# How to differentiate a rocky planet: insight from the basaltic volcanism of the Moon

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# Formation of the rocky planets

## Carbonaceous chondrite

Unnamed carbonaceous chondrite from my drawer

**Heterogeneous material**
**No structure**

## Rocky planet

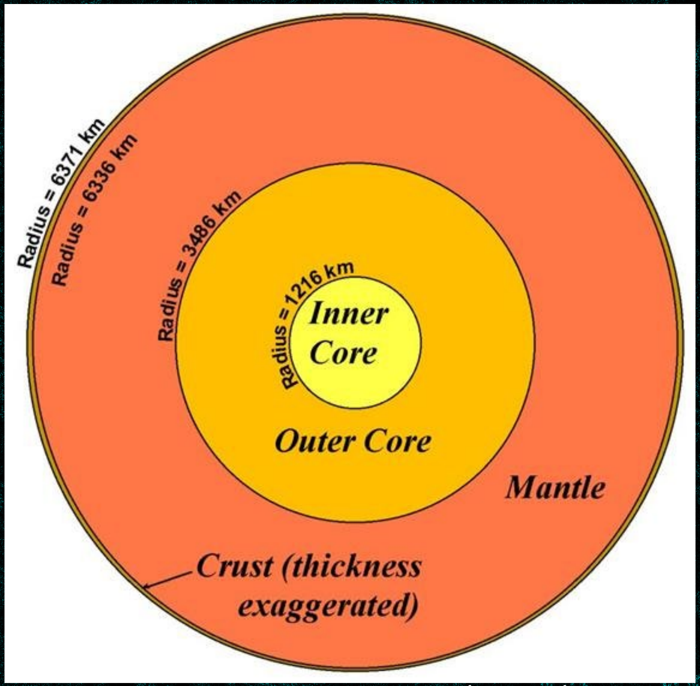


Image credit: Purdue Uni.

**Layered structure:**
**core, mantle and crust**

- ➢ How to achieve this?
- ➢ How long to achieve this?

# The formation of planets

**Step 1 = Accretion:**

- Beginning of collision between newly formed objects

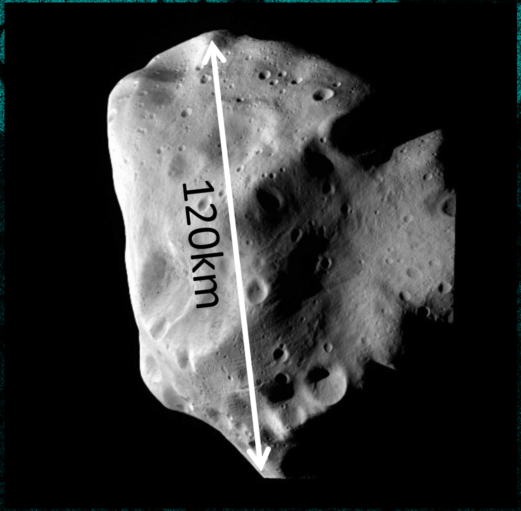
- Then a lot of collisions

➡ **Planetesimal formation**

(solid objects of 1-100 km)

- Planetesimals → planetary embryos → planets

➡ **Less and less collisions but more and more energetic**




Planetesimal Lutetia
(image from ESA website)

Image from NASA website

# Step 2 = Planetary-scale melting
**(relevant for rocky planets)**

Heat from collisions and radioactive elements accumulation

➡ Migration of the elements and compounds within the planetary body according to density

=

**Planetary differentiation**

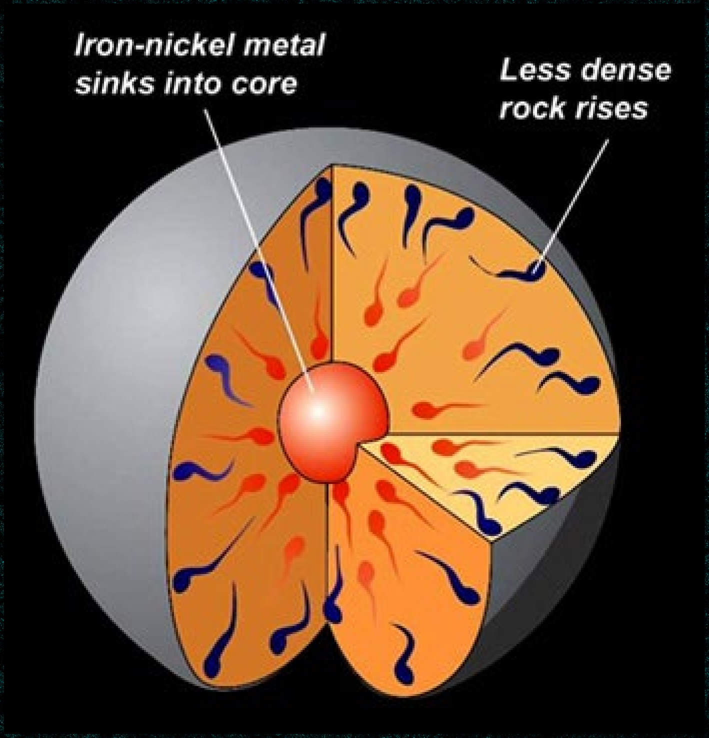



Image credit: Carleton Uni.

# Internal structure of rocky planets
## (based on Earth’s)

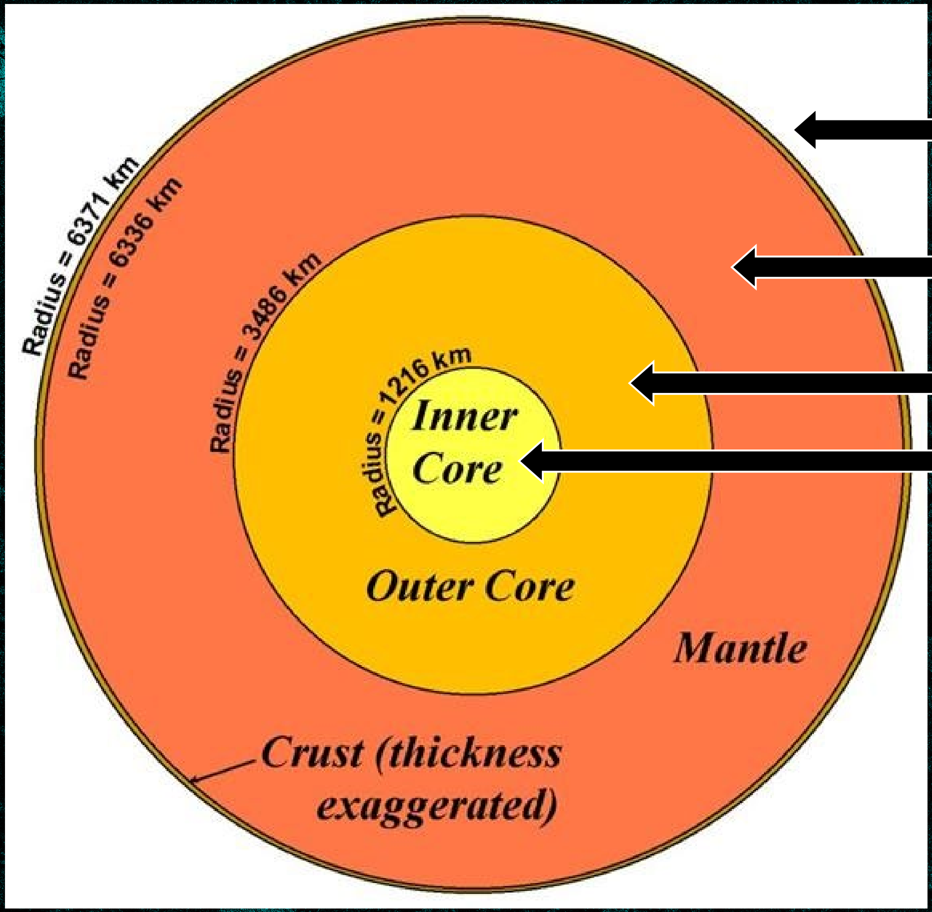



Image credit: Purdue Uni.

