TIMING OF LUNAR BASALTIC MAGMATISM: NEW INSIGHTS

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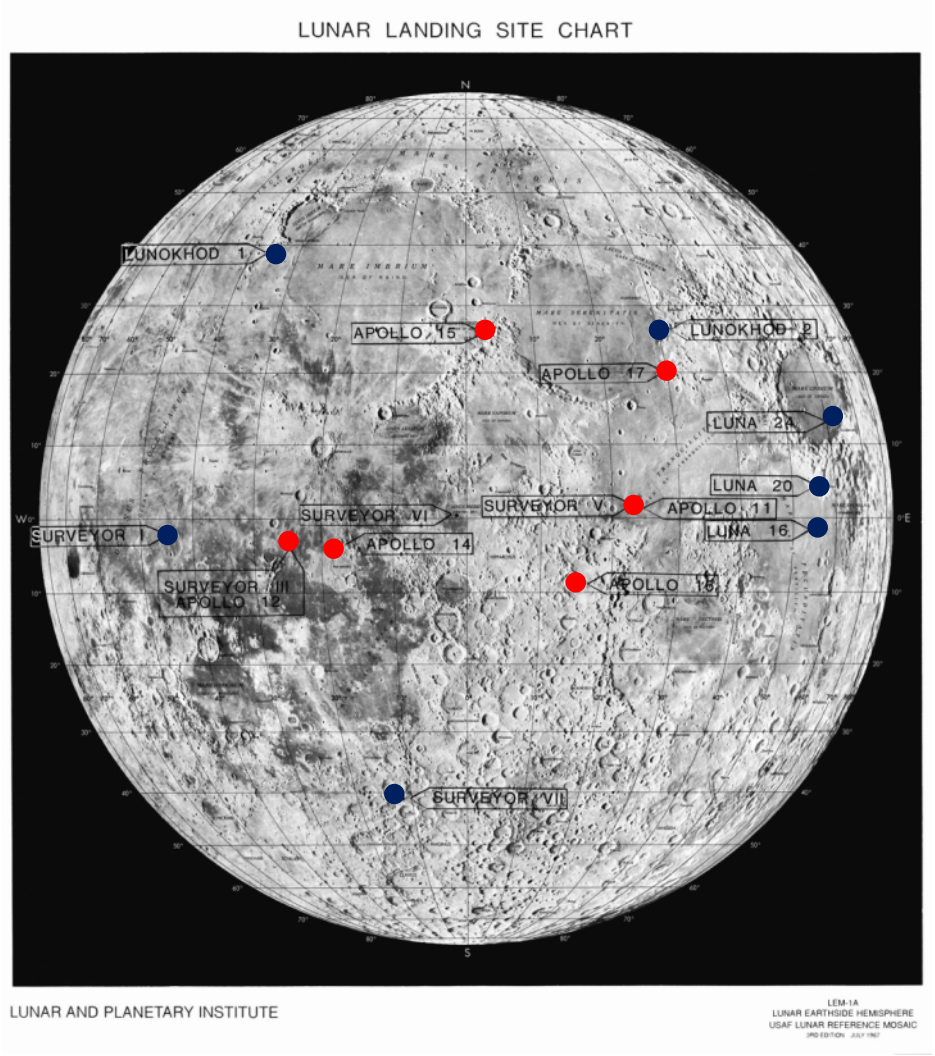
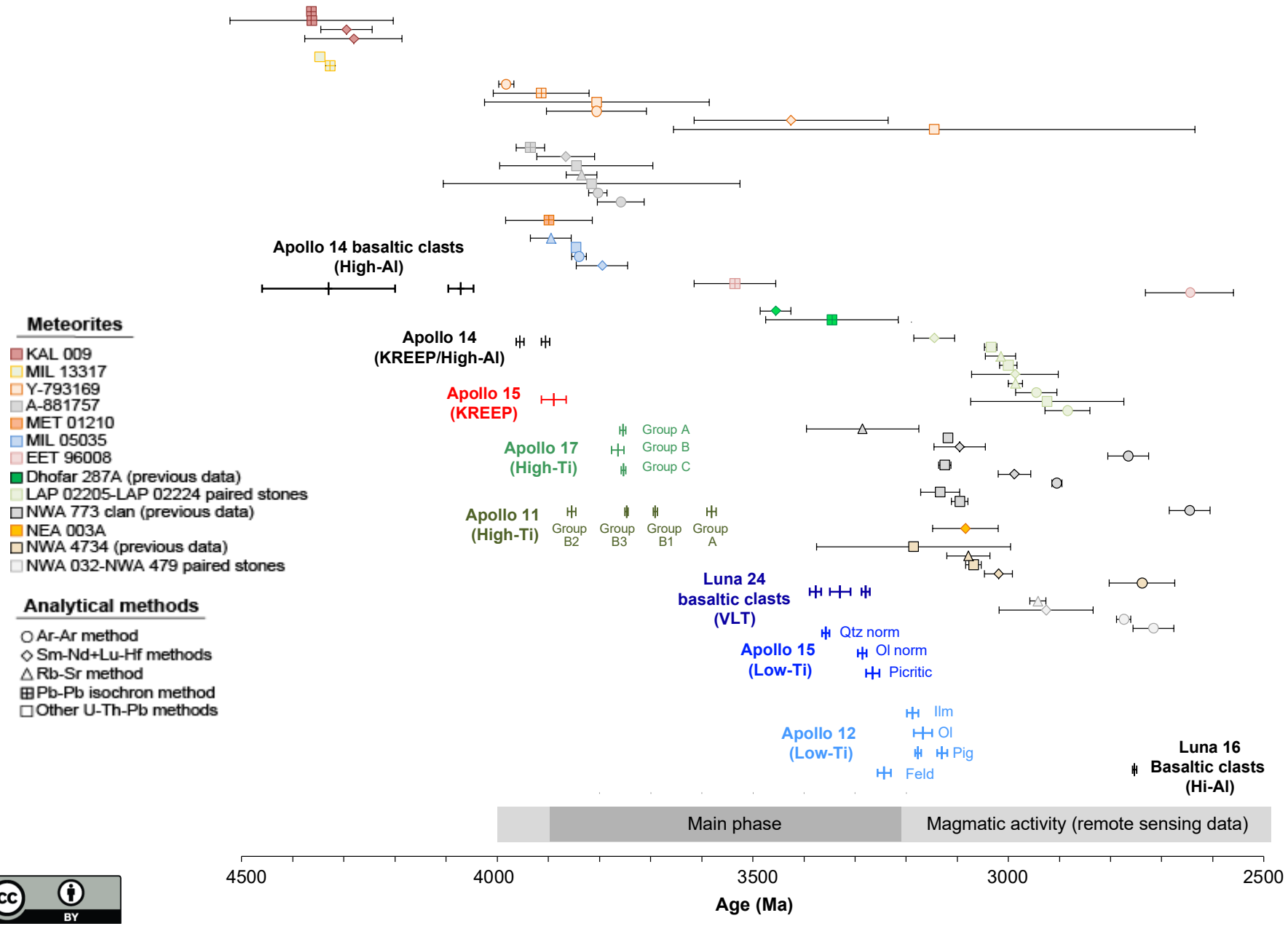
How do we know about lunar magmatism?

