Quantitative EPMA Compositional Mapping of Lunar Mare Basalt Breccia Northwest Africa NWA 12384

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Summary

Lunar basalt breccia meteorite NWA 12384 overview detailed in [1] and adjacent poster

Fully quantitative EPMA compositional stage mapping applied to clast 2 of NWA 12384
- Multipass WDS X-ray intensity maps for 13 elements
- Full Φ(ρz) correction at each pixel yields element wt% data directly
  - EPMA calibration and MAN background correction yield improved accuracy
- Quantitative map data and wt% tiff images used for analysis and clustering

Downstream processing using Matlab, Fiji Xlib cluster plugin
- Mineral classification method produces phase image and quantitative phase chemistry

Method applied to basalt clast 2 of NWA 12384 end-cut EC-1
- Provides discrete point analysis
- Modal recalculation to obtain bulk chemistry of clast
- Compared with bulk analysis of NWA 12384 and shock melt vein

Preliminary equilibrium crystallization modelling consistent with petrography and mineral chemistry and similar to Apollo 15 pigeonite basalts

EPMA Compositional Mapping Procedures

A. **EPMA Stage Mapping**
   - Mosaic BSE imaging and full-sample X-ray stage mapping of NWA 12384 end-cut EC-1
   - Al-Mg-Fe RGB map used to identify and delineate 25 clasts
   - Probe for EPMA and Probe Image:
     - 13 element WDS calibration, mean atomic number background correction
     - Fixed electron beam, stage slew for map strip collection
     - Map conditions: 15kV 100nA, 1024x1024 pixel, 5 micron step, 30 msec dwell for each map pass
     - Raw X-ray maps: 32-bit intensity resolution, deadtime corrected.

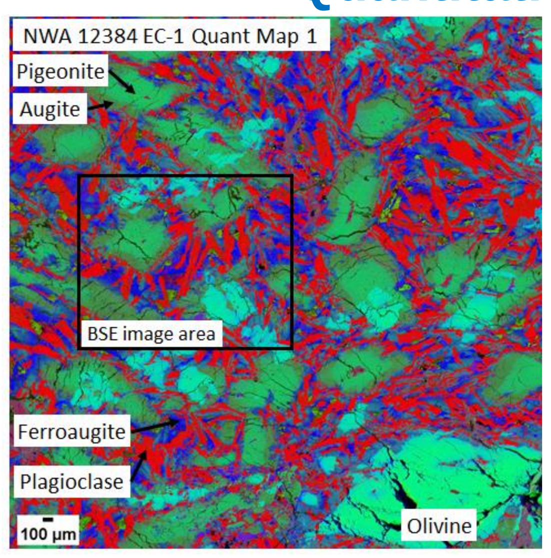
B. **CalcImage map correction**: X-ray map intensities to concentration
   - Full Φ(ρz) ZAF correction, complete analysis protocol same as used for point analysis.

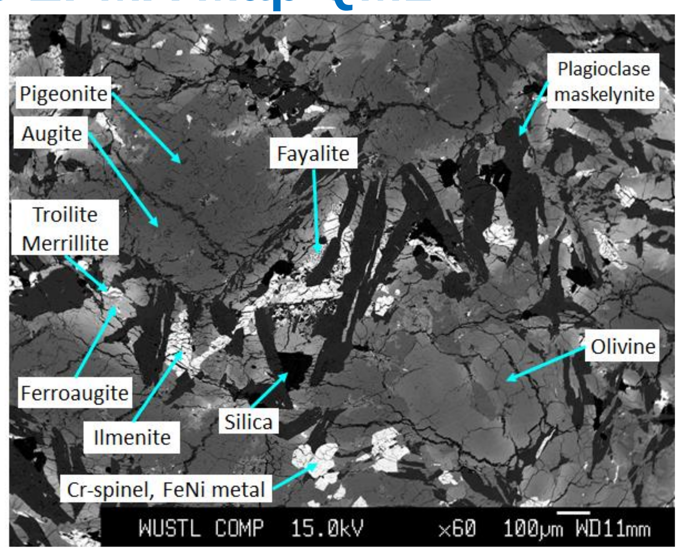
C. **Map data produced**: Element, analytical total, oxide, formula, MAN, detection limit
   - Golden Software Surfer & Scripter: generate contour quantitative maps.