**K-Na-Al-Ca silicates (plagioclase)**

**Mg-Fe silicates (olivine, pyroxene)**
**Al-Ti-Ca oxides**

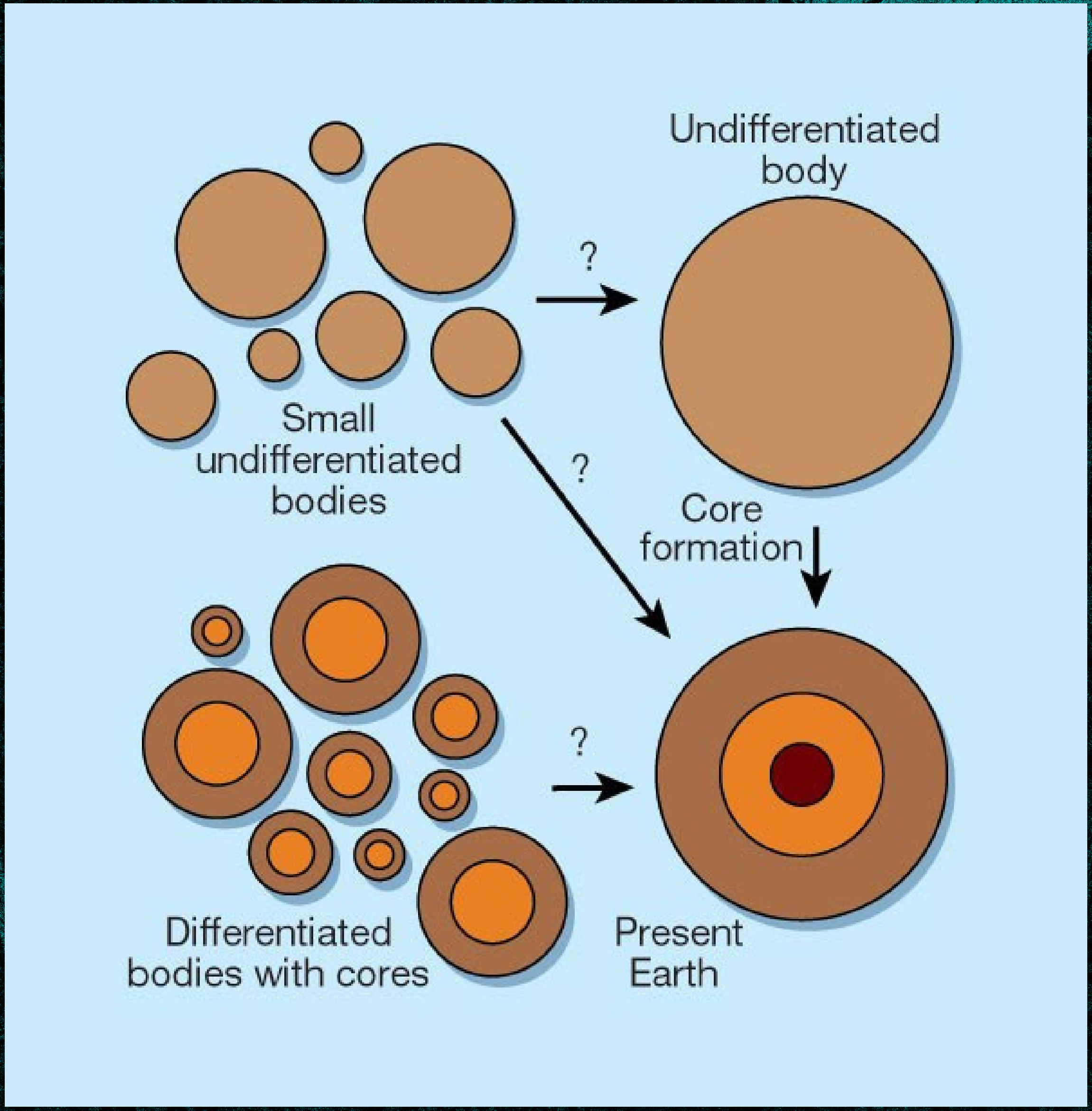
**Ni-Fe-S alloys** + impurities (Si, O)

**Ni-Fe alloys (+metals)**

Density

# Differentiation of the planets

Alternative models




From Minarik, Nature, 2003.

# Geology of the Moon ("selenology")

Basalt
(≈ lavas from Hawaii)

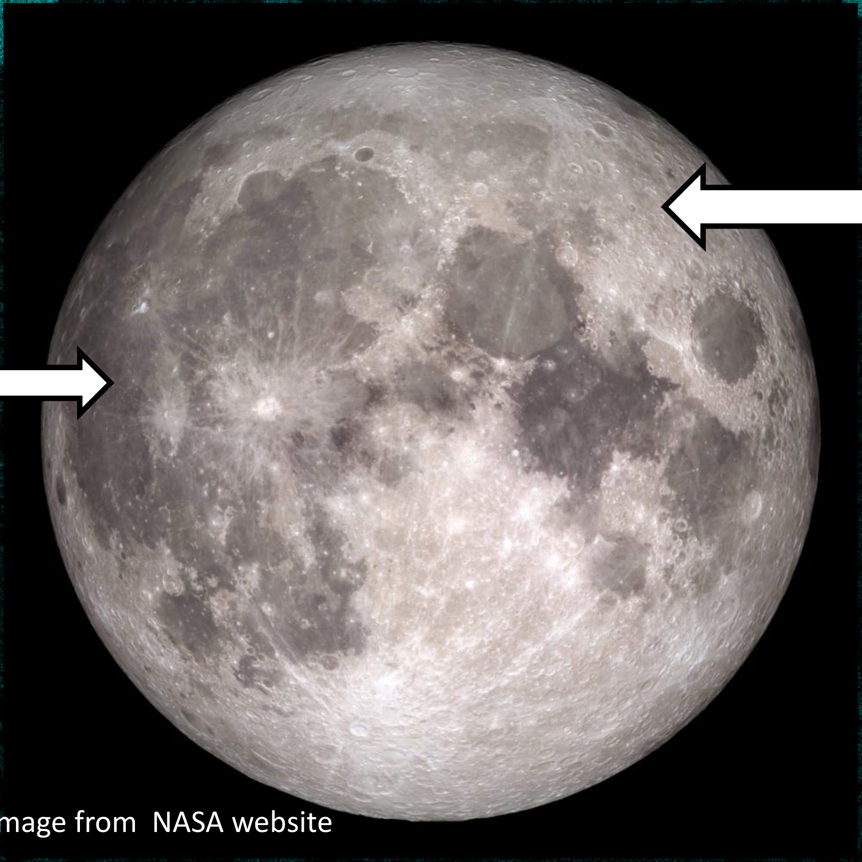


Image from NASA website

Anorthosite crust
90-100% anorthite
(K-Al-Ca plagioclase)

Regolith = "lunar soil" covers all the planet

**Less than 600kg of rocks from the Moon:**

Apollo (USA): 380kg
Luna (USSR): 301g
Chang'e 5 (China): 1.7g
Meteorites: 190kg

# A brief overview of the Early history of the Moon

Lunar meteorite NWA14178 (Image from L. Labenne)

# 1. Initial formation (Very chaotic): ~4500-4400 Ma

Giant impact between a Mars-size object and Earth

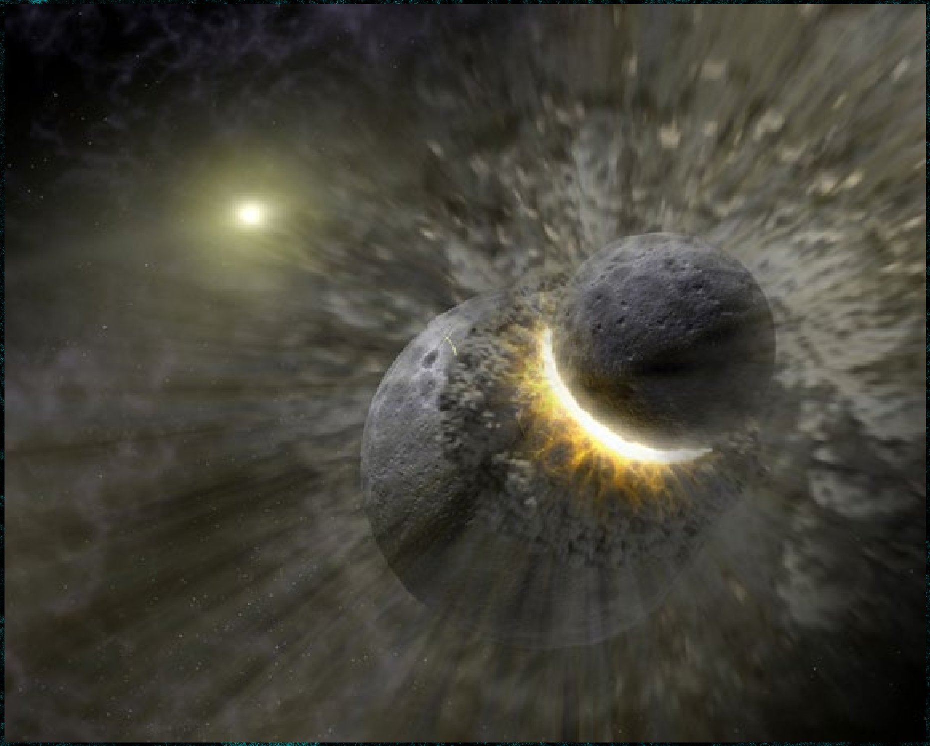


Image from SSERVI-Nasa website

Isotope evidence of genetic relation between Earth and the Moon:
**Similar Oxygen and Titanium Isotope ratios**

