Development of Martian Regolith Simulants

***In Situ* Resource Availability And Potential**

Laura E. Fackrell

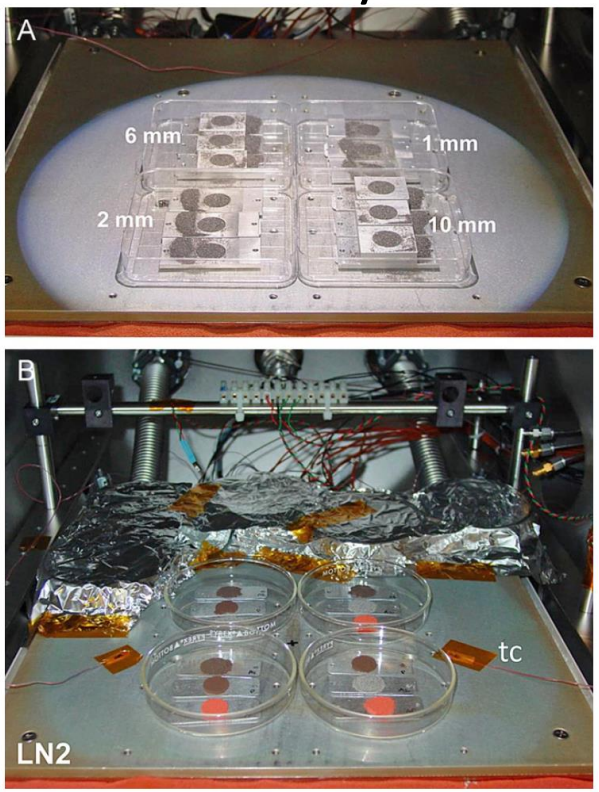
Mars Simulants and Exploration

Appropriate analog materials are an essential tool in the studies of the Martian surface and mission preparation

Growth Experiment

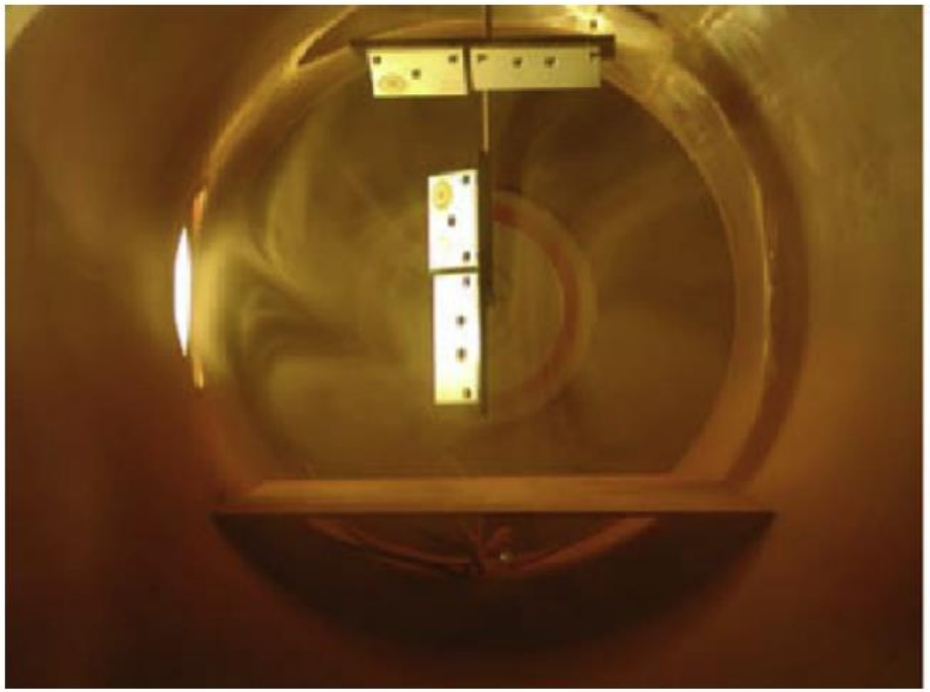
Wamelink et al. 2014

Habitability



Schuerger et al. 2012

Rover Testing



Seiferlin et al. 2008

Martian Simulant Development

Application

Characteristics

Volume

Materials

Wamelink et al. 2014

Martian Simulant Development

Application

- Plant Growth Experiment

Characteristics

- Chemical
- Mineral
- Growth Limiting Conditions (Salinity, toxicitiy)

Volume

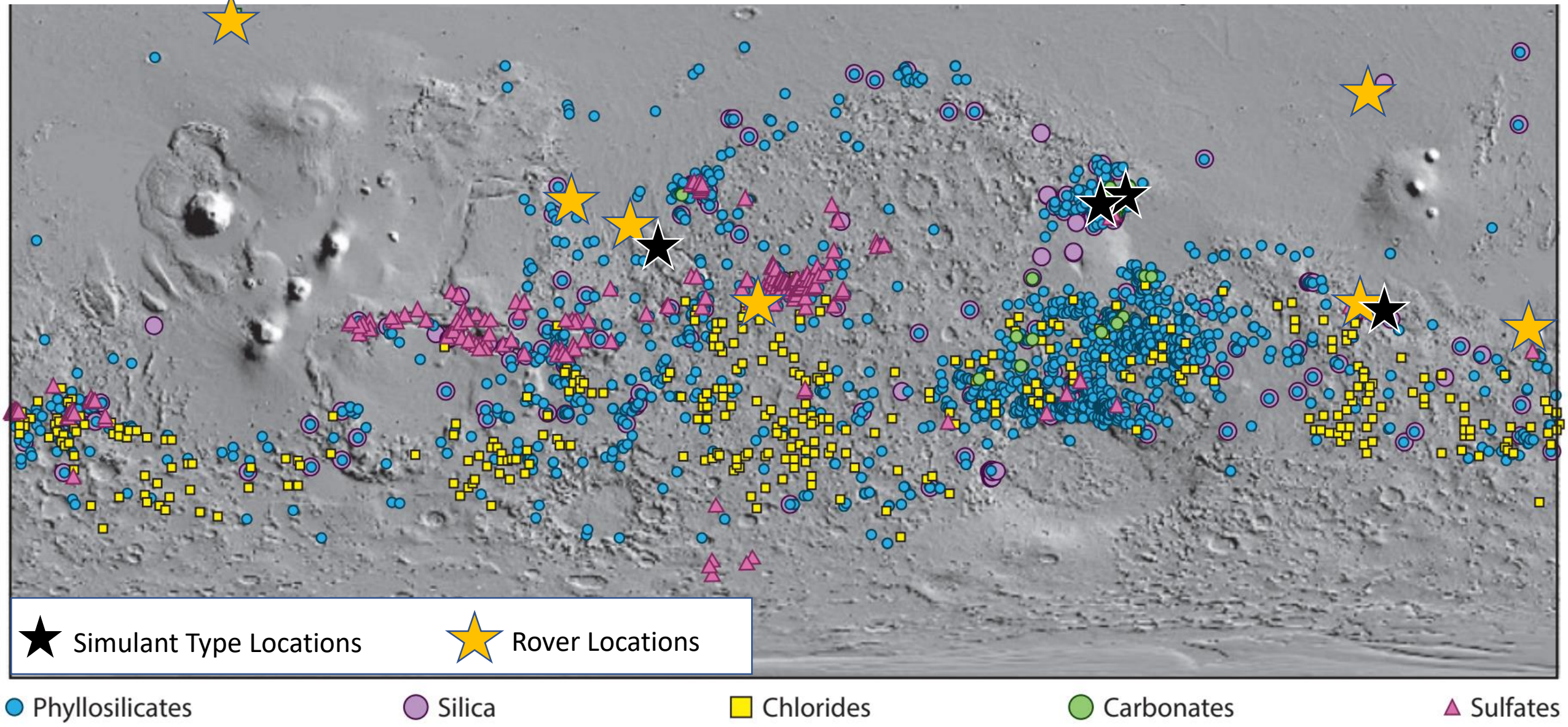
- Several Kg

Materials

- Field Samples
- Purchased in Bulk

Wamelink et al. 2014

Methods: Composition Determination



Adapted from Ehlmann and Edwards 2014

Table 1: Martian Regolith Components

Components	Regolith 1: Basalt (unaltered)	Regolith 2: Sulfate	Regolith 3: Phyllosilicate I	Regolith 4: Phyllosilicate II	Regolith 5: Carbonate
Basalts and Primary Silicates	Fresh basalt[1] Olivine[3]	Non-Fresh basalt[2]	Non-Fresh Basalt[2]	Non-Fresh Basalt[2]	Non-Fresh Basalt[2] Olivine[5]

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Phyllosilicates	-	-	Nontronite[3]	Chlorite[3]	Nontronite[3]




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Sulfates	-	Copiapite[4]	-	-	





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Sulfates	-	Copiapite[4]	-	-	
Carbonates	-	-	-	-	Magnesite[3]




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Sulfates	-	Copiapite[4]	-	-	
Carbonates	-	-	-	-	Magnesite[3]
Amorphous	Volcanic Glass[1] and/or Nano-phase ferric oxides[5]	Hydrated silica[3] and Nano-phase ferric oxides[5]	Ferrihydrite/Goethite[5]	Ferrihydrite/Goethite[5]	Hydrous magnesium silicates[5]




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Sulfates	-	Copiapite[4]	-	-	
Carbonates	-	-	-	-	Magnesite[3]
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Salts	Anhydrite, Epsomite[5] Perchlorate*[5]	Anhydrite, Epsomite[5] Perchlorate*[5]	Anhydrite, Epsomite[5] Perchlorate*[5]	Anhydrite, Epsomite[5] Perchlorate*[5]	Anhydrite, Epsomite[5] Perchlorate*[5]




