# Adrift again: recent geochronology and paleomagnetics undermine a Neoarchean collision model for the Limpopo Belt

GSZ Summer Symposium 25/11/2016

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1) What is the Limpopo Belt? Its tripartition & shearzones
2) Mini-historical review of geochronology to 1990 and concept of an Archean continent collision
3) Later geochronology and model of a Paleoproterozoic continental collision
4) Status 2011: the two high grade tectonometamorphic events in the Central Zone
5) Crust accretion stories
6) Things fall apart: new age results from the Southern Marginal Zone and Paleomagnetism
7) Where to now?

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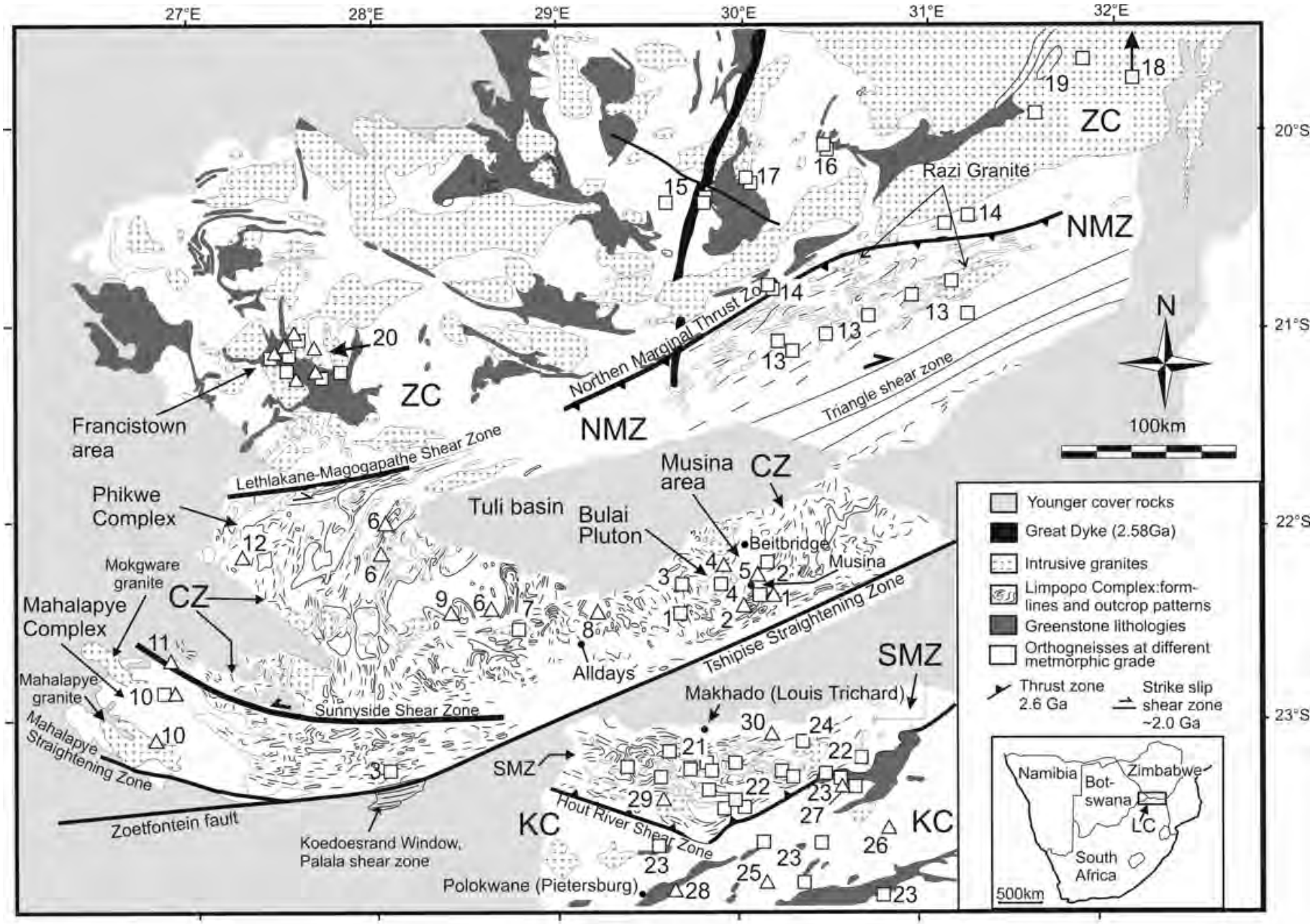