Landing sites

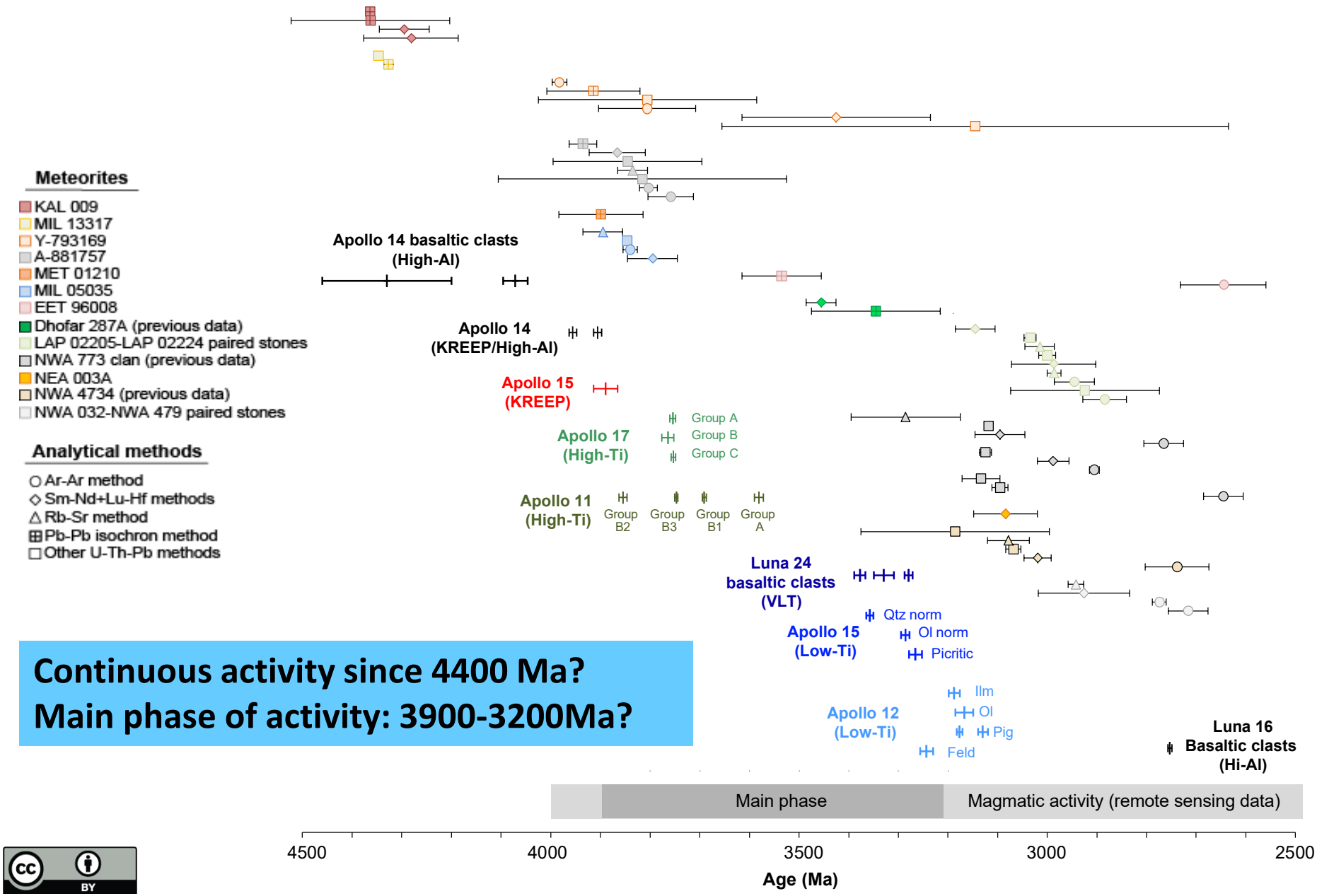
Meteorites



Basaltic magmatic activity on the Moon: Previous studies



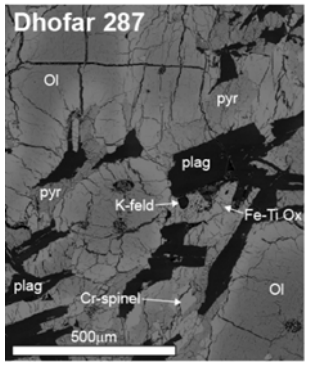
Basaltic magmatic activity on the Moon: Previous studies



Continuous activity since 4400 Ma?
Main phase of activity: 3900-3200Ma?

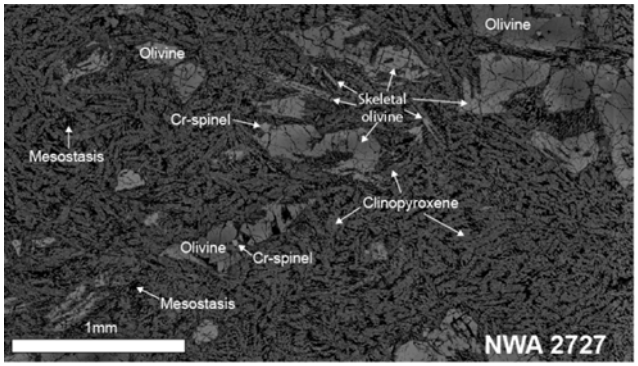
Basaltic magmatic activity on the Moon: Investigated samples

- **NWA 4734: basalt (coarse-grained)**
- **Dhofar 287: basalt (coarse-grained)**
- **LAP 02224: basalt (coarse-grained)**

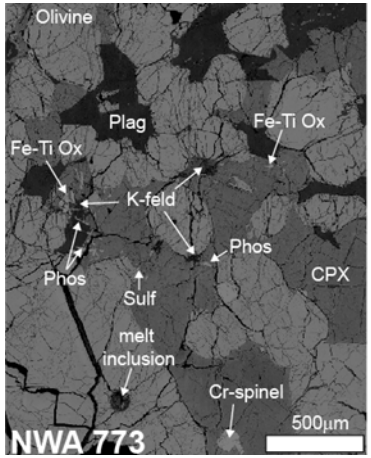


Sub-surface crystallisation

- **NWA 773 clan: 6 stones**
  - **NWA 2700: basalt (fine-grained)**
  - **NWA 2727: basalt (fine grained)**
  - **NWA 773: gabbro**
  - **NWA 2977: gabbro**
  - **NWA 3170: gabbro**
  - **NWA 3333: gabbro**



Surface crystallisation



Crystallisation in depth

All basaltic rock types on the Moon are represented

Methodological approach

How to date lunar basaltic rocks?

- Classic radiometric techniques:
  - ^{40}Ar-^{39}Ar
  - Rb-Sr
  - Sm-Nd
  - U-Pb

Based on the radioactive decay of a element (^{40}K, ^{87}Rb, ^{143}Sm, ^{235}U and ^{238}U) into a daughter element (^{39}Ar, ^{143}Nd, ^{206}Pb and ^{207}Pb)

- A novel approach:
  - In-situ Pb-Pb by SIMS

Methodological approach

How to date lunar basaltic rocks?

Issues:

- Few minerals suitable for dating

(containing large quantities of parent element and no initial daughter element)

- Impossible to monitor the presence of terrestrial contamination

(from sample prep., desert alteration)

- A novel approach:
  - In-situ Pb-Pb by SIMS

In-situ Pb-Pb dating by SIMS

Principle:

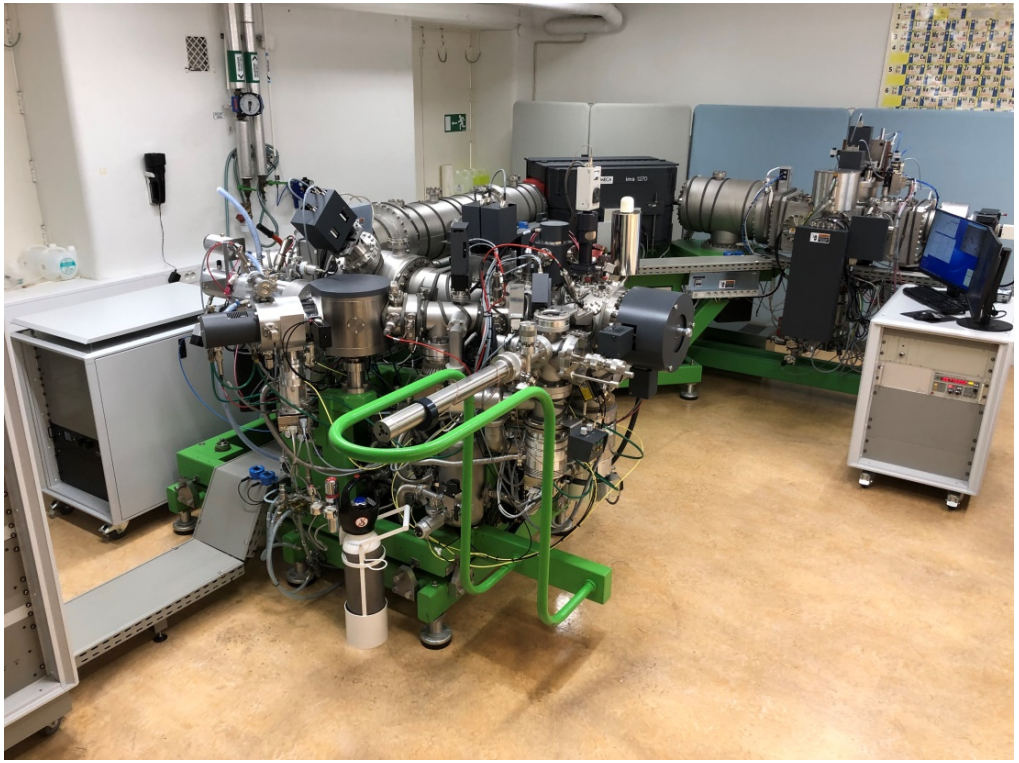
Construction of $^{207}Pb/^{206}Pb$ vs $^{204}Pb/^{206}Pb$ isochrons from in-situ analyses of minerals containing Pb

Advantages of SIMS Pb-Pb dating:

1) Analysis of Pb isotopes only

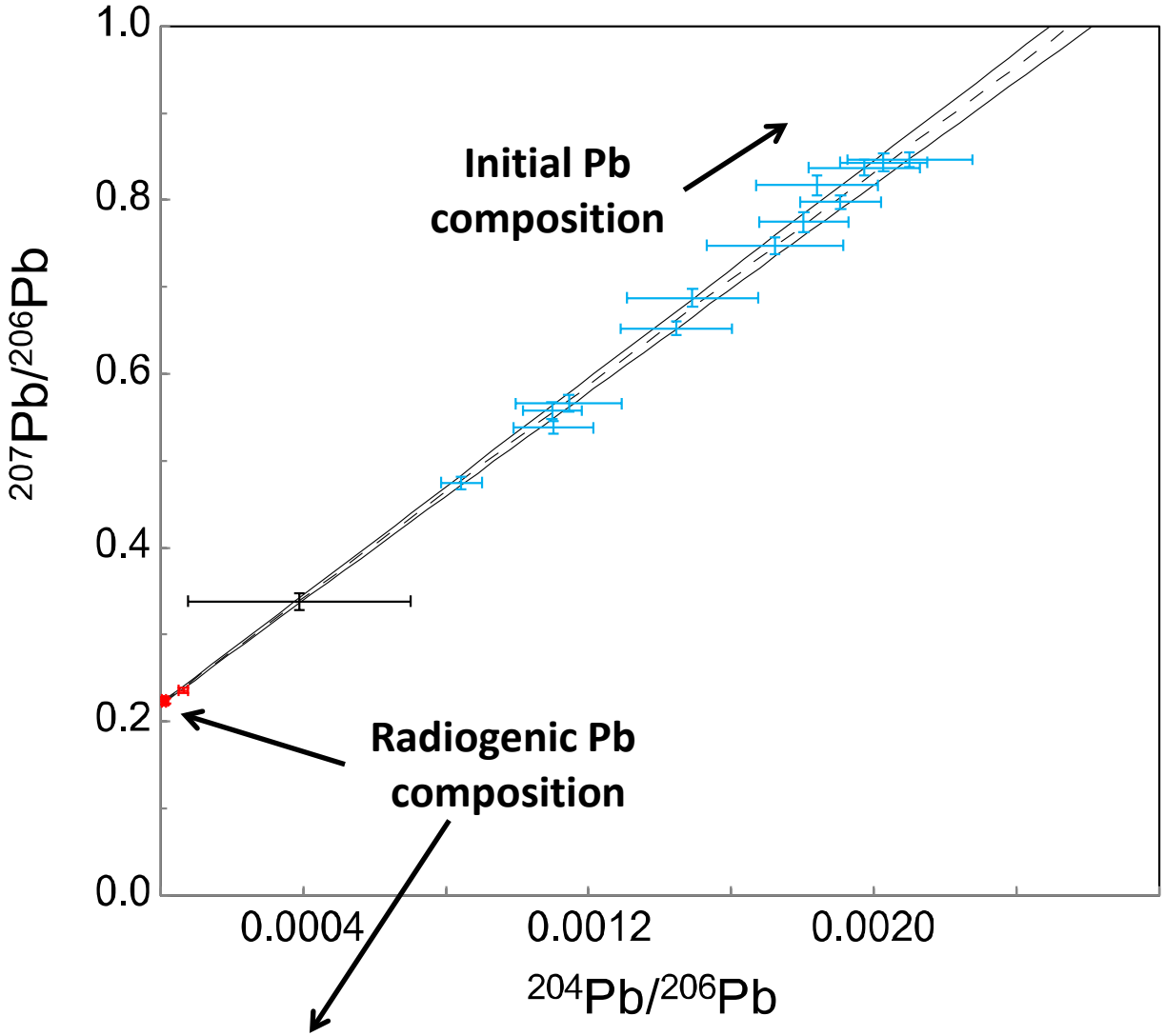
2) High spatial resolution

3) Monitoring terrestrial Pb contamination



CAMECA IMS1280 at NRM-Geovetenskap

Pb-Pb Isochron:



$$^{207}Pb^{*}/^{206}Pb^{*} = {}^{235}U/{}^{238}U \times [\, e^{\lambda_{235} t} - 1 / e^{\lambda_{238} t} - 1]$$

λ: decay constant

Spatial resolution:

Possibility of analysing small individual grains containing Pb

Analysis of phases formed during the late stage of crystallisation

- Phosphates

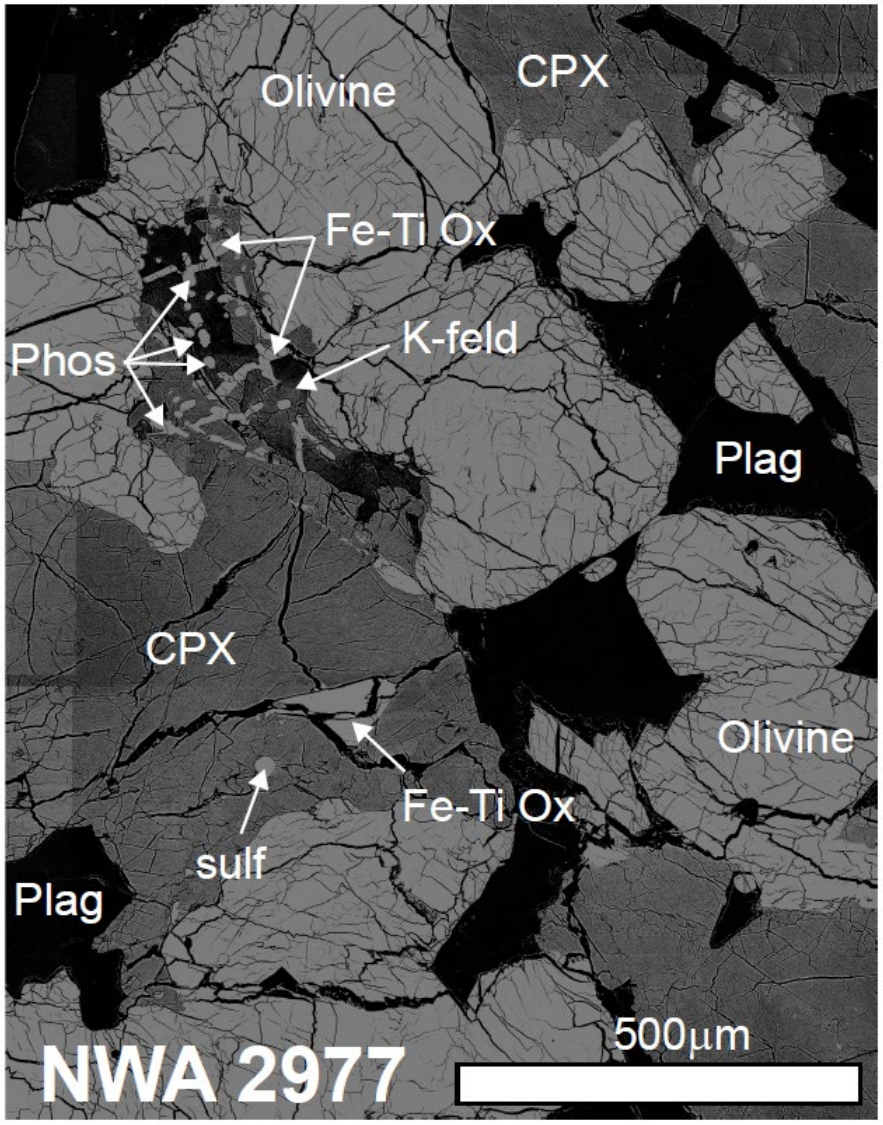
(radiogenic + minor initial Pb bearing phase)

- Potassium feldspars

(initial Pb bearing phase)

- Zr-oxides and -silicates

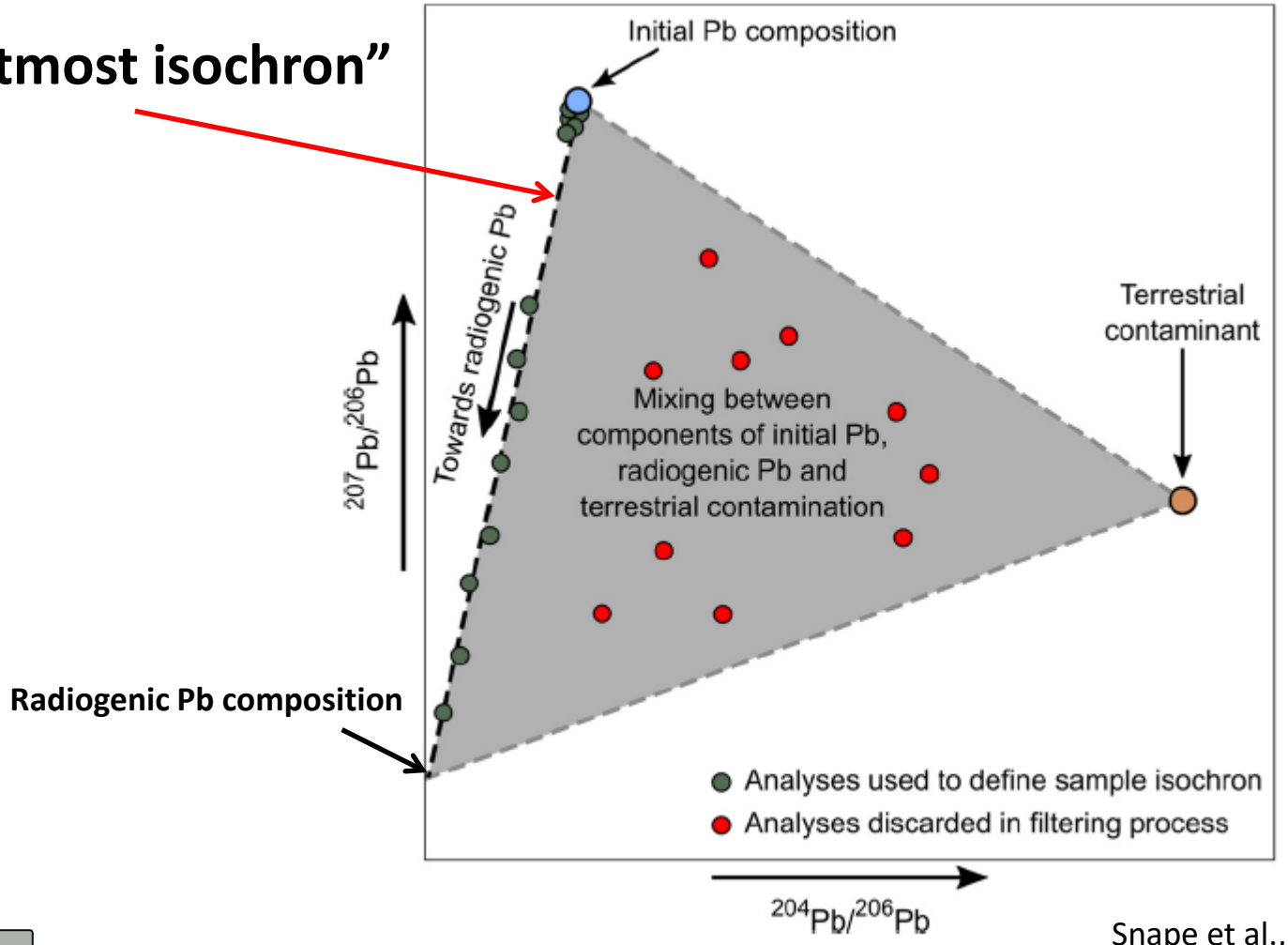
(Baddeleyite, zircon, zirconolite: radiogenic Pb bearing phase)