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Sulfates	-	Copiapite[4]	-	-	
Carbonates	-	-	-	-	Magnesite[3]
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Iron Oxides	Magnetite	Hematite[3,4]			

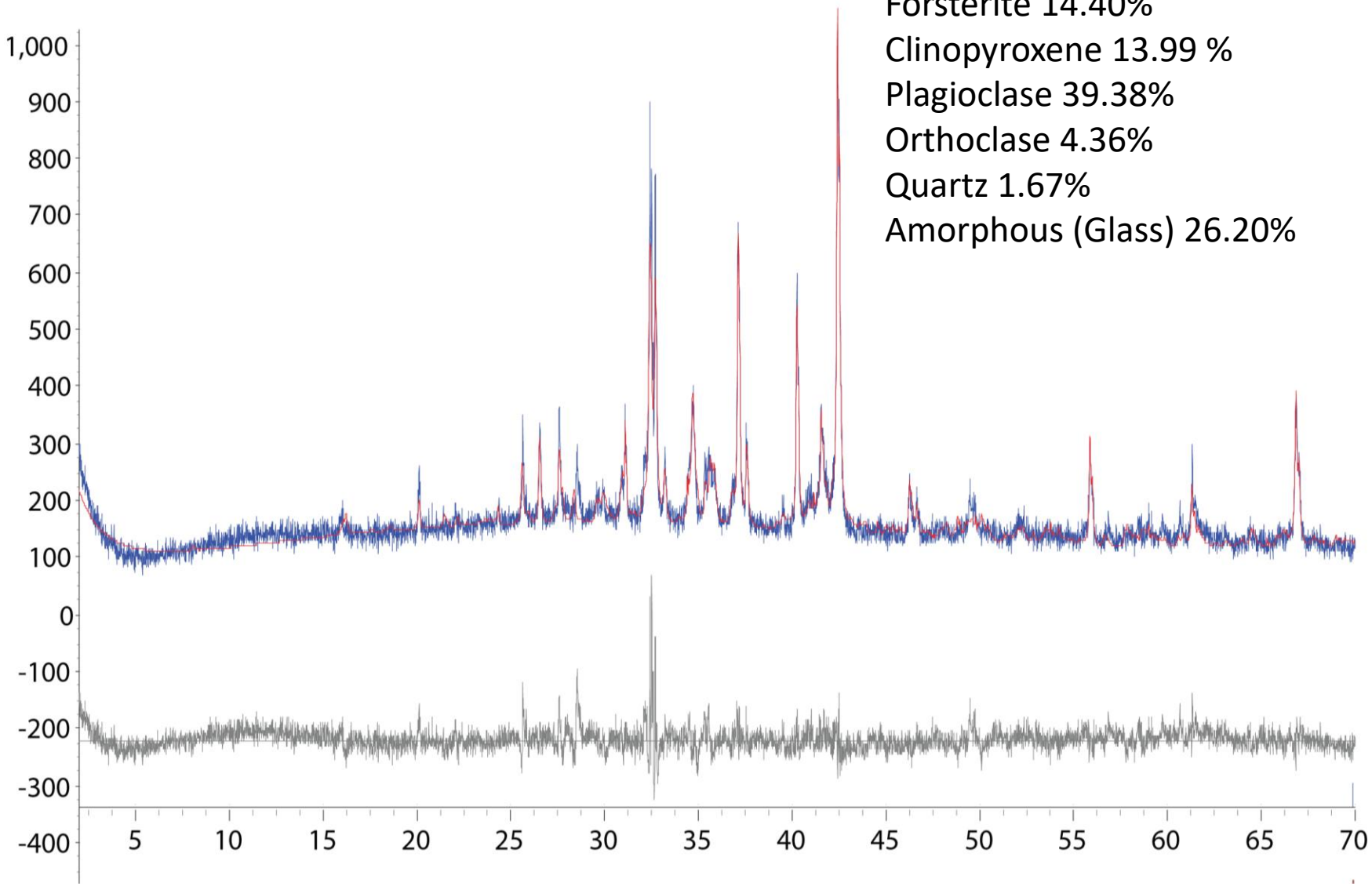



Table 1: Martian Regolith Components

Regolith 1: Basalt (unaltered)	**Regolith 2: Sulfate**	**Regolith 3: Phyllosilicate I**	**Regolith 4: Phyllosilicate II**	**Regolith 5: Carbonate**
90g NM Basalt 2g-FeO 2g Anhydrite 1g Epsomite/Perchlorate 1g Magnetite 4g Olivine	45g EWash Basalt 30g Copiapite** 15g Hematite 5g Nano-FeO 2g Opal-CT 2g Anhydrite 1g Epsomite	45g EWash Basalt 32g Nontronite Swa-1 15g Ferrihydrate 5g Magnetite 2g Anhydrite 1g Epsomite	45g EWash Basalt 32g Chlorite 15g Illite 5g Allophane 2g Anhydrite 1g Epsomite	45g EWash Basalt 25g Magnesite 15g Notronite 7g Olivine Dust 5g Hydrous Mg Silicate 2g Anhydrite 1g Epsomite
Estimated Expected Ratio 65-70% Primary Minerals 30% Amorphous 2% Salts	Estimated Expected Ratio 40% Primary Minerals 20% Sulfate 10% Iron Oxide 30% Amorphous 2% Salts	Estimated Expected Ratio 40% Primary Minerals 30% Phyllosilicate 30% Amorphous 2% Salts	40% Primary Minerals 30% Phyllosilicate 30% Amorphous 2% Salts	40% Primary Minerals 30% Carbonate 30% Amorphous 2% Salts



Methods: Analysis of Components



Forsterite 14.40%
Clinopyroxene 13.99 %
Plagioclase 39.38%
Orthoclase 4.36%
Quartz 1.67%
Amorphous (Glass) 26.20%

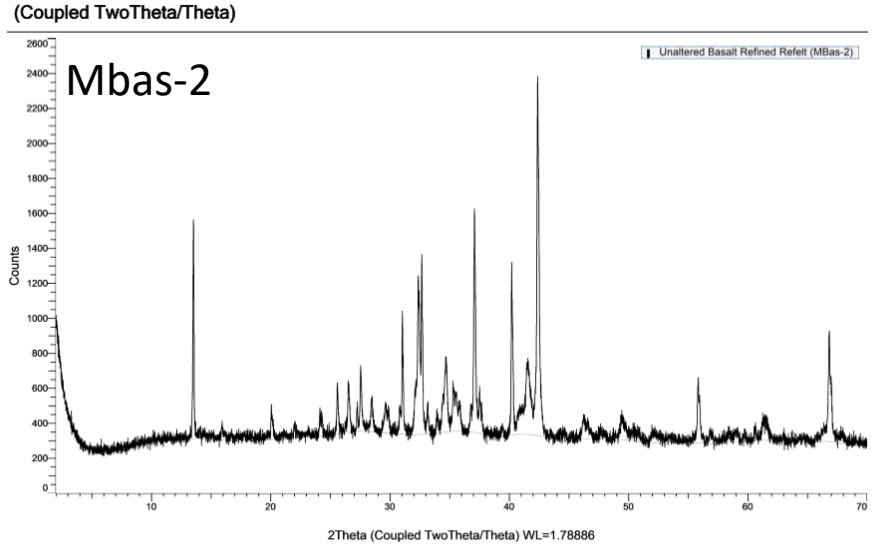
Methods: Making Simulants

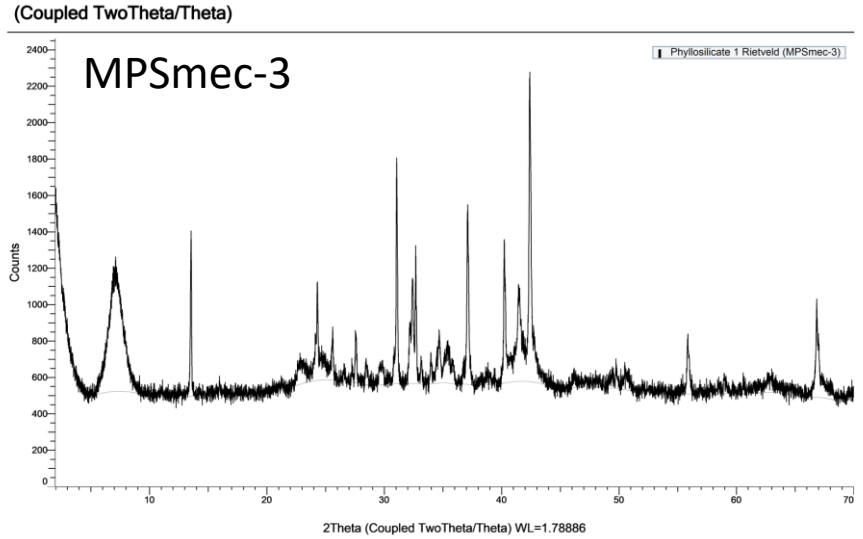
- Components mechanically crushed and weighed
- All components except epsomite mixed together (Dry Ingredients)
- Epsomite was added in solution (Wet ingredients)
- This mud-like mixture dried in oven at 60°C
- The dried ‘mud’ then crushed again