# 2. Planetary differentiation: ~4500-4400 Ma?

Accumulation of heat from impact and radioactive elements led to a global magma ocean (Lunar Magma Ocean: LMO)

## LMO crystallisation sequence hypothesis

- Denser minerals (olivine first then pyroxene), crystallised first then sank and accumulated forming different layers

    - ***Formation of a stratified mantle with layers of different compositions***

- At some stage, plagioclase (anorthotite) crystallised but was less dense than the remaining liquid and formed a compact crystal network floating on the top of the liquid

    - ***Formation of the anorthositic crust***

Image from Wikipedia

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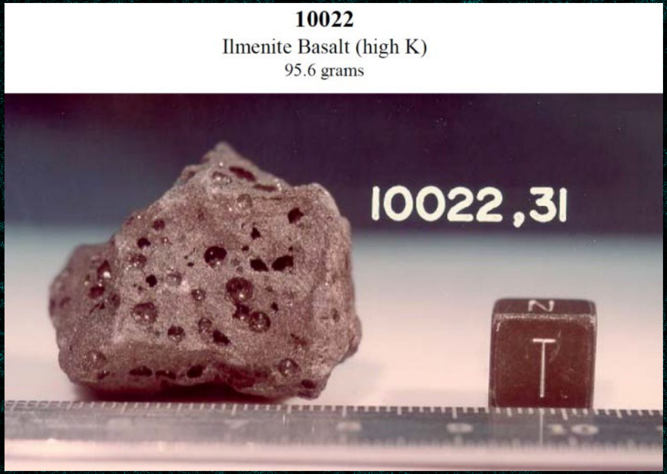
**This is a model**
**This is not confirmed so far**

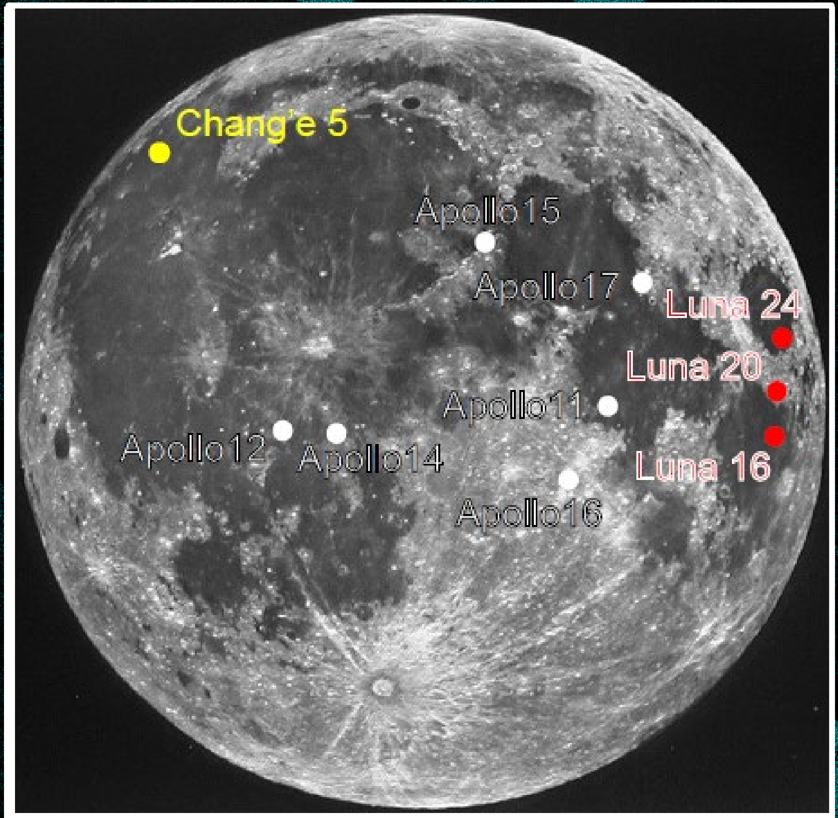
# 3. Volcanic activity: ~4400-2000 Ma (?)

Apollo 11 landing site




Lunar meteorite


Images from Nasa website



# The chemical groups of lunar basalts

- Low Titanium ($TiO_2$ < 6% wt%) = Low-Ti group

  → Several subgroups

  - **Low $^{238}U/^{204}Pb$ ($^{238}U/^{204}Pb = \mu$) basalts**

    → Depleted in REE and other mineral-incompatible elements compared to the other basalts (= "depleted source")

  → Most abundant basalt type on the Moon

- High-Titanium ($TiO_2$ > 6% wt%) = High-Ti

**Derived from the different layers in the mantle formed during LMO crystallisation**

- High Potassium-REE-Phosphorus-U = KREEP

  → Enriched in REE and other mineral-incompatible elements compared to the other lunar basalts (= "enriched source")

  → High $^{238}U/^{204}Pb$ ($\mu$)

**Source = last liquid crystallised from LMO**

**Sandwiched between the crust and mantle layers source of the low-Ti and high-Ti basalts**

# What are the processes involved in the formation and chemical evolution of the lunar mantle?

- **From which cumulate layers are derived the different chemical groups ?**
  - *How many mantle chemical components?*
  - *Should we expect other chemical types of basalts?*
  - *What is the chemical composition of these components?*

**Age of the Moon?**

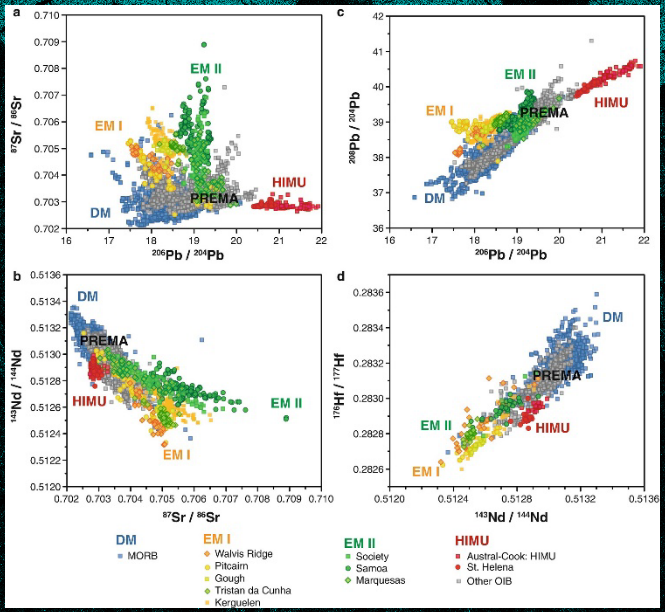
- **When the mantle components formed (end of LMO crystallisation)?**
  - *When really started the basaltic volcanism?*
  - *How long it lasted (exhaustion of mantle component)?*

- **Limited constraints on the chemical characteristics of the mantle sources of the basalts**

**Few radiogenic isotope data available**

**(= classic toolkit for mantle source tracing)**

- *Data with large uncertainty*
- *No systematics using Sr-Nd-Pb-Hf initial isotopic ratios*




From Stacke, Encyclopedia of Geochemistry, 2018.

$$(^{87}Sr/^{86}Sr)_{meas} = (^{87}Sr/^{86}Sr)_0 + {}^{87}Rb/^{86}Sr\,(e^{\lambda Rb * t}-1)$$

- **Poor chronological constraints on the timing of the volcanic activity**
  - *Few data*
  - *Low precision of the data*
  - *Inconsistency of dates obtained by different techniques on the same sample*
  - *Methodological and analytical issues*

**Need for better ages**

- Data filtering
- New data

# Methodological approach

1. **Determination of accurate and reliable chronology of lunar basaltic magmatism**
2. **Determination of radiogenic isotope ratios of lunar basalts**

