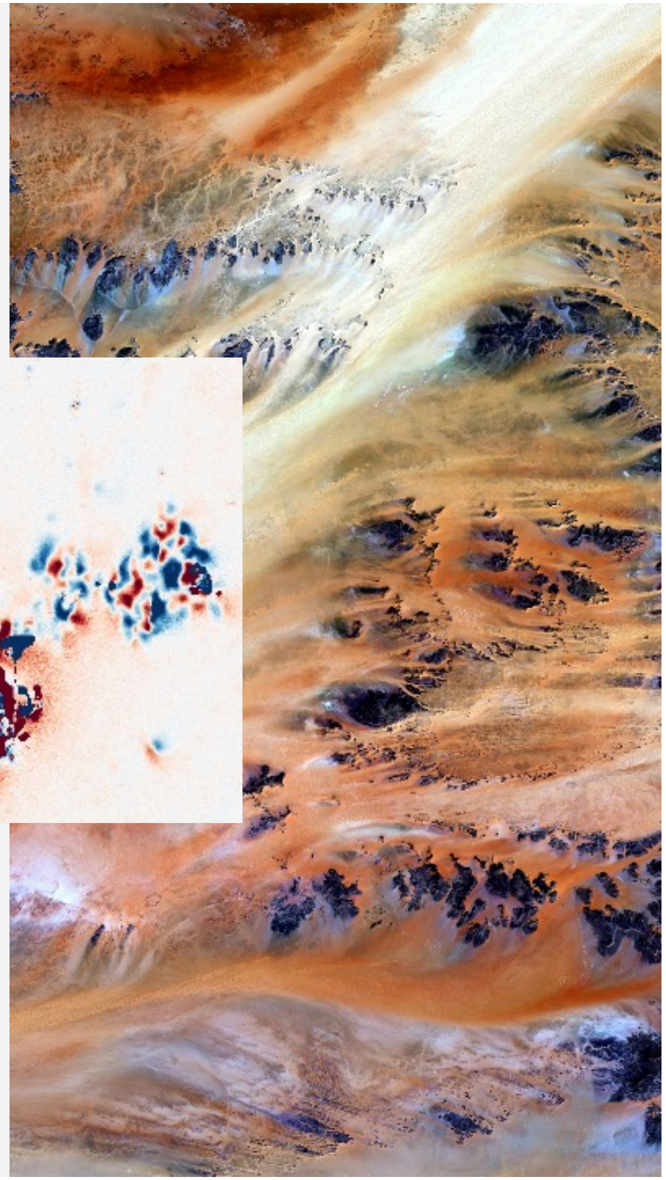
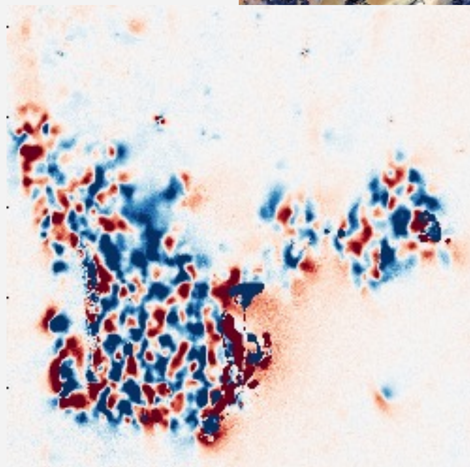
CFIGS

New advances of paleomagnetism in paleogeography and mineral exploration



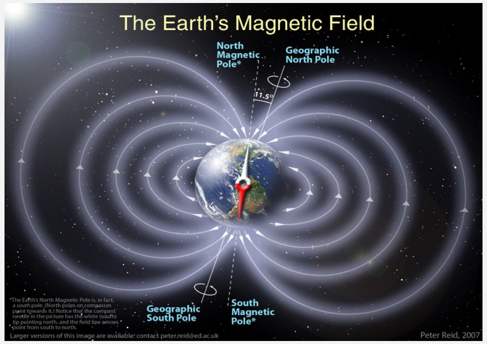


Uwe Kirscher-IASGT Conference 2026,
Accra, Ghana

7/22/26

AGATE PROJECT

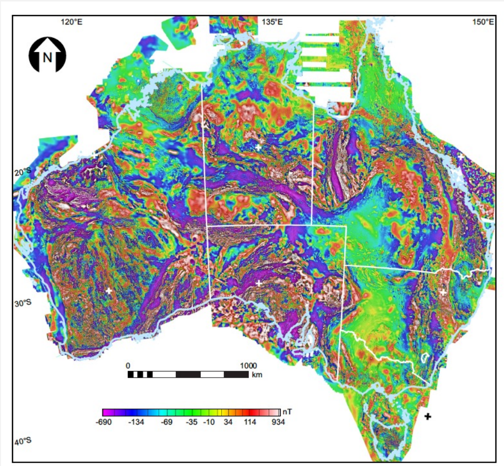
Paleomagnetism



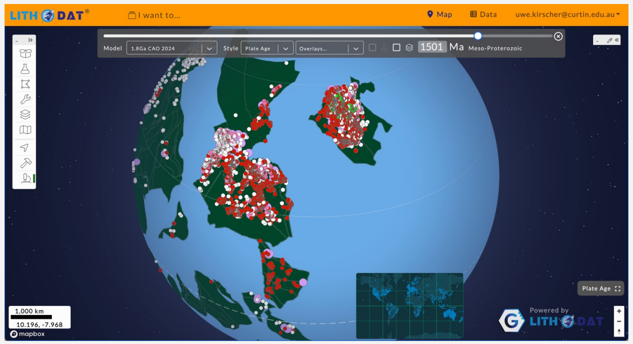
Problems:

- Not enough remanence data
- Not enough paleomagnetic targets
- Bulk measurements

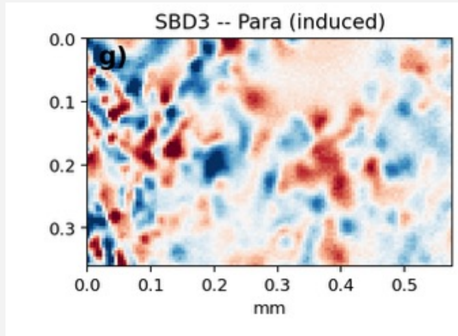
1. Magnetic remanence for exploration



3. Paleogeography



2. Rock magnetism and Rock Characterization

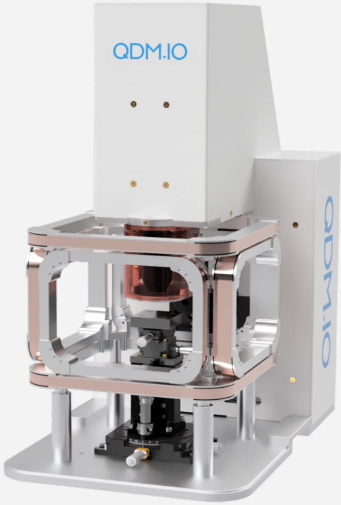


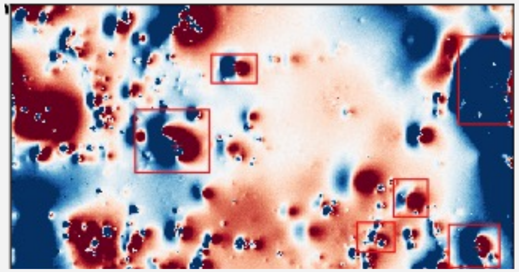
Instrumentation

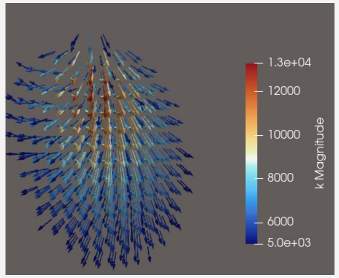
- Fluxgate magnetometers since ca. 1930s
- First SQUID and spinner magnetometer used in the 1960s
- (Plate tectonic revolution in the 1960s)
- Improvements in automation and precision
- But: no fundamentally new instruments in palaeomagnetism for over 50 years

- NOW: New diamond-based quantum sensors for in-situ measurements

Now: in-situ micro-paleomagnetism







⊹ I: Availability of new quantum sensors for in-situ paleomagnetism

⊹ II: New range of data with new set of challenges

⊹ III: Progress is being made to address all challanges

Australian Government
Department of Industry, Science and Resources

2023

National Quantum Strategy

Building a thriving future with Australia's quantum advantage

industry.gov.au/quantum

Theme 3: A skilled and growing quantum workforce

The Australian Government will:

- promote Australia as the world's top destination for people studying, undertaking research in and working in quantum industries
- cement Australia's status as a high-value location for companies establishing their own quantum-related capabilities

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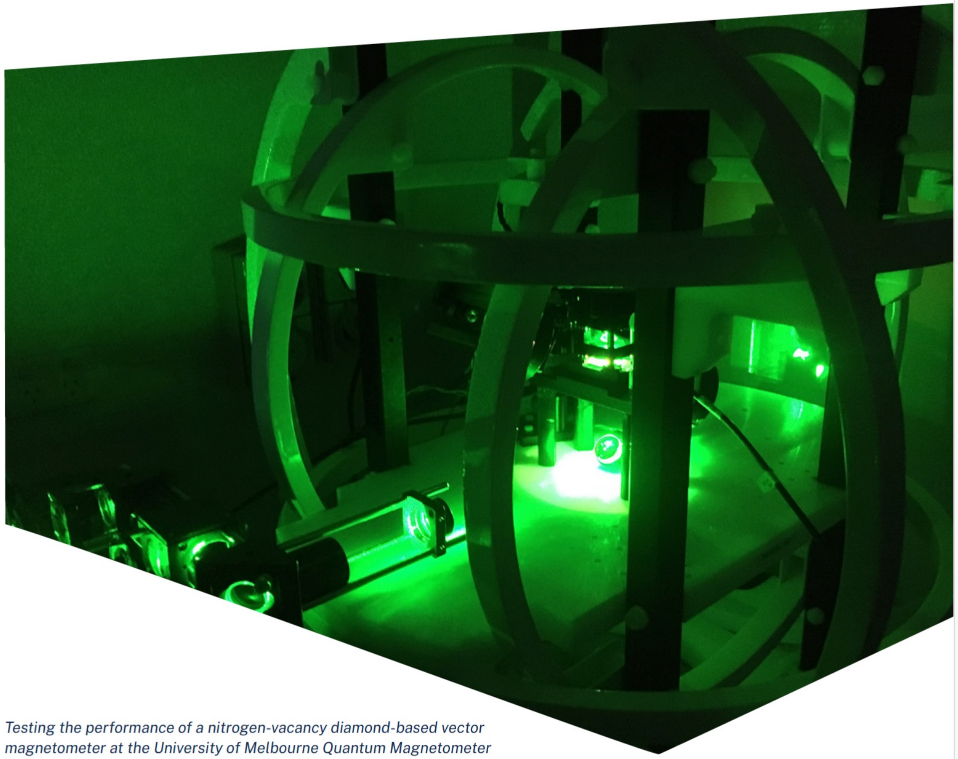
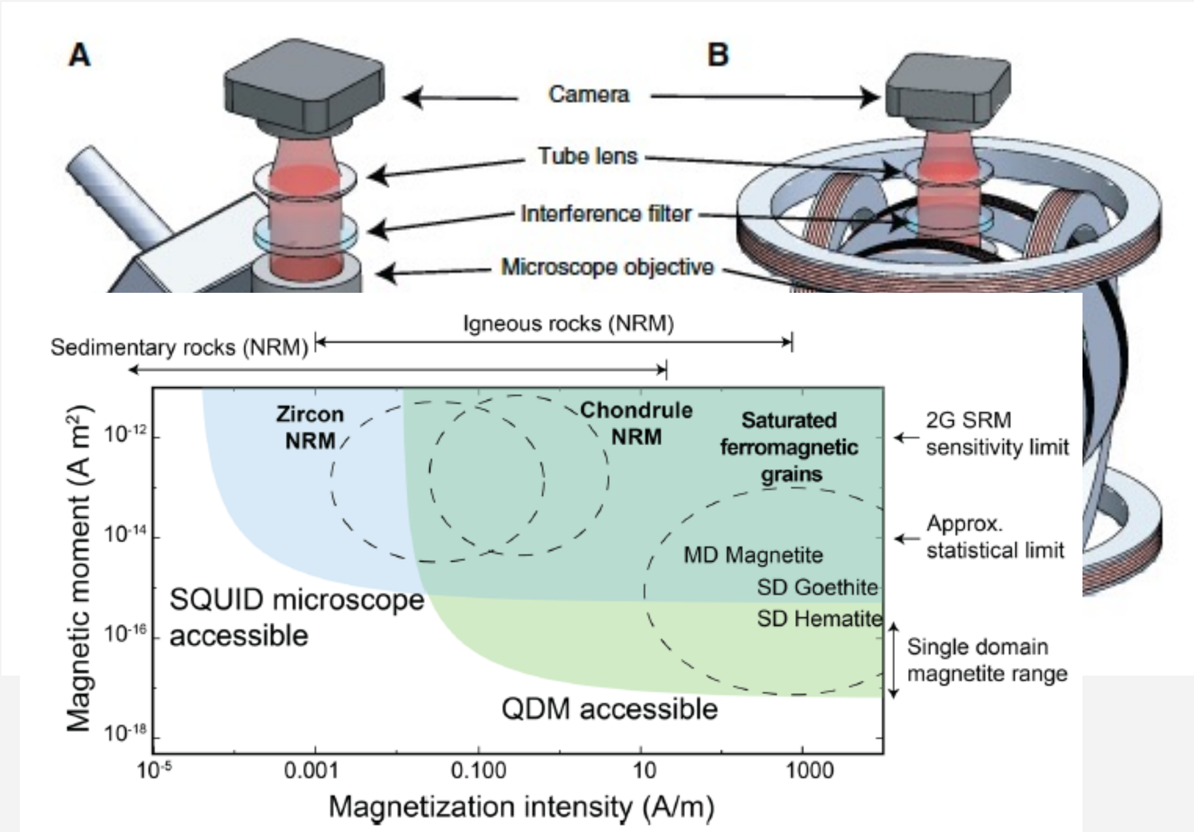


Testing the performance of a nitrogen-vacancy diamond-based vector magnetometer at the University of Melbourne Quantum Magnetometer Test and Measurement Facility. Credit: Chris Lew, University of Melbourne

Testing the performance of a nitrogen-vacancy diamond-based vector magnetometer at the University of Melbourne Quantum Magnetometer Test and Measurement Facility. Credit: Chris Lew, University of Melbourne

Quantum Diamond Microscope.