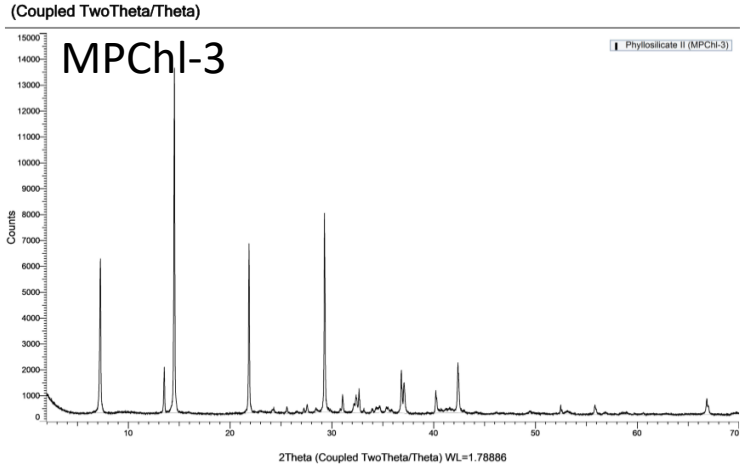
Methods: Analysis of Simulants

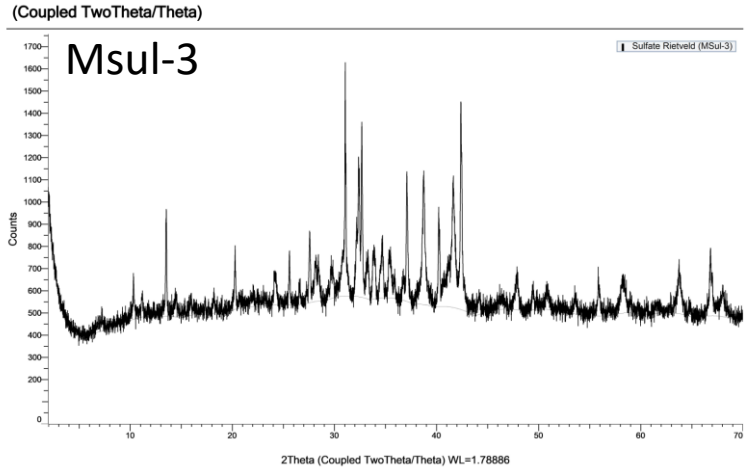
- Final Simulants analyzed with XRD and Reitveld analysis
- Additional XRF and Spectral analysis forthcoming
- Full pattern fitting is also intended to be applied for better constraint of disordered and amorphous phases

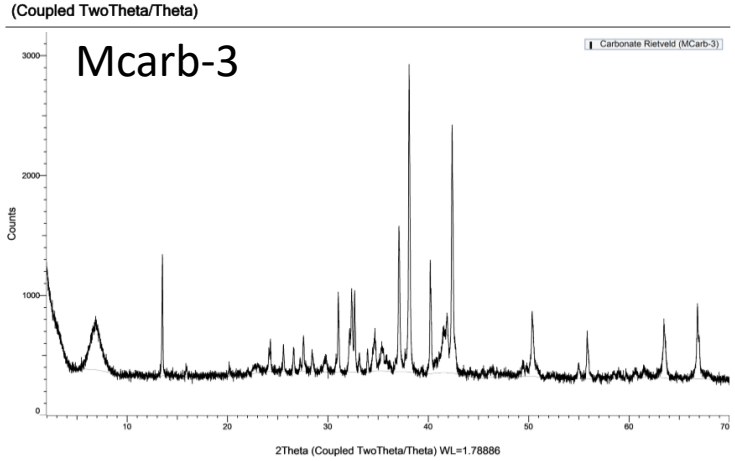
Results


(Coupled TwoTheta/Theta)
Mbas-2
Unaltered Basalt Refined Refelt (MBas-2)
Counts
2Theta (Coupled TwoTheta/Theta) WL=1.78886


(Coupled TwoTheta/Theta)
MPSmec-3
Phyllosilicate 1 Rietveld (MPSmec-3)
Counts
2Theta (Coupled TwoTheta/Theta) WL=1.78886


(Coupled TwoTheta/Theta)
MPChl-3
Phyllosilicate II (MPChl-3)
Counts
2Theta (Coupled TwoTheta/Theta) WL=1.78886


(Coupled TwoTheta/Theta)
Msul-3
Sulfate Rietveld (MSul-3)
Counts
2Theta (Coupled TwoTheta/Theta) WL=1.78886


(Coupled TwoTheta/Theta)
Mcarb-3
Carbonate Rietveld (MCarb-3)
Counts
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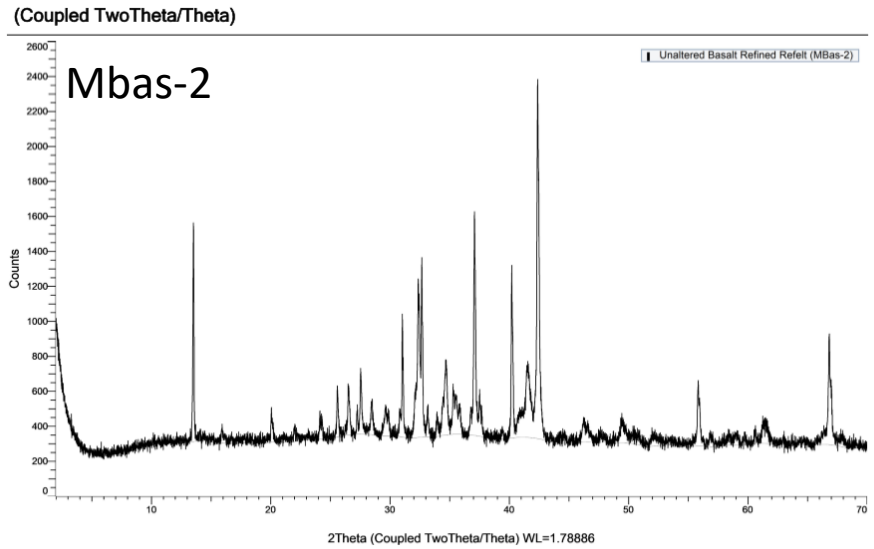
Results


