BAE SYSTEMS

Characterization Strategies and Requirements for Lunar Regolith Simulant Materials

Paul Carpenter
XD42
BAE Systems
Analytical & Ordnance Solutions
Marshall Space Flight Center, AL 35812, USA
paul.carpenter@msfc.nasa.gov

Outline

BAE SYSTEMS

- Development of LRSM and characterization
  - Bulk chemical and microanalysis methods
- Lunar regolith simulants JSC-1 and MLS-1
  - Bulk chemistry and electron-probe microanalysis data
- Root simulant development strategies
  - JSC-1 example
  - Japanese simulants FJS-1, Type 1-3
  - Synthetic agglutinate microspheres, status report
- Quality control and standard development
- Oxygen fugacity control and Mössbauer characterization
- Source localities for anorthosite simulants

Development of LRSM and Characterization

- LRSM development sequence
- Bulk chemical analysis methods
- Microchemical / structural analysis methods

Development and Distribution of LRSM: Role of Characterization

- Identification of source materials, localities, mines, synthetic materials relative to requirements
- Initial batching for test screen evaluation: processing and required physical, chemical, mineralogical characterization
- Evaluation of initial screen relative to requirements list
- Batch production quantity, processing, synthesis, mixing
- Characterization and quality control of master simulant batch
- Subdivision for distribution, quality control of sub-batches
- Curation, storage, shelf monitoring
- Guidelines for simulant use
- Requests for simulant
- Oversight by monitoring committee

Characterization Requirements for Lunar Regolith Simulant Materials

BAE SYSTEMS

- Bulk and microchemical analysis required to support physical and chemical characterization of LRSM
- **Bulk analysis**: large/many particles, representative sample from parent
  - XRF, ICPMS, INAA, XRD, Mössbauer, many others
- **Microanalysis**: few/individual, analysis of dust, grain, rock fragments
  - EPMA, SEM, TEM, SIMS, optical microscopy, others
- Calibration and quality control of LRSM root and composite simulant reference "standards" for development and distribution
- Diverse set of lunar materials requires relatively diverse set of LRSM—there is no single simulant that represents the spectrum of lunar materials
- Anticipate need for real-time autonomous analysis for material selection, process monitoring, error recovery, etc. on planetary surfaces
- Characterization is part of overall strategy on Earth, moon, Mars

Characterization Methods: Electron-probe microanalysis / SIMS

- **EPMA Electron-probe microanalysis / SEM Scanning electron microscopy / TEM Transmission electron microscopy**

Nearly all lunar samples analyzed using EPMA / SEM
Polished, conductive sample, 1 µm spatial resolution, vacuum technique
Analytical sensitivity:
Wavelength-dispersive spectrometer 0.x mg/g to x µg/g sensitivity, serial
Energy-dispersive spectrometer 0.x mg/g best case, parallel
New Si-drift detector with digital electronics ~ WDS performance
Micro and bulk analysis capabilities with high-speed sample mapping

- **SIMS Secondary-ion mass spectrometry**

Recent use for spatial trace element analysis beyond EPMA sensitivity
Polished, conductive sample, ~1-10 µm spatial resolution, vacuum technique
Analytical sensitivity µg/g to ng/g but calibration requires bracketing stds

BAE SYSTEMS

Lunar Regolith Simulants JSC-1 and MLS-1

Bulk chemistry and target Apollo soils

Electron-probe microanalysis characterization

Lunar Mare Basaltic Simulants: JSC-1, MLS-1 and Apollo Soils

Simulant Materials:

JSC-1: Basalt ash
Merriam crater
SF Volcanic field, AZ
~ Apollo 14/15, KREEP

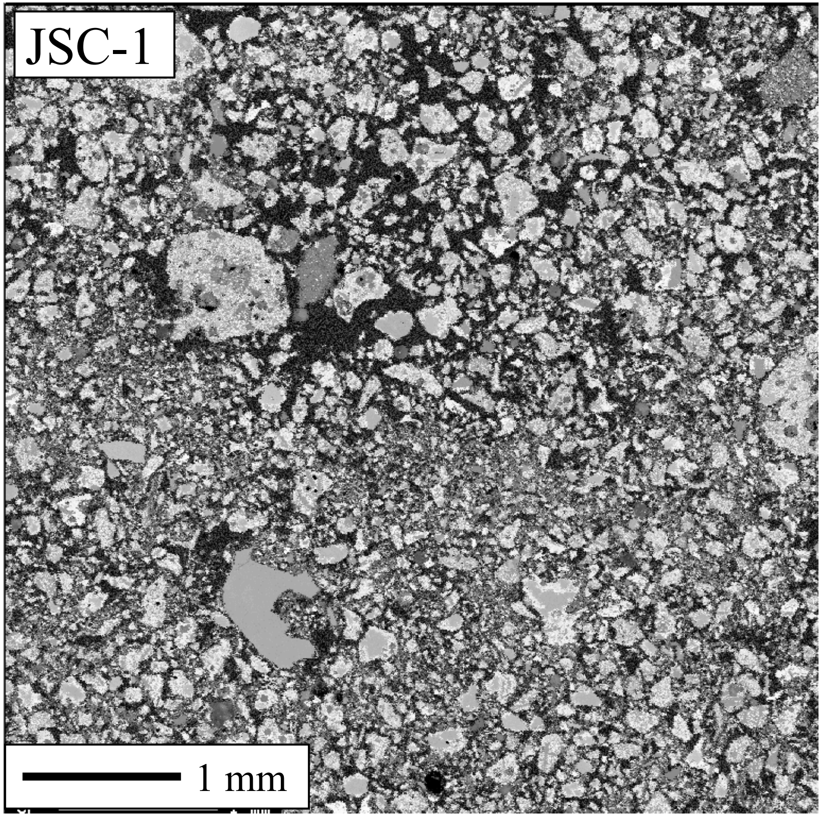
MLS-1: High-Ti Basalt/
microgabbro, Duluth, MN
~ High Ti Apollo 11

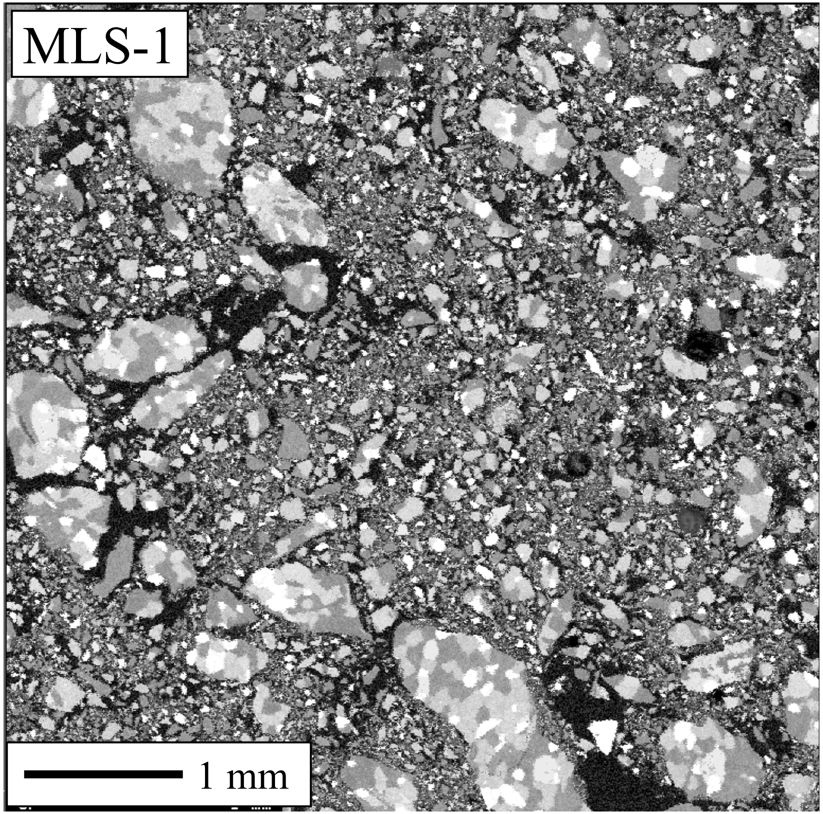
Apollo data from
McKay et al., chapter 7,
Lunar Sourcebook,
Table 7.15, p. 346

Oxide	JSC-1	Apollo 14 Avg Soil	MLS-1	Apollo 11 Soil 10002
SiO_2	47.71	48.1	43.9	42.2
TiO_2	1.59	1.7	6.30	7.8
Al_2O_3	15.02	17.4	13.7	13.6
Cr_2O_3	0.04	0.23		0.30
Fe_2O_3	3.44		2.60	
FeO	7.35	10.4	13.40	15.3
MnO	0.18	0.14	0.20	0.20
MgO	9.01	9.4	6.70	7.8
CaO	10.42	10.7	10.10	11.9
Na_2O	2.70	0.70	2.10	0.47
K_2O	0.82	0.55	0.20	0.16
P_2O_5	0.66	0.51		0.05
LOI	0.71			
Total	99.65	99.8	99.20	99.9