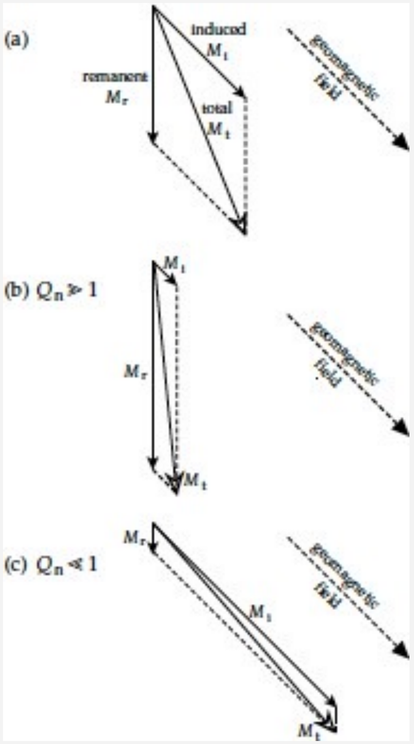


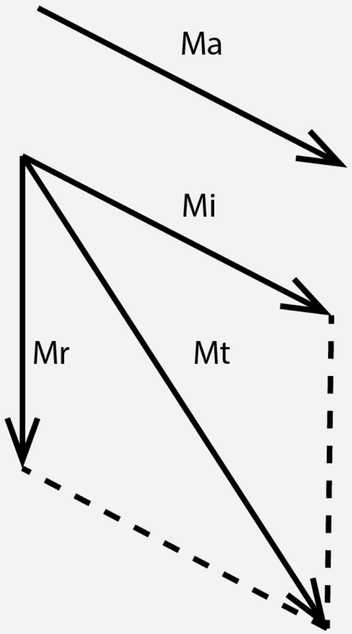
- Diamond with N-vacancies (NV) centers
- NV fluorescence is detected using microwave frequencies via optically detected magnetic resonance (ODMR) spectroscopy
- 2 states yield remanent (sum) and induced (difference) magnetization map of a sample

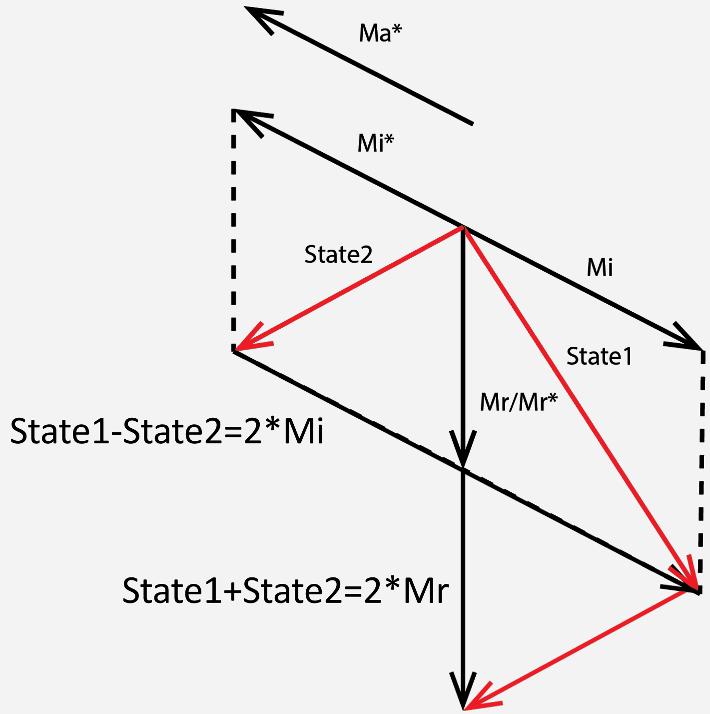
QDM principle:

Magnetic Surveying

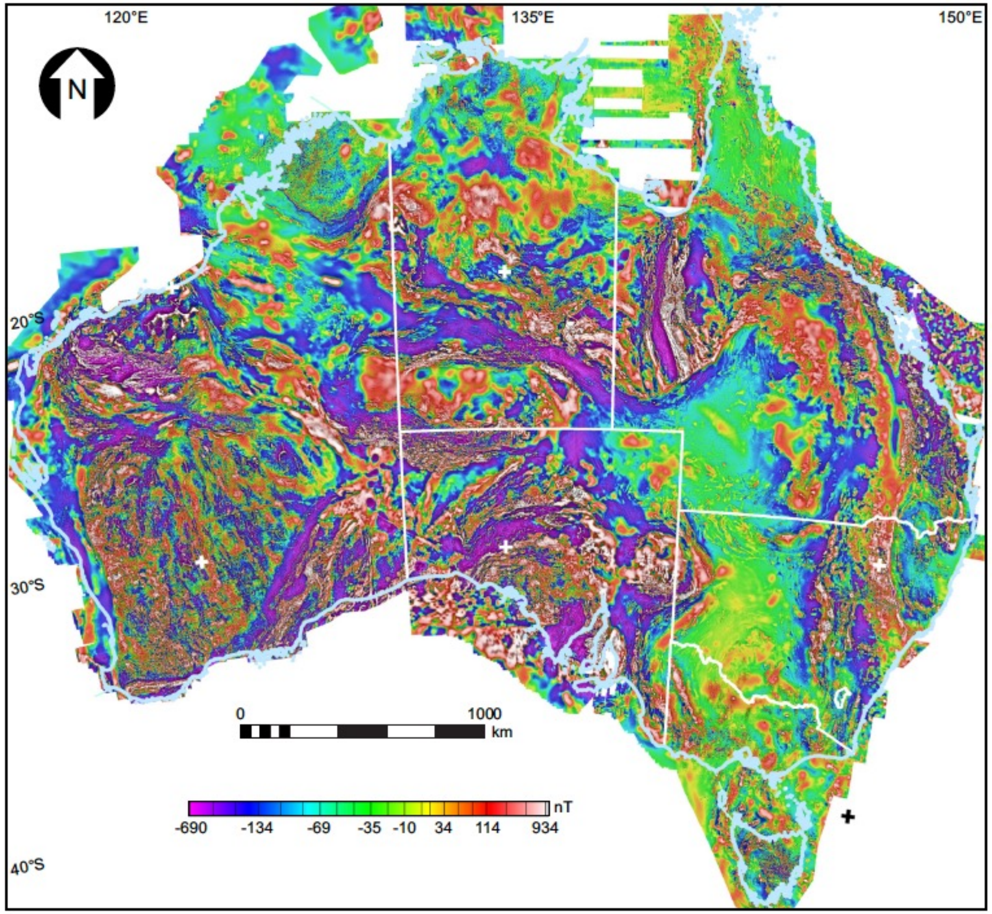
Koenigsberger ratio:
$Q_n = M_r / M_i$







1. Remanence

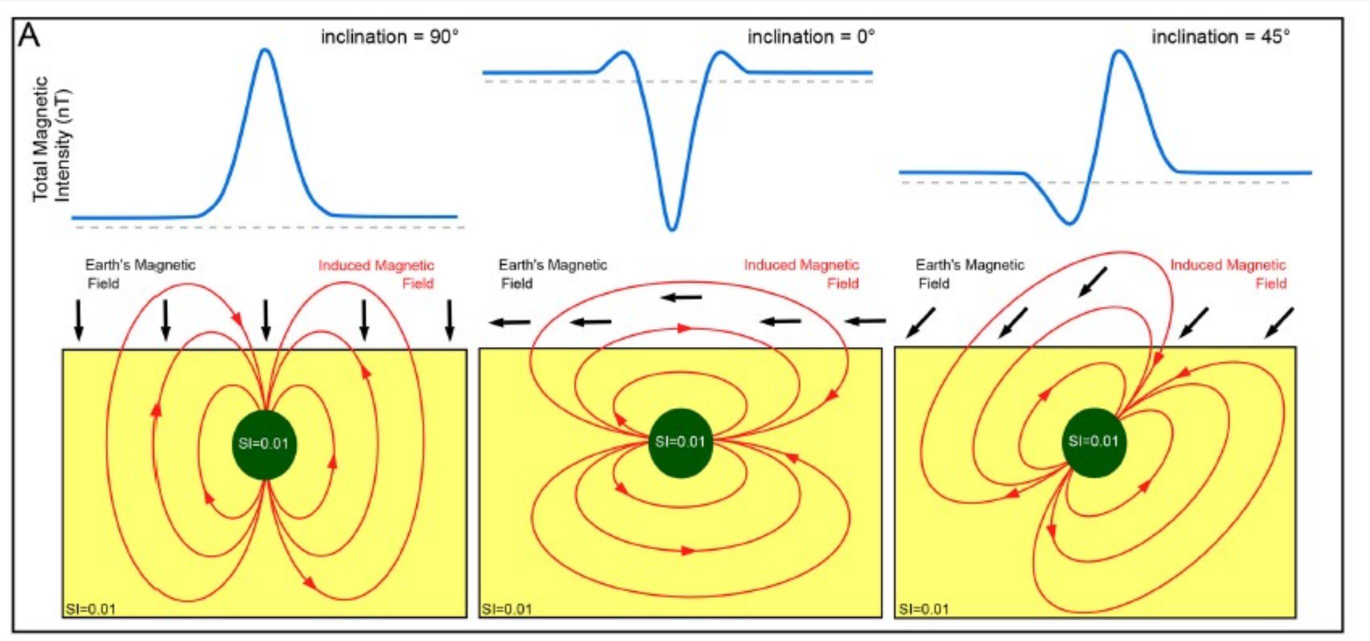


Geology from aeromagnetic data (Betts et al. 2024)

- Aeromagnetic data is one of the most widely used geophysical methods that is extensively applied in resource exploration, regional mapping
- Despite more accessible data and improved processing methodologies, interpretation of aeromagnetic data remains challenging for many geoscientists, resulting in a shortage of expertise in this area.

1. Remanence

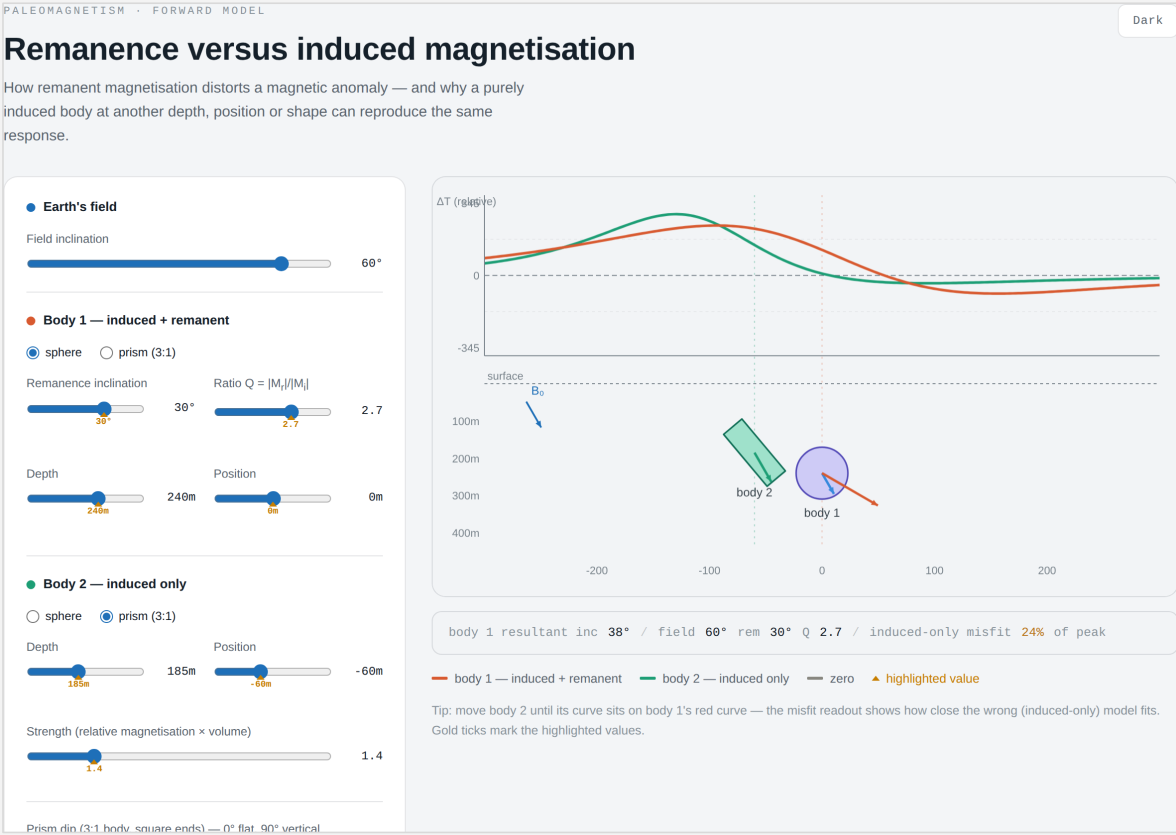
Principles of aeromagnetic surveys.



- Aeromagnetic surveys use the Earth magnetic field magnetizing buried magnetizable structures.
- Aeromagnetic anomalies look different at different places on Earth and for bodies with various magnetic parameters.
- Aeromagnetic data is now largely available.

Betts et al., 2024

Remanence versus induced magnetisation



Live interactive forward model

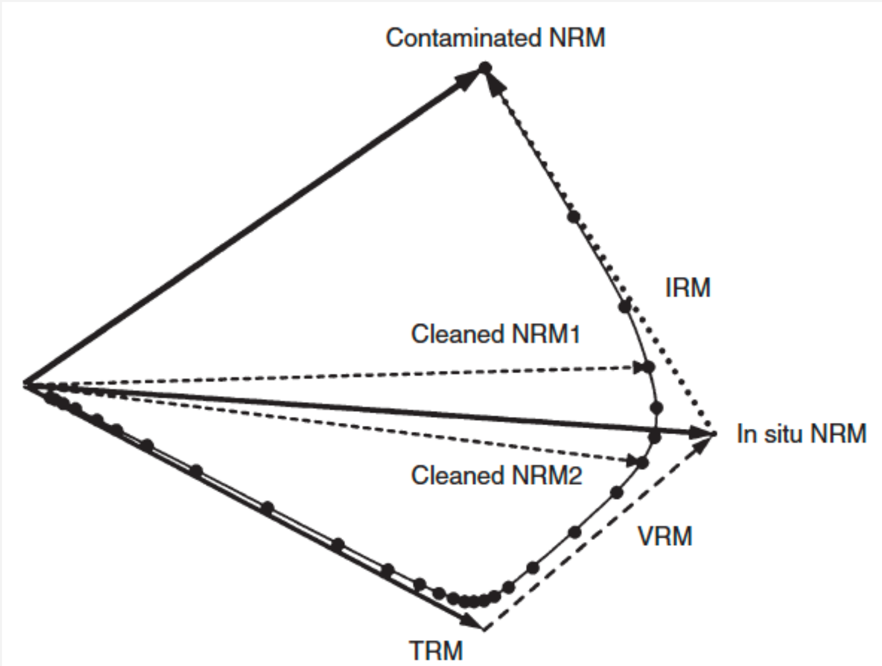
How remanent magnetisation distorts a magnetic anomaly — and how a body at another depth, position or shape can reproduce the same response.

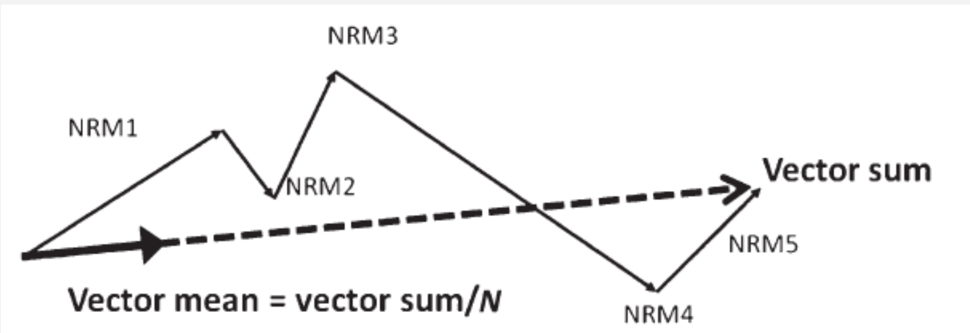
Drag the sliders to explore field inclination, the Koenigsberger ratio Q, body geometry, and inversion ambiguity.

Open the interactive model

Opens in your browser. Keep magnetic-anomaly-remanence.html in the same folder as this presentation.