(Coupled TwoTheta/Theta)
Mbas-2
Unaltered Basalt Refined Refelt (MBas-2)
Counts
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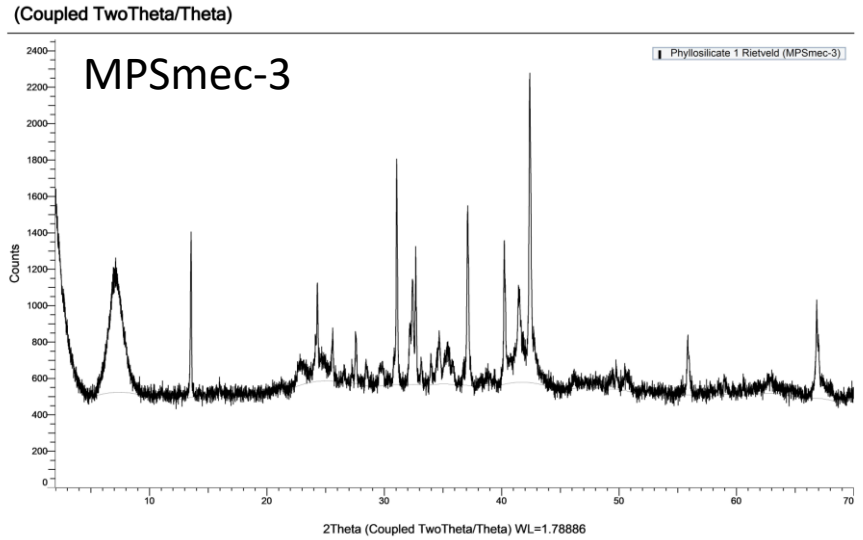
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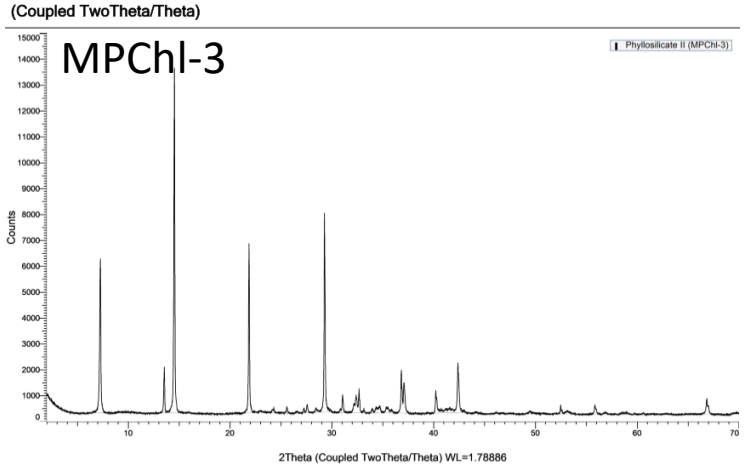
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Counts
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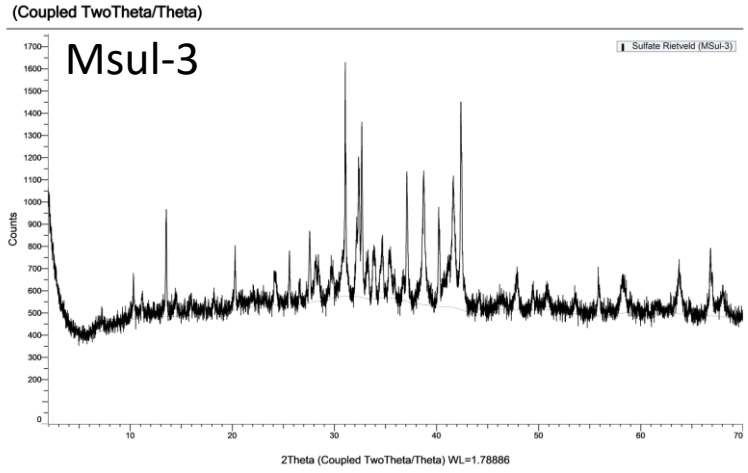
