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Understanding the Complex Magnetic Signatures of Magmatic Ni-PGE systems.

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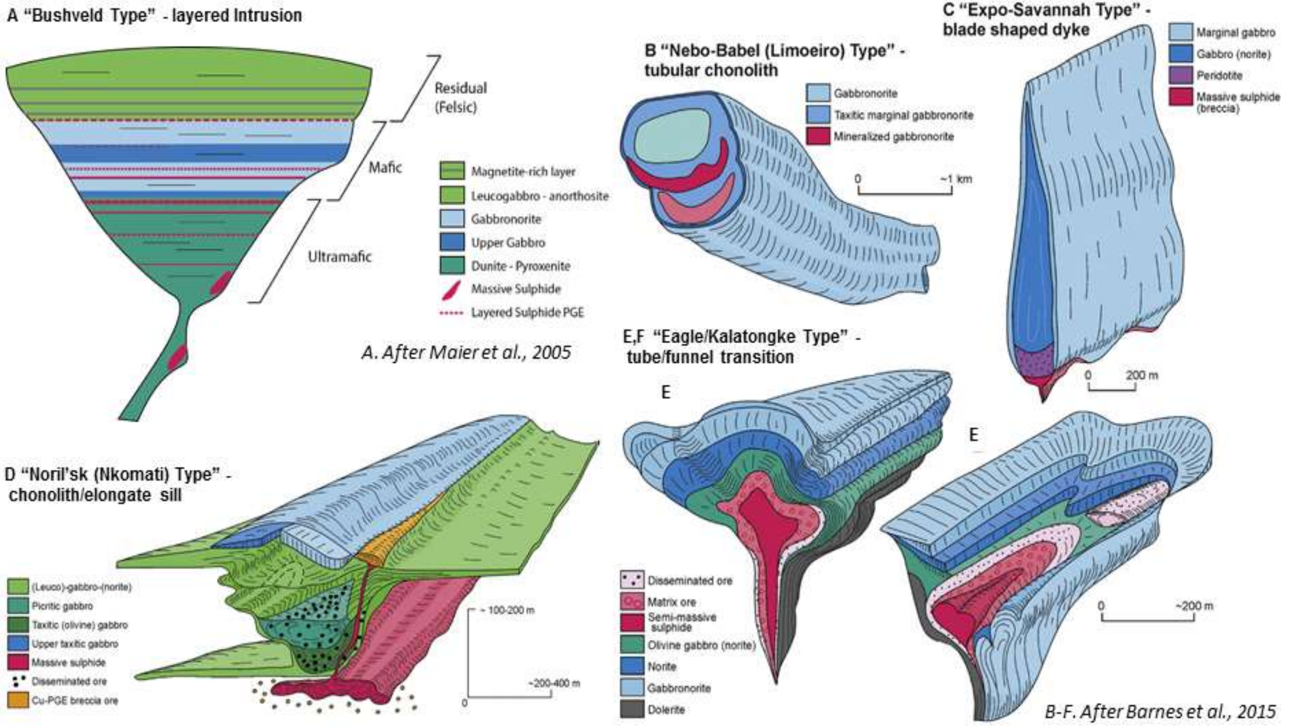
EXPLORATION 17
DMEC CONFERENCES

Introduction

- Magmatic Ni-PGE deposits are magnetically complex styles.
- Exploration has been focused on layered intrusions, e.g., the Bushveld Complex
- However, recent work suggests Ni-PGE deposits are associated with specific intrusion types:
  - chonoliths,
  - bladed-dykes and
  - funnels
- These acted as high-throughput magma conduits



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Magmatic Ni-PGE systems

- Rocks are compositionally diverse,
- Strong, stable and often complex remanent magnetization,
- Held in magnetite, titanomagnetite and pyrrhotite.
- We look at case studies from central and NW Australia, and examine FOUR processes that control remanence in magmatic Ni-PGE systems:

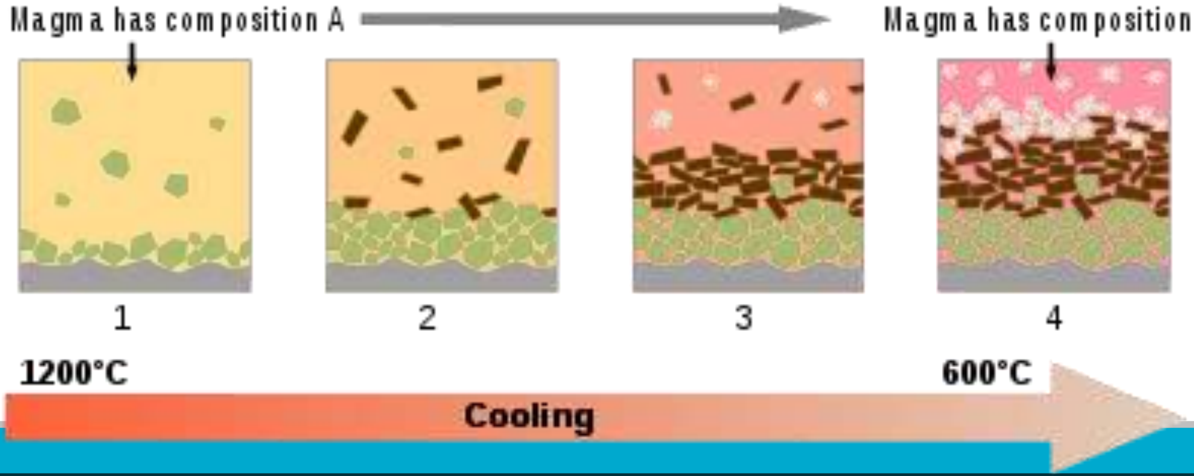
1. How does the process of fractional crystallization influence magnetic properties in mafic rocks?
2. How is extremely strong and stable remanent magnetization formed in mafic rocks?
3. How can completely different mafic rocks have identical remanence directions?
4. How can almost identical rocks have completely different magnetic signatures?

How does the process of fractional crystallization influence magnetic properties in mafic rocks?

Fractional Crystallization

- removal and segregation of crystals from a melt,
- which sink to form a cumulate at the base of the intrusion,
- thus changing the composition of the magma.

- orthopyroxene, clinopyroxene and olivine typically crystalize early
  - forming pyroxenite and dunite.
- The exact minerals precipitated vary, based on the composition of the magma,



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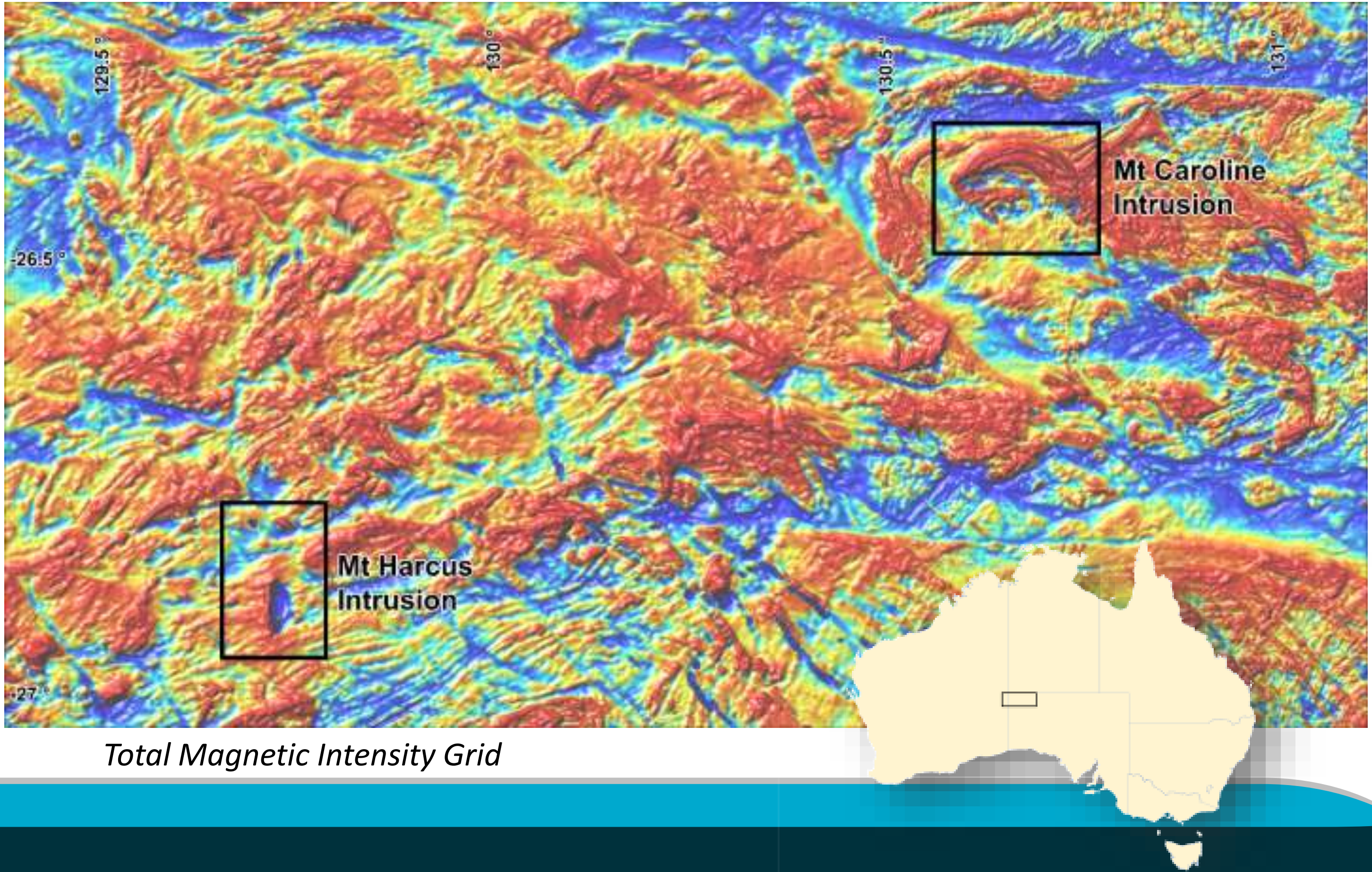
Both Giles aged intrusions ~1070 Ma



Total Magnetic Intensity Grid

Mt Caroline Intrusion

- 5 individual drill holes were sampled:
  - W2: lowermost basal unit,
  - W15: upper part of the basal unit,
  - C5: the highly magnetic mid - upper unit
  - C2 and C4 sample the more weakly magnetic parts.
- The results are discussed sequentially from the base of the to the middle to upper layers

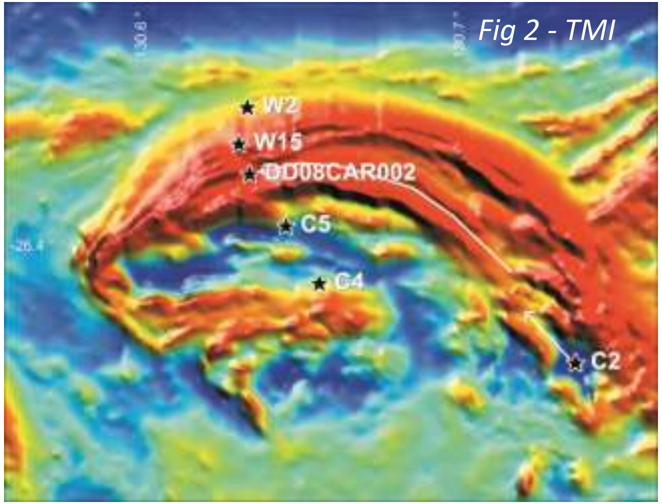


Fig 2 - TMI

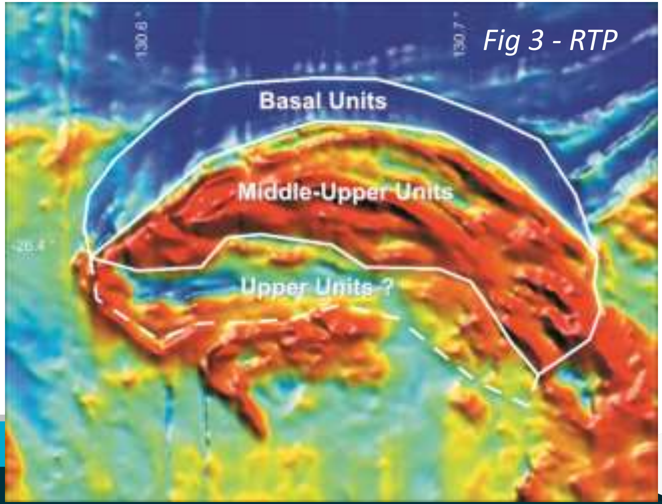


Fig 3 - RTP

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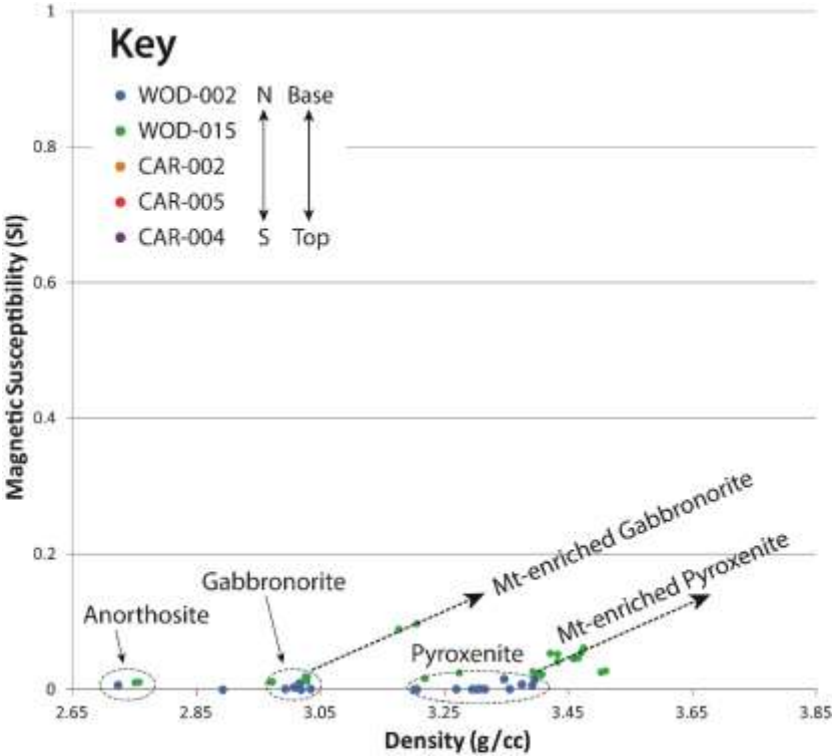
Basal Layers: density

- comprised of orthopyroxene, clinopyroxene and plagioclase.
- They have bi-modal base density
  - Not related to Iron oxides or sulfides
- Dense samples are pyroxenite
  - >90% pyroxene SG 3.3 - 3.5g/cc
- Interlayered Gabbronorites
  - significant plagioclase (SG: ~2.7 g/cc)
  - Feldspar reduces the bulk rock density
  - Density is inversely proportional to their plagioclase content.



