The geophysical characteristics of granites and shear zones in the Yilgarn Craton, and their implications for gold mineralisation

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The Archaean Yilgarn Craton provides two thirds of the Australian gold output of ~ 300 tonnes per year yet occupies only 10% of the continent. Granite[1] and gneiss of granitic composition, comprise more than 80% of the craton. Extensive, generally thin (less than 100 m) regolith, however, conceals much of the basement geology. Aeromagnetic and gravity data effectively "see" through the regolith and their interpretation provide detail of the basement not readily obtained from outcrop mapping. Note, however, that geophysical and geological mapping are not equivalent. For example, variations in granite mineralogy and texture, observed in outcrop, are often unresolved in regional geophysical surveys.

The following sections describe the granite-dominated aeromagnetic map units of the Yilgarn Craton, discuss the correlations between geophysical data and geochemical suites, and speculate on the relationships between shear zones seated in felsic crust and greenstone hosted gold. Gravity data (broad station spacing, low resolution), and gamma-ray spectrometric data (limited ground penetration, <0.5 m), are drawn on where they complement the discussion.

Aeromagnetic map units

The Yilgarn Craton has been subdivided into five main, regionally distributed, aeromagnetic map units (Whitaker, 2001, Whitaker and Bastrakova, 2002): undivided gneiss–migmatite–granite, banded (granitic) gneiss, granite plutons, sinuous gneiss, and greenstone. Rocks of granitic composition, which may contain diffuse compositional layering or zonation, make up the components of the first three map units. Inter-layered rock types including basalt, ultramafic rocks, sedimentary rocks, and intermediate to felsic volcanic rocks, give the well developed compositional layering in sinuous gneiss and greenstone. Only the first three map units are described here.

Undivided gneiss–migmatite–granite (Agmg; Fig.1) comprises 60% of the Yilgarn Craton. Moderate magnetisation characterises much of the unit. Compositional banding and internal boundaries are rare. Regional variations in magnetisation are gradual and not readily ascribed to changes in mapped geology. Poorly magnetised faults and moderately- to highly-magnetised dykes are commonly the most visible features. Agmg includes several ovoid-shaped, composite bodies of granite and granitic gneiss, ranging in size from 10 km to 40 km diameter. Diffuse internal banding, where present in these 'domes', parallels adjacent margins. Large areas of Agmg coincide with Bouguer gravity anomalies in the range of -750 to -450 μmsec^{-2}. In outcrop, changes in rock type, from granitic gneiss to migmatite to granite, may occur across nebulous boundaries over short distances (tens of metres), and remain unresolved in regional geophysical data. Agmg envelopes examples of all other geophysical map units.

Banded (granitic) gneiss occurs in elongate, moderately- to highly-magnetised belts, 50 km to 100 km long and 5 km to 25 km wide. Diffuse internal bands of higher and lower magnetisation parallel the elongation of the belts. Locally, large-scale, tight to isoclinal folds overprint the banding. Banded gneiss is spatially associated with regional shear zones and is inferred to result from earlier shear zone-related deformation events. It often forms the interface between Agmg and greenstone. Enclaves of greenstone, and amphibolite of uncertain origin, are locally abundant in several of the belts. Banded gneiss is, on average, more highly magnetised than adjacent Agmg and is also associated with relatively higher Bouguer gravity anomalies (approximately 70 μmsec^{-2} higher than adjacent Agmg).

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[1] Granite is used here as a general term to indicate felsic intrusive rocks

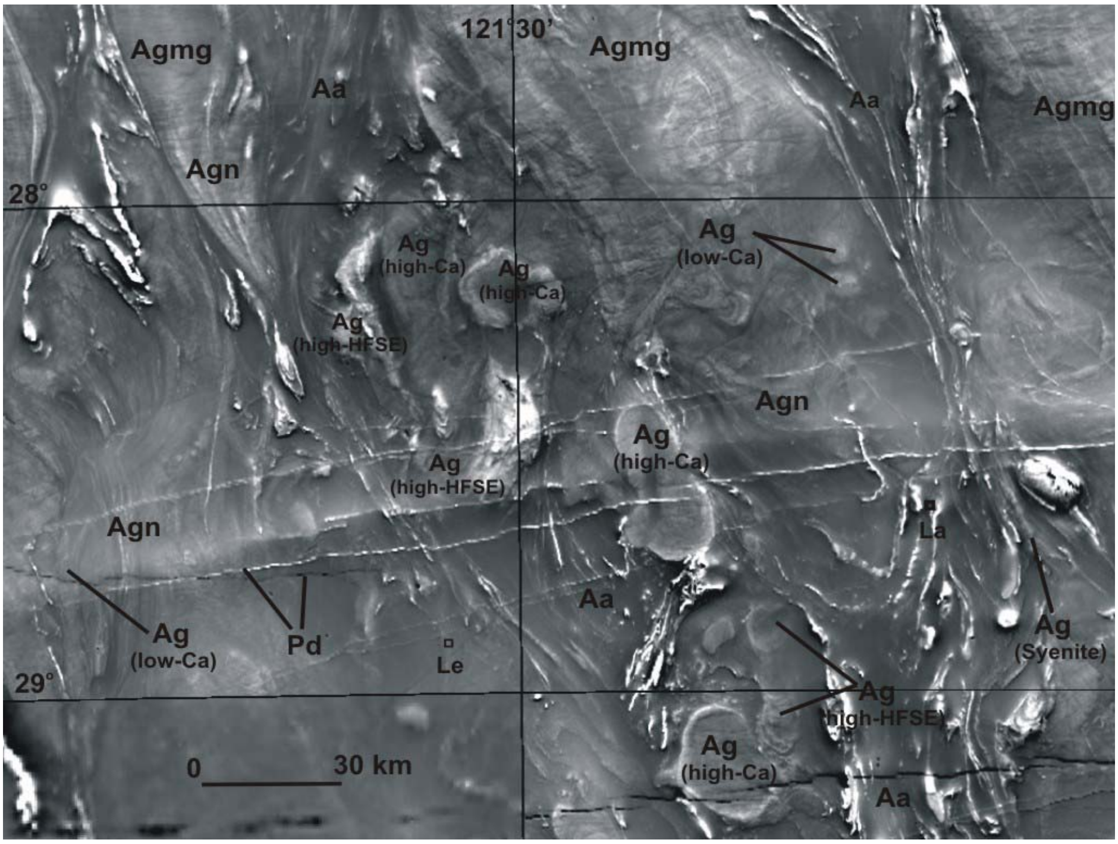

Figure 1 Total magnetic intensity image of the Leonora – Laverton area of the northeastern Yilgarn Craton. Black to white represents low to high magnetisation. Aeromagnetic map units are labelled; Agmg = undivided gneiss-migmatite-granite, Agn = banded (granitic) gneiss, and Ag (high-Ca) = granite (geochemical group). Other features labelled include greenstone = Aa, and Proterozoic dykes =Pd. Leonora (Le) and Laverton (La) are also located.

Circular to elongate granite plutons comprise less than 10% of the basement surface of the Yilgarn Craton. They range in diameter from 1 km, and less, to greater than 30 km, and from poorly- to highly-magnetised intrusions. Many plutons are simply zoned with more magnetised rims than cores. Granite plutons are particularly abundant within greenstones of the Norseman-Wiluna Belt (Gee et al. 1981), often forming regionally aligned groups. Poorly magnetised plutons correlate strongly with the greenstone belts and are rare in extensive regions of Agmg. Moderately- to highly-magnetised plutons define an unusual, 200 km-wide, northwest-trending corridor that traverses Agmg in the southern parts of the Southern Cross and Murchison domains. They, too, are much less common in regions of Agmg throughout the rest of the Yilgarn Craton. Bouguer gravity anomalies associated with several of the larger granite plutons are very low (-750 to -850 $\mu msec^{-2}$) and are commonly 100–150 $\mu msec^{-2}$ lower than adjacent regions of Agmg.

Geochemical granite groups, magnetic susceptibility, and gamma-ray data

Champion and Sheraton (1993; 1997) subdivided the granites of the eastern Yilgarn Craton into two main (high-Ca, 60% of granites; low-Ca, 20% of granites) and three minor (high-HFSE, mafic, and syenitic) geochemical groups. These groups are not uniquely discriminated by aeromagnetic data (e.g., in extensive regions of Agmg, high-Ca and low-Ca granite types are not resolved). This lack of discrimination is readily explained by magnetic susceptibility data which show that greater than 90% of susceptibilities for high-Ca and low-Ca granites fall within the same range (0–900 × 10^{-5} SI). The only real differences between the two are the greater relative abundance of low susceptibility granite (<100 × 10^{-5} SI) for the high-Ca group and the associated more pronounced bimodal character to their data (Fig. 2). Fewer susceptibility data are available for the minor granite groups, however, values extensively overlap with the major granite groups. Both the syenitic and mafic groups show peaks at low susceptibility (0–100 × 10^{-5} SI), coincident with the lower modal peak of the high-Ca group. The spatial relationships of these low susceptibility values is yet to be determined, but many correlate with the abundant, poorly magnetised intrusions in, and around, greenstone belts. It is surprising that more intrusions are not resolved in the aeromagnetic data, given the range of measured susceptibilities and the apparent capacity of high-Ca granites, particularly, to form magnetically zoned plutons. It may be that modes of intrusion differ between regions; harder-to-detect granite sheets may be more prevalent in areas where individual intrusions are not resolved.

Gamma-ray spectrometric data provide some discrimination of the main geochemical suites. In outcrop areas, high-Ca granites correlate with K-only anomalies in ternary (K, Th, U) images of the data, low-Ca granites with regions of anomalously high K, Th, and U. High-HSFE granites also correlate with K-only anomalies and are not discriminated from the high-Ca group. Syenite correlates with anomalously high K, Th and variable to high U. The radiometric characteristics of the mafic group are unknown but are expected to be similar to the high-Ca group on geochemical grounds. Gamma-ray spectrometric data are, however, of limited regional use for classifying granite in the Yilgarn Craton due to the very small ground penetration of gamma rays and the laterally extensive regolith cover.

Shear zones in felsic crust and gold mineralisation
Gold mineralisation in the Yilgarn Craton is highly correlated with greenstone belts but it is rarely coincident with high amplitude, or even moderate amplitude, geophysical anomalies. Several authors have inferred that gold mineralisation is commonly located in second and third order structures adjacent to regional shear zones (e.g., Groves et al., 1990). However, the importance of the shear zones has been disputed (Vearncombe, 1998). There is also disagreement as to the nature of some large scale structures that disrupt the greenstone belts and felsic crust. Although gold mineralisation is generally located along faults, the vast majority of faults are barren and regional spatial associations with mineralisation have been difficult to establish. However, an empirical association between gold mineralisation and regional shear zones is apparent.

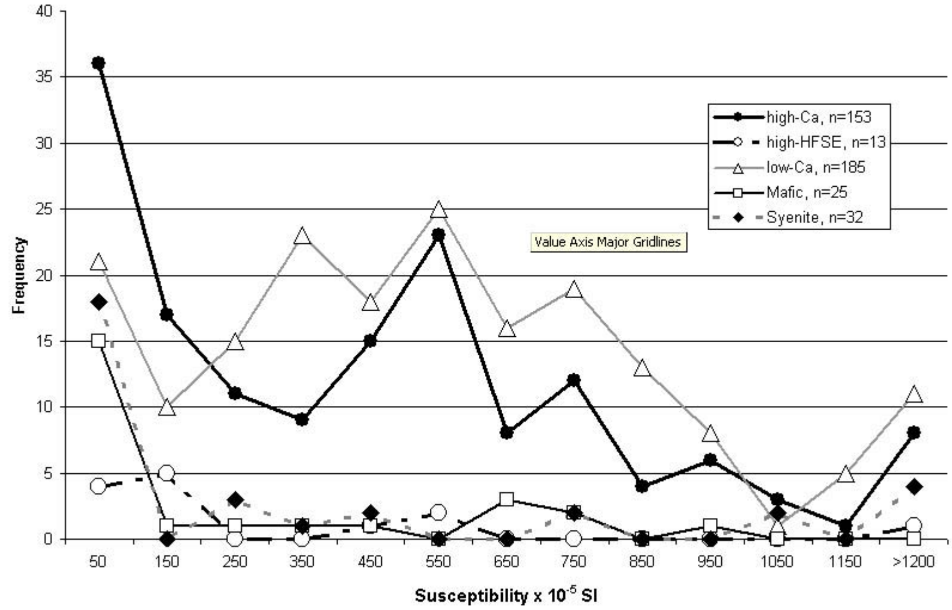

Figure 2 Plot of the susceptibility distribution for the five granite geochemical groups of Champion and Sheraton (1997). Note the extensive overlap of values between groups. The cause of the high number of samples at low susceptibility for all groups may relate to sampling of abundant, poorly magnetised intrusions, spatially associated with the greenstone belts.