Monitoring terrestrial Pb contamination

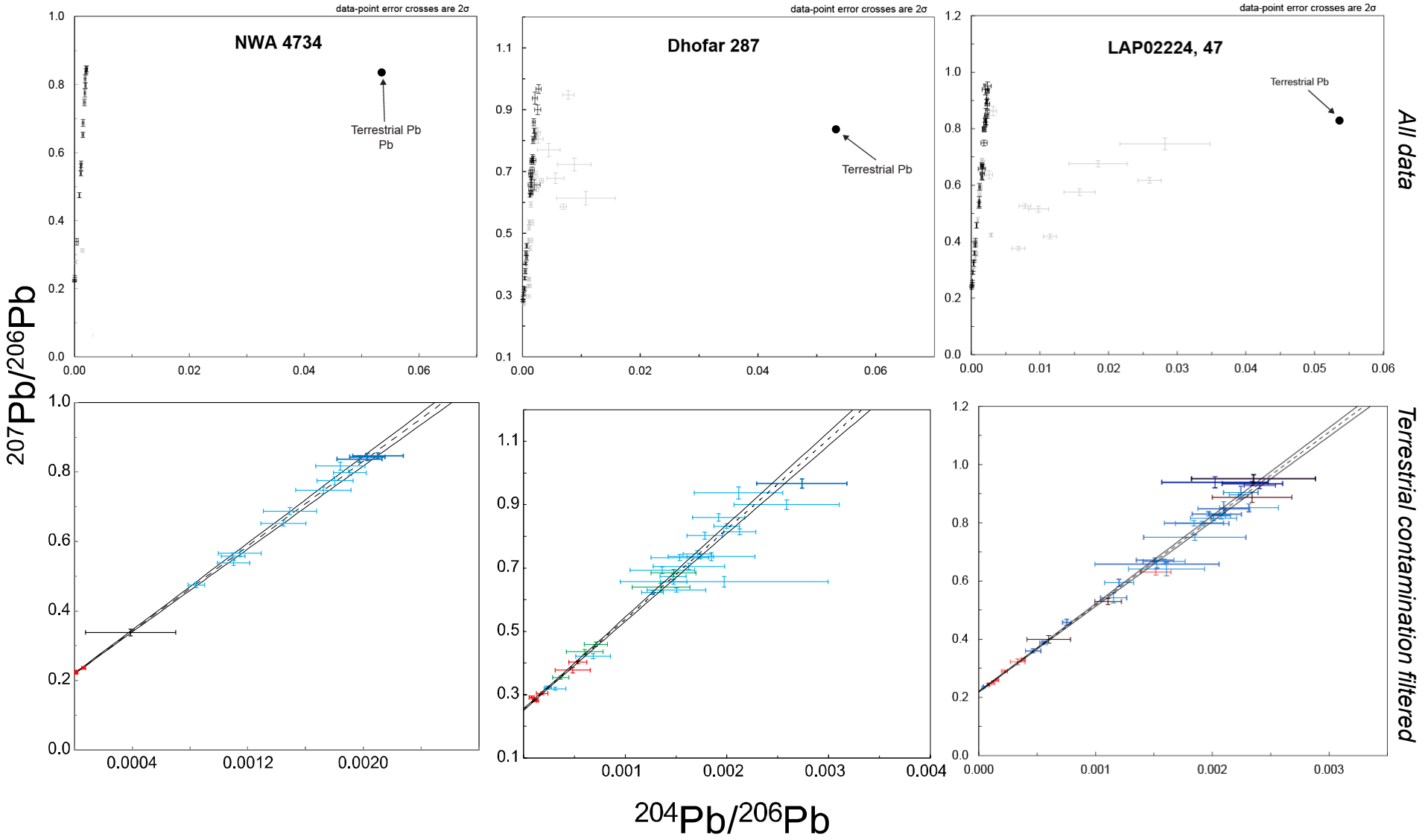
Data contaminated by terrestrial Pb tend to yield older dates

”Leftmost isochron”



Snape et al., 2016

Results I: coarse-grained basalts

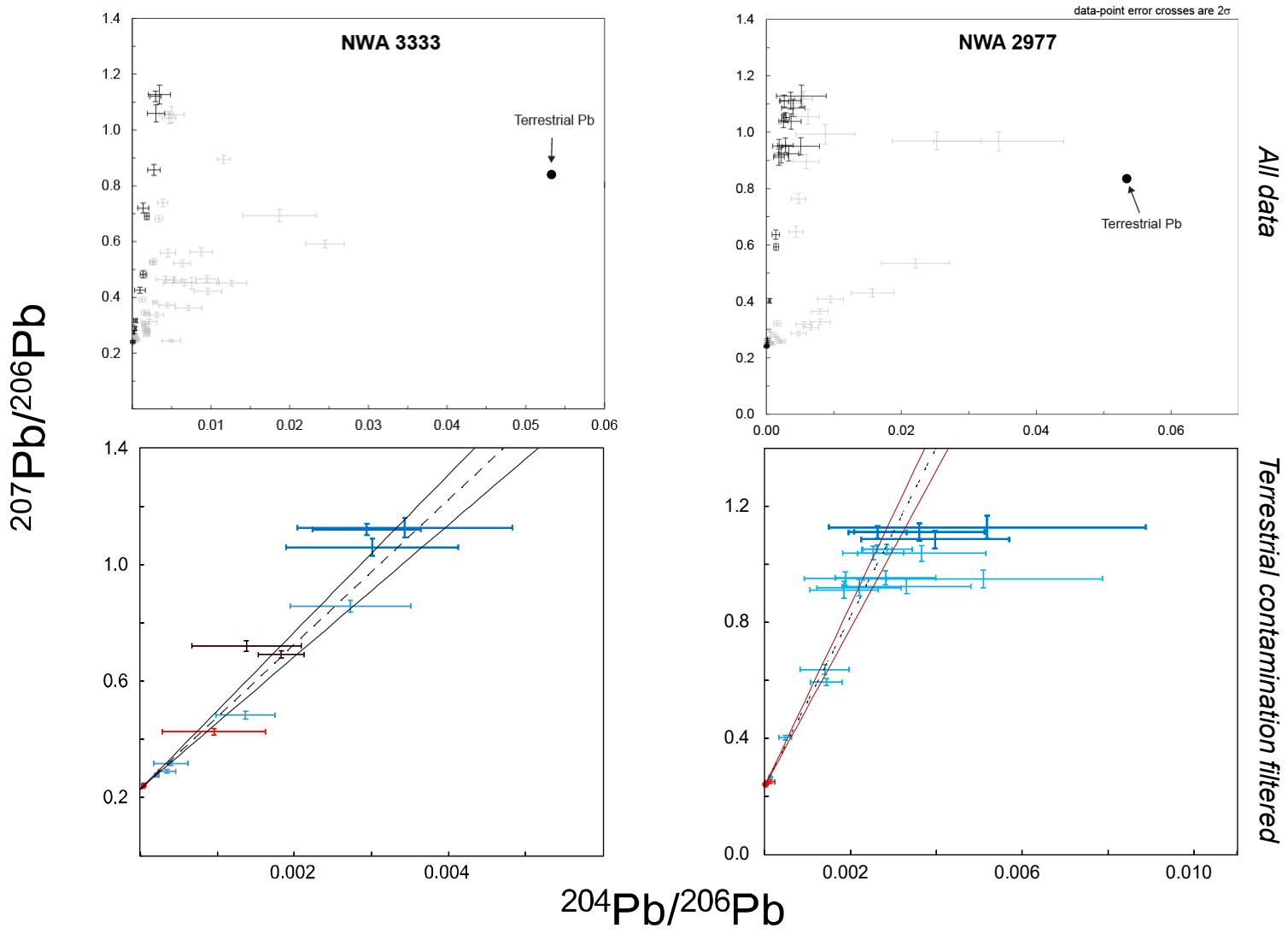


Age = 2981 ± 12 Ma (95% confidence) on 18 points; MSWD = 0.60; Probability of fit = 0.89