## ➡ 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 $^{207}Pb$)**

# 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

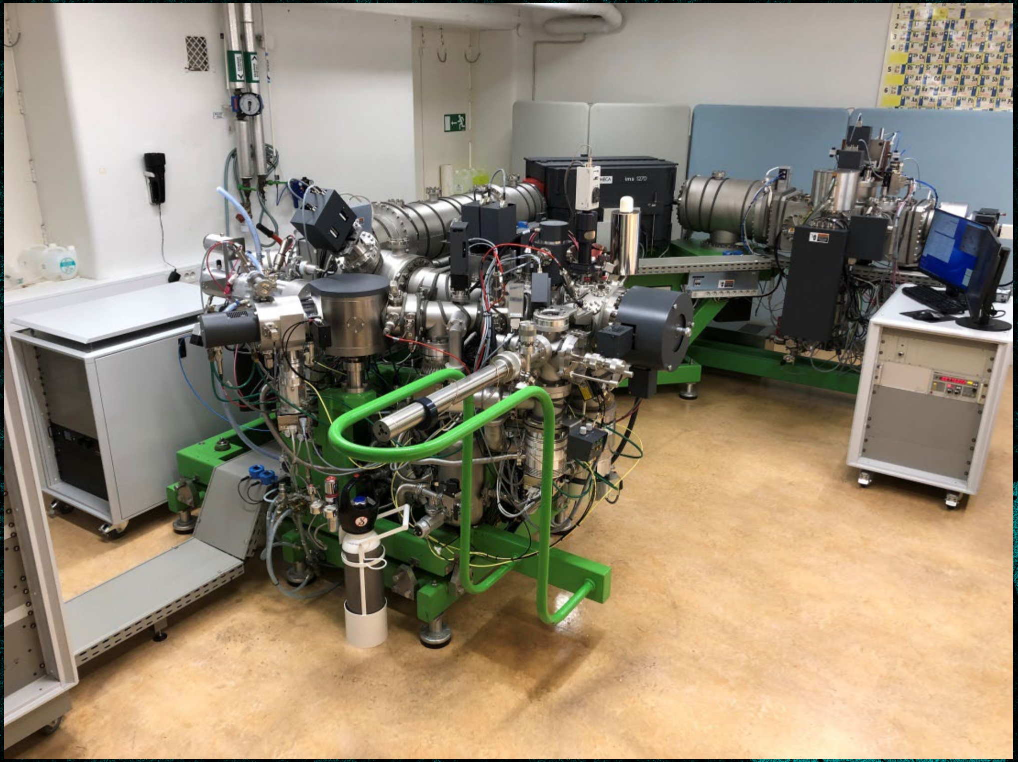
# In-situ Pb-Pb dating by SIMS

## Principle:

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

## Advantages:

1) Analysis of Pb isotopes only
2) High lateral resolution
3) Monitoring terrestrial Pb contamination



*CAMECA IMS1280 at NRM-Geovetenskap*

# Lateral resolution:

*Possibility of analysing small individual grains containing Pb*

- Phosphates

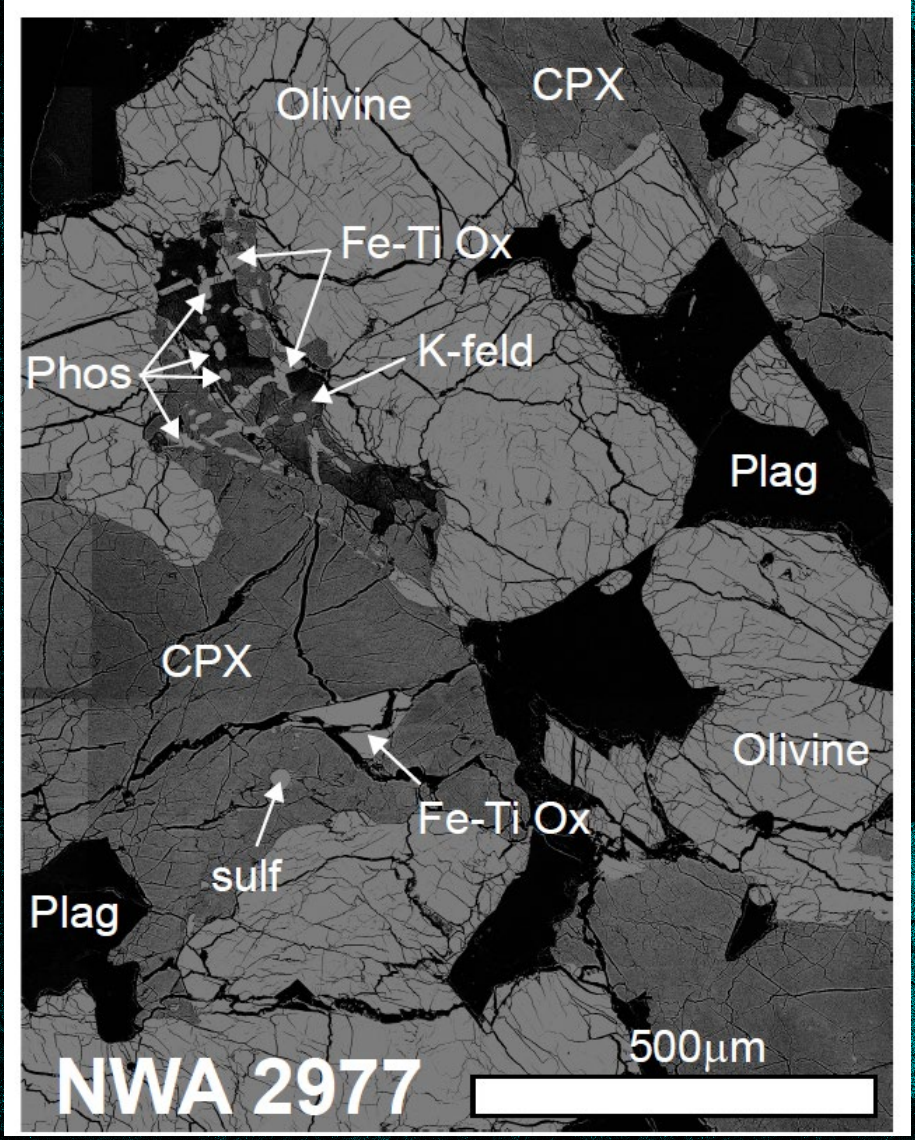
(radiogenic + minor initial Pb bearing phase)

- Potassium feldspars

(initial Pb bearing phase)