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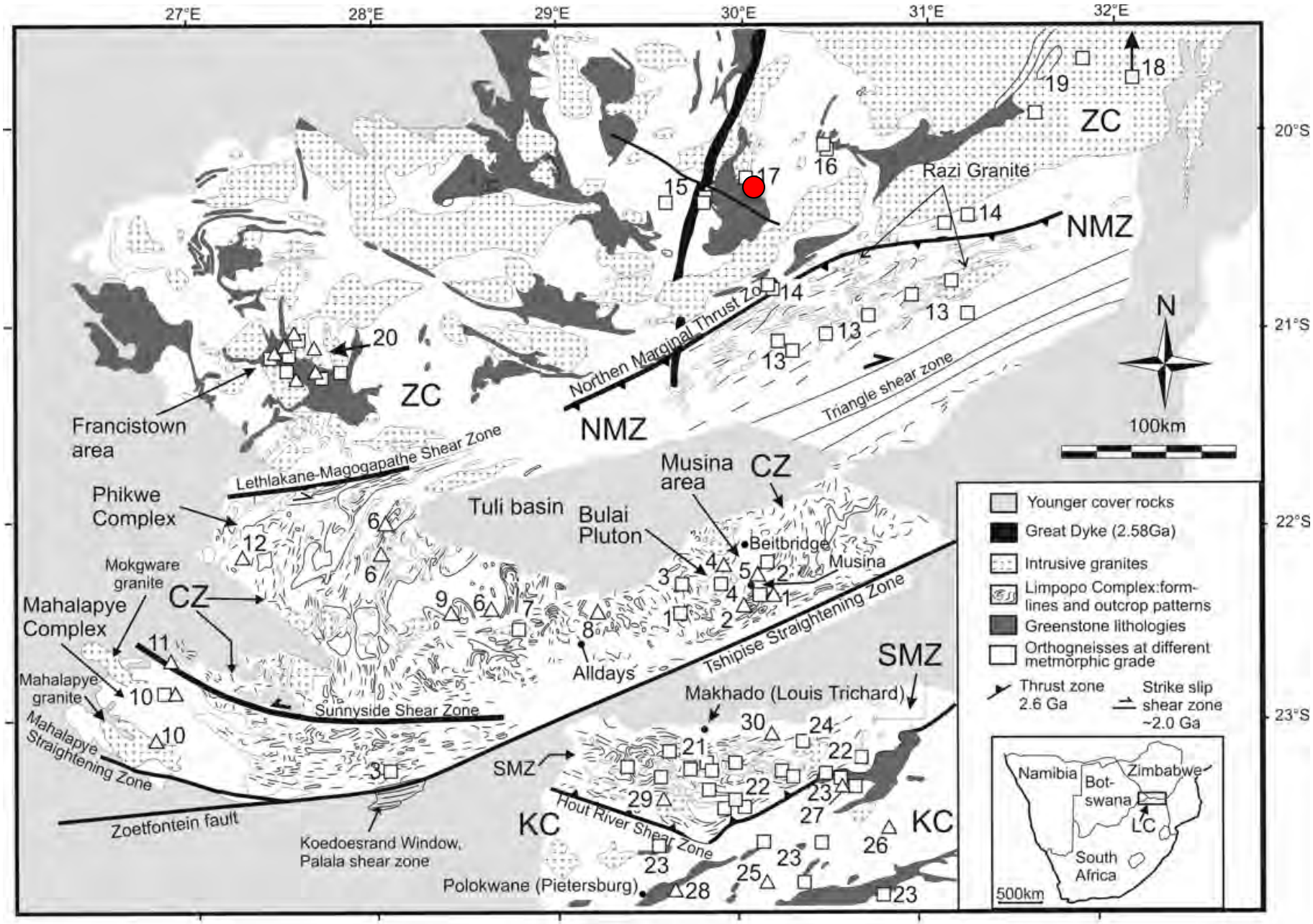
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NMZ
CZ
SMZ
KC
Razi Granite
Northen Marginal Thrust Zone
Triangle shear zone
Francistown area
Lethlakane-Magogapathe Shear Zone
Phikwe Complex
Tuli basin
Bulai Pluton
Musina area
Beitbridge
Musina
Mokgware granite
Mahalapye Complex
Mahalapye granite
Mahalapye Straightening Zone
Sunnyside Shear Zone
Alldays
Tshipise Straightening Zone
Makhado (Louis Trichard)
Hout River Shear Zone
Zoetfontein fault
Koedoesrand Window, Palala shear zone
Polokwane (Pietersburg)
N
100km
Younger cover rocks
Great Dyke (2.58Ga)
Intrusive granites
Limpopo Complex:form-lines and outcrop patterns
Greenstone lithologies
Orthogneisses at different metmorphic grade
Thrust zone 2.6 Ga
Strike slip shear zone ~2.0 Ga
Namibia
Bot-swana
Zimbabwe
LC
South Africa
500km
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Famous unconformity of the Belingwe Greenstone Belt.

