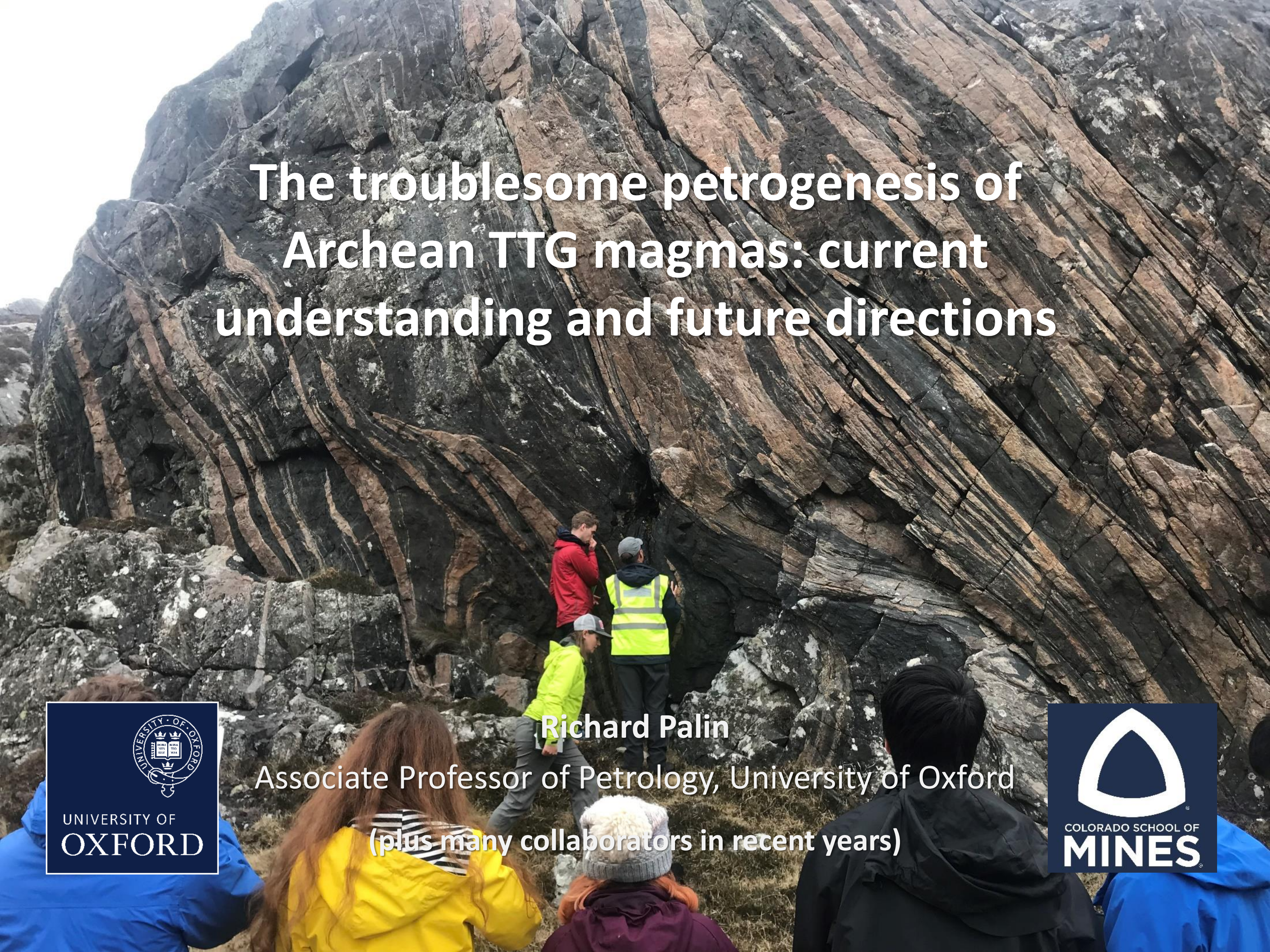


The troublesome petrogenesis of Archean TTG magmas: current understanding and future directions

Richard Palin

Associate Professor of Petrology, University of Oxford

(plus many collaborators in recent years)

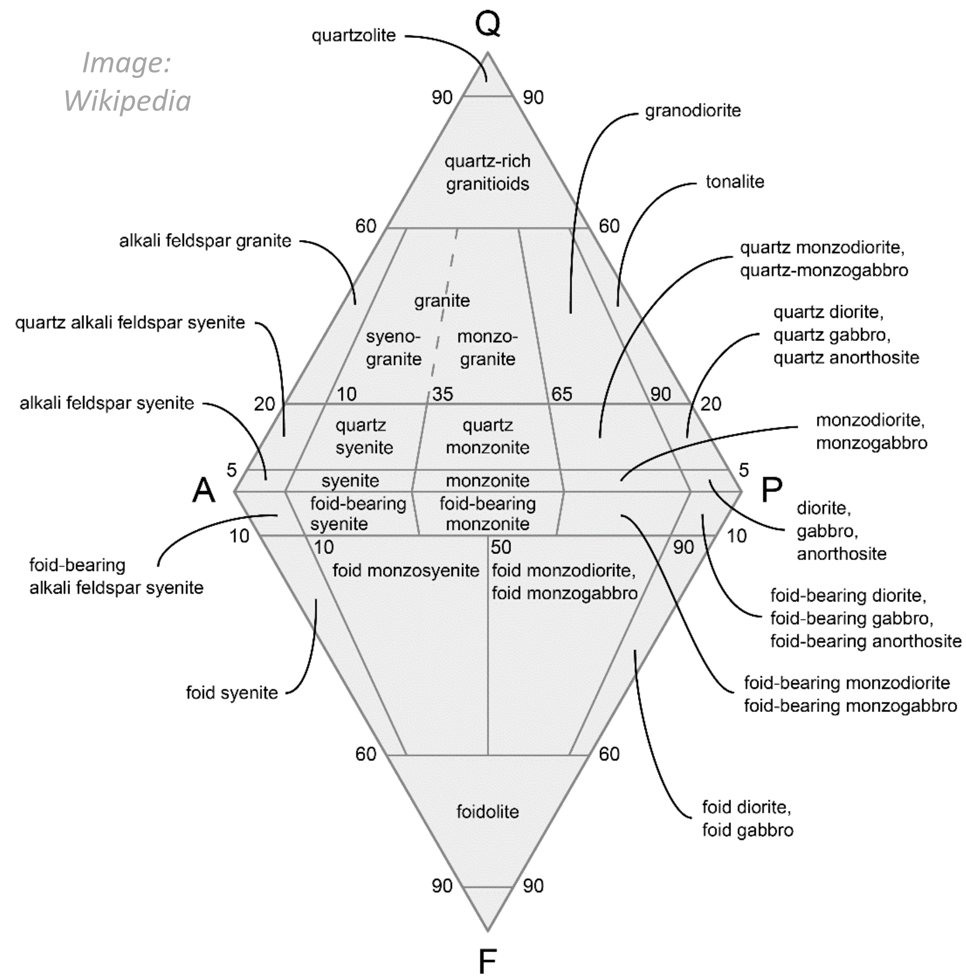
UNIVERSITY OF OXFORD

COLORADO SCHOOL OF MINES

Plutonic igneous rock classification

- What are **TTGs**?
  - Let's make sure we are all on the same page, right from the start
- **Mineralogical** definition
  - Variable **geochemical** features, especially for TEs

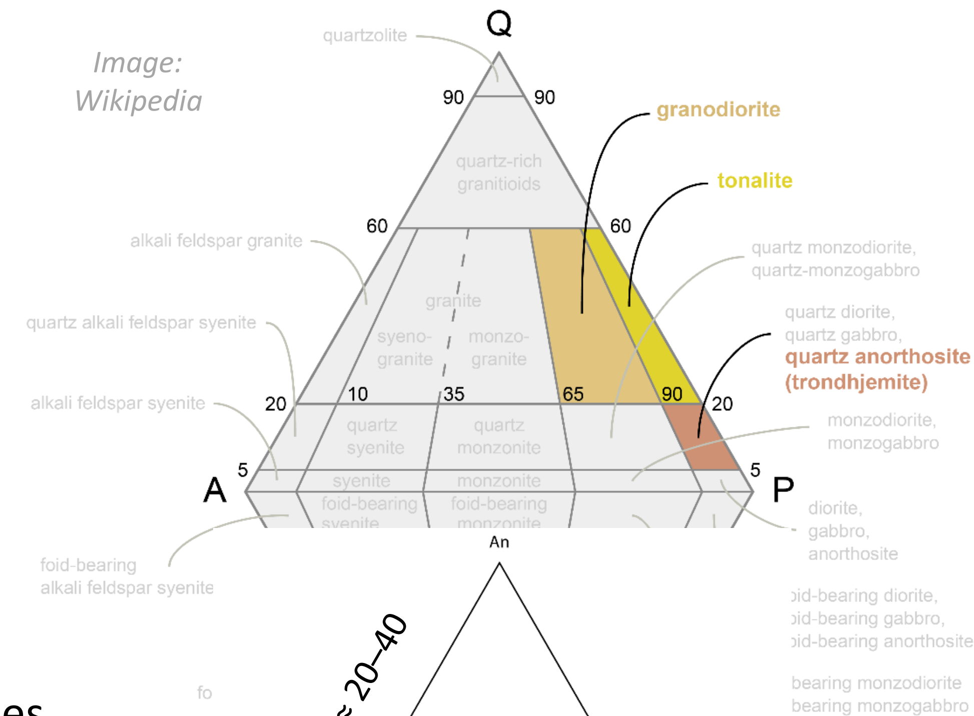
Image: Wikipedia



Plutonic igneous rock classification

- What are **TTGs**?
  - Let's make sure we are all on the same page, right from the start
- **Mineralogical** definition
  - Variable **geochemical** features, especially for TEs
- Many classification schemes exist, which are often used directly to make **geodynamic** interpretations
- When discussing Archean processes or terranes, be careful to note what you're referring to…
  - Don't confuse (or equate) **TTGs** with **TTG (grey) gneisses**

Image: Wikipedia



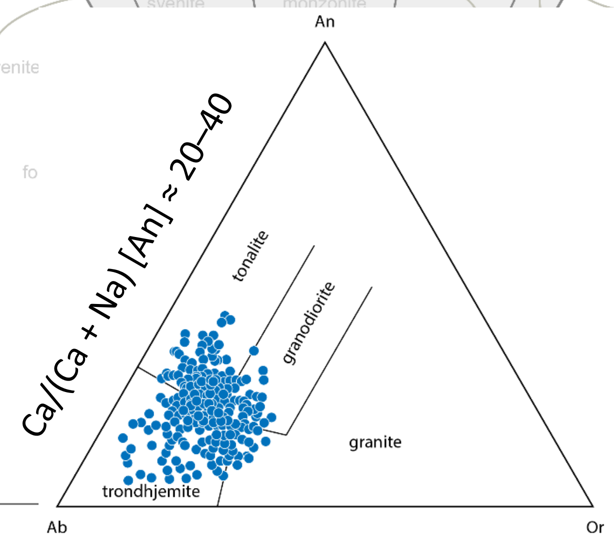


Image: Palin et al. (2016) Data: Moyen (2011)

Resources

- Literature on Archean TTGs and their **processes of formation** is forever growing
- Typically, a few published in *Science/Nature* (and daughter journals) each year
  - Key papers date back to the early 1970s – for newcomers, this can be daunting
    - **Review papers** are often the best places to start

Lithos 148 (2012) 312–336

Contents lists available at SciVerse ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Invited Review Article

Forty years of TTG research

Jean-François Moyen [a,c,d,*], Hervé Martin [b,c,d]