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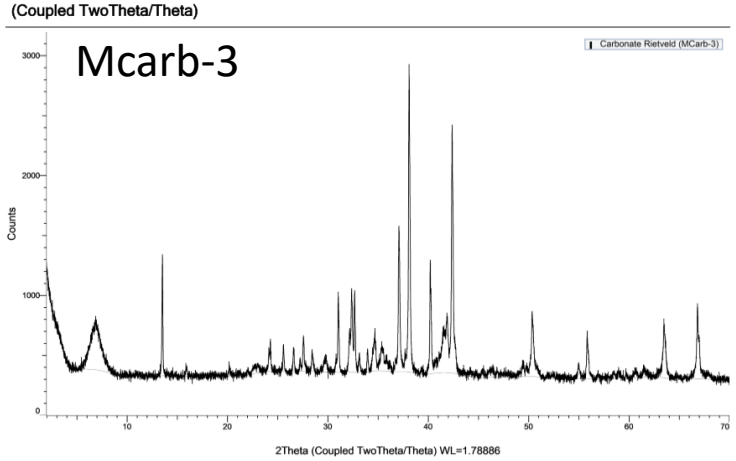
(Coupled TwoTheta/Theta)
Mcarb-3
Carbonate Rietveld (MCarb-3)
Counts
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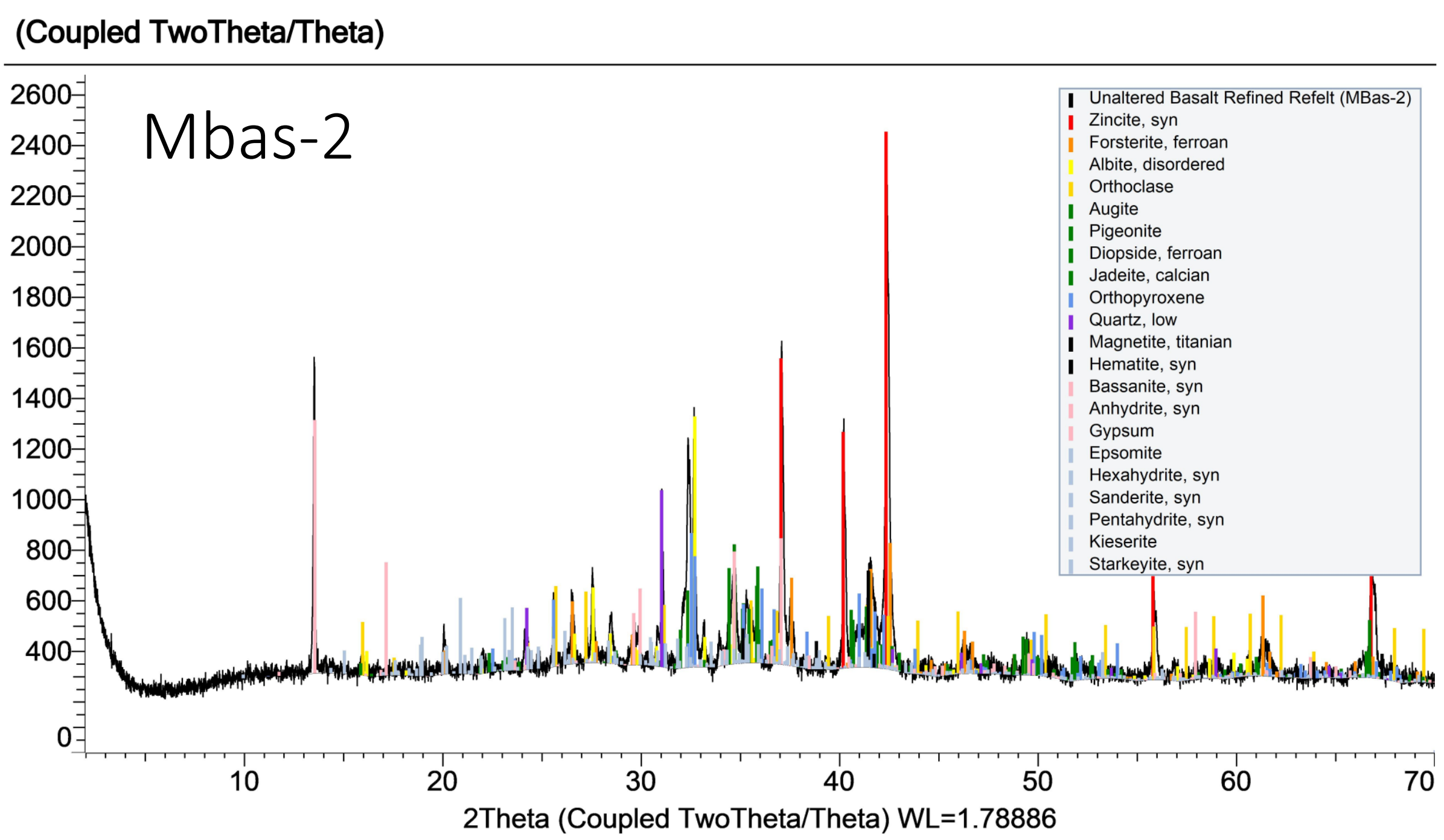
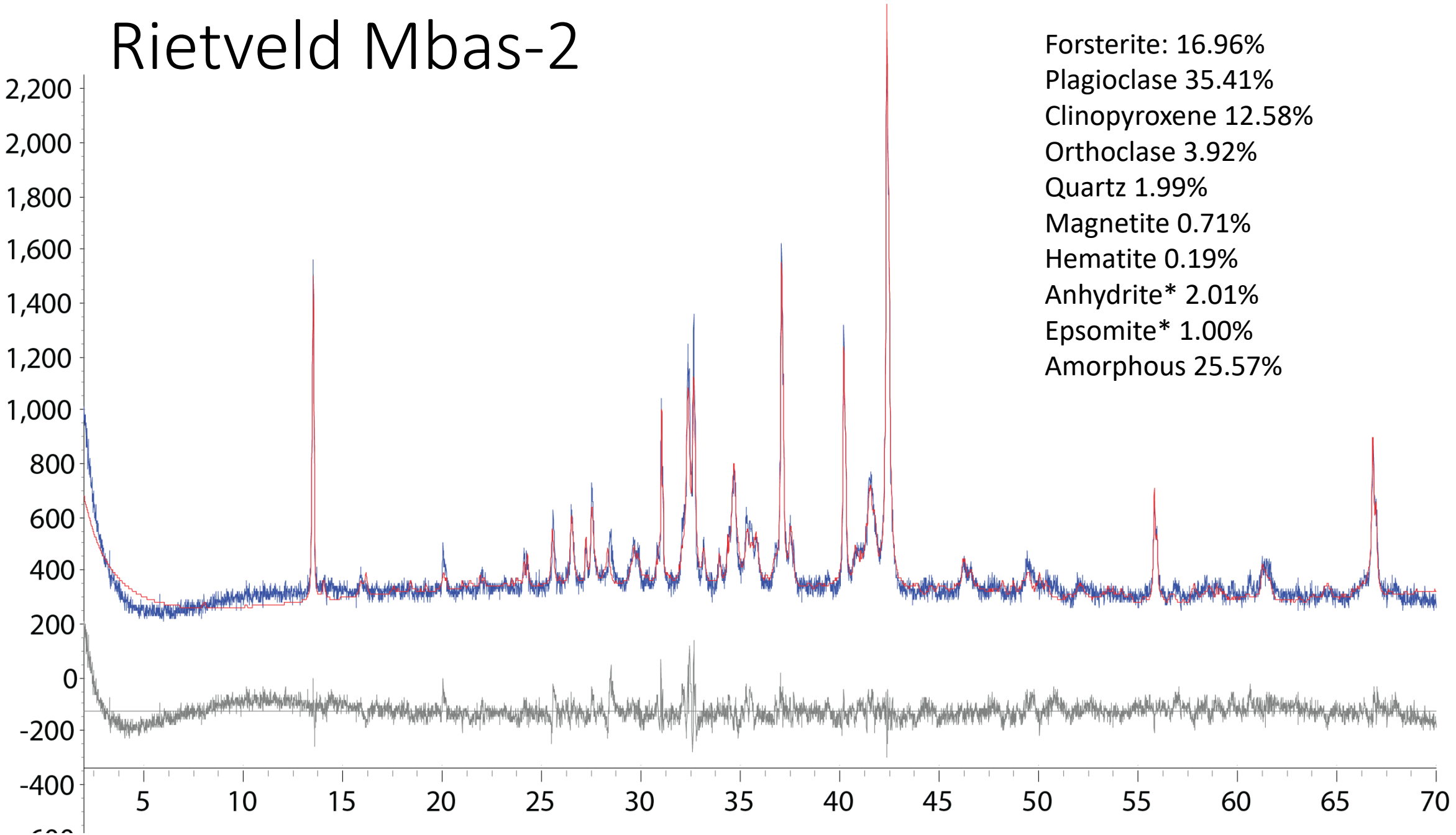
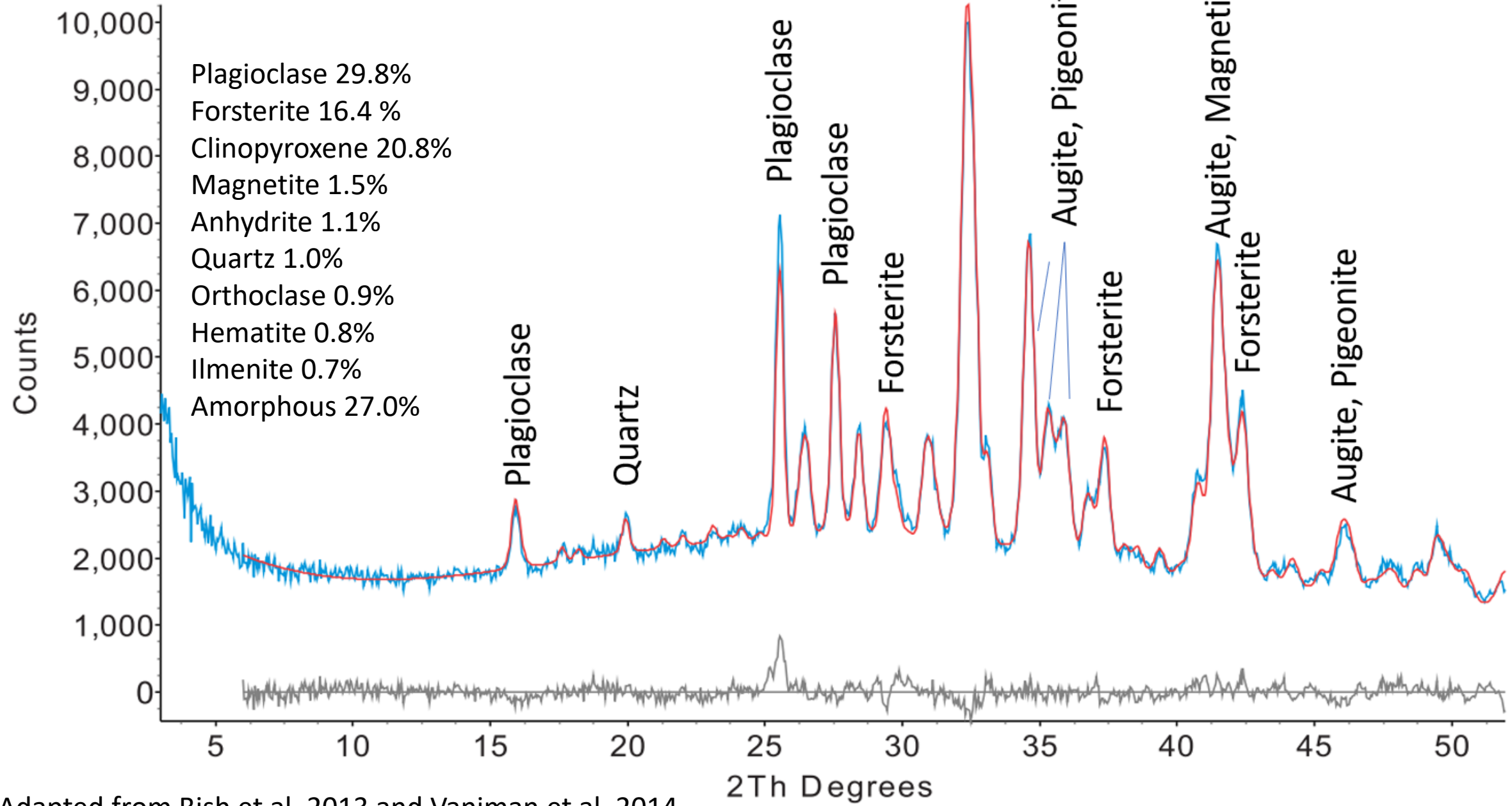