D. **Data processing**: Two methods used here
   1. Filtered data: phases identified via stoichiometric formula
      - Filtered by cation sum (± 0.1 cation sum per 24 oxygen) and analytical total (99-101 wt%)
      - These data plotted on ternary composition plots, represent subset of total map data
   2. Cluster analysis of full map data set
      - Matlab script convert EPMA map data to 32-bit tiff quant images, stoichiometric inspection
      - Fiji Xlib: clustering and phase classification using quantitative element weight % data
      - Cluster data used for classification map and modal recalculation of EPMA bulk composition

E. **Advances over previous mapping procedures**:
   - Method is concentration-based with accurate MAN background correction
   - Historical X-ray intensity map conversion of k to C via y = mx + b conversion from k to C
     - Neither slope m (~ZAF) nor intercept b (background) are constants. Derived C not accurate.

Quantitative EPMA Map QM1

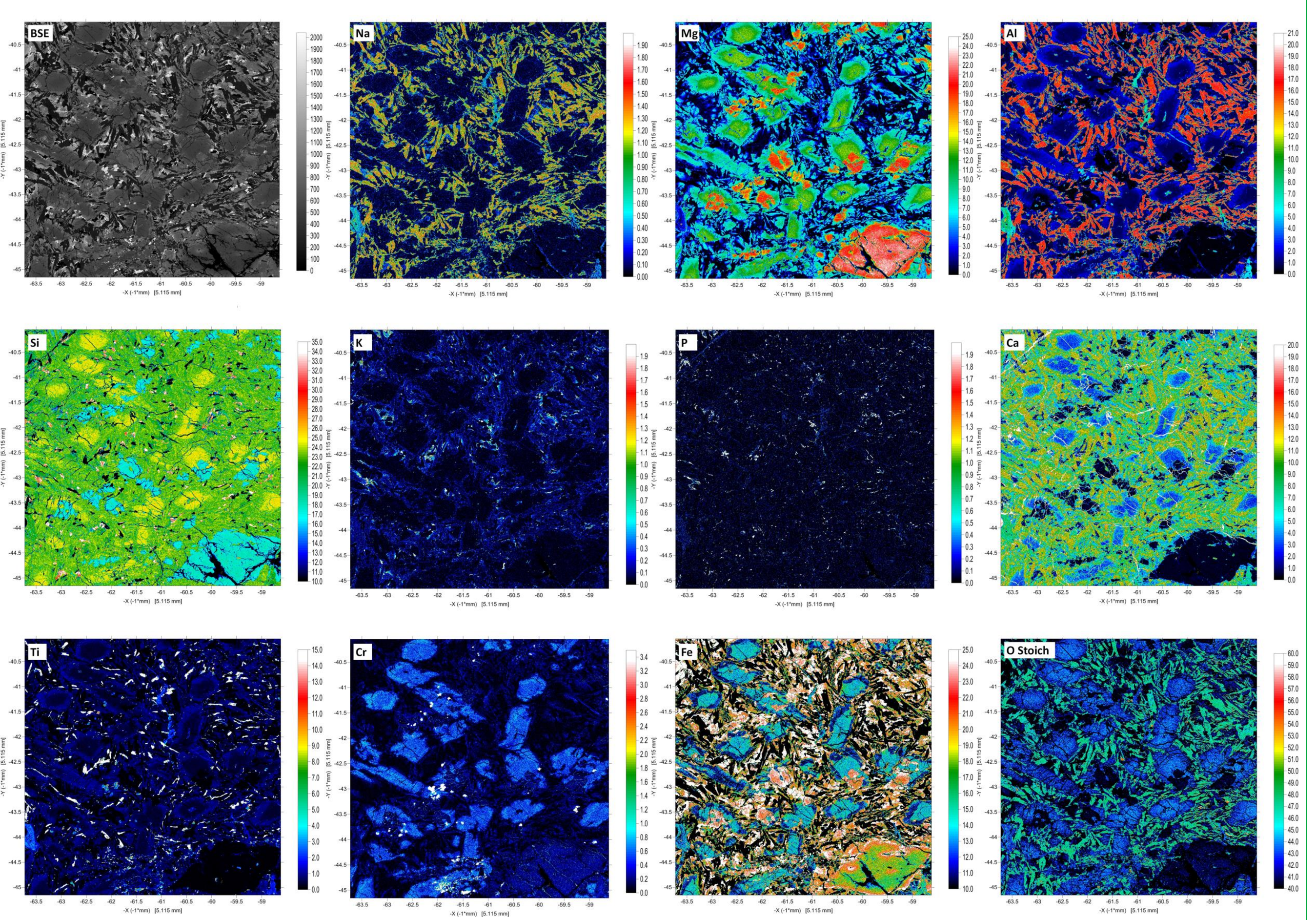




NWA 12384 Quantitative Map QM1 and BSE detail image

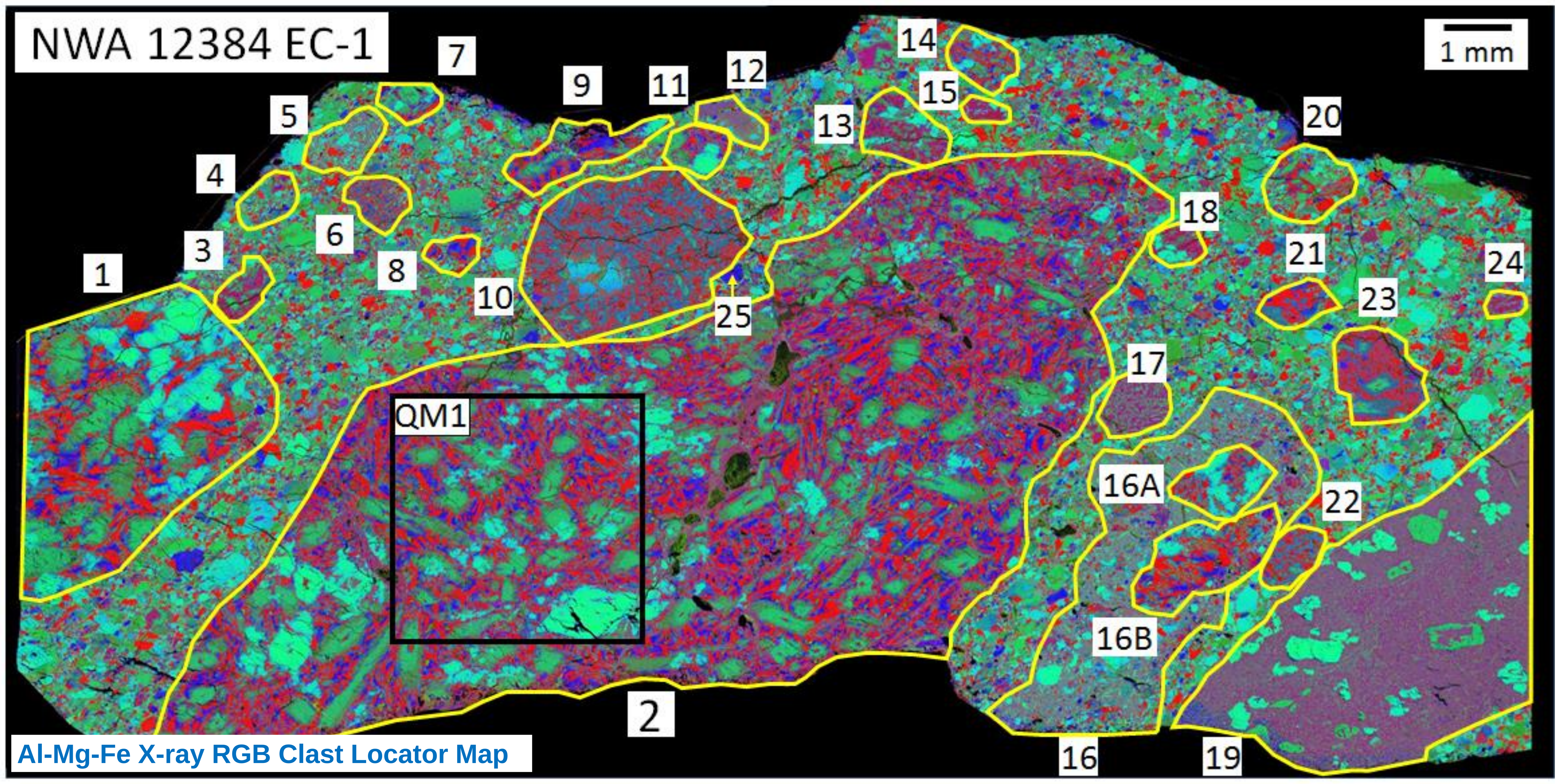
Left: Al-Mg-Fe RGB index map with mineral phases (olivine blue-green, pigeonite – augite green, Fe-rich pyroxene and ilmenite blue, plagioclase red).
Right: Detail BSE shows representative textural relations.