[a] Université Jean-Monnet, Université de Lyon, 23 rue du Docteur Michelon, 42023 Saint-
[b] Clermont Université, Université Blaise Pascal, Laboratoire Magmas et Volcans, 5 rue Ke
[c] CNRS, UMR 6524, LMV, F-63038 Clermont-Ferrand, France
[d] IRD, R 163, LMV, F-63038 Clermont-Ferrand, France

This paper is a masterclass in scientific reasoning

Archean granitoids: classification, petrology, geochemistry and origin

Check for updates

JEAN-FRANÇOIS MOYEN

Laboratoire Magmas et Volcans, UJM-UCA-CNRS-IRD, Université de Lyon, 23 rue Dr Paul Michelon, 42023 Saint Etienne, France

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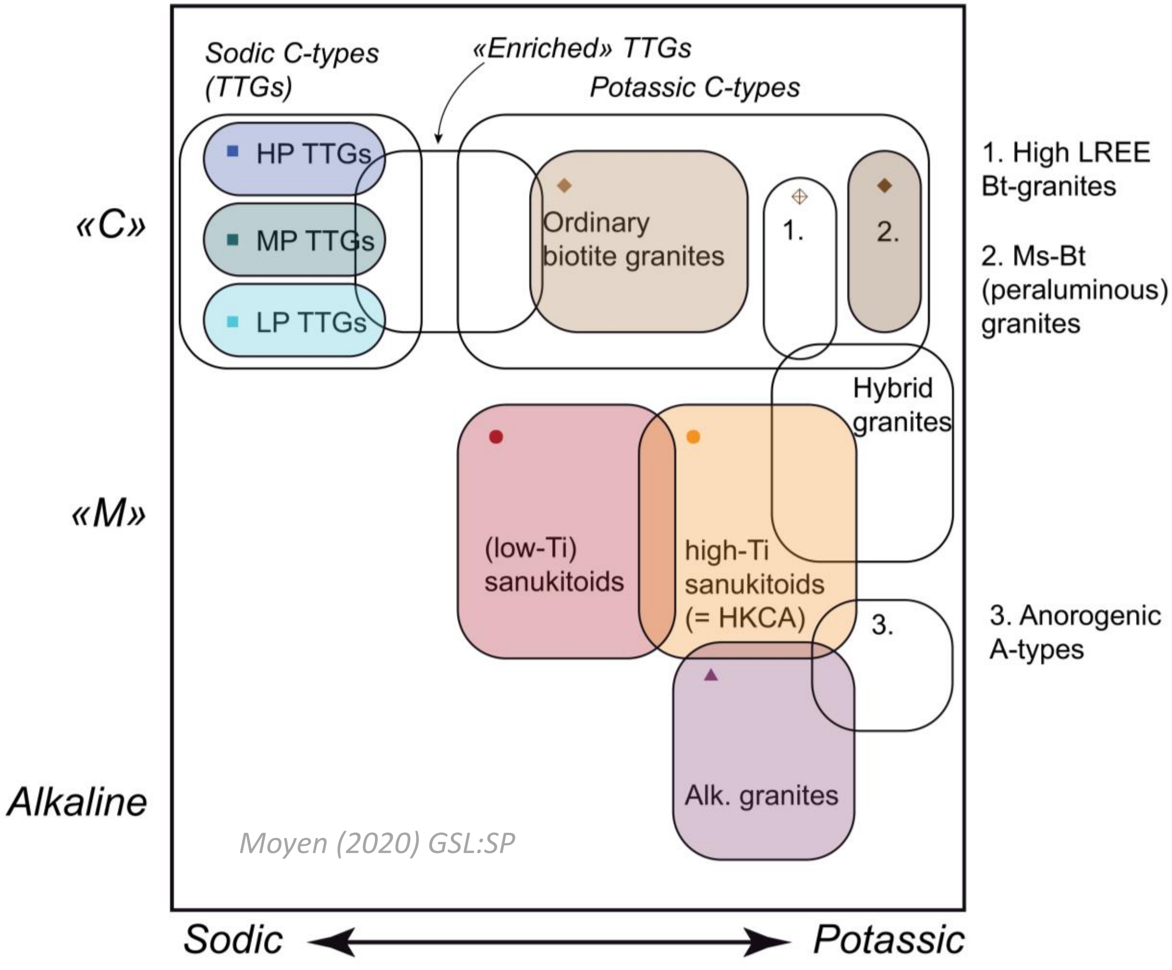
jean-francois.moyen@univ-st-etienne.fr

Geol. Soc. London: Special Publ. (2020)

Archean granitoids

- Wide variety of granitoid rocks in Archean cratons
- Two key variables
  - Magma **source**
    - Crust (C) vs mantle (M)
  - **Composition**
    - Sodic vs potassic
- **TTGs** are sodic granitoids that are generated by melting of crustal rocks
  - But not always *in* the crust



Archean TTG magmas

- In 2002, Martin and Moyen started to compile **petrological information** about TTGs from all Archean cratons worldwide, producing a valuable database
  - This has been expanded several times over the past 20 years (>3000 entries)
    - Beware the effects of **sampling bias** and **misclassification**!

Table 1
Distribution of the geochemical types identified in the database. The percentages are “cumulative”, i.e. 65–70% of the samples are classified as granitoids, out of which 10–15% are potassic, etc. The column to the right indicates the global proportion in the complete database. Due to sampling bias, this is unlikely to be an adequate image of the Archaean crust as a whole.

						% Total
Non granitoids (leucosomes/restites, metasediments, amphibolites…)	30–35 %					30 %
Granitoids	65–70%	Potassic	10–15 %			10 %
		Misc.	15 %			10 %
		Sodic TTG	70–75 %	High pressure	20 %	10 %
				Medium pressure	60 %	30 %
				Low pressure	20 %	10 %

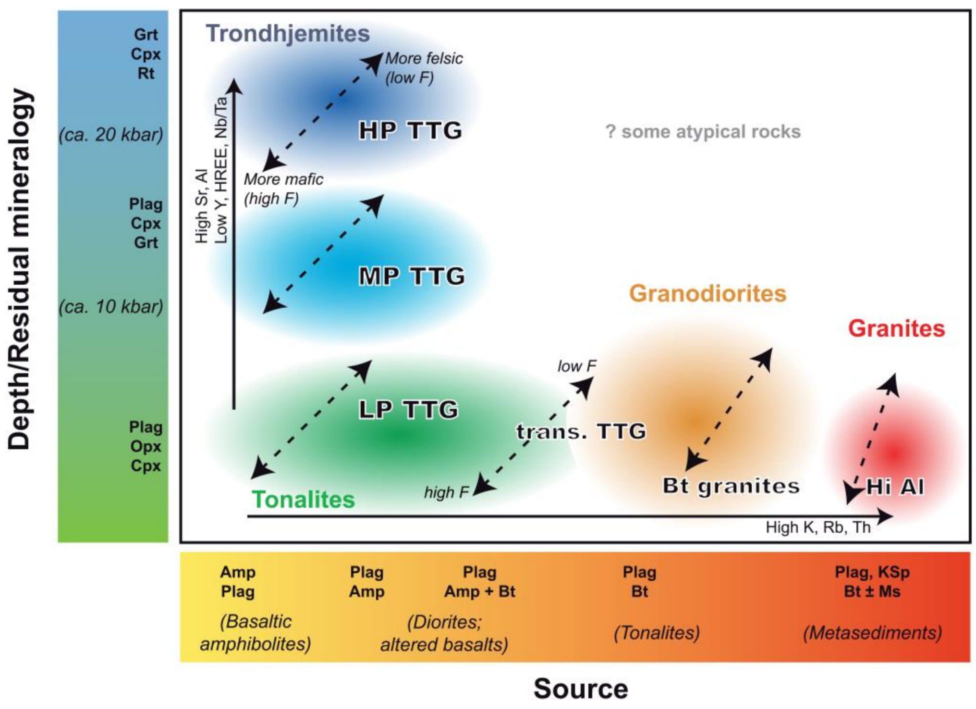
Table: Moyen (2011)

- No formal geochemical definition exists, but most agree that Archean TTGs are:
  - **Silica-rich** (SiO_2 > 64 wt.%), **sodic** (Na_2O ≈ 3–7 wt.%), and **low K_2O/Na_2O** (<0.5)
  - Relatively **leucocratic**; $Fe_2O_3^t$ + MgO + MnO + TiO_2 ≈ 5 wt. %
    - Average **Mg#** [molecular Mg/(Mg + Fe^{2+}) × 100] ≈ 43

Classification systems

- Several classification systems for TTGs/grey gneisses exist in the literature
  - The system based on **pressure of formation** is most popular
    - "Low" (L), "medium" (M), and "high" (H) pressure
  - Readily lends itself to **geodynamic interpretation**
- How was this classification scheme developed?

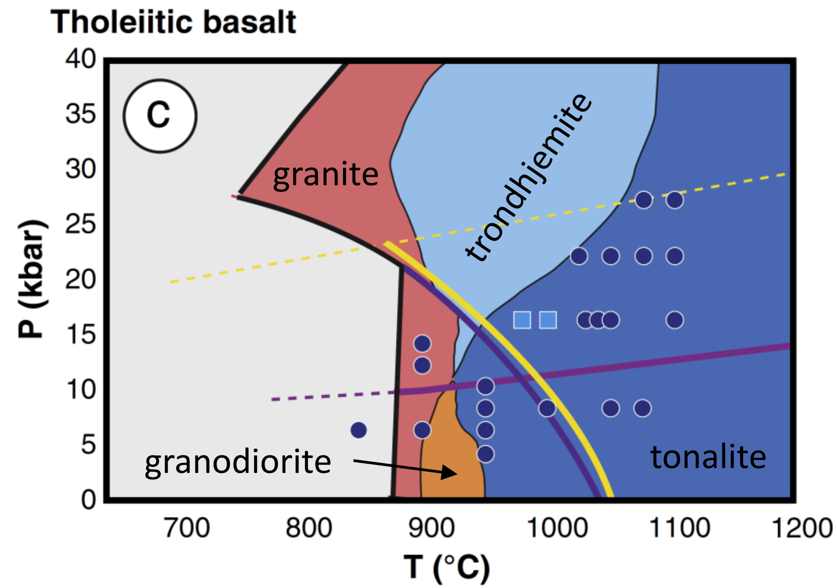
Moyen (2020) GSL:SP

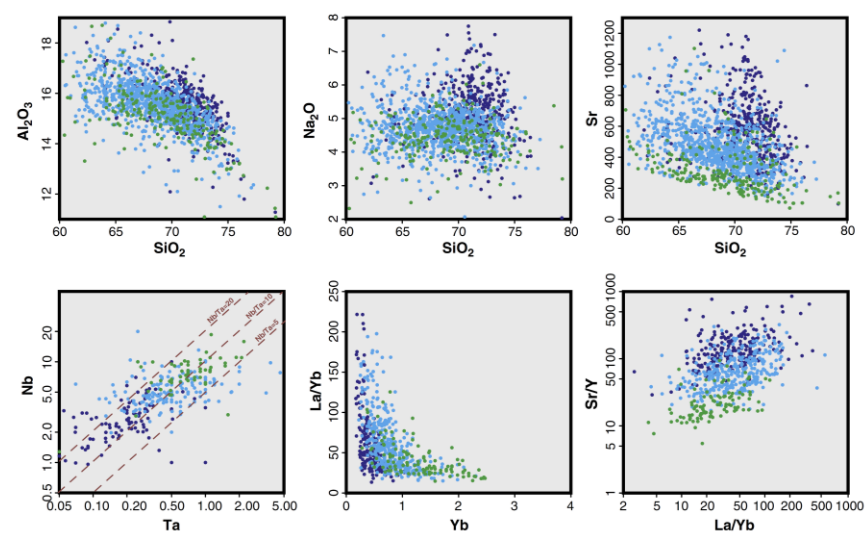


- **Early experimental studies** (i.e. piston cylinder experiments) performed on **basalt (*sensu lato*)** at various *P–T* conditions, fluid contents, starting materials etc.
  - Constrained the protoliths and broad *P–T* range needed to form each TTG type