Comparison of JSC-1 and MLS-1: EPMA Backscattered-electron Stage Maps

BAE SYSTEMS





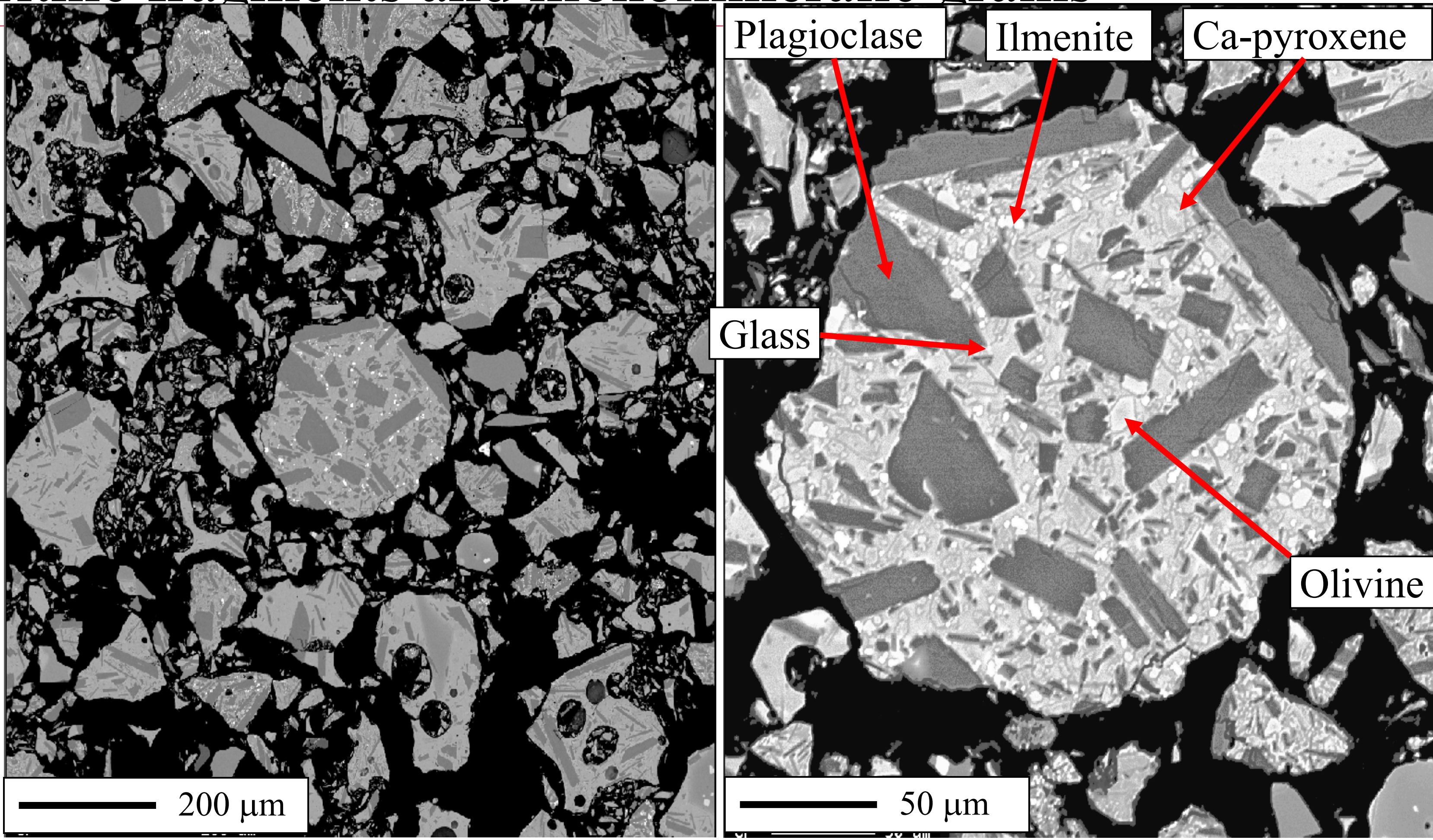
L: JSC-1 BSE digital image R: MLS-1 BSE digital image

Polished mount, large area map. BSE contrast is function of average Z.

Image segmentation yields phase area fraction, convert to weight fraction.

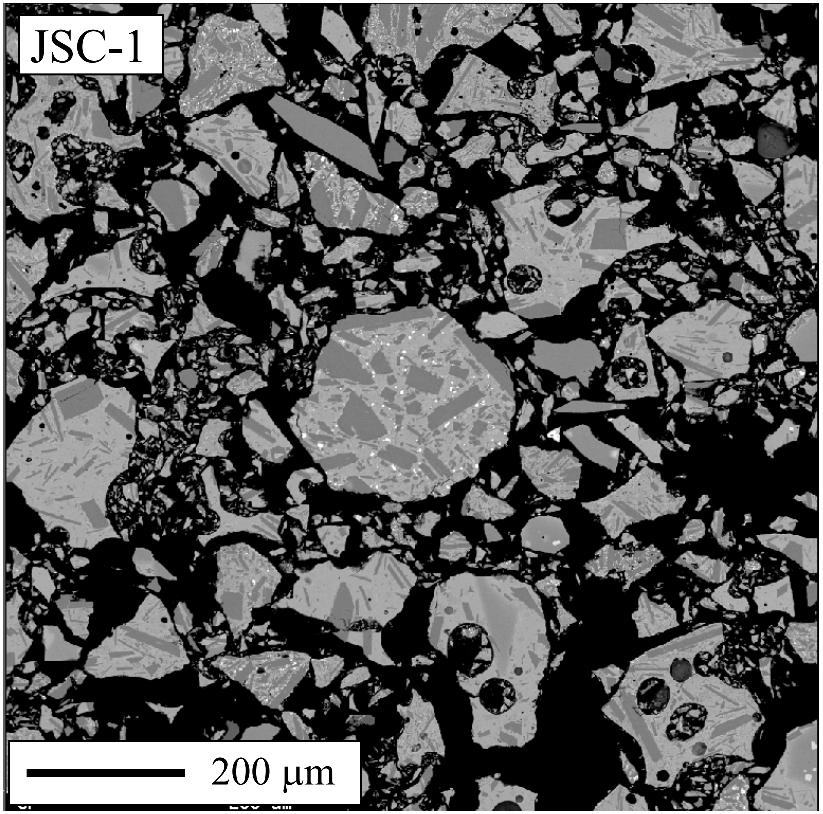
Resolution ~1 μm, acquisition time beam ~ minutes, stage ~ hours.

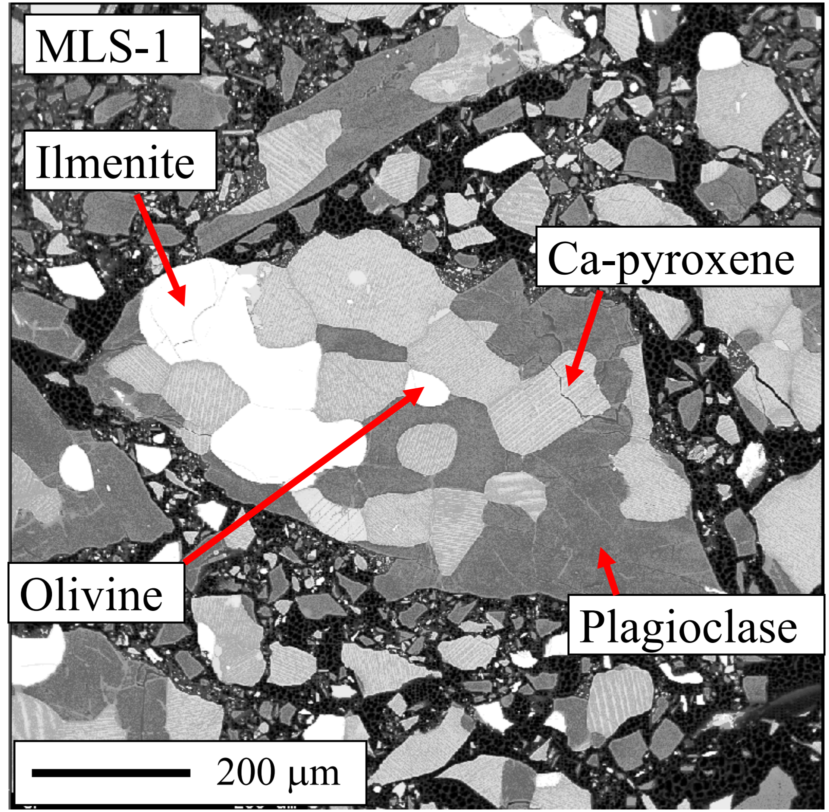
JSC-1: BSE images
Lithic fragments and monomineralic grains



JSC-1 BSE digital image, beam maps (L) 100x mag, (R) 300x mag, enhanced contrast
Dark to bright: plagioclase, glass, olivine, Ca-pyroxene, ilmenite, magnetite
Expect coarse size plagioclase dominant, fine size oxide, olivine, cpx, glass

JSC-1 vs. MLS-1: BSE images, 100x Magnification





JSC-1: Finer lithic and grain size. Expect lithics to persist to finer fraction vs. MLS-1
MLS-1: Grain size issue apparent, ~ 5x larger max grain size than JSC-1.
Ilmenite mode greater (high Ti), Ca-pyroxene with cpx lamellae, plagioclase secondary crystallization, absence of glass. Monomineralic grains at coarse size.
Dark to bright: plagioclase, cpx, olivine, ilmenite, magnetite

Lunar Simulant Mineral Chemistry Electron Microprobe, XRD

BAE SYSTEMS

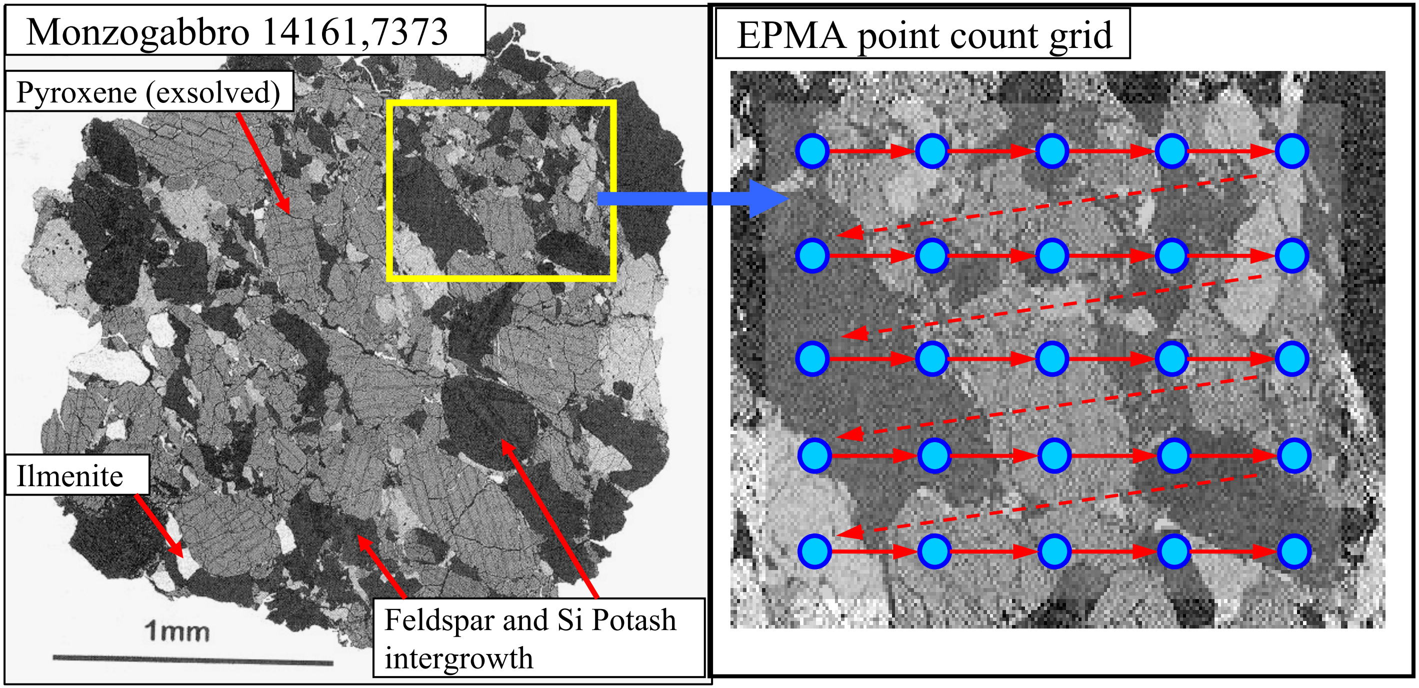
- **JSC-1**:

Plagioclase $An_{64-71}Ab_{28-33}$ Or_{1-3}
Olivine Fo_{82-86}
Ca-pyroxene Wo_{45} En_{34-38} Fs_{17-21}
Ilmenite ~ $Fe^{2+}_{0.85}$ $Fe^{3+}_{0.09}$ $(MgMn)_{0.103}$ $(AlCr)_{0.0025}$ $Ti_{0.95}$ O_3
Other: Chromite, Clay, Cristobalite?, Magnetite?, Hematite?

- **MLS-1**:

Plagioclase An_{44-50} Ab_{46-60} Or_{3-5}
Olivine Fo_{48-51}
Ca-pyroxene Wo_{39-41} En_{39-41} Fs_{19-22}
Ilmenite ~ $Fe^{2+}_{0.95}$ $Fe^{3+}_{0.0875}$ $(MgMn)_{0.075}$ $(AlCr)_{0.0025}$ $Ti_{0.95}$ O_3
Magnetite-Ulvospinel ~ $Fe^{2+}_{0.22}$ $Fe^{3+}_{2.05}$ $(MgMn)_{0.03}$ $(AlCr)_{0.12}$ $Ti_{0.25}$ O_4

EPMA: Micro vs. Macro Analysis
Quantitative EPMA point count grid

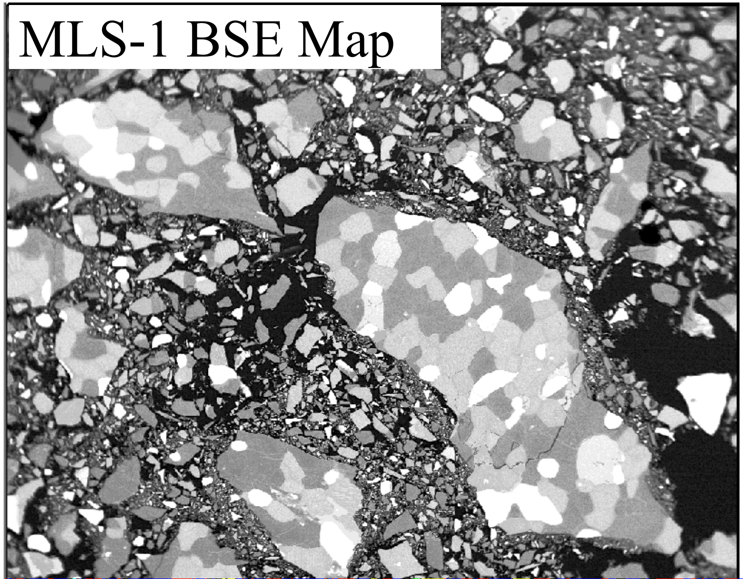


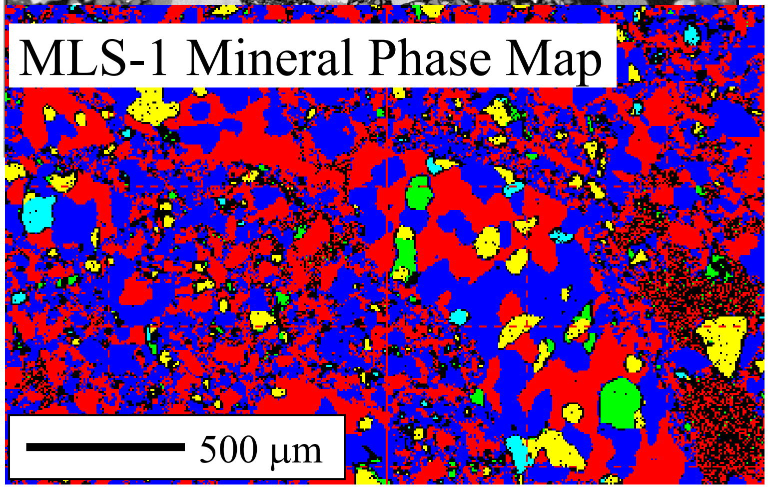
Left: Backscattered-electron digital image, contrast is function of average Z. Image segmentation yields phase area fraction, convert to weight fraction. Resolution ~1 μm, acquisition time ~ minutes.

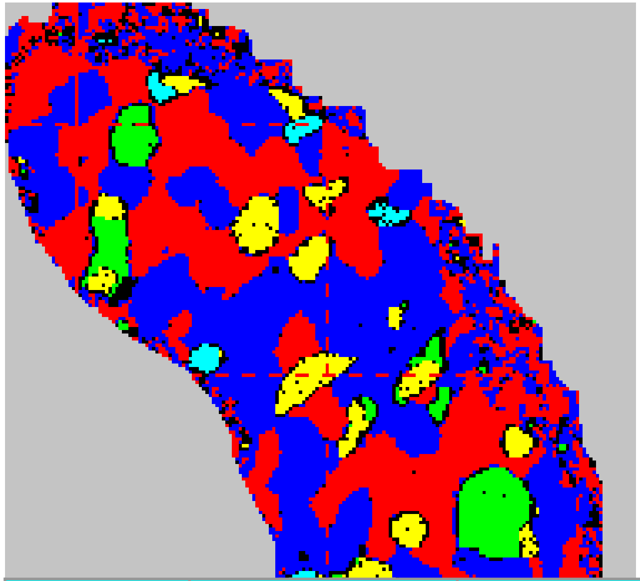
Right: EPMA pc grid example. Grid spacing adjusted for sampling requirements. Resolution ~1 μm, acquisition time ~ hours-days.

MLS-1 Mineralogy BSE and Phase Map
Area Fraction of Mineral Composition

BAE SYSTEMS







Color	Phase	Area %
Blue	Ca pyroxene	40
Red	Plagioclase	37
Yellow	Ilmenite	3.2
Green	Olivine	2.0
Cyan	Magnetite	0.9
	Other	16.7

Root Simulant Development Strategies

Root simulant materials and target Apollo soils

Least-squares bulk chemistry match

- JSC-1 example
- FJS-1 Japanese simulant examples

Synthetic Agglutinate-like microspheres, status

Calculation of Root Simulant Mix for Apollo 16 Target

BAE SYSTEMS

- Example for Apollo 16 highland anorthosite target.

  SiO_2 = (% olivine)*41.23 + (% plagioclase)*43.19 + (% quartz)*100 = 46.29, etc.
- Match using 16% olivine (Fo_{92}), 78% plagioclase (An_{100}), and 6% quartz, R=1.33
- CaO of target satisfied, but mix cannot match MgO and FeO simultaneously
- Pro's: Evaluation of proposed roots, proportions, source materials

  Could use root basalt and mineral separates from that same root (JSC-1, MLS-1?)
- Con's: Chemical match masks mineralogical requirements (but use mineral input)

Oxide	Fo_{92}	An	Q	Root Mix	A 16*	Diff^2
SiO_2	41.23	43.19	100	46.29	45.00	1.65
Al_2O_3		36.65		28.59	27.30	1.66
FeO	7.89			1.26	5.10	14.73
MgO	50.89			8.14	5.70	5.97
CaO		20.16		15.72	15.70	0.00
Total	100	100	100	100	(100.78)	

Sum of $(L_i-C_i)^2$ = 24.75, R = sqrt(24.75 / n=14 oxides) = 1.33
For mix of 16% olivine Fo_{92}, 78% Plagioclase An100, 6% quartz
Apollo 16 analysis includes other minor elements not listed here

$$R = \sqrt{\frac{\sum_{i=1}^{n}(L_i - C_i)^2}{n}}$$

Root Mixtures: JSC-1 and Component Minerals
Can JSC-1 be Used for Several Root Simulants?

BAE SYSTEMS

- Root simulants using JSC-1 and JSC-1 mineral separates (ilmenite, olivine, Ca-pyroxene, plagioclase, glass). Mineral compositions from EPMA, ilmenite Fe^{2+}/Fe^{3+} calculated by stoichiometry.
- For each proportion mix, determine least-squares match for all component oxides to compared to target Apollo oxide composition.

Apollo Target	Apollo 11 High Ti			Apollo 14 Low Ti / KREEP		Apollo 16 Highland	
R min	1.68	1.41	1.43	1.51	1.22	1.90	1.88
JSC-1 %	86	61	50	100	71	27	23
Ilmenite %	14	12	15		2		
Olivine %		2	5		4	3	5
Ca-pyroxene		15					
Plagioclase		10	8		10	70	70
Glass			22		13		2

Notes:
Apollo compositions from McKay et al., Chapter 7, Lunar Sourcebook, Table 7.15, p. 346.
Glass and Ca-pyroxene present separation challenge due to grain size in JSC-1 bulk material.
Minor phases and trace glass chemistry ignored.