Quantitative Element Wt% Maps



NWA 12384 QM1 Element Wt% Contour Maps

Quantitative element wt% maps for labelled elements.
Maps have adjusted color scale to highlight phase chemistry.
Each map is fully quantified with oxygen calculated by stoichiometry.
Not shown are maps for MAN background, analytical total, detection limit (typically ~ 0.1 wt%), oxide, and cation stoichiometry on 24 oxygen basis.
Fiji Xlib plugin is used for cluster analysis with 32-bit .tif versions of wt% element maps as input.



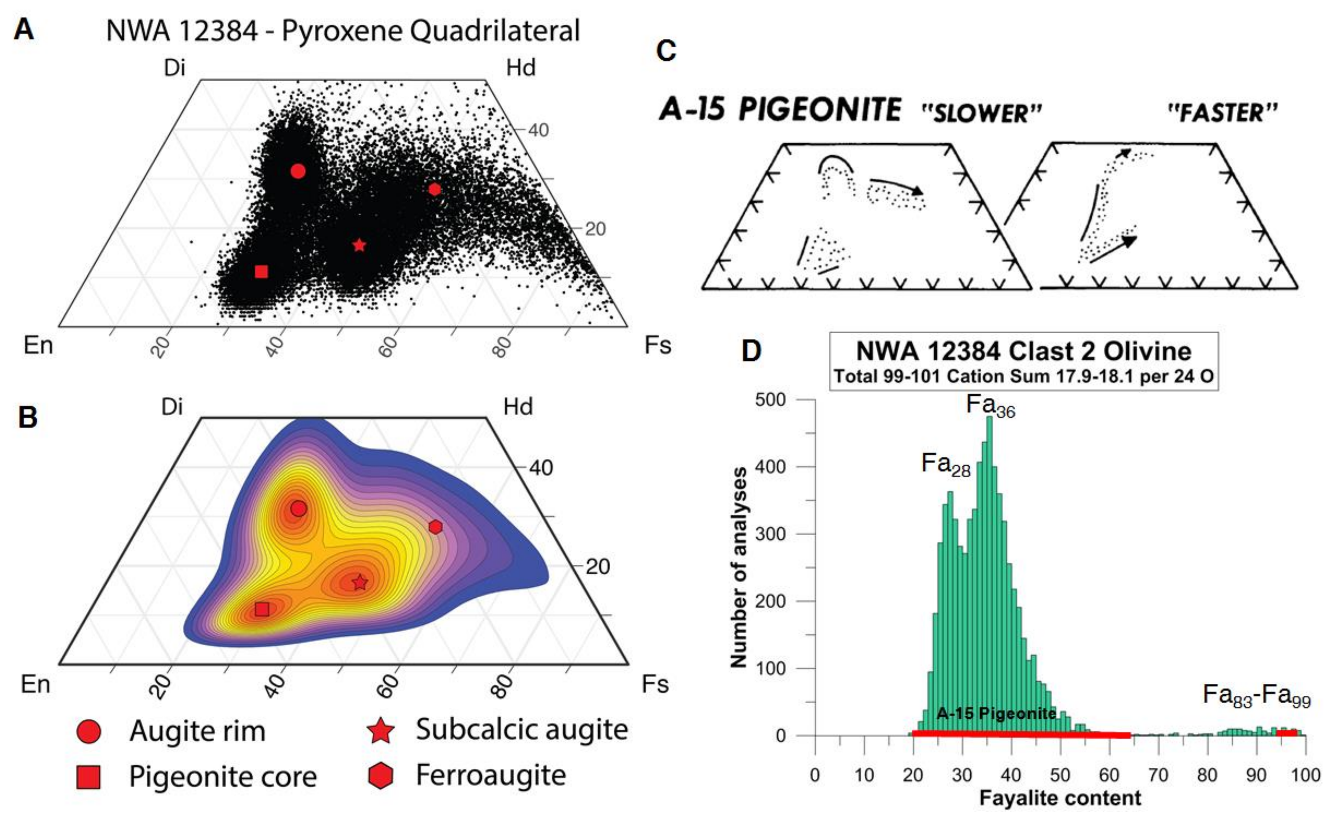
Al-Mg-Fe X-ray RGB Clast Locator Map

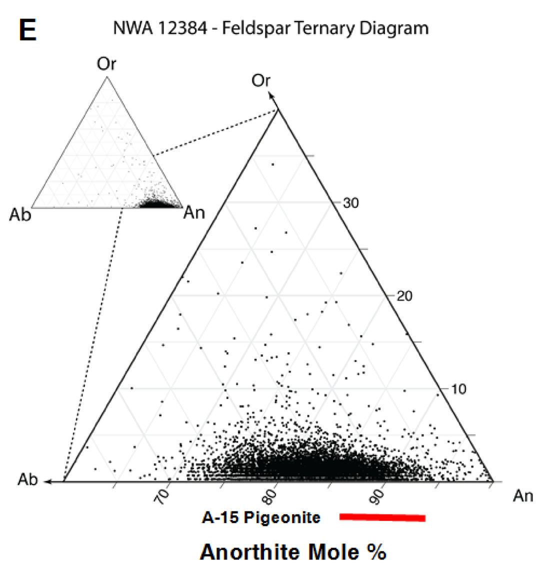
NWA 12384 Clast 2

Petrography and Mineral Chemistry of Clast 2 Pigeonite Basalt

- Pigeonite phenocrysts mantled by augite
- Sub-calcic augite and ferroaugite-hedenbergite are intersertal
- Olivine forms subhedral crystals mantled by sub-calcic augite, and partially replaced by pigeonite
  - Bimodal chemistry: large olivine is more Mg-rich than smaller more Fe-rich olivines
- Plagioclase shocked to maskelynite
- Accessory phases: Cr-spinel, ilmenite, troilite, merrillite, fayalite, and silica
- Sinuous shock melt vein

Mineral Chemistry Using Filtered Data Set





Mineral Chemistry of High Quality Map Data

- A and B: Pyroxene analyses from QM1 map with best compositional and analytical totals plotted on pyroxene quadrilateral. Cluster means for pigeonite, augite, sub-calcic augite, and ferroaugite-hedenbergite are plotted in B. Pigeonite is mantled by augite and both sub-calcic augite and ferroaugite are in groundmass.
- C: Pyroxene trends for Apollo 15 pigeonite basalts for comparison [2], illustrating similarity of composition. Pigeonite to augite trend is observed for NWA 12384.
- D: Fayalite content of QM1 map olivine showing bimodal composition of larger olivine phenocryst (Fa_{28}) vs. smaller olivines (Fa_{36}).
- E: Plagioclase compositional range with range for Apollo 15 pigeonite basalts shown for comparison. More sodic range suggests higher cooling rate for plagioclase.