Geochemistry

- In general, TTG mineralogy and major element composition requires partial melting of **hydrated metabasalt**
  - E.g. Rapp et al. (1991), Wolf and Wyllie (1994), Foley et al. (2002)
  - Degree of melting (F) has a key control, alongside *P* and *T*
- Trace element geochemistry implies variable amounts of **garnet** (HREE, Y), **rutile** (Nb, Ta), and **plagioclase** (Sr, Eu) left behind in the residuum following melt extraction
  - Thus, conventionally, one may assume that LP ≈ amphibolite, MP ≈ garnet amphibolite or granulite, and HP ≈ eclogite



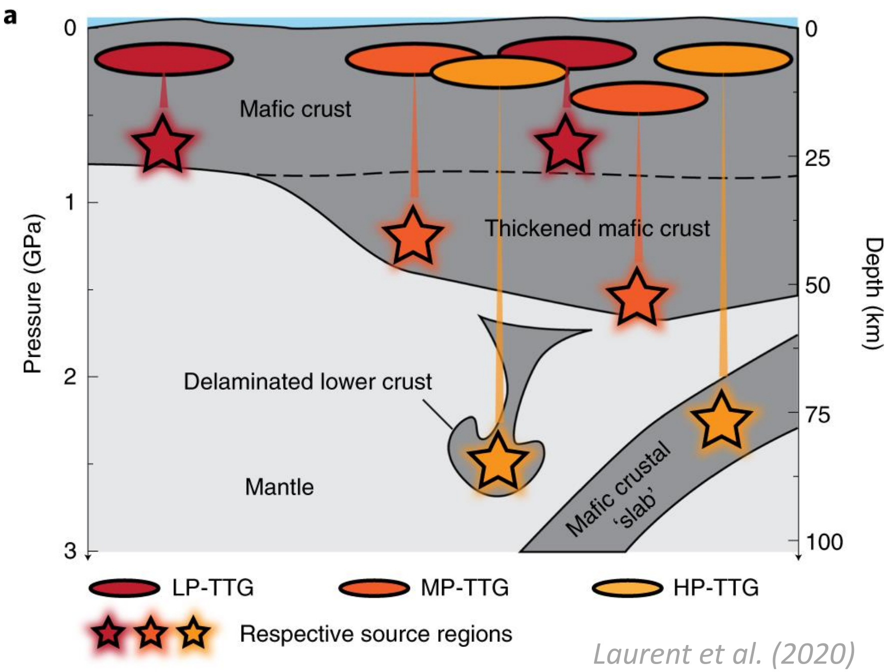


HP MP LP

Moyen and Martin (2012) Lithos

Geodynamic implications

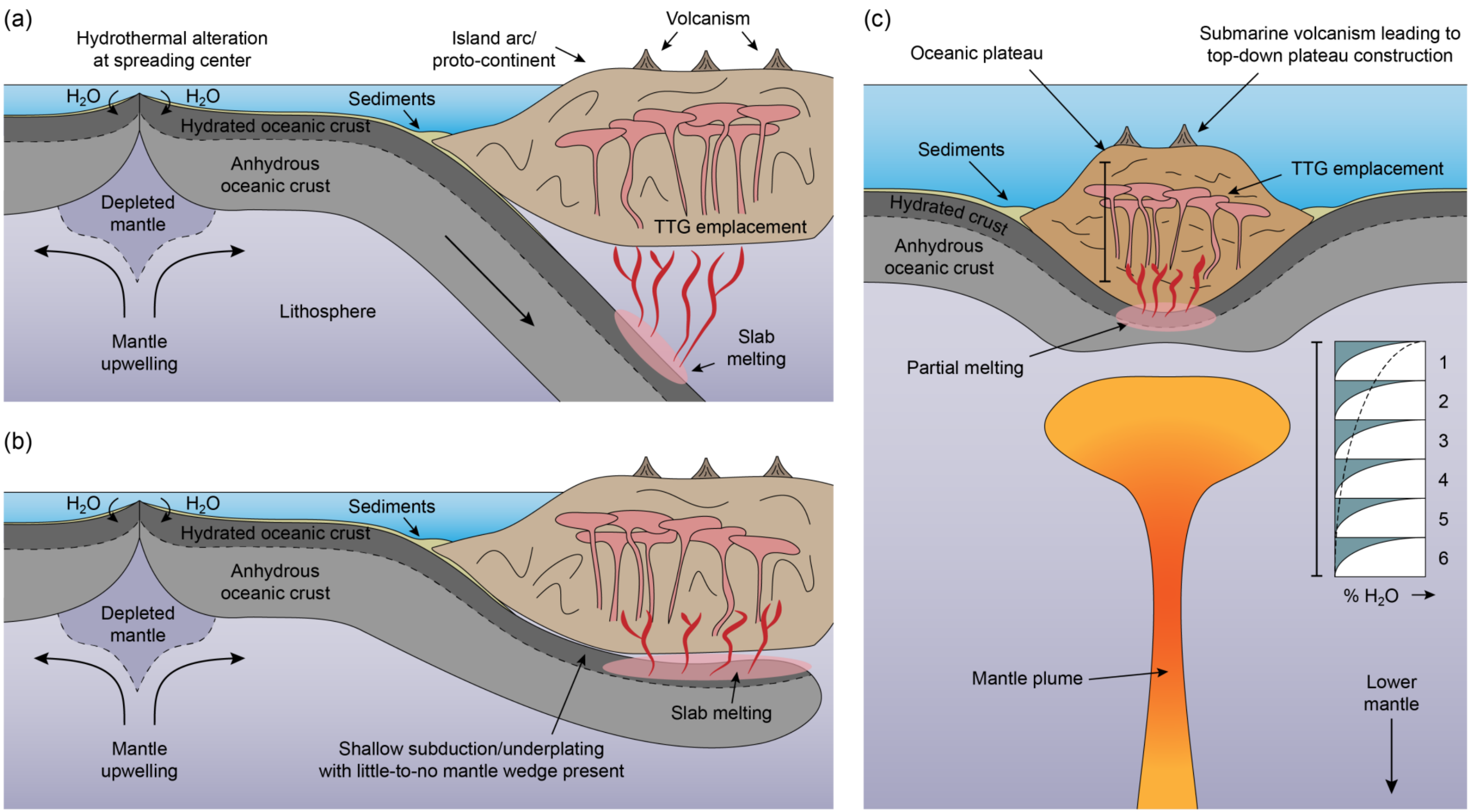
- Imagine that your trace element data *imply* TTG melt derivation from an **eclogite precursor** (i.e. at HP conditions) – how do you interpret this?
  - **Steep subduction?** Implications for OC architecture (i.e. cold, dense, rigid slab)
  - **Delamination/dripping of lower crust into the mantle?** High mantle T_P?
  - **Extremely thick crust?** Himalayan-type orogenesis in the Archean?
  - Most Archean TTG-related studies ultimately discuss **plate tectonics** and **crust formation** on Earth or Earth-like planets
- 'Conventional' tectonic models fit melting of basalts at various depths, assuming that the bulk geochemistry of TTGs **faithfully reflects those of the parent liquids**
  - What if this is not true?



Laurent et al. (2020) Nature Geoscience

Geodynamic implications

- Without entering debate, here are some mechanisms that have been proposed…

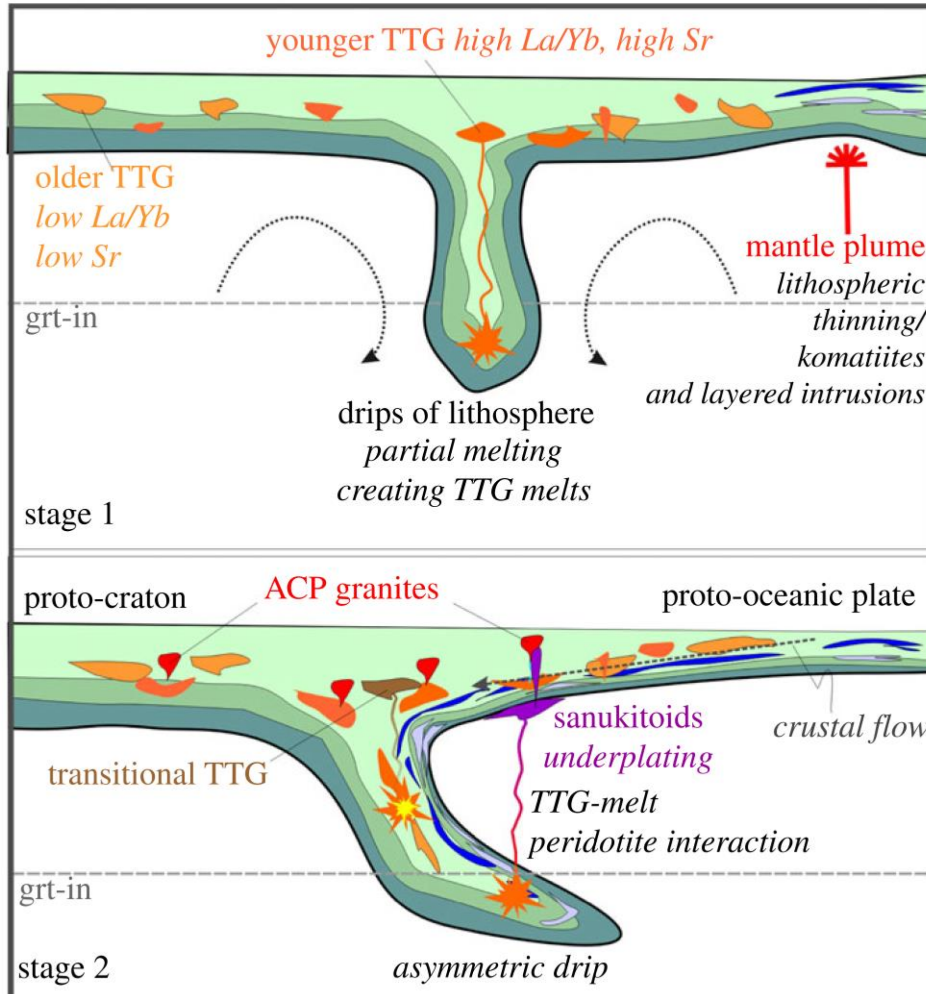


Palin et al. (2016) Precambrian Research

Geodynamic implications

Nebel et al. (2018)
Phil. Trans. R. Soc. A

- **Sagduction** and **drips** into the mantle have been popularized by some workers in recent years
  - Mostly based on numerical modelling results
- Did they occur? Did they not?
  - If they did, were they related to TTG formation?
- Many open questions



ELSEVIER
Precambrian Research
Volume 379, 1 September 2022, 106708

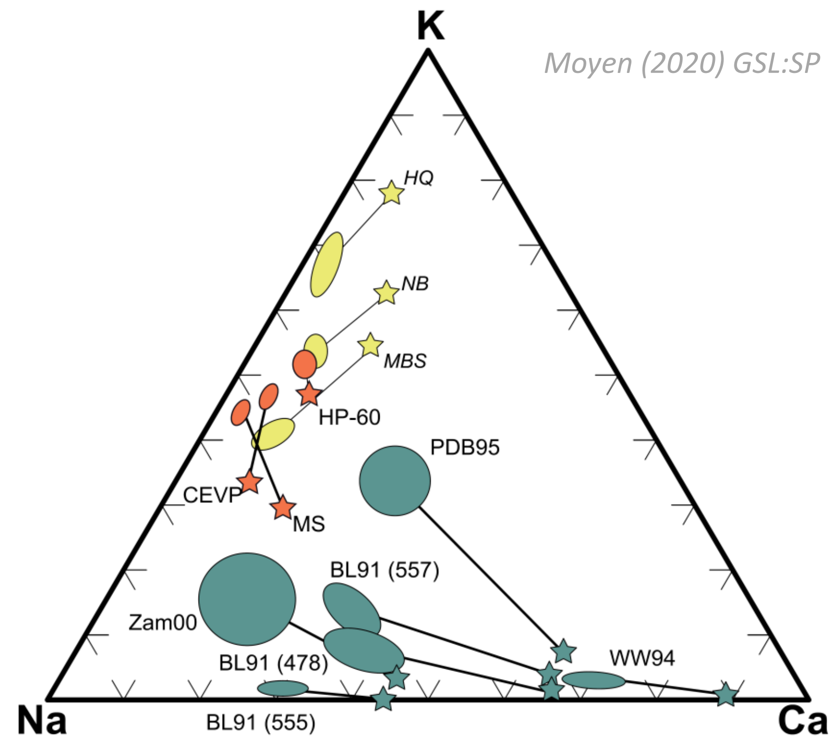
Testing the importance of sagduction: insights from the Lewisian Gneiss Complex of northwest Scotland