Abundant shear zones delineate a 200 km wide, north-trending corridor that transects both greenstone and adjacent felsic crust in the central east of the Yilgarn Craton. This corridor is largely coincident with the Norseman-Wiluna Belt (Gee et al., 1981), the region of highest gold production and resources for the Yilgarn Craton. Within this corridor, intersecting north-northwest and north-trending shear zones define a distinctive rhomboid to sigmoidal internal geometry. Greenstones are strongly aligned with these shear zones and are extensively disrupted. Highly mineralised sites include greenstones adjacent to bends and intersections of the shear zones. Interpretation of seismic reflection data indicates that many of these structures pass through the greenstones and extend deep into underlying felsic crust (Goleby et al., 2003). Ridley (1990) and Mikucki & Ridley (1993) argued that the silicic and potassic alteration associated with many of the Norseman-Wiluna gold deposits provides circumstantial evidence that mineralising fluids were in chemical equilibrium with (underlying) granitic rocks.

In contrast, the architecture of other areas of the Yilgarn Craton is different. For instance, in the vicinity of the Yalgoo Dome in the north west of the Yilgarn Craton, large, circular to ovoid, granite intrusions dominate the regional structure and greenstone is not greatly disrupted by, or preferentially aligned with, the sparse shear zones. The gold endowment of this area is low. Proximity of shear zones and dismemberment of greenstone is successively higher for the Southern Cross and north-east Murchison domains which correlate with an apparent increase in gold endowment. The shear zones are, therefore, considered the main mineralising fluid pathways in the crust, as has been suggested by numerous authors. Greenstones adjacent to the shear zones provide effective structural and chemical traps (see Hagemann & Cassidy, 2000).

Is this empirical relationship between shear zone patterns, greenstone alignment and disruption, and gold endowment applicable in other Archaean terranes? Certainly structural patterns in the Superior Province of Canada lend support to the model. Greenstone alignment and intersecting regional structural zones in the Abitibi sub-province define a remarkably similar rhomboid geometry to that of the Norseman-Wiluna Belt in the Yilgarn Craton. Further more, like the Norseman-Wiluna Belt, the Abitibi sub-province hosts several world class lode-gold deposits spatially associated with the regional fault or shear zones (see Fig. 2 in Robert & Poulsen, 1997). Elsewhere in the Superior Province, these structures are less abundant, greenstone belts are less regionally aligned, and gold endowment is considerably lower. The Pilbara Craton of northwest Australia provides another example. Large ovoid-shaped regions of granite dominate the structure of the Plibara, greenstones are not regionally aligned, and shear zones are not abundant. The structural style of the Pilbara Craton is most similarly linked with that of Yalgoo Dome area in the Yilgarn Craton and its greenstones are equally poorly mineralised with gold.

In summary, gold mineralisation is strongly correlated with shear zones and associated disruption of greenstones. The relationship between felsic crust and mineralisation is more tenuous but is implied through continuity of shear zones in greenstone into surrounding and underlying felsic crust and the nature of alteration associated with gold mineralisation. Thus felsic crust plays an important role in the mineralisation process in the Yilgarn Craton. This role is related to subsequent deformation of the felsic crust rather than directly with magmatic events.

Acknowledgments

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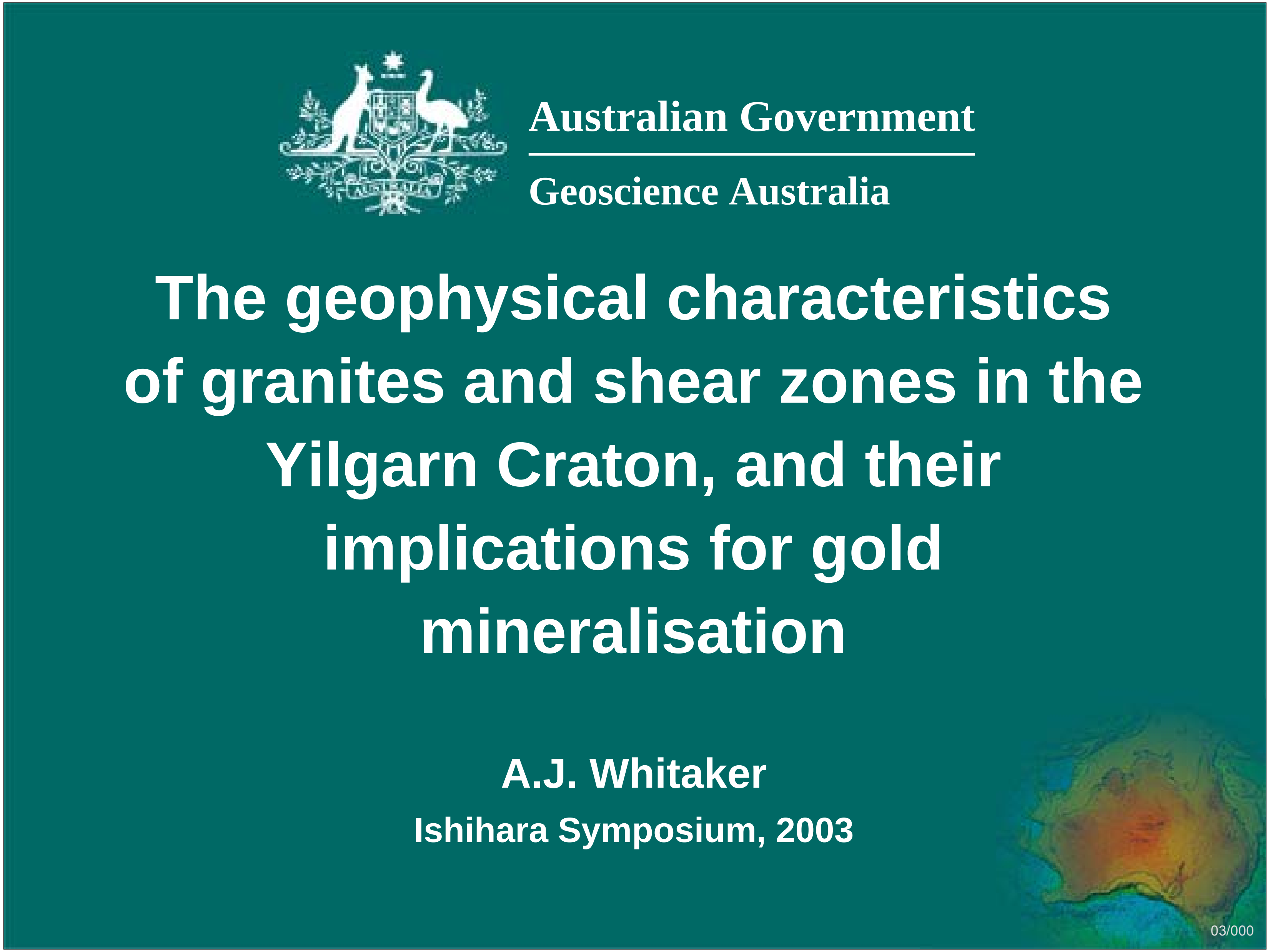

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The geophysical characteristics of granites and shear zones in the Yilgarn Craton, and their implications for gold mineralisation

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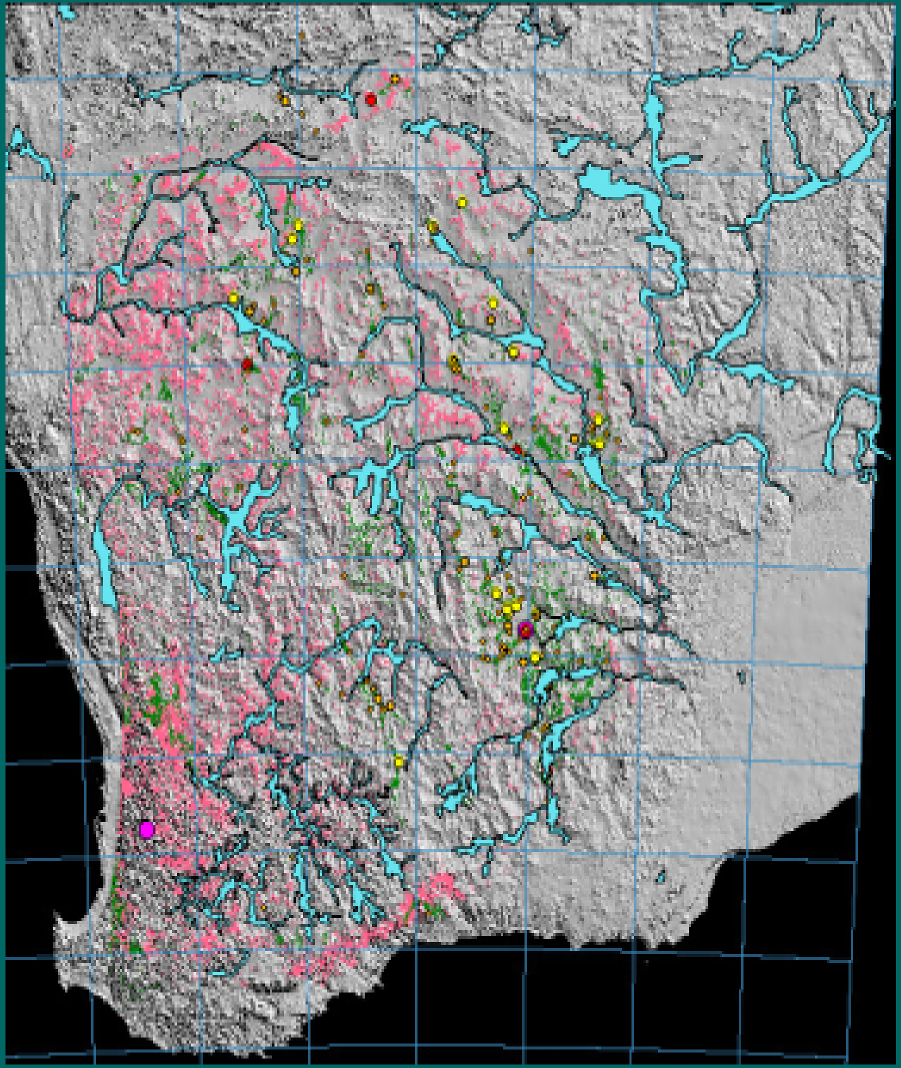
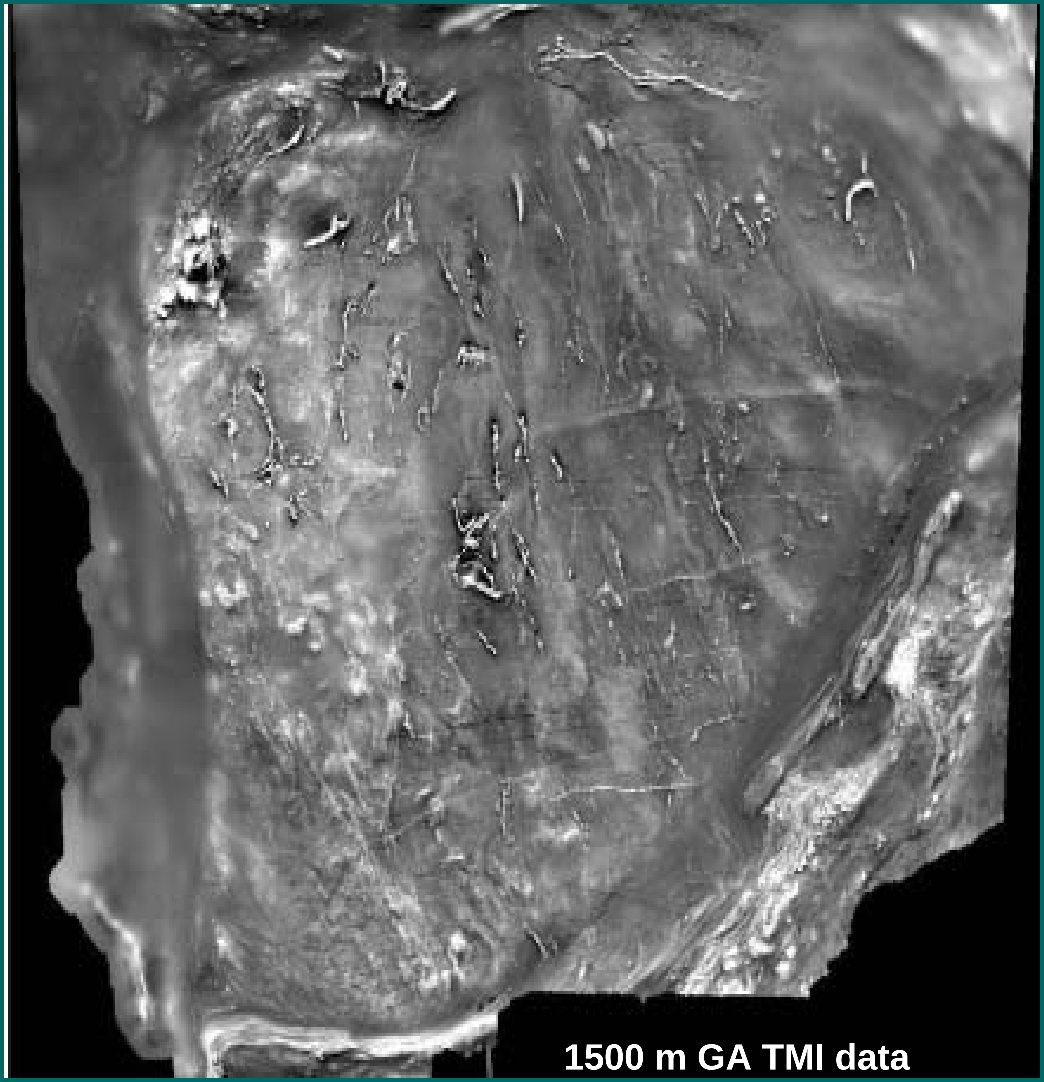
Ishihara Symposium, 2003