Simulant Development in Japan
Mixtures from Root Materials

BAE SYSTEMS

- Identify root components, iterate on component proportion (basalt + ilm + ol)

For each proportion mix, determine least-squares match for all component oxides compared to target Apollo oxide composition.

- Mt. Fuji basalt, ilmenite from Florida, and olivine from Horoman and Hokkaido islands crushed and physically mixed.
- Best fit for Apollo 14, R = 1.82 for 88:0:12 mix.
- Type 1 ~ Apollo 16 highland, Type 2 ~ Apollo 14 KREEP, Type 3 ~ Apollo 11 high Ti

Apollo Target	**11**	**12**	**14**	**15**	**16**	**17**
R min	**2.91**	**2.50**	**1.82**	**2.63**	**4.03**	**2.56**
Basalt, %	**81**	**83**	**88**	**81**	**100**	**82**
Ilmenite, %	**8**	**1**	**0**	**0**	**0**	**3**
Olivine, %	**11**	**16**	**12**	**19**	**0**	**15**
Simulant Type	**3**		**2**		**1**	

Data from Shigeru Aoki, Lunar Exploration Technology Office, Japan Aerospace Exploration Agency, and Hiroshi Kanamori, Institute of Technology, Shimizu Corporation

Lunar Mare Basaltic Simulants: Japanese Simulants FJS-1, Type 1-3 Root-type

BAE SYSTEMS

Simulant Materials:

FJS-1: Mt. Fuji basalt, Japan, ~ Apollo 16

Type 1: ~ Apollo 16
Type 2: ~ Apollo 14
Type 3: ~ Apollo 11
Mixtures of Mt. Fuji basalt, ilmenite, olivine

Data from:
Shigeru Aoki
Lunar Exploration Technology Office, Japan Aerospace Exploration Agency

Hiroshi Kanamori
Institute of Technology, Shimizu Corporation

Oxide	FJS-1		Type 1	Type 2	Type 3
SiO_2	49.14		49.1	49.7	46.0
TiO_2	1.91		1.9	1.7	6.7
Al_2O_3	16.23		16.2	14.8	13.7
Cr_2O_3	0.00				
Fe_2O_3	4.77		4.8	4.7	5.9
FeO	8.30		8.3	8.2	7.9
MnO	0.19		0.19	0.19	0.28
MgO	3.84		3.8	8.1	7.3
CaO	9.13		9.1	8.4	7.8
Na_2O	2.75		2.8	2.6	2.6
K_2O	1.01		1.0	0.92	0.87
P_2O_5	0.44		0.44	0.40	0.39
LOI	0.43		0.43	0.47	0.58
Total	98.14		98.1	100.2	100.0

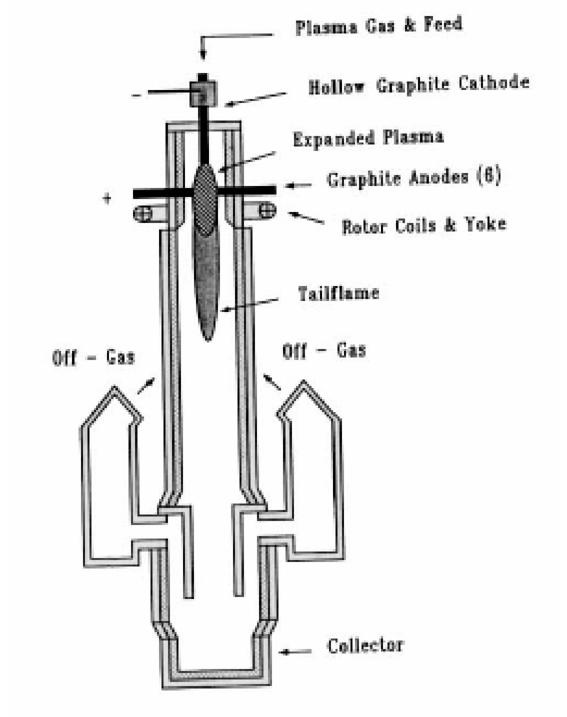
Synthetic Production of Agglutinate-like Glass Microspheres

BAE SYSTEMS

•Weiblen: ISSP (right)
In-flight Sustained Shockwave Plasma reactor
MLS-1 source, plasma melting, spherical agglutinate-like
Further work was to generate metallic Fe, other simulants

•NIST: K411 microspheres
Plasma torch melted NIST K411 glass (MgSiCaFe glass)
NIST SRM 2006 is K411 in 2 – 40 µm microsphere
Particle analysis via EPMA/EDS, good agreement between K411 (SRM 470 bulk) and SRM 2006 microspheres

•Corning:
Long history of research glass technology
Initial discussions for microsphere and glass fiber research
Small scale vs. large scale



BAE SYSTEMS

Quality Control and Standard Development

Bulk chemistry vs. variability of MLS-1

Bulk Chemistry of MLS-1
Variability of Sub Samples: Major elements

BAE SYSTEMS

Oxide	MLS-1	Min	Max	Range rel to Accepted, %
SiO_2	43.86	41.7	45.90	9.6
TiO_2	6.32	4.82	7.43	41.4
Al_2O_3	13.68	11.76	15.60	28.0
Fe_2O_3	2.60	0.90	4.10	123.1
FeO	13.40	12.00	14.40	17.9
MnO	0.198	0.182	0.218	18.0
MgO	6.68	5.57	8.44	42.8
CaO	10.13	9.04	11.48	24.2
Na_2O	2.12	1.97	2.27	14.3
K_2O	0.281	0.17	0.35	64.6
P_2O_5	0.20	0.02	0.45	215
Total	99.47	88.13	110.64	22.6

Gross analytical errors and/or inadequate sampling of MLS-1 source material

Bulk Chemistry of MLS-1
Variability of Sub Samples: Trace elements

BAE SYSTEMS

Element	MLS-1 ppm	Min ppm	Max ppm	Range rel to Average, %
Th	14	13	15	14%
Sr	212	173	253	38%
Co	64	53	84	48%
Ba	95	62	117	58%
V	761	506	952	59%
Cu	445	214	706	111%
Ni	97	53	163	113%
Cr	173	89	366	160%
Zr	47	19	113	200%
Rb	4	1	10	225%

Variations in oxide, sulfide, others in coarse ground material, small sampling

Ranked by range error relative to average value

Data quoted from NASA TM-103563, “Differential Thermal Analysis of Lunar Soil Simulant”, Tucker and Setzer, Dec. 1991

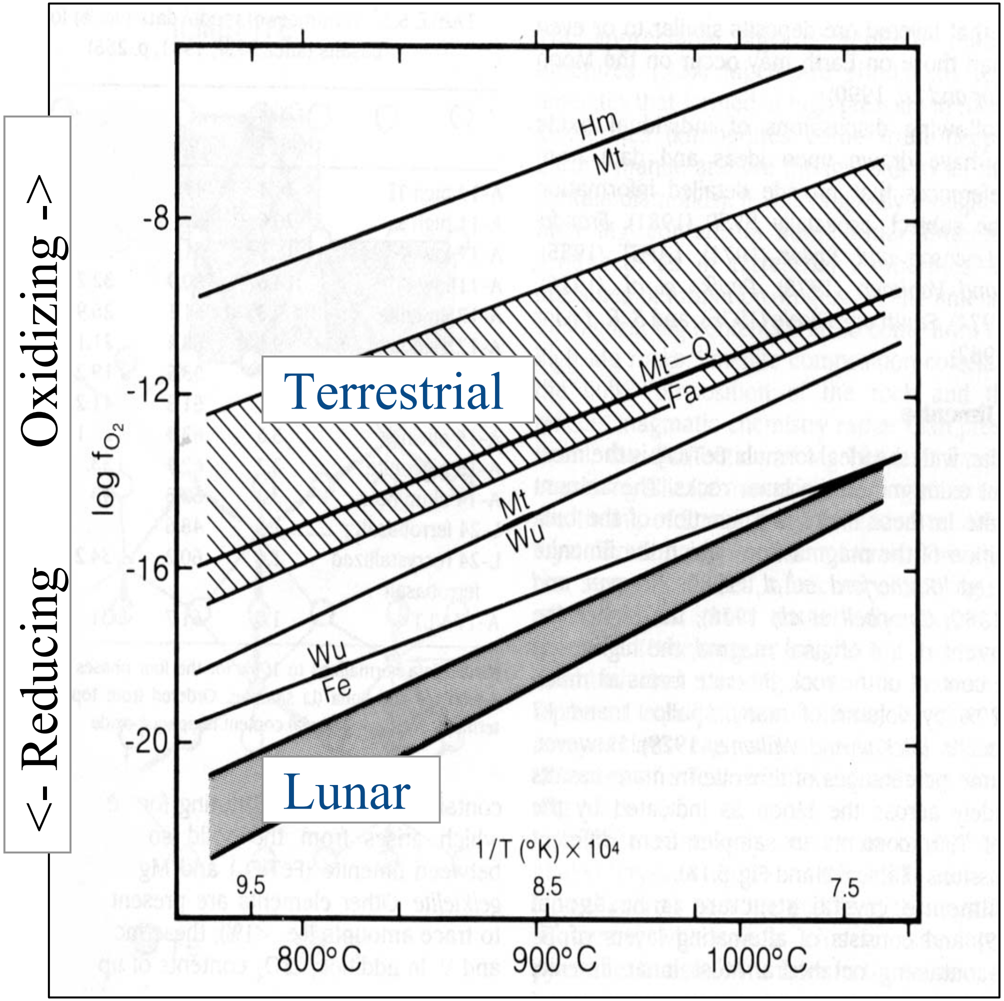
Oxygen Fugacity Control
Mössbauer Characterization

Oxygen fugacity of lunar vs. terrestrial igneous rocks

Mössbauer characterization / Fe valence state

Oxygen Fugacity Regimes for Lunar vs. Terrestrial Igneous Rocks

BAE SYSTEMS



Terrestrial rocks contain Fe^{2+} and Fe^{3+} and form at approximately the FMQ Fe_2SiO_4 | $Fe_3O_4 + SiO_2$ buffer.

