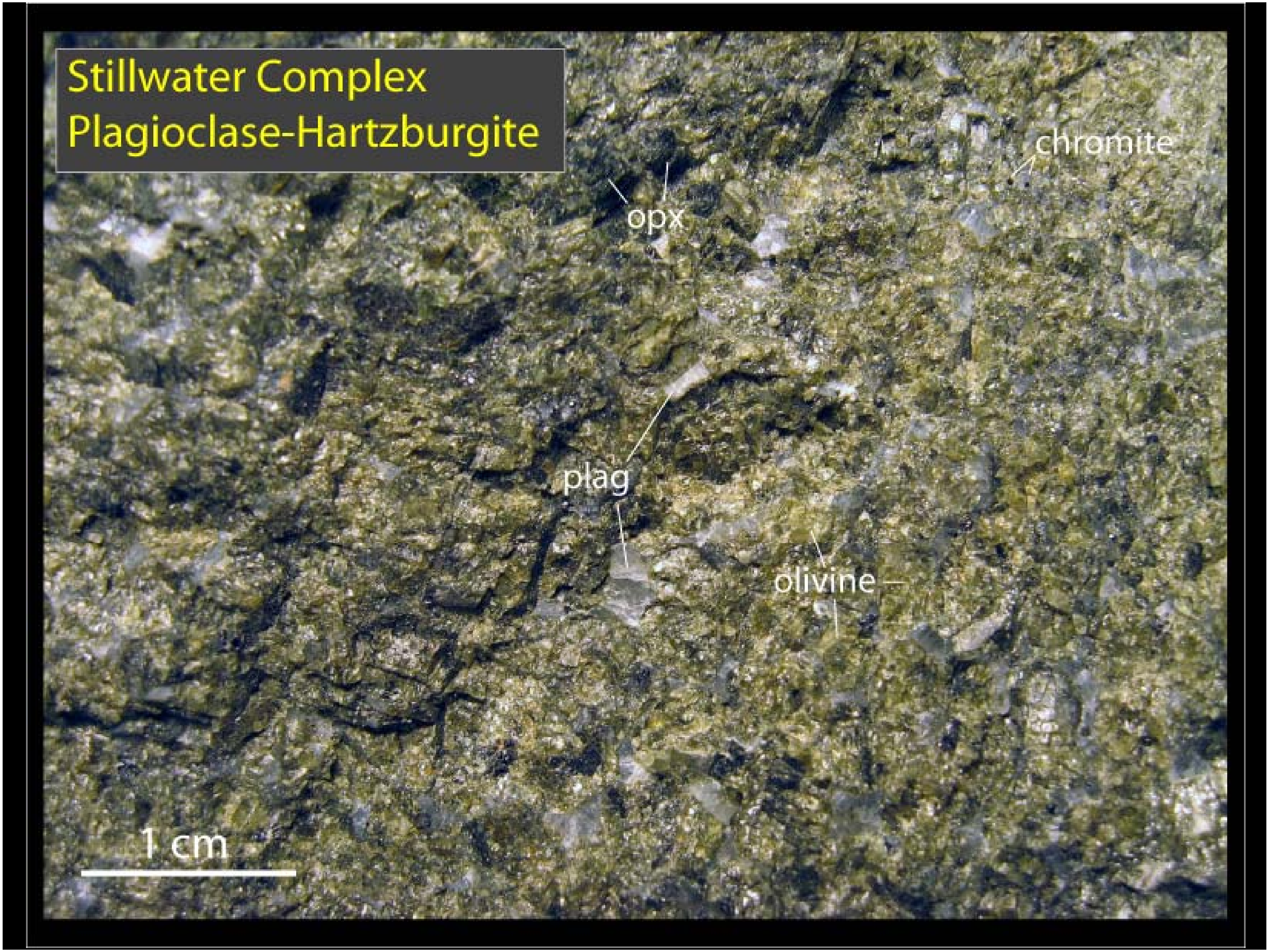
After McCallum et al. (1980)


Banded Ser
Middle Banded
Lower Banded Zone
Ultramafic Series
Orthopyroxenite Zone
Peridotite Zone
4500
4000
3500
3000
2500
2000
1500
1000
500
200
0 20 40 60 80 100
cumulus mode %
84 80 76
mol % Mg/(Mg+Fe)
70
60 90 80 70 60
mol % An in plagioclase
Cumulus Mode
Plagioclase
Cpx
Opx
Olivine
Mineral Chemistry
Orthopyroxene
Olivine
Plagioclase
Limestone
Stratigraphic height meters
Upper Banded Zone
Porphry Intrusion
Banded Series
Middle Banded Zone
Lower Banded Zone
Zone
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
80 70 60 90 80 70 60
mol % An in plagioclase