1. Remanence

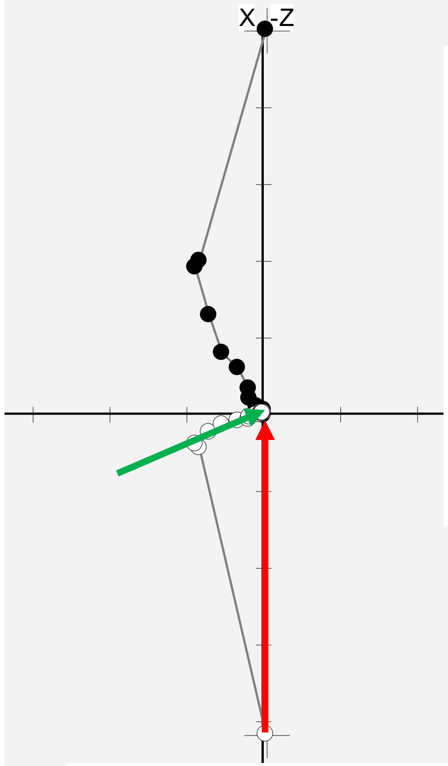


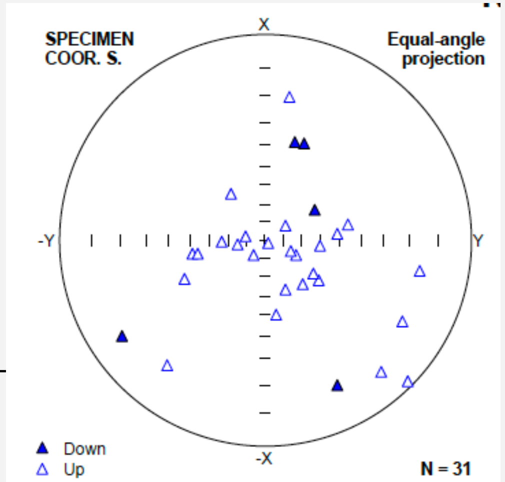


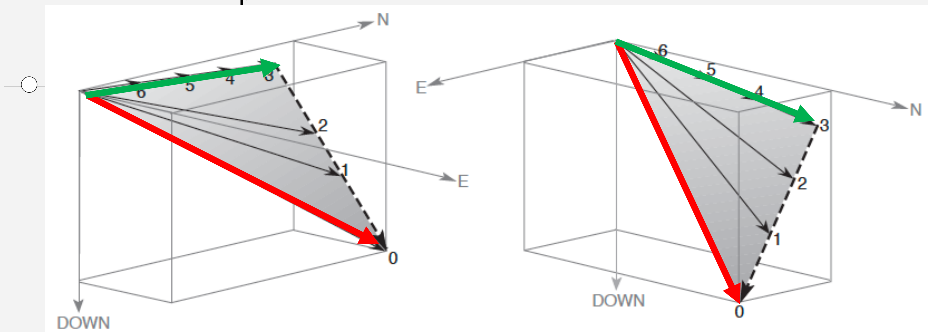
Clark, 2014

- Different types of remanence: Natural remanence magnetization (NRM), Thermo-remanent magnetization (TRM), Detrital, Viscous, Chemical remanent magnetization (DRM, VRM, CRM).
- Due to metamorphism or other thermo-chemical events, the NRM normally consists of a number of different magnetic remanence-components, where the remanence direction is related to the age of formation of the magnetic phases

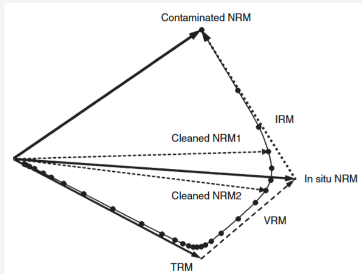
Remanence directions







- Due to complex remanence pattern (various components related to recent or "old" overprints, cleaning is necessary
- Demagnetisation of the remanence vector is usually shown with an endpoint projection to vertical and horizontal planes
- NRM direction can be quite different from Characteristic remanence directions



Butler

1. Remanence

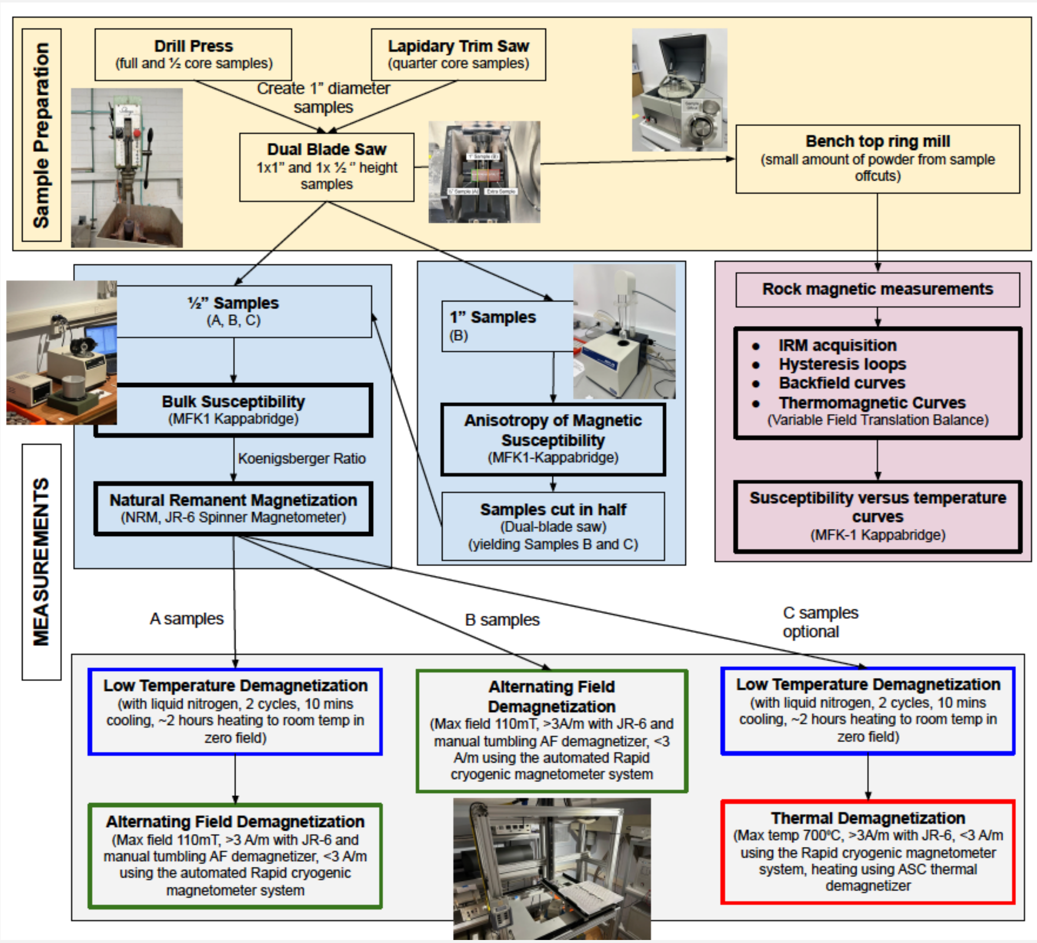
Main Problems:

- Remanence data not available on a large scale
- When available, remanence data contaminated with overprints

Solutions:

- 1. Increase amounts of measurements of samples using automated systems (RAPID)
- 2. Application of advanced in-situ scanning of remanence signal bypassing overprints

Solution 1:


Sample Preparation
Drill Press
(full and ½ core samples)
Lapidary Trim Saw
(quarter core samples)
Create 1" diameter samples
Dual Blade Saw
1x1" and 1x ½ " height samples
Bench top ring mill
(small amount of powder from sample offcuts)
MEASUREMENTS
½" Samples
(A, B, C)
Bulk Susceptibility
(MFK1 Kappabridge)
Koenigsberger Ratio
Natural Remanent Magnetization
(NRM, JR-6 Spinner Magnetometer)
1" Samples
(B)
Anisotropy of Magnetic Susceptibility
(MFK1-Kappabridge)
Samples cut in half
(Dual-blade saw)
(yielding Samples B and C)
Rock magnetic measurements
IRM acquisition
Hysteresis loops
Backfield curves
Thermomagnetic Curves
(Variable Field Translation Balance)
Susceptibility versus temperature curves
(MFK-1 Kappabridge)
A samples
B samples
C samples optional
Low Temperature Demagnetization
(with liquid nitrogen, 2 cycles, 10 mins cooling, ~2 hours heating to room temp in zero field)
Alternating Field Demagnetization
(Max field 110mT, >3A/m with JR-6 and manual tumbling AF demagnetizer, <3 A/m using the automated Rapid cryogenic magnetometer system
Low Temperature Demagnetization
(with liquid nitrogen, 2 cycles, 10 mins cooling, ~2 hours heating to room temp in zero field)
Alternating Field Demagnetization
(Max field 110mT, >3 A/m with JR-6 and manual tumbling AF demagnetizer, <3 A/m using the automated Rapid cryogenic magnetometer system
Thermal Demagnetization
(Max temp 700°C, >3A/m with JR-6, <3 A/m using the Rapid cryogenic magnetometer system, heating using ASC thermal demagnetizer


WARP
Curtin University
SQUID
QDM
Spinner
Kappabridge

Solution 2 (identifying remanence carrying grains):

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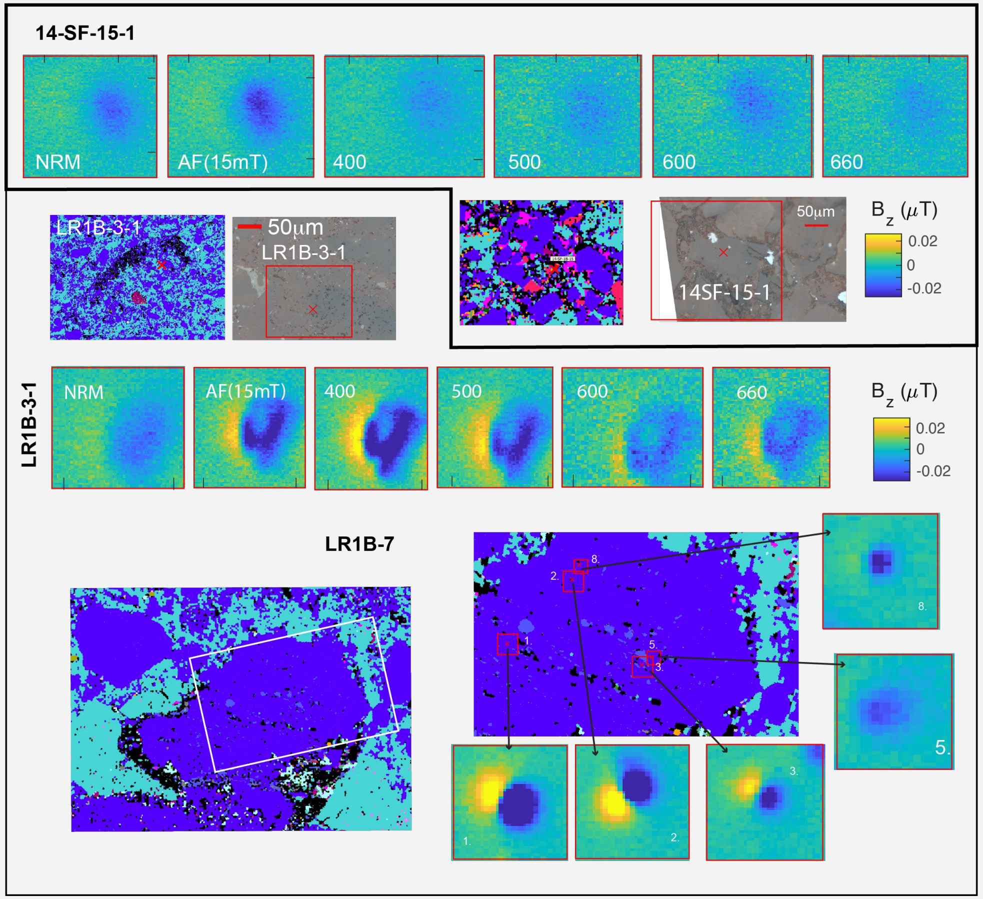
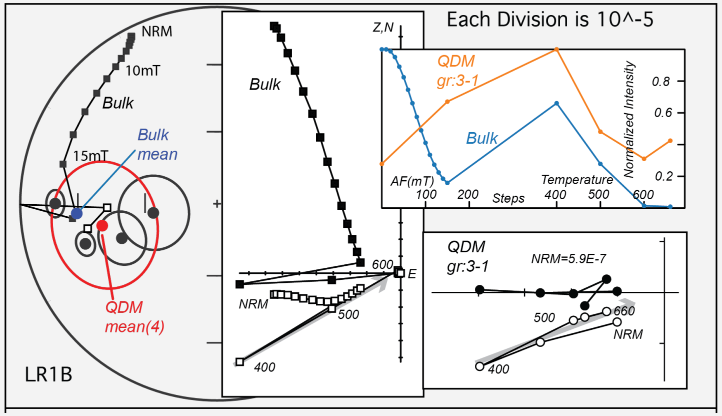


Scottish Stac Fada Formation.

- Matrix has certain consistent direction (based on un-oriented samples) which agree with bulk direction
- Larger quartz grain contains randomly oriented dipoles, representing a micro-conglomerate test



2. Characterization

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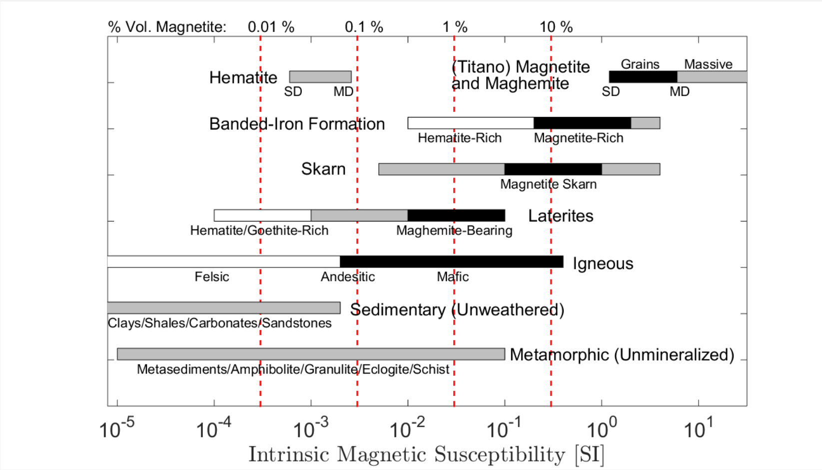
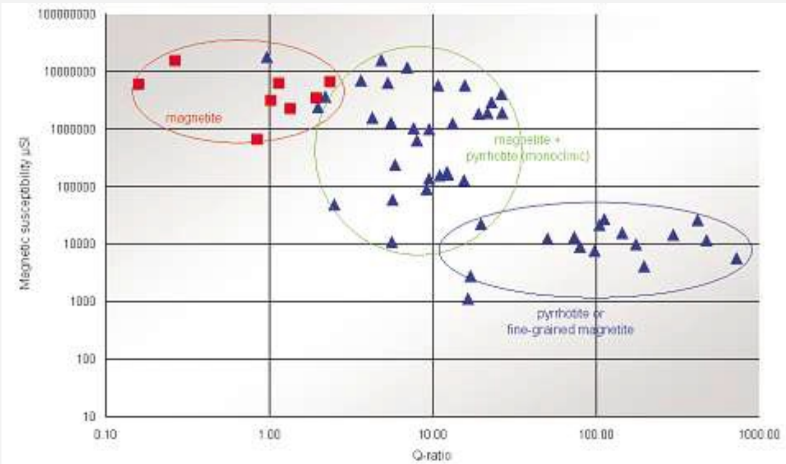
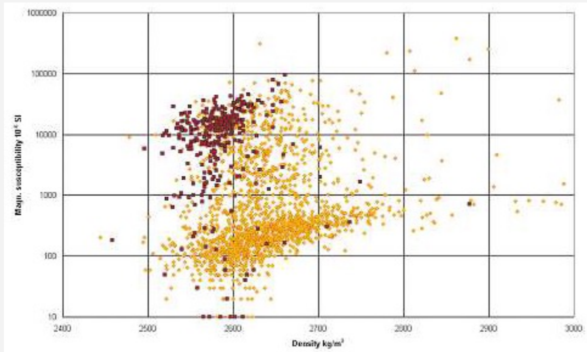




- Parameters such as susceptibility are problematic since they are not distinct
- Pyrrhotite's polytypes range from strongly ferrimagnetic to antiferromagnetic, causing unpredictable geophysical responses and serious processing problems in gold mining operations.
- Thermomagnetic analysis, XRD, and QDM imaging can distinguish them reliably.