Pyroxenite

Gabbronorite

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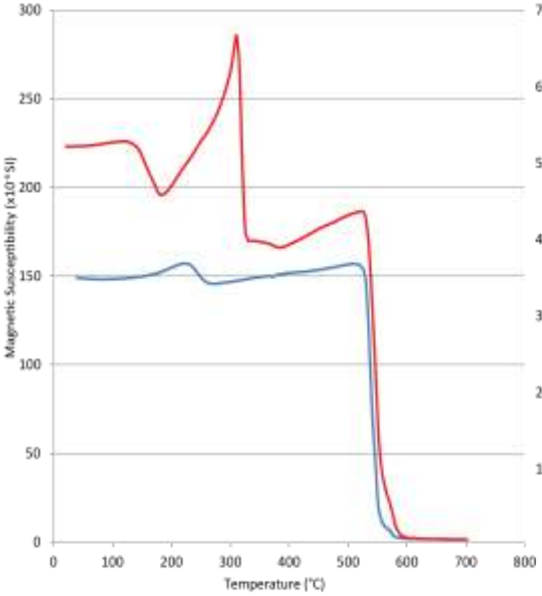
Basal Layers: magnetics

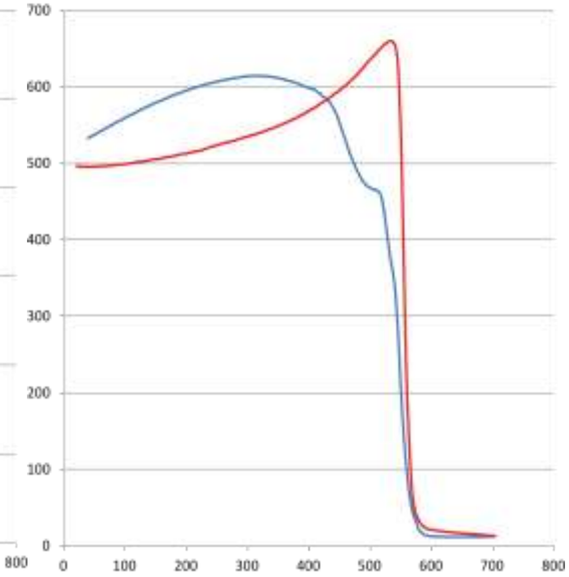
- Lowermost basal units are weakly magnetic
- Some samples had elevated susceptibility and remanence
  - contain significant pyrrhotite
  - This probably means Sulphur saturation has happened
- In the majority of samples,
  - the magnetization is low coercivity (soft);
  - Held in multi-domain (MD) magnetite/pyrrhotite.

Lower Basal



Pyrrhotite+Magnetite

Upper Basal



Magnetite-only

Middle - upper Layers

- As fractional crystallization continues the magma becomes increasingly felsic,
- precipitation of pyroxenite ceases.
- Gabbronorites are interlayered with plagioclase and magnetite-rich units
  - leucogabbro, leucogabbronorite, and anorthosite.
  - Magnetite-precipitation is triggered by episodic increases in f_{O2} (oxygen fugacity).
- In some layered intrusions magnetite can be semi-massive,
  - e.g., the Bushveld Complex
- In Mt Caroline, magnetite is relatively disseminated, occurs with plagioclase.

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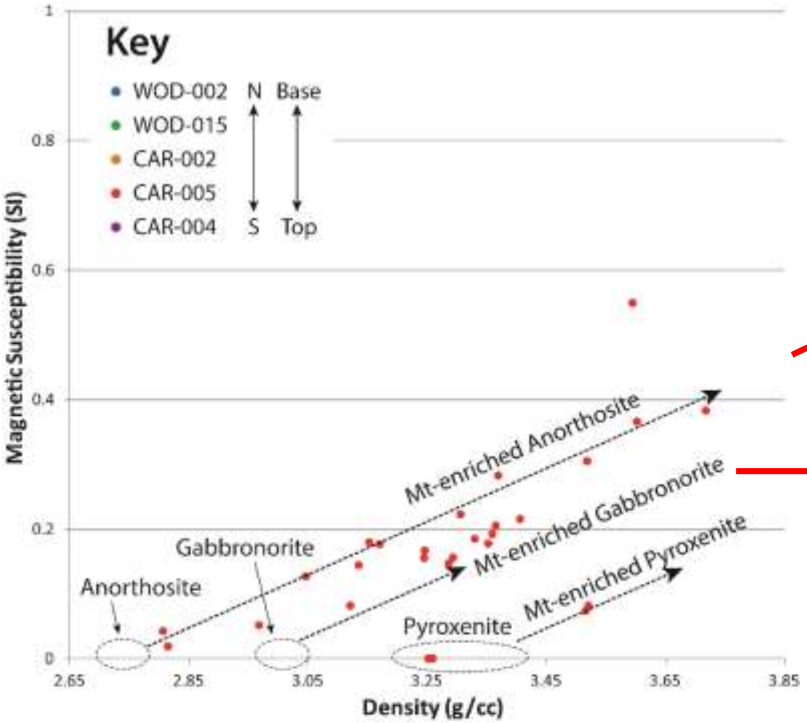
Upper Mt-rich Horizons (Susc vs Density)



Semi-massive Magnetite with Poikilitic texture

Disseminated Magnetite in Gabbronorite

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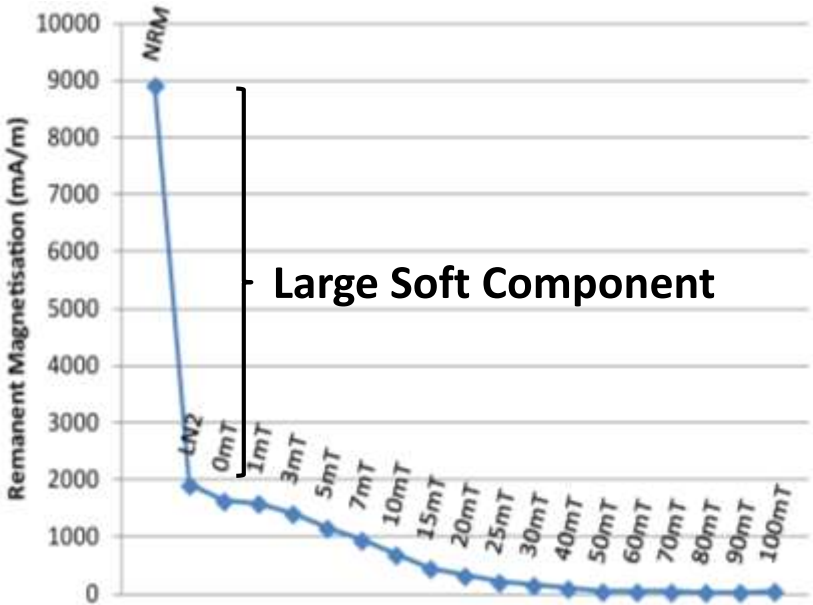
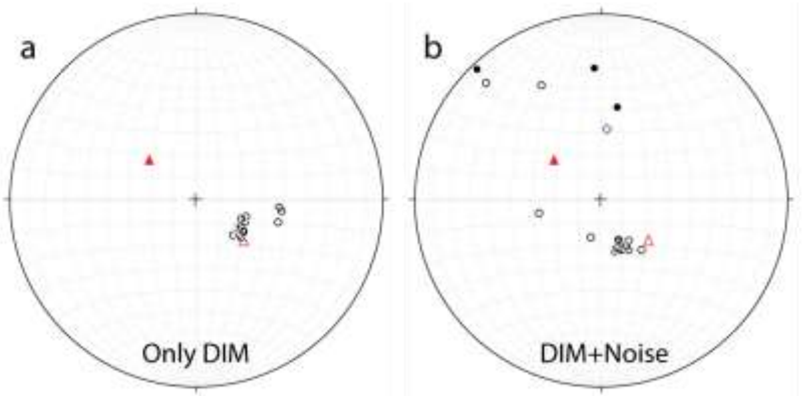
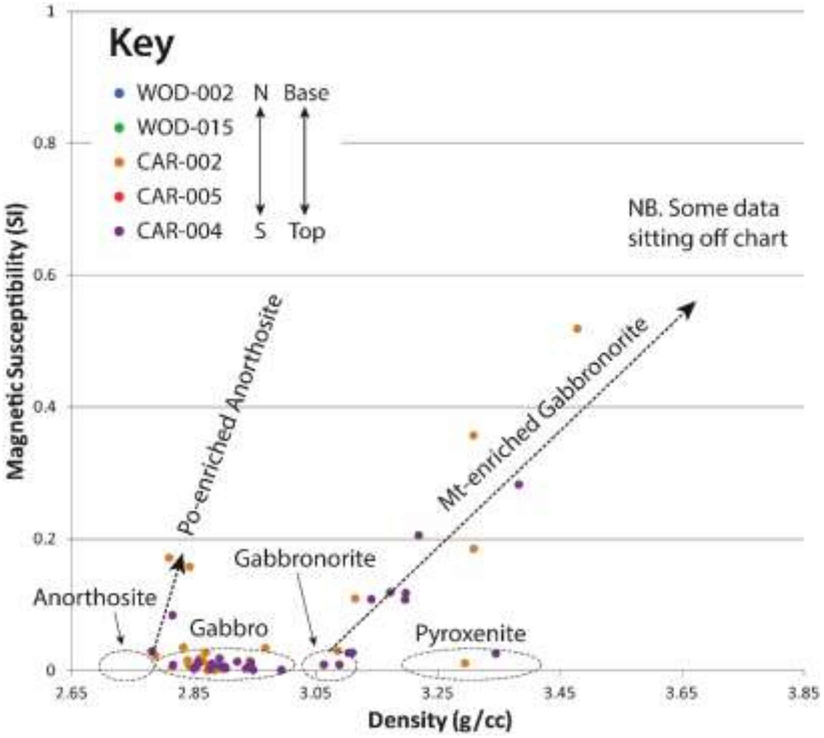
Upper Mt-rich Horizons (Demag behavior)

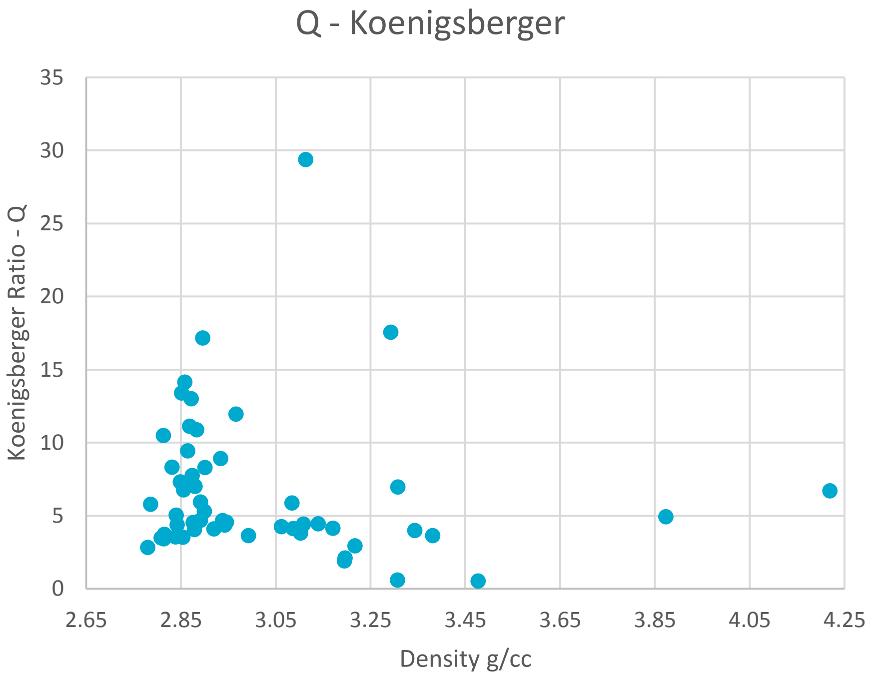




Directions indicate Drilling Induced magnetisation

Upper Mt-poor Units





- Mostly Low Magnetic Susceptibility
- But associated with high remanent magnetism
- 5-15 times stronger than induced magnetism

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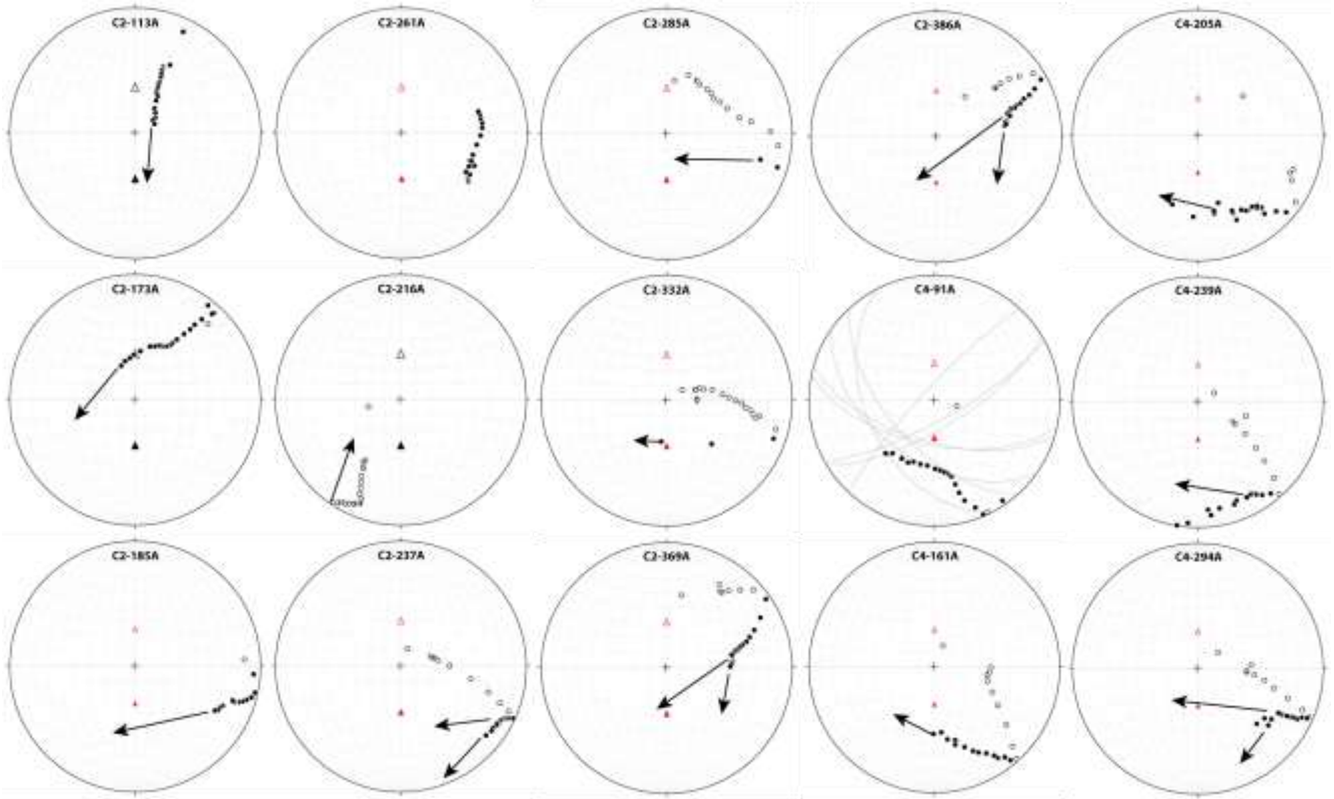
Upper Mt-poor Horizons (Remanence)