Yilgarn Craton

- 70% Australian Au (~200t/yr)
  mostly from greenstone
- 80% granite/ granitic gneiss
  links with Au, alt. & struct.
- Extensive regolith - shallow
  (~15% outcrop)
- Geophysical data
  TMI, Gravity
  'see through' cover

Digital elevation model
Granite and greenstone outcrop
Gold deposits



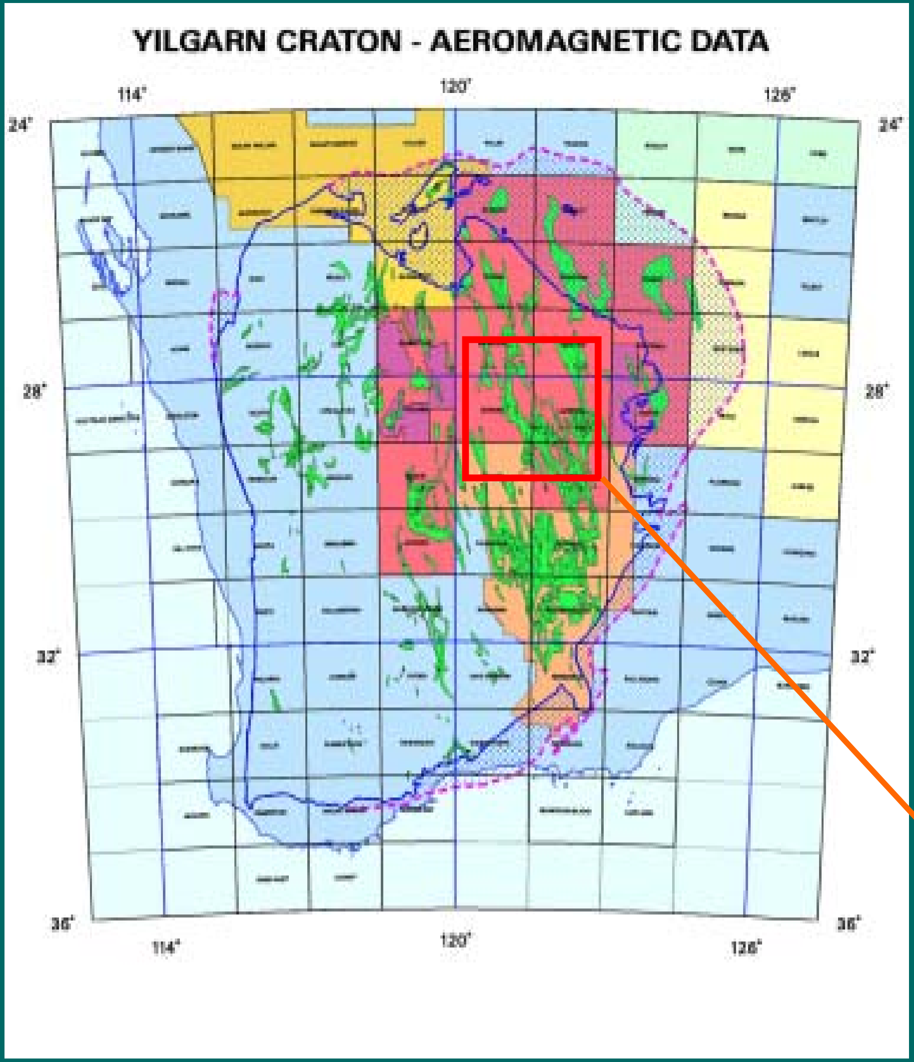
Scope

Aeromagnetic map units
(not equivalent to
geological mapping)

Granite suites (geochem)
geophysical data
rock properties

Shears in felsic crust
links with Au

Distinctive shear pattern
200 km wide zone
with abundant Au



Data coverage

- Aeromagnetics
  GA 1500m
  GA & GSWA ~400m
  Fugro data ~200m
  De Beers/Pitt ~200m
  Resolution issues
- Gravity
  2 – 11km station spacing
- Radiometrics
  0.5m ground penetration
- Geology
  up to ~40 yrs old

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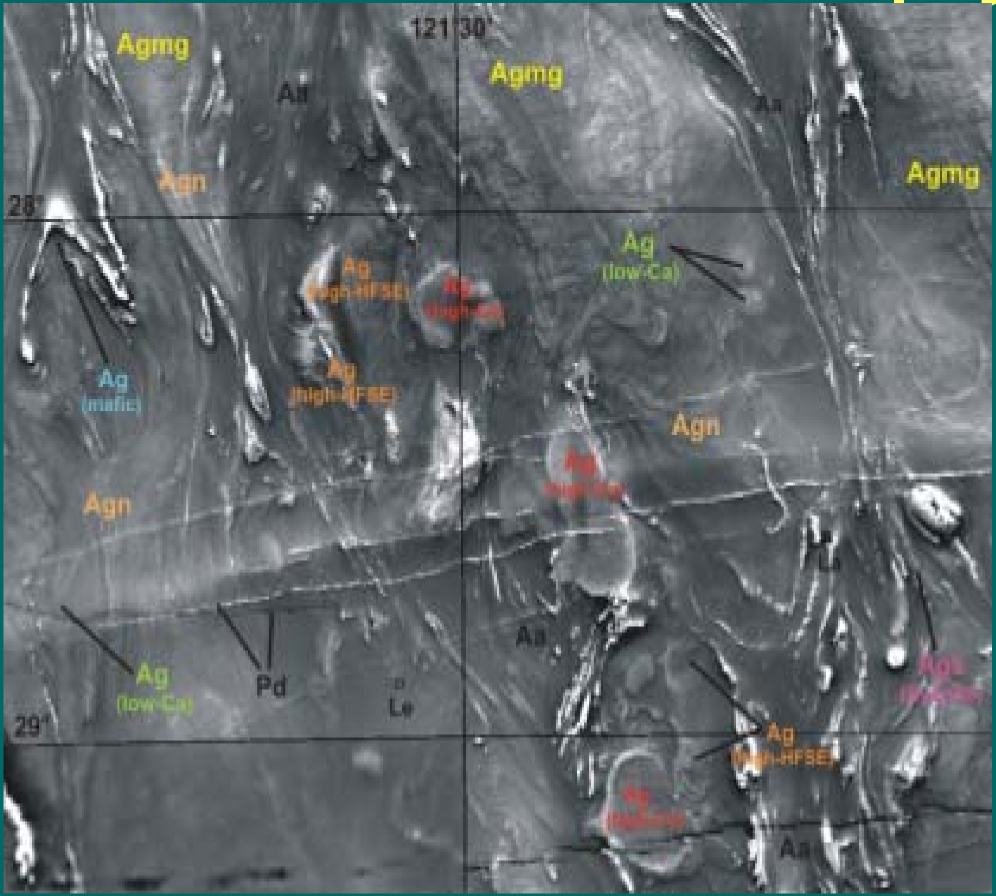
TMI Survey Index

Geophysical map units



TMI Leonora region
400 m & 1500 m GA data

50 km

Granitic map units

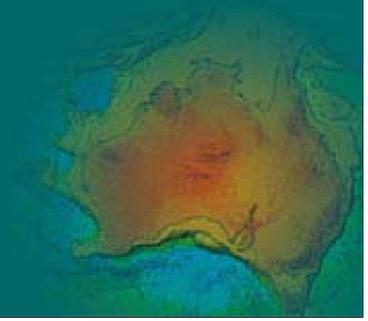
- gneiss-migmatite-granite (Agmg)
- banded gneiss (Agn)
- granite plutons (Ag)
- syenite (Ags)

Greenstone

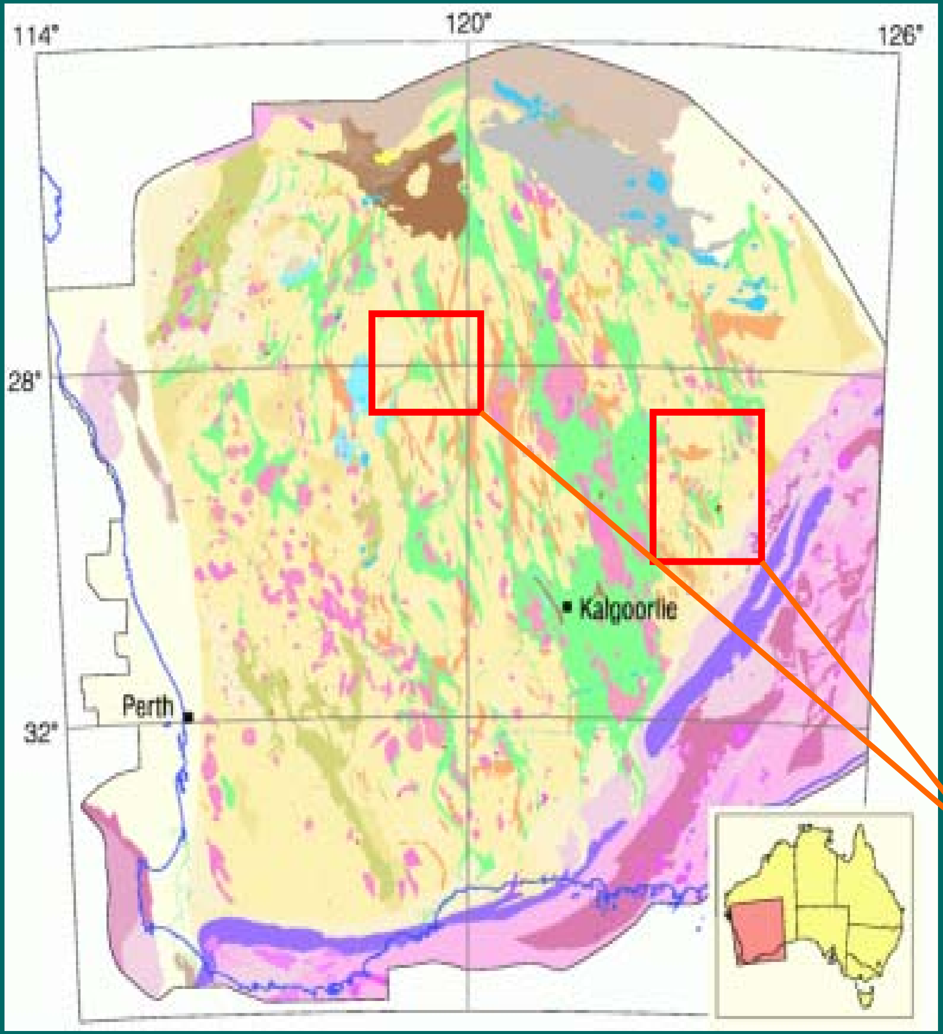
- (Aa, low mag)

Other features

- dykes (Pd)
- faults & shear zones
- small intrusives



Geophysical map units



Gneiss-migmatite-granite

>80% little subdivided

Plutons ~10%

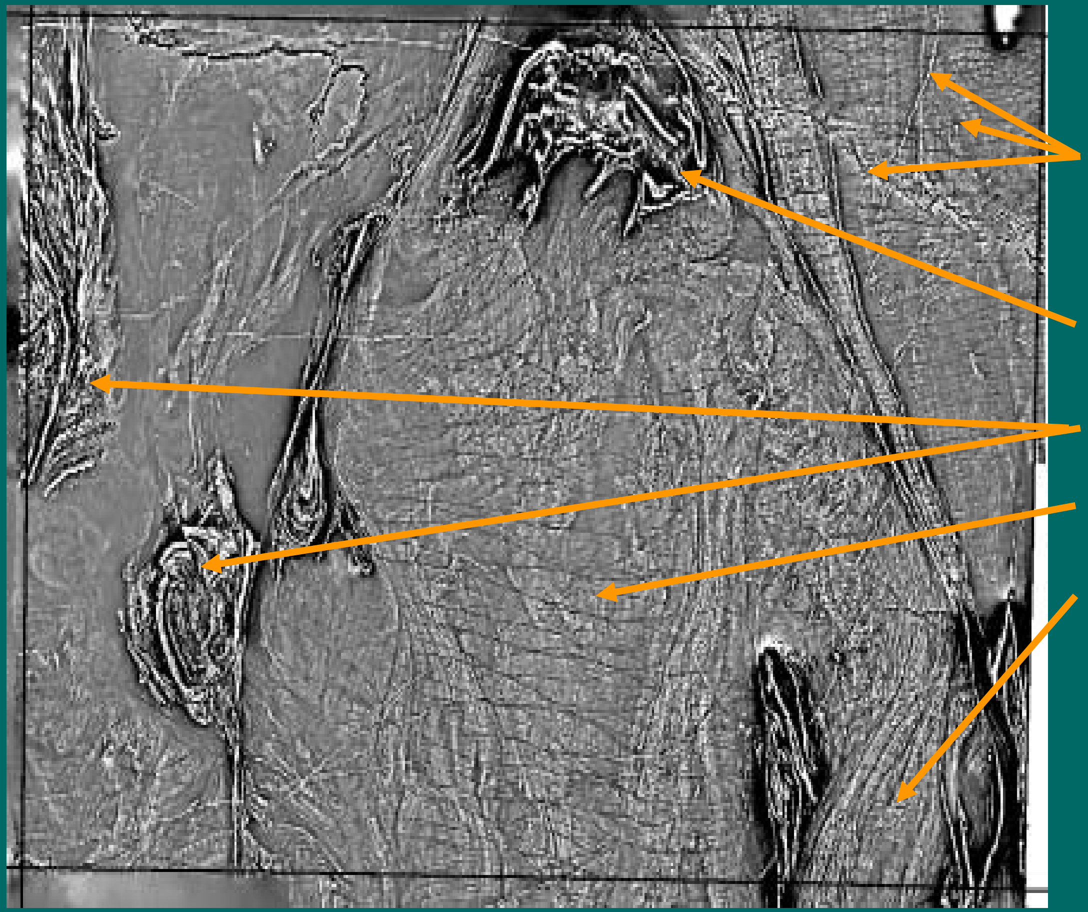
spatial associations

Banded gneiss

old shear zones?