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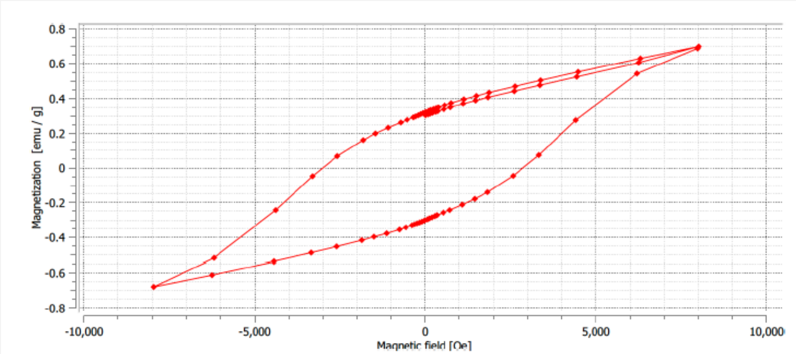
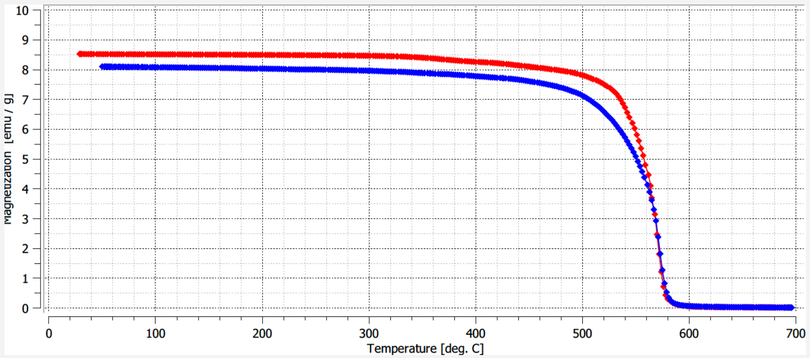
Traditional Rock magnetic characterization

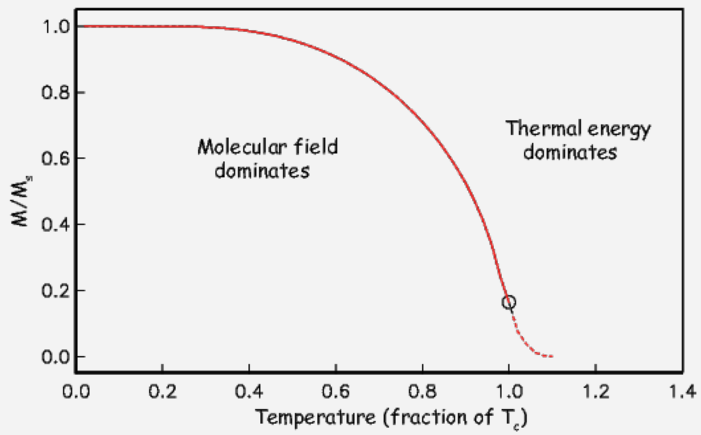
- Magnetic hysteresis Loops



- Thermomagnetic curves



- Curie temperature indicates magnetic phase
- No spatial information
- Dominated by strong phase (magnetite)



New Rock magnetic characterization

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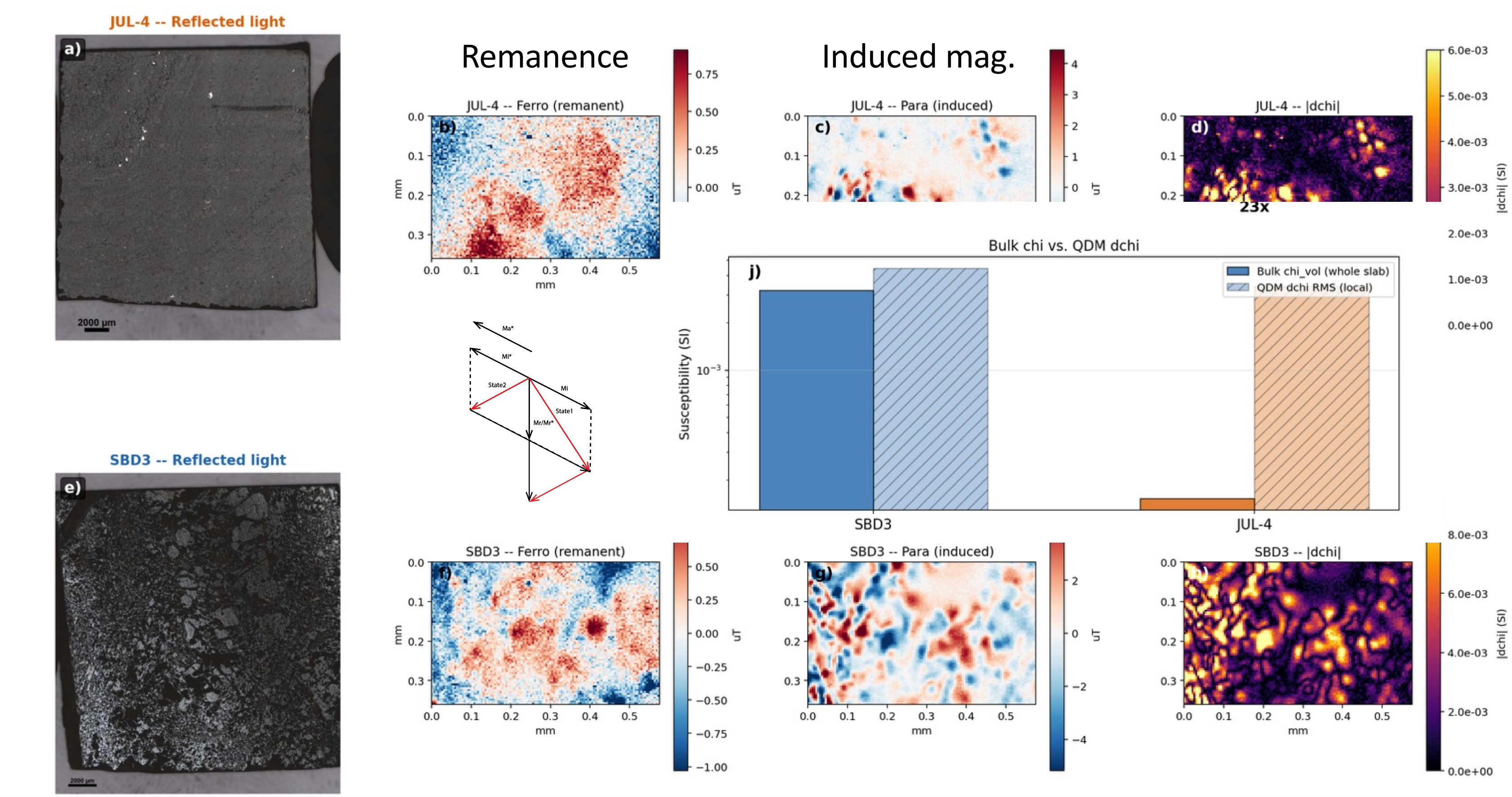


Pyrrhotite is not one mineral: monoclinic vs hexagonal

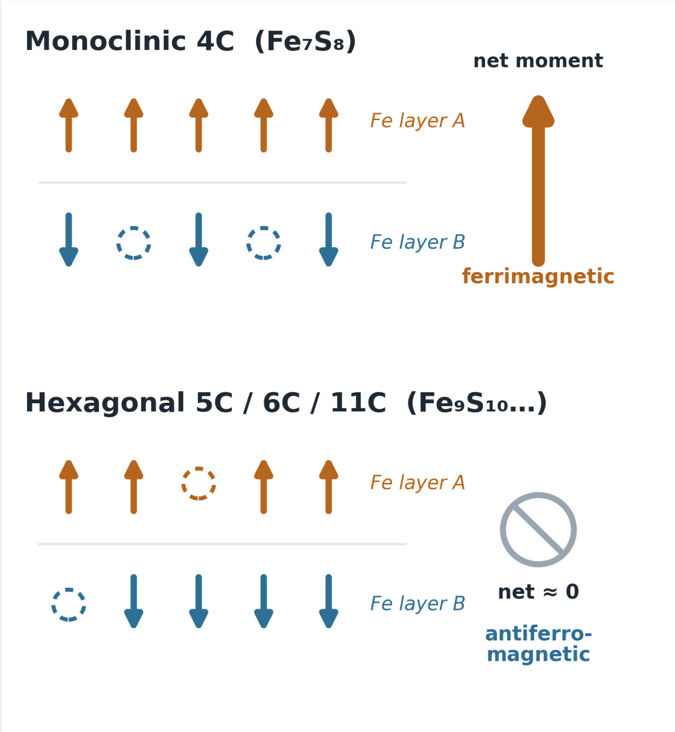
Pyrrhotite is a family of Fe-deficient superstructures, Fe(1–x)S. Two coexist in most ore systems – and they behave completely differently in a magnetic survey.

Monoclinic 4C · Fe_7S_8

- Ordered Fe vacancies → unequal sublattice moments → ferrimagnetic
- Strong induced magnetisation; carries a stable remanence (often Q > 1)
- Curie temperature ≈ 320 °C

Hexagonal 5C / 6C / 11C

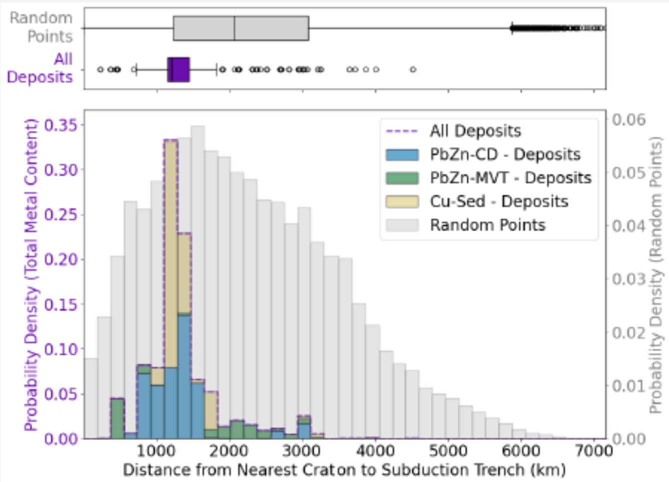
- Members Fe_9S_{10}, $Fe_{10}S_{11}$, $Fe_{11}S_{12}$; vacancies balanced → moments cancel → antiferromagnetic at room T
- Magnetically near-silent – little induced or remanent signal
- λ-transition ≈ 200–250 °C (turns ferrimagnetic only on heating)



Vacancy ordering sets the net moment: ordered (monoclinic) → ferrimagnetic; balanced (hexagonal) → antiferromagnetic. Schematic.

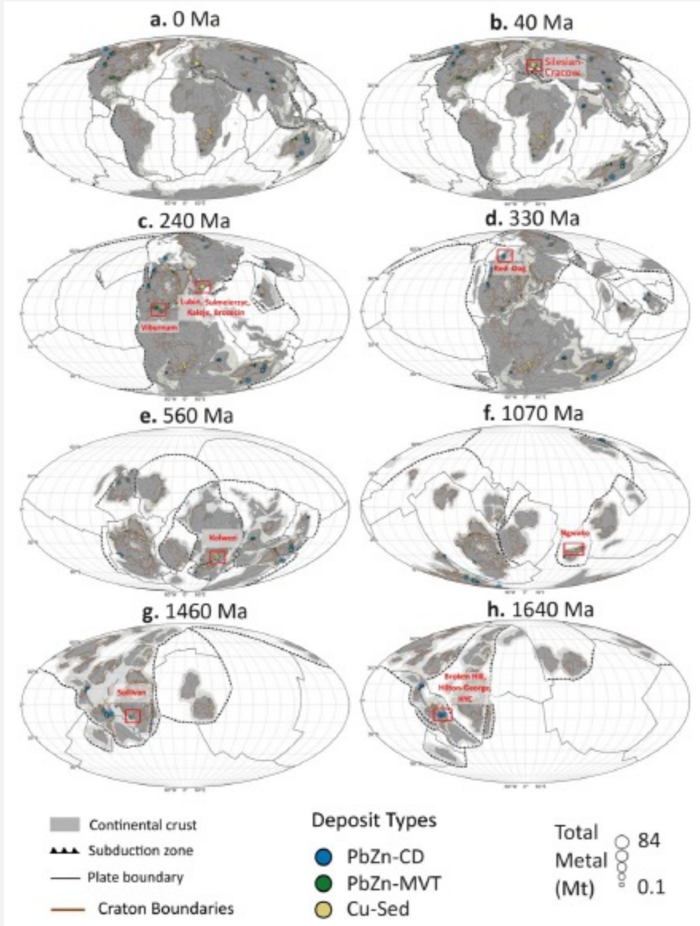
Schematic. Superstructures and magnetic character after Néel (1952); Rochette et al. (1990); Horng & Roberts (2018); Tang & Chen (2022).

3. Paleogeography



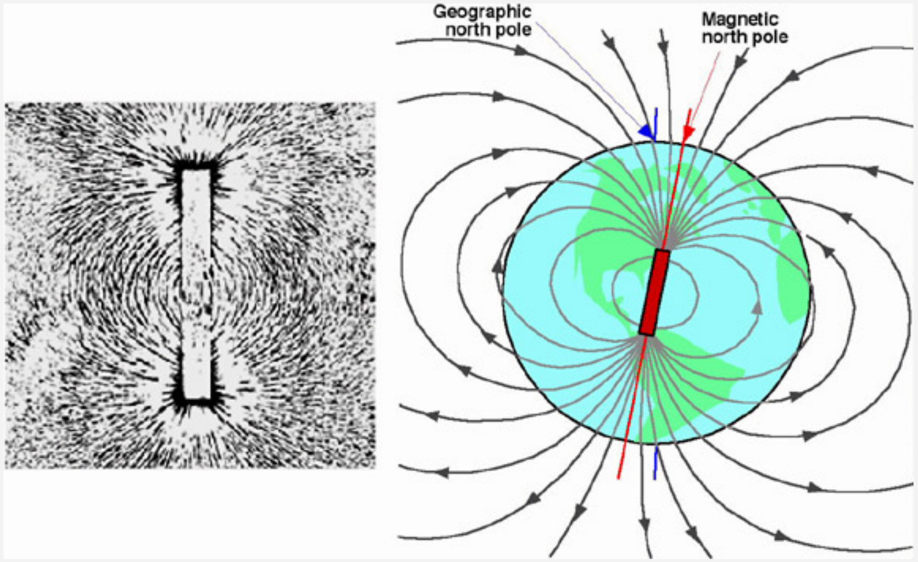
"Here we show that mineralised craton edges consistently cluster 800–1,800 km from subduction zones at the time of formation, with some as far away as ~3000 km—a spatial pattern distinct from random craton-edge locations. [...] These results identify subduction–craton coupling as a first-order control on sediment-hosted mineral systems across multiple supercontinent cycles and provide a predictive geodynamic framework for understanding the distribution of continental resources through deep time."