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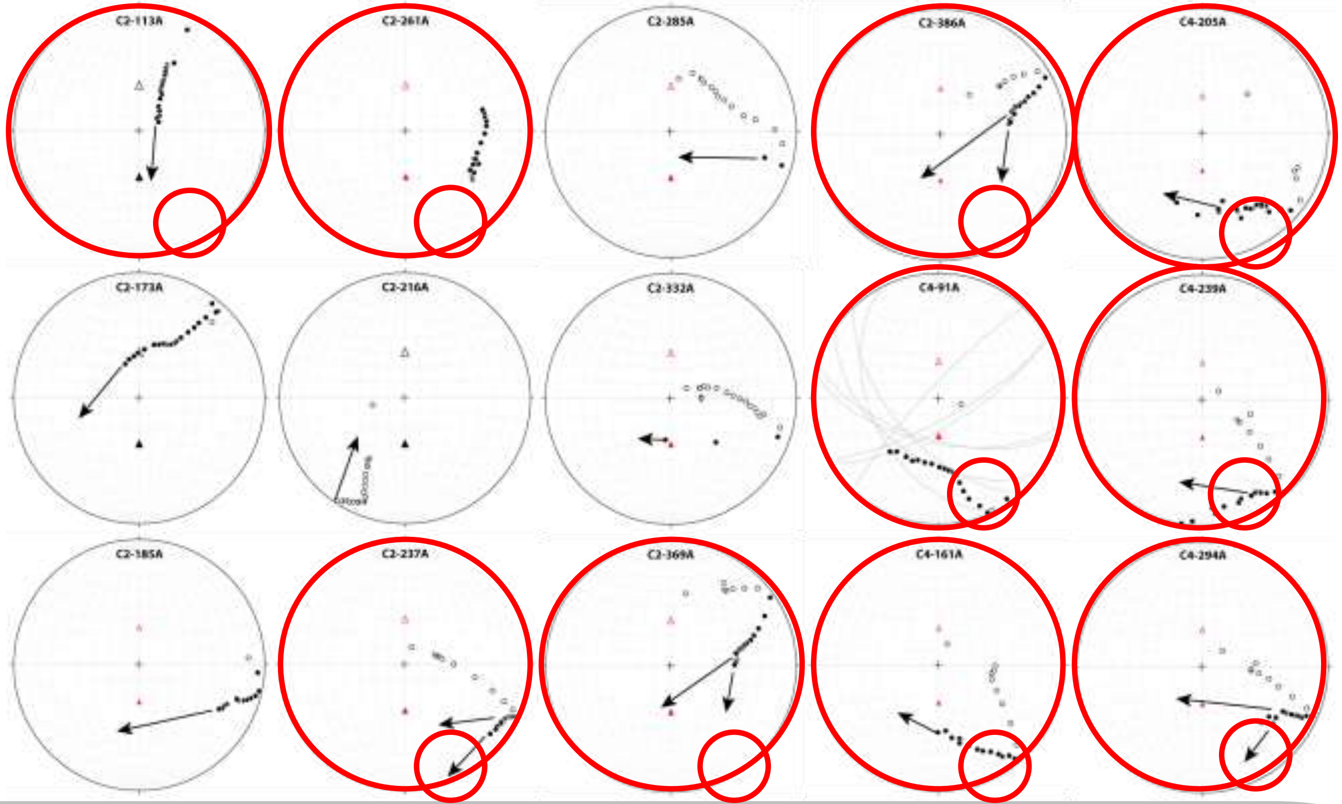
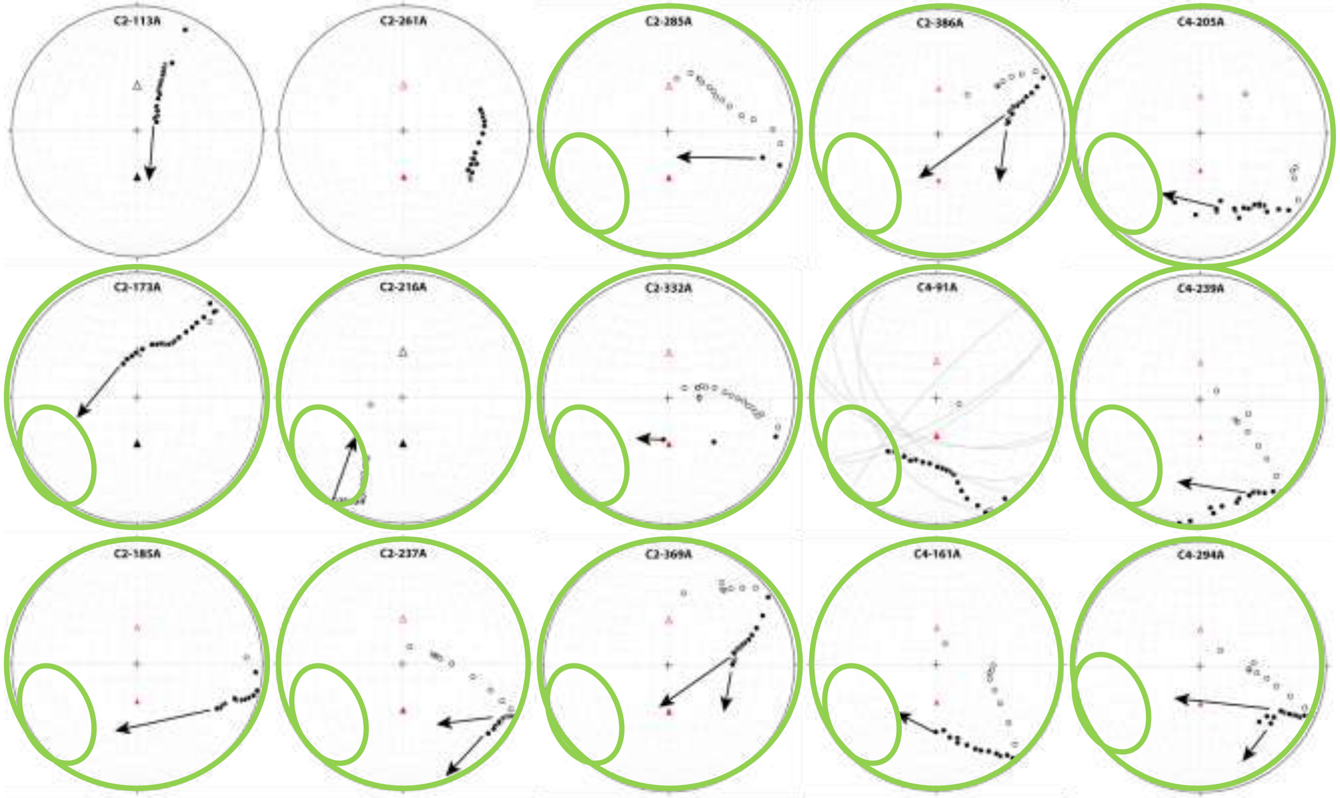
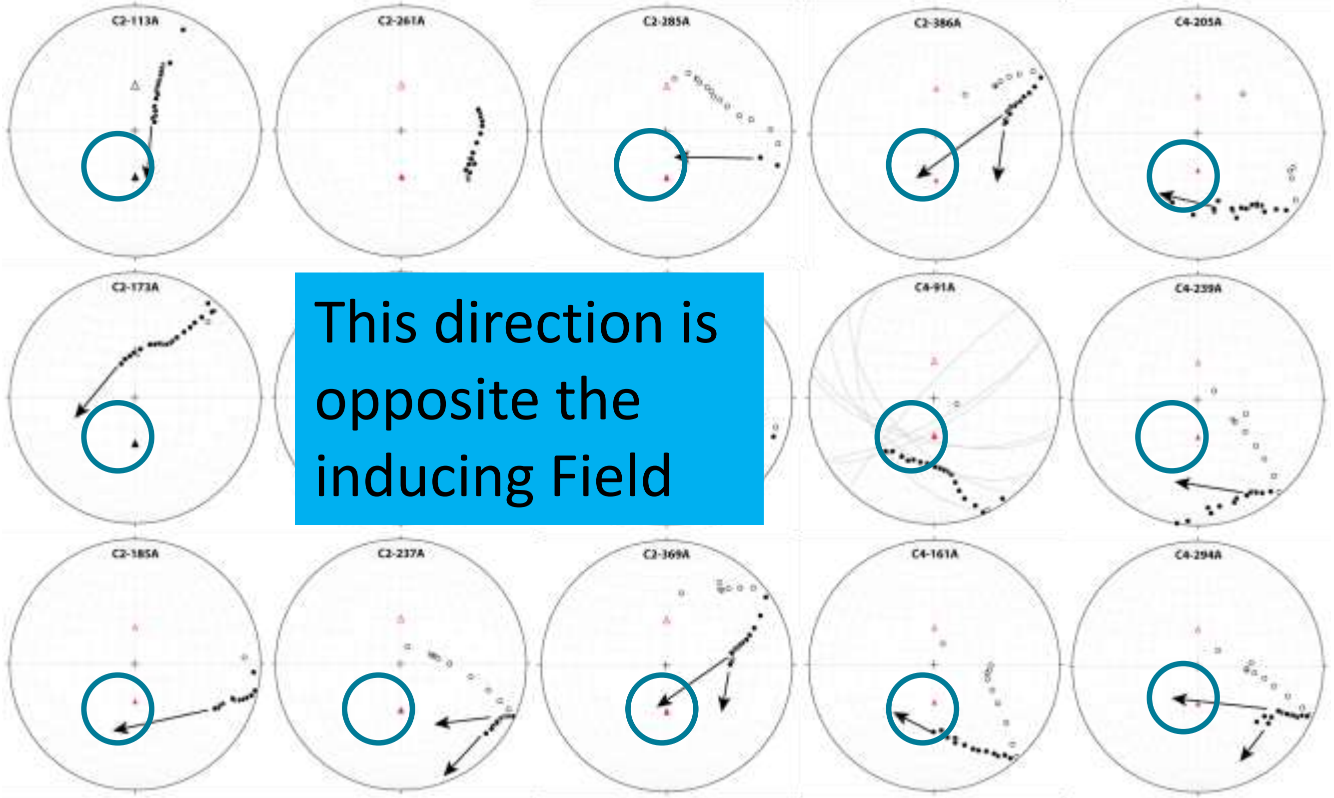
Upper Mt-poor Horizons (Remanence)



Upper Mt-poor Horizons (Remanence)



Upper Mt-poor Horizons (Remanence)