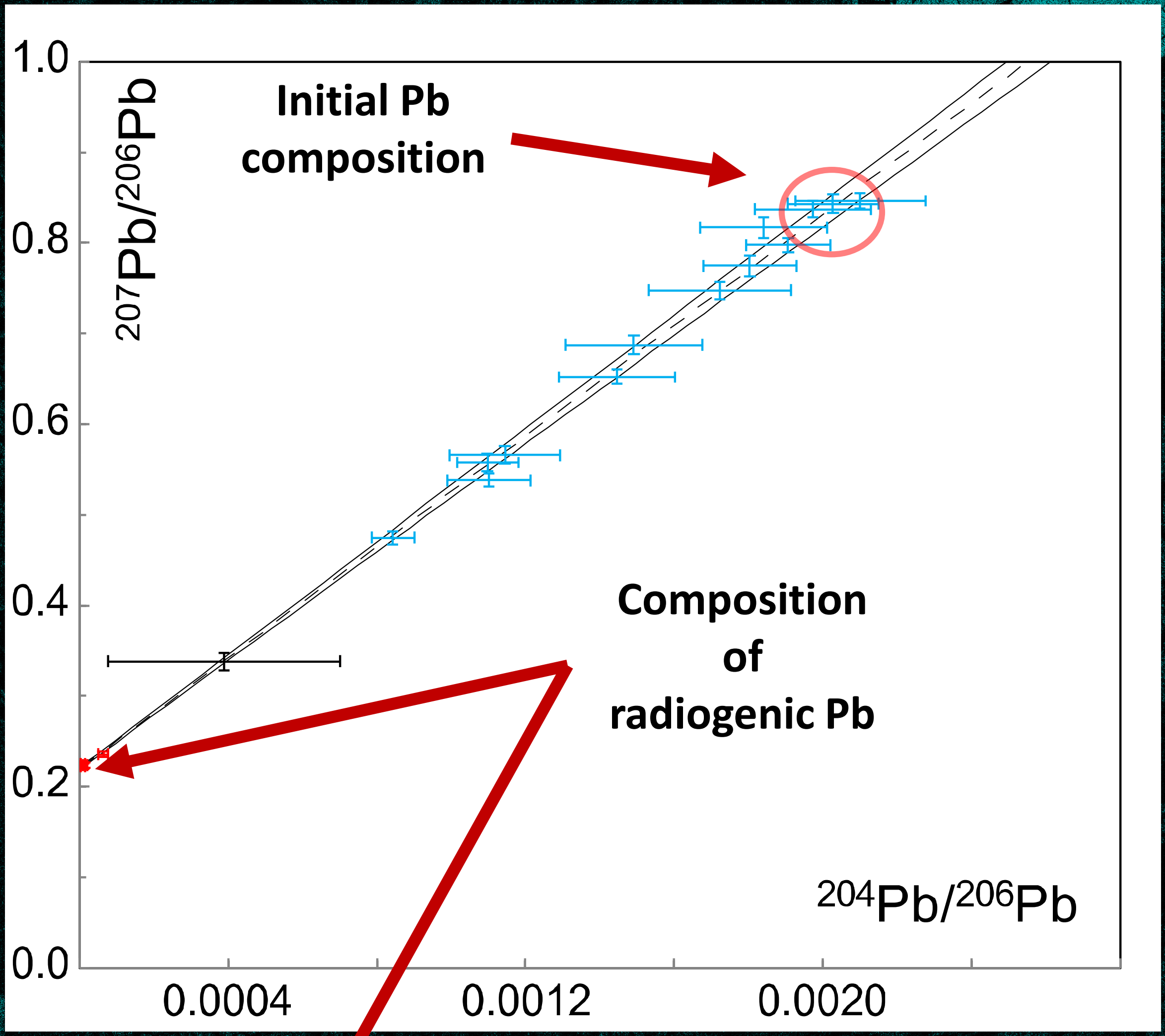
- Zr-oxides and -silicates

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




From Merle et al., Meteoritics and Planetary Sciences, 2020.

# Pb-Pb Isochron:




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

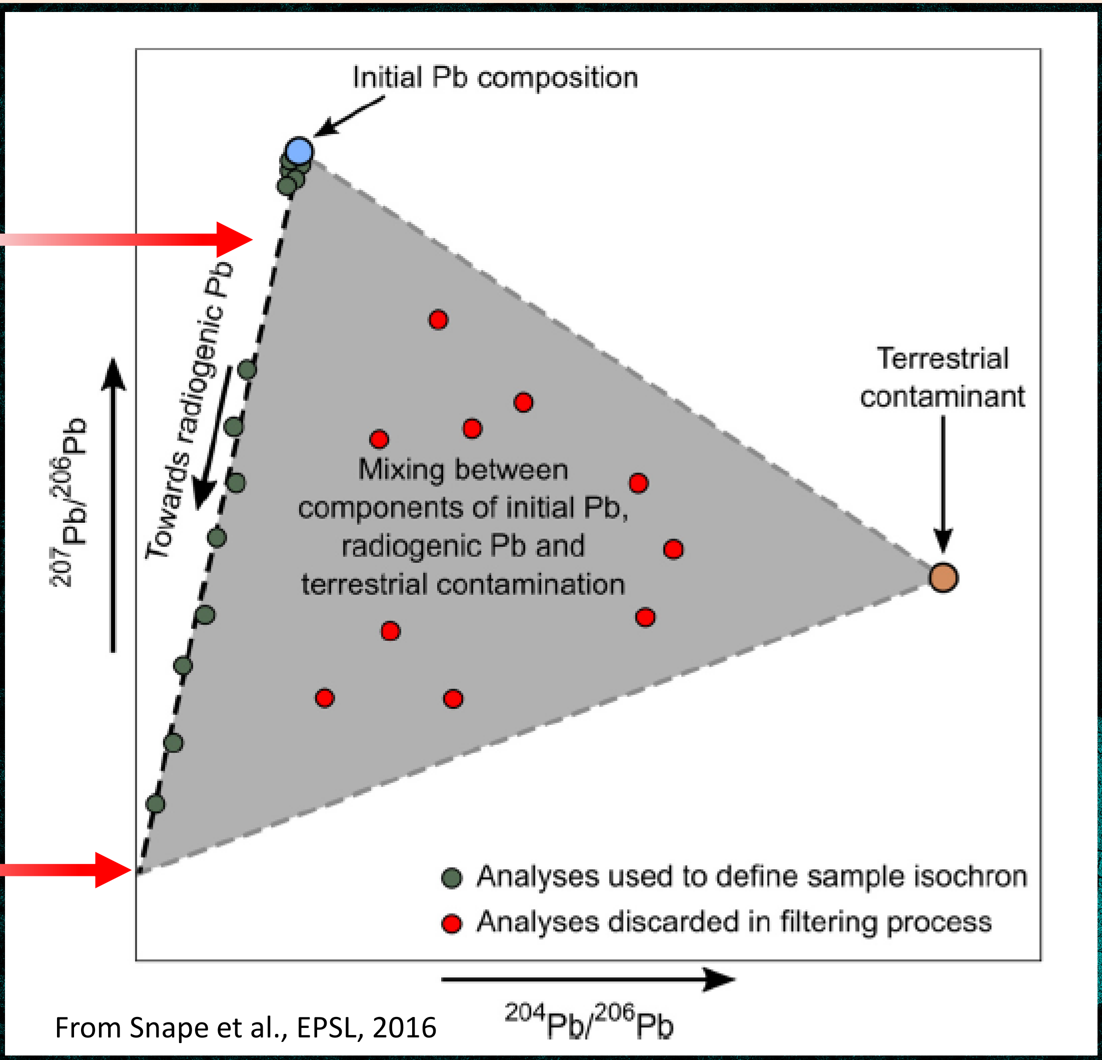
$\lambda$: decay constant

# Monitoring terrestrial Pb contamination

**U-Pb data contaminated by terrestrial Pb tend to yield older dates**

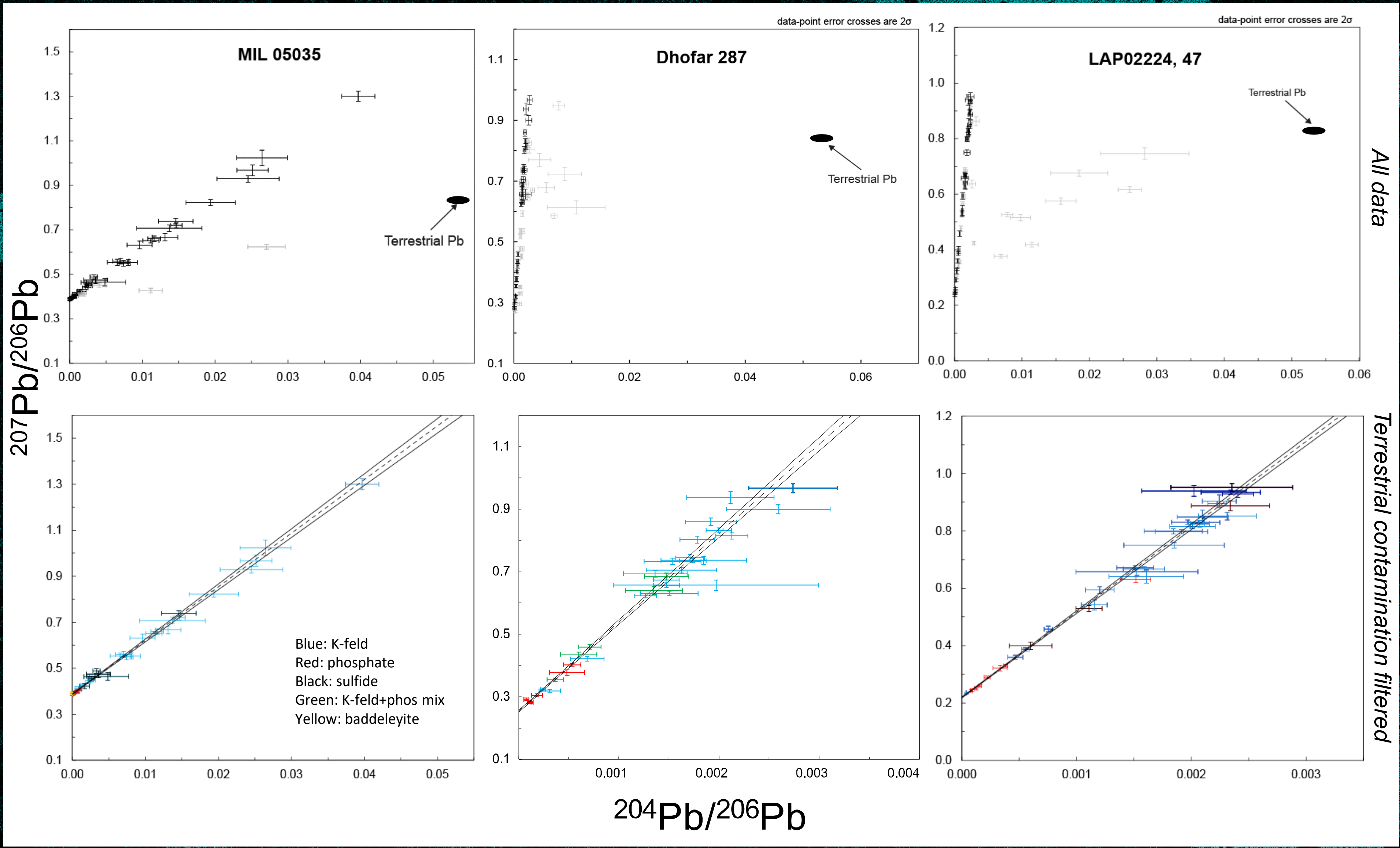
"Leftmost isochron"