(Coupled TwoTheta/Theta)
Mbas-2
Unaltered Basalt Refined Refelt (MBas-2)
Zincite, syn
Forsterite, ferroan
Albite, disordered
Orthoclase
Augite
Pigeonite
Diopside, ferroan
Jadeite, calcian
Orthopyroxene
Quartz, low
Magnetite, titanian
Hematite, syn
Bassanite, syn
Anhydrite, syn
Gypsum
Epsomite
Hexahydrite, syn
Sanderite, syn
Pentahydrite, syn
Kieserite
Starkeyite, syn
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
0
10
20
30
40
50
60
70
2Theta (Coupled TwoTheta/Theta) WL=1.78886

Rietveld Mbas-2



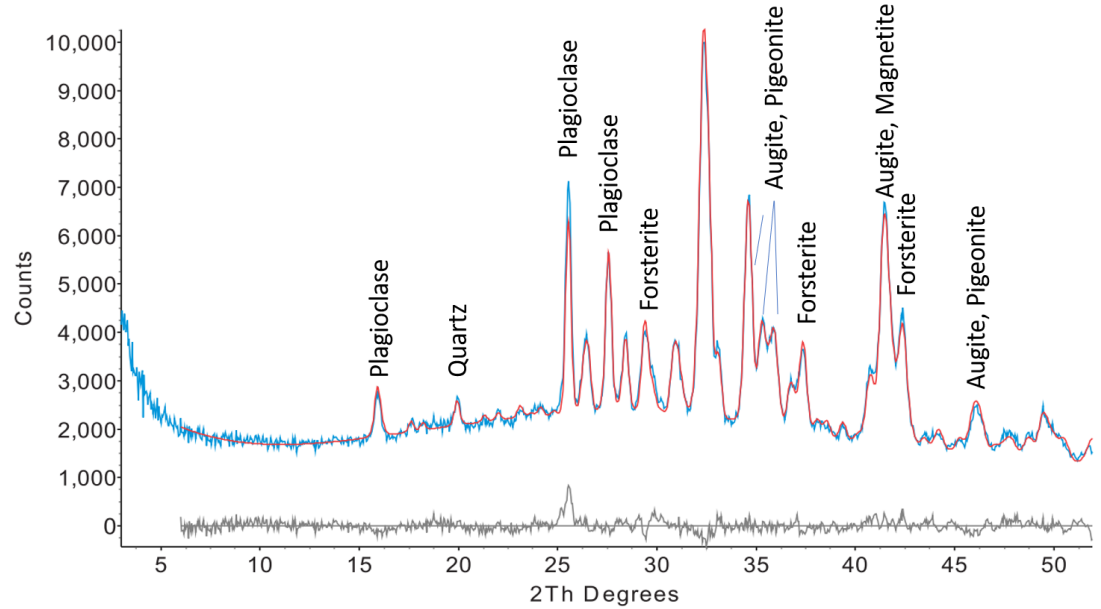
Forsterite: 16.96%
Plagioclase 35.41%
Clinopyroxene 12.58%
Orthoclase 3.92%
Quartz 1.99%
Magnetite 0.71%
Hematite 0.19%
Anhydrite* 2.01%
Epsomite* 1.00%
Amorphous 25.57%

Rocknest



Adapted from Bish et al. 2013 and Vaniman et al. 2014

	Regolith 1: Basalt (unaltered)-MBas-2		
Mineral	**Type Locality Mineralogy (%)**	**Simulant Mineralogy (%)**	**FOM Score**
Plagioclase	29.8	35.41	0.298
Forsterite	16.4	16.96	0.164
Clinopyroxene	20.8	12.58	0.1258
Orthopyroxene			
Magnetite	1.5	0.71	0.0071
Gypsum/Anhydrite	1.1	2.01	0.011
Bassanite			
Quartz	1.0	1.99	0.01
Orthoclase	0.9	3.92	0.009
Hematite	0.8	0.19	0.0019
Illmenite	0.7		
Goethite			
Akaganeite			
Halite			
Epsomite		1.00	0.01
Pyrite			
Pyrrhotite			
Smectite			
Amorphous	27.0	25.57	0.2557
			Total Score 0.89



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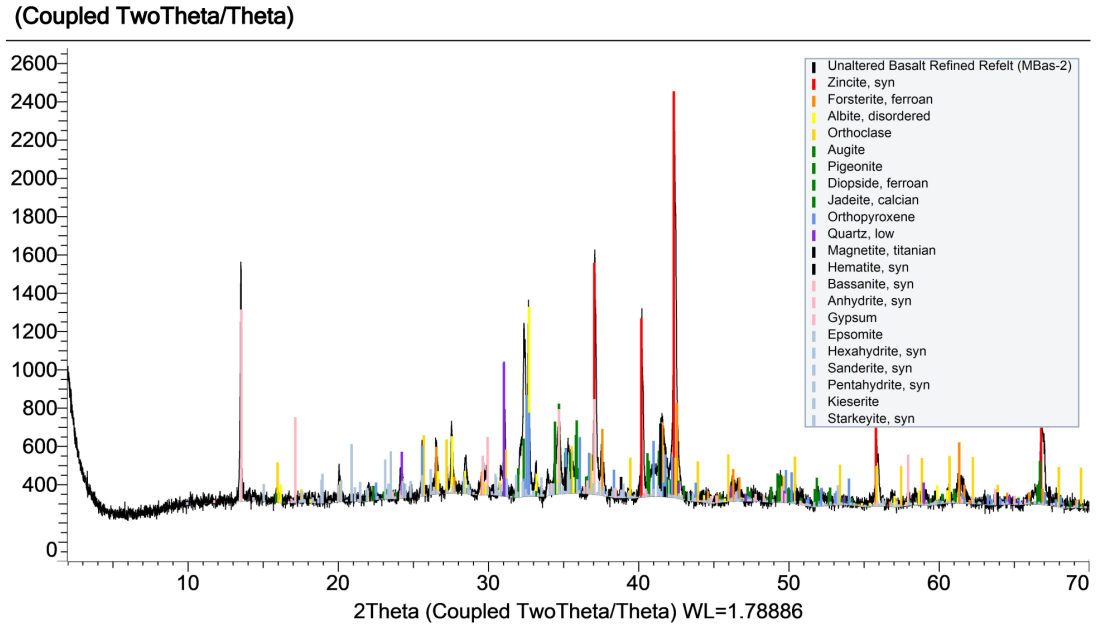