This direction is opposite the inducing Field

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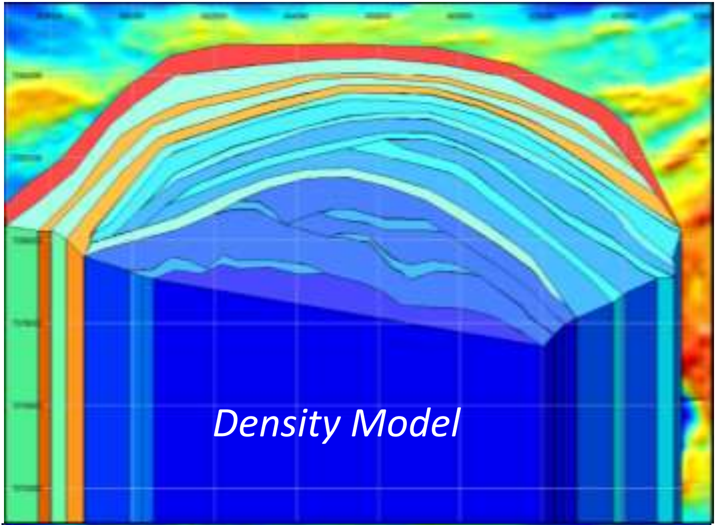
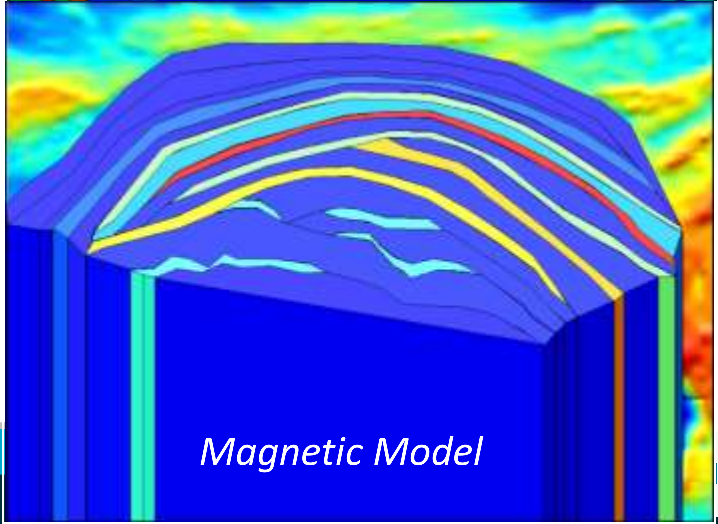
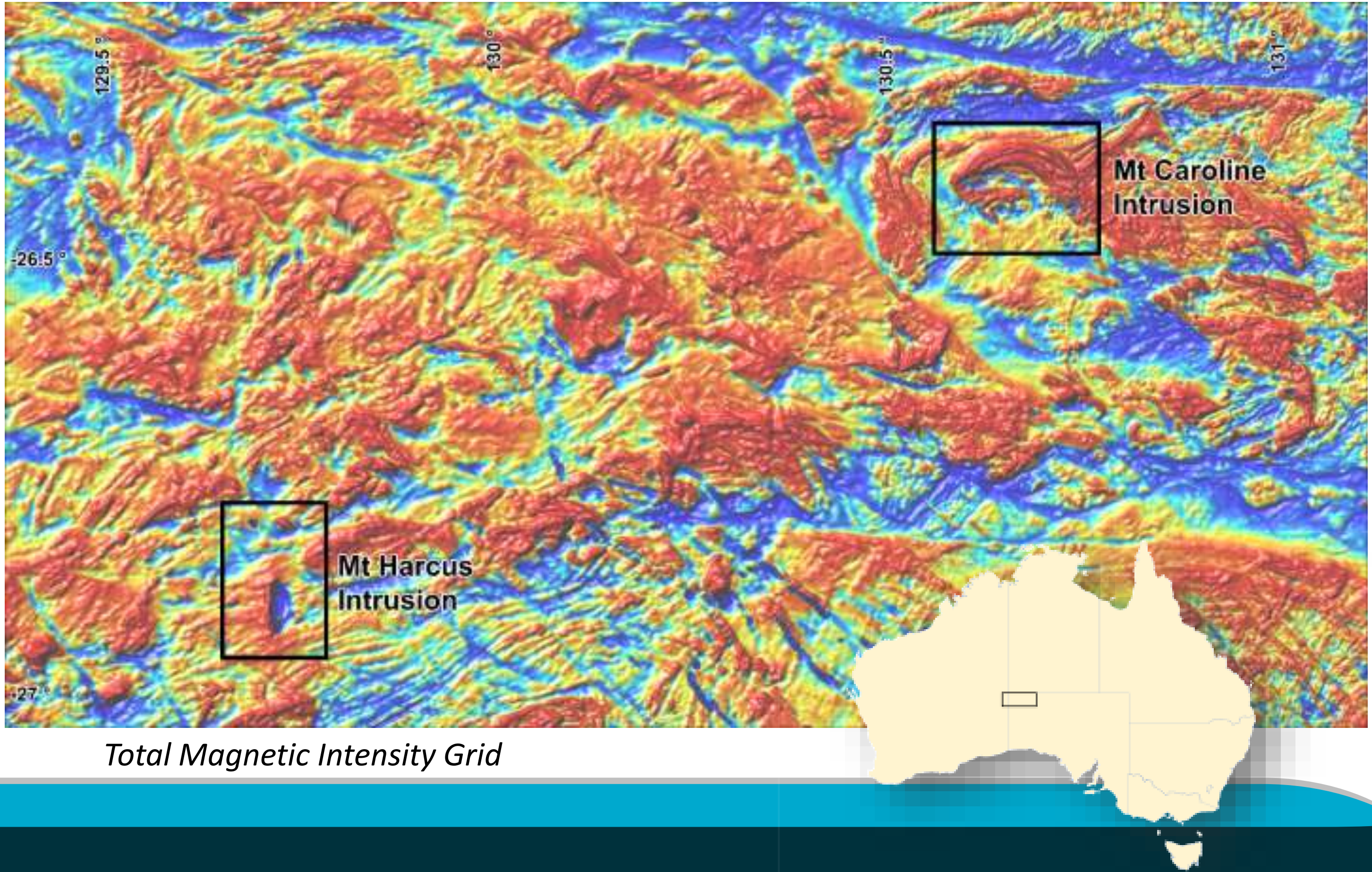
Conclusions

- Fractional crystallization causes a decrease in density toward the top of a layered intrusion
- also plays a role in determination of the magnetic properties of a layered intrusion.
- At Mount Caroline
  - the lower layers are weakly magnetic
    - Bi-modal density due to pyroxenites
  - the middle layers switch between:
    - strongly induced layers (+'ve)
    - and strongly negative remanence





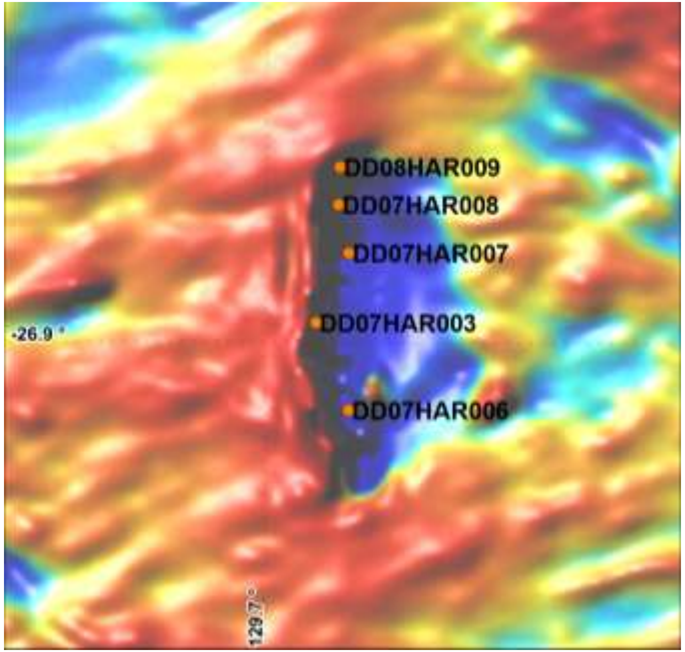
How is extremely strong and stable remanent magnetization formed in mafic rocks?



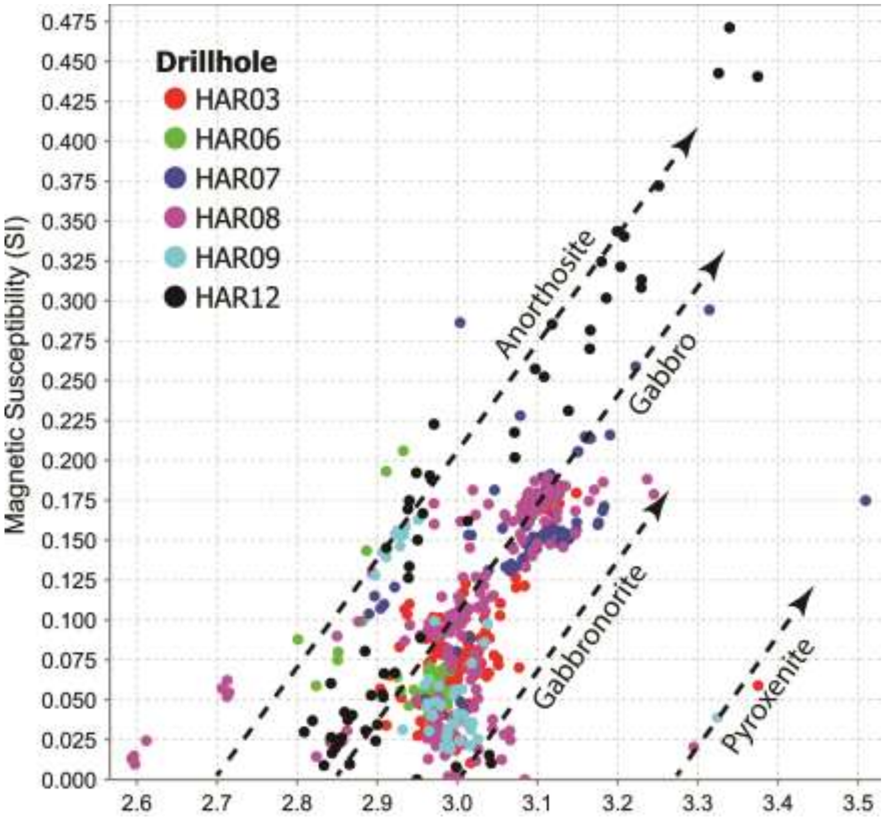
Total Magnetic Intensity Grid

Mt Harcus

- Associated with a large Negative

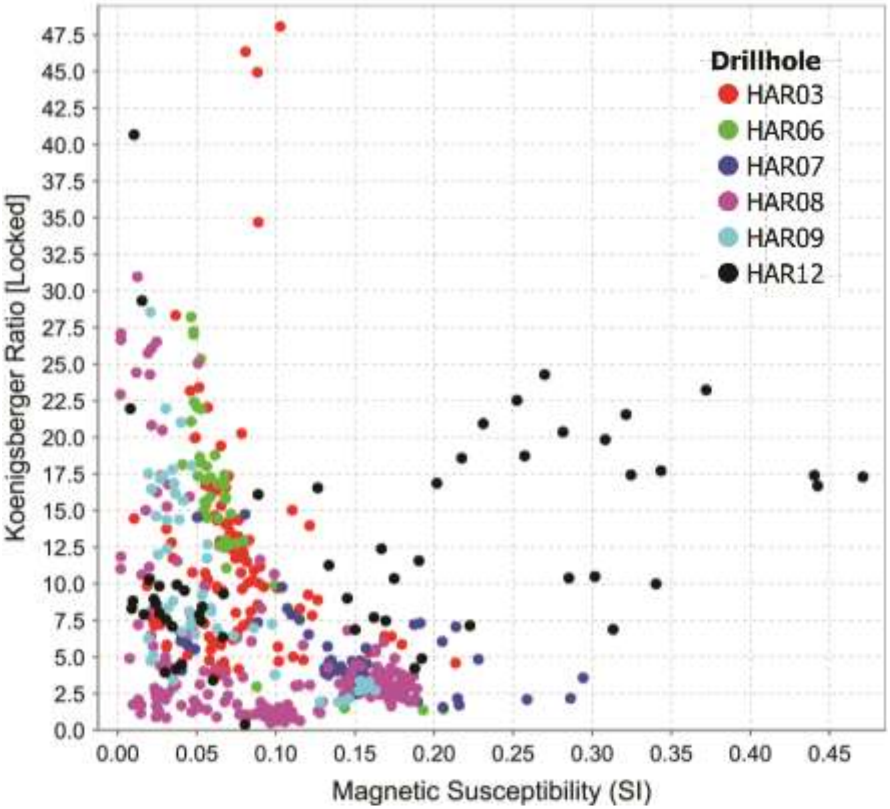


- More homogeneous the Mt Caroline



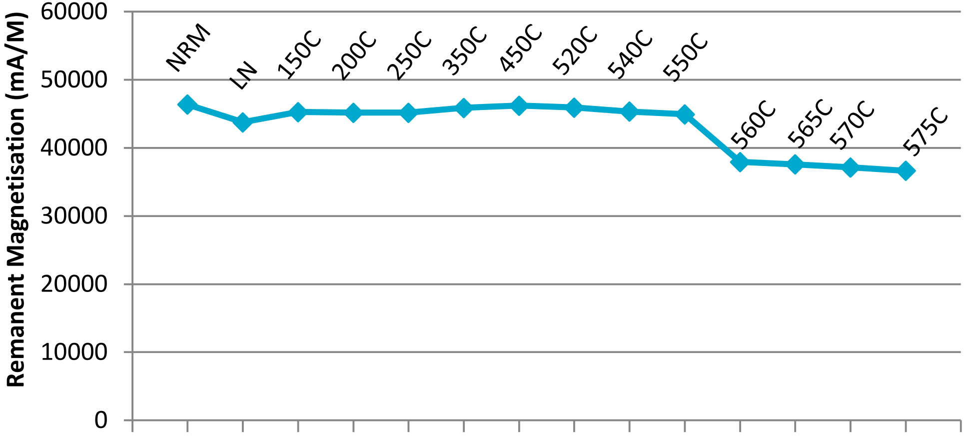
Remanent Magnetisation

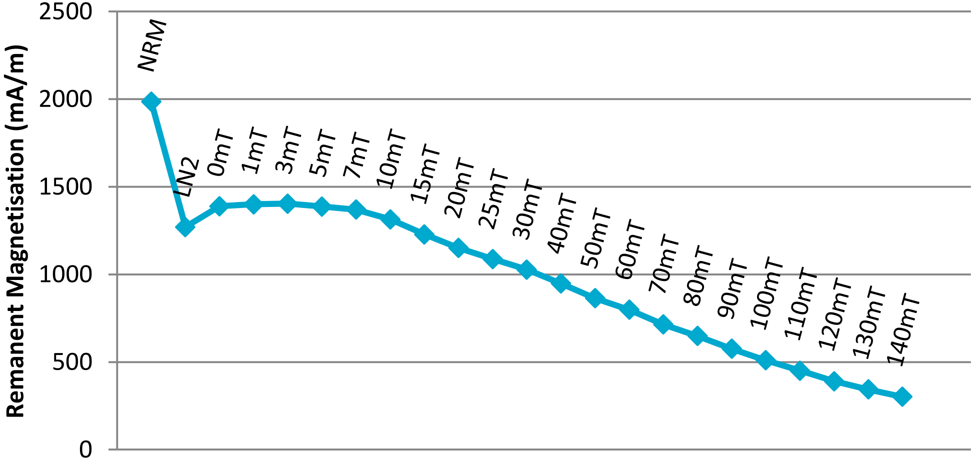
- Highly Variable magnetic Properties
- Dominated by high remanence, Low Magnetic Susceptibility
- Remanence commonly 10-30x stronger than induced magnetization
- Twice as strong as at Mt Caroline



Demag behavior

- High intensity remanence (<60 A/m)
- Remanence is very stable
- Consistent with single domain magnetite
  - Minimal intensity loss right up to the curie point
  - Not demagnetized Alternating Field of 140mT
- **The extreme stability is due to lamellar crystal structure**





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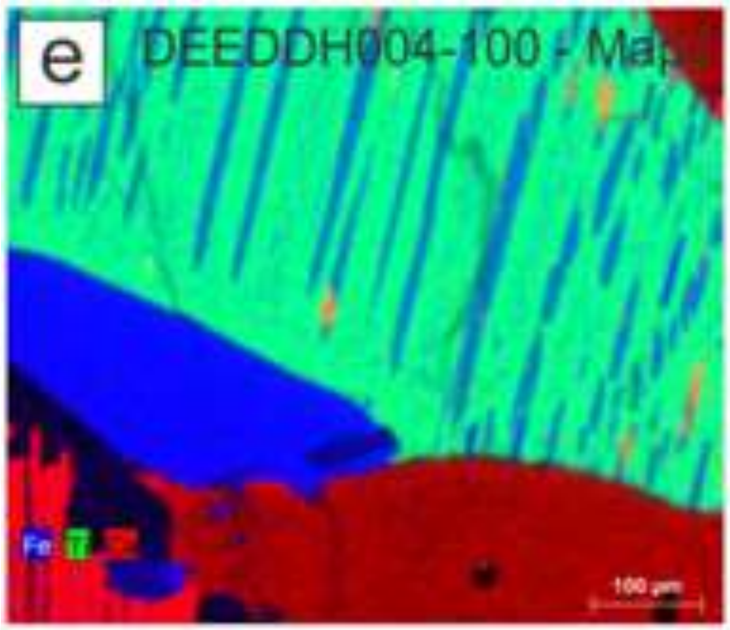
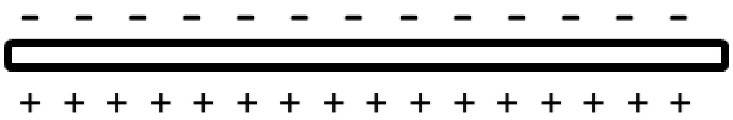
How does it form?