References

[1] Carpenter P. et al. (2019) LPS L 2125
[2] Members of the. Basaltic Volcanism Study Project (1981), Basaltic Volcanism of the Terrestrial Planets, Pergamon

QM1 Cluster Analysis

QM1 Cluster Map

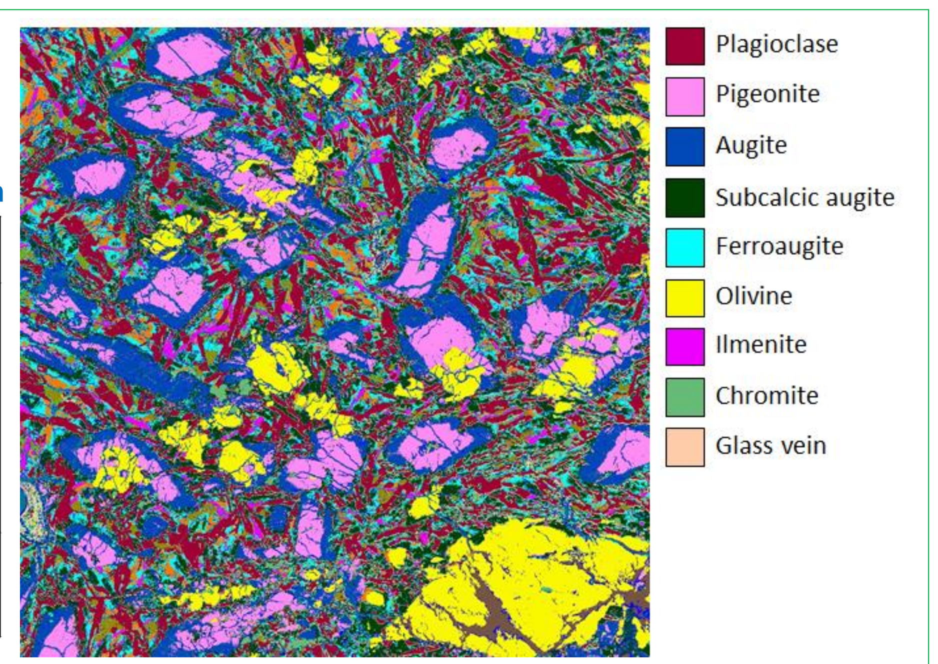


Table 2
CIPW Normative Calculation

Normative Phase	Bulk WC	Clast 2 EPMA recomb.	Clast 16 glass matrix	Glass Vein
Quartz	0.00	0.00	0.00	2.16
Plagioclase	22.05	25.42	23.34	36.41
Orthoclase	0.06	0.47	0.47	1.00
Diopside	24.11	21.21	16.62	16.37
Hypersthene	26.96	35.53	37.53	35.09
Olivine	22.38	11.08	15.19	0.00
Ilmenite	3.80	5.13	4.54	6.59
Apatite	0.30	0.21	0.42	0.49
Chromite	0.44	0.81	0.84	0.37
Total	100.10	99.86	98.95	98.48
Mg#	55.00	49.80	52.60	36.80

Notes: All data are CIPW normative recalculations
Bulk WC is bulk wet chemical analysis from cuttings from EC-1
Clast 2 EPMA recomb. is EPMA quantitative map modal recombination
Clast 16 glass matrix is EPMA spot average of clast 16 glass matrix
Glass vein is EPMA spot average analysis of glass vein

Table 1
Cluster Compositions and Bulk Chemistry Recombination

	Mineral cluster compositions, wt%							Recalculated EPMA bulk composition Compared to bulk wet chemistry of rock and EPMA average of shock glass vein		
	Plagio clase	Pigeo nite	Augite	Subcalcic augite	Ferro augite	Olivine	Ilmenite	Bulk Recalc.	Bulk WC	Glass vein
SiO_2	49.61	51.93	48.46	48.85	45.77	36.56	8.02	45.60	45.25	45.94
TiO_2	0.24	0.72	1.47	1.51	1.68	0.11	44.81	2.70	2.00	3.47
Al_2O_3	31.02	2.04	4.31	2.84	2.60	0.42	1.35	8.82	7.51	12.64
Cr_2O_3	0.01	0.75	0.69	0.32	0.18	0.31	0.22	0.55	0.30	0.25
FeO	1.93	18.44	15.47	25.37	30.41	28.49	39.70	20.32	20.43	18.46
MnO	0.02	0.33	0.27	0.38	0.40	0.29	0.31	0.27	0.28	0.23
MgO	0.64	19.97	12.82	12.01	6.41	30.86	1.30	11.32	13.98	6.02
CaO	16.18	5.41	14.46	7.93	12.46	0.93	2.80	9.70	9.81	10.48
Na_2O	1.64	0.05	0.18	0.08	0.08	0.02	0.13	0.40	0.40	0.61
K_2O	0.17	0.01	0.03	0.04	0.06	0.01	0.05	0.08	0.01	0.17
P_2O_5	0.05	0.00	0.05	0.03	0.24	0.02	0.18	0.09	0.13	0.21
Total	101.50	99.64	98.22	99.36	100.30	98.01	98.88	99.85	100.90	98.49
Wt% phase	18.56	12.40	14.71	17.50	9.91	11.53	3.54			
Mg#		0.66	0.62	0.47	0.28	0.66		0.50	0.55	0.37