Sophie R. Miocevich [a], Alex Copley [a], Owen M. Weller [b]

Key issues remaining

- Some key issues have been discussed and approached in great detail
  - Diverse protolith compositions (MORB, EAT, DAT, OIB etc.)
  - Effect of ***P–T*** conditions of melting, plus $\boldsymbol{M(H_2O)}$ content
  - These are *metamorphic* issues
- How, then, can some Archean terranes can have **two** (or **all three**!) "types" of TTG present, often with **similar ages** (cf. Halla *et al*., 2009)?
  - Start (re)examining *igneous* processes in more detail

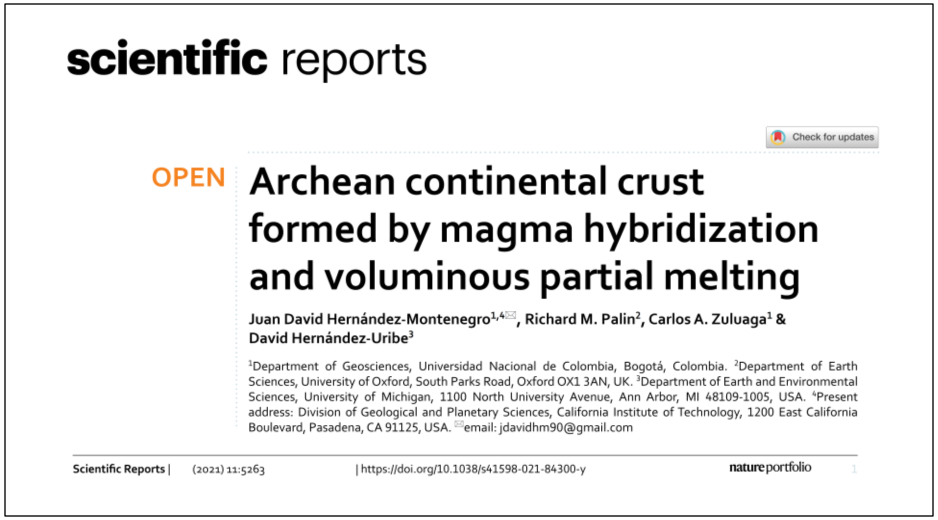
Moyen (2020) GSL:SP



- Does it **help** or **hinder** to have classification systems with boxes rather than considering diversity in compositional characteristics as true spectra?
  - Note that Moyen (2020) himself argues to move away from the box system

Magma hybridization

- Studies of modern-day magmatic systems have revealed the complexity of **melt generation** and **transport** through the crust
  - Isolated, melt-rich magma chamber ✗
  - Vertically extensive crystal mush zone ✓
- Would you expect melt fractions generated at depth *not* to mix during ascent?


scientific reports

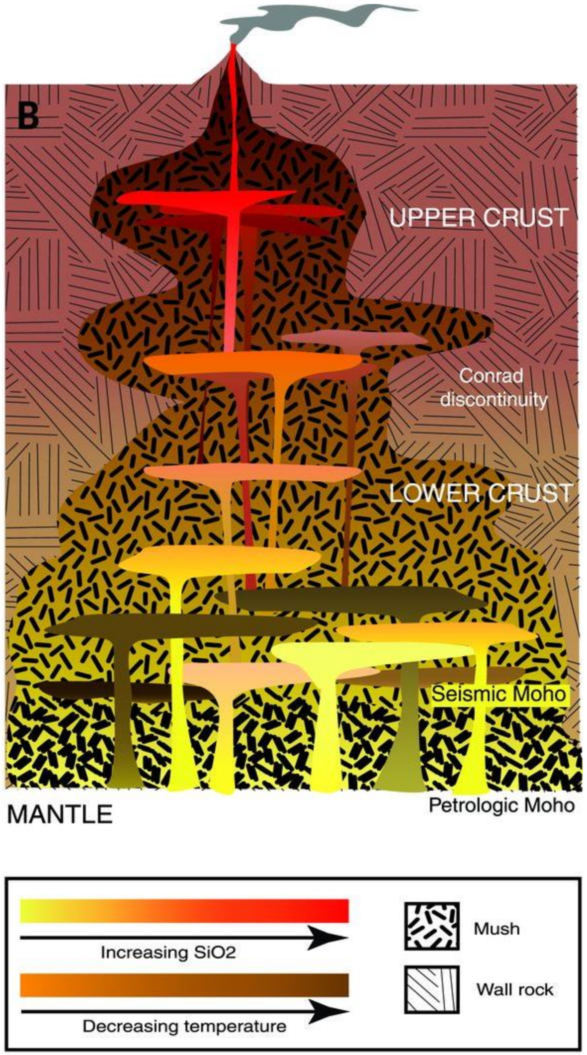
Check for updates

OPEN **Archean continental crust formed by magma hybridization and voluminous partial melting**

Juan David Hernández-Montenegro[1,4], Richard M. Palin[2], Carlos A. Zuluaga[1] & David Hernández-Uribe[3]

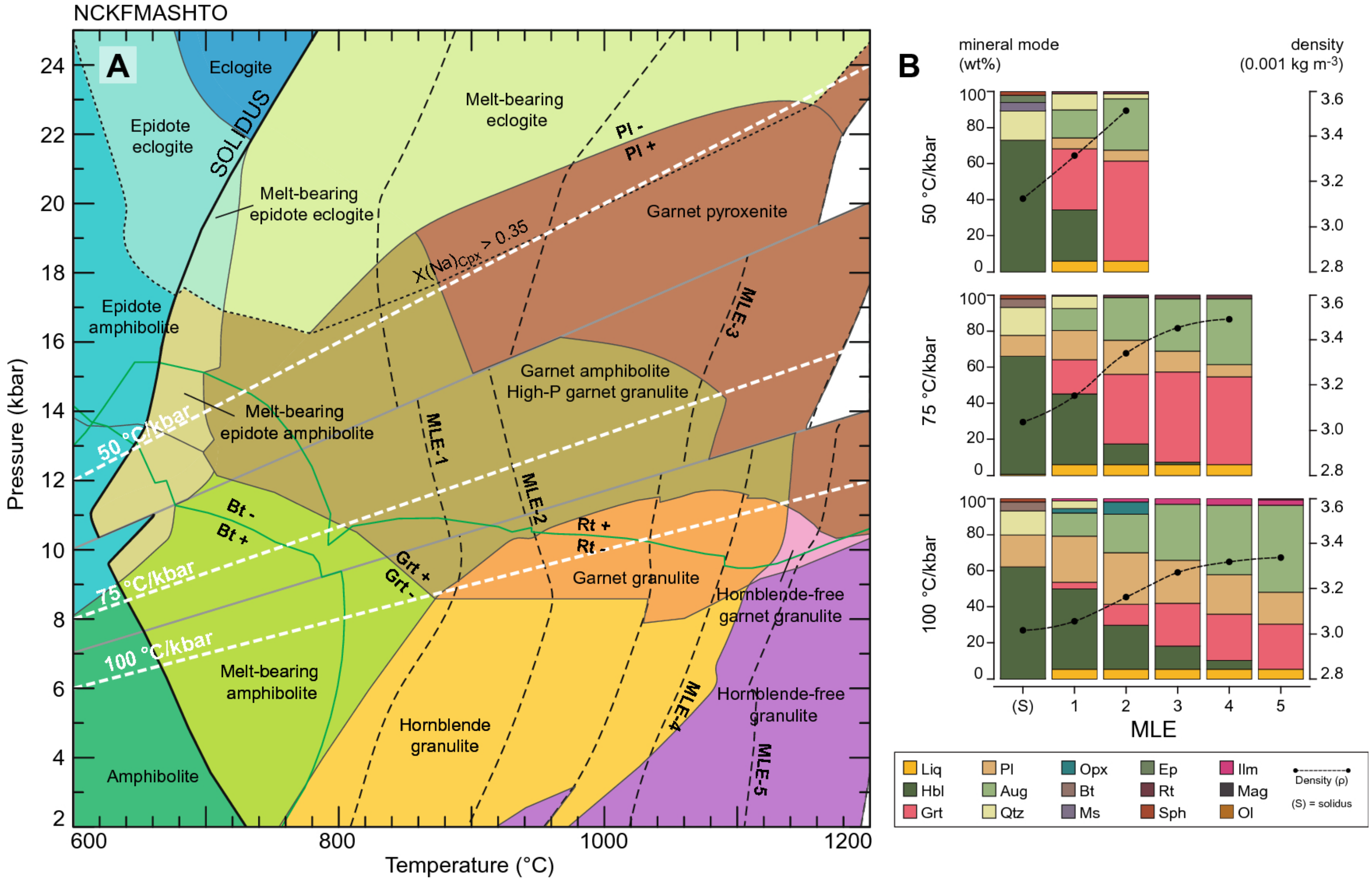
[1]Department of Geosciences, Universidad Nacional de Colombia, Bogotá, Colombia. [2]Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, UK. [3]Department of Earth and Environmental Sciences, University of Michigan, 1100 North University Avenue, Ann Arbor, MI 48109-1005, USA. [4]Present address: Division of Geological and Planetary Sciences, California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA. email: jdavidhm90@gmail.com

Scientific Reports | (2021) 11:5263 | https://doi.org/10.1038/s41598-021-84300-y nature portfolio