Radiogenic Pb composition




From Snape et al., EPSL, 2016

# Isochrons from lunar basaltic meteorites (low-Ti group)



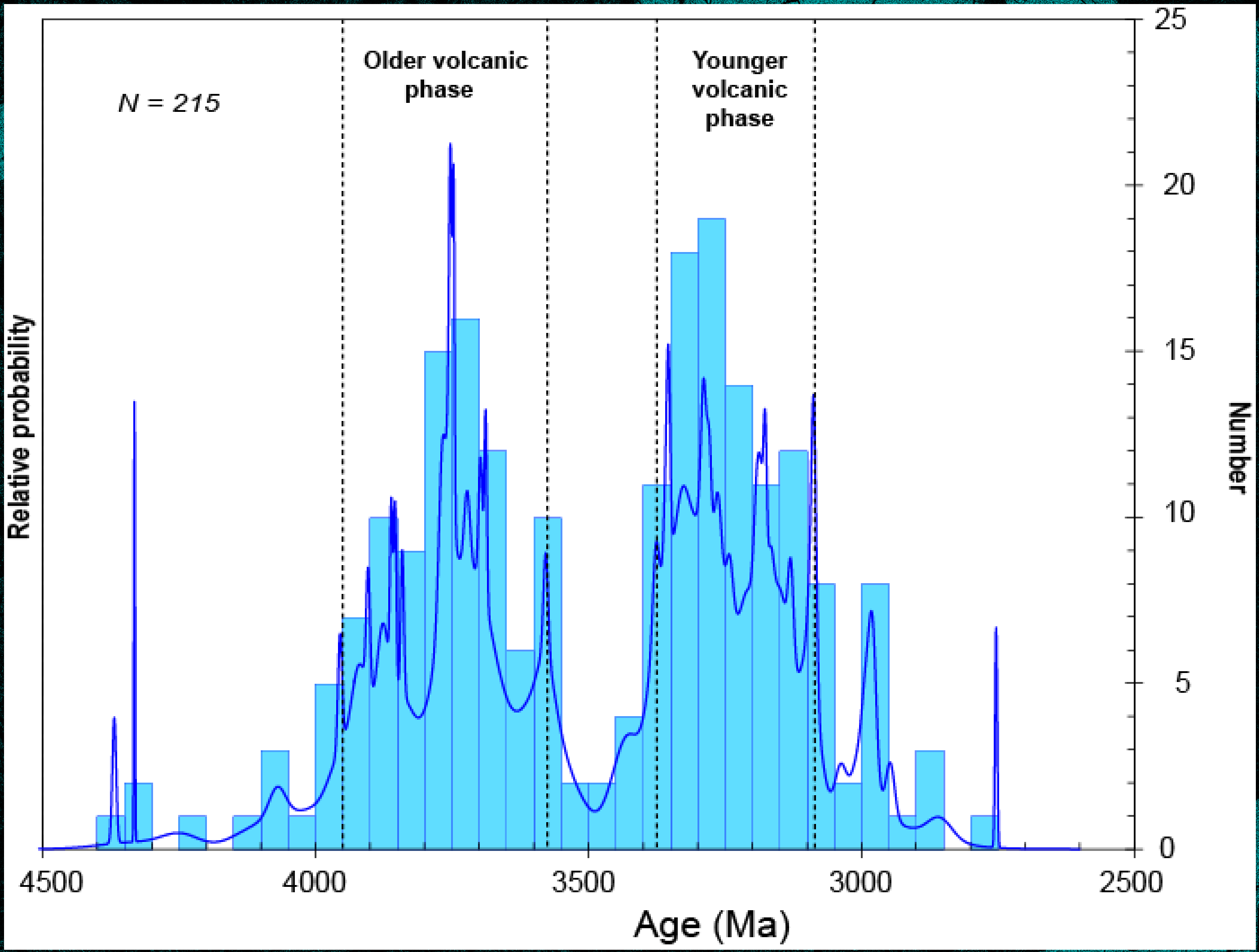

**Age = 3861 ± 5 Ma** (95% confidence) on 46 points; MSWD = 0.91; Probability of fit = 0.64

**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

# Chronology of volcanic events on the Moon:

**New filtered age database of lunar basaltic rocks:**
**Meteorites**
**+**
**Apollo**
**+**
**Luna**
**(Soviet missions) collections**




Updated from Merle et al., Meteoritics and Planetary Sciences, 2020.

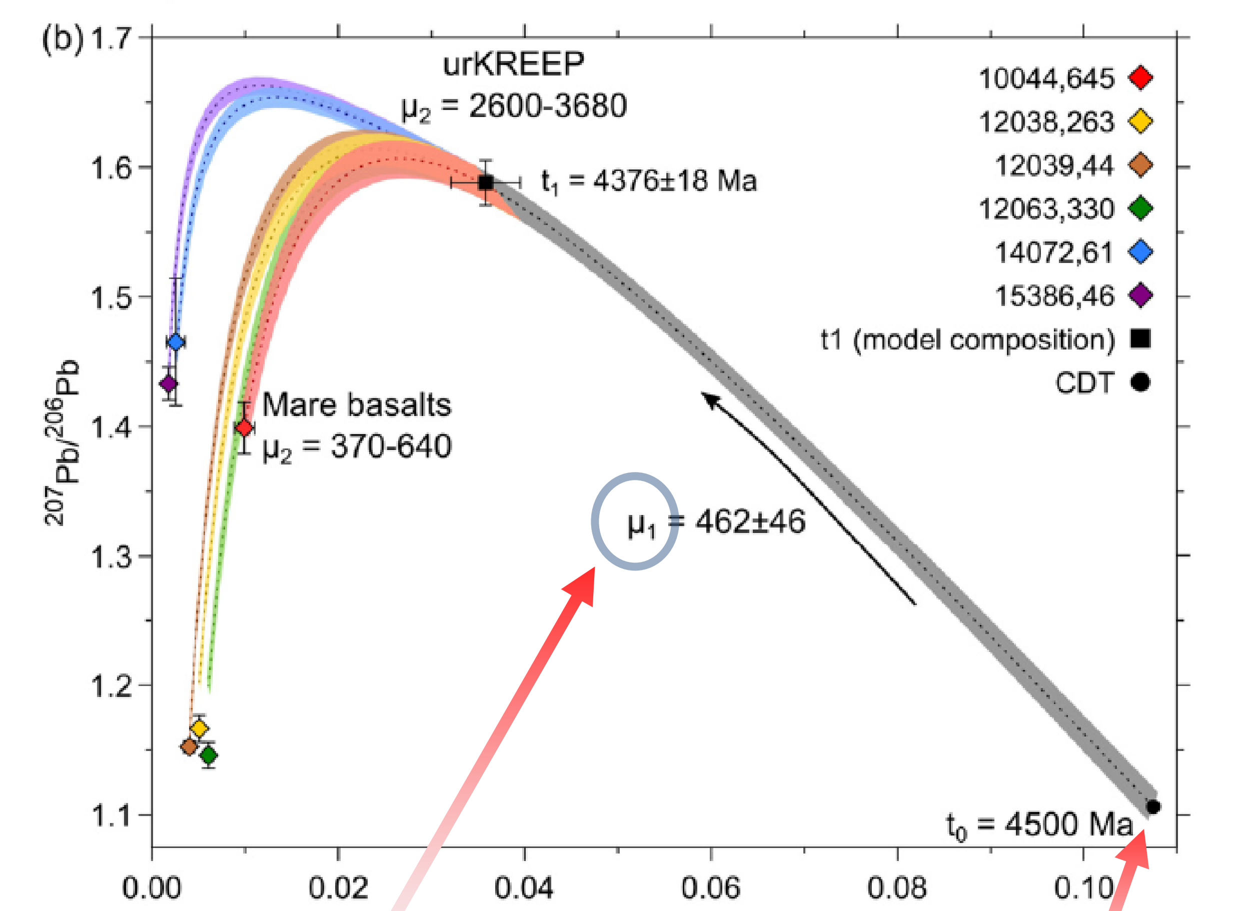
**Two main magmatic phases:**

**4000-3600 Ma and 3400-3100 Ma**

# initial Pb isotope ratios of lunar basalts

**Early model**

- Assumption 1: Moon formed at 4500Ma
- Assumption 2: All sources are formed at the same time