Next Slides

Geophysical map units



Sills, dykes, faults

Plutons not apparent

Greenstone

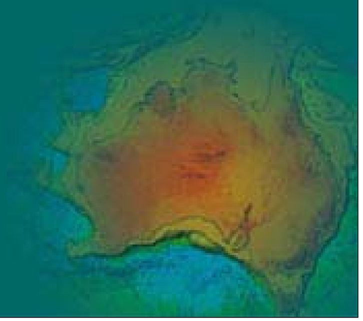
Layered intrusions

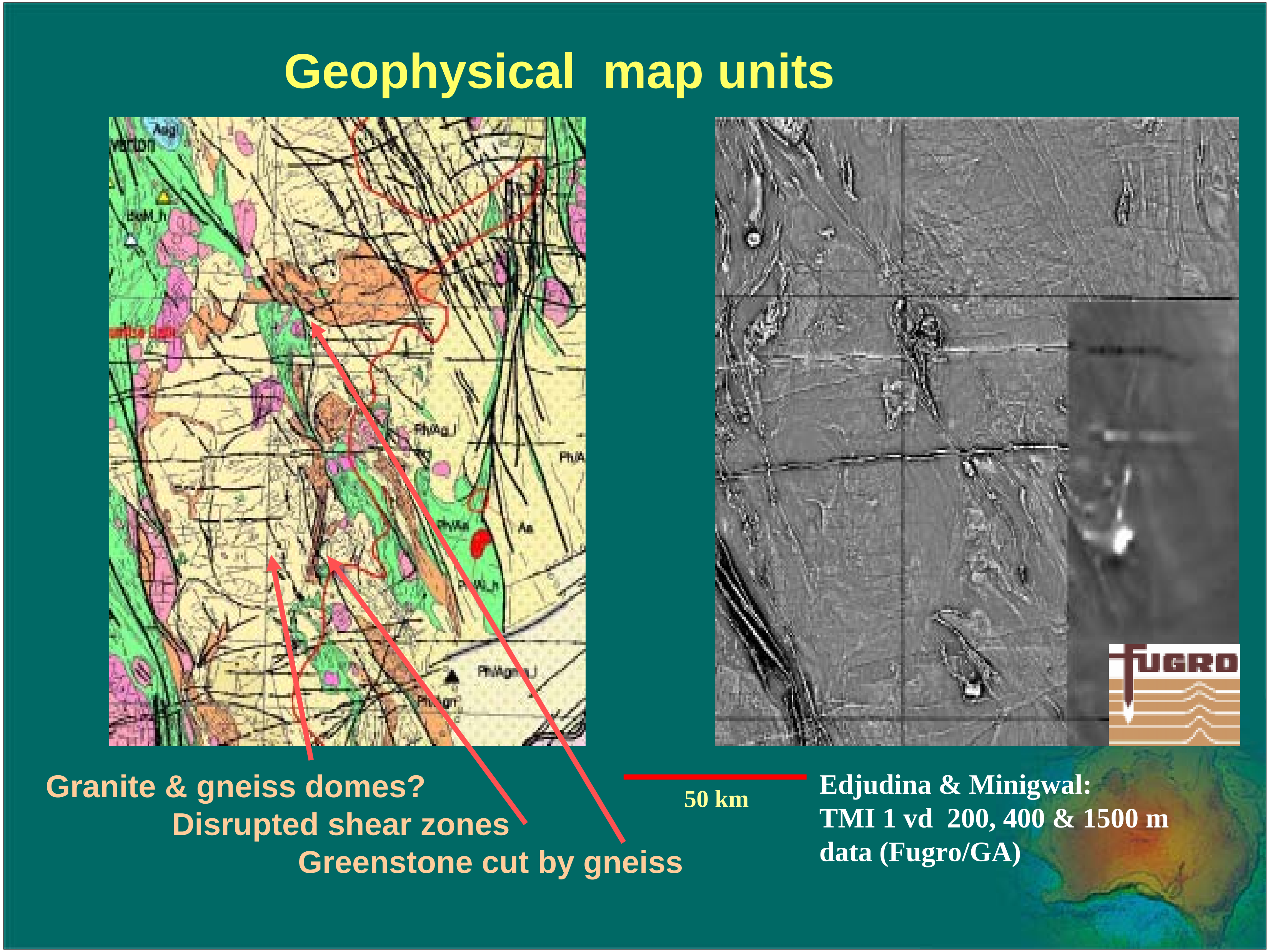
Gneiss-migmatite-granite

Banded granitic gneiss

Youanmi - 200 m & 400m TMI 1st vert. derivative data (GA/GSWA)

50 km





Geophysical map units

Granite & gneiss domes?

Disrupted shear zones

Greenstone cut by gneiss

50 km

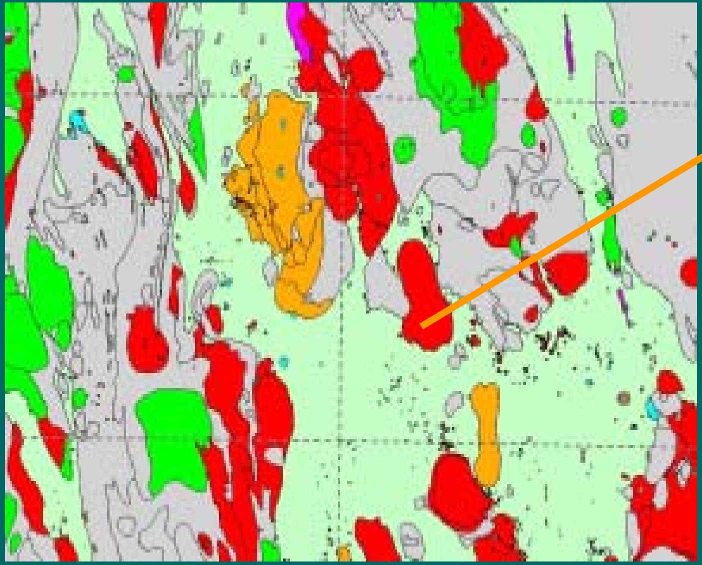
Edjudina & Minigwal:
TMI 1 vd 200, 400 & 1500 m
data (Fugro/GA)

Granite suites

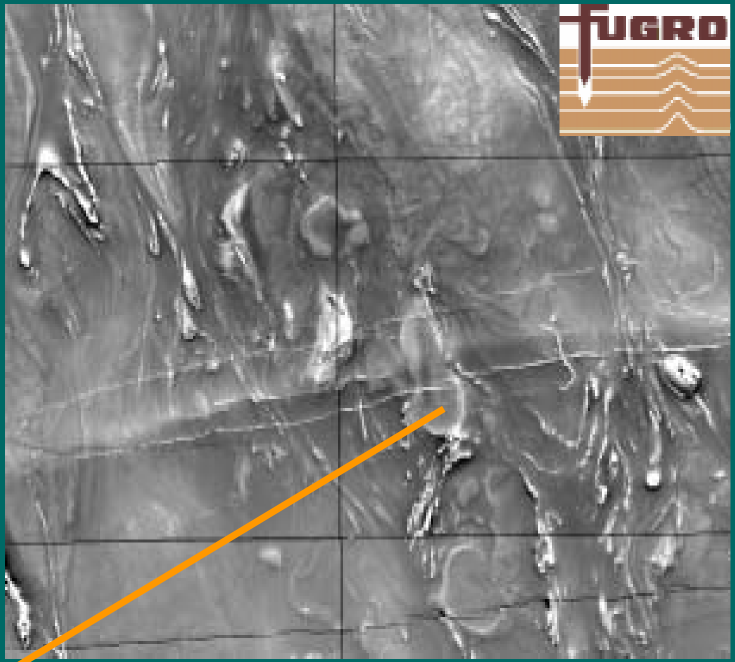
Champion & Sheraton (1997)
5 geochemical groups
not distinguished in TMI

Major groups: high-Ca & low-Ca
zoned high Ca in greenstone
banded gneiss – high Ca

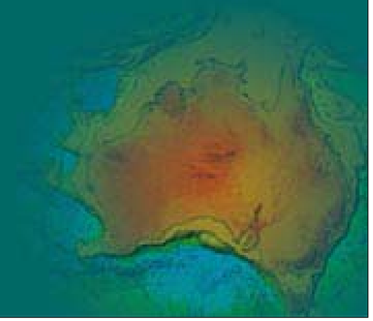
Minor: high HFSE, mafic, syenitic
small plutons, dykes, sheets



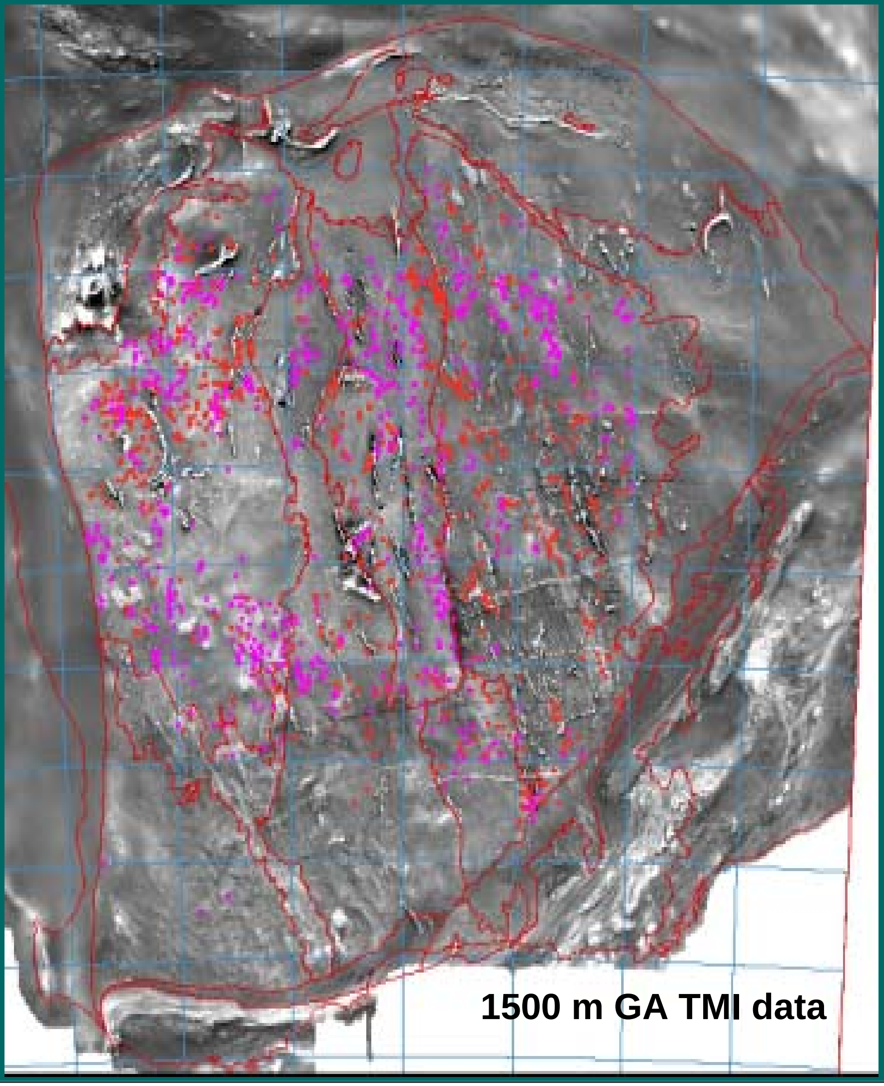
🟥 High-Ca granite
🟩 Low-Ca granite
🟧 High HFSE granite
🟦 Mafic granite
🟪 Syenite
⬜ Unassigned



TMI 1 200 & 400 m data
(Fugro/GA)