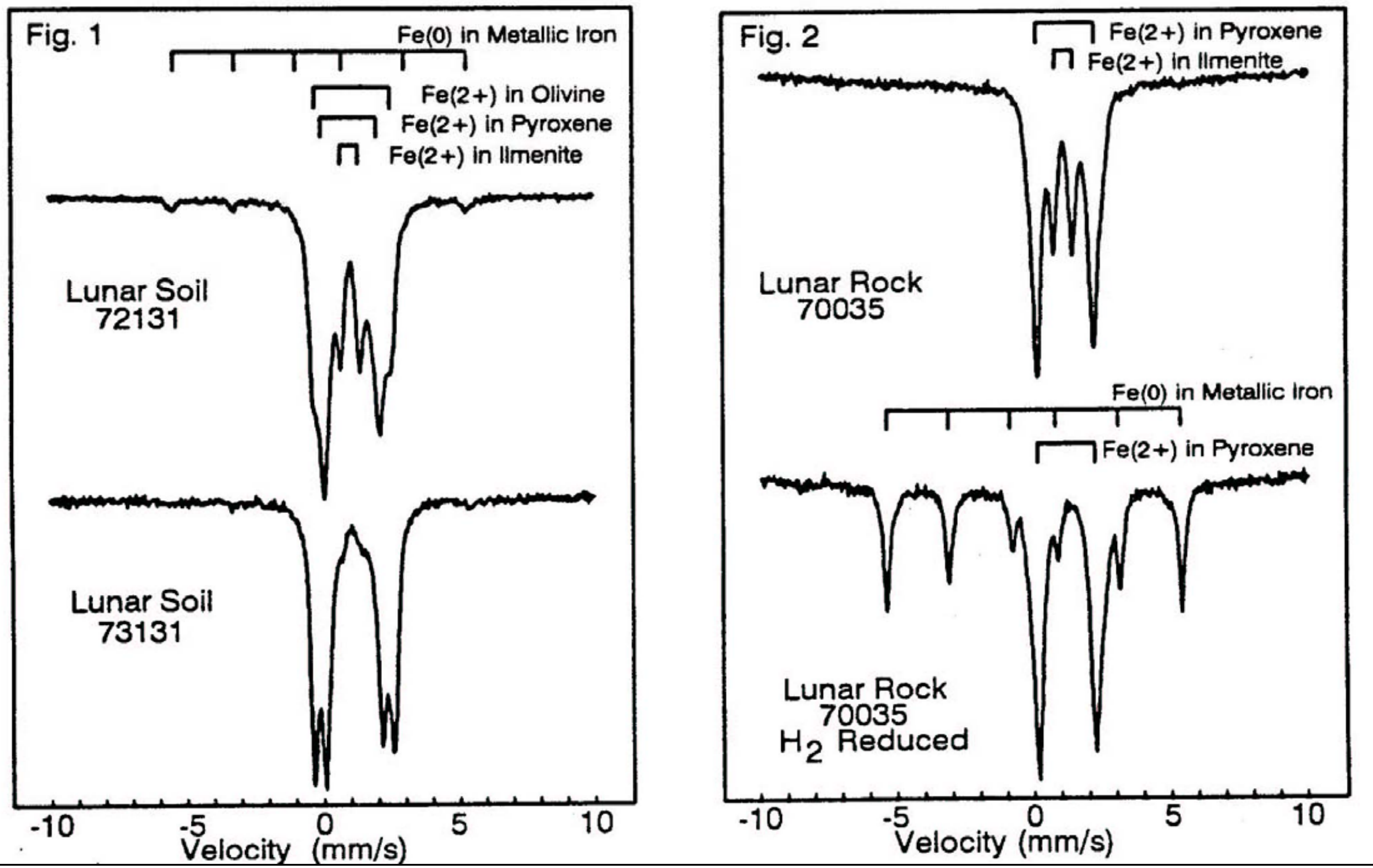
Lunar rocks contain Fe^0 and Fe^{2+} and formed at approximately the FeWu, i.e. Fe | FeO buffer.

These buffer curves quantitatively describe the required oxygen fugacity fO_2 to be used on processed materials.

Lunar conditions can be simulated on Earth using fO_2 constrained systems.

Experiments / procedures on Earth must address *f*O2 control if aiming to duplicate lunar surface conditions

Mössbauer Spectroscopy: Confirmation of reduction Fe^{2+} to Fe^0



Examples of Mössbauer characterization of lunar materials [from *R.V. Morris, D.G. Agresti, et al.* (1992) in *Joint Workshop on New Technologies for Lunar Resource Assessment*]

BAE SYSTEMS

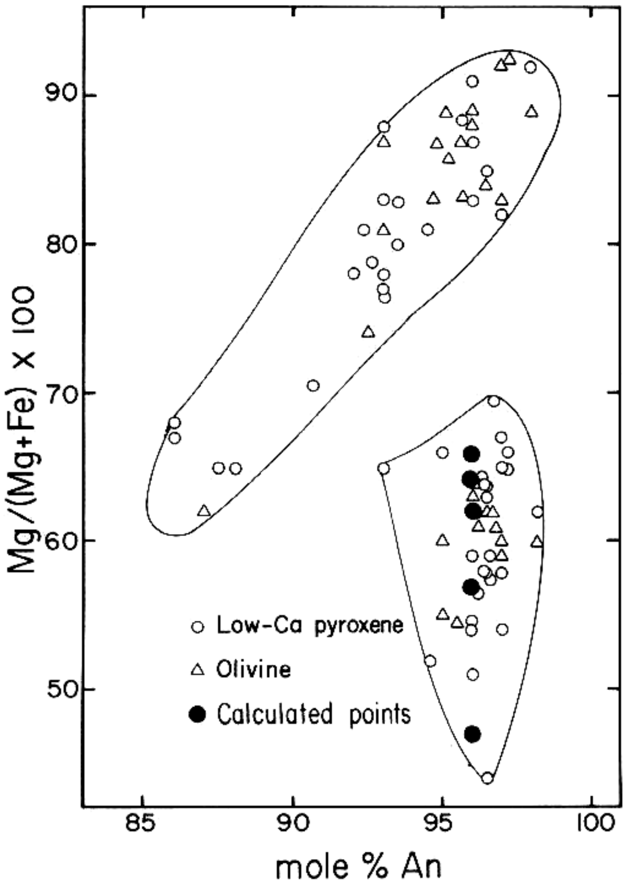
Source Localities for Anorthosite Simulant

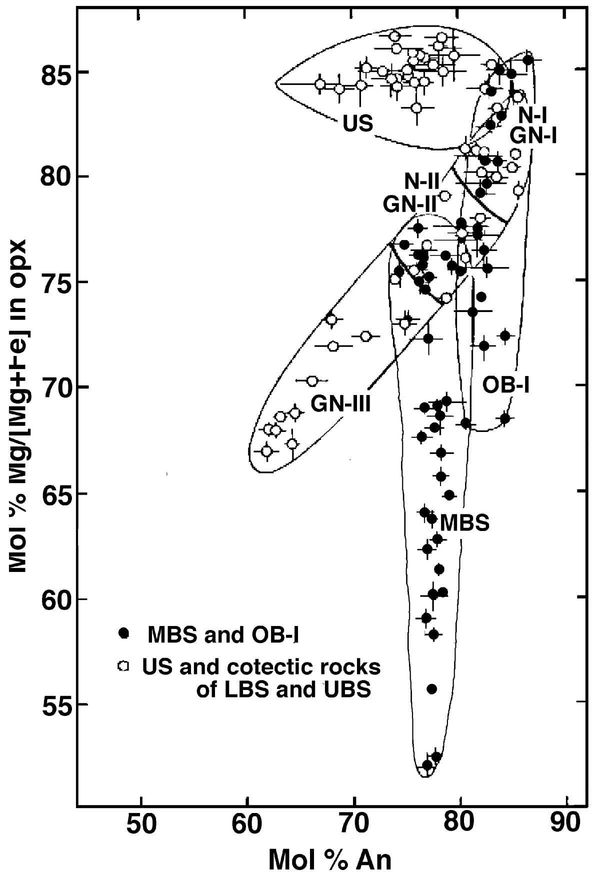
Stillwater intrusion, Montana, banded series

Duluth complex, Minnesota

Trends of Coexisting MgFe Minerals vs. Plagioclase, Compare Pristine Lunar vs. Stillwater

BAE SYSTEMS





Pristine Lunar Highlands Trends

From "A comparison of fractionation trends in the lunar crust and the Stillwater Complex, L.D. Raedeke and I.S. McCallum

Stillwater Trends

From "The Stillwater Complex: A review of the geology", I. S. McCallum

Simulant Sources for Highlands Anorthosite

BAE SYSTEMS

- Lunar anorthosite plagioclase is Ca-rich, ~ An_{85-96}
- Terrestrial anorthosites generally more Na-rich
- **Stillwater intrusion**, Montana

Anorthosite, olivine-gabbro, norite; Anorthosite of MBZ possible simulant?