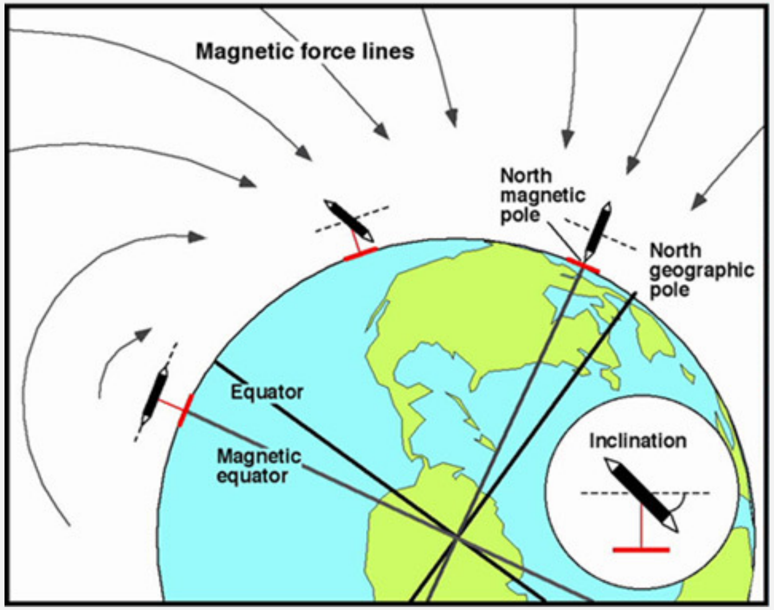
Shirmard et al., 2026



3. Paleogeography

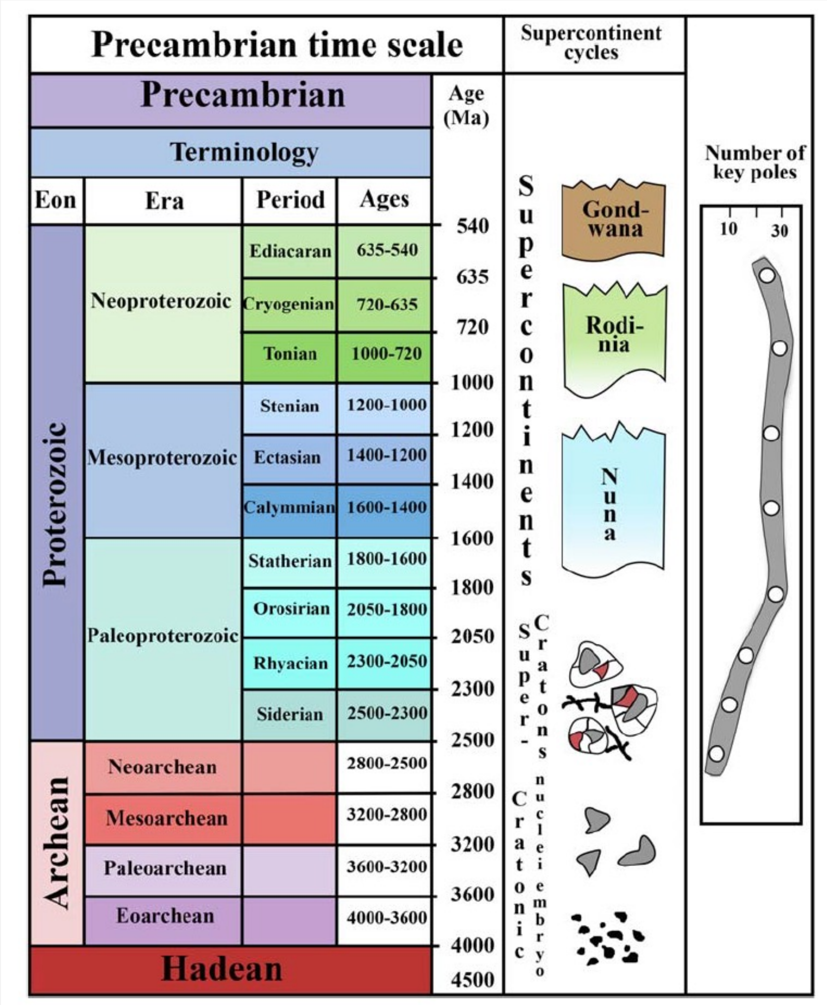
- Paleolatitude can be reconstructed

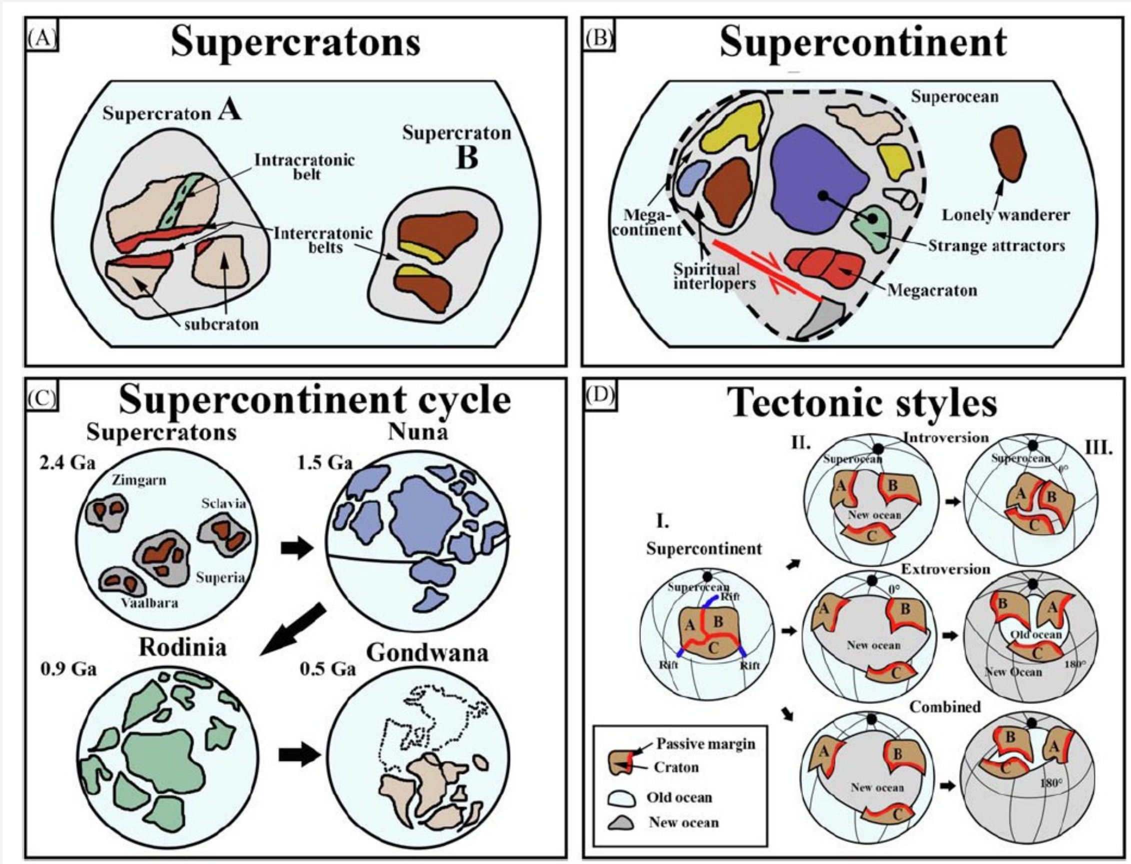




Inclination – Latitude

tan(I) = 2 * tan (λ)





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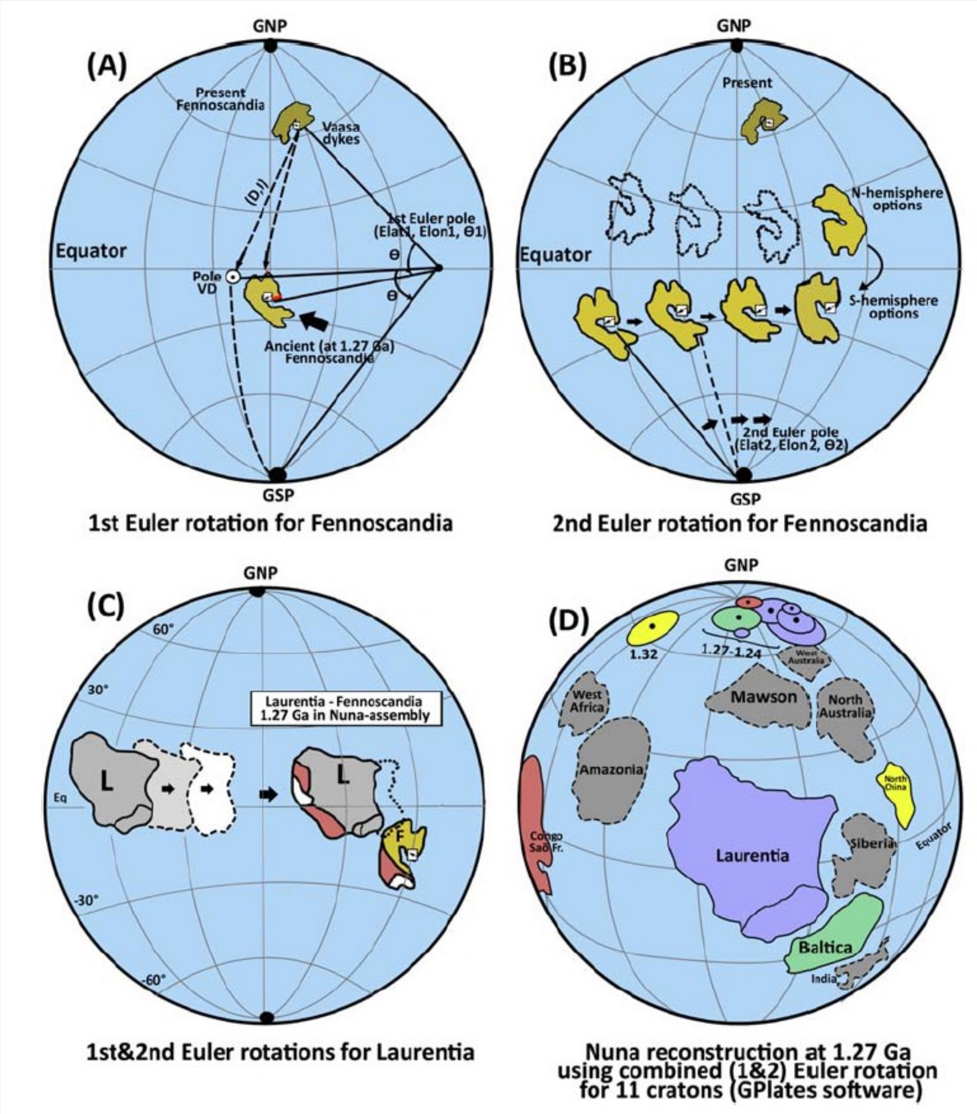

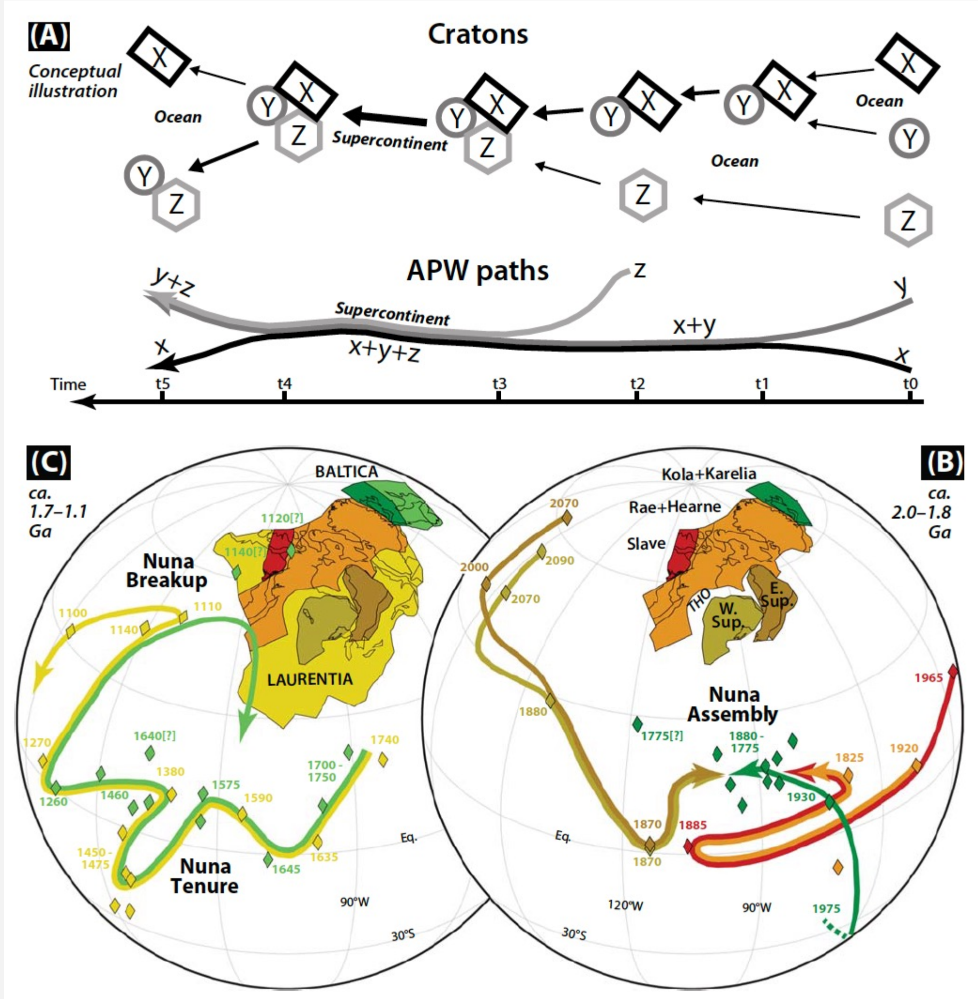

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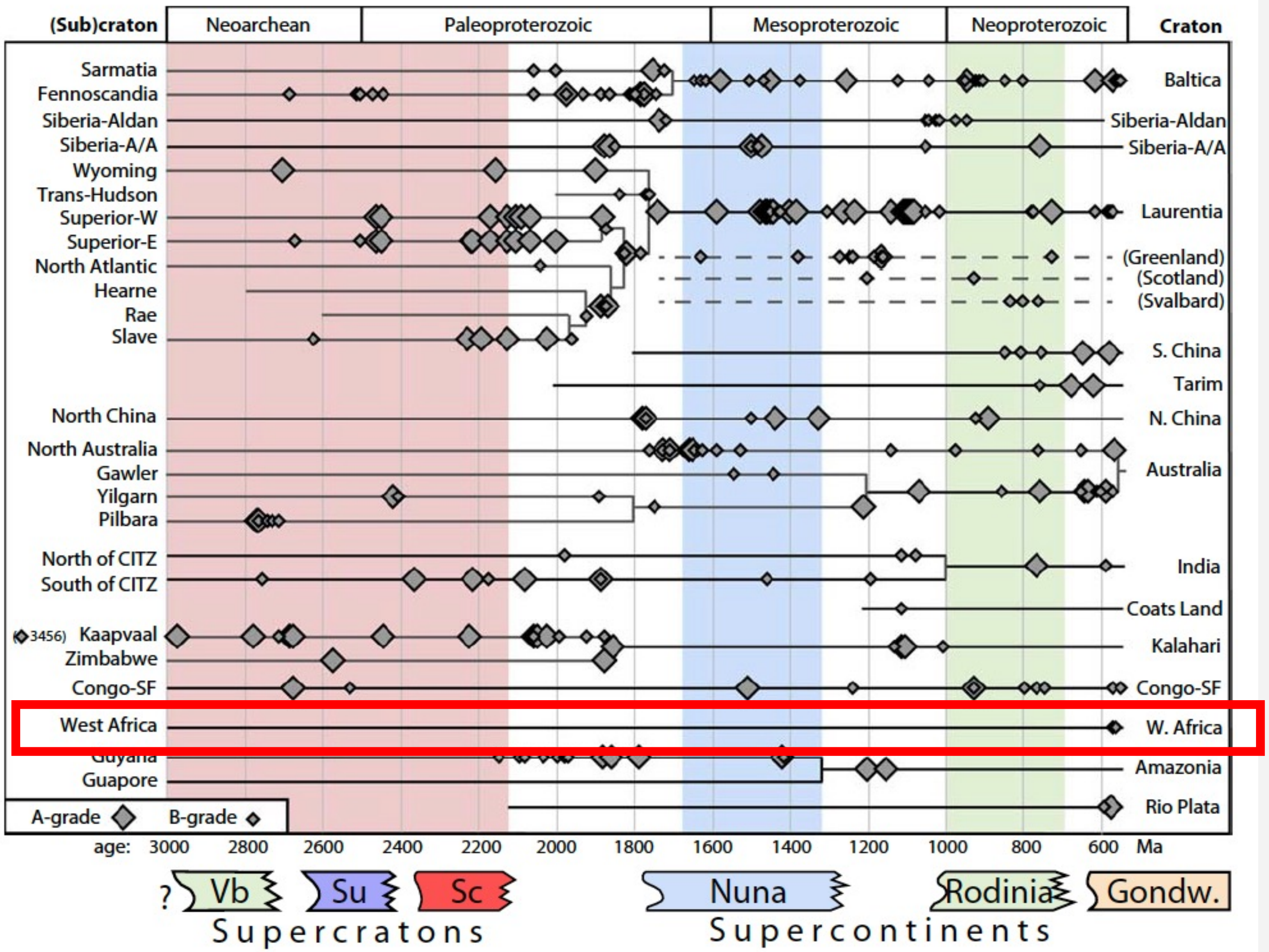