Major Granite suites

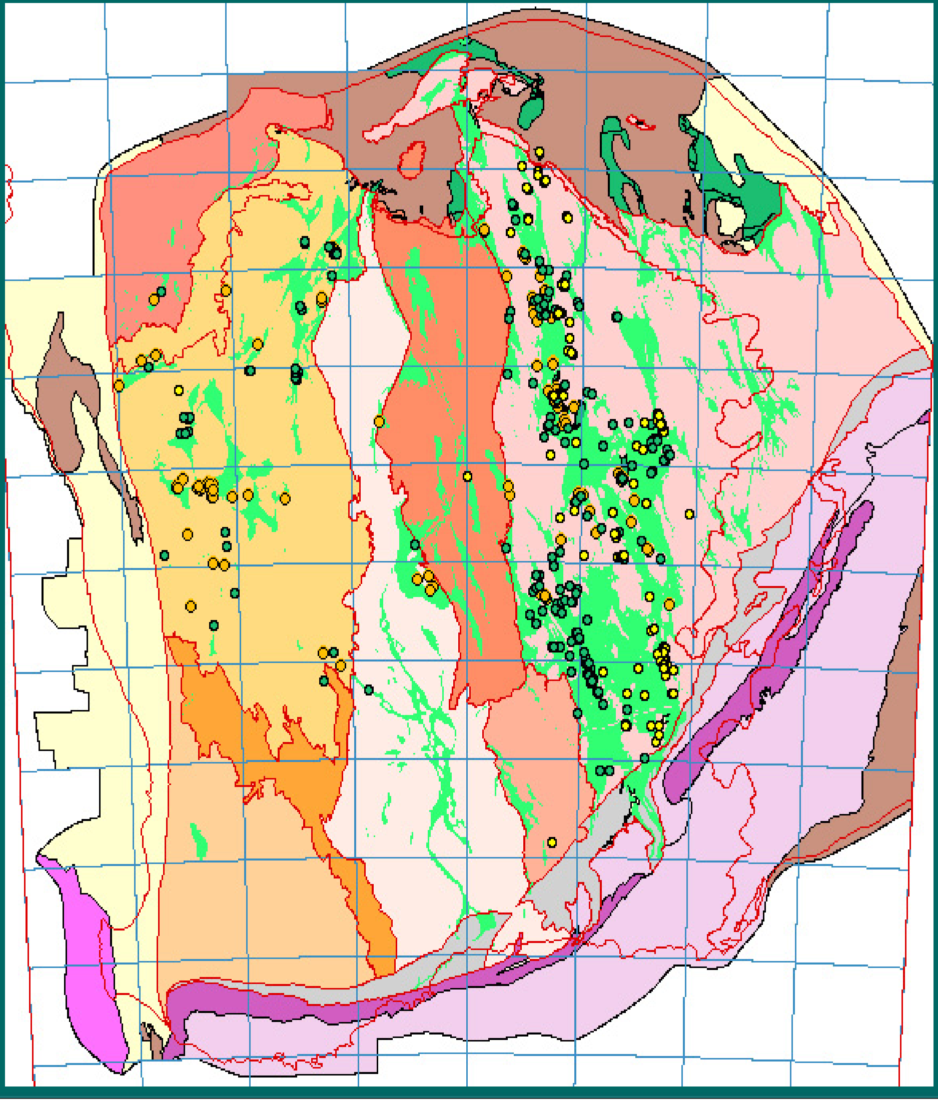


- ● High Ca
- ● Low Ca
  not distinguished in Agmg

- only 10% of granite distinguished as plutons
- may reflect non-resolvable dykes and sheets

Dykes in image - dolerite

Minor Granite suites

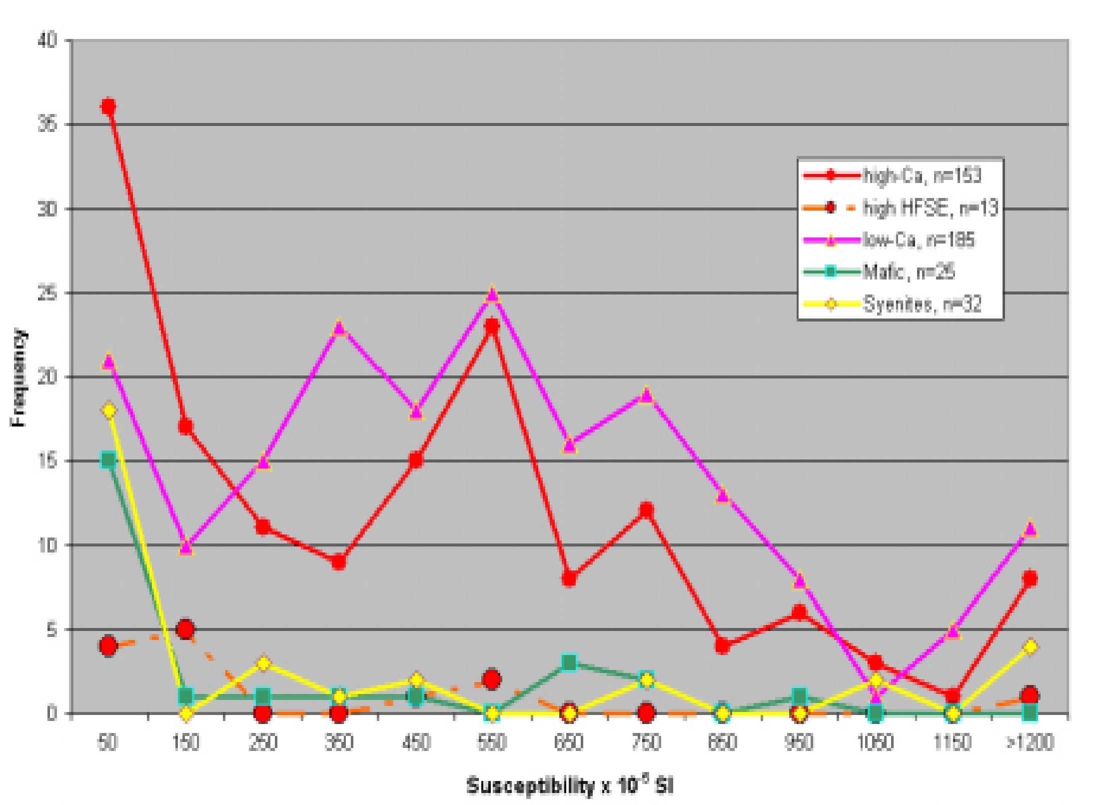


- ● High HFSE granite
- ● Mafic granite
- ● Syenite

- Occur as sheets, small plutons, & dykes
- Spatial associated with Norseman-Wiluna belt & greenstones

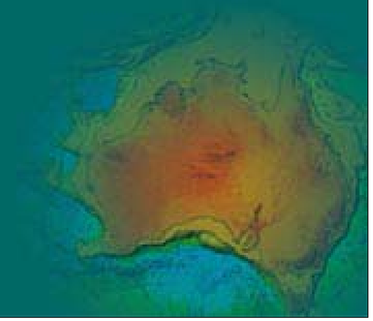
Greenstone belts
and magnetic domains

Granite suites - Susceptibility

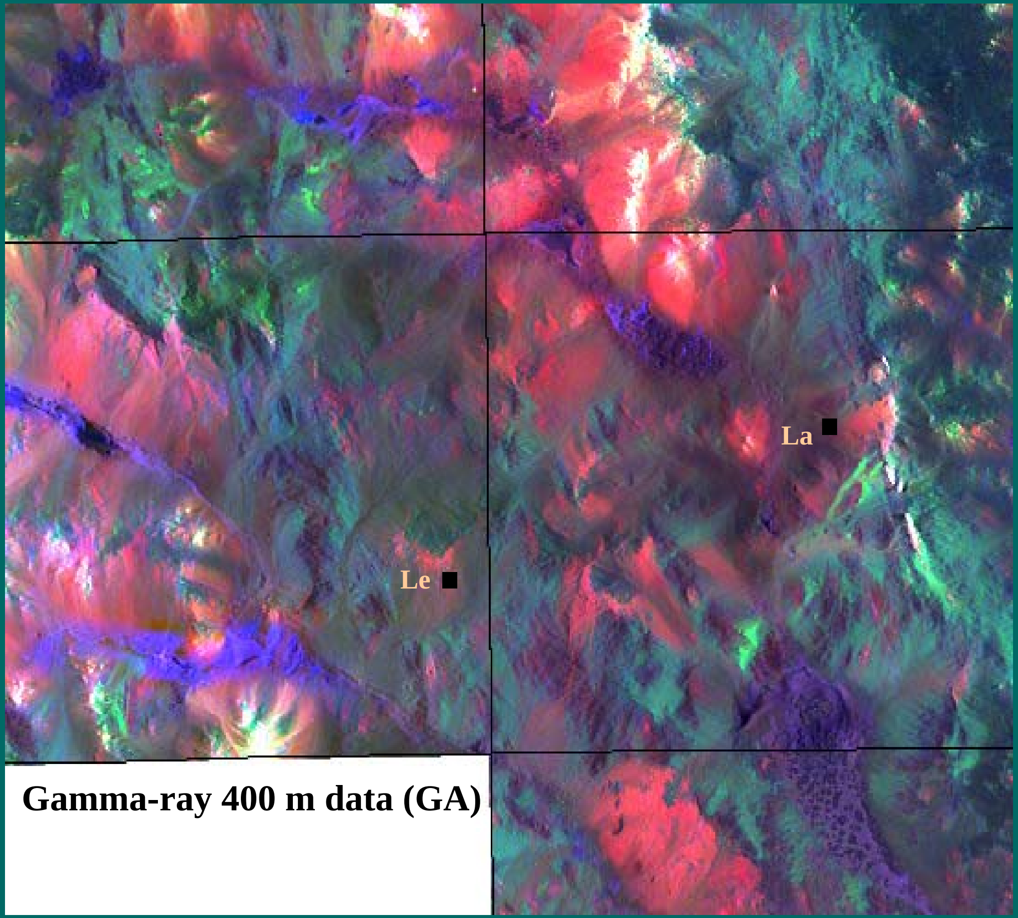


Overlapping Susc.

Peaks at low Susc.
low mag intrusives
in greenstone

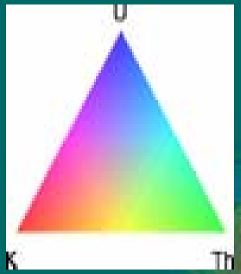


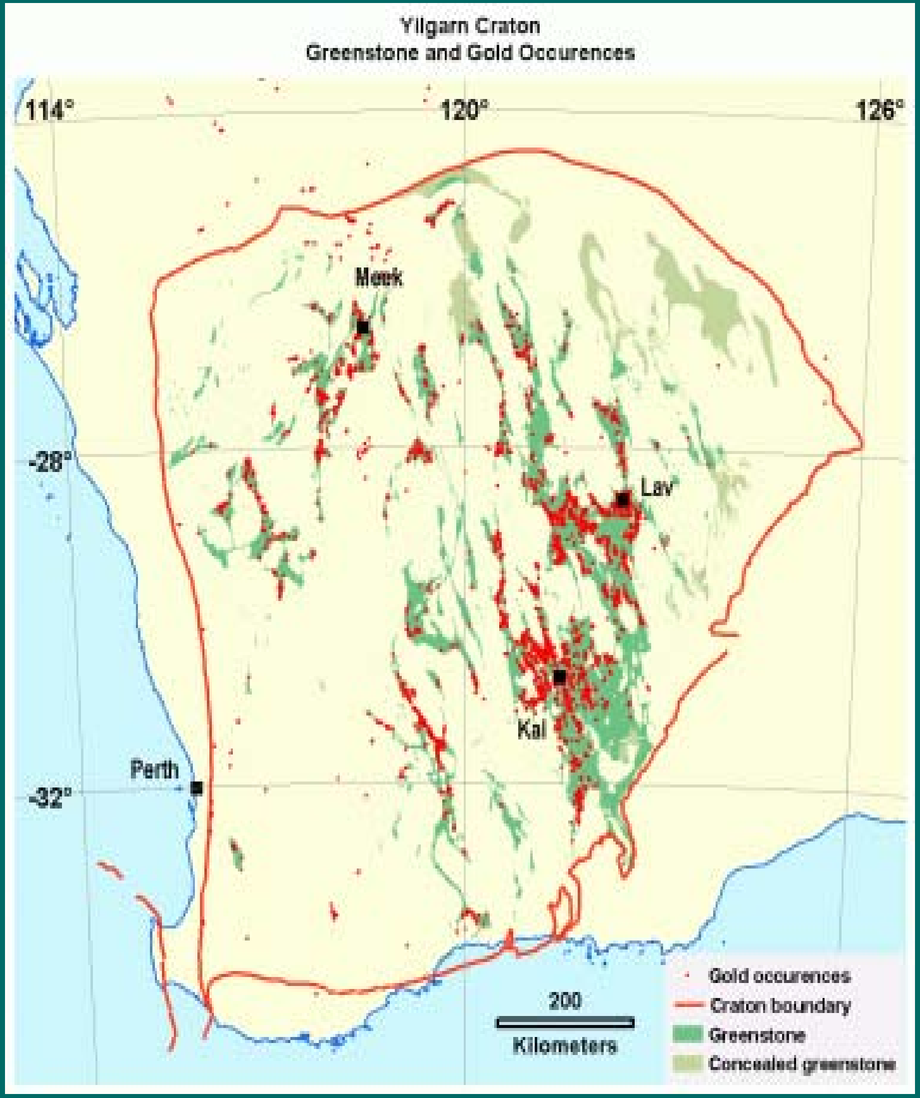
Granite suites – Gamma-ray data



Gamma-ray 400 m data (GA)