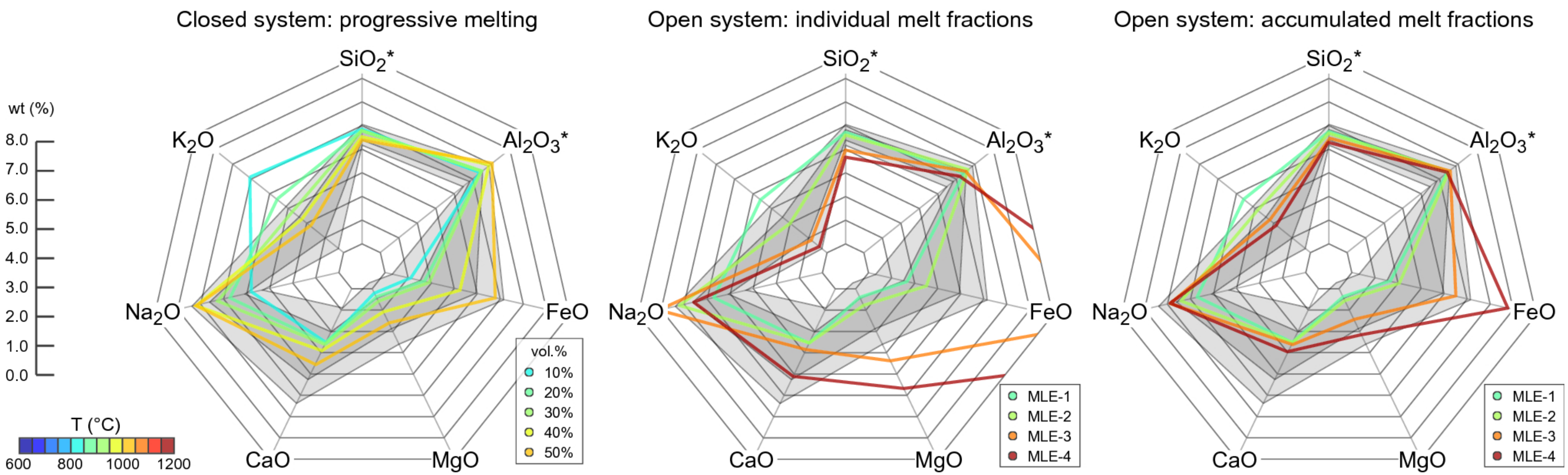
Cashman et al. (2017) Science

Our approach



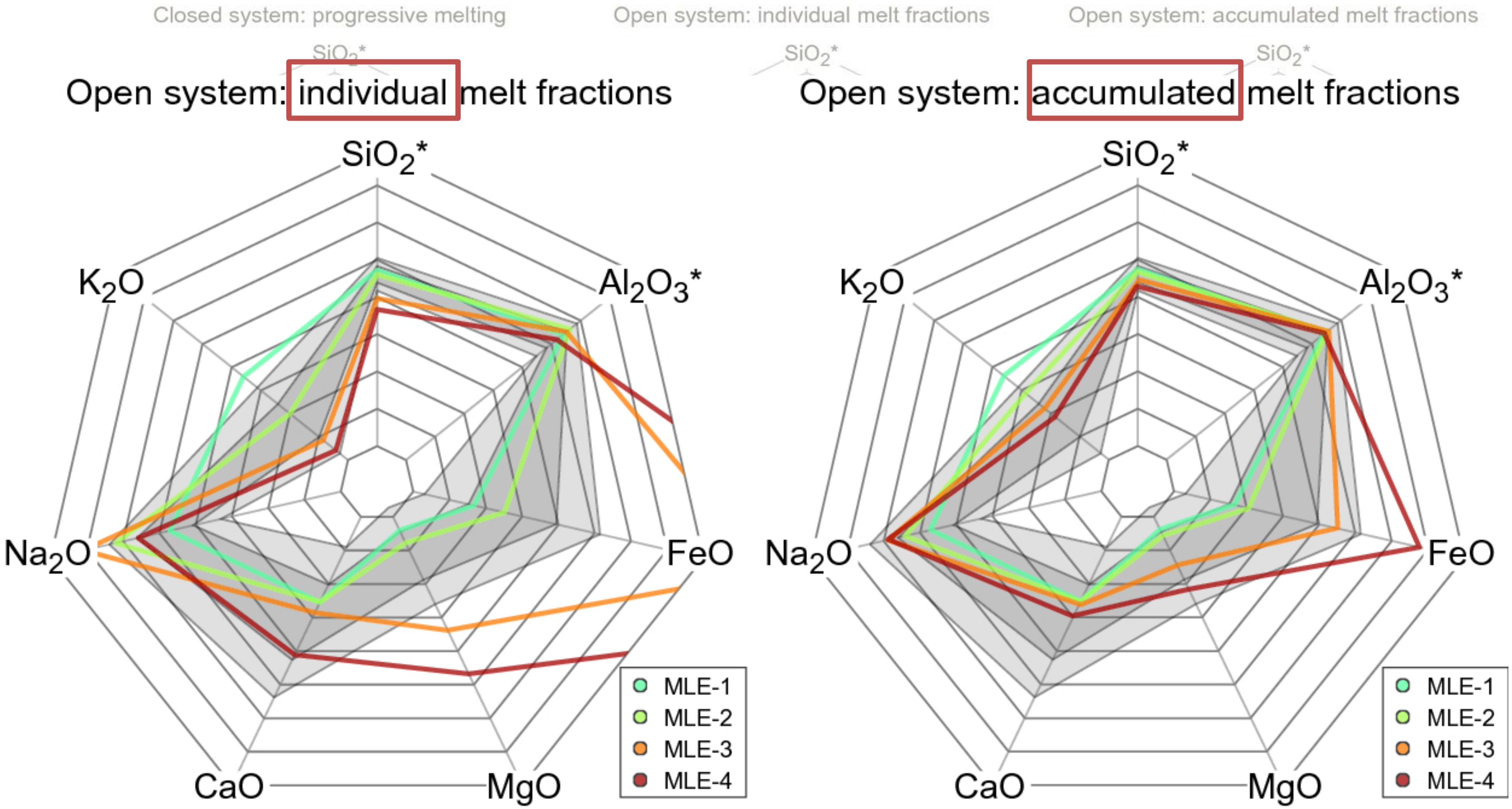
Hernandez-Montenegro et al. (2019) Scientific Reports

Major elements



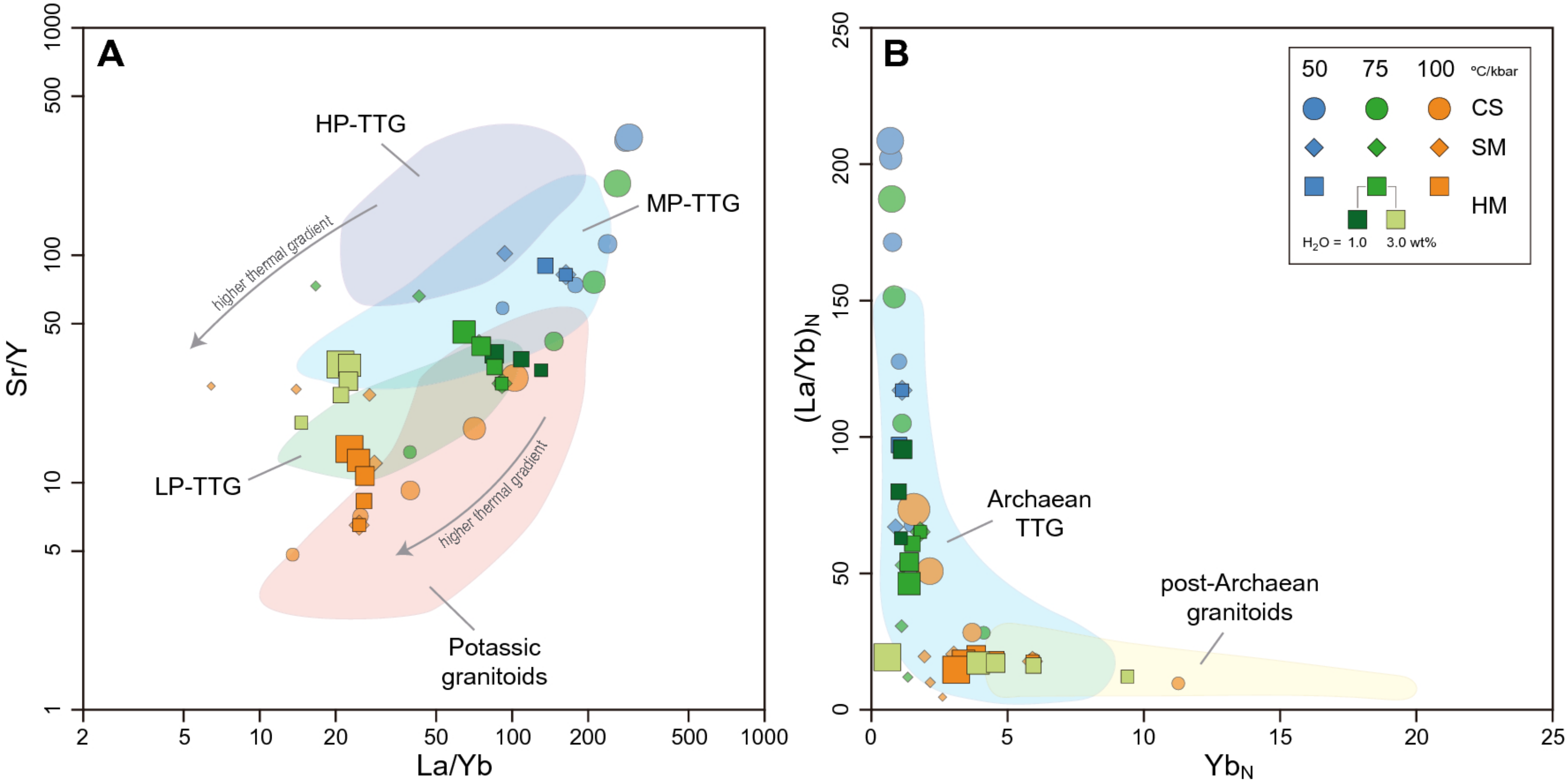
- Example **major-element** compositions for melt fractions for a 75 °C/kbar geotherm
- Baseline compositions of melt generated at closed system (CS) conditions
  - Not realistic to hold large volumes of melt *in situ*
- Similar calculations for open system (OS) conditions
  - Generally good, but some issues – FeO spirals out of control after several MLEs
    - Problems with the **model setup** or ***a–X* relations**?

Major elements



- Problems with the **model setup** or ***a–X* relations**?

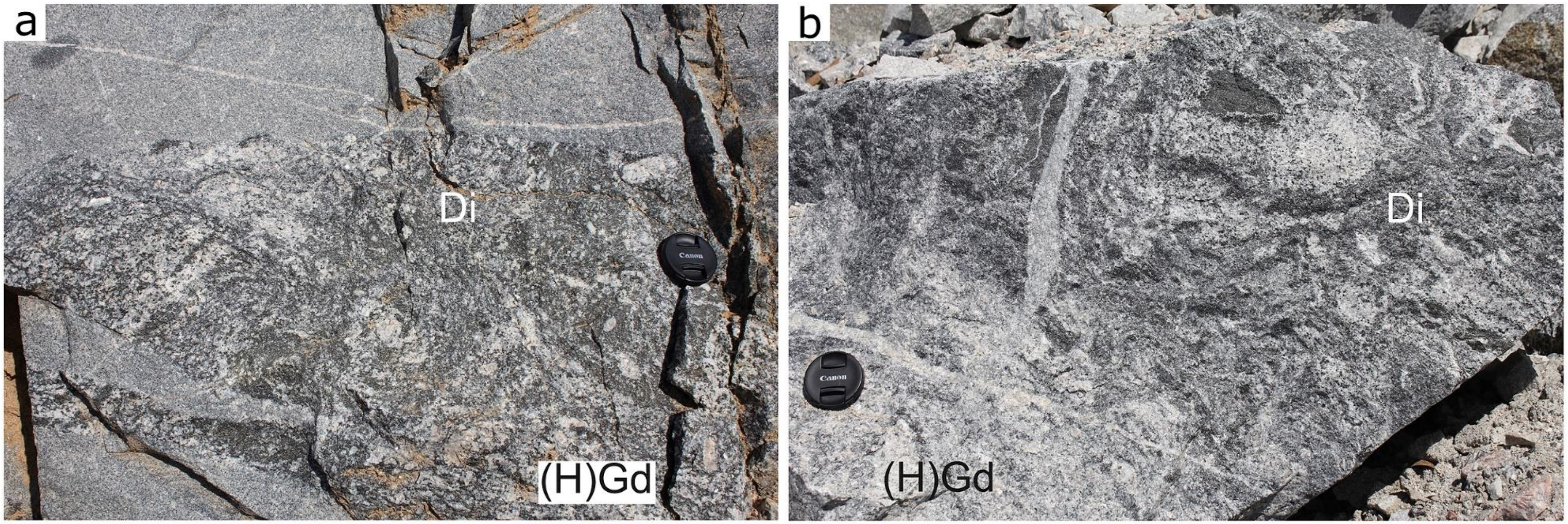
Trace elements



- Modeled **trace element ratios** compared against the Moyen *et al.* dataset
  - Hybridization <u>averages</u> signatures for **low-** and **high-temperature** fractions