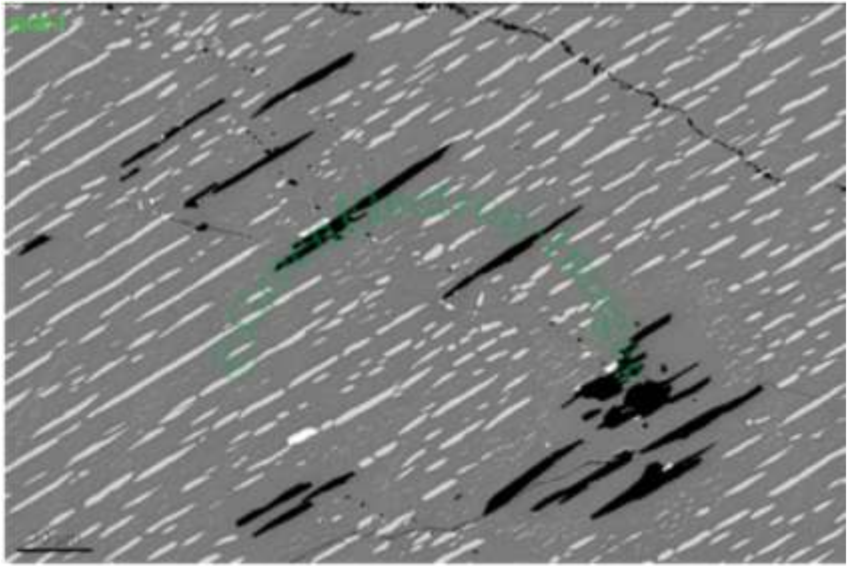
- Titanomagnetite crystallises at high temperatures (~1300°C)
- As it cools (at ~580°C) it will exsolve into Ti-rich and Ti-poor minerals, e.g., magnetite and ilmenite.
- The resulting partitioning of the magnetite grains can lead to more extreme remanence in the rock.



Exsolution Lamellae



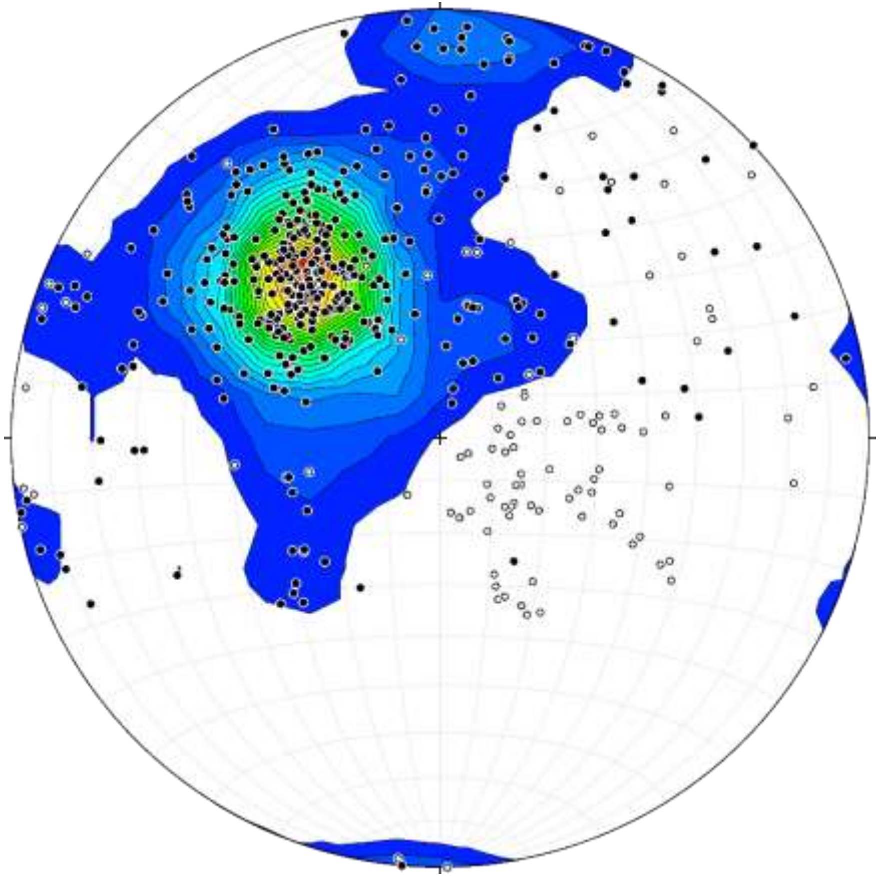
- Remanence in SD magnetite is very stable.
- Elongate, platy grains can have extreme remanence
- They have a high ratio of surface area to volume,
- hence hold more charge



Densely packed exsolution lamellae of titano-magnetite (light grey), in an ilmenite host (mid grey). The black phase is magnesium spinel, the brilliant white blebs appear to be baddleyite (ZrO_2). From: www.greenelectron-images.co.uk

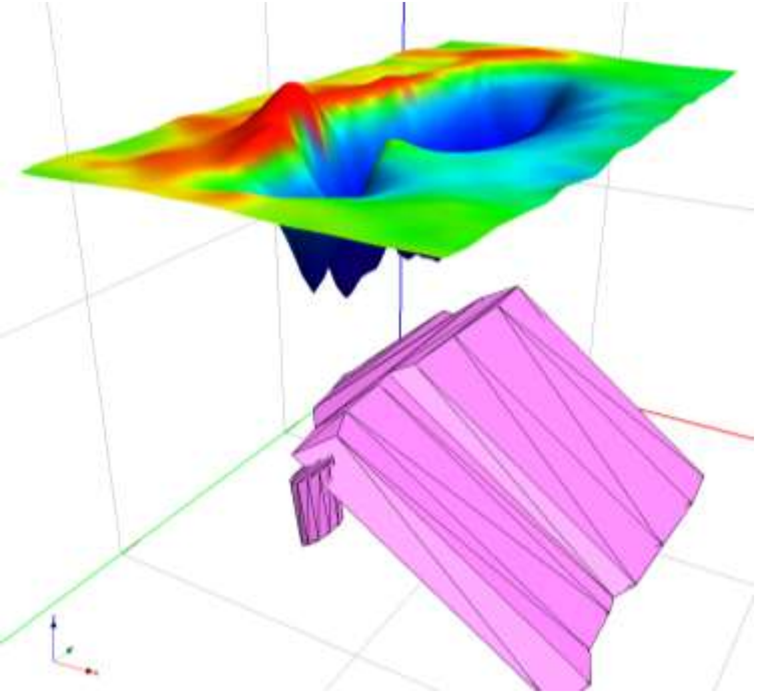
Remanence Directions

- Quite a spread of data
- But unlike Mt Caroline well clustered
- Implies that the remanence is resistant to metamorphic overprints
- Remanence oriented Dec: 320, Inc: 49

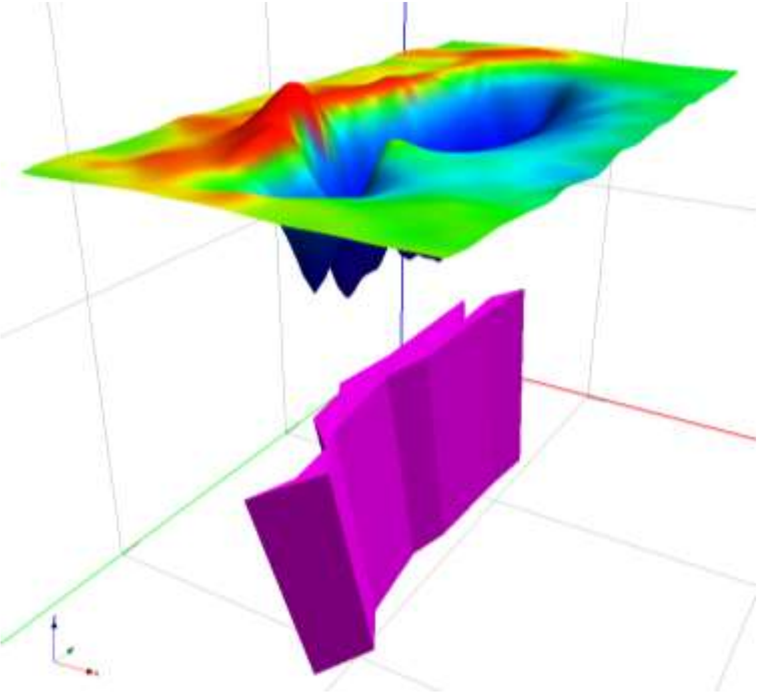


How does this change our model?

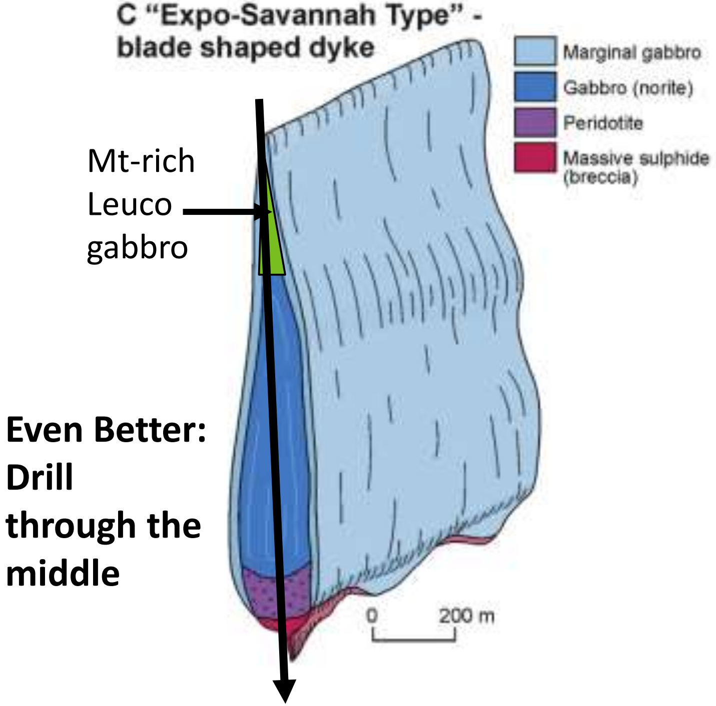
Unconstrained

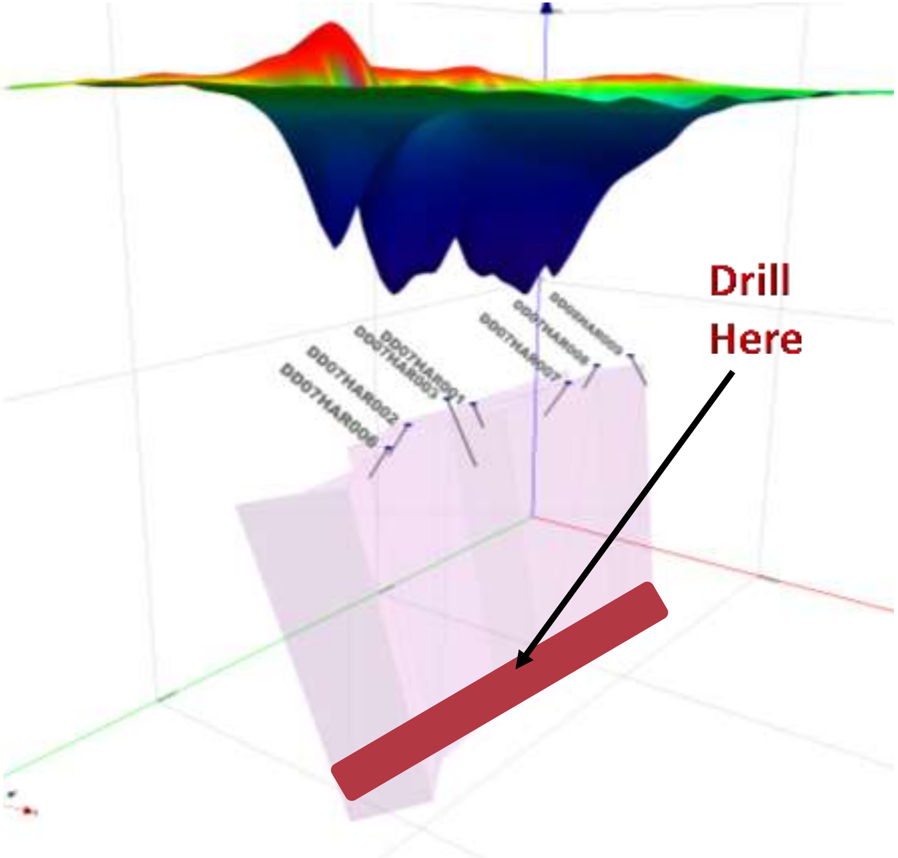


K and J constrained



Implications





How can completely different mafic rocks have identical remanence directions?