- High-Ca/ high HFSE
  K only - red
- Low-Ca
  K, Th, & U - white
- Syenite
  K, Th, & U - white





Shears & Au

Au largely in greenstone belts

Most gold in E Goldfields
  Au per km^2 greenstone varies

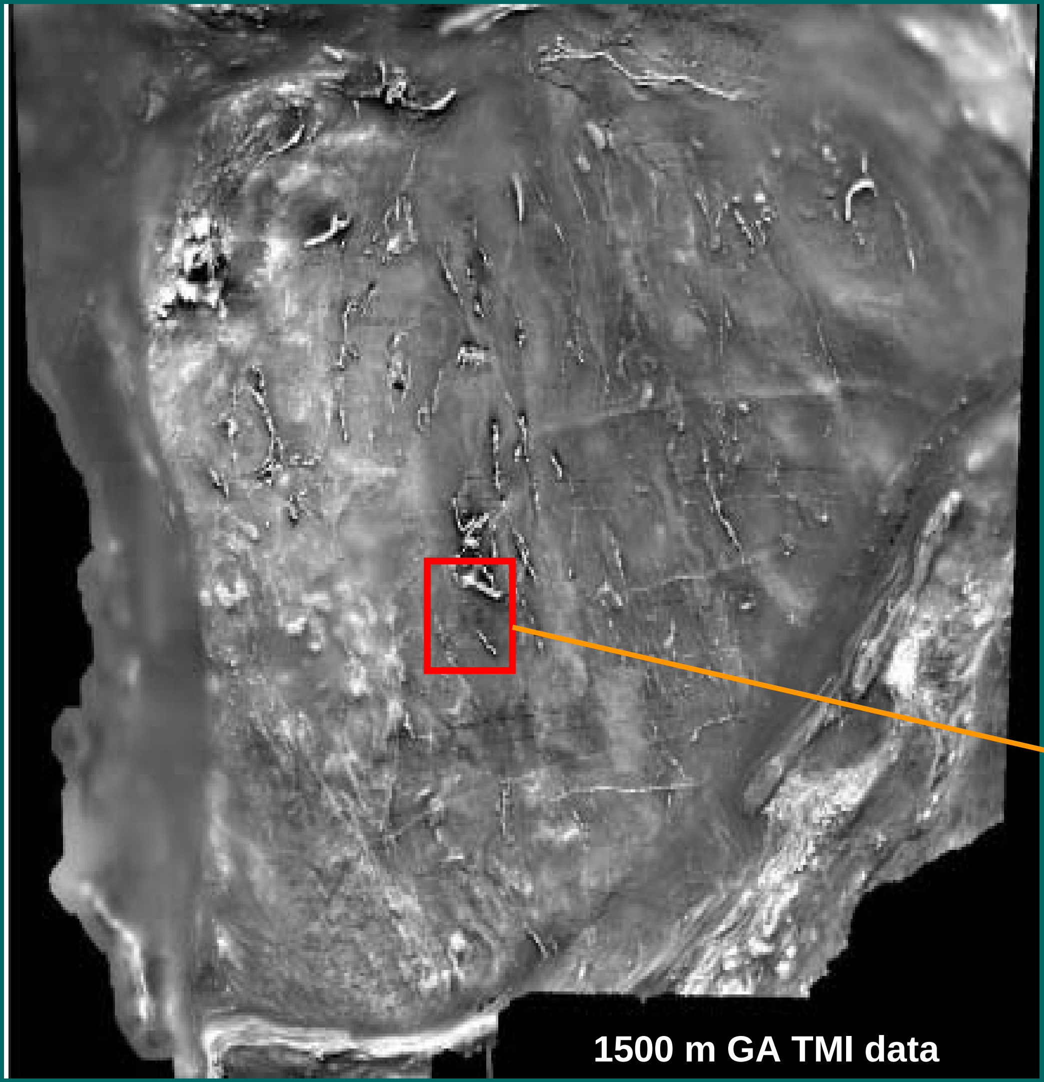
Fluids have seen felsic crust
  alteration (+K, +Si,)
  isotopes (Pb)

Au & positive mag anomalies
  very few (most local mag lows)

Faults host Au
  systematic patterns?

Shears spatial link to Au

Shears & Au



1500 m GA TMI data

Greenstone
- poorly magnetised
- structure not clear

Felsic crust (Agmg, Ag)
- underlies greenstone
- moderate magnetisation
- structure evident

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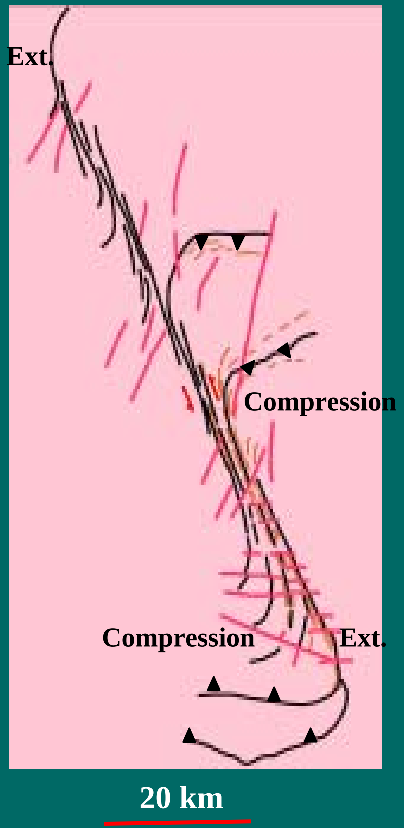
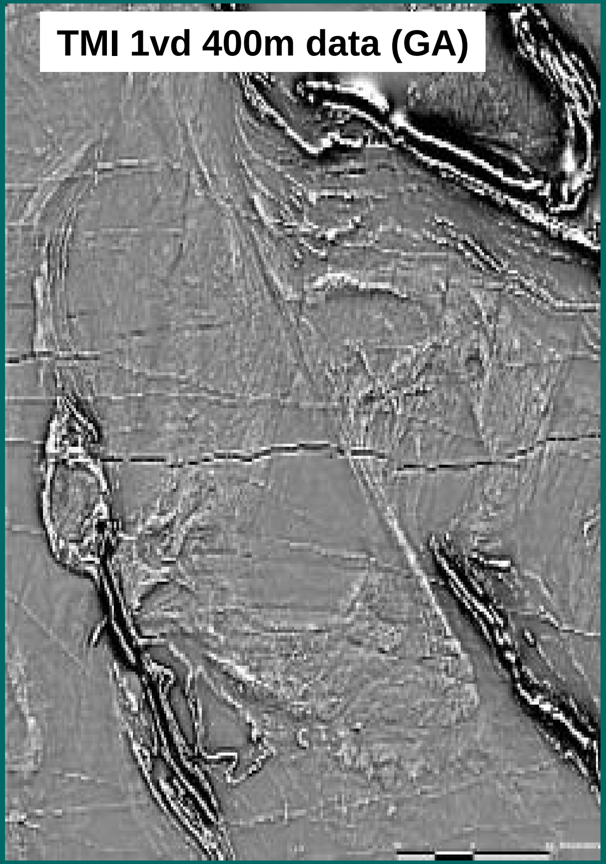


Koolyanobbing Shear Zone
Amphibolite grade
Ductile shear zone



Shears & Au

Shears

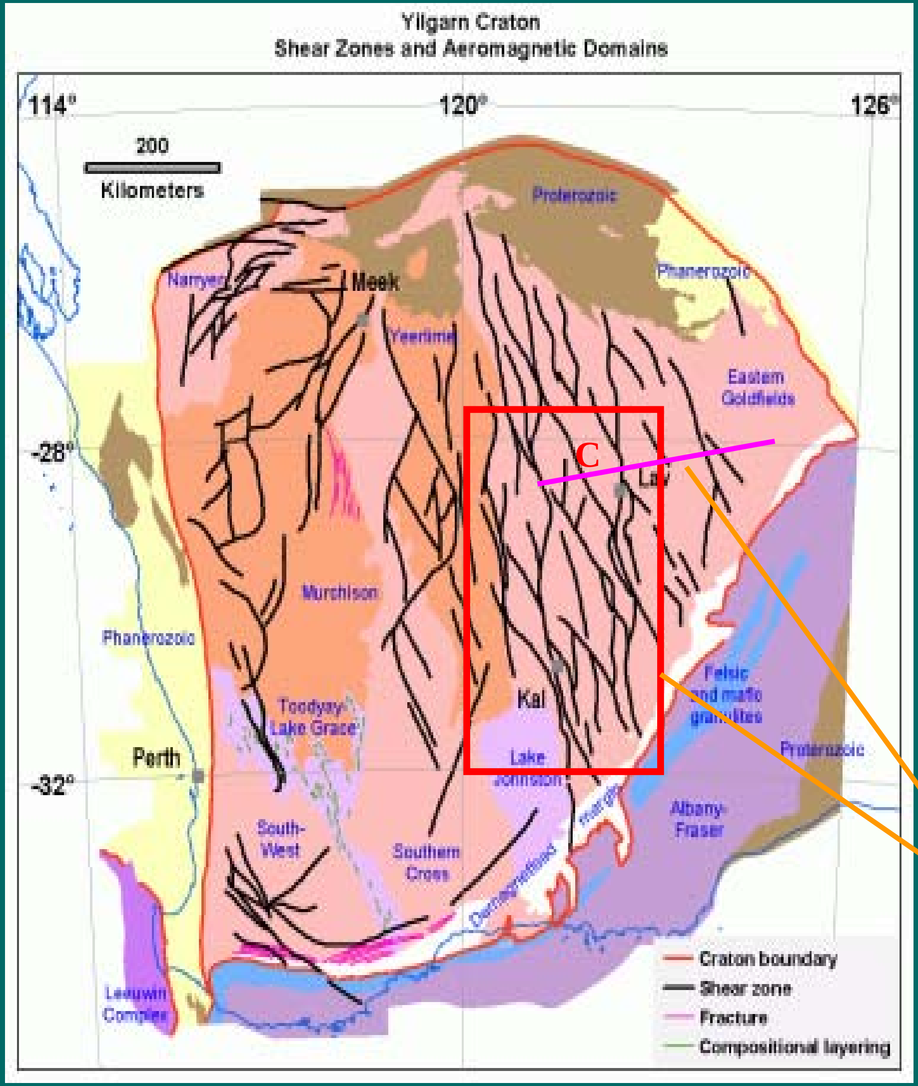
>100km long, >1km wide
30 - 50 km movement
thrusts at right angles

Faults

<50km long, <300m wide,
<5km movement
overprint shears

Model for greenstone

tectonic zones
thrusts in greenstone
expect areas of extension
ends of shears -curvature



Shears & Au

Norseman – Wiluna Belt

- craton scale shear 200 km wide
- distinctive pattern NNW & N
- NE of Celia lineament (C) part of Belt
- fewer shears E & W

Shear zones

- episodic reworking?
- greenstone preservation?
- greenstone mineralisation?

Nth Goldfields seismic line

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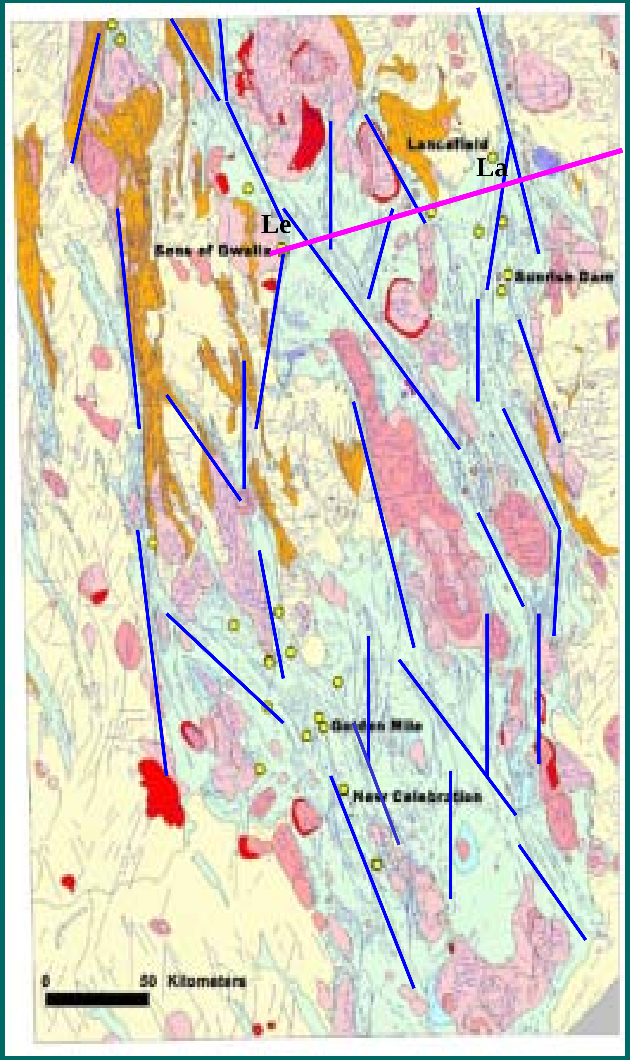