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Goethite			
Akaganeite			
Halite			
Epsomite		1.00	0.01
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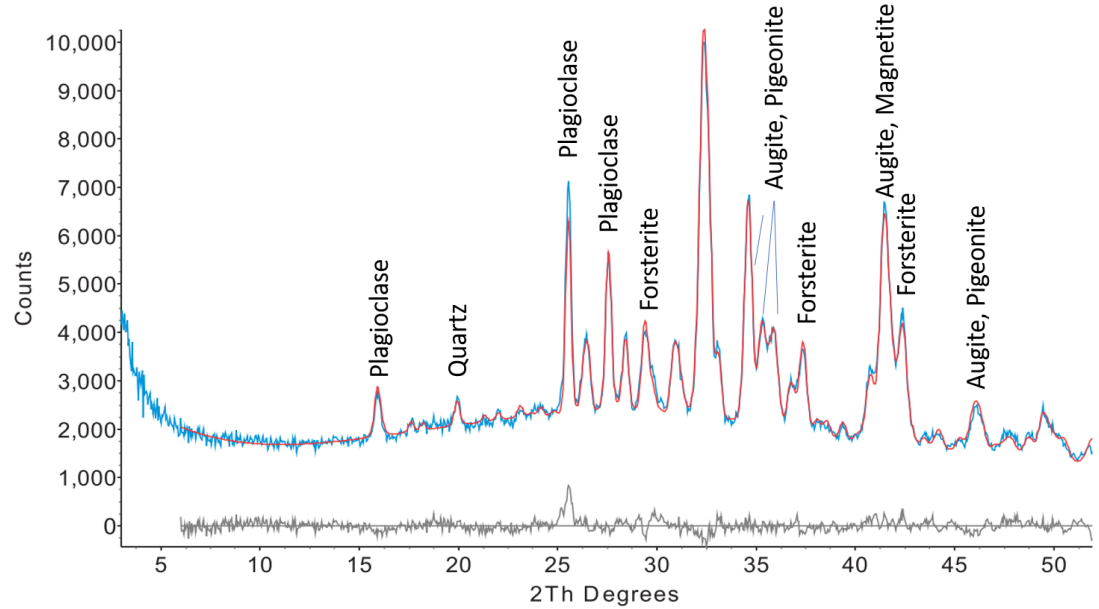

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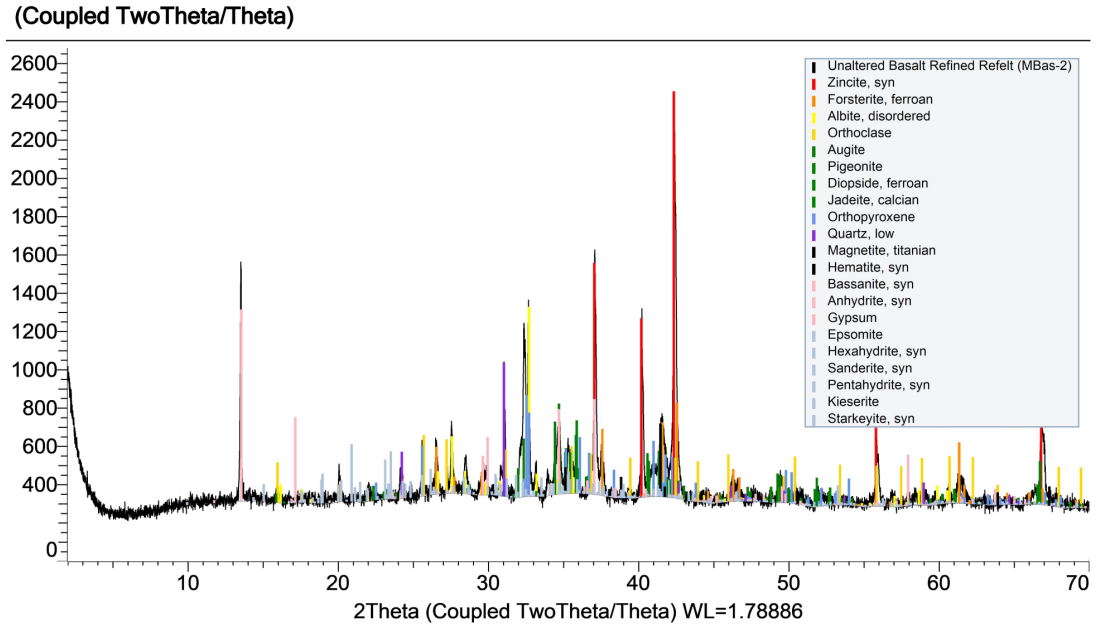
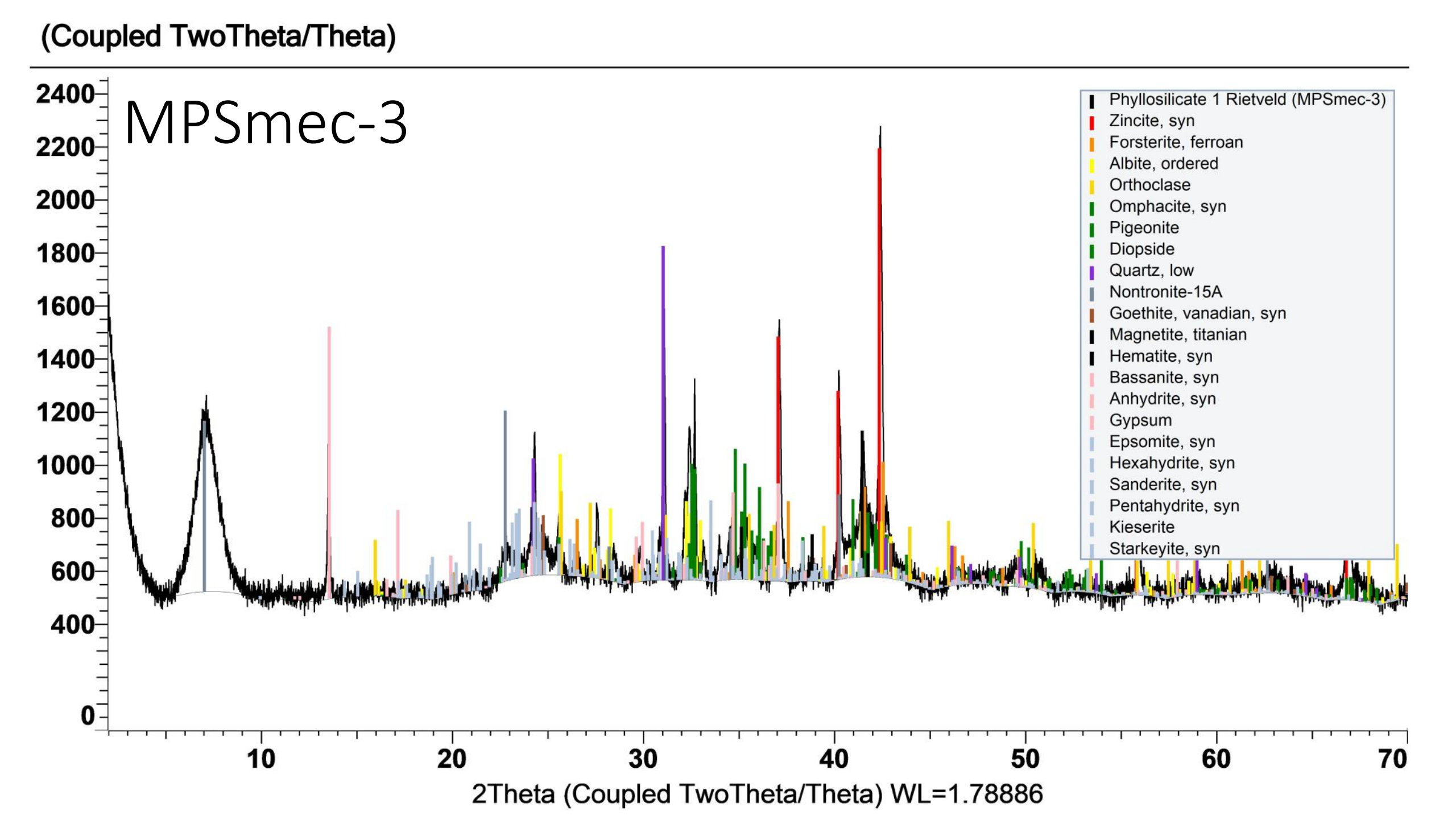
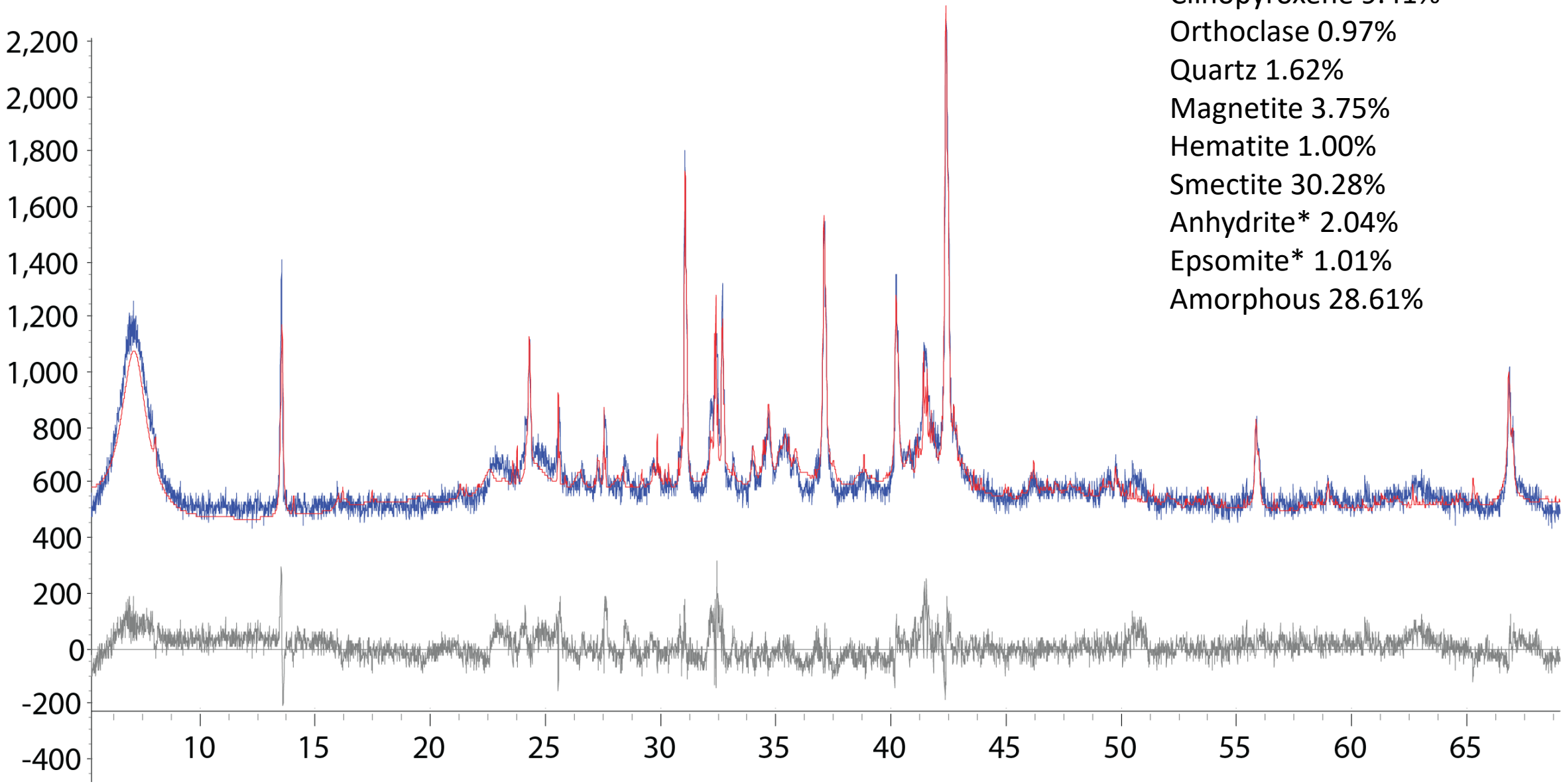
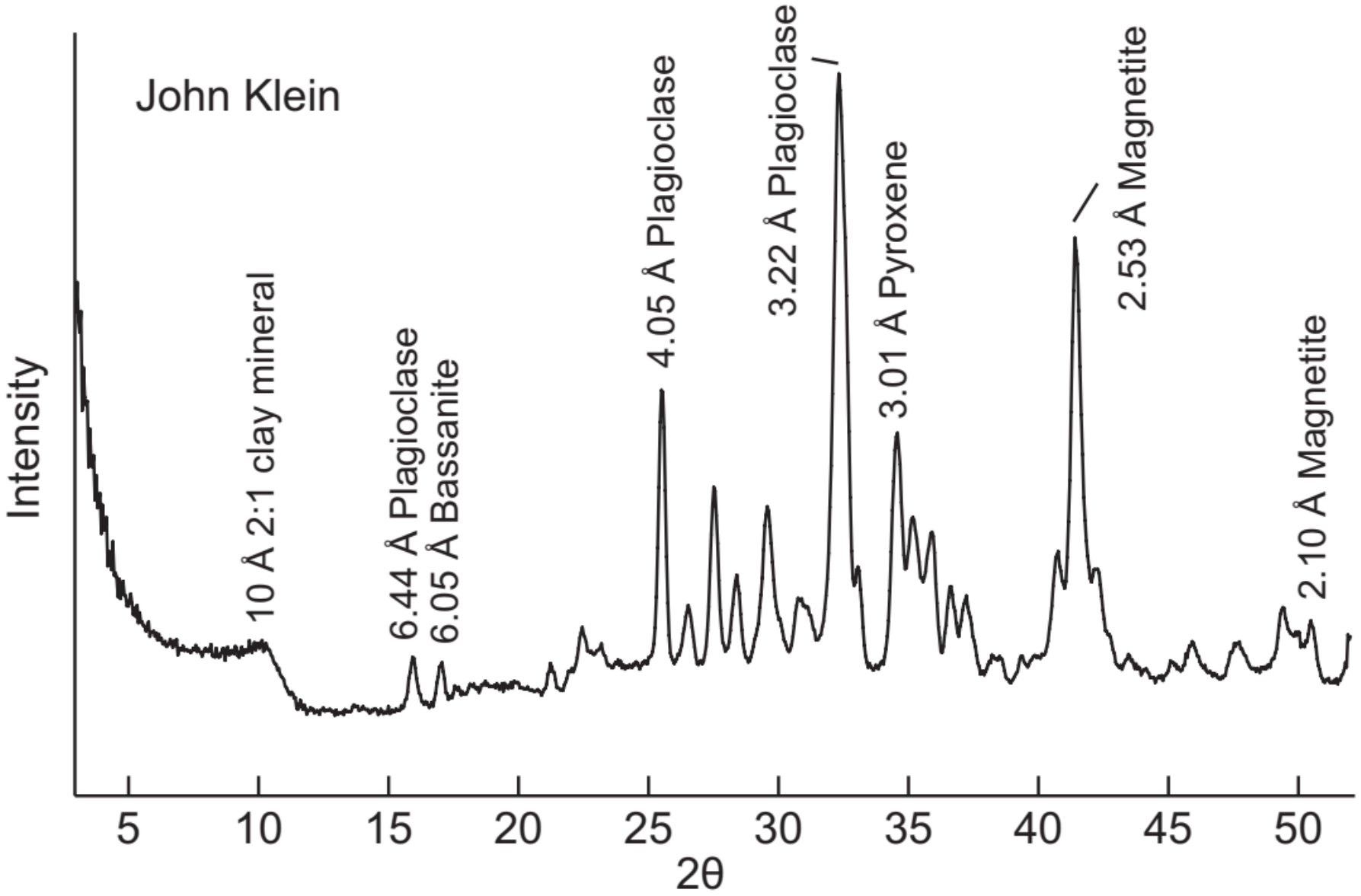