Not including chromite, cluster glass vein, fayalite-hedenbergite, cracks, alteration, clusters representing phase boundaries
Number of analyses: plagioclase 204432, pigeonite 111147, augite 131099, subcalcic augite 151488, ferroaugite 85768, olivine 105864, ilmenite 22356, EPMA glass vein 10
Phase wt% example: plagioclase area fraction 0.2225, density 2.75, AF*D = 0.6118, bulk density 3.30, wt% = 100*0.6118/3.30 = 18.56

Mineral compositions from cluster analysis using full map data set:
Wt% oxide values listed in Table 1, note excellent cluster cation sums
- Plagioclase $Ca_{0.80}Na_{0.14}K_{0.01}Al_{1.65}Si_{2.25}O_8$, sum 4.99, $An_{83.8}Or_{1.1}$
- Pigeonite $Ca_{0.22}Mg_{1.13}Fe_{0.58}Al_{0.09}Si_{1.92}O_6$, sum 4.00, $Fs_{30.0}Wo_{11.2}$
- Augite $Ca_{0.59}Mg_{0.79}Fe_{0.49}Al_{0.17}Si_{1.87}O_6$, sum 4.00, $Fs_{26.3}Wo_{31.6}$
- Subcalcic augite $Ca_{0.32}Mg_{0.74}Fe_{0.85}Al_{0.12}Si_{1.90}O_6$, sum 4.00, $Fs_{44.5}Wo_{16.7}$
- Ferroaugite $Ca_{0.53}Mg_{0.38}Fe_{0.99}Al_{0.12}Si_{1.89}O_6$, sum 3.99, $Fs_{52.2}Wo_{27.9}$
- Olivine $Mg_{1.30}Fe_{0.66}Ca_{0.04}Si_{0.98}O_4$, sum 3.01, $Fa_{33.6}$

NWA 12384 QM1 Cluster Analysis

- This section shows results of Fiji Xlib unsupervised K-means cluster analysis on full QM1 data set
- QM1 cluster map illustrates phase definitions for compositions listed in Table 1.
  Mineral cluster compositions are compared with stoichiometric formula for silicate phases
- Mineral cluster analyses and their area fraction are used with phase densities to calculate wt% phase in QM1 map and used for modal recombination to calculate bulk composition of QM1 map
- Bulk chemistry estimate agrees well with wet chemistry for NWA 12384 and highlights differences between QM1 basalt composition vs. bulk. Glass vein is more aluminous in comparison to both
- Table 2 shows CIPW normative recalculation
- Preliminary equilibrium crystallization modelling agrees well with observed QM1 phase assemblage, and mineral chemistry derived from EPMA quantitative compositional mapping and cluster results.

Conclusions

1. Fully quantitative EPMA compositional stage mapping is applied to analysis of NWA 12384.
2. Mineral chemistry is evaluated using filtered data and cluster means with excellent agreement. Chemical variation observed for NWA 12384 QM1 is similar to average Apollo 15 pigeonite basalt.
3. Modal recombination using cluster means is accurate and agrees with bulk wet chemistry.
4. Preliminary crystallization modelling agrees with petrographic observations and results of EPMA compositional mapping.