Identifying magma mixing/hybridization in nature

- Interesting, but it's just a model, and **all models are wrong**, as we know



- **Field evidence (Loureiro et al., 2022; JSAES)**
  – Water-fluxed melting in the Pinheiro Machado Complex, Brazil
  – Diorite containing felsic blebs, separated by diffuse, gradational boundaries
    - Newly generated patches of **hybrid granodiorite [(H)Gd]**

Identifying magma mixing/hybridization in nature

- Several **geochemical**, **mineralogical**, **geochronological**, and **isotopic** methods can identify magma mingling in the crust
  - Many published studies have used them to great effect
  - The effects of hybridization can also be **forward modelled**
    - However, some effects are very subtle (cf. mass ratios)
- Can this process explain the rich diversity of Archean TTG magma compositions *without* invoking source rock/pressure differences?
  - **Probably not**, but it's something to consider nonetheless

RESEARCH ARTICLE | APRIL 01, 2012

Magma hybridization in the middle crust: Possible consequences for deep-crustal magma mixing

Calvin G. Barnes; Carol D. Frost; Øystein Nordgulen; Tore Prestvik

+ Author and Article Information

Geosphere (2012) 8 (2): 518–533. https://doi.org/10.1130/GES00730.1 Article history

JOURNAL ARTICLE

Multiple Mixing and Hybridization from Magma Source to Final Emplacement in the Permian Yamatu Pluton, the Northern Alxa Block, China FREE

Jianjun Zhang, Tao Wang, Antonio Castro, Lei Zhang, Xingjun Shi, Ying Tong, Zhaochong Zhang, Lei Guo, Qidi Yang, Linda Maria Iaccheri

Journal of Petrology, Volume 57, Issue 5, May 2016, Pages 933–980, https://doi.org/10.1093/petrology/egw028

ELSEVIER

Geochimica et Cosmochimica Acta

Volume 56, Issue 3, March 1992, Pages 971-986

Oxygen isotope evidence for large-scale hybridization of the lower crust during magmatic underplating ☆

Pamela D. Kempton, Russell S. Harmon

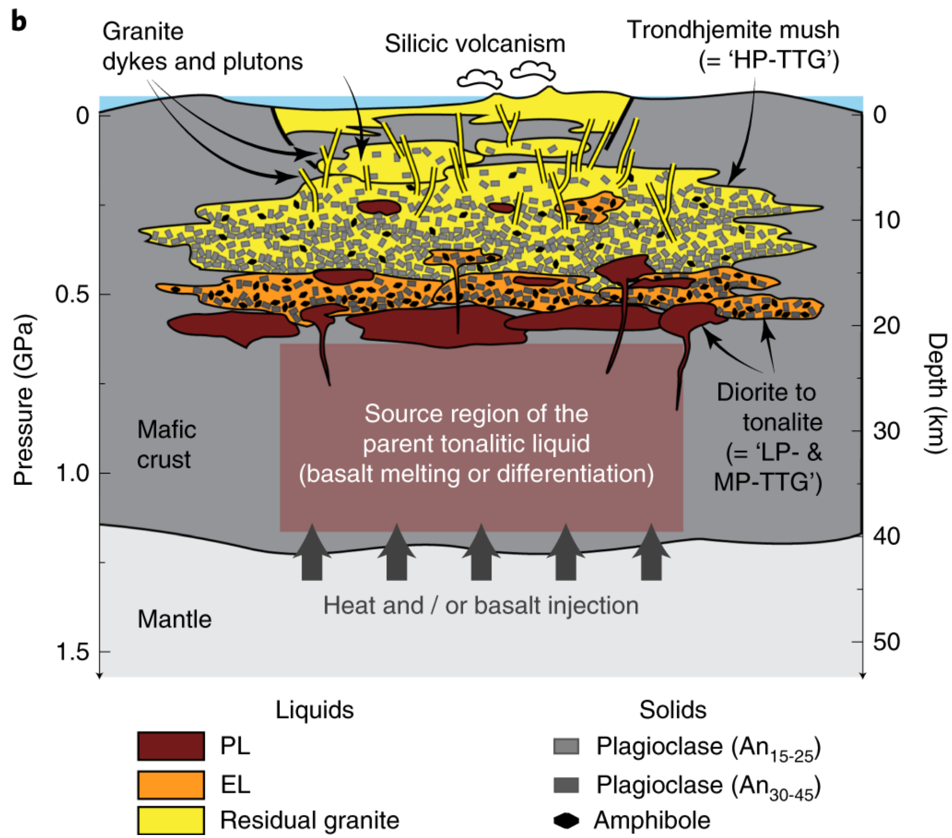
Fractional crystallization

- Archean TTGs having been affected by FC during ascent or when cooling/solidifying is not a new idea (cf. Martin, 1987)
  - Several recent studies have provided new and strong **field**, **petrographic**, and **geochemical** evidence to rejuvenate this proposition
- High-profile paper by Laurent *et al*. (2020) in *Nature Geoscience*
  - **All LP/MP/HP types derived from one parent tonalitic magma in the deep crust?**
- Examined Pl ± Hbl fractionation
  - HP-types produced at low-*P*!

nature geoscience ARTICLES
https://doi.org/10.1038/s41561-019-0520-6

Earth's earliest granitoids are crystal-rich magma reservoirs tapped by silicic eruptions

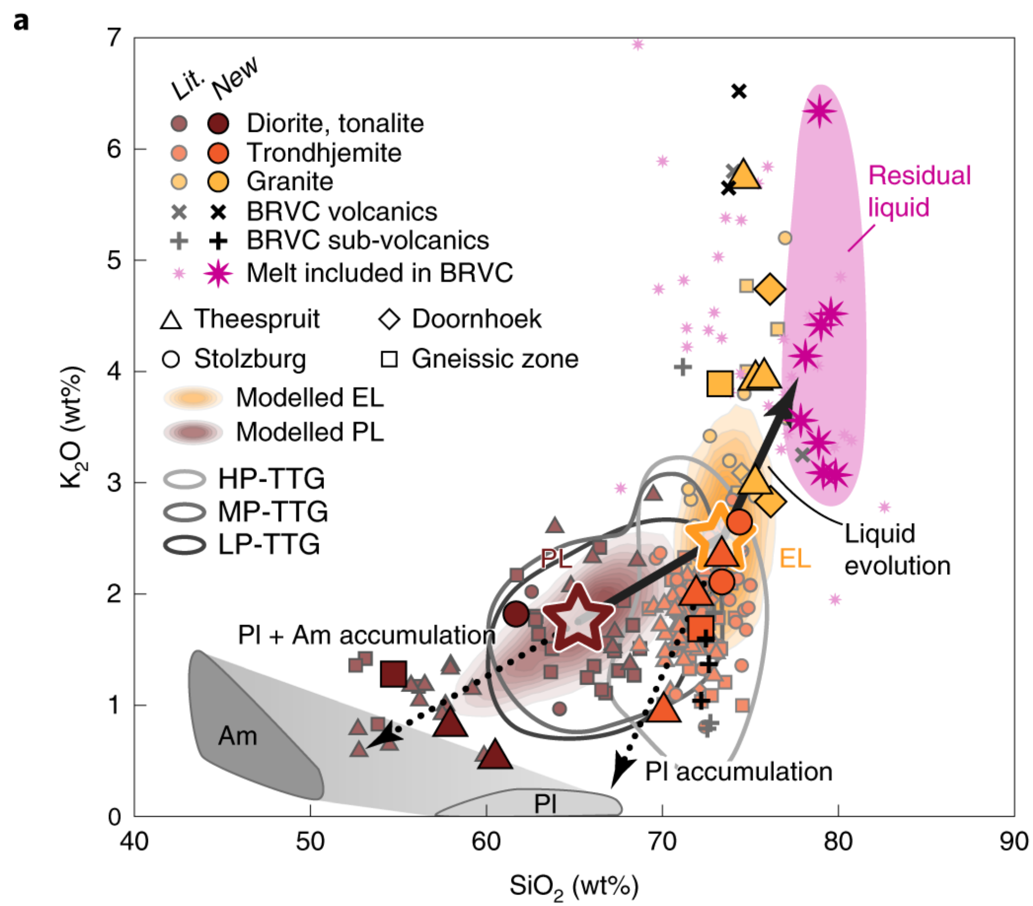
Oscar Laurent[1*], Jana Björnsen[1], Jörn-Frederik Wotzlaw[1], Simone Bretscher[1], Manuel Pimenta Silva[1], Jean-François Moyen[2], Peter Ulmer[1] and Olivier Bachmann[1]



Generating multiple TTG types from a single source

- U–Pb zircon shows coeval petrogenesis of **TTGs** and **silicic volcanic** sequences in the Barberton at ~3.45 Ga

Laurent et al. (2020) Nat. Geosci.



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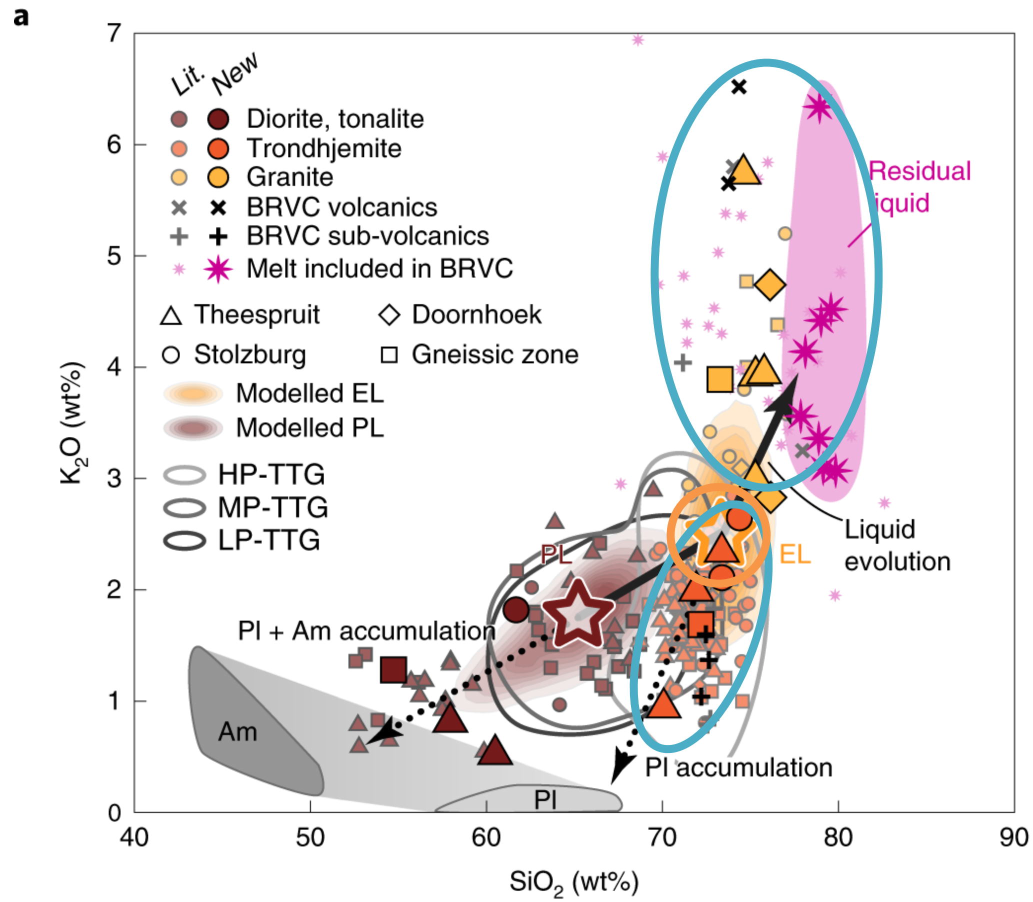
- Trondhjemites (crystal-rich) and volcanics (liquid-rich) are **complementary products** of the same **evolved liquid (EL)**

Laurent et al. (2020) Nat. Geosci.