Age = 3208 ± 22 Ma (95% confidence) on 33 points; MSWD = 1.4; Probability of fit = 0.077

Age = 2977± 13 Ma (95% confidence) on 42 points; MSWD = 1.2; Probability of fit = 0.18

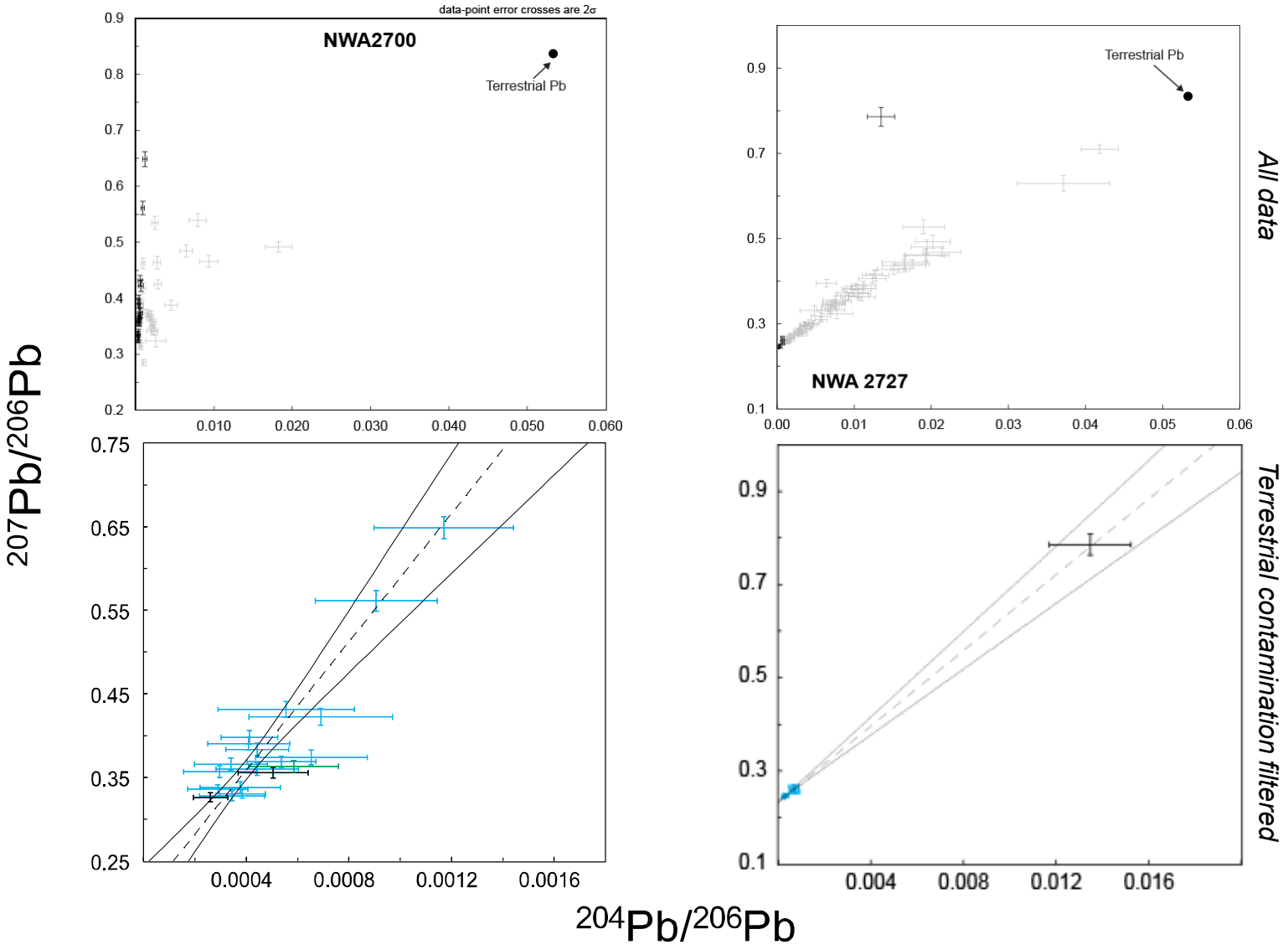
Results II: gabbros (NWA 773 clan)



Age = 3038 ± 20 Ma (95% confidence)
on 14 points; MSWD = 1.5;
Probability of fit = 0.13

Age = 3085 ± 9 Ma (95% confidence)
on 30 points; MSWD =1.5;
Probability of fit = 0.052

Results III: fine-grained basalts (NWA 773 clan)



Age = 2871 ± 300 Ma (95% confidence)
on 19 points; MSWD = 1.5;
Probability of fit = 0.072

Age = 3081 ± 21 Ma (95% confidence)
on 5 points; MSWD = 1.04;
Probability of fit = 0.37

Summary of new ages

- **NWA4734:** 2981 ± 12 Ma
- **Dhofar 287:** 3208 ± 22 Ma
- **LAP 02224:** 2977 ± 13 Ma
- **NWA 773 clan:** 5 stones with reliable and precise ages
  - NWA 2727: 3081 ± 21 Ma
  - NWA 773: 3087 ± 7 Ma
  - NWA 2977: 3085 ± 9 Ma
  - NWA 3170: 3088 ± 11 Ma

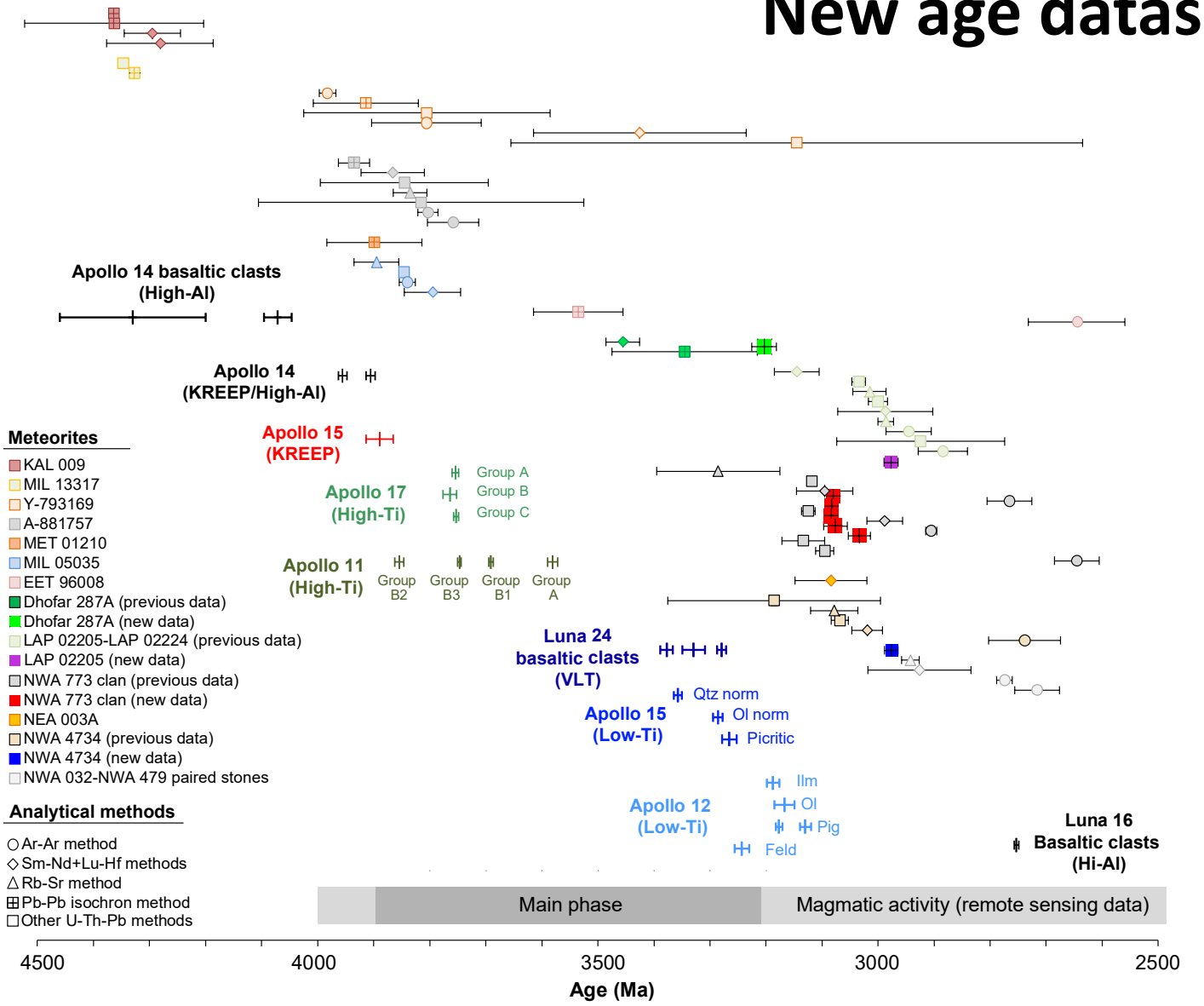
  Average age: **3086 ± 5 Ma**

  - NWA 3333: 3038 ± 20 Ma

  Younger magmatic event

2 magmatic events recorded in NWA 773 clan

New age dataset



Data quality assessment required

(Based on methodological parameters)