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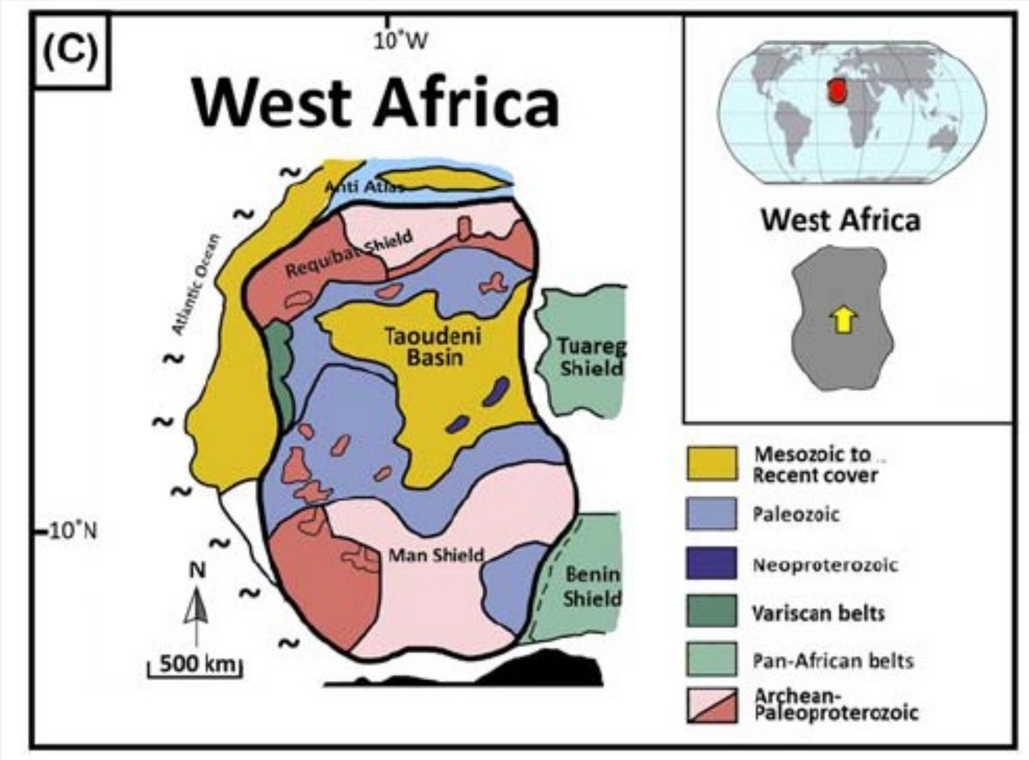
CHAPTER

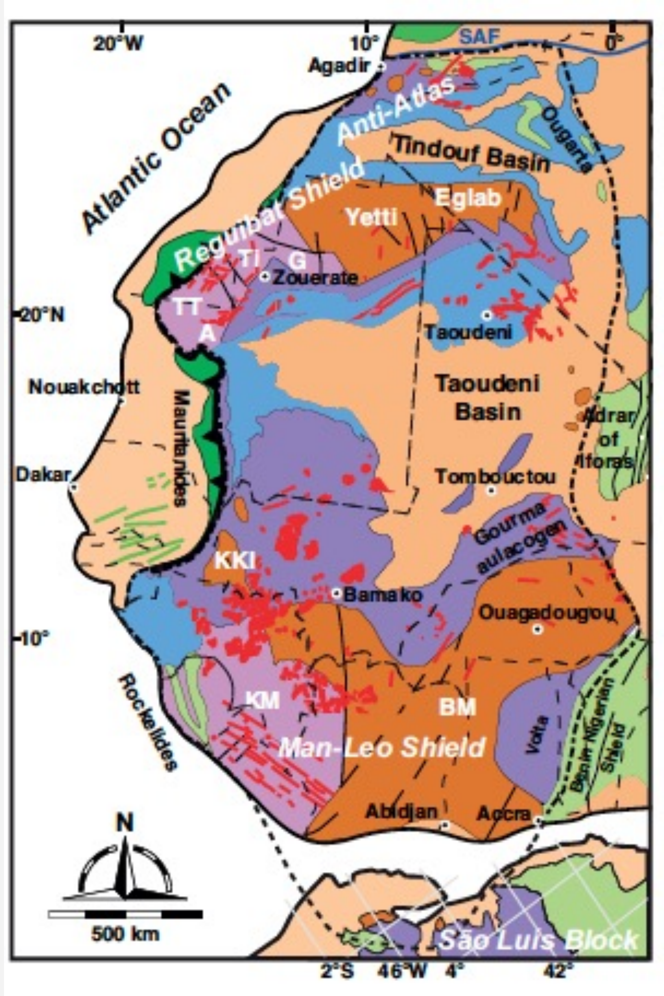
13

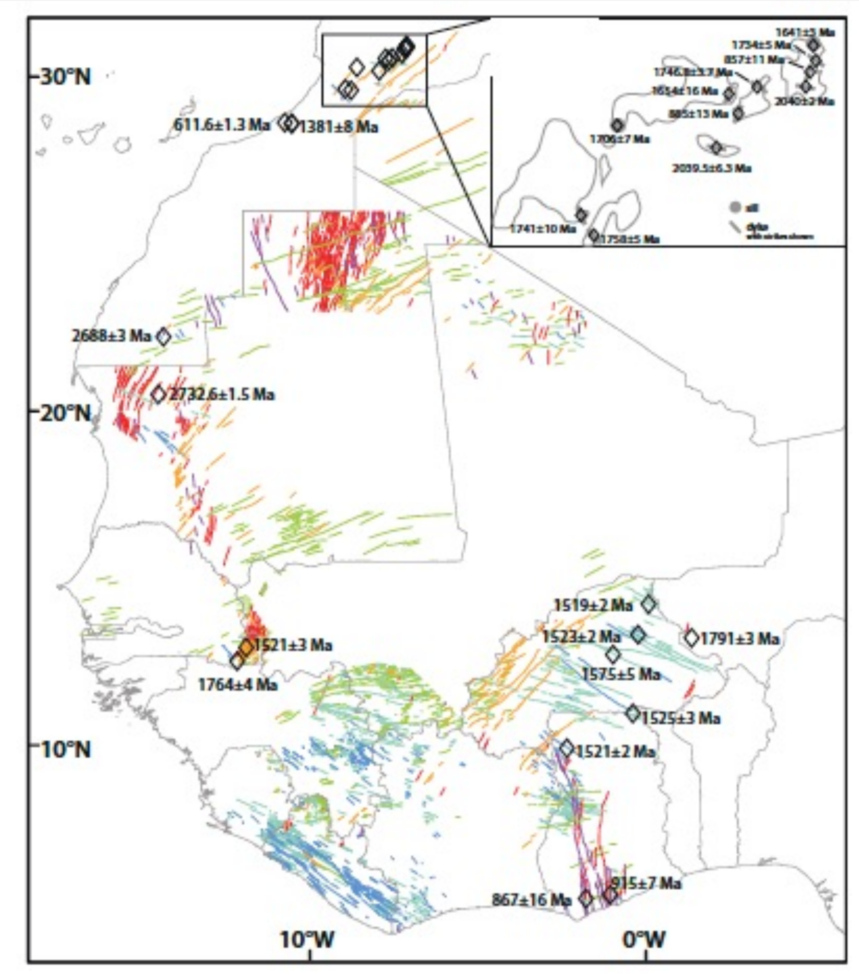
Constraints on the Precambrian paleogeography of West African Craton

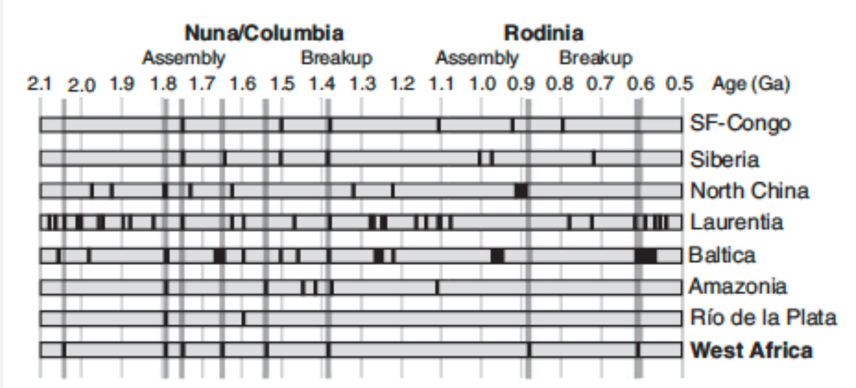
Zheng Gong and David A.D. Evans

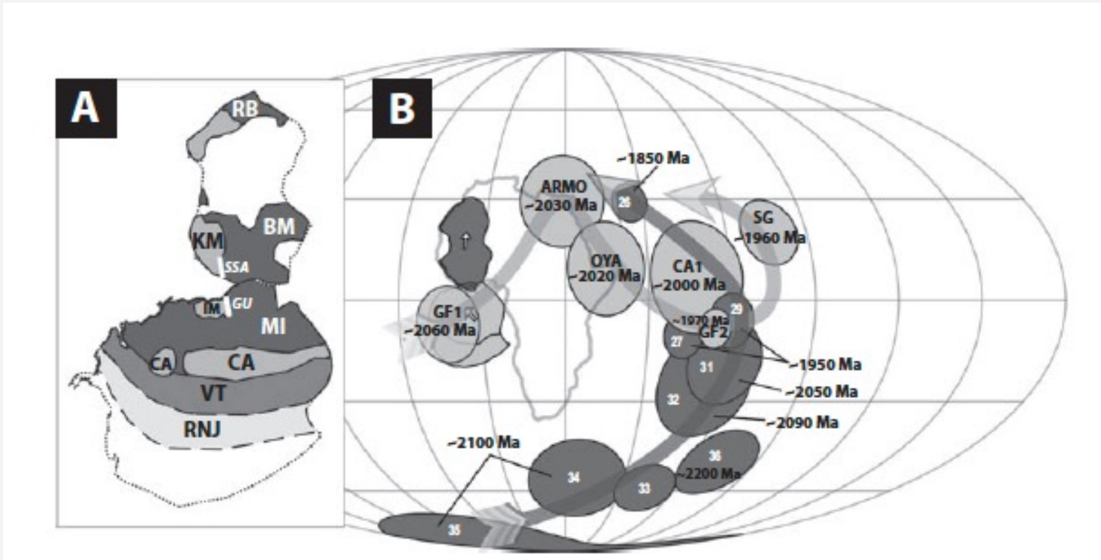
Department of Earth and Planetary Sciences, Yale University, New Haven, CT, United States











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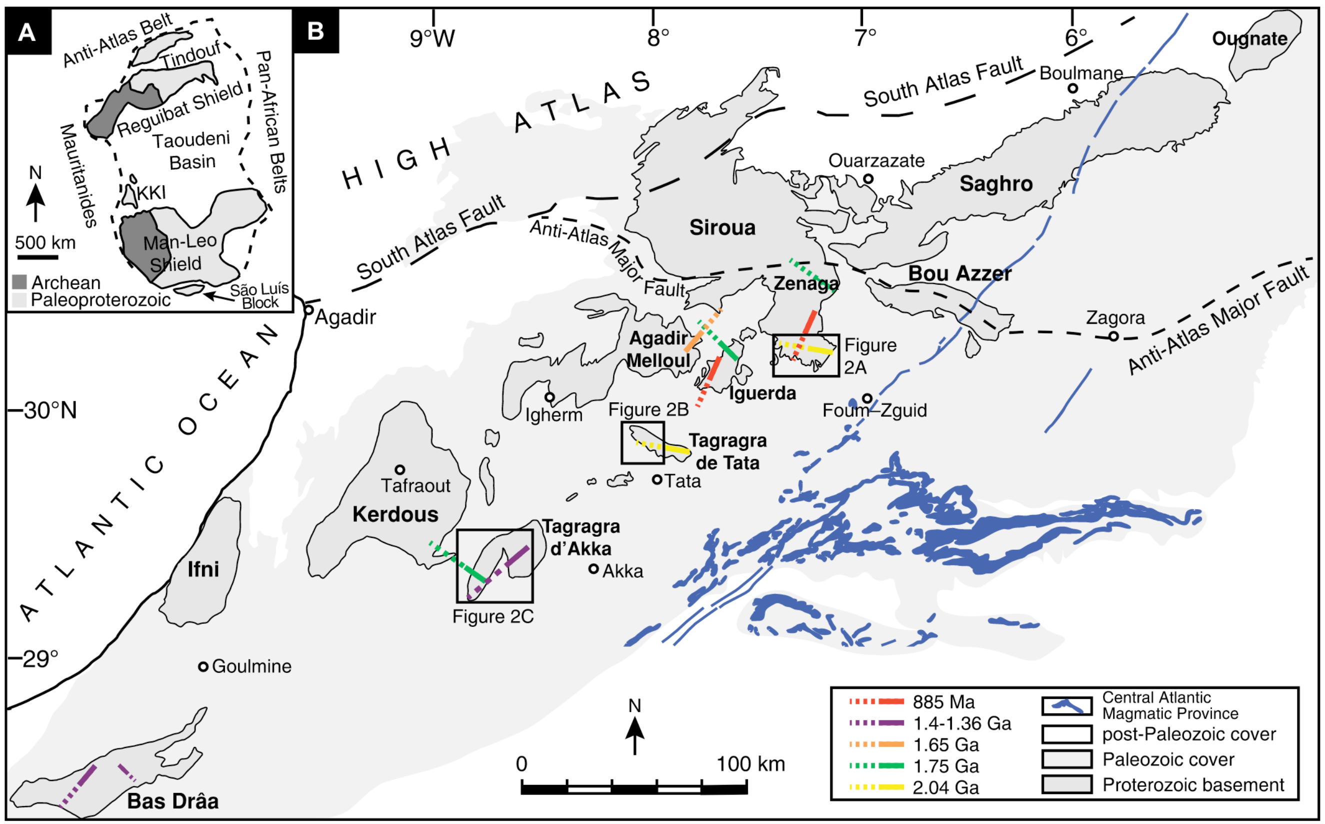
https://doi.org/10.1130/(

Manuscript received 25 Janu
Revised manuscript received 25 Ma
Manuscript accepted 11 A

Reorienting the West African craton in Paleoproterozoic–Mesoproterozoic supercontinent Nuna

Zheng Gong[1*], David A.D. Evans[1], Nasrrddine Youbi[2,3], Abdelhak Ait Lahna[2], Ulf Söderlund[4,5], Malika Ait Malek[2], Bin Wen[1], Xianqing Jing[1], Jikai Ding[1], Moulay A. Boumehdi[2] and Richard E. Ernst[3,6]