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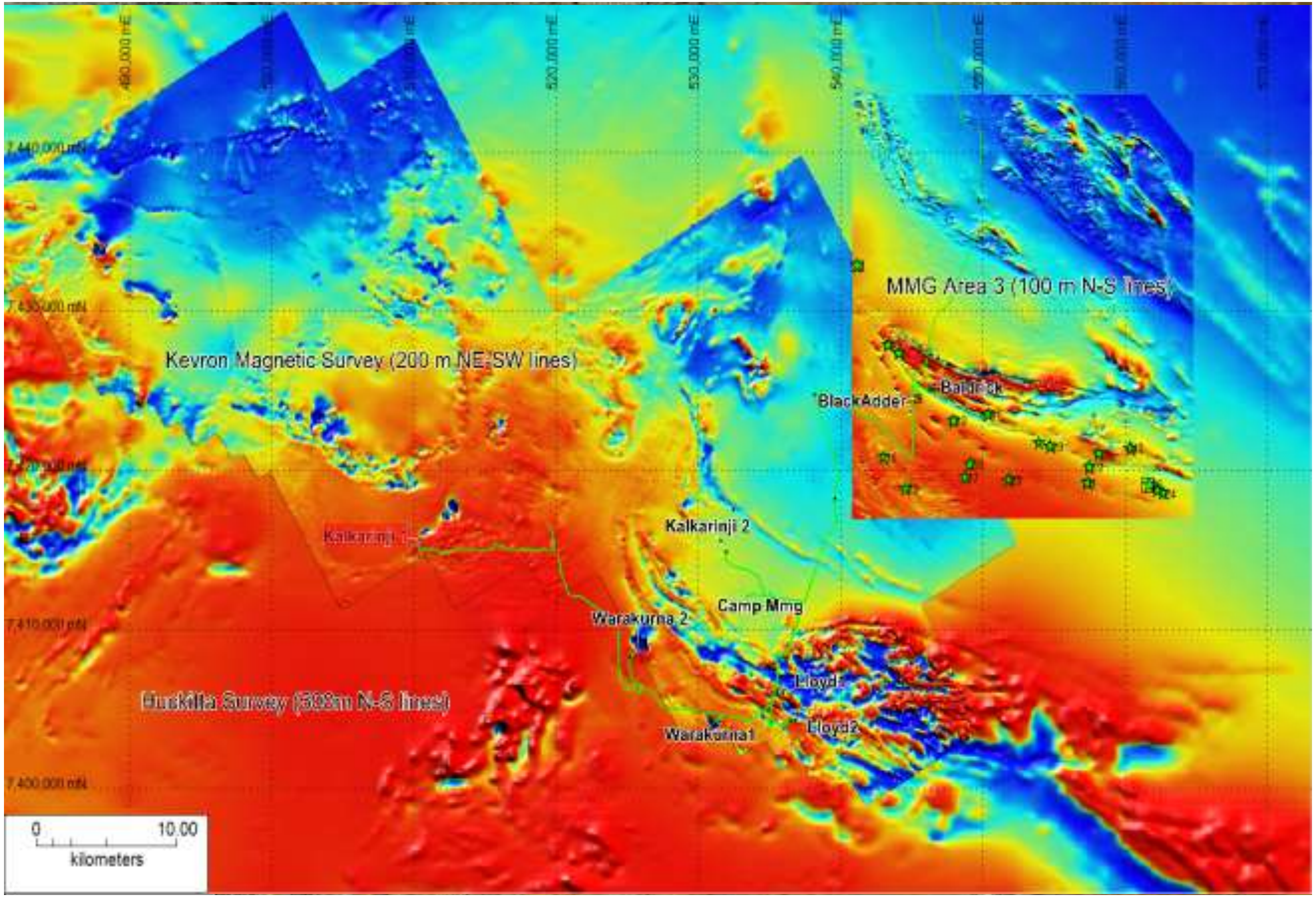
Curie Point

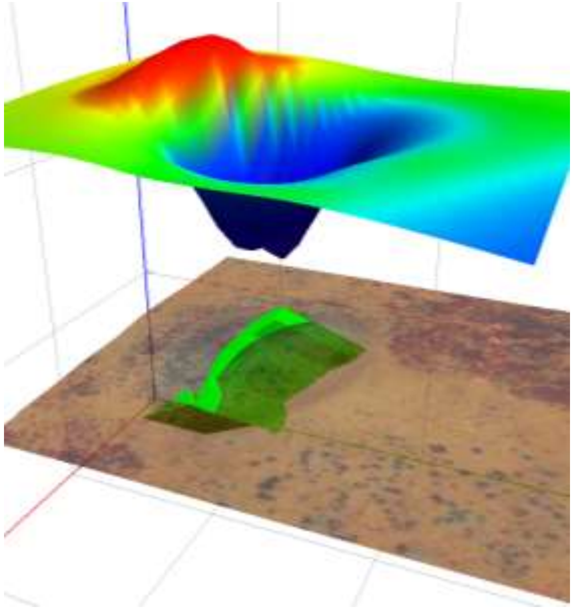
- Generally, we assume that rocks acquire magnetization very soon after crystallization.
- Rocks can record a number of different magnetizations, including cooling and/ or exsolution reactions.
- However, we often fail to consider that the most critical factor that controls the magnetization direction is when the rock cools through the Curie point.
  - The Curie point is different in different types of minerals
  - For pyrrhotite the Curie point is much lower, which is significant for metamorphic events in particular.
- Magnetization(s) may take hundreds of millions of years to be acquired
  - rocks were intruded deep in the crust (e.g., >20km),
  - tectonically moved into the mid-lower crust.

Mineral	Formula	Mag Sus (SI)	Q	Curie point
Magnetite (MD)	$Fe^{3+}{}_2Fe^{2+}O_4$	3.8-10.0	0.05-0.5	580°C
Maghemite	Fe2O3	variable	0.05-0.5	545-675°C
Ilmenite	Fe_2TiO_3	0.03 - 3.5	?	50-300°C
Pyrrhotite (m-clin)	Fe_7S_8	variable	1-500	320°C
Hematite	$Fe^{3+}{}_2O_3$	0.0005 - 0.01	30-1000	685°C

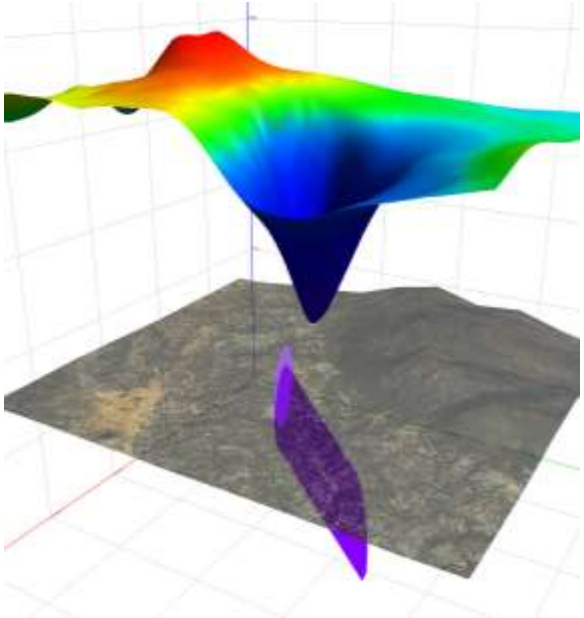
Arunta


Kevron Magnetic Survey (200 m NE-SW lines)
MMG Area 3 (100 m N-S lines)
BlackAdder
Baldrick
Kalkarinji 2
Camp Mmg
Warakurna 2
Lloyd1
Lloyd2
Warakurna1
0
10.00
kilometers

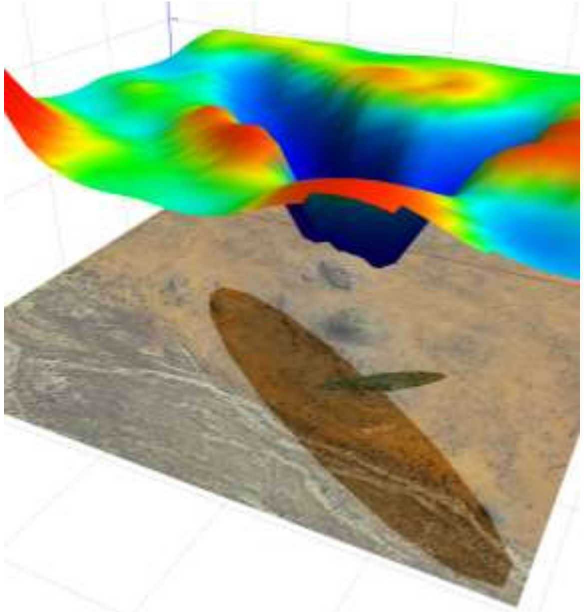
Magnetic Anomalies



Lloyd Suite 405 Ma



Kalkarinji Suite 500 Ma

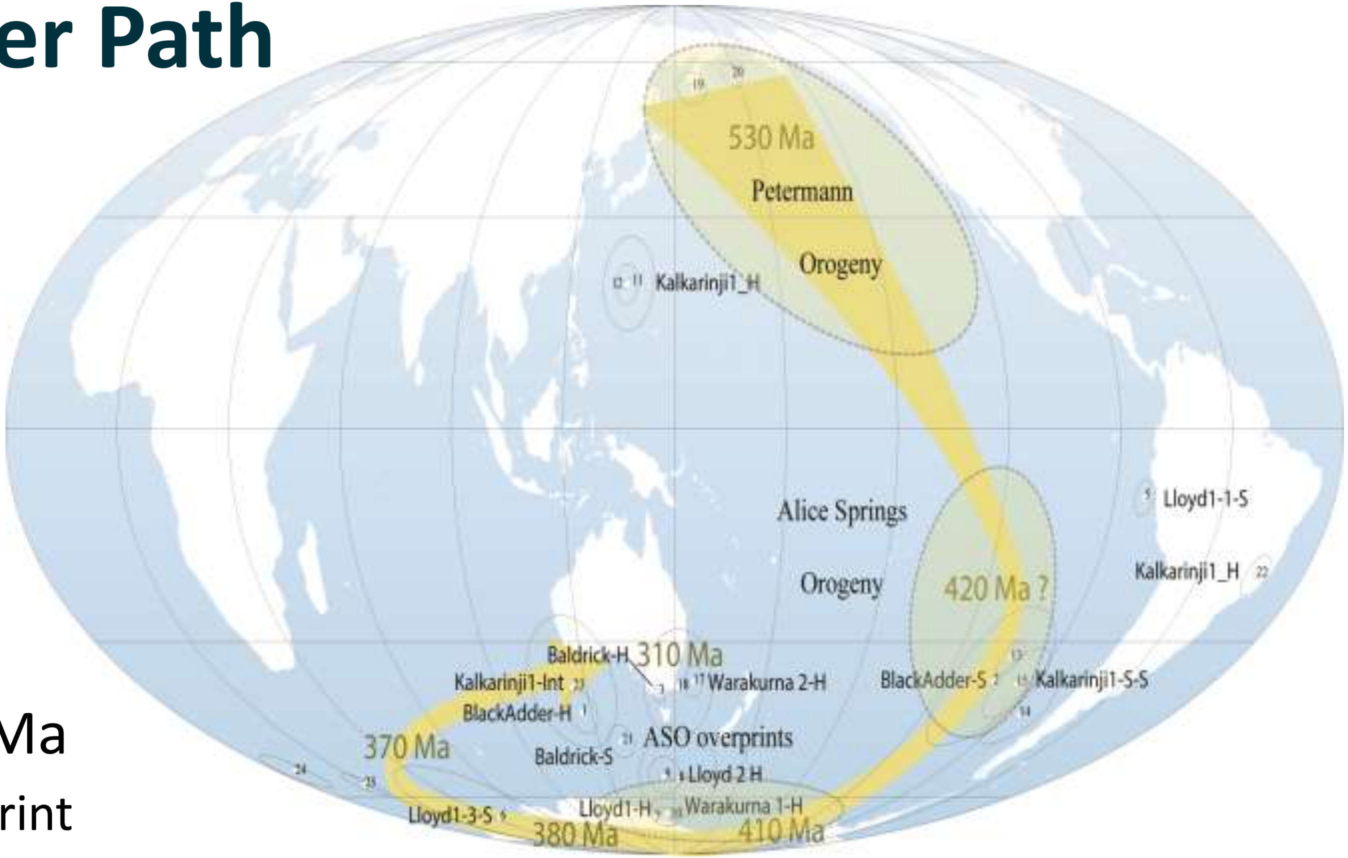


Warakurna Suite 1070 Ma

Polar Wander Path

Arunta Block

- None at 530 Ma
- Few ~430 Ma
  - Early ASO
- Some at 380 Ma
- Some at 360 Ma
- Most ~340-310 Ma
  - Latest ASO Overprint



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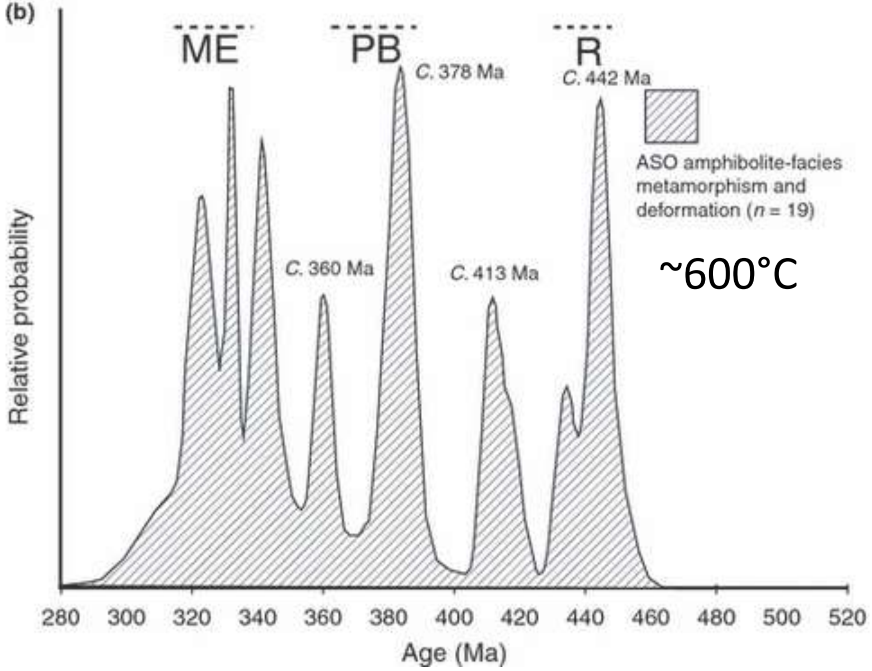
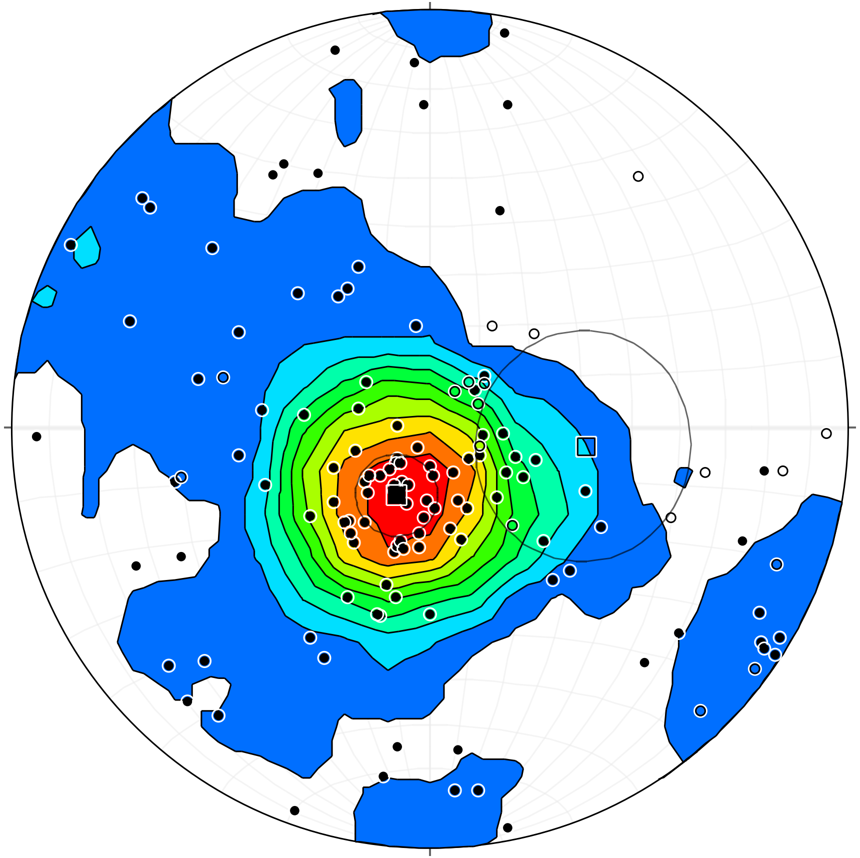
Metamorphic Events