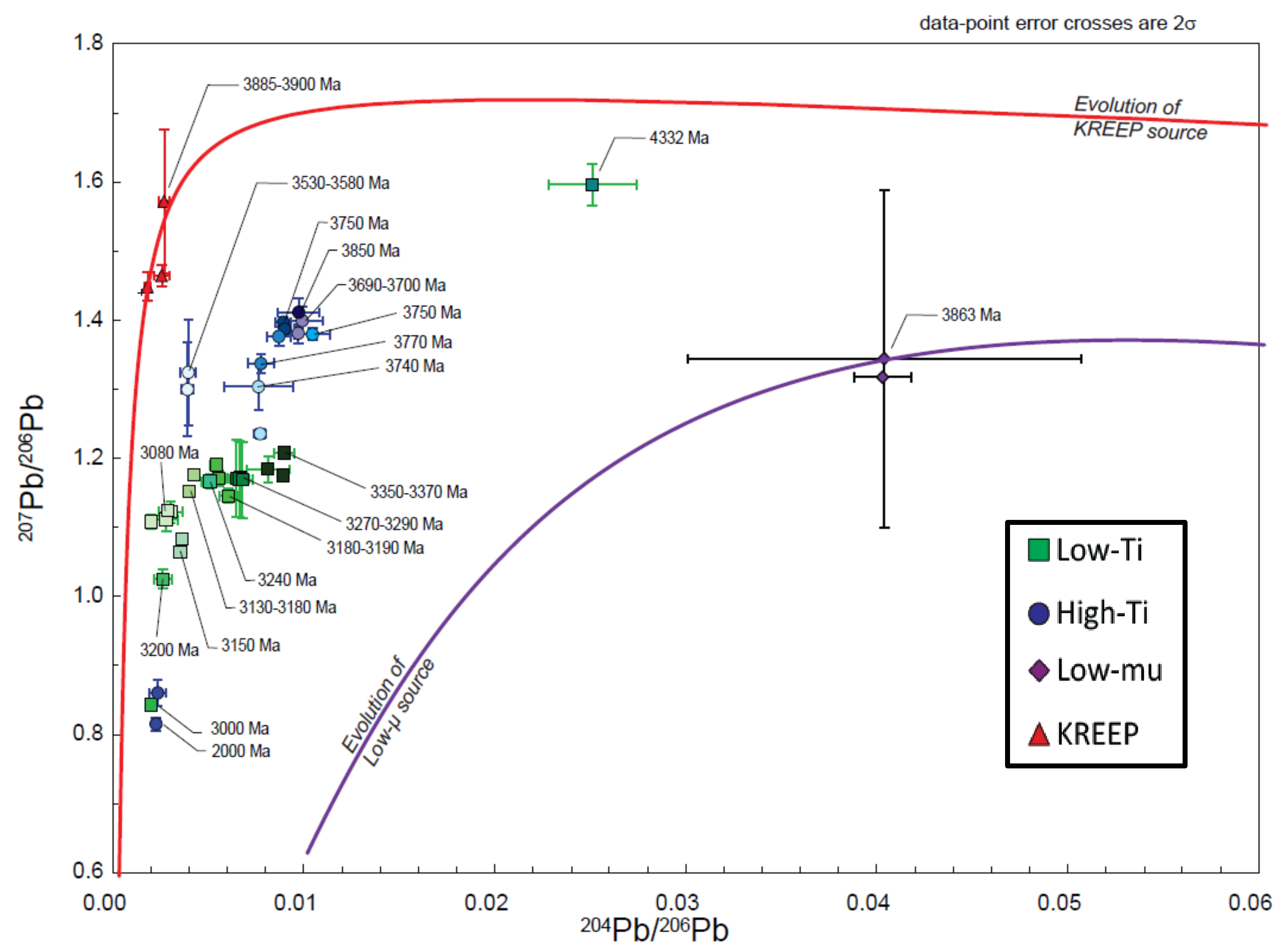

From Snape et al., 2016

$$(^{206}Pb/^{204}Pb)_t = {}^{238}U/^{204}Pb\ (e^{\lambda 238U * t}-1)+(^{206}Pb/^{204}Pb)_0$$

# initial Pb isotope ratios of lunar basalts: Looking for a new model

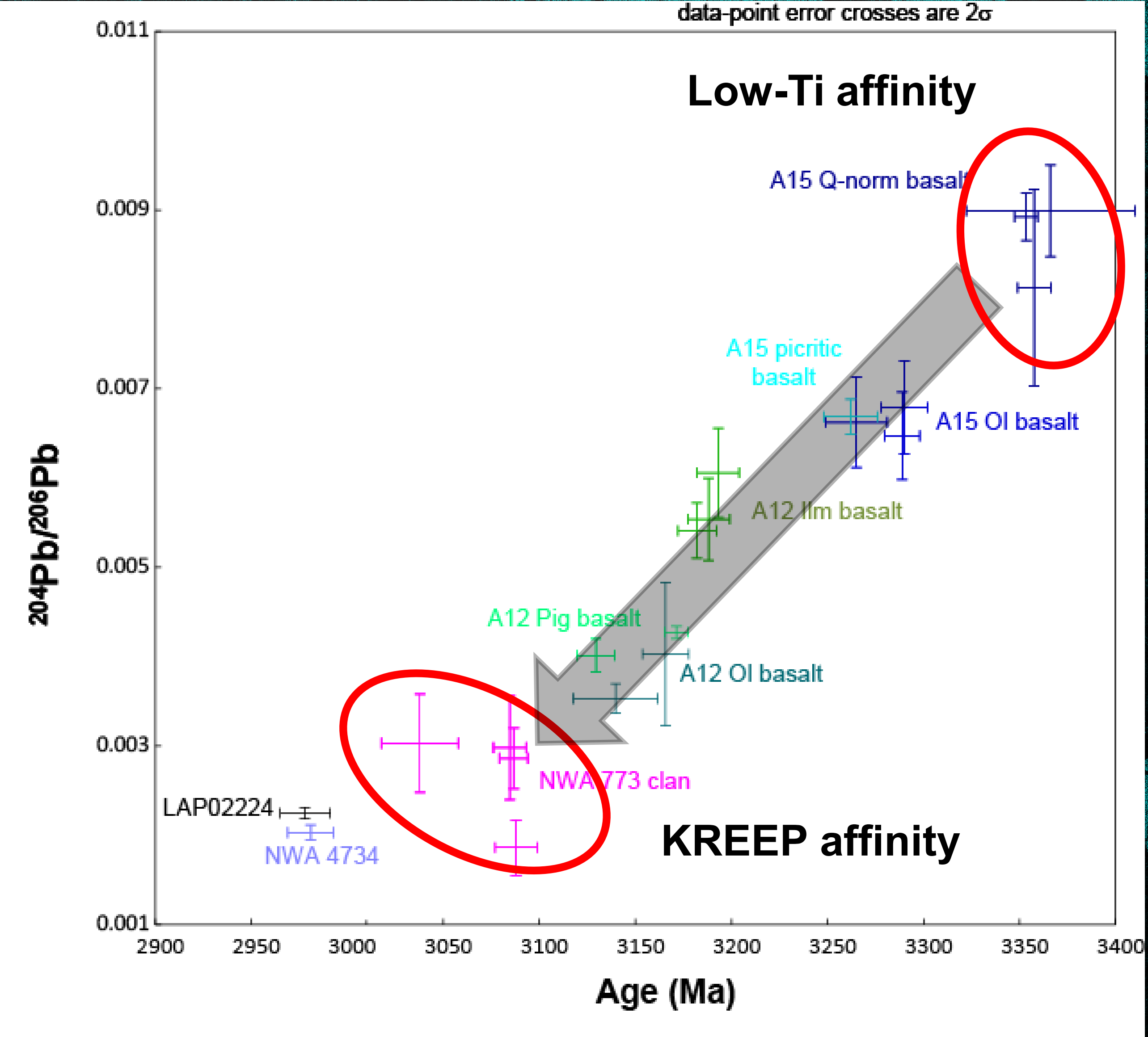
μ values of mantle sources calculated using Monte Carlo simulations