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

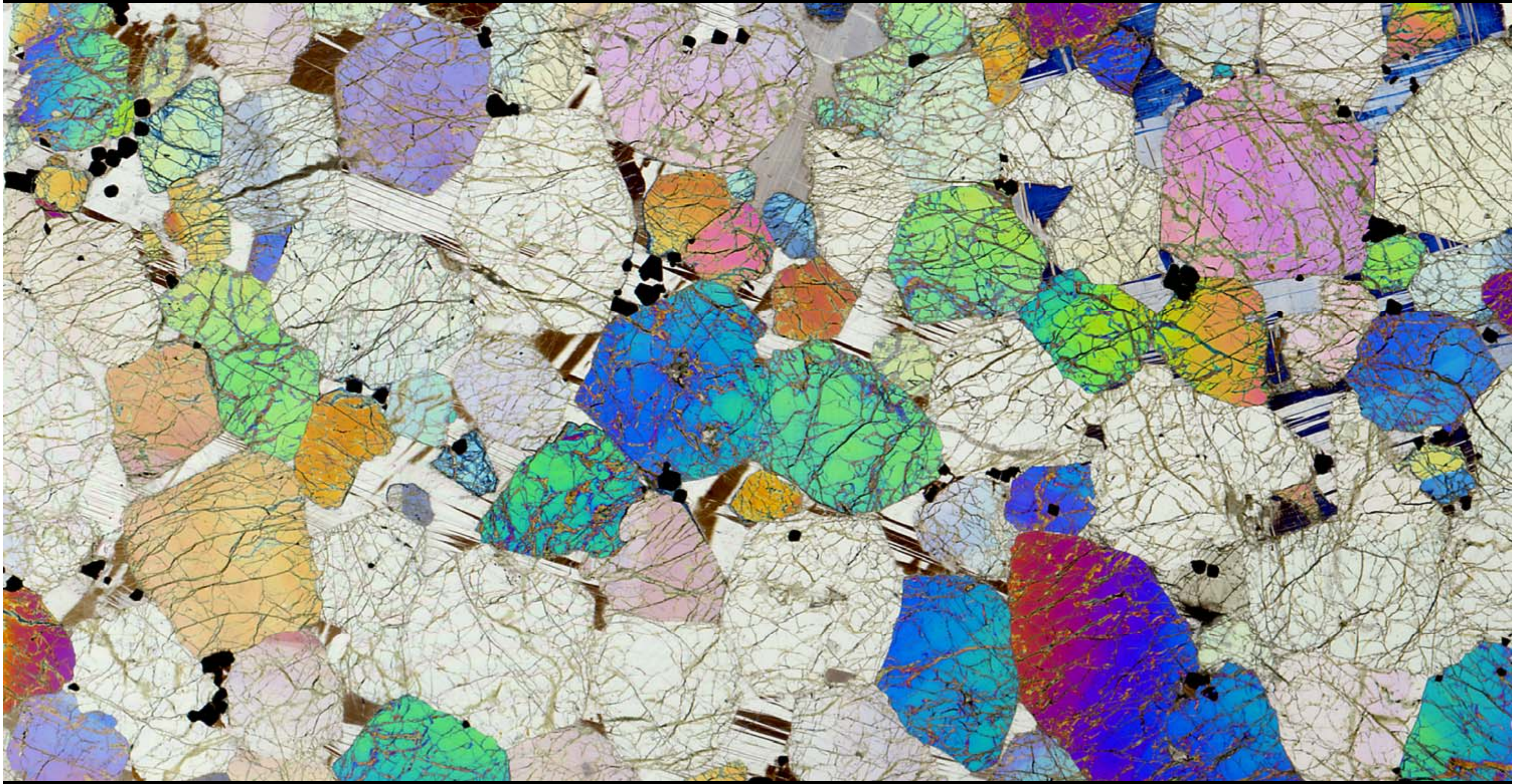
Hand cobbing material off the dump.
This approach makes Dr. Rickman
even more crazy.