~600°C



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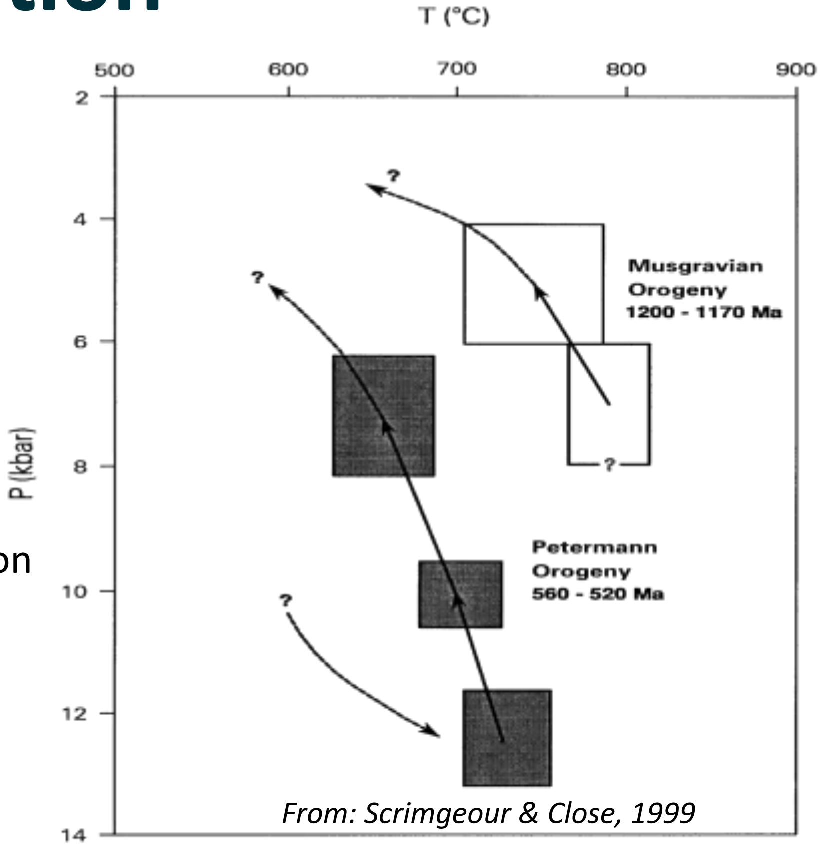
Remanence and exhumation

Different parts of the Musgrave (and Arunta) were:

1. Exhumed at different times
2. Variably metamorphosed

The acquisition of magnetisation is:

1. Spatially Variable and Temporally Variable
2. But it all post-dates the Petermann orogeny
3. All rocks cooled through ~600°C during exhumation from 530 Ma to ~310 Ma
4. None of the remanence was acquired during crystallization

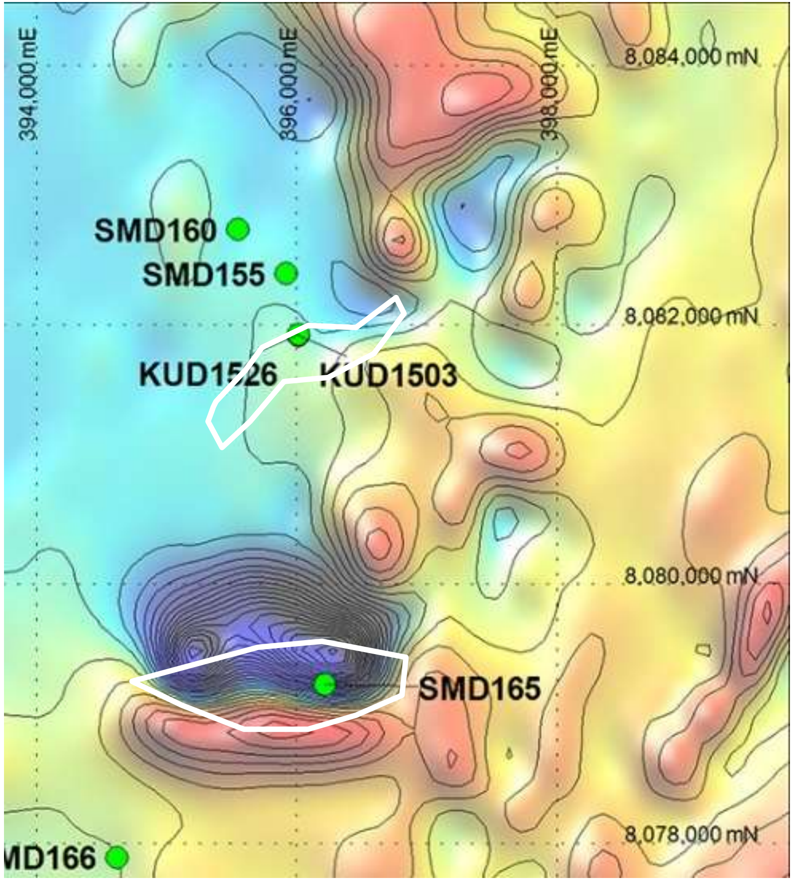


From: Scrimgeour & Close, 1999

How can almost identical rocks have completely different magnetic signatures?

Savannah Study

- Savannah and Dave Hill are contemporaneous intrusions.
- Dave Hill associated with a large negative Magnetic Anomaly
- Savannah essentially has no significant magnetic anomaly
- What's going on??



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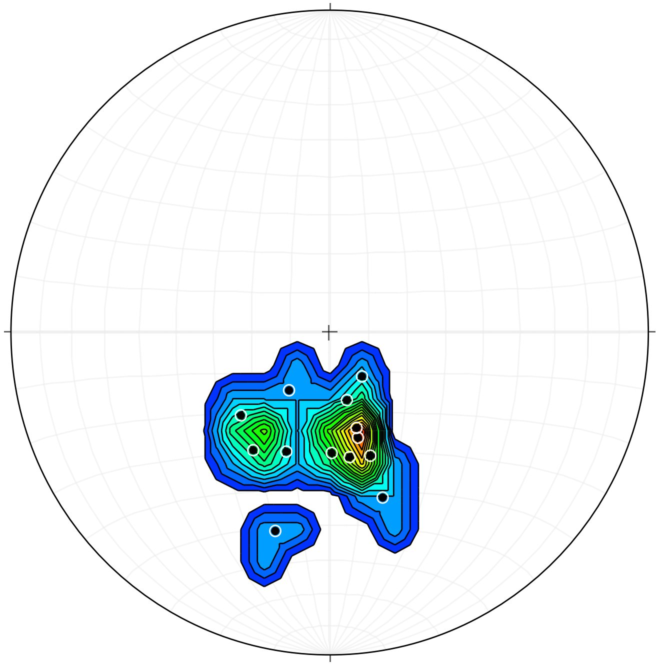
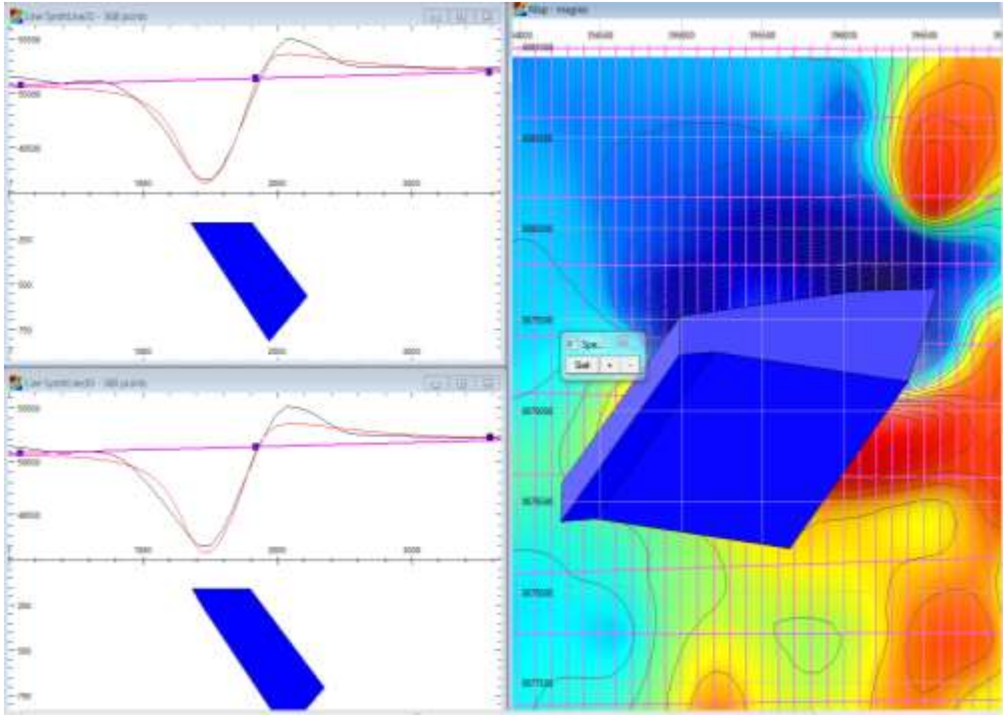
Dave Hill Intrusion



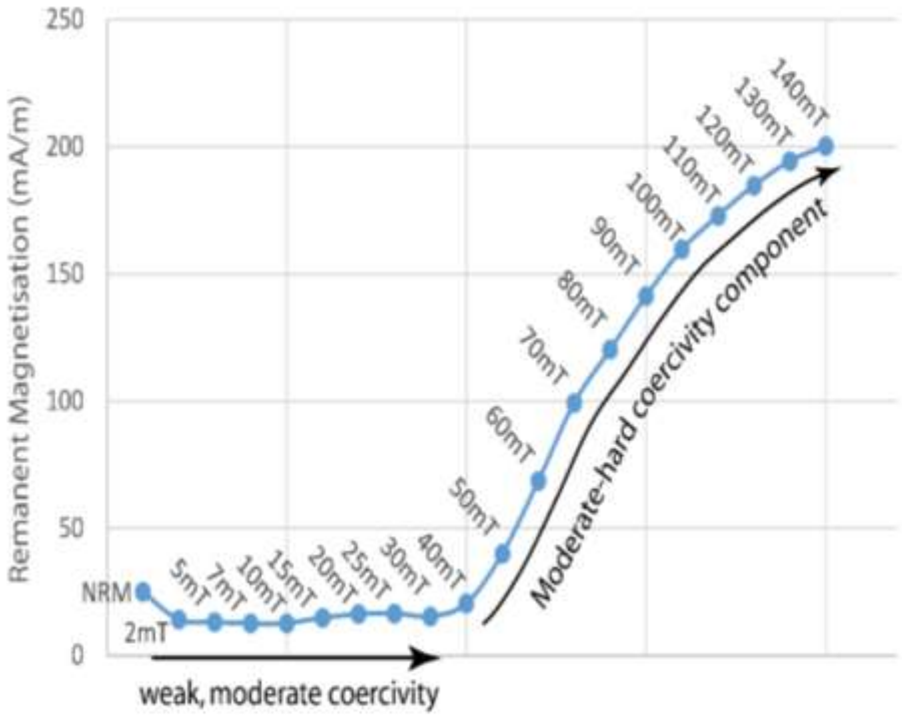
Measured Remanence directions



Constrained Model based on Remanence directions

Savannah

- The NRM for Savannah was low
- Samples contained two antiparallel magnetizations of approximately equal intensity
  - the weaker was removed first leaving a progressively stronger resultant.
  - The stronger one was so stable that the highest remanent magnetization intensity occurs on the last step.



Implications

- high coercivity opposite polarity magnetizations often account for <10% of total magnetization.
- In this case the two components
  - account for ~95% of the palaeomagnetic signal
  - have approximately equal intensity,
  - They are effectively self-cancelling
- Koenigsberger ratios are misleading in terms of describing the strength of the remanence

- When Remanence is re-calculated based on not scalar sum of remanent intensities,
  - NRM was 15x higher than measured
  - Koenigsberger ratio would be 4.2.
- These results are more consistent with those from Dave Hill

Savannah is a rare case in which the lithologies have strong remanence and weak susceptibility, but because the remanence is largely self-cancelling, the magnetic anomaly at Savannah is non-existent.


Questions?