(Coupled TwoTheta/Theta)
MPSmec-3
Phyllosilicate 1 Rietveld (MPSmec-3)
Zincite, syn
Forsterite, ferroan
Albite, ordered
Orthoclase
Omphacite, syn
Pigeonite
Diopside
Quartz, low
Nontronite-15A
Goethite, vanadian, syn
Magnetite, titanian
Hematite, syn
Bassanite, syn
Anhydrite, syn
Gypsum
Epsomite, syn
Hexahydrite, syn
Sanderite, syn
Pentahydrite, syn
Kieserite
Starkeyite, syn
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
0
10
20
30
40
50
60
70
2Theta (Coupled TwoTheta/Theta) WL=1.78886

Rietveld MPSmec-3

Forsterite: 1.62%
Plagioclase 19.14%
Clinopyroxene 9.41%
Orthoclase 0.97%
Quartz 1.62%
Magnetite 3.75%
Hematite 1.00%
Smectite 30.28%
Anhydrite* 2.04%
Epsomite* 1.01%
Amorphous 28.61%

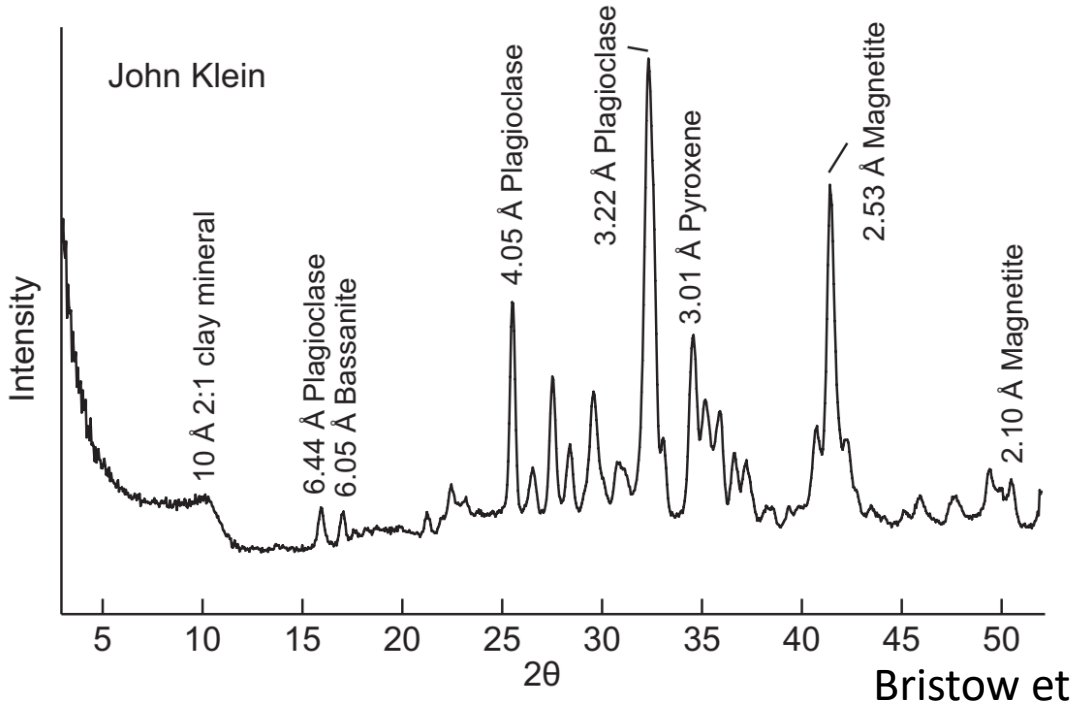




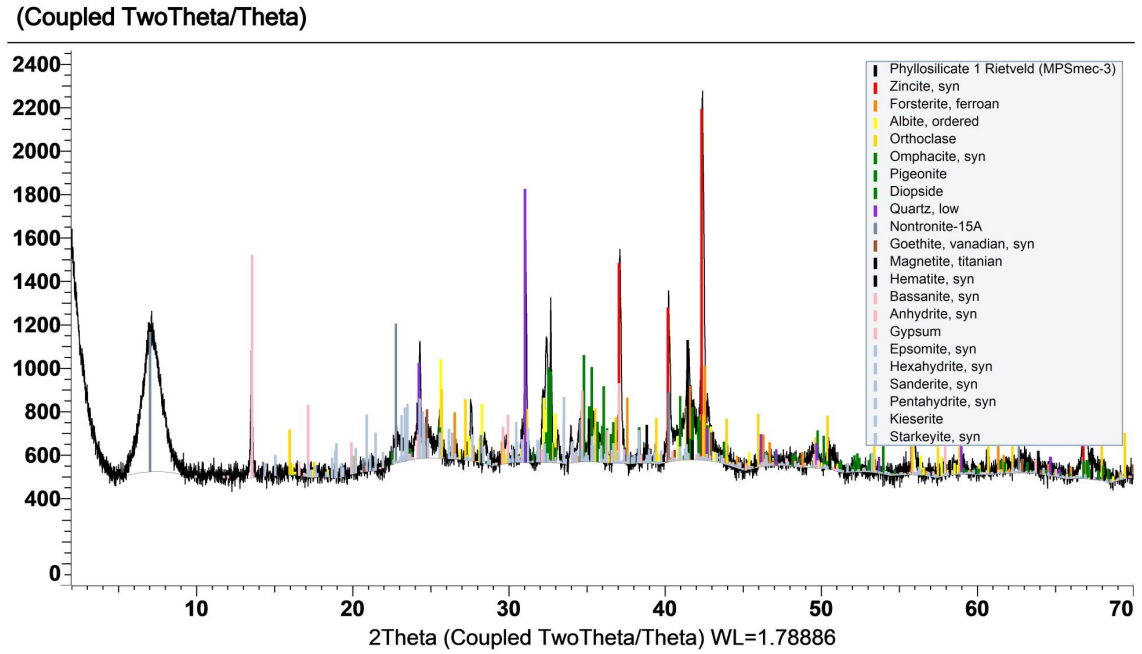
Plagioclase 22.4%
Forsterite 2.8%
Clinopyroxene 9.4%
Orthopyroxene 3.0%
Anhydrite 2.6%
Bassanite 1.1%
Quartz 0.4%
Orthoclase 1.2%
Magnetite 3.8%
Hematite 0.6%
Smectite 22%
Amorphous 28%

Adapted from Bristow et al. 2015 and Vaniman et al. 2014

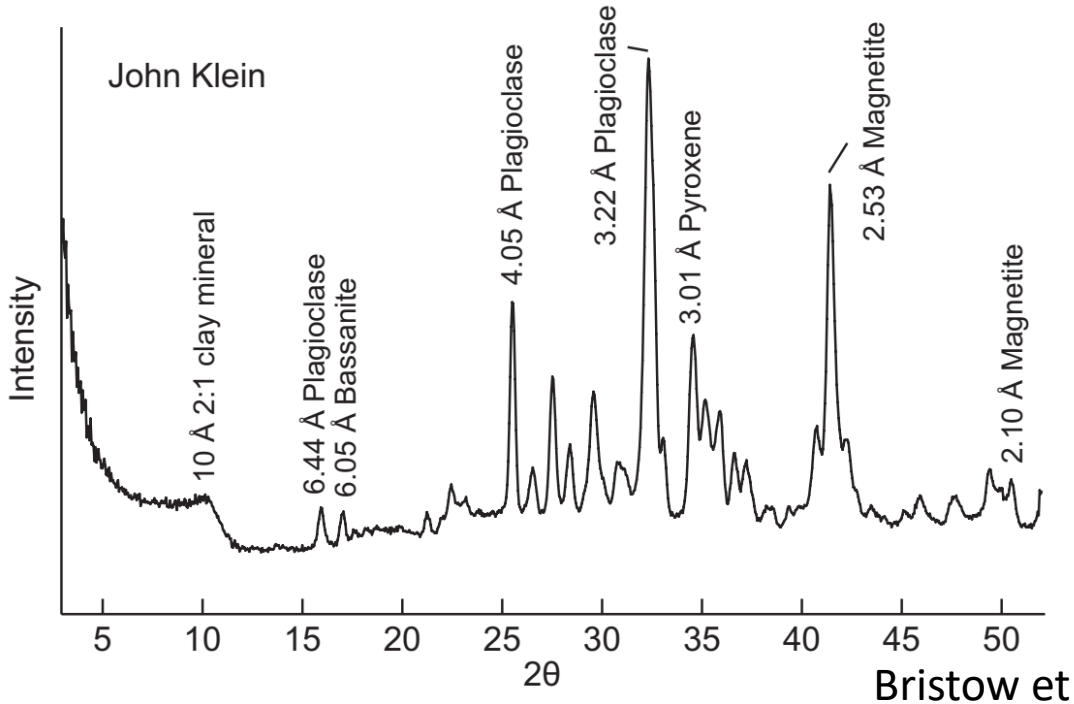
Mineral	Type Locality Mineralogy (%)	Simulant Mineralogy (%)	FOM Score
Plagioclase	22.4	19.14	0.1914
Forsterite	2.8	1.62	0.0162
Clinopyroxene	9.4	9.41	0.094
Orthopyroxene	3.0		
Magnetite	3.8	3.75	0.0375
Gypsum/Anhydrite	2.6	2.04	0.0204
Bassanite	1.1		
Quartz	0.4	1.62	0.004
Orthoclase	1.2	0.97	0.0097
Hematite	0.6	1.0	0.006
Illmenite			
Goethite		0.42	
Akaganeite	1.1		
Halite	0.1		
Epsomite		1.01	
Pyrite	0.3		
Pyrrhotite	1.0		
Smectite	22	30.28	0.22
Amorphous	28	28.61	0.28
			Total Score 0.88



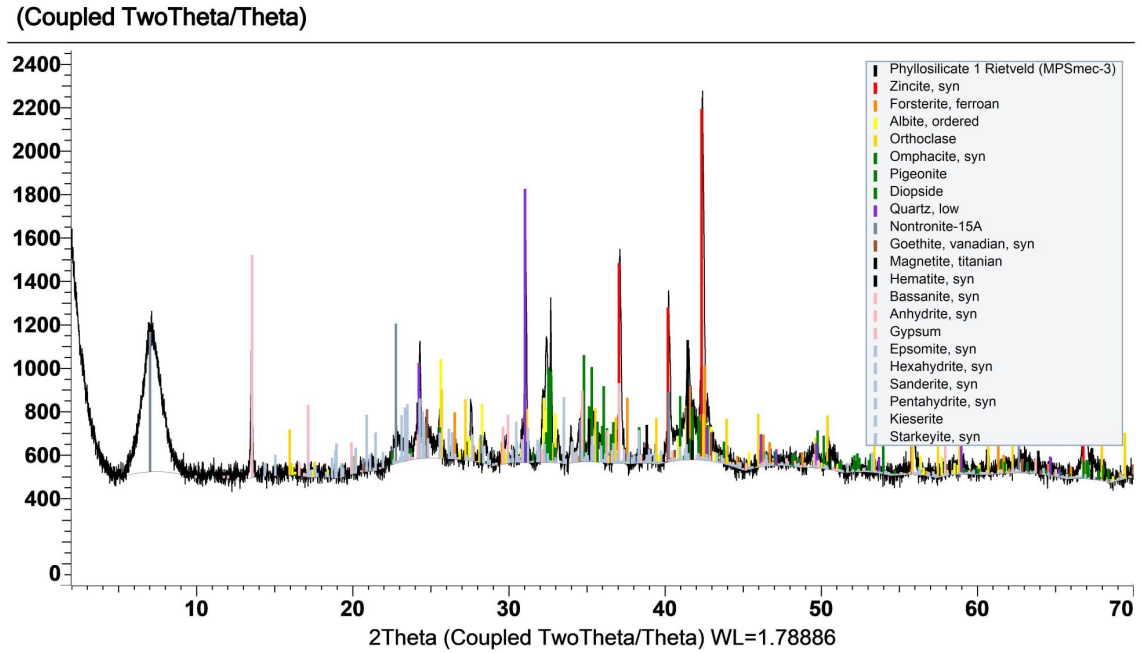
Bristow et al. 2015



Mineral	Type Locality Mineralogy (%)	Simulant Mineralogy (%)	FOM Score
Plagioclase	22.4	19.14	0.1914
Forsterite	2.8	1.62	0.0162
Clinopyroxene	9.4	9.41	0.094
Orthopyroxene	3.0		
Magnetite	3.8	3.75	0.0375
Gypsum/Anhydrite	2.6	2.04	0.0204
Bassanite	1.1		
Quartz	0.4	1.62	0.004
Orthoclase	1.2	0.97	0.0097
Hematite	0.6	1.0	0.006
Illmenite			
Goethite		0.42	
Akaganeite	1.1		
Halite	0.1		
Epsomite		1.01	
Pyrite	0.3		
Pyrrhotite	1.0		
Smectite	22	30.28	0.22
Amorphous	28	28.61	0.28
			Total Score 0.88



Bristow et al. 2015



Conclusions

- Five simulants produced appropriate for the intended application
- Variability of mineralogy to include clays, sulfates and carbonates

- Some important limitations
  - These simulants are not made to all characteristics of Mars Soils
  - Some characteristics (volatile content, etc..) are assumed to be altered in a ‘Martian Greenhouse setting’
  - Chlorite and Carbonate regolith not yet studied by rovers, detailed mineralogic and chemical data not available for comparison, spectral data is available

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