Anorthosite: Plagioclase An_{75-80}, Olivine ~ Fo_{65-78}, Augite, Fe-Ti oxides

Active mining by Stillwater Mining Company, interested in simulant issues

- **Duluth complex**, Minnesota

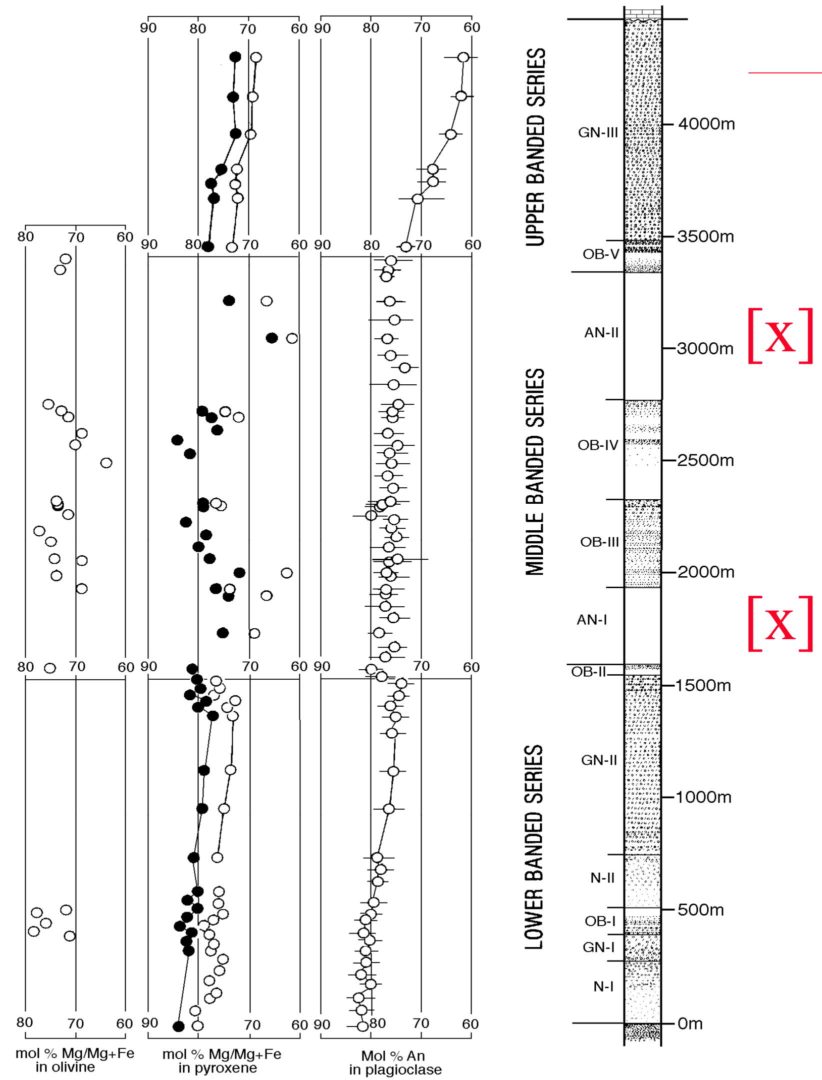
Anorthosite: Plagioclase An_{55-65}, Olivine Fo_{40-66}, Augite, Fe-Ti oxides

Troctolite: Plagioclase An_{52-71}, Olivine Fo_{49-66}

Access to material in quarry, tbd

Stillwater Intrusion Banded Series

Middle Banded Series has anorthosites with consistent plagioclase composition and relatively consistent olivine and pyroxene compositions



Olivine Fo% Opx En% Plag An%

Conclusions

BAE SYSTEMS

- Development of LRSM requires physical and chemical, mineralogical characterization via bulk and microanalytical methods
- Lunar regolith simulants JSC-1 and MLS-1 provide good framework for general LRSM discussion
- Root simulant development strategies can be quantified
- Quality control is central to LRSM standard development
- Oxygen fugacity control and Mössbauer characterization are important for processing using LRSM
- We should pursue development of anorthosite simulants at localities discussed

Additional Material

BAE SYSTEMS

Characterization Methods

Characterization Methods: Bulk Chemistry/Structure Non-destructive for Lunar Materials

BAE SYSTEMS

- **X-ray fluorescence**

New XRF systems ~10's μm beam, microanalysis of ng to pg equivalent.
Sensitivity major, minor, trace (μg/g)
Can analyze insulating materials in-situ, proven for MER, on-line monitoring
Rapid acquisition via energy-dispersive detection systems—if bright source

- **INAA Instrumental Neutron Activation Analysis**

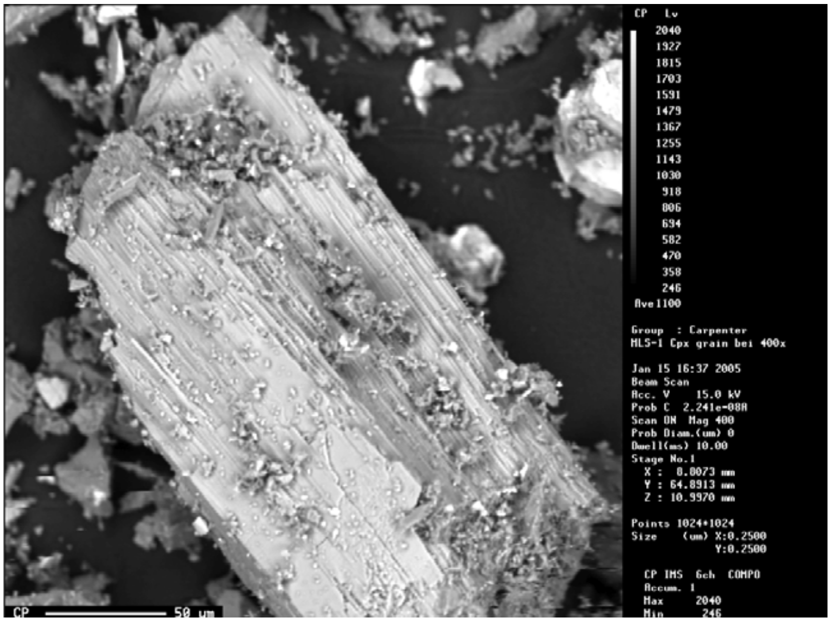
Analysis of mg quantity for major, minor, trace (μg/g, ng/g?)
Extensively used for lunar trace element data
Nuclear reactor, multiple counting experiments, not real-time

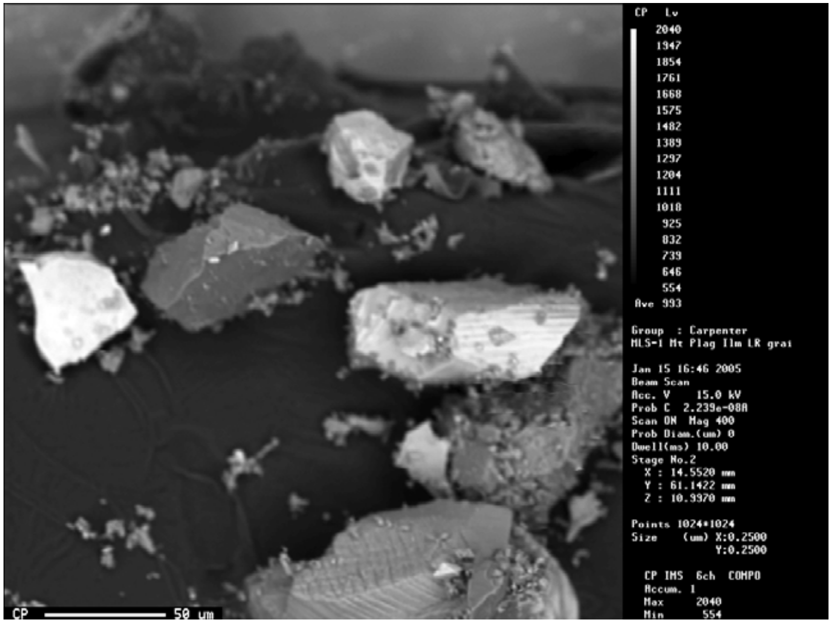
- **ICPMS**

High analytical sensitivity, to ng/g levels
Requires sample digestion, not real-time

MLS-1 Grain Mount
BSE Images of Unpolished Grains

BAE SYSTEMS

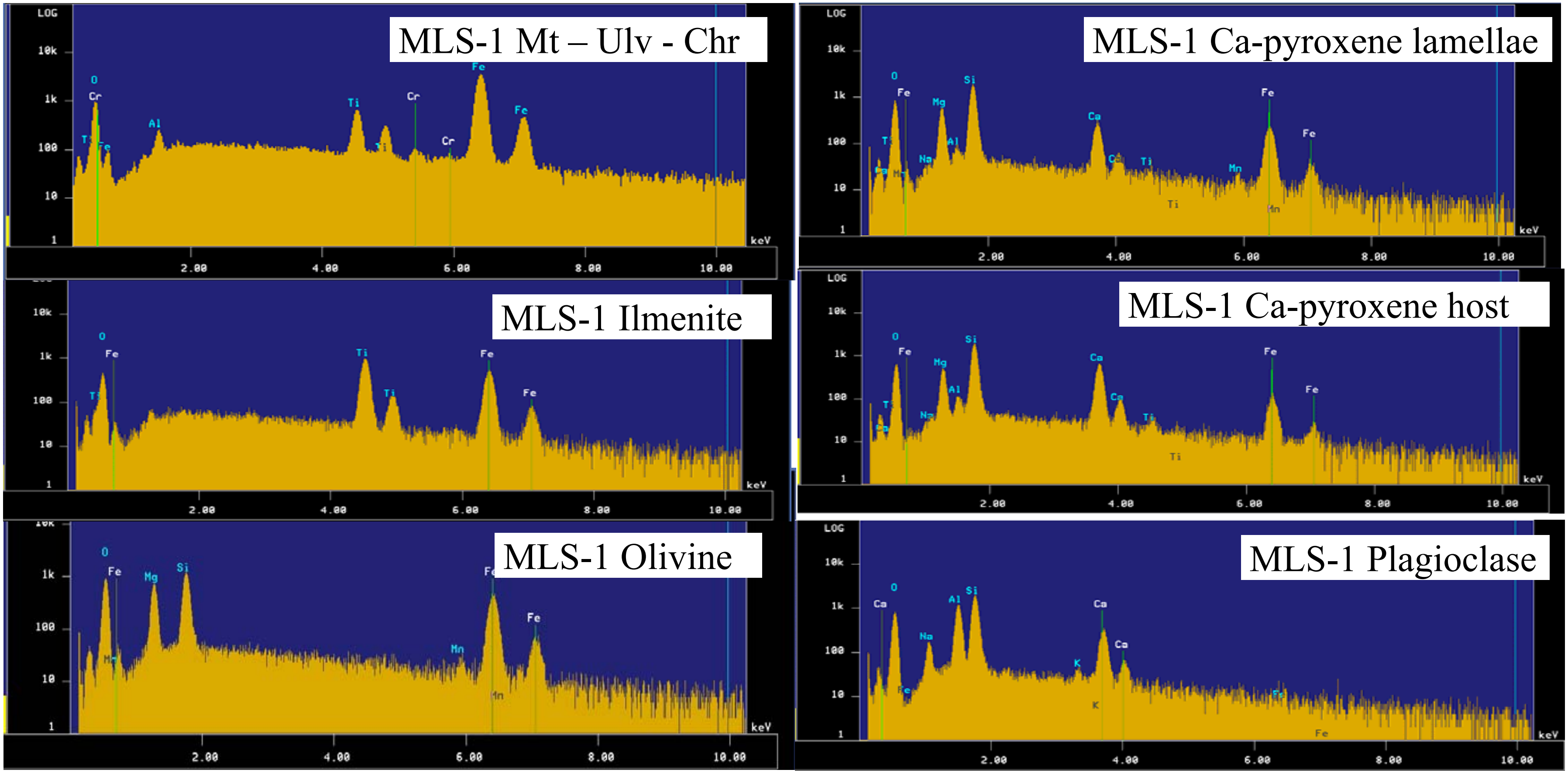




Left: BSE of Ca-pyroxene with exsolution lamellae.
Right: BSE of Magnetite, Plagioclase, and Ilmenite grains. Scale 50 μm.