Modelling Implications - Gravity

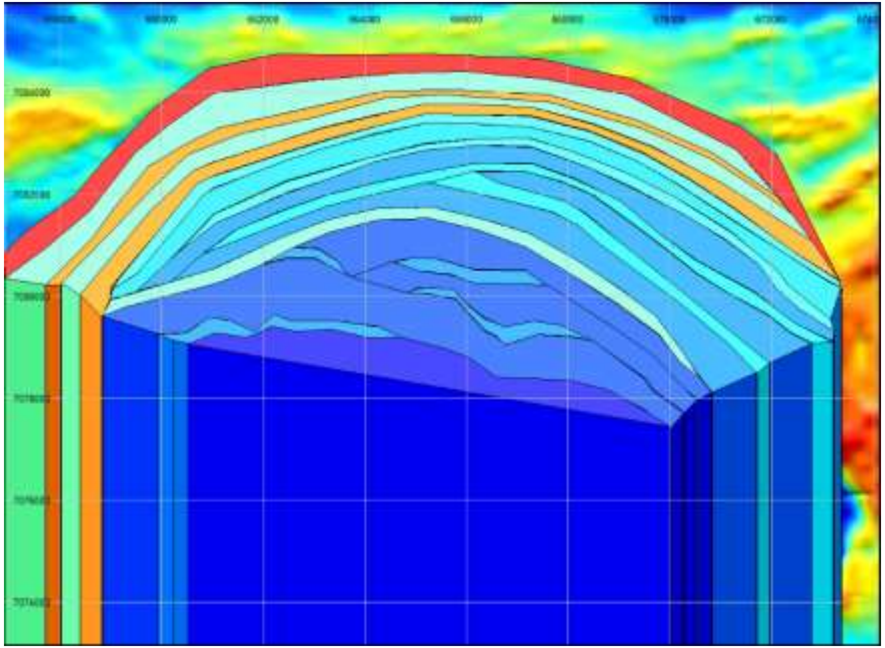
- Fractional crystallization causes a decrease in density toward the top of a layered intrusion

Basal Layers (Pyroxenite/Gabronorite)

- Bi-modal density related to the plagioclase/pyroxene ratio

Middle to Upper Layers

- Bi-modal density related to Mt-saturation



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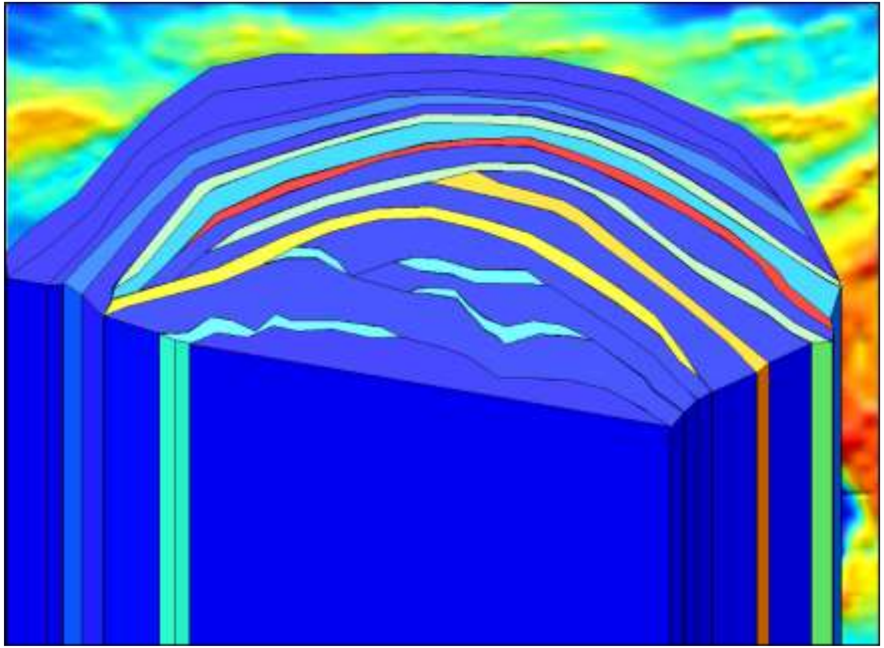
Modelling Implications - Magnetics

Mt-poor Layers (e.g., Gabbronorites)

- *In situ* remanent magnetization is very stable.
- 5-15 times stronger than induced
- Multiple components, but
- Oriented opposite to the local magnetic field.
- such rocks can essentially be treated as a negative susceptibility.

Mt-rich Layers (e.g., Anorthosites)

- The *in situ* remanent magnetization would almost certainly have been parallel to the local magnetic field.
- The remanence is artificially enhanced by ~300%
  - drilling induced magnetization (DIM) **discussed later today.**
- such rocks can essentially be treated as a purely induced magnetization for modelling purposes.
- intensities will be ~50% to 200% higher than measured magnetic susceptibility.



Magnetic Model

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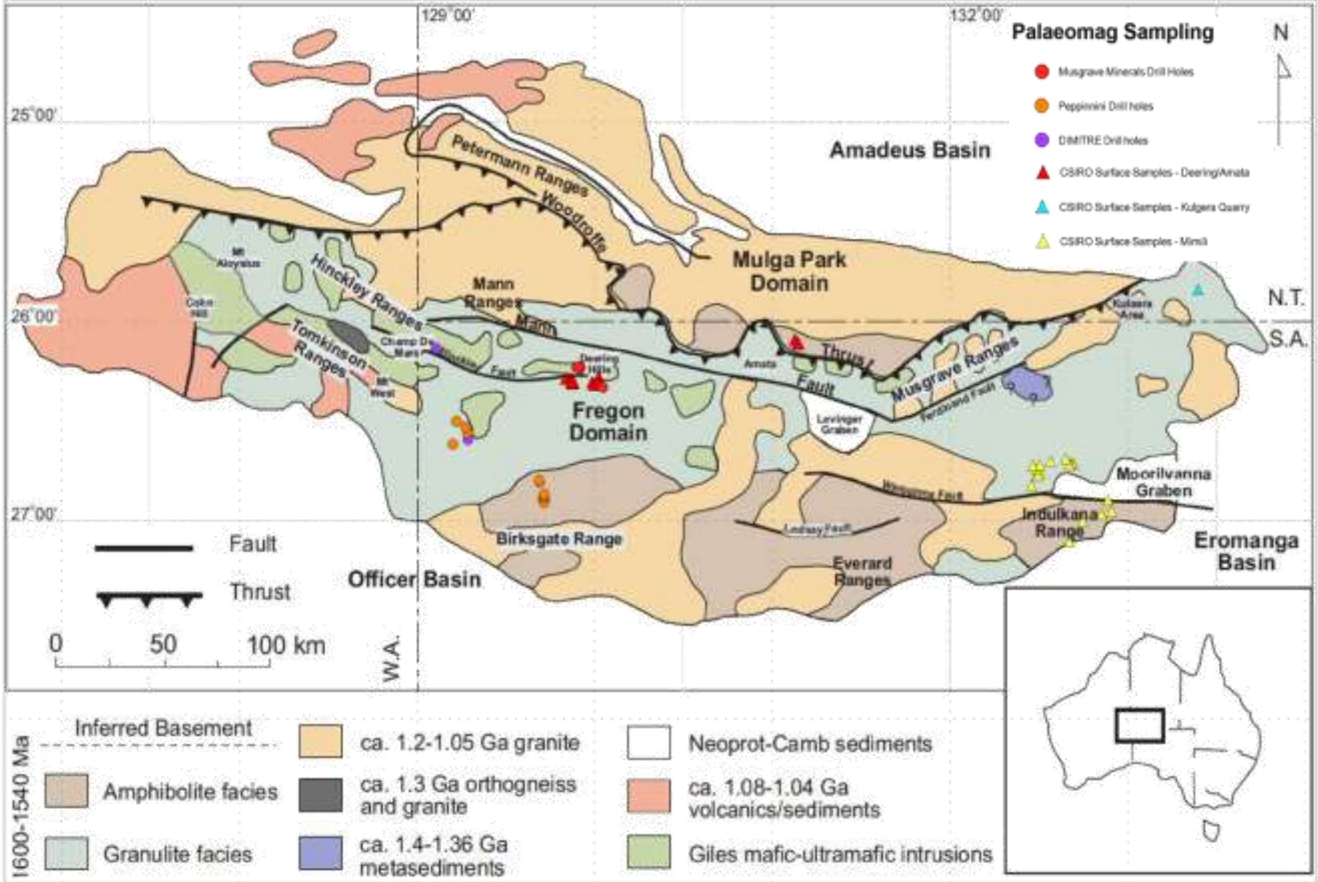
Musgrave



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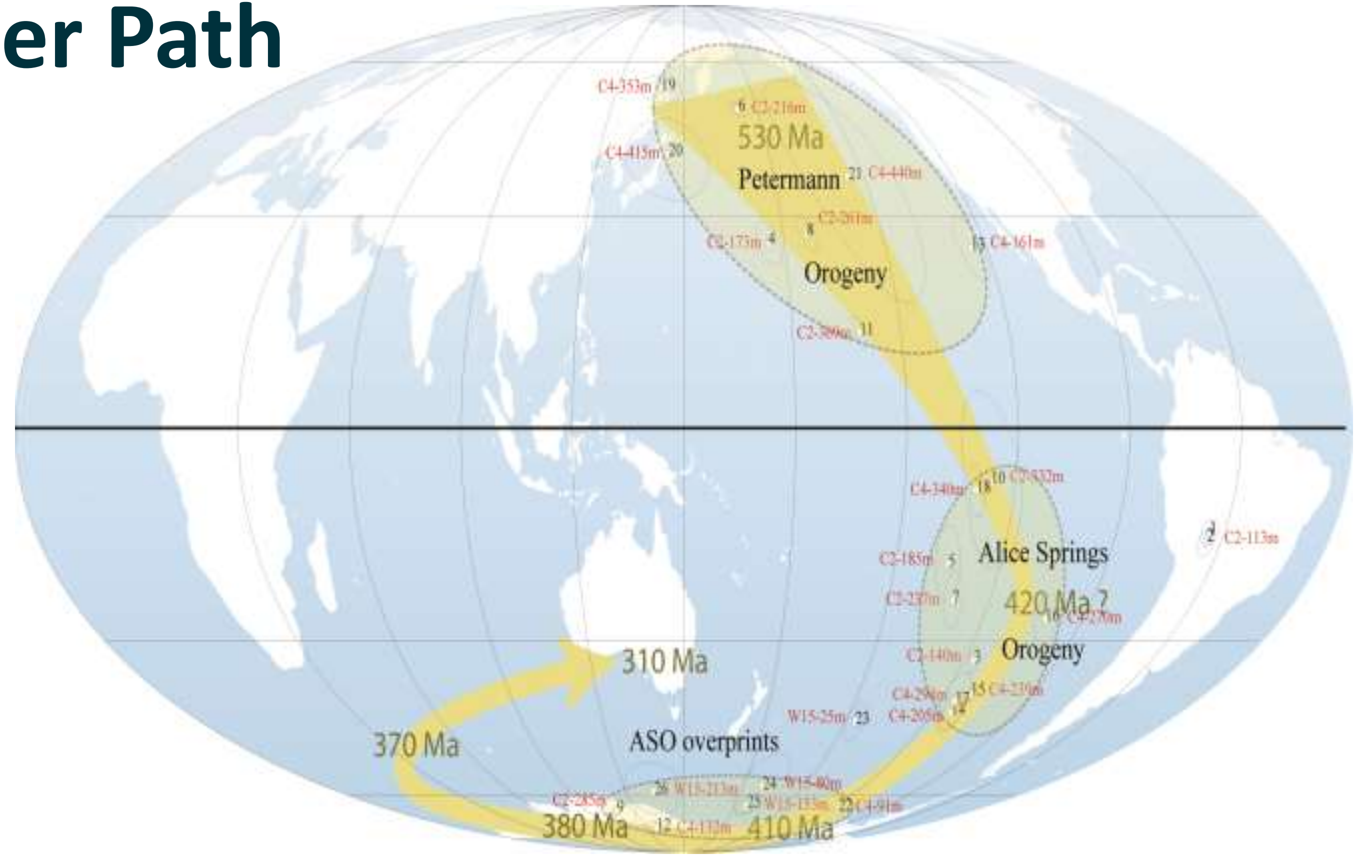
Polar Wander Path

Mt Caroline Poles

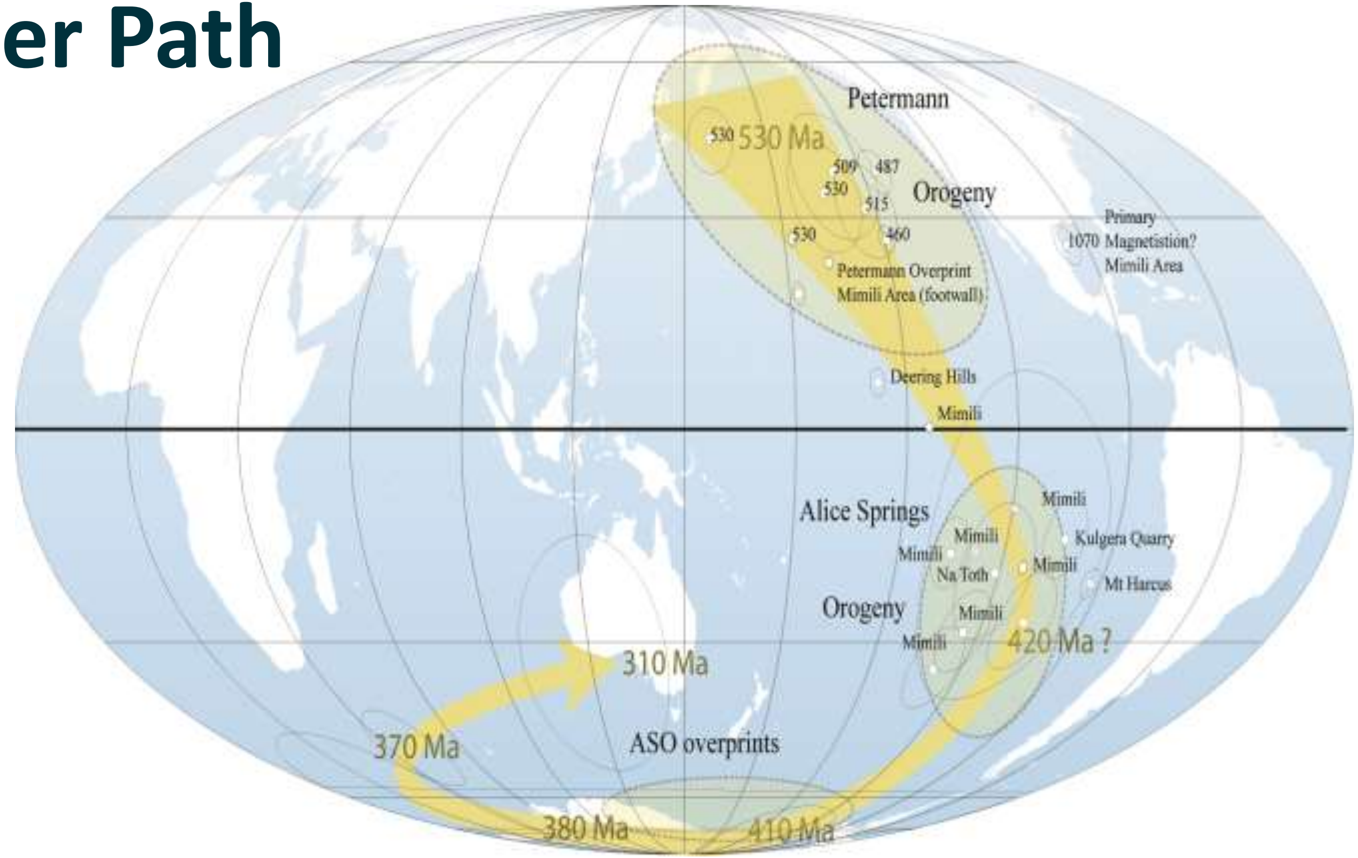
- ~530 Ma
  - Petermann Orogeny
- ~430 & 400 Ma
  - Alice Springs Orogeny
  - Latest in Pyrrhotite?



Polar Wander Path

Musgrave Block

- ~530 Ma
  - Petermann Orogeny
- ~430 Ma
  - Alice Springs Orogeny



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