2.7 Ga metasediments of the Manjeri Formation (right) overlie a regolith in 3.5 Ga Shabani Gneiss

Low grade metamorphism only.

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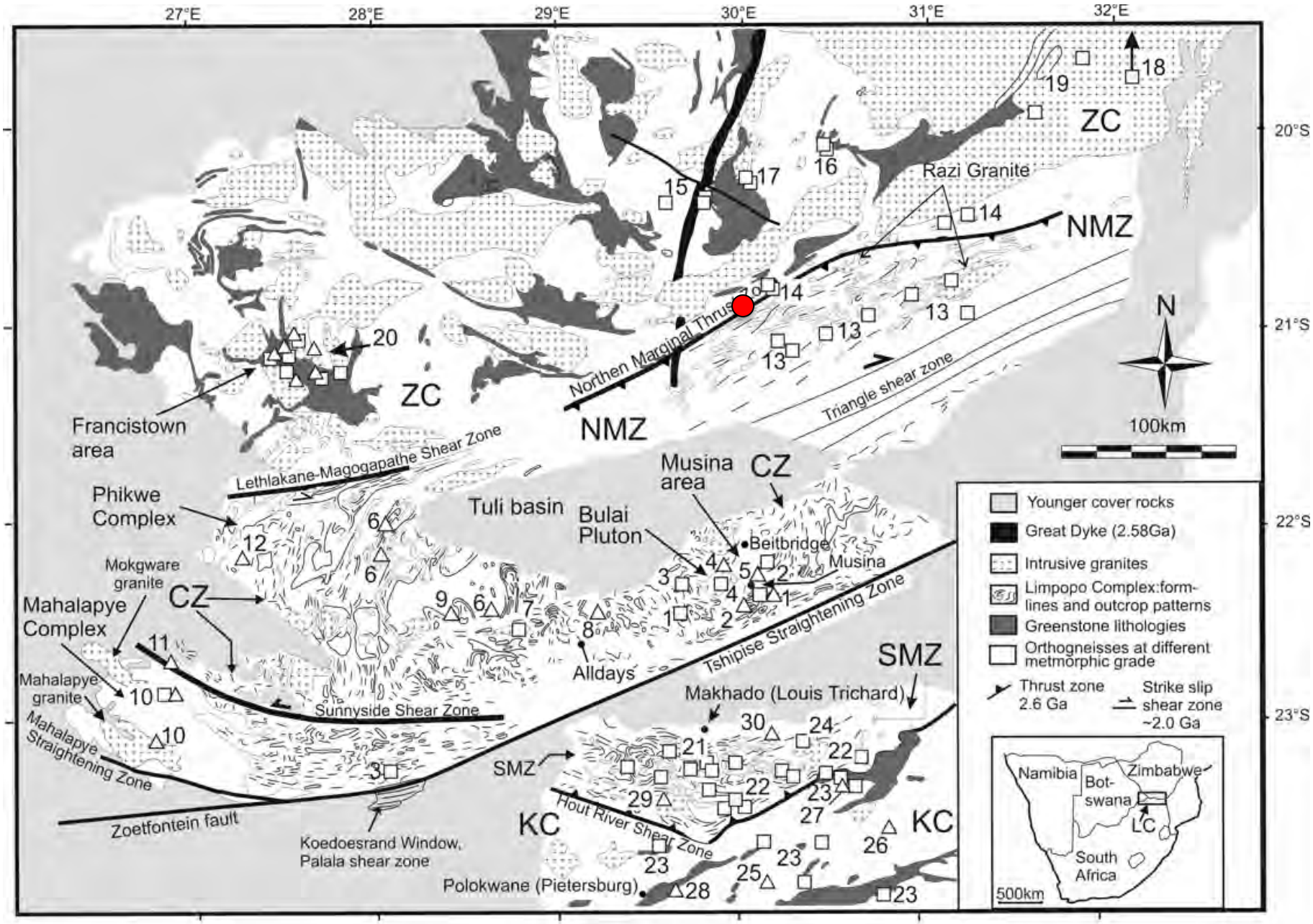