Data filtering-Step 1: methodological criteria

- Dates with doubtful geological meaning: **Have to be discarded**
  - Unreliable methodology
    - Rocks suite isochrons
    - Whole-rock isochrons
    - Whole-rock K-Ar or Ar-Ar dating
      - Unpicked mineral or whole-rock fractions
    - No Ar degassing plateau developed (< 50% degassed Ar = disturbed patterns)

  Presence of impact melt and/or terrestrial alteration products

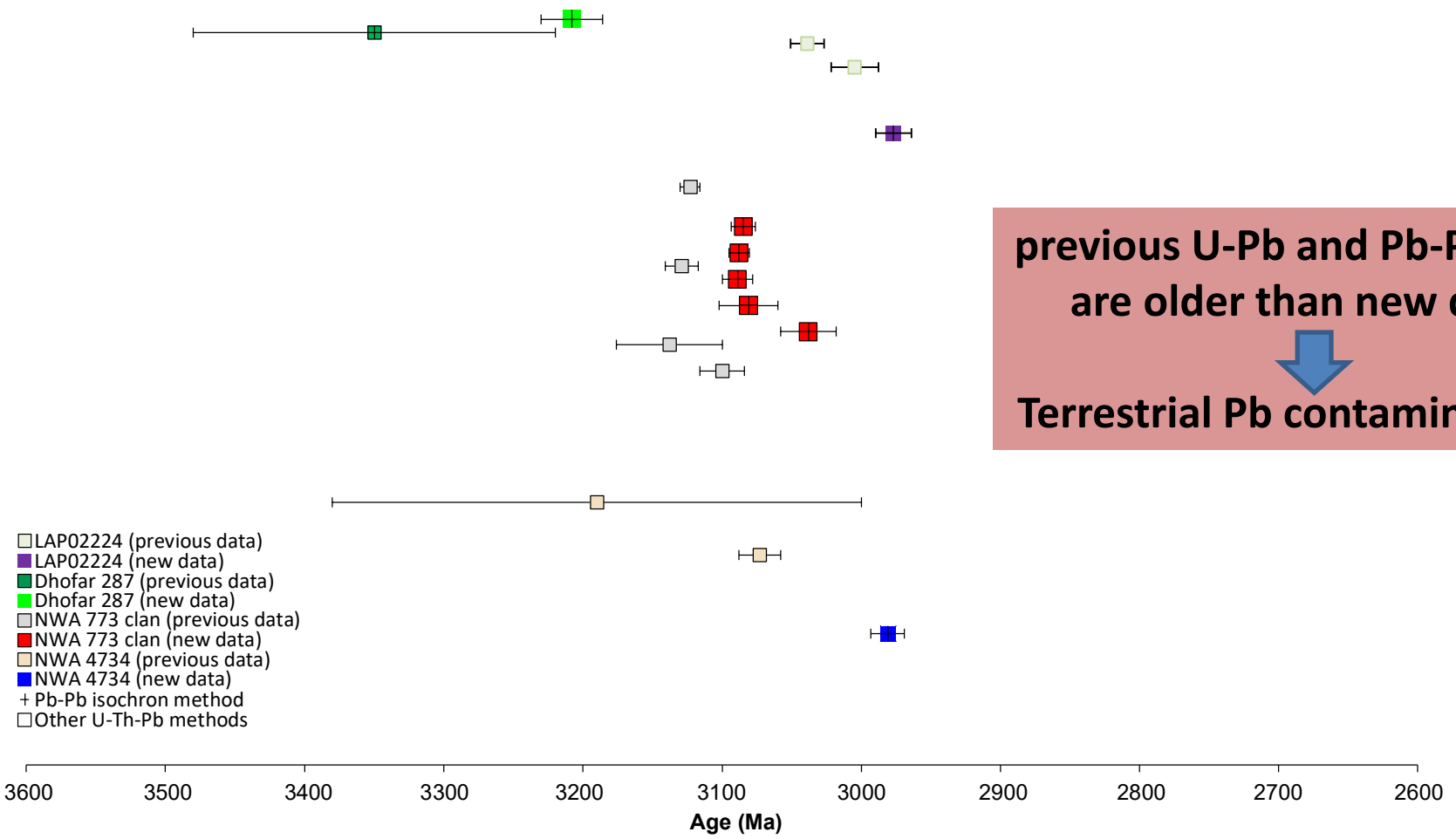
  - Statistically non-valid age calculation
    - Mean Square Weighted Deviation (MSWD) >2; Probability of fit: P < 0.05
    - 2-points isochrons
  - Imprecise ages: Uncertainty > 3% (> 100 Myrs) = Too large to be meaningful

- "Age estimates": **Need careful data quality assessment**
  - Magmatic groundmass Ar-Ar plateau age
    - Hand-picked fractions only
  - Mini-plateau (50-70% degassed Ar)
    - Mineral fractions only
  - Whole-rock+ mineral Rb-Sr or Sm-Nd isochrons

Analytical issues? Terrestrial contamination?

Data reprocessing

Most of previously published U-Pb and Pb-Pb dates pass through the quality test



previous U-Pb and Pb-Pb data are older than new data

Terrestrial Pb contamination?

Data filtering-Step 2:

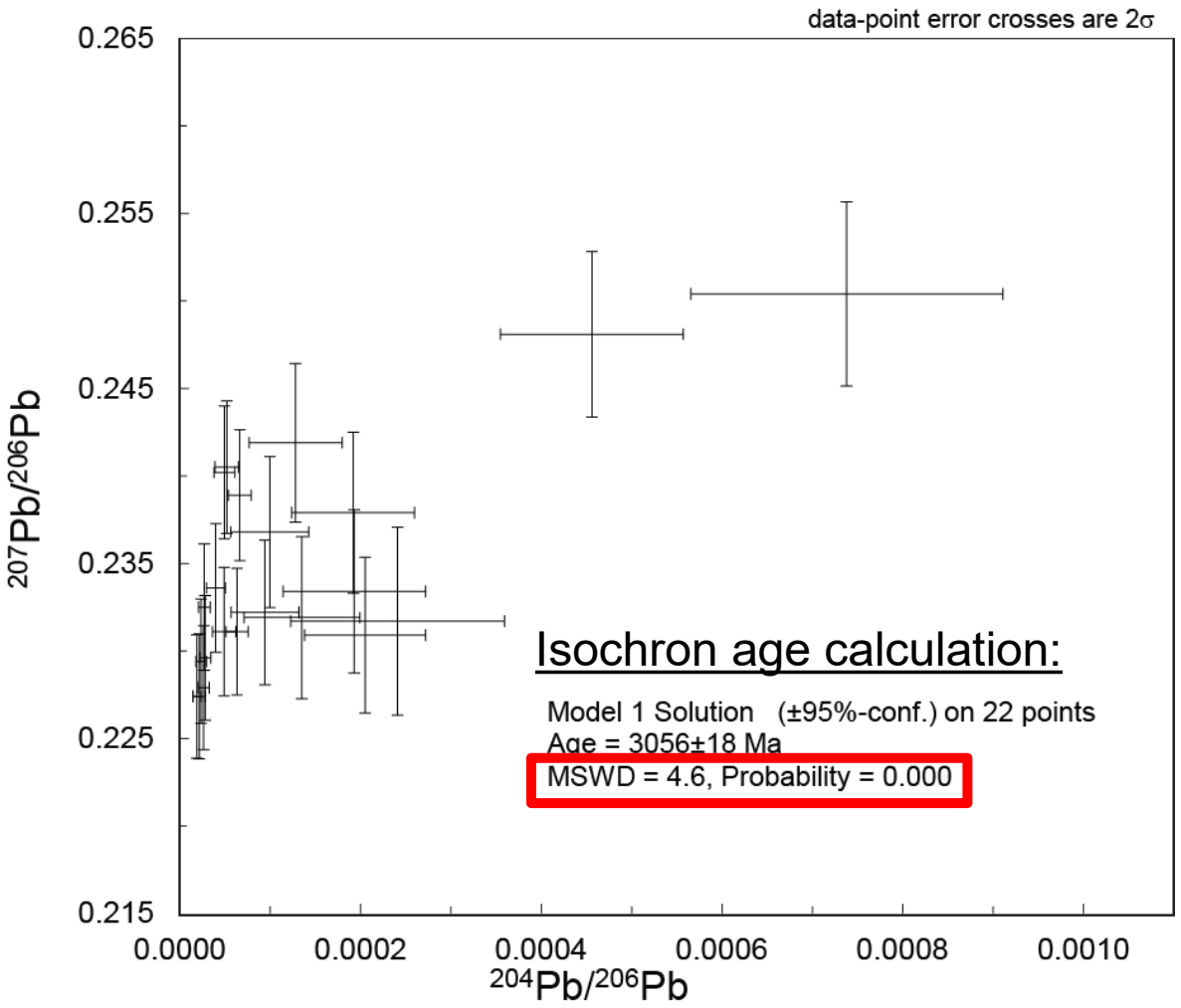
Tracing evidence of terrestrial contamination in U-Pb/Pb-Pb datasets