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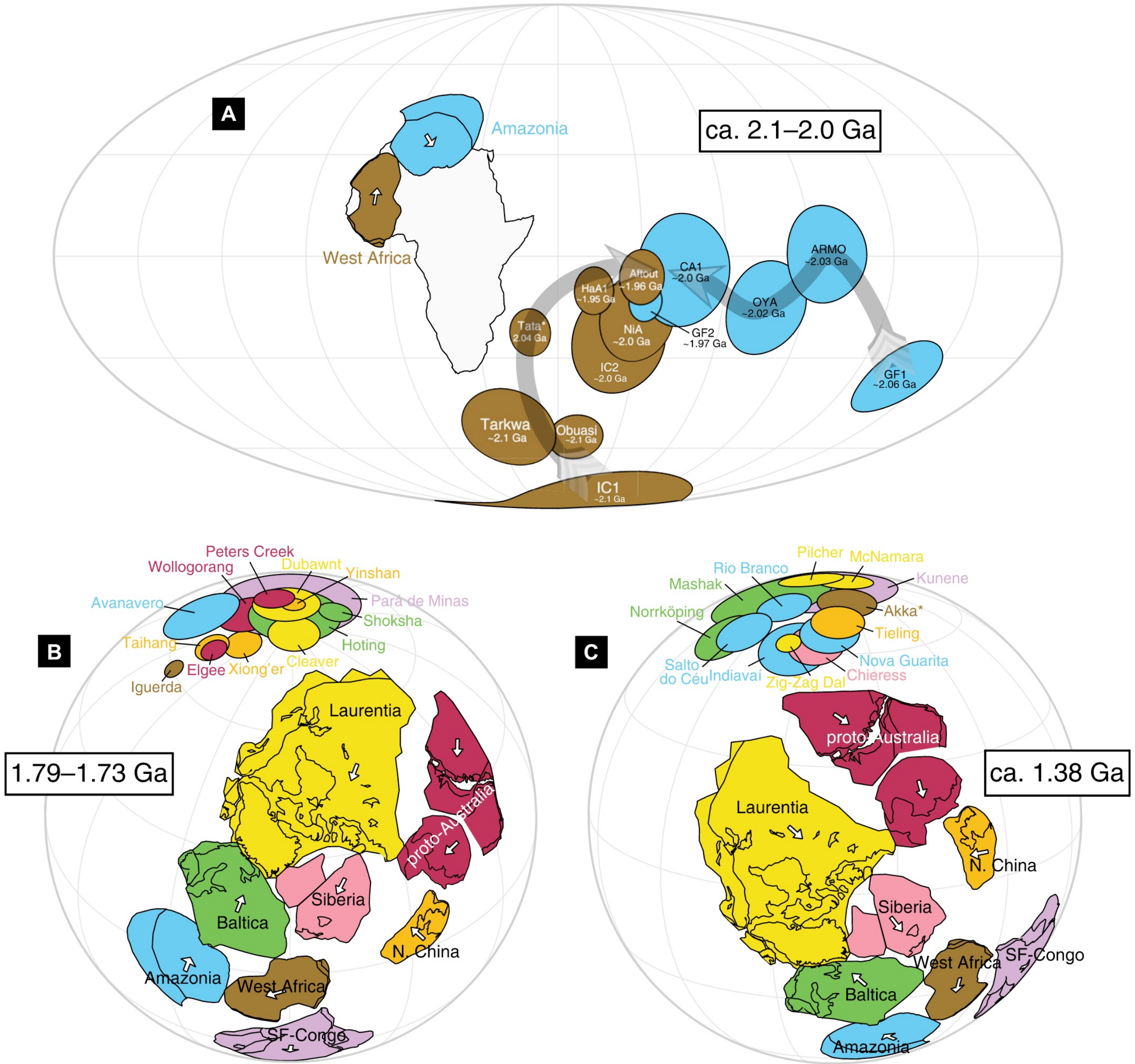

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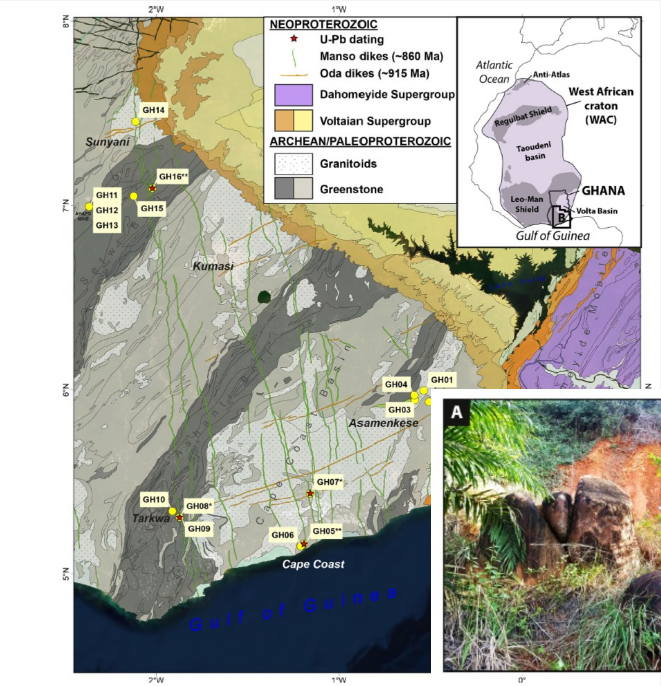
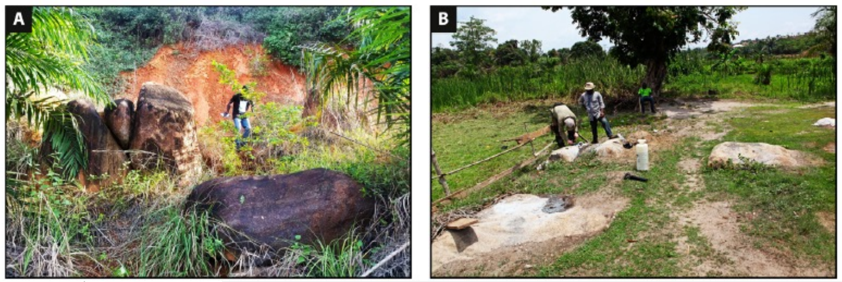
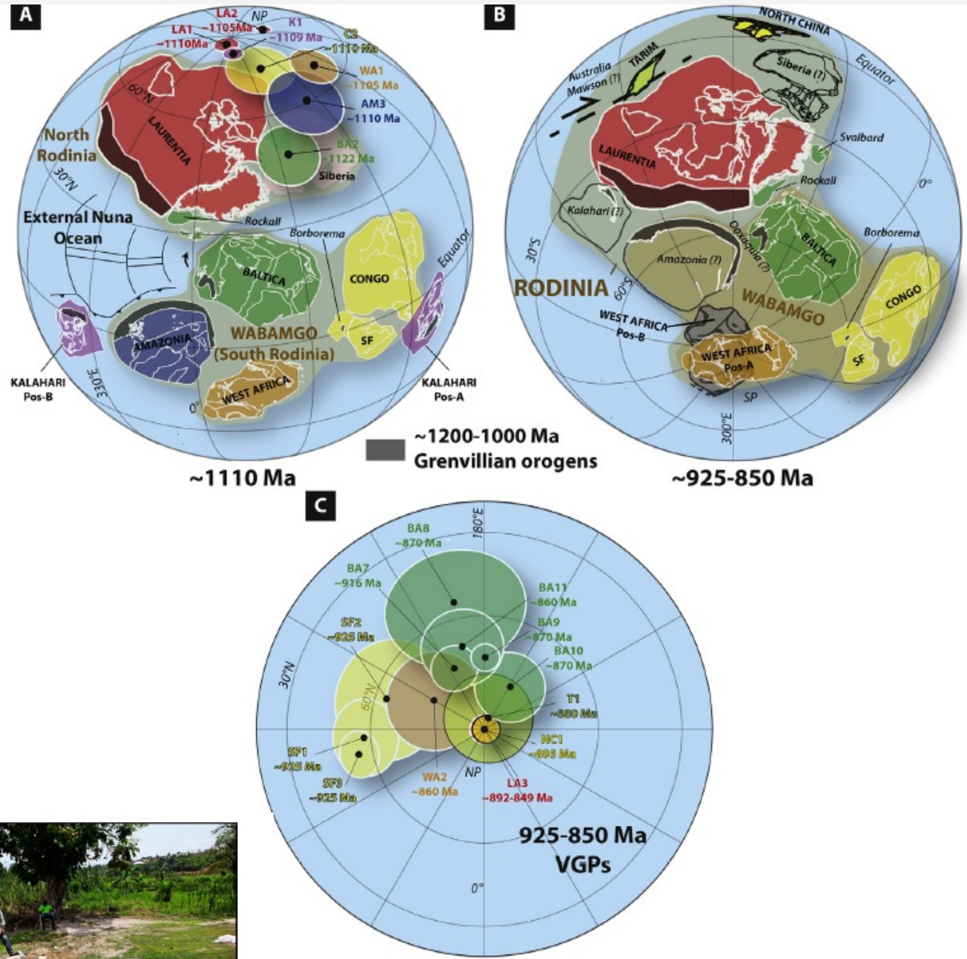
West Africa in Rodinia: High quality paleomagnetic pole from the ~ 860 Ma Manso dyke swarm (Ghana)

Check for updates

Paul Yves Jean Antonio [a,b,*], Lenka Baratoux [b], Ricardo Ivan Ferreira Trindade [a], Sonia Rousse [b], Anani Ayite [c], Cristiano Lana [d], Mélina Macouin [b], Emmanuel Williams Kobby Adu [e], Caroline Sanchez [f], Marco Antônio Leandro Silva [d], Anne-Sophie Firmin [b], Carmen Irène Martínez Dopico [g], Arnaud Proietti [h], Prince Ofori Amponsah [e], Patrick Asamoah Sakyi [e]







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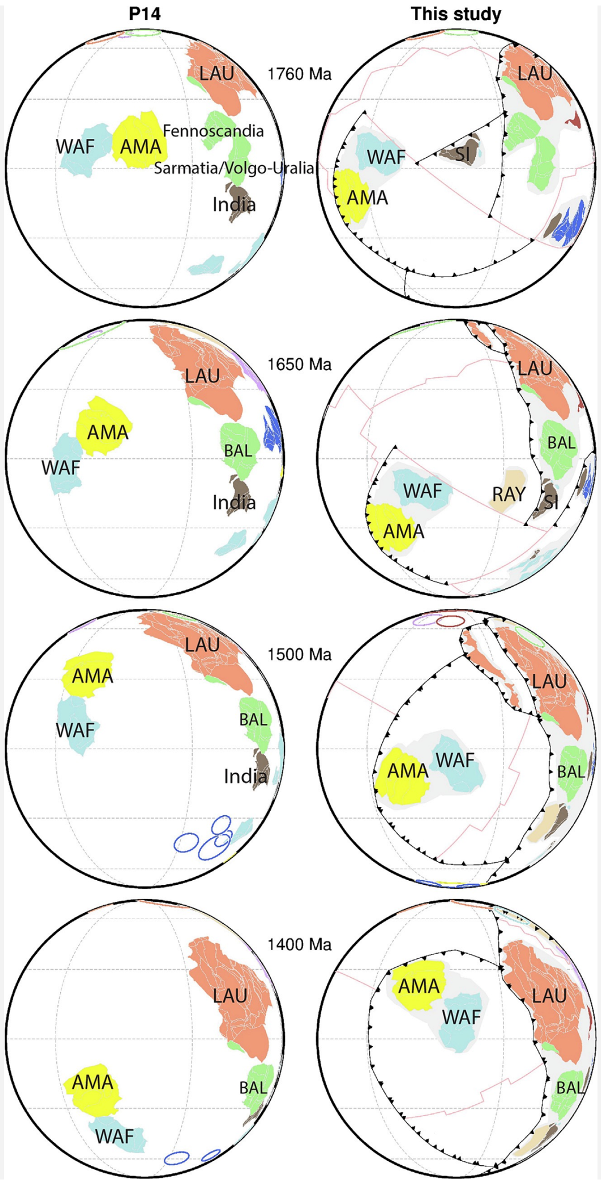
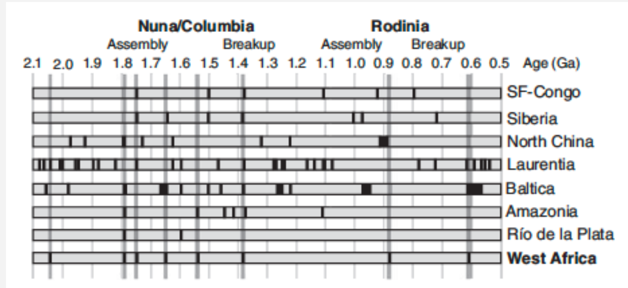
Cao et al., 2024

- Following Pisarevsky et al. (2014), West Africa–Amazonia are left out of Nuna.
- They drift ~2000–5000 km west of Laurentia–Baltica until colliding with Laurentia at ~1.07 Ga (Rodinia); positions set by nine palaeomagnetic poles.
- Rigid Gondwana WAC–Amazonia fit (Trompette, 1994) rejected: the 860 Ma West Africa pole (Antonio et al., 2021) would need an unreasonable ~80° rotation.
- West Africa rifts from Amazonia at ~720 Ma, then accretes onto the Sahara Metacraton at ~600 Ma.
- SAMBA left open — Amazonia placed outside Nuna, but the debate is flagged as unresolved.





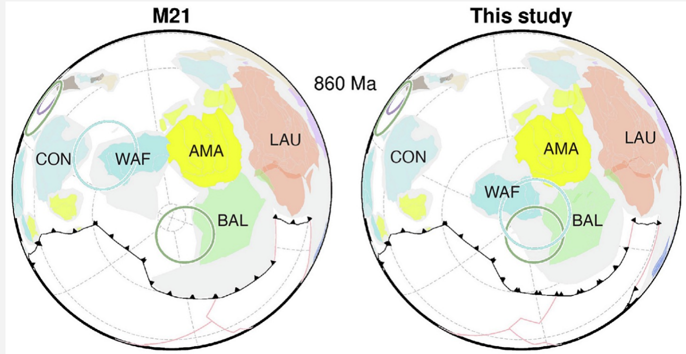


Fig. 10 — WAC rotated relative to Amazonia at 860 Ma (pole 9968; light-blue circle). Cao et al. (2024), Geosci. Front. (CC BY-NC-ND).

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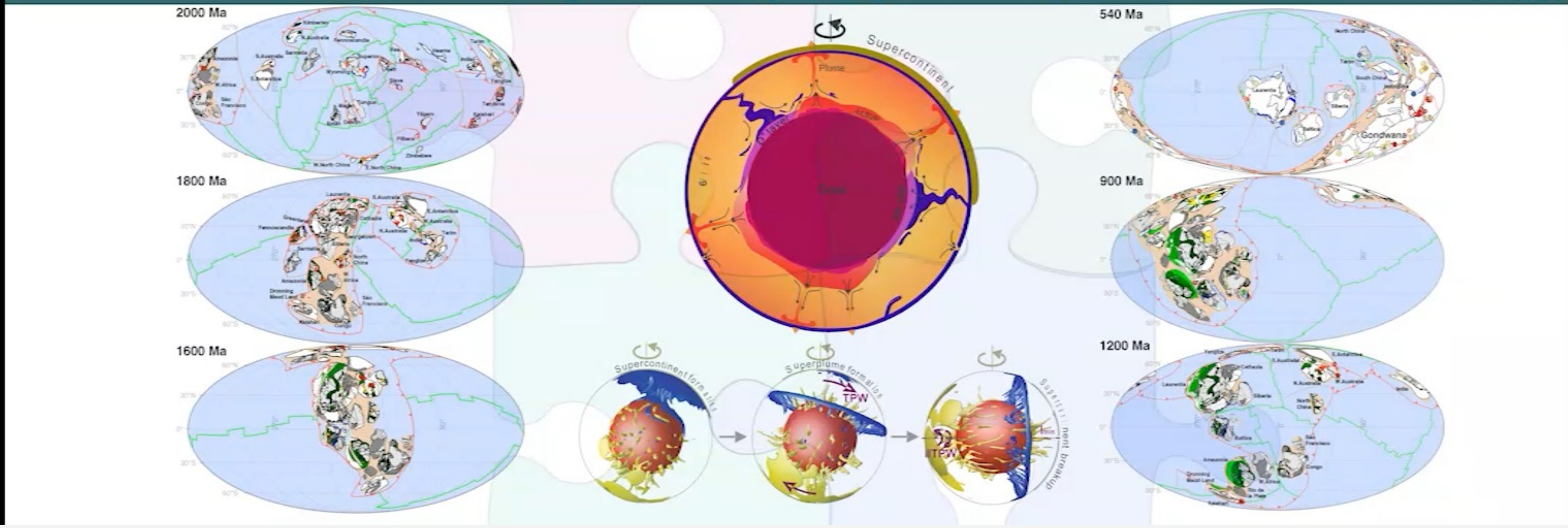
Supplementary material 7 – *Senario Ia* (0-90W-0)

A dynamic 2000-540 Ma Earth history:

From cratonic amalgamation to the age of supercontinent cycle

Zheng-Xiang Li*, Yebo Liu*, Richard Ernst
(*z.li@curtin.edu.au; yebo.liu@curtin.edu.au)

V1 2023



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2 Baltica + Atlantica: the pre-Columbia (SAMBA) link

Terentiev & Santosh (2020) · Earth-Science Reviews 210, 103378

WHERE IT PLACES WAC + AMAZONIA

WAC + Amazonia (Atlantica) behave as one block, joined to Baltica along the Volga-Don ↔ Eburnean/Birimian ↔ Trans-Amazonian orogens — the SAMBA fit.