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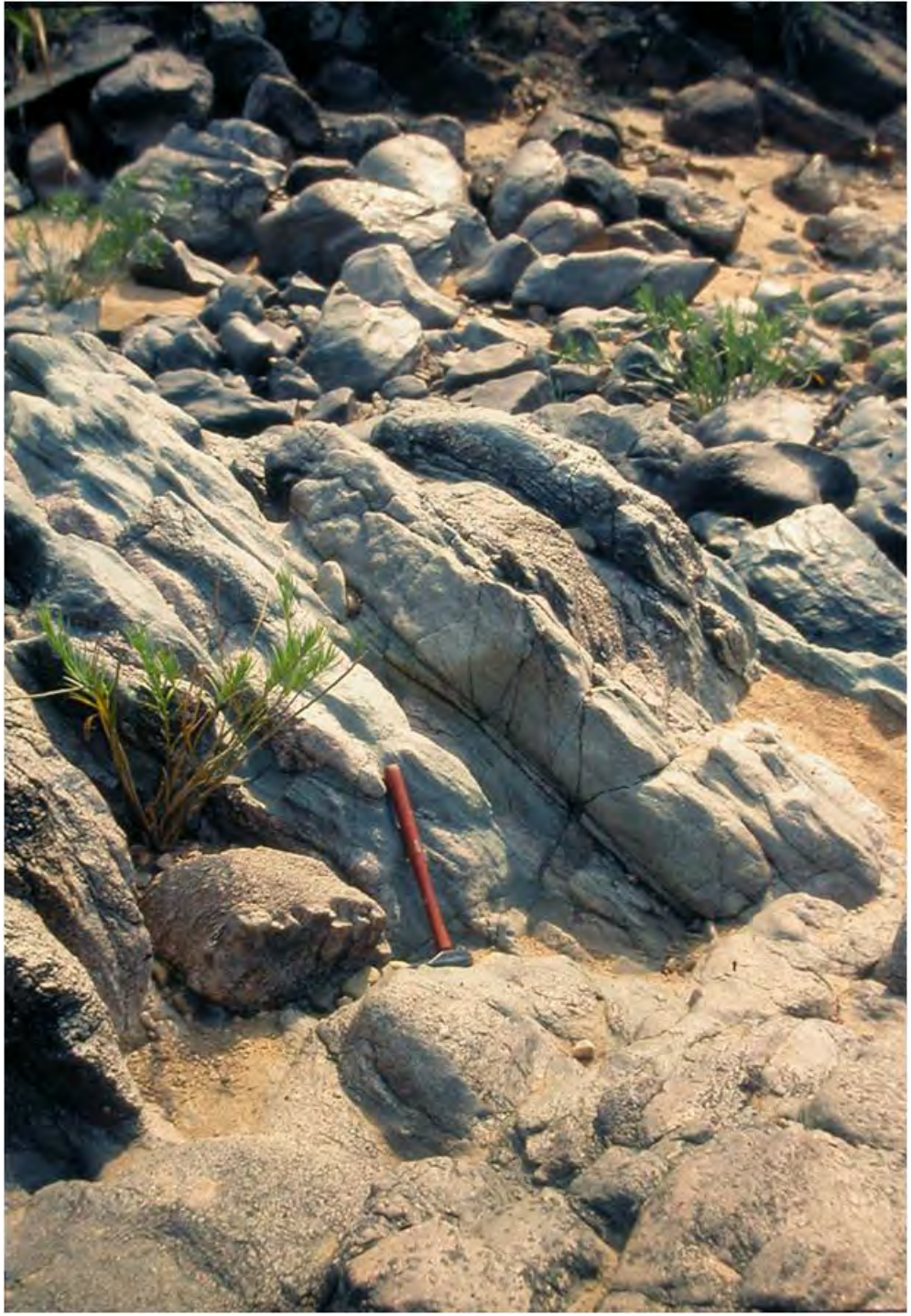