MLS-1 EDS Spectra of Mineral Components

BAE SYSTEMS



BSE and X-ray maps are used to identify minerals and produce phase map

Characterization Methods: Powder X-ray Diffraction

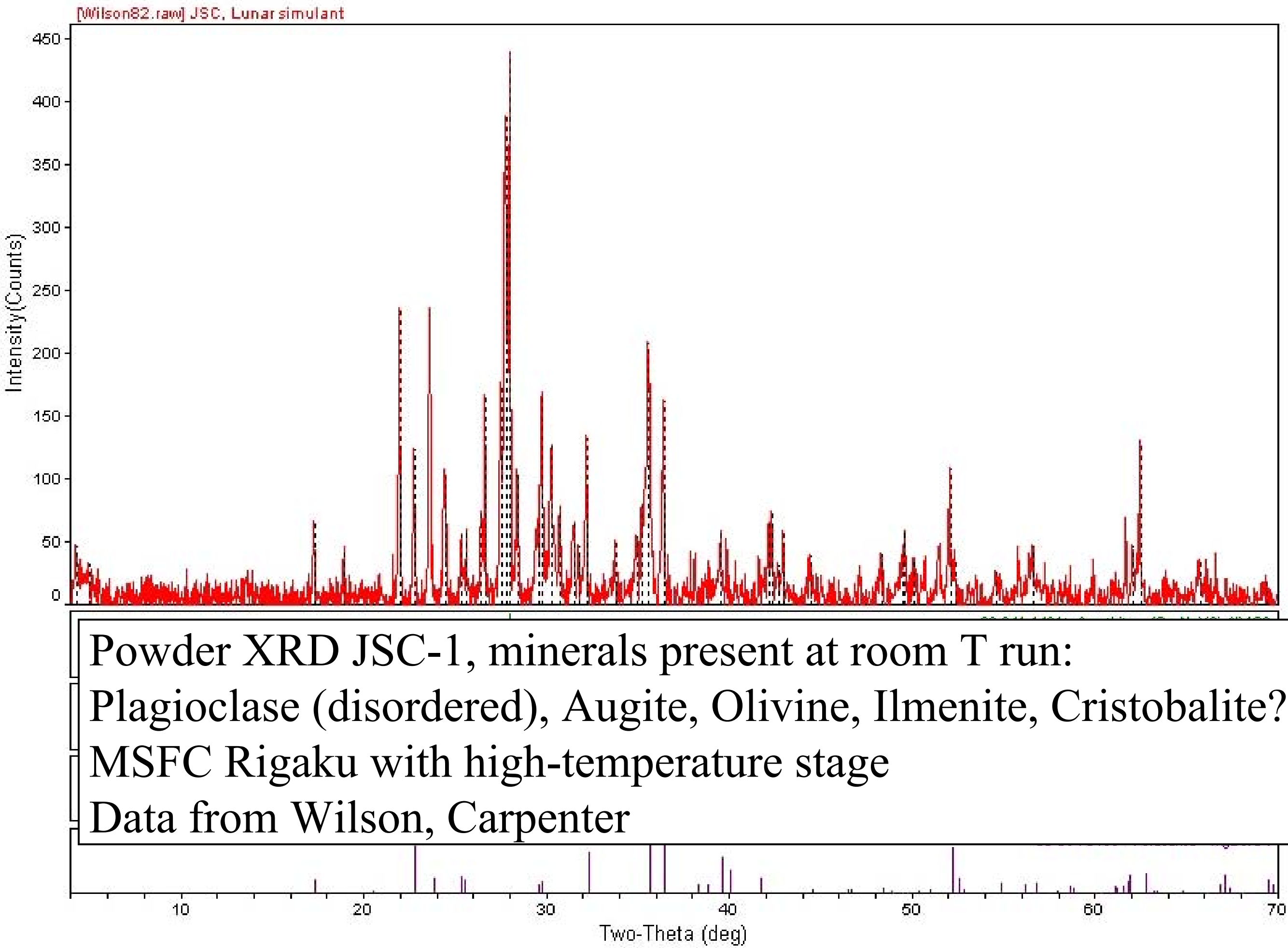
BAE SYSTEMS

- Mineral identification, crystallographic structure, sample mg quantity
- Modal analysis (volume percentages), detection limit ~ 0.X%
- Rietveld refinement: Whole pattern fitting vs. individual peak analysis, yields mineral abundance and cell information
- High temperature furnace attachment
- Lunar simulant characterization needs:

Analysis of grain size fractions: mineralogy, particle size analysis
Sintering and melting, phase/structural changes
Onset of reaction analysis

Powder X-ray Diffraction: JSC-1

BAE SYSTEMS



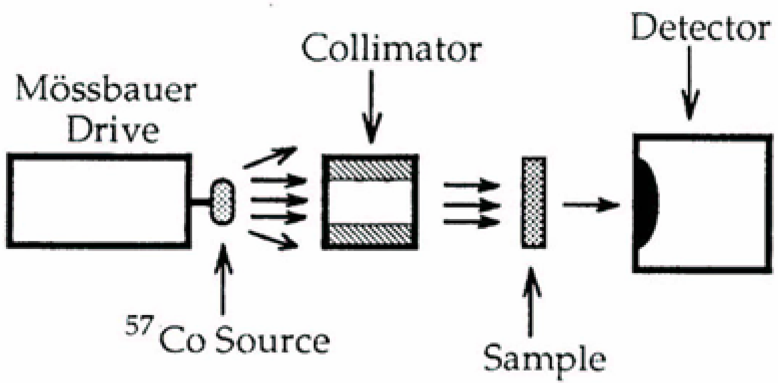
Powder XRD JSC-1, minerals present at room T run:
Plagioclase (disordered), Augite, Olivine, Ilmenite, Cristobalite?
MSFC Rigaku with high-temperature stage
Data from Wilson, Carpenter

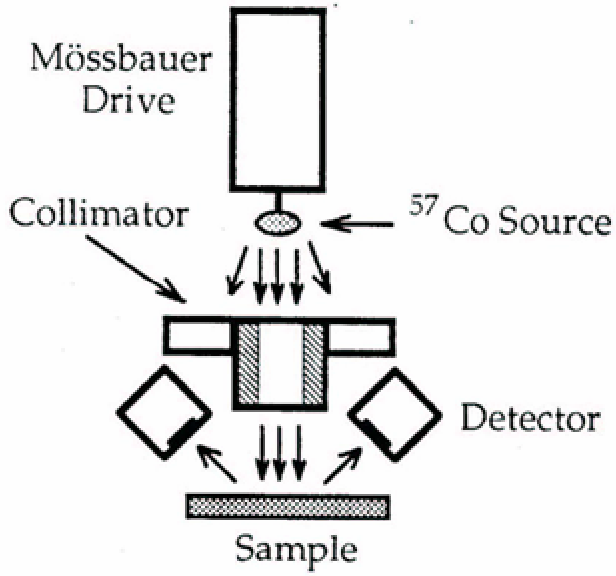
Mössbauer Spectroscopy

BAE SYSTEMS

- A nuclear gamma resonance technique
- Several dozen nuclear isotopes exhibit the Mössbauer effect
- For planetary applications (Moon, Mars, etc.), the Fe-57 isotope is most important. The gamma source is Co-57 (270-day half life).
- Iron-containing minerals in a sample are characterized; those without iron are invisible to the technique
- Two in-situ planetary instruments are now operating on Mars
- The source is vibrated. Energy of emitted gammas are then Doppler shifted to sweep through resonant transition energies of a sample
- Spectra are superpositions of doublets and/or sextets
- Ferrous and ferric states are distinguished, e.g. olivine and jarosite
- Magnetic materials are identified, e.g. iron metal, magnetite, hematite
- Suitable for characterizing simulant material or monitoring processes

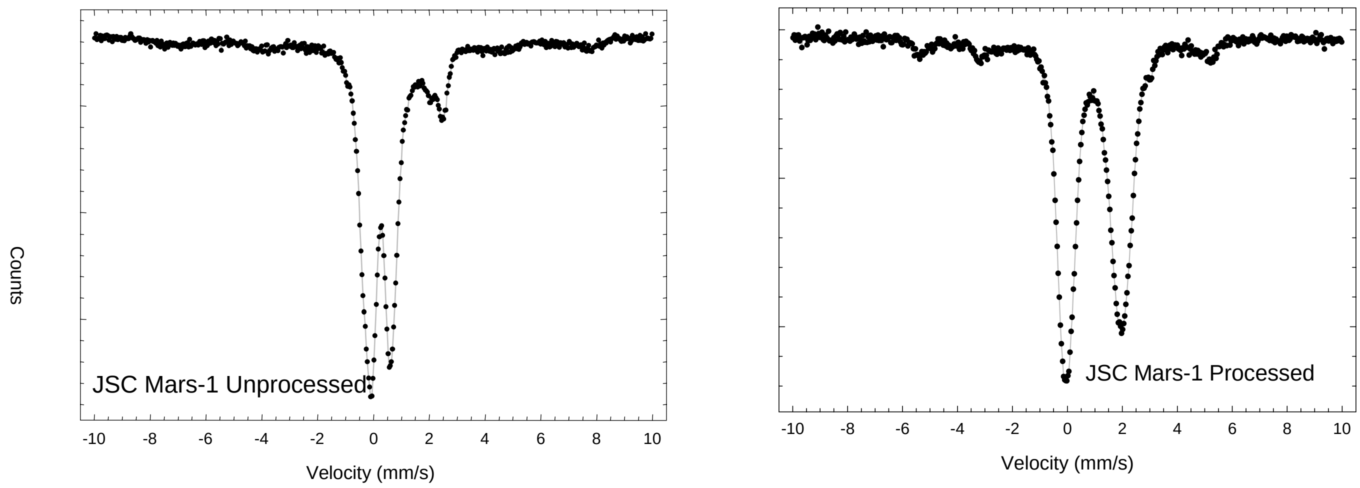
Comparison of transmission and backscatter Mössbauer geometries
[from *T.D. Shelfer* (1992) UAB Ph.D. dissertation]