Gone the assumptions…



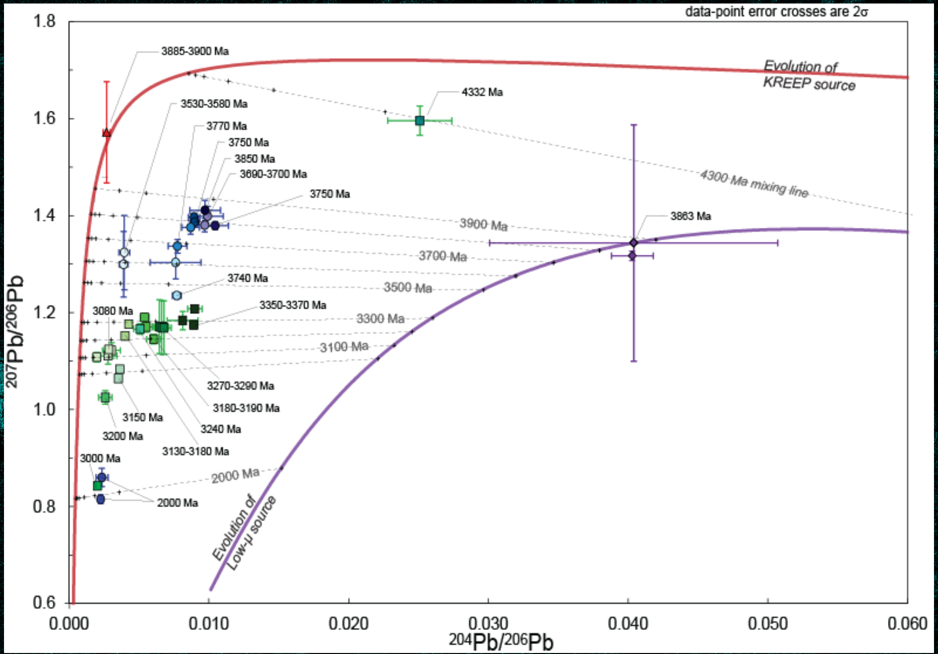
# initial Pb isotope ratios of lunar basalts

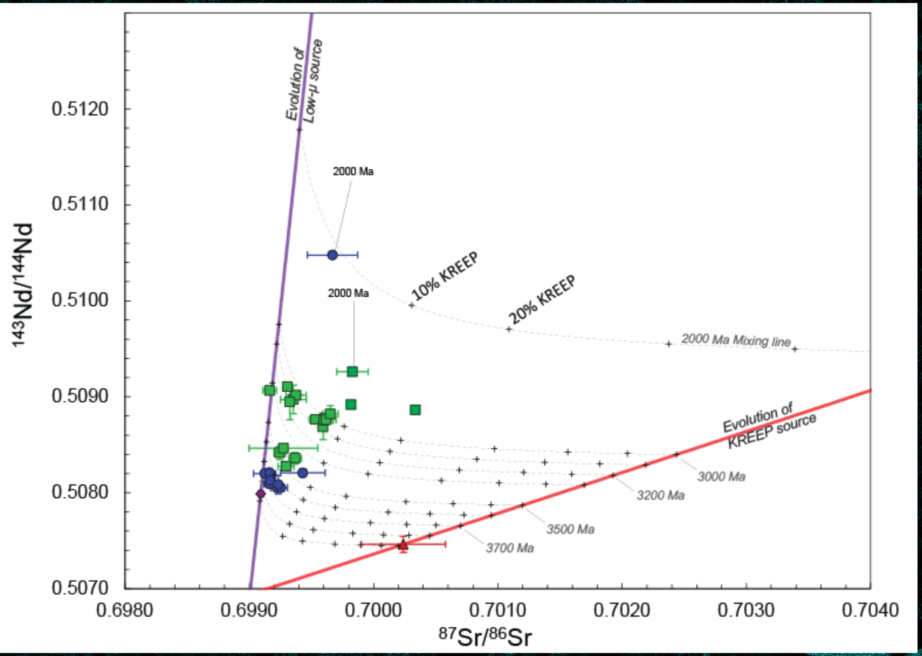
Progressive contribution of a KREEP-like component in the source of the low-Ti basalts from 3400 Ma until 3100 Ma




Merle et al., Meteoritics and Planetary Sciences, 2020.

# Plausible new model:
# Binary mixing




Low- Ti basalts are derived from source mixing involving two components:

- 10-20% KREEP
- 90-80% low-μ component

**What is the driving process?**

Thermo-mechanical erosion of KREEP layer (sandwiched between the crust and the other mantle layers)

➡ **Convection….**

# Concluding remarks (for now…)

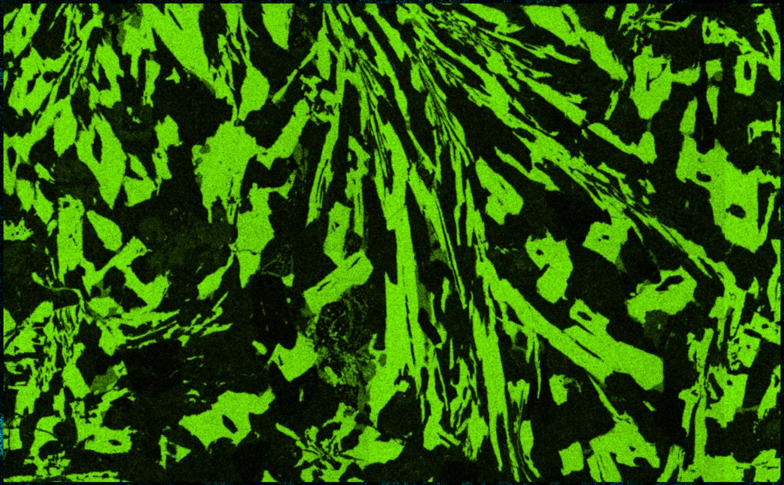
- **We still don't know when the Moon formed and when LMO crystallisation terminated**
  - *Do we have the relevant data?*
  - *Need more data…*

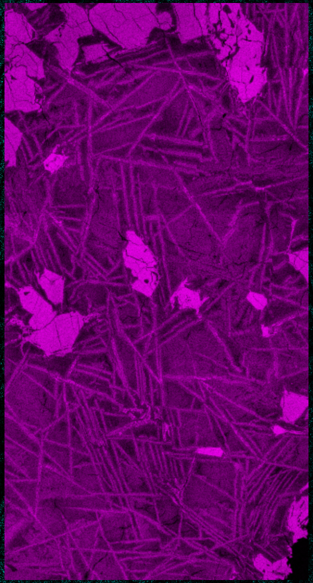
- **Better chronology of the volcanic activity**
  - *2 phases (4000-3600 Ma and 3400-3100 Ma)?*
    - *At least, we can make sense of radiogenic isotope ratios*

- **Satisfactory model: Binary mixing (KREEP+Low µ components)**
  - explain the chemical characteristics of the low-Ti basalts
    - Partly satisfactory for High-Ti basalts

⬇

**Driving process = convection**



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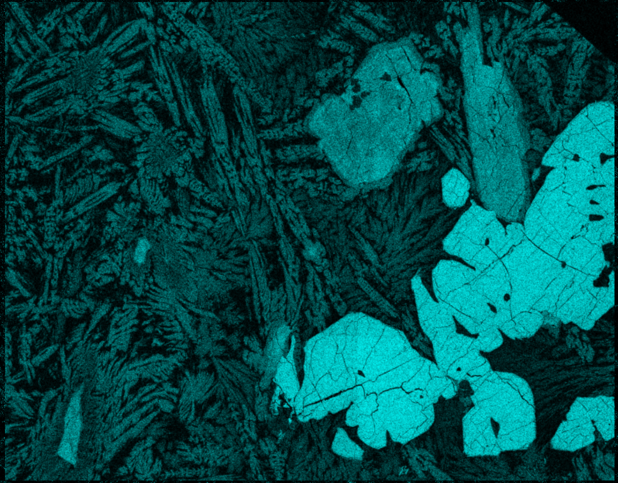

# Thank you