North Limpopo Thrust zone (north vergent) is boundary between low grade Zimbabwe Craton and high grade Northern Marginal Zone

Here seen in high grade rocks and intruded by 2.65 Ga granitoid (some are charnockitic)

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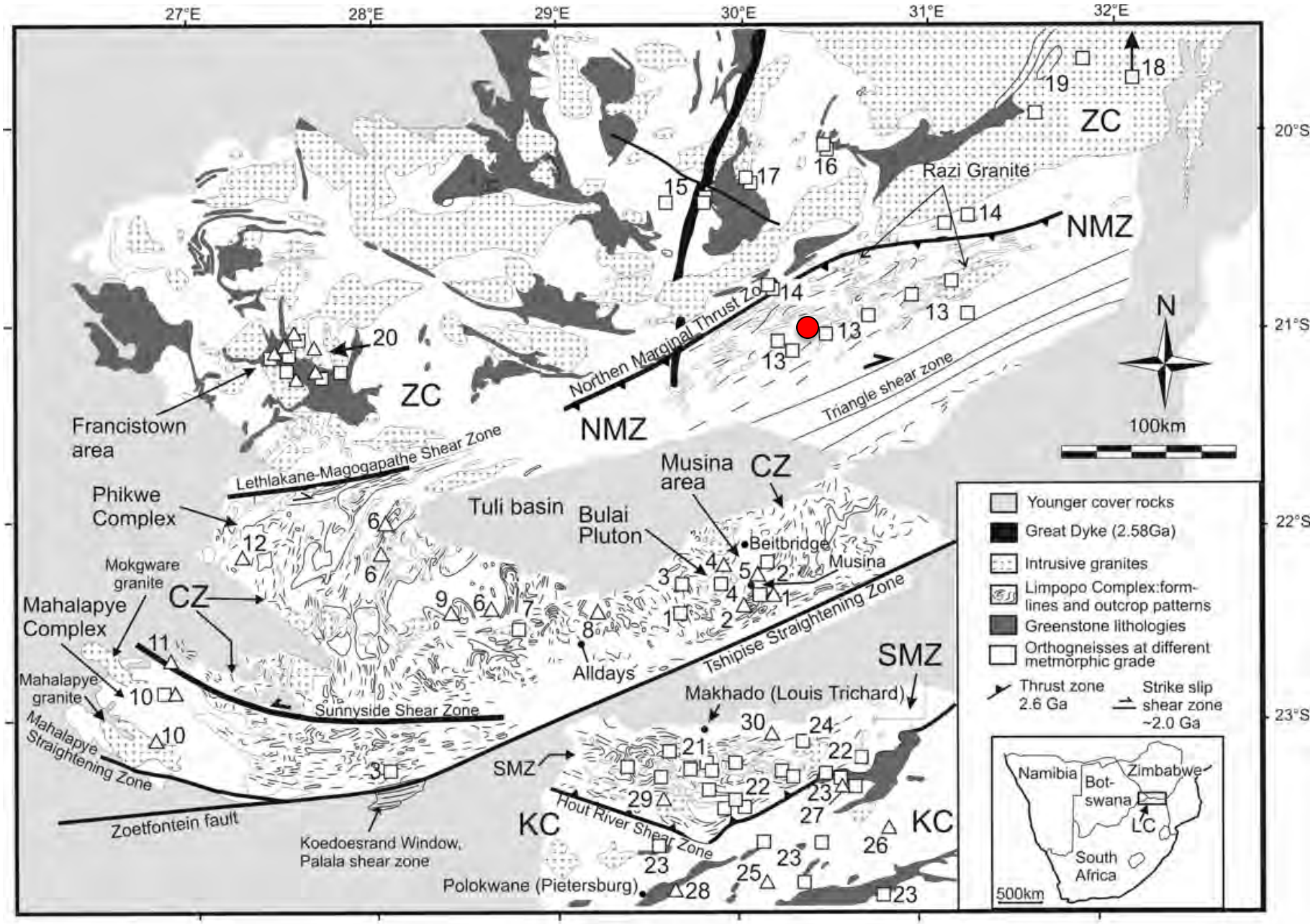
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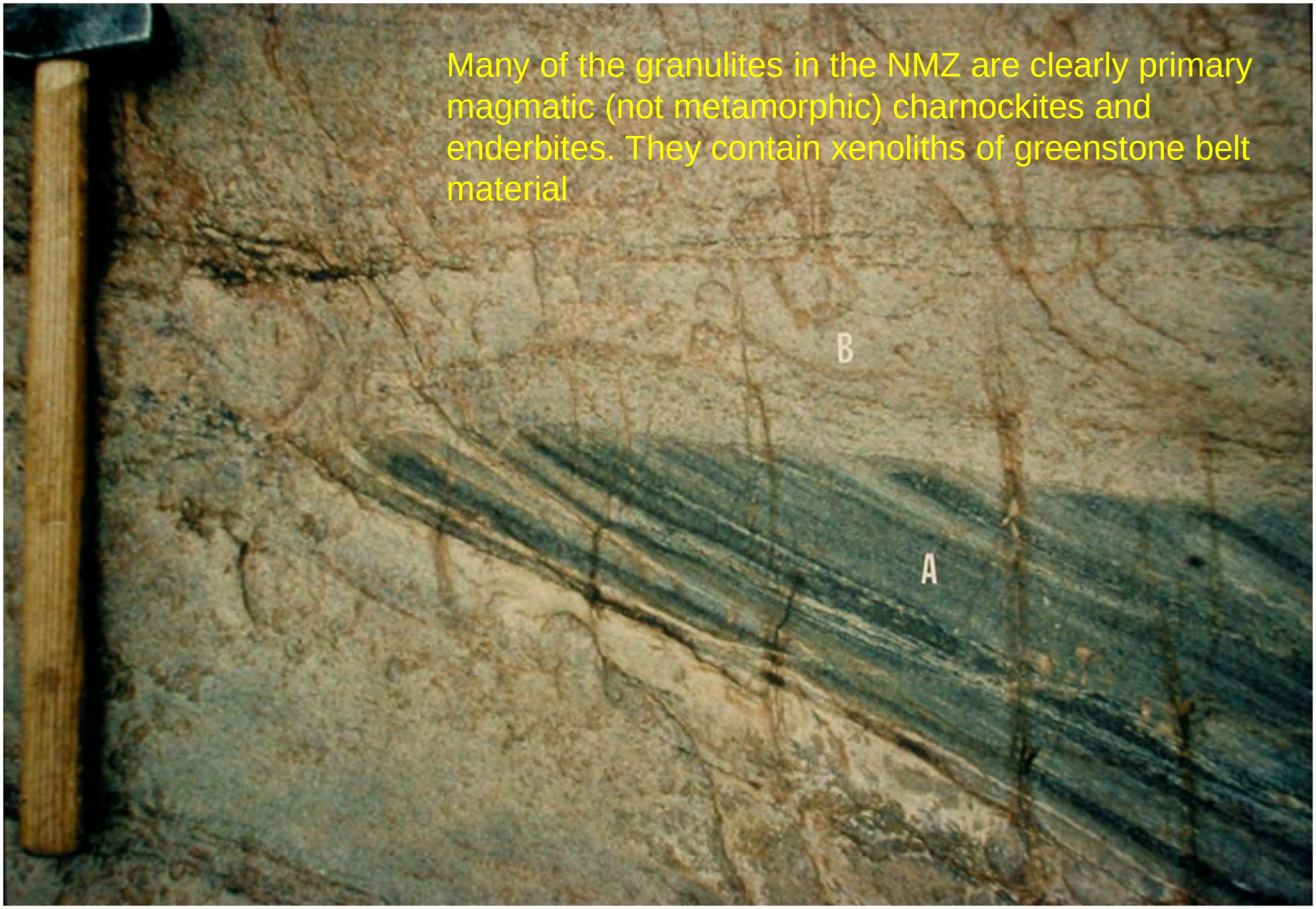