Shears & Au

Tectonic zones - shears

- distinctive rhomboid pattern
- crustal plumbing

Faults - brittle fracture

- tap shears & host Au

Crust to east & west

- less disrupted by shears
- similar abundance of faults?
- much lower gold

Le = Leonora, **La** = Laverton

Nth Goldfields seismic line – west

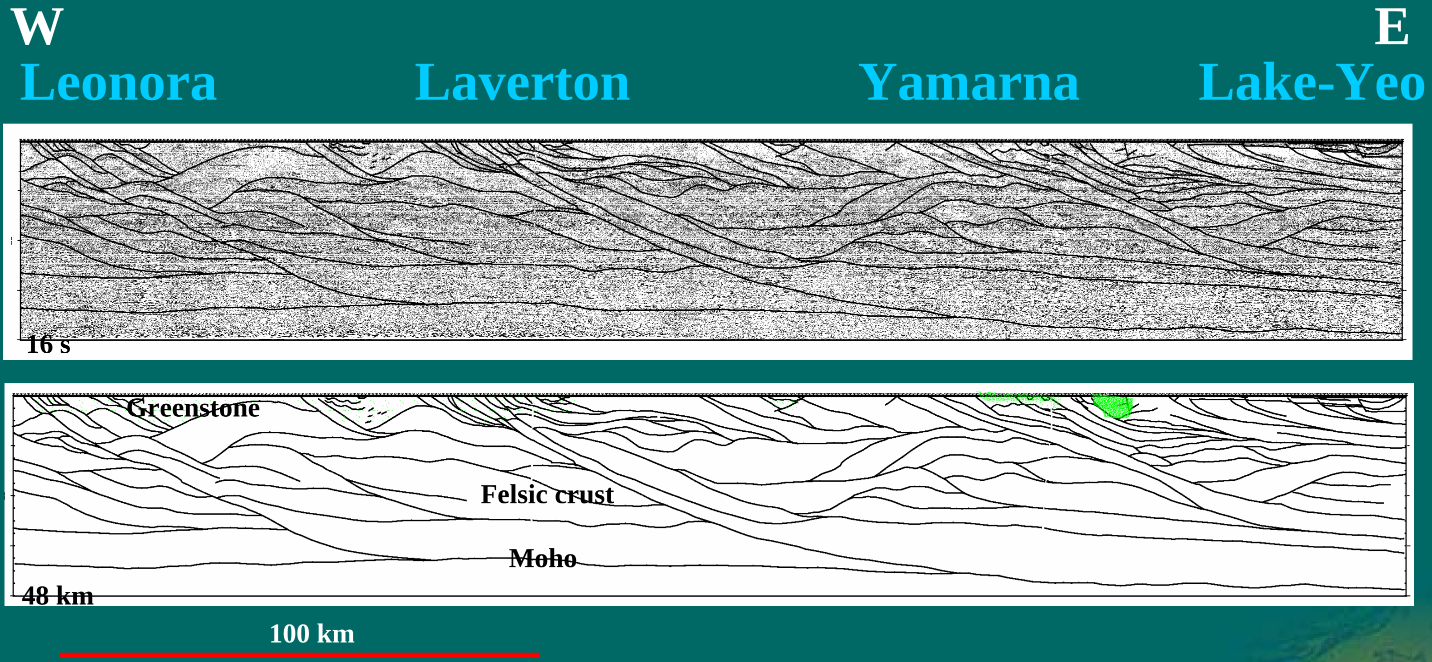
Leonora-Norseman area

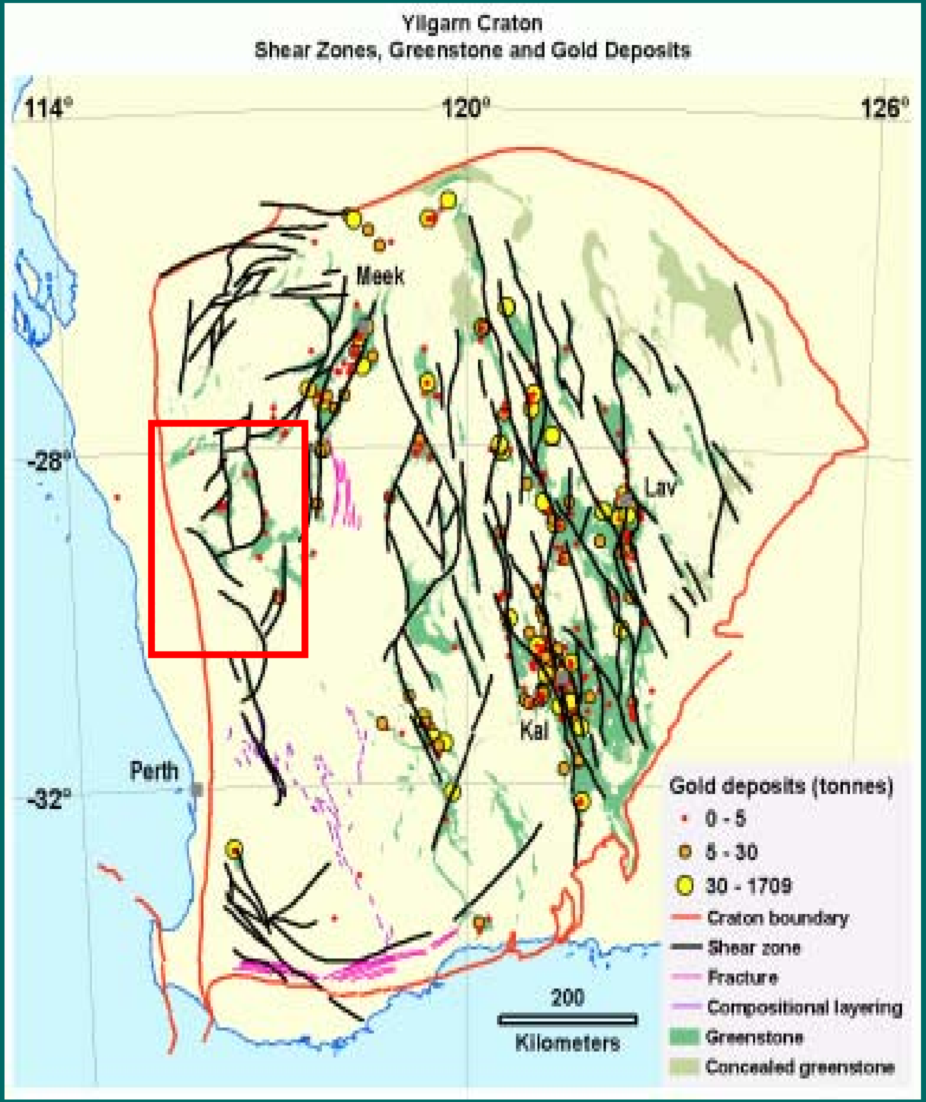
Shears & Au

Crustal scale structures

Greenstone – uppermost crust

01AGSNY1





Shears & Au

Well mineralised sites

Regional scale

- junction of shear zones
- greenstone/shear-obtuse angles
- between parallel shear zones

Local scale

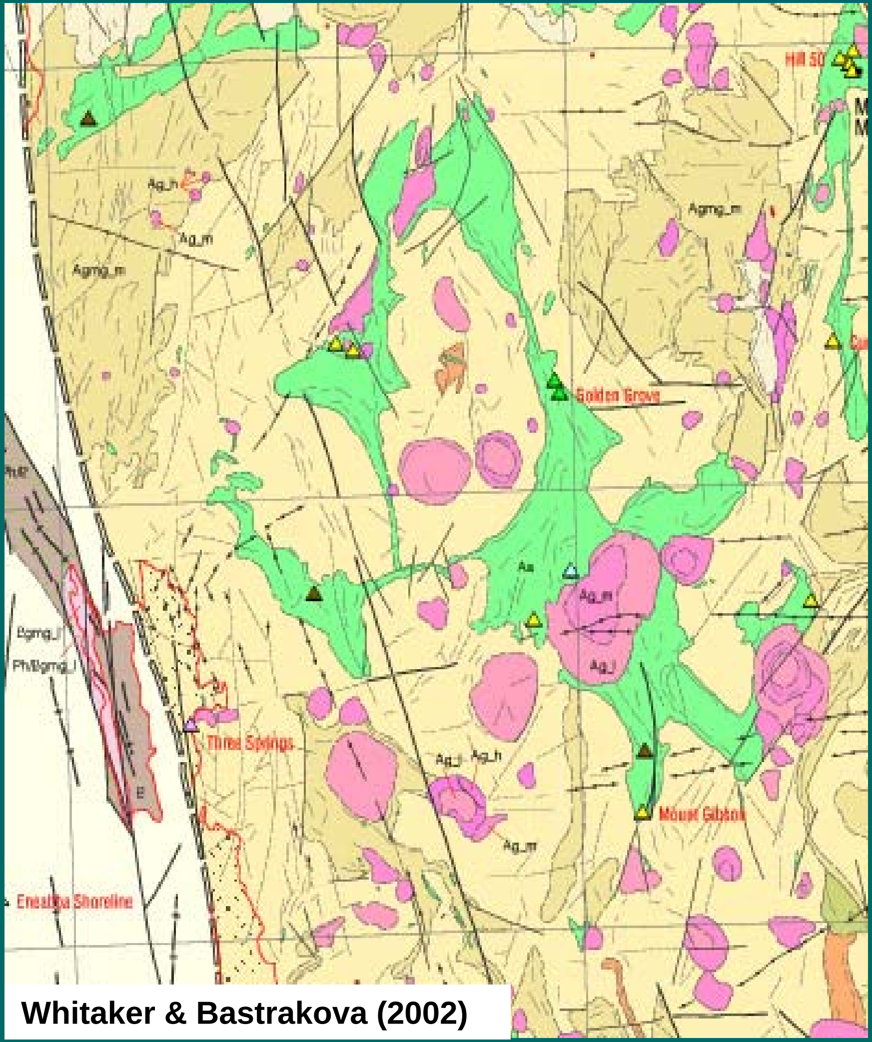
- rheology contrasts
- sills
- small - late granite plugs
- dykes (some evident in magnetics)

Under explored ?

- deposits correlate with outcrop
- thin cover 85% of region

Au and structural style

☐ Next slide



Whitaker & Bastrakova (2002)