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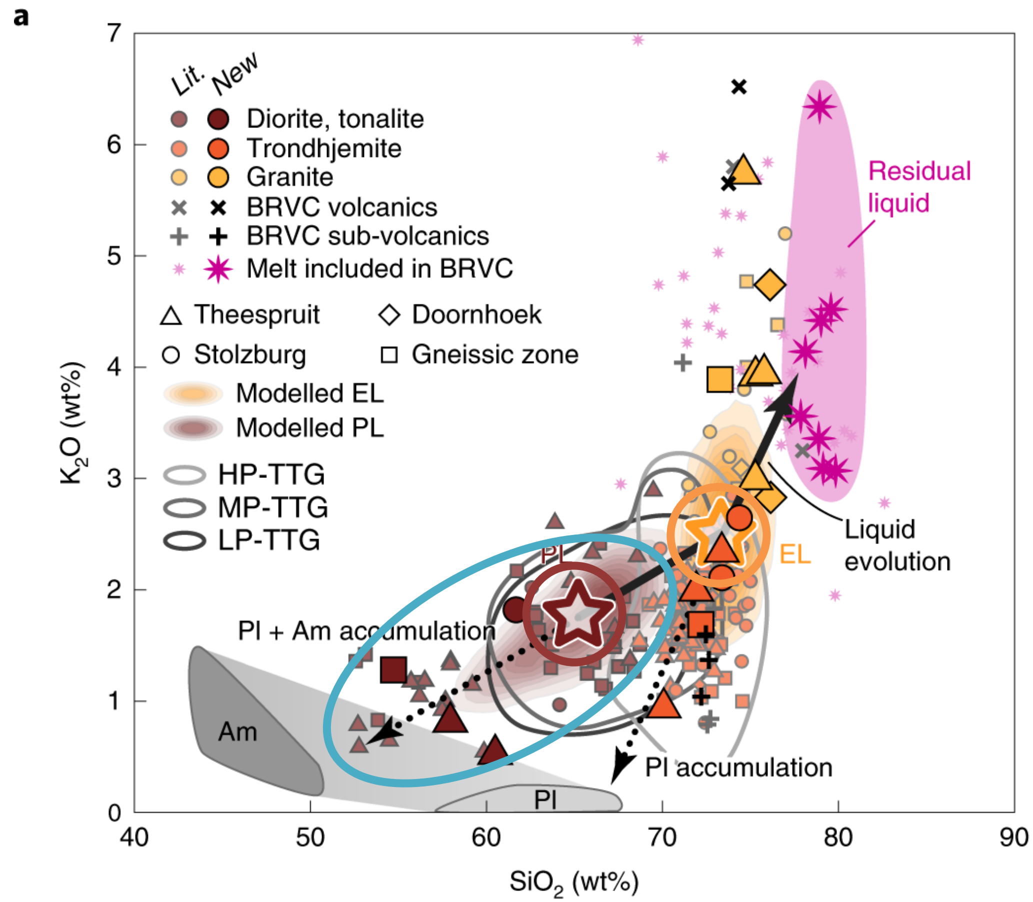
- Diorites/tonalites crystallized from an *even less-evolved* **parental liquid (PL),** with EL produced via FC as a complementary fraction

Laurent et al. (2020) Nat. Geosci.



Generating multiple TTG types from a single source

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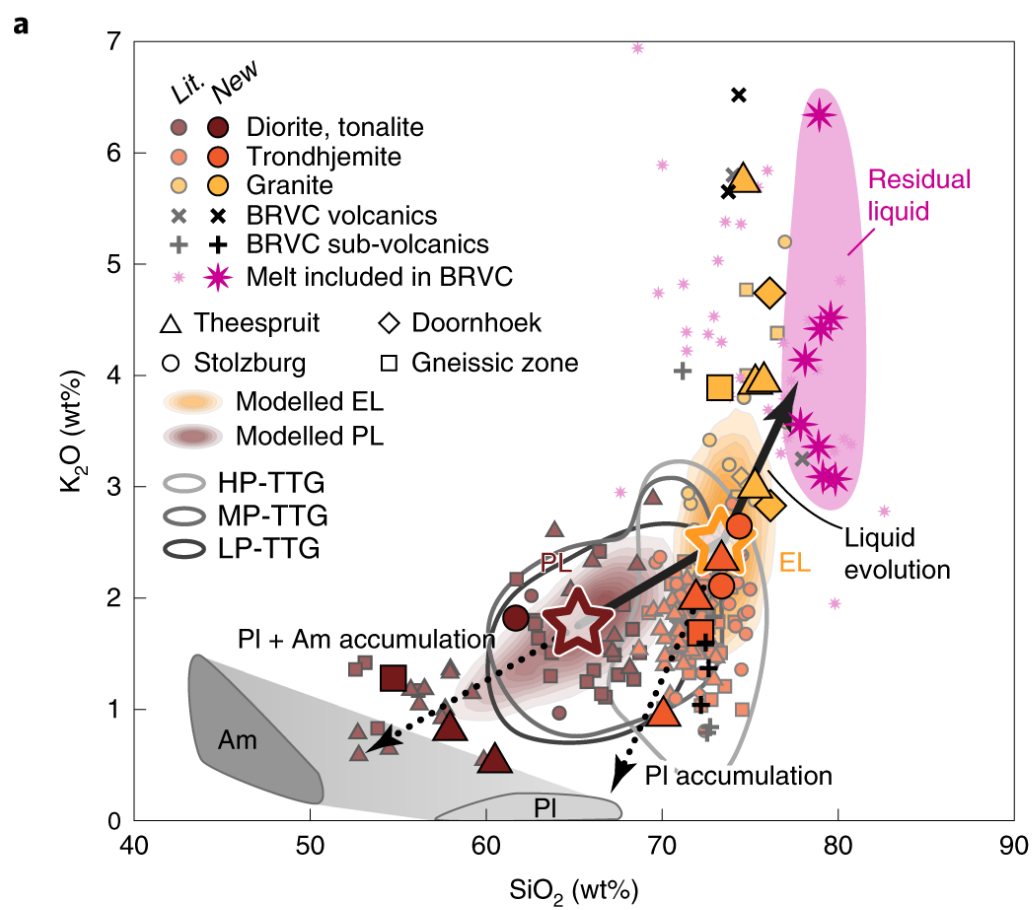
- Trondhjemites (crystal-rich) and volcanics (liquid-rich) are **complementary products** of the same **evolved liquid (EL)**
- Diorites/tonalites crystallized from an *even less-evolved* **parental liquid (PL),** with EL produced via FC as a complementary fraction
- **La/Yb** and **Sr/Y** in the melt **continuously evolved** due to sequential Hbl fractionation and/or Pl accumulation

Laurent et al. (2020) Nat. Geosci.



Hbl-bearing source?

- Rollinson (2021) showed in several case studies that the most primitive TTG melts in different terranes were **tonalitic**
  - Initially evolved along the hornblende control line and *then* the plagioclase control line
  - Supported in some regions by associated **hornblendite cumulates**
- Hornblende in the source region implies amphibolite, not eclogite – **a constraint on crustal thickness?**

Precambrian Research 367 (2021) 106448

Contents lists available at ScienceDirect

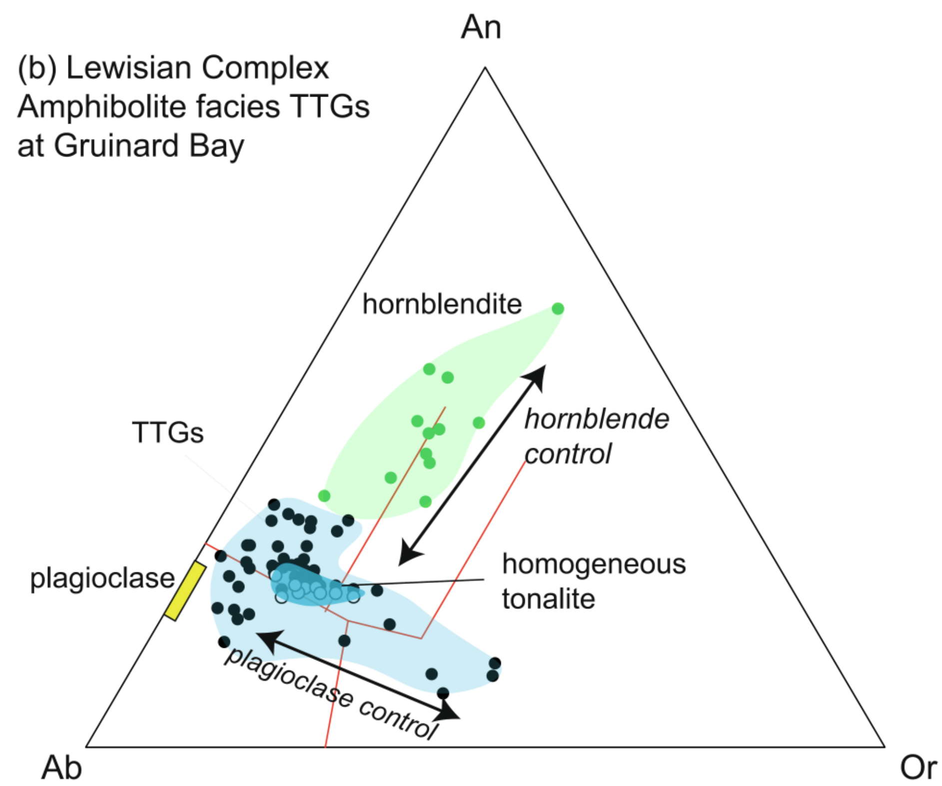
Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Do all Archaean TTG rock compositions represent former melts?

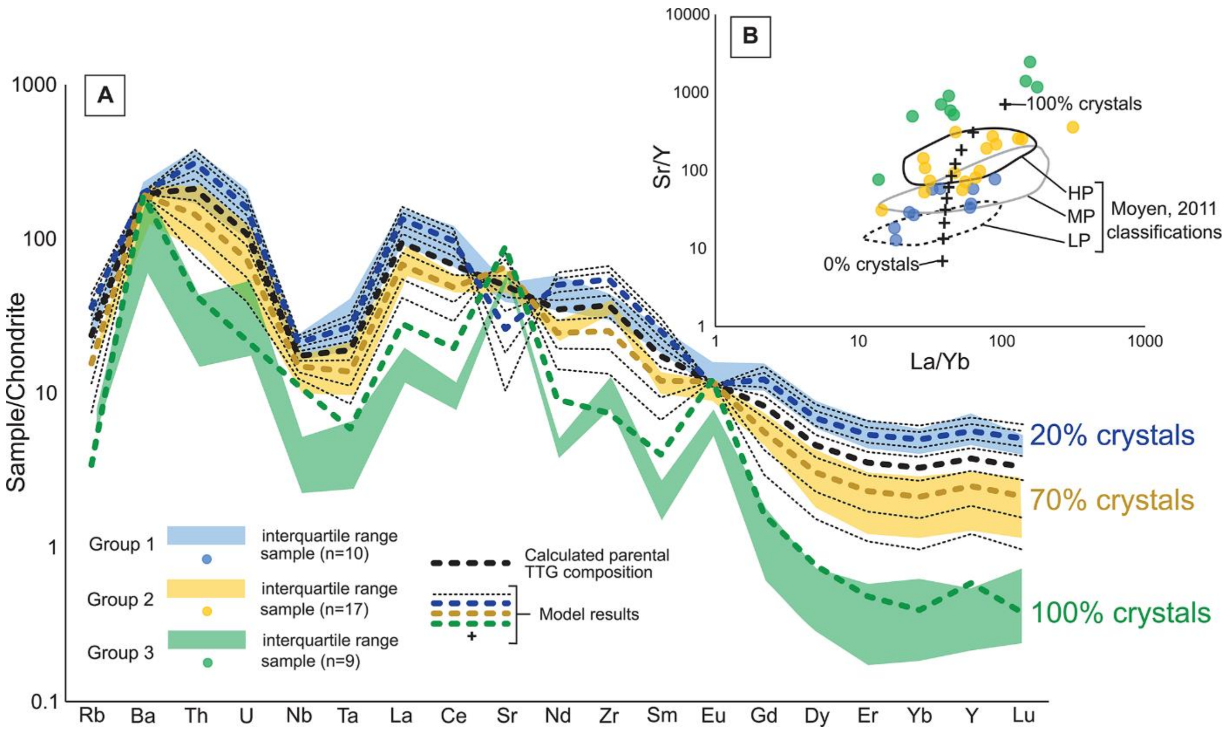
Hugh Rollinson

School of Built and Natural Environment, University of Derby, Kedleston Road, Derby DE22 1GB, UK



Kendrick et al. (2021) *Geology*

- Petrological–geochemical model focused on **plagioclase fractionation** and different degrees of liquid–crystal separation
  - Long-lived, mid-crustal crystal mushes with local mobilization of melt
    - 0–100% residual plagioclase spans **all LP, MP, HP trace element profiles**



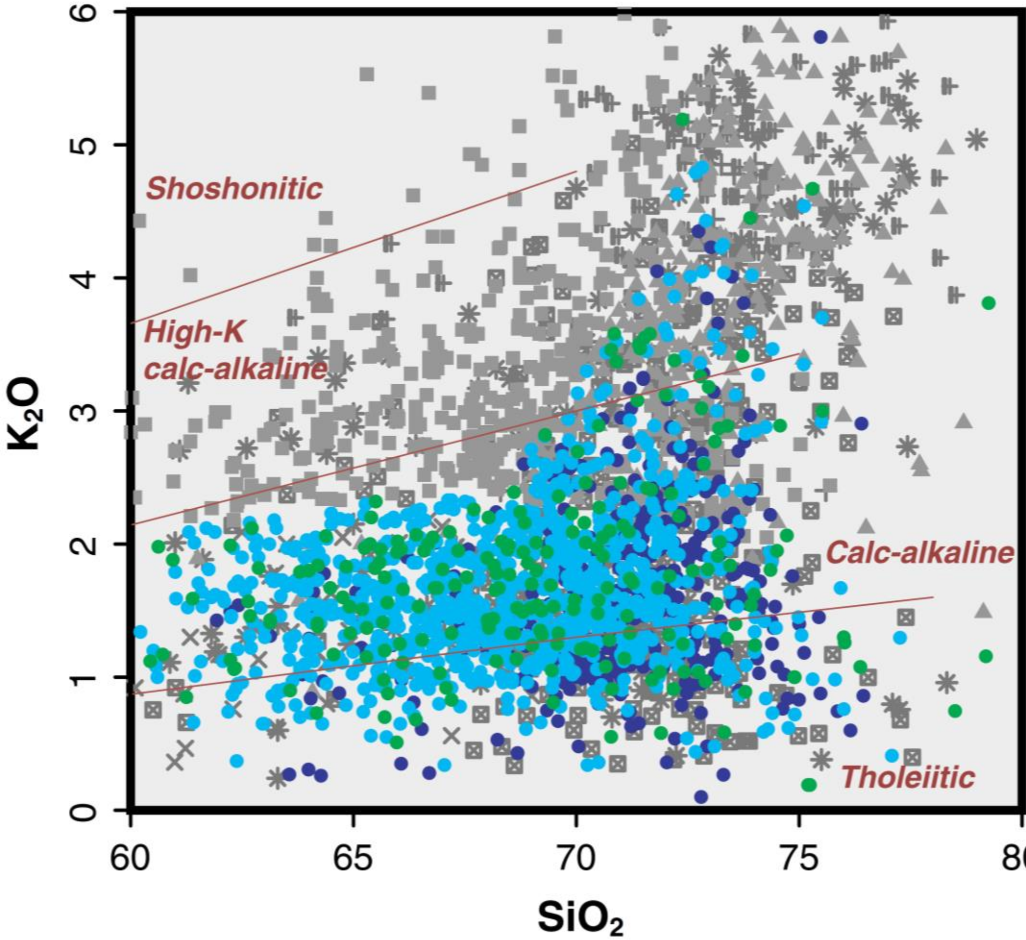
- *"Our results suggest that **trace element compositions of TTGs may not primarily reflect the depth of the source** and cannot be used alone to infer Archean geodynamic settings."*

Discussion

- Where does this leave petrological modelling and/or experimental petrology studies for examining TTG petrogenesis?
  - Clearly useful for examining **characteristics of the source**
  - Harder – for ex-pet, at least – to examine **melt evolution** after leaving the anatectic zone
- Should we, as a community, **move on from** the LP/MP/HP scheme?
  - If some kind of division is retained, should it be renamed based on the **geochemistry**?
    - Some people do this already
  - If so, what do we **replace** it with?

Discussion

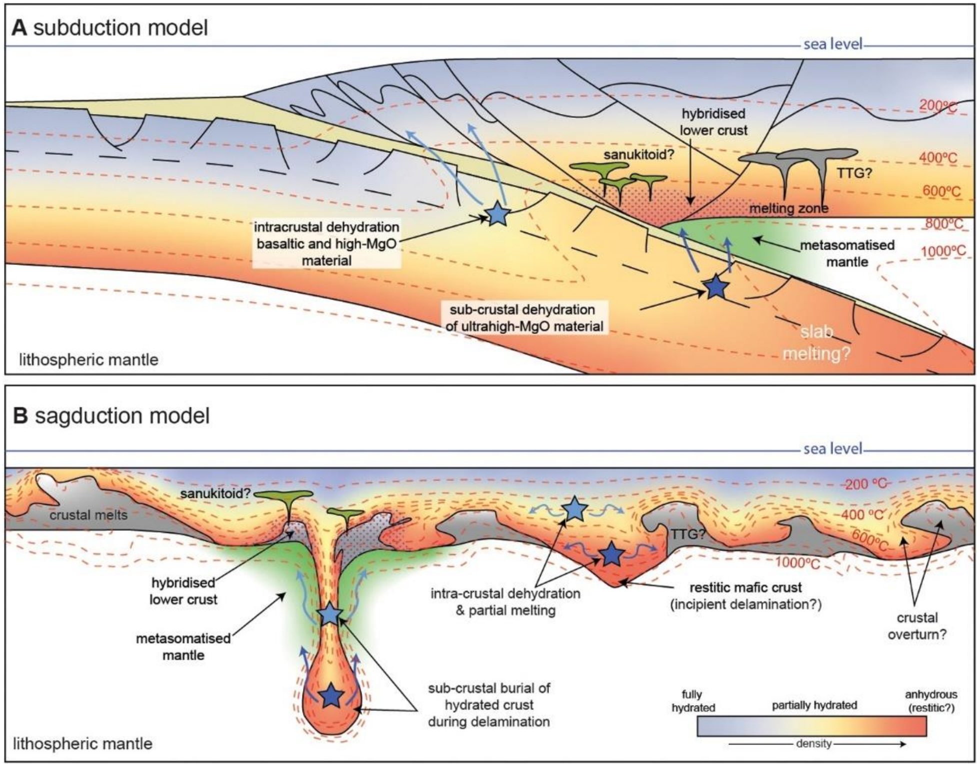
- **TTG gneisses** in Archean terranes show a broader compositional diversity than TTG magmas
  - Often, more potassic
  - **Misclassification** or actual **compositional changes** during metamorphism?
- Do TTG gneisses often **undergo partial melting** at the final stages of their metamorphic transformation?
  - Late-stage Bt-bearing granites



Moyen and Martin (2012) Lithos

Future directions

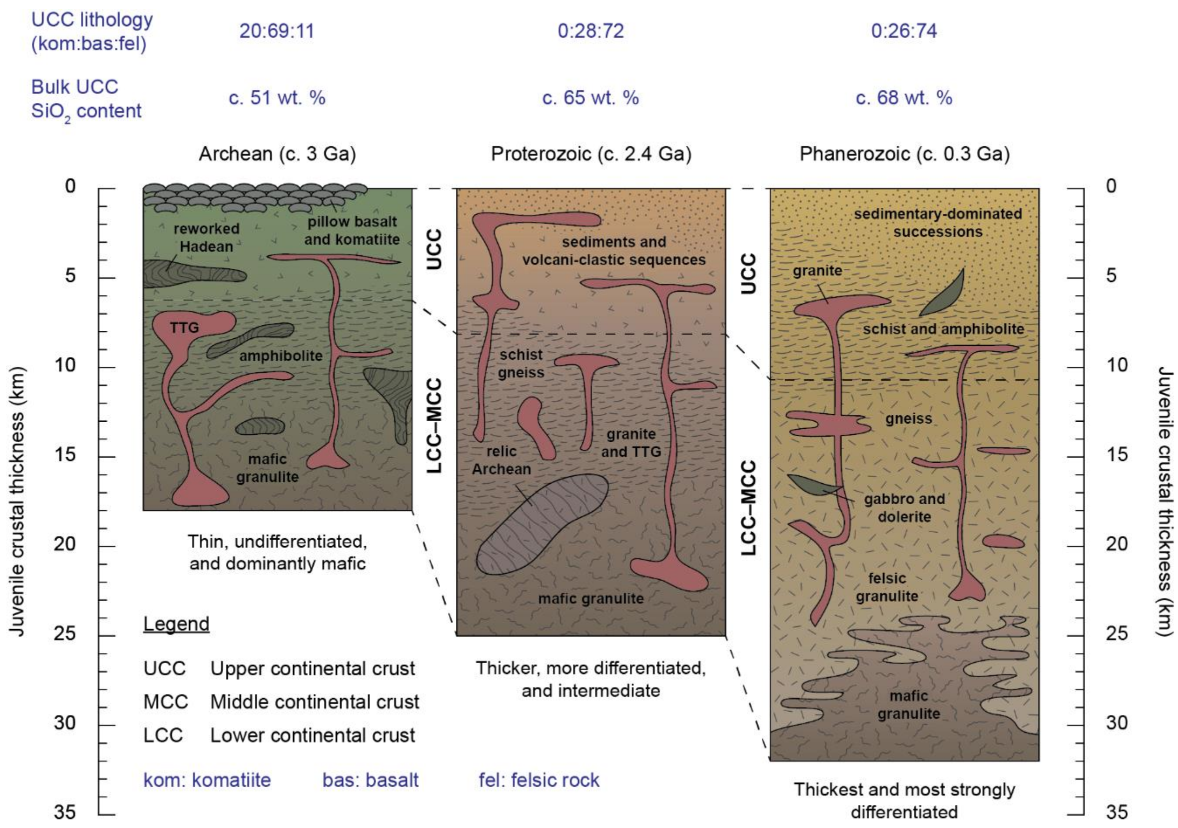
- While none of the topics discussed so far are settled, there are **additional issues** that are also worthy of focus
- **Amphibole dehydration melting** vs **fluid-fluxed melting**
  - Some TTGs have low *T* (~750–850 °C) of formation, and so **require addition of free H_2O**
- Where does the water come from to hydrate the metabasalt and cause melting?
  - **Modern-style subduction** (Laurie and Stevens, 2021)
  - **Komatiite dehydration** (Tamblyn et al., 2023)
  - **Greenstone drips** (van Kranendonk, 2011)



Hartnady et al. (2022) EPSL

Future directions

- How **heterogeneous** was the Archean crust?
  - Presumably much less differentiated than Proterozoic and Phanerozoic crust
- Igneous processes are important
  - But, can the diversity in TTG compositions inform us about the **geology of the crust** at any place or time?
- Changes in TTG "type" (i.e. composition) during the Archean
  - Track **maturation** of the crust?



Palin et al. (2021) Geoscience Frontiers