Many of the granulites in the NMZ are clearly primary magmatic (not metamorphic) charnockites and enderbites. They contain xenoliths of greenstone belt material


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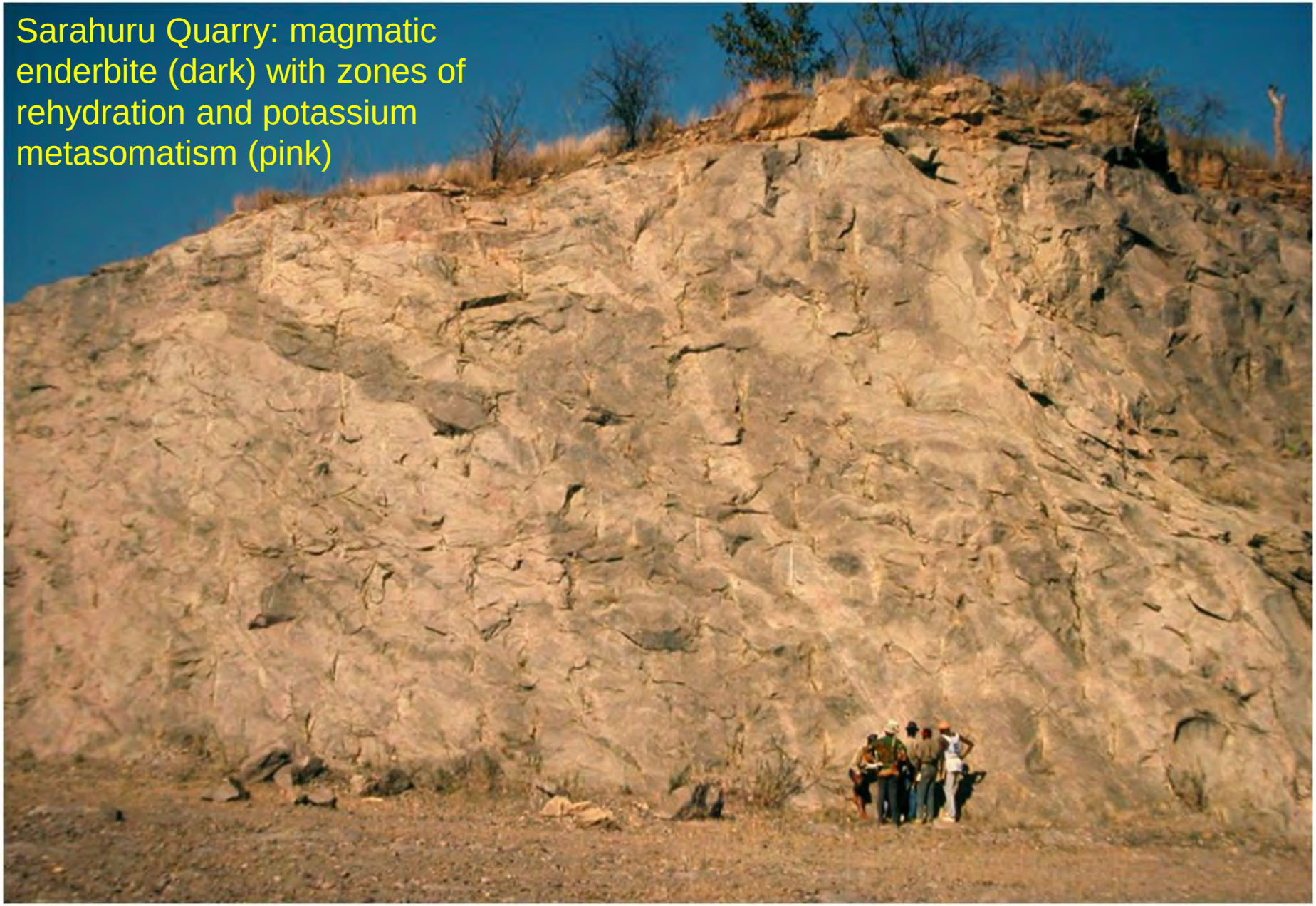