Shears & Au

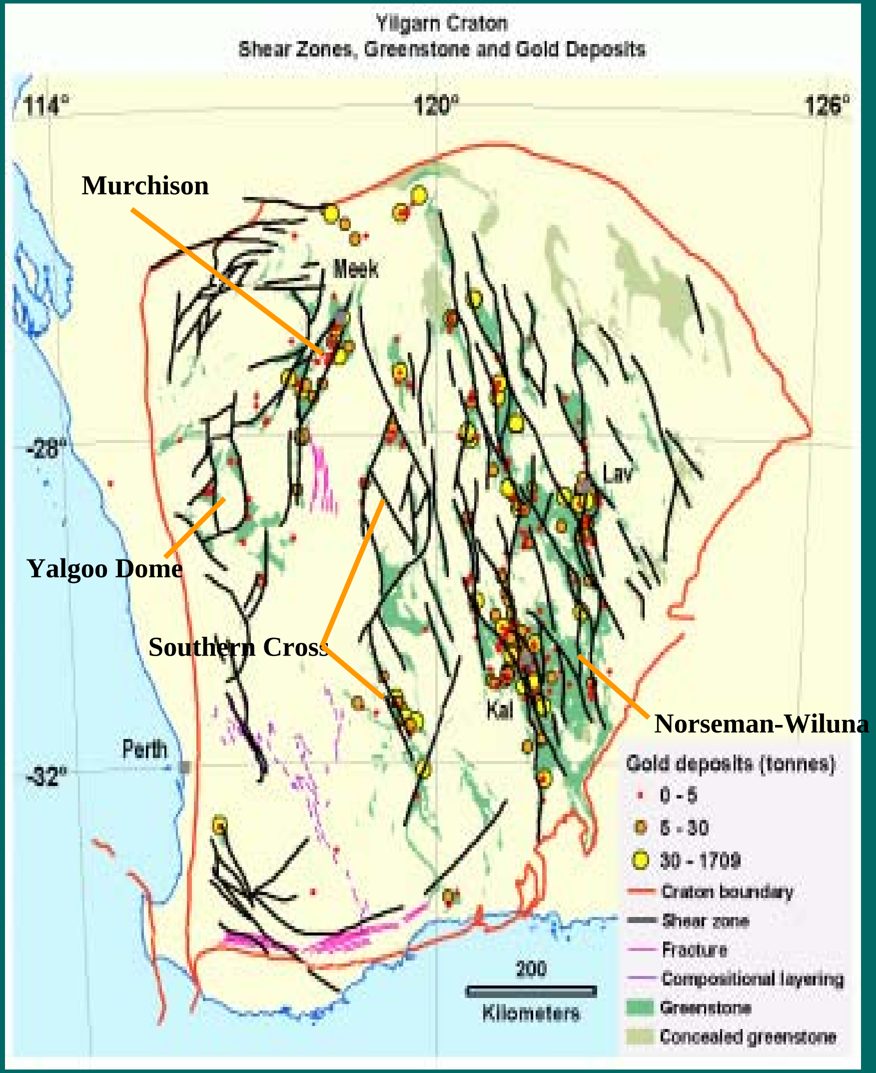
Yalgoo Dome

Shear zones
- rare
- few intersections

Greenstone
- not regionally aligned
- low internal disruption

Granite shape dominates
- Pilbara like

Low Au endowment
- Au resources = 57 t
- Deposits > 100t Au = 0



Shears & Au

Southern Cross & Murchison

- greater shear interaction
- greenstone alignment & greater disruption

Southern Cross

- Au resources = 440 t
- Deposits > 100t Au = 0

Murchison

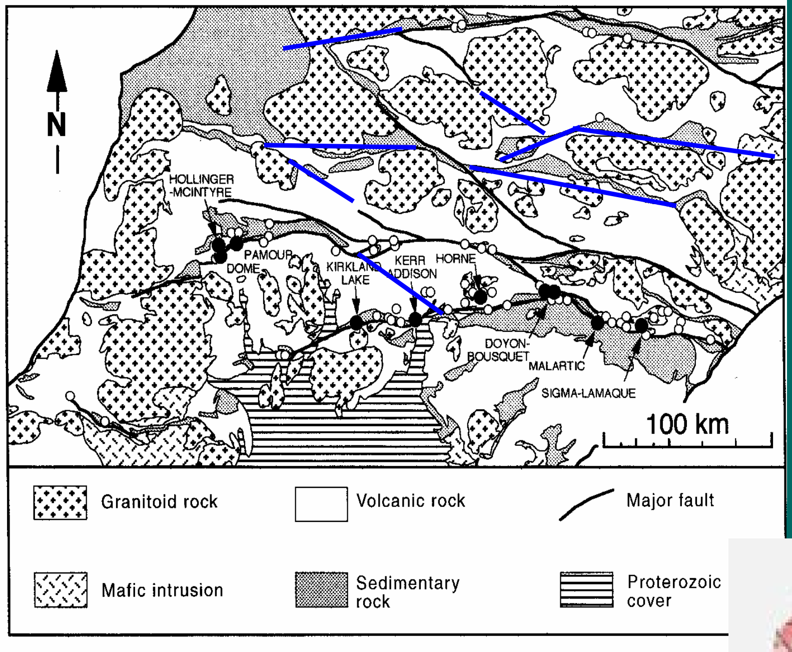
- Au resources = 640 t
- Deposits > 100t Au = 1

Norseman-Wiluna Belt

- Au resources = 5861 t
- Deposits > 100t Au = 16

Shears & Au

Robert & Poulsen (1997)



Superior Province Canada

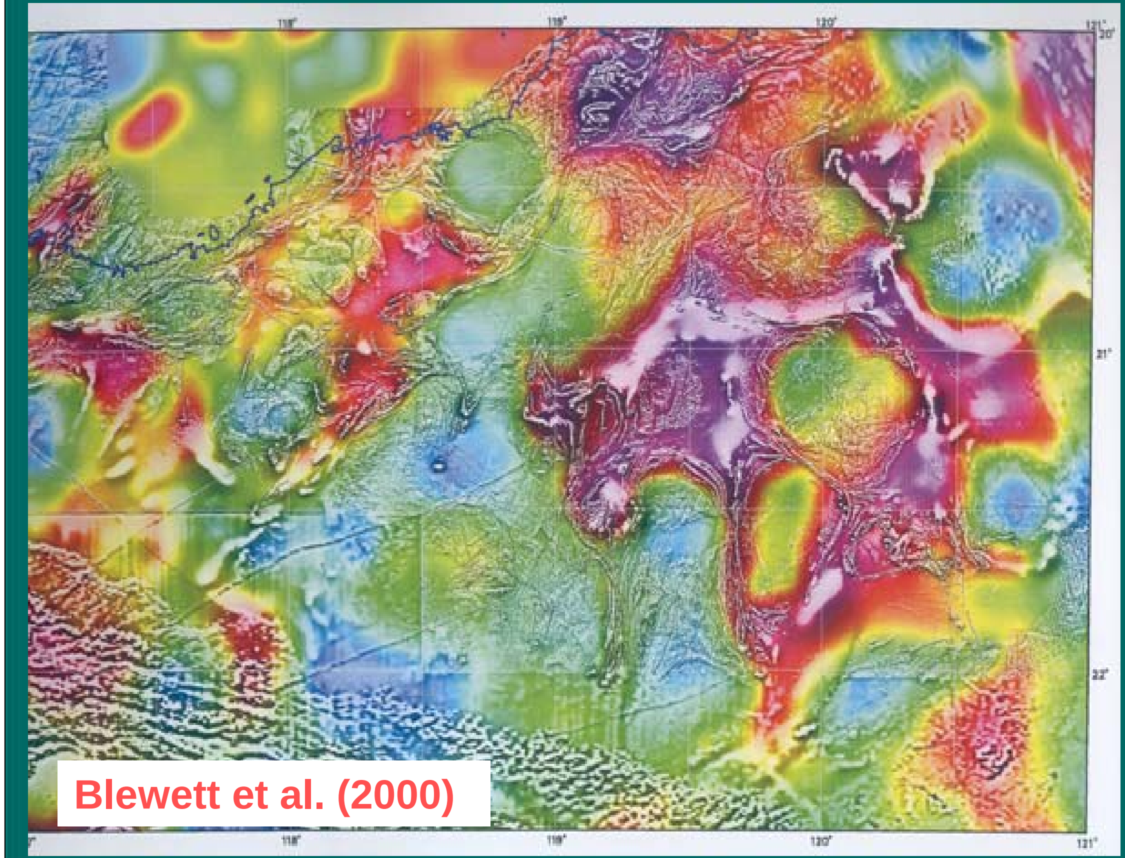
Abitibi –sub-province

- crustal scale shears
- rhomboid pattern
- aligned greenstone

- Au resources = 11000 t
- Deposits > 100t Au = 10

Geology of Ontario, Map 2545 (1991)

Shears & Au



Blewett et al. (2000)

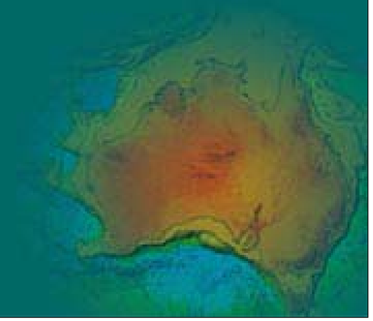
Pilbara Craton

Shear zones
- rare

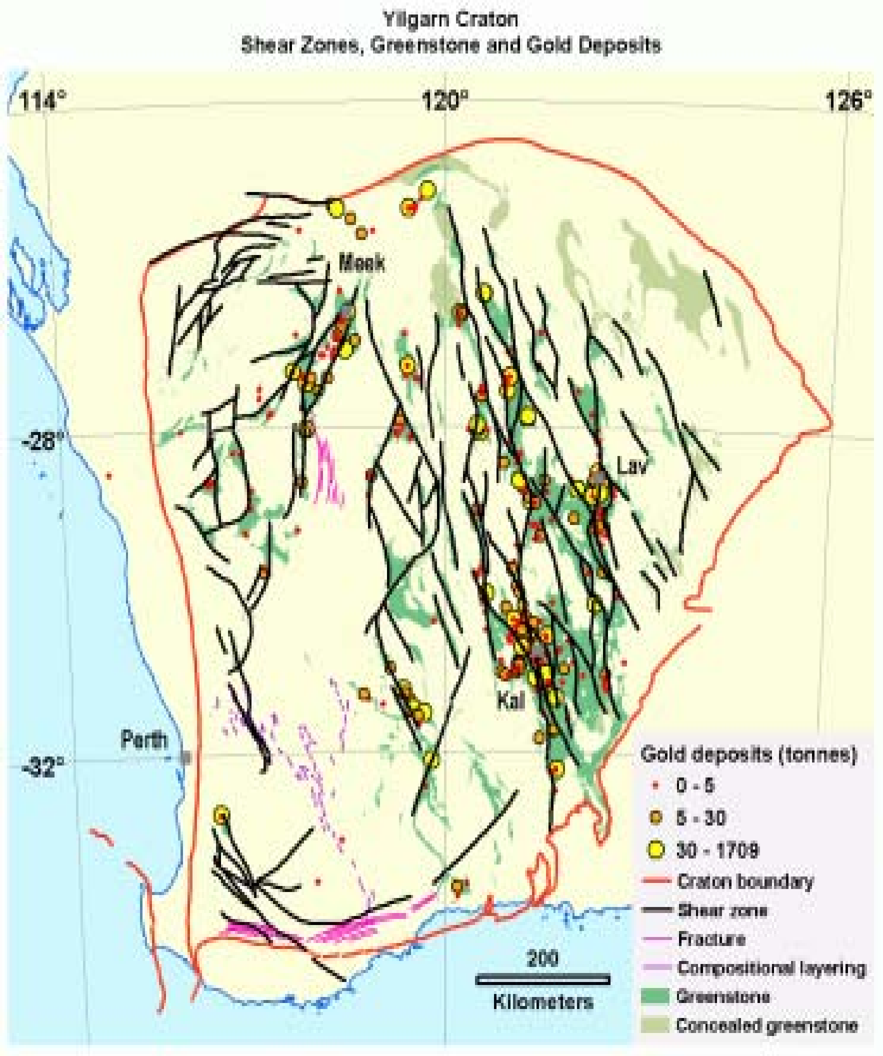
Greenstone
- not regionally aligned
- disruption low

Granite ‘domes’
- dominate pattern

Low Au
- Au resources = 30t
- Deposits > 100t Au = 0



Conclusions


Yilgarn Craton
Shear Zones, Greenstone and Gold Deposits

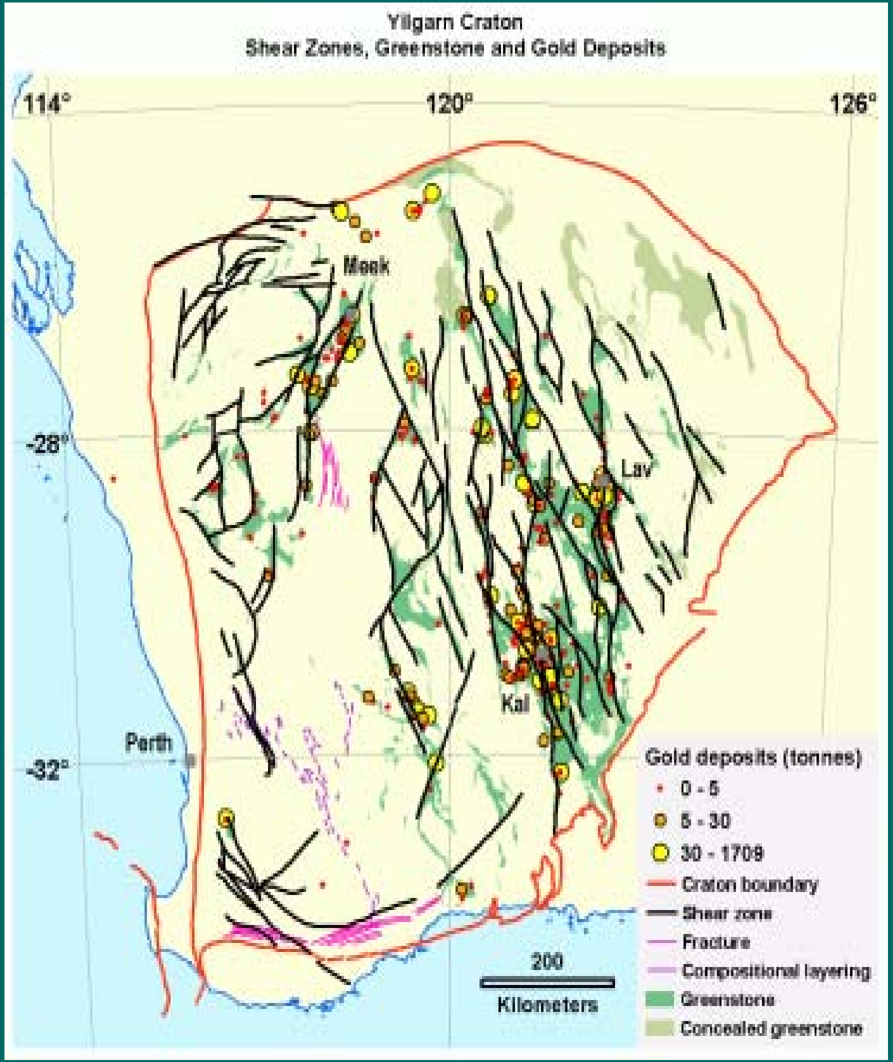
Geophysical interpretation

- not equivalent to geological mapping
- many plutons, but only 10% of granite subdivided
- contrasts in crustal structure

Granite suites

- not discriminated in geophysics
- zonations apparent in some
- some sheet like

Conclusions


Yilgarn Craton
Shear Zones, Greenstone and Gold Deposits

Shears zones and Au - Factors

- sigmoidal-rhomboid shear pattern
- greenstone disruption
- shear intersections
- small late plutons in shear zones

Mineralisation related to

- defomation of felsic crust
- underlying the greenstones