Example from NWA 4734

Previously published age:

3073 ± 15 Ma

(weighted average $^{207}Pb/^{206}Pb$ age)



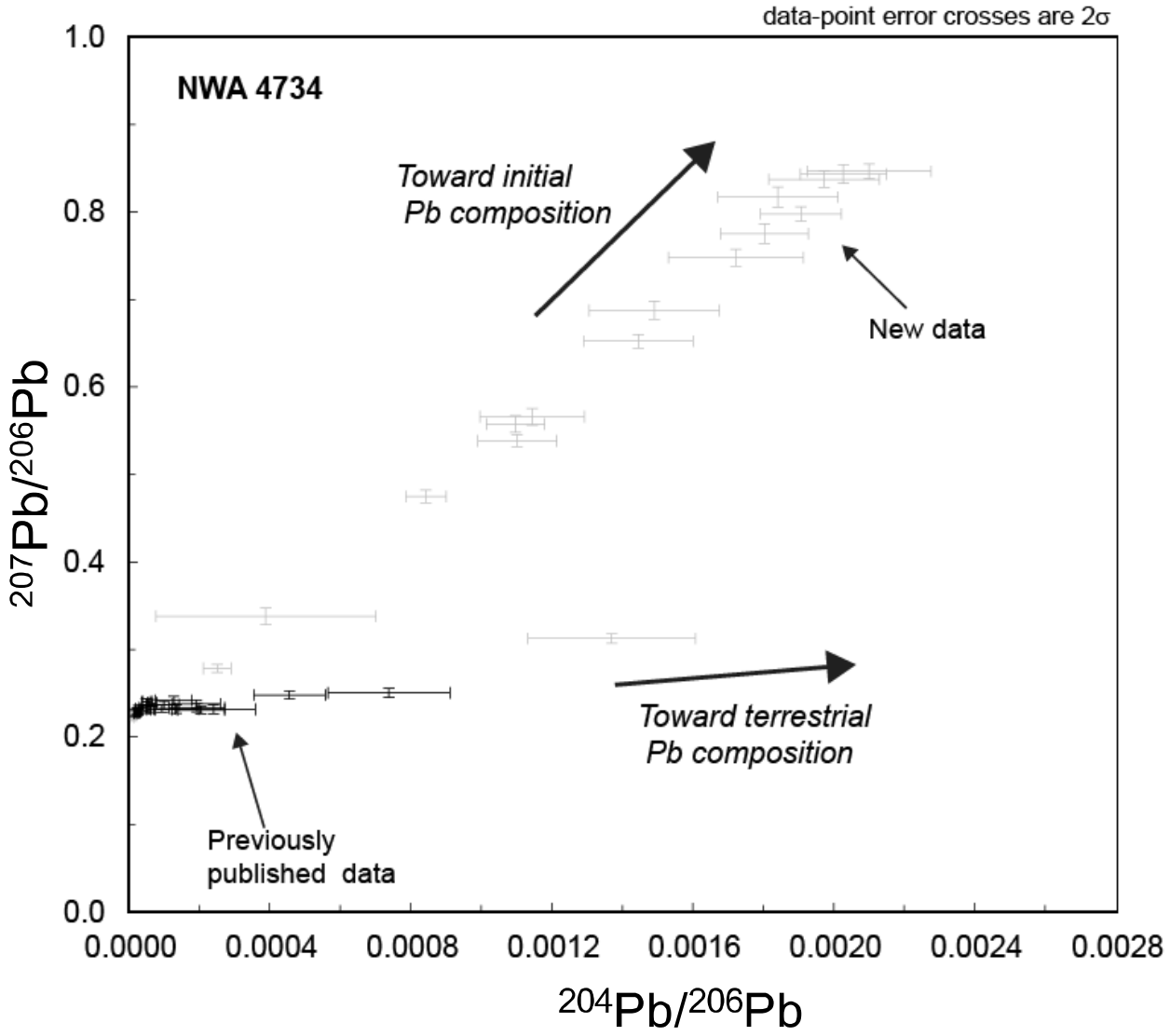
Wang et al., 2012

Data filtering-Step 2:

Tracing evidence of terrestrial contamination in U-Pb/Pb-Pb datasets

Example from NWA 4734

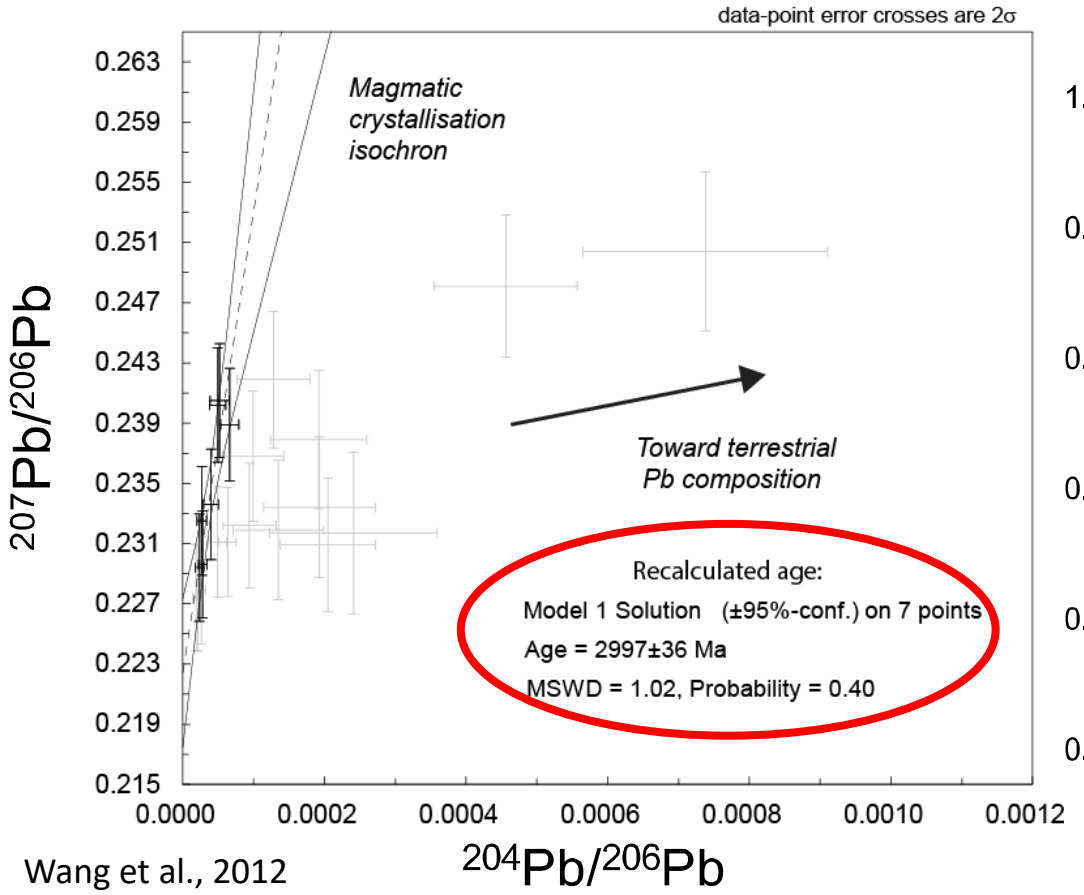
Comparison old data vs new data



Tracing evidence of terrestrial contamination in U-Pb/Pb-Pb datasets

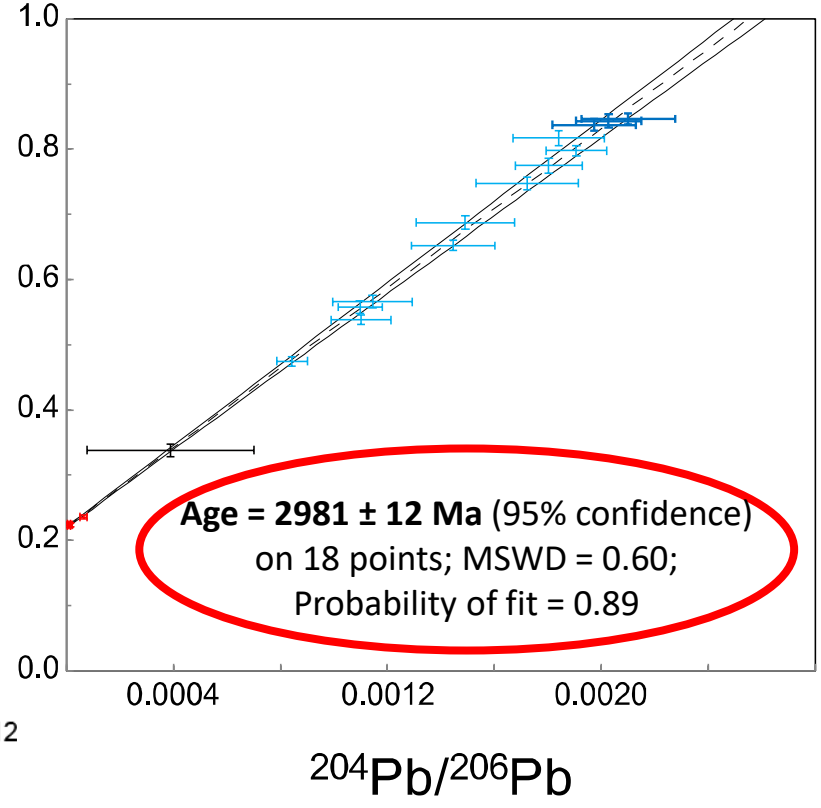
Example from NWA 4734

Previous data filtered for terrestrial Pb contamination



Wang et al., 2012

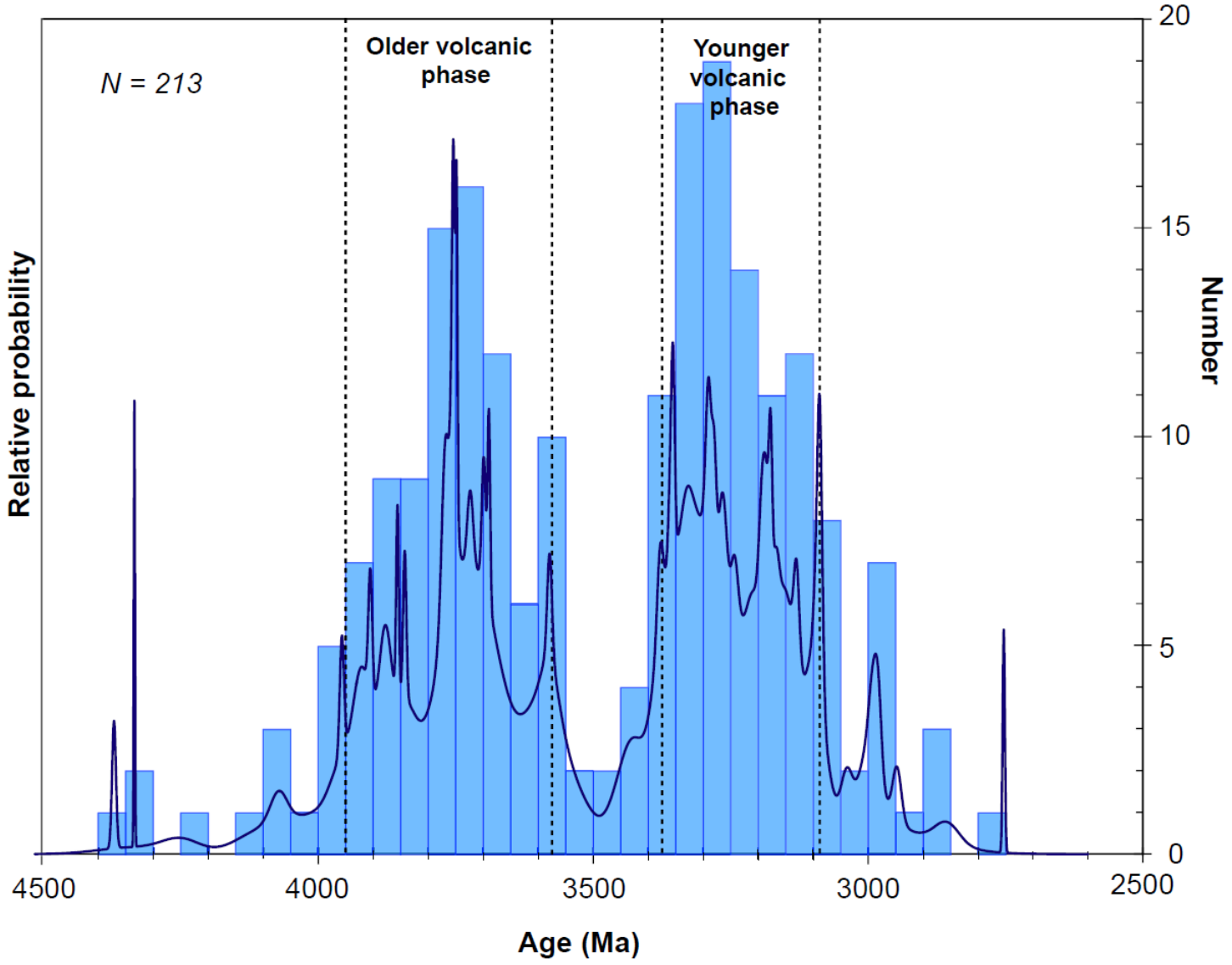
New data



Identical ages

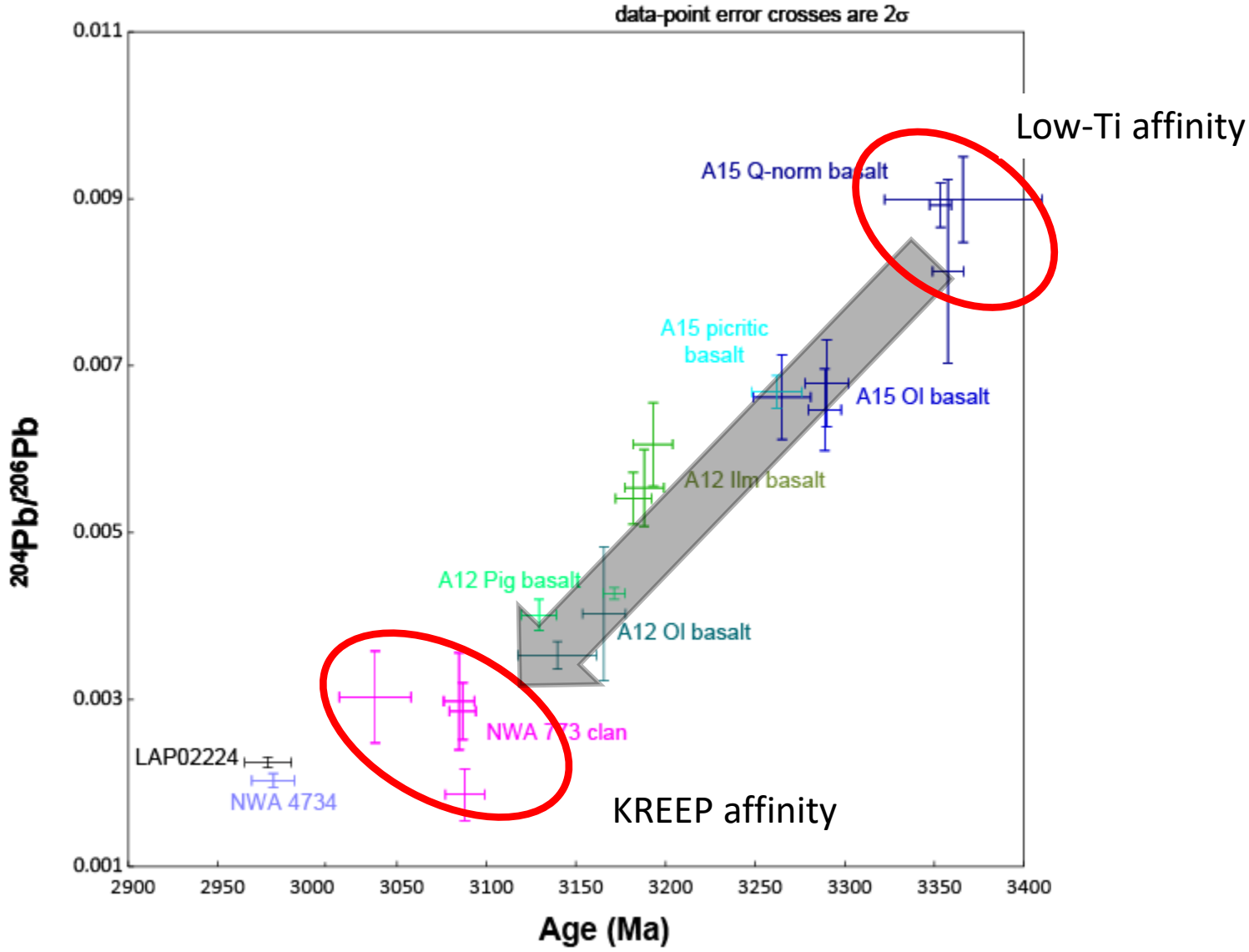
Towards a new chronology of magmatic events on the Moon:

New filtered age dataset



Two magmatic phases: 3950-3575 Ma and 3375-3075 Ma

Pb initial ratios of lunar basalts



Progressive contribution of a
KREEP-like component from 3400 Ma until 3100 Ma

Summary

Geochronology:

- Two major magmatic phases on the Moon:

  - **3950-3575 Ma**
  - **3375-3075 Ma**

Isotope geochemistry:

- Progressive contribution of a KREEP-like component in the chemical characteristics of the low-Ti basalts from 3400 Ma until 3100 Ma