Mössbauer characterization of unprocessed and processed Martian simulant

BAE SYSTEMS



Examples of Mössbauer characterization of unprocessed and processed Martian simulant [2003, unpublished]
Before processing, the spectrum is dominated by a strong central ferric doublet and weaker iron-oxide sextet in the baseline. After processing (microwave heating), there is clear evidence of reduction, the principal feature being that of a ferrous glass. The weak sextet of alpha-iron is also evident.

Root Simulants

Mass Balance Modeling of Lunar Soils Using Root Simulants

BAE SYSTEMS

- Select root simulant components and target composition in weight % format.
  - For each root component, iterate mix fraction, (i.e., basalt, ilmenite, etc.):
  - Sum oxide wt % contribution from each simulant component (FeO of mix = c_1 * FeO in basalt + c_2 * FeO in ilmenite + …)
  - Calculate R, least squares, sum of differences between root mix, C_i, and Apollo target, L_i, for all oxides
- Minimum R for root simulant mix is observed for best match to Apollo soil composition.
- Fidelity of root simulant mix is function of R, several approximations may be possible depending on accuracy needed.

$$R = \sqrt{\frac{\sum_{i=1}^{n} (L_i - C_i)^2}{n}}$$

Lunar Mare Basaltic Simulants: Japanese Simulants FJS-1, MKS-1, Type 1-3

Simulant Materials:

FJS-1: Mt. Fuji basalt, Japan

MKS-1:

Type 1, 2, 3:
Physical mixtures of Mt. Fuji basalt, ilmenite, olivine

Data from:
Shigeru Aoki
Lunar Exploration Technology Office, Japan Aerospace Exploration Agency

Hiroshi Kanamori
Institute of Technology, Shimizu Corporation

Oxidc	FJS-1	MKS-1		Type 1	Type 2	Type 3
SiO_2	49.14	52.69		49.1	49.7	46.0
TiO_2	1.91	1.01		1.9	1.7	6.7
Al_2O_3	16.23	15.91		16.2	14.8	13.7
Cr_2O_3	0.00	0.00				
Fe_2O_3	4.77	4.78		4.8	4.7	5.9
FeO	8.30	7.50		8.3	8.2	7.9
MnO	0.19	0.22		0.19	0.19	0.28
MgO	3.84	5.41		3.8	8.1	7.3
CaO	9.13	9.36		9.1	8.4	7.8
Na_2O	2.75	1.90		2.8	2.6	2.6
K_2O	1.01	0.58		1.0	0.92	0.87
P_2O_5	0.44	0.14		0.44	0.40	0.39
LOI	0.43	0.50		0.43	0.47	0.58
Total	98.14	100.0		98.1	100.2	100.0

Martian Soil Simulant Mars-1

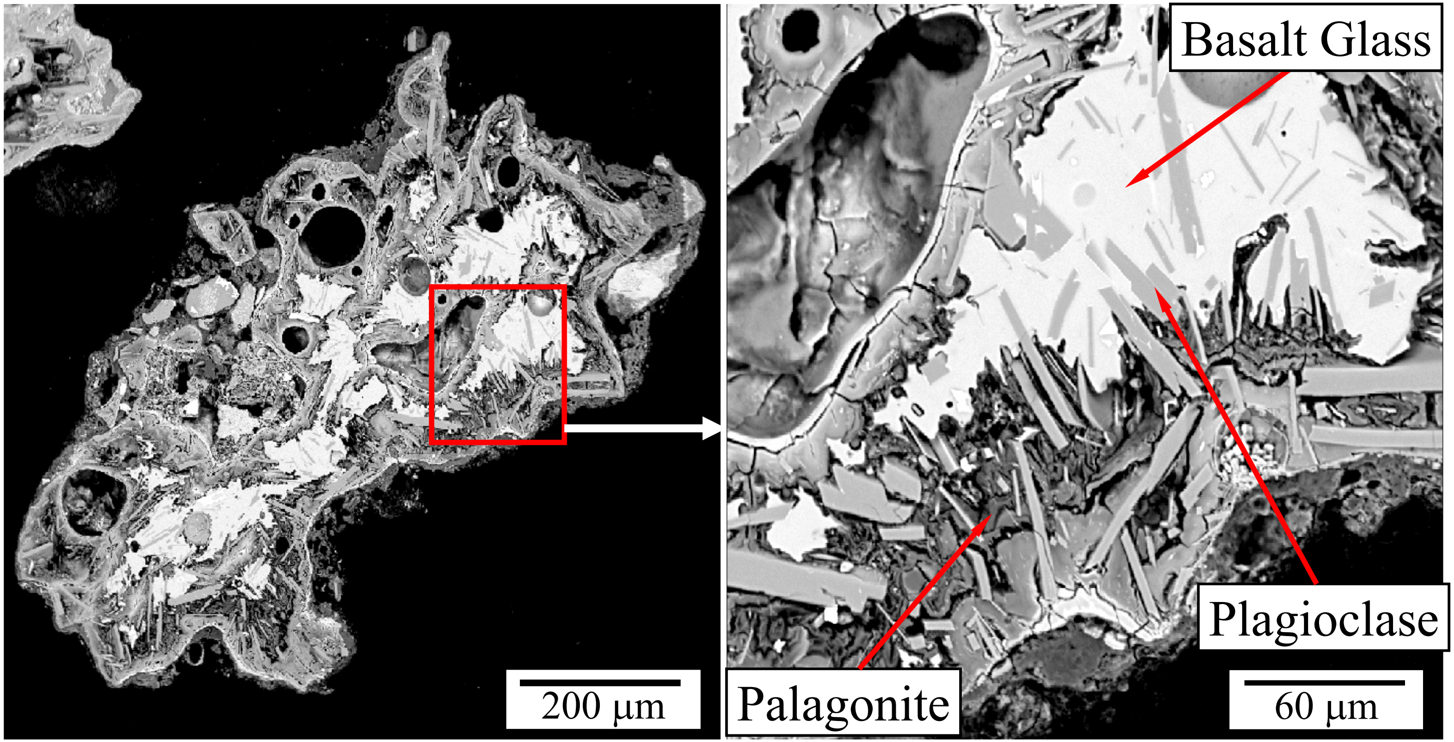
Mars Rock and Soil Chemistry / Geology

BAE SYSTEMS

- Martian meteorites (>29 found to date – 7/2004 New Nakhlite! MIL-03346)
  SNC, ALH84001: peridotites, pyroxenites, basaltic rocks (ol, cpx, opx, plag)
- Viking 1 and Viking 2 landers (1976)
  XRFS, GCMS, NMS, Magnetic: soil chemistry, organics, magnetic minerals
- Mars Global Surveyor
  Global imaging calibrated using lander and rover data
- Pathfinder (1997), Spirit, Opportunity (2004) – Hematite (Fe_2O_3) Identified
  Panoramic Camera: High resolution imaging
  Thermal Emission Spectrometer: Mineral identification, test for H_2O, OH
  Mossbauer Spectrometer (Co^{57} source): Fe oxidation state
  APXS (Cm^{244}) Alpha Proton X-ray Spectrometer: Major element rock analysis
  Microscopic Imager: Fine scale imaging of grains

JSC Mars-1 Martian Soil Simulant: Typical Grain

BAE SYSTEMS



- Rock fragment with glass, plagioclase, augite, Ti-magnetite, palagonite alteration.

JSC Mars-1 Compared to Martian Soil / Rock

•Mars-1 Simulant
XRF norm volatile free
Fe_2O_3* 15.6
$Fe^{3+} / Fe^{2+} \sim 3.2$

•Pathfinder Soil
APXS A-2 Deploy

•Pathfinder SFR
Soil-free rock

•Viking Lander 1
XRF norm volatile free
(Total 89%), avg 3, Fe_2O_3 *

•Shergotty meteorite
INAA

•Yellow: Mars-1 differs from Soil / SFR

•Blue: Soil differs from SFR

	Mars-1	Soil	SFR	VL-1	Sher
SiO_2	43.5	40.9	57.7 ± 1.5	48.4	51.36
TiO_2	3.8	0.7	0.5 ± 0.15	0.74	0.87
Al_2O_3	23.3	10.4	12.3 ± 0.7	8.2	7.06
Cr_2O_3		0.3			
Fe_2O_3	15.6	21.2		20.8	
FeO			14.2 ± 0.8		19.41
MnO	0.3	0.5			0.52
MgO	3.4	8.7	0.8 ± 0.8	6.7	9.28
CaO	6.2	6.1	6.7 ± 0.5	6.6	10
Na_2O	2.4	3.2	4.2 ± 0.6		1.29
K_2O	0.6	0.5	1.2 ± 0.08	< 0.17	0.16
P_2O_5	0.9	0.9	0.4 ± 0.2		0.8
SO_3		6.0	0.1 ± 0.04 S	7.4	0.13 S
Cl		0.7	0.4 ± 0.1	0.8	0.01
LOI	(22)				
Total	(100)	100.1	98.5	(100)	100.9

JSC Mars-1 BSE Image
Range of chemical weathering