CATERPILLAR
773D


Stillwater Complex
Plagioclase-Hartzburgite
chromite
opx
plag
olivine
1 cm


1 cm
Chromite-Hartzburgite
(olivine cumulate)

Cumulate olivine and chromite with post-cumulus plagioclase



Thin section view with crossed-polarizers


cpx
opx
Pl
1 cm
Stillwater
Plagioclase-Orthopyroxenite

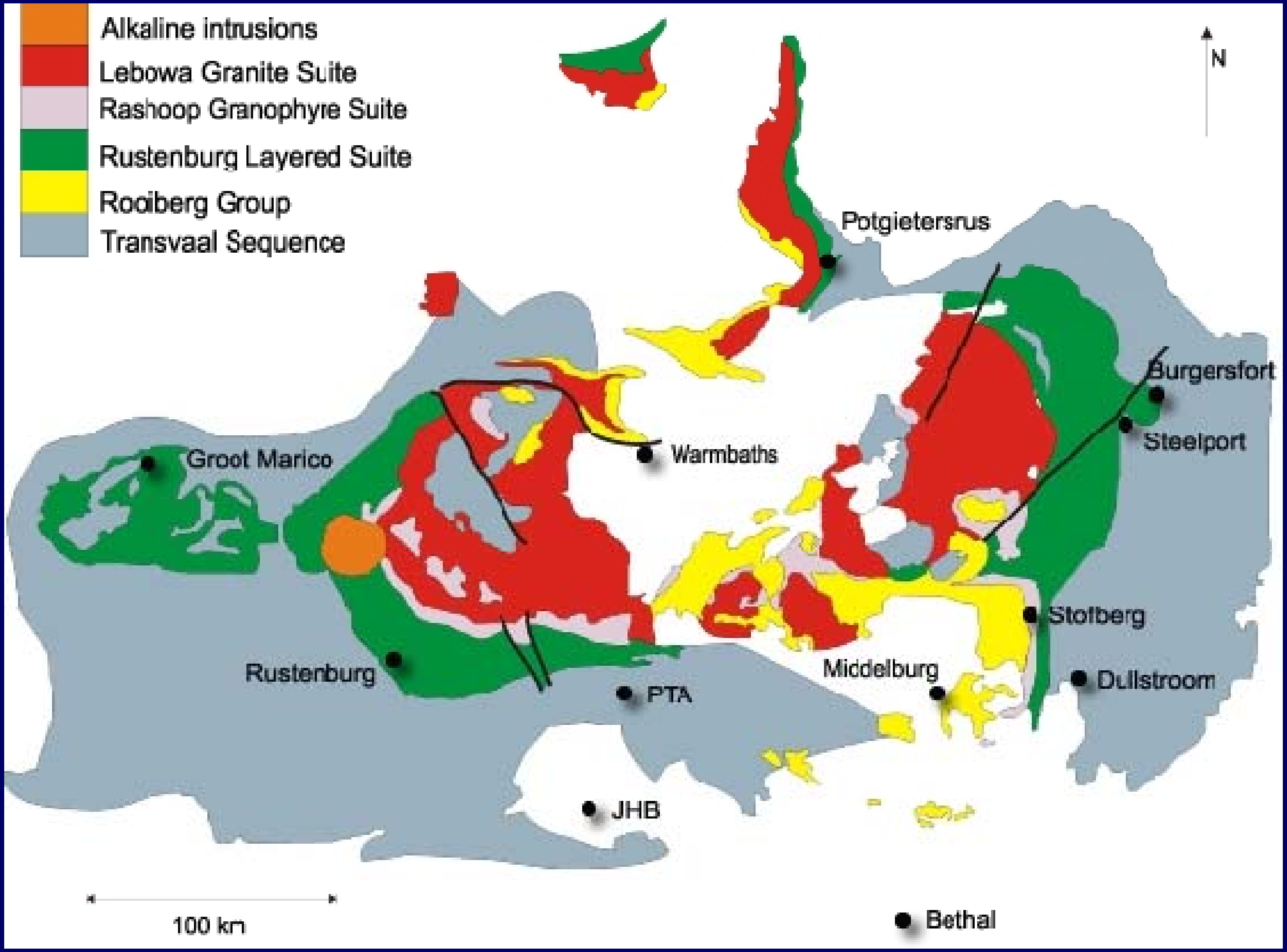

norite
2-pyroxene
gabbro-norite
clinopyroxene
leucogabbro
pyroxene-rich norite
CM
WEAR GOGGLES
USA


ANORTHOSITE
poikilitic
clinopyroxene
1 cm


NORITE FEED STOCK


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

Dimension stone investigations: Bushveld Complex, South Africa



NERO IMPALA® MEDIUM


Springbock quarry


CAT

Bushveld (Rustenburg) norite & gabbro for pyroxene feedstock

- Main zone (Rustenburg series) produces one of the planets major dimension stones (aka Impala black, in the trade “black granite”),
- Extremely fresh, pyroxenes are typical lunar, plagioclase too sodic (An60-70), basically tri-mineralic, very simple cumulate texture,
- Relatively homogeneous,
- Unlimited supply for at least 30 years,
- We can probably use waste material.

The end

(for now)

[redacted]


LHT-1M
inches
SEPM
Society for Sedimentary Geology
www.sepm.org