- Amazonia + West Africa collided along the Trans-Amazonian and Eburnean/Birimian orogens at ~2.1–2.0 Ga (Atlantica).
- Volga-Don (Baltica), Eburnean/Birimian (WAC) and Trans-Amazonian (Amazonia) orogens share near-identical lithologies and ages (2.23–2.05 Ga; collision ~2.12–2.10 Ga).
- Matching Archean blocks: Kursk-Azov ↔ Kénéma-Man ↔ São Francisco; Imataca ↔ Dniester-Bug; Volgo-Uralia ↔ Reguibat.
- Best junction: Volga-Don orogen ↔ Eburnean/Birimian (northern Kédougou-Kéniéba and Anti-Atlas inliers).
- Refines Johansson's SAMBA; link persists through Columbia to ~1.6 Ga and until Rodinia break-up.

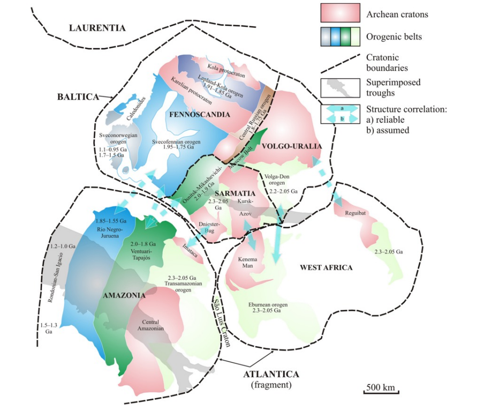

Fig. 14 — Baltica–Amazonia–West Africa, 'Atlantica (fragment)'. Terentiev & Santosh (2020), Earth-Sci. Rev. © Elsevier.

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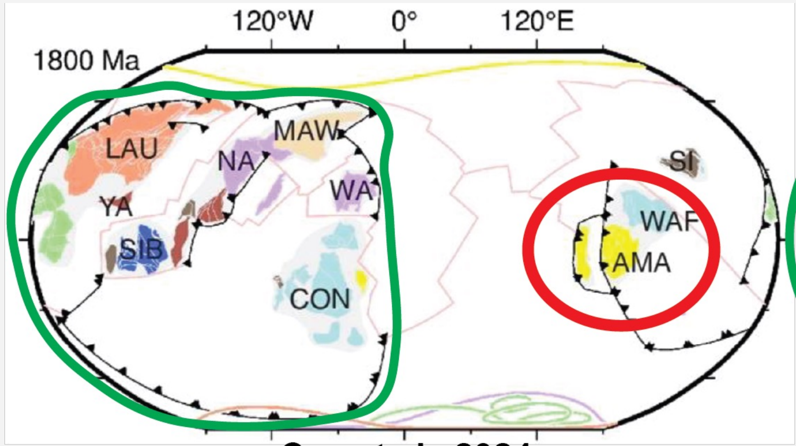
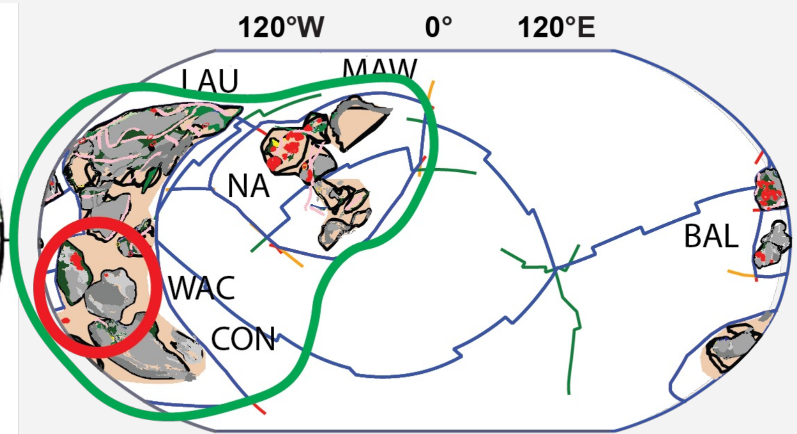
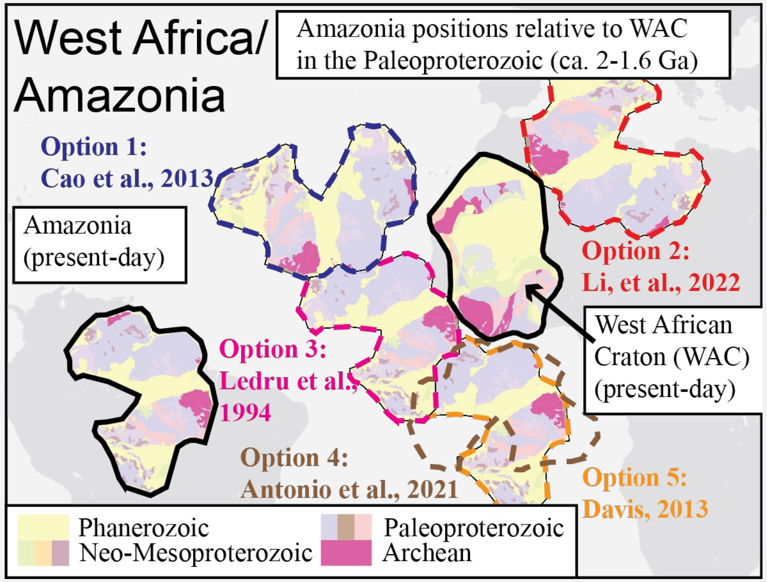


Cao et al., 2024

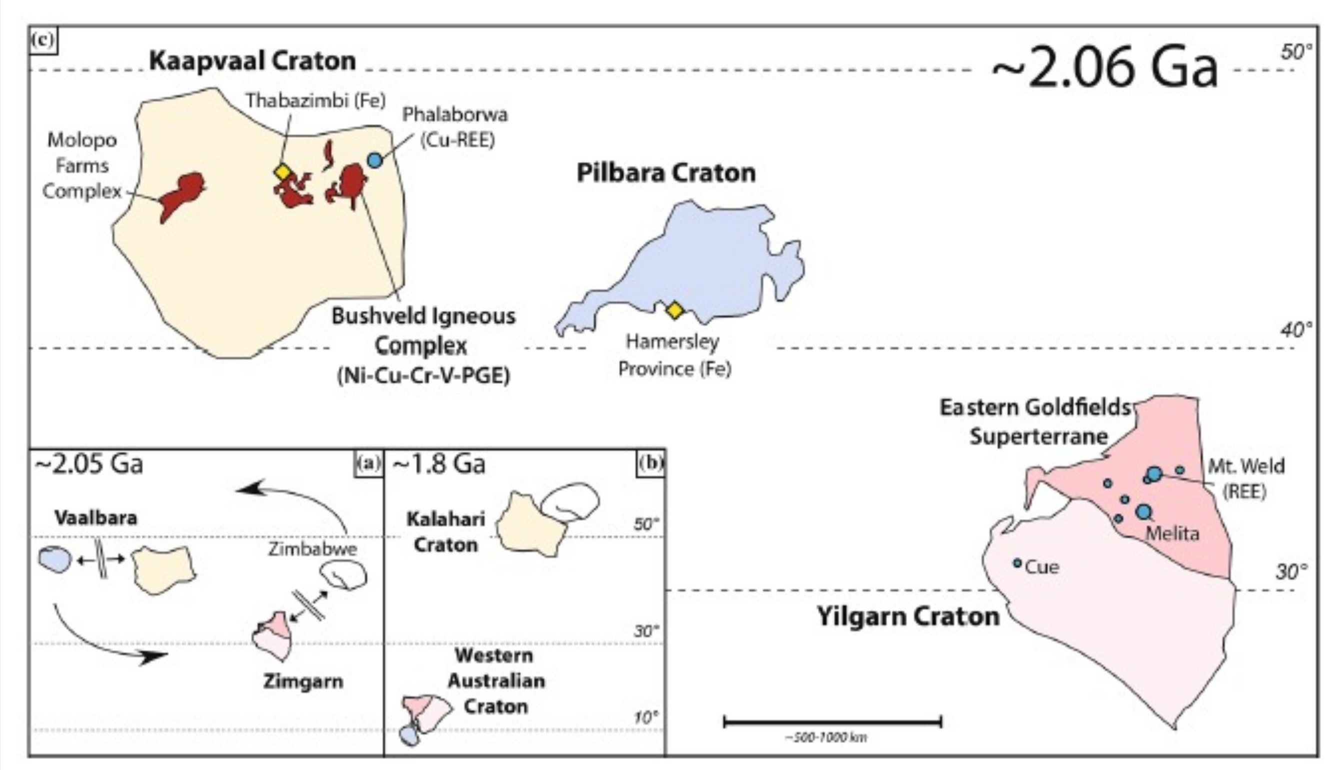


Li et al., 2023



- Large uncertainties remain
- Paleomagnetic data from more dyke swarms
- Other targets?

Case study on carbonatite as complex example: Fiorentini et al., 2020: Mt Weld



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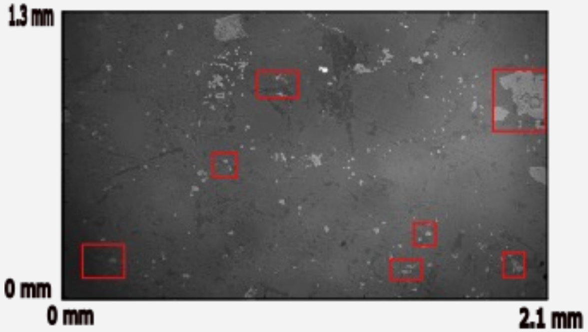
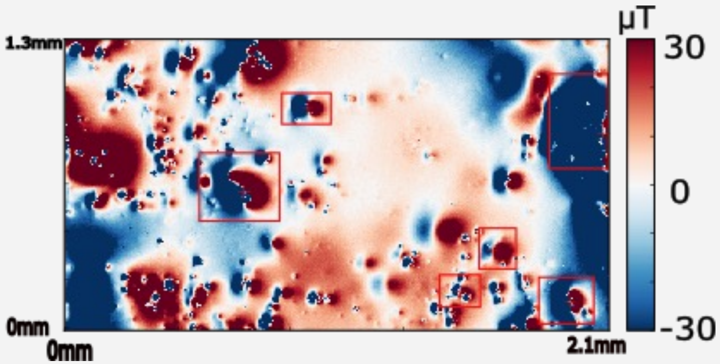
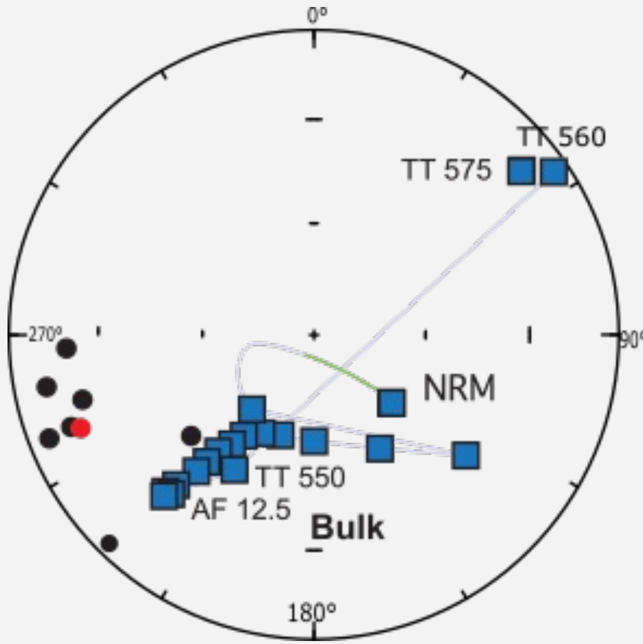
Quantum Diamond Microscopy of Primary Remanence Direction (Mt Weld)

Breccia Phlogopite Phoscorite







- Primary magnetic signal
- Positive baked contact test using an intruding ca. 1.2 Ga dyke
- Constraining Yilgarn position at 2 Ga

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Ahmed Bekhit PhD: 3D inversion of micromagnetic data using Tomofast

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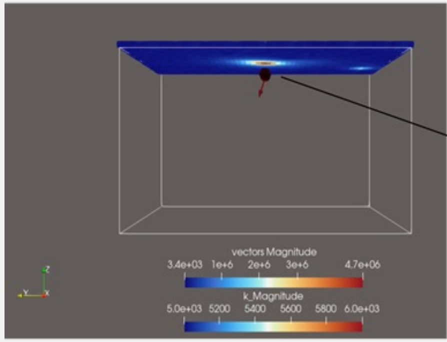
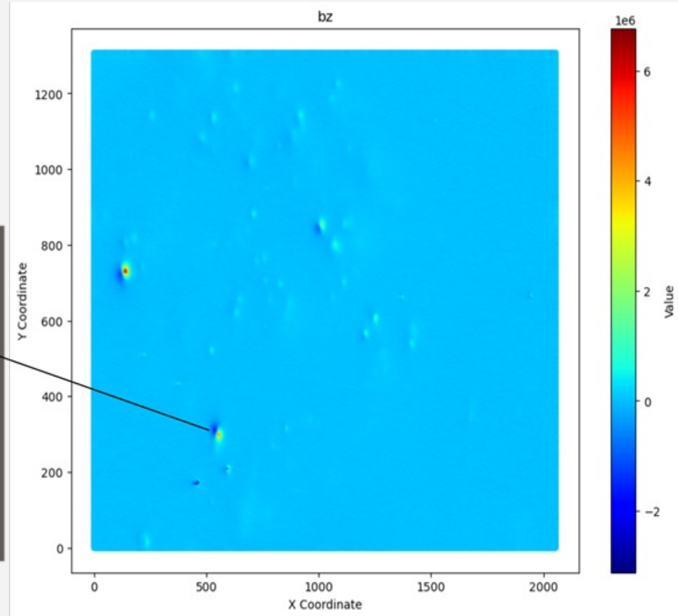
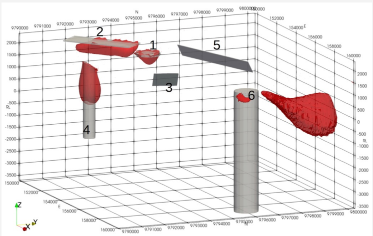
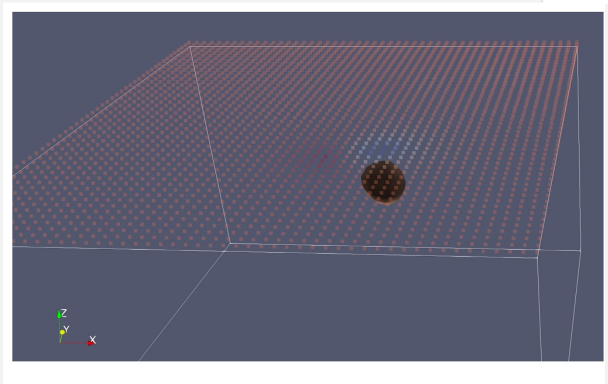
- 3d inversion using Tomofast-x
- Ability to investigate more complex signals quantitatively

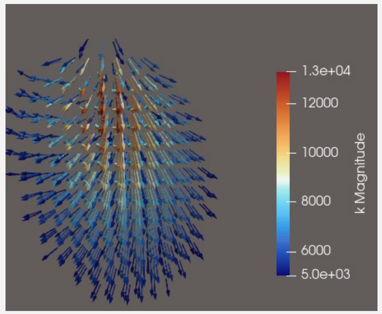






Tomofast-x 2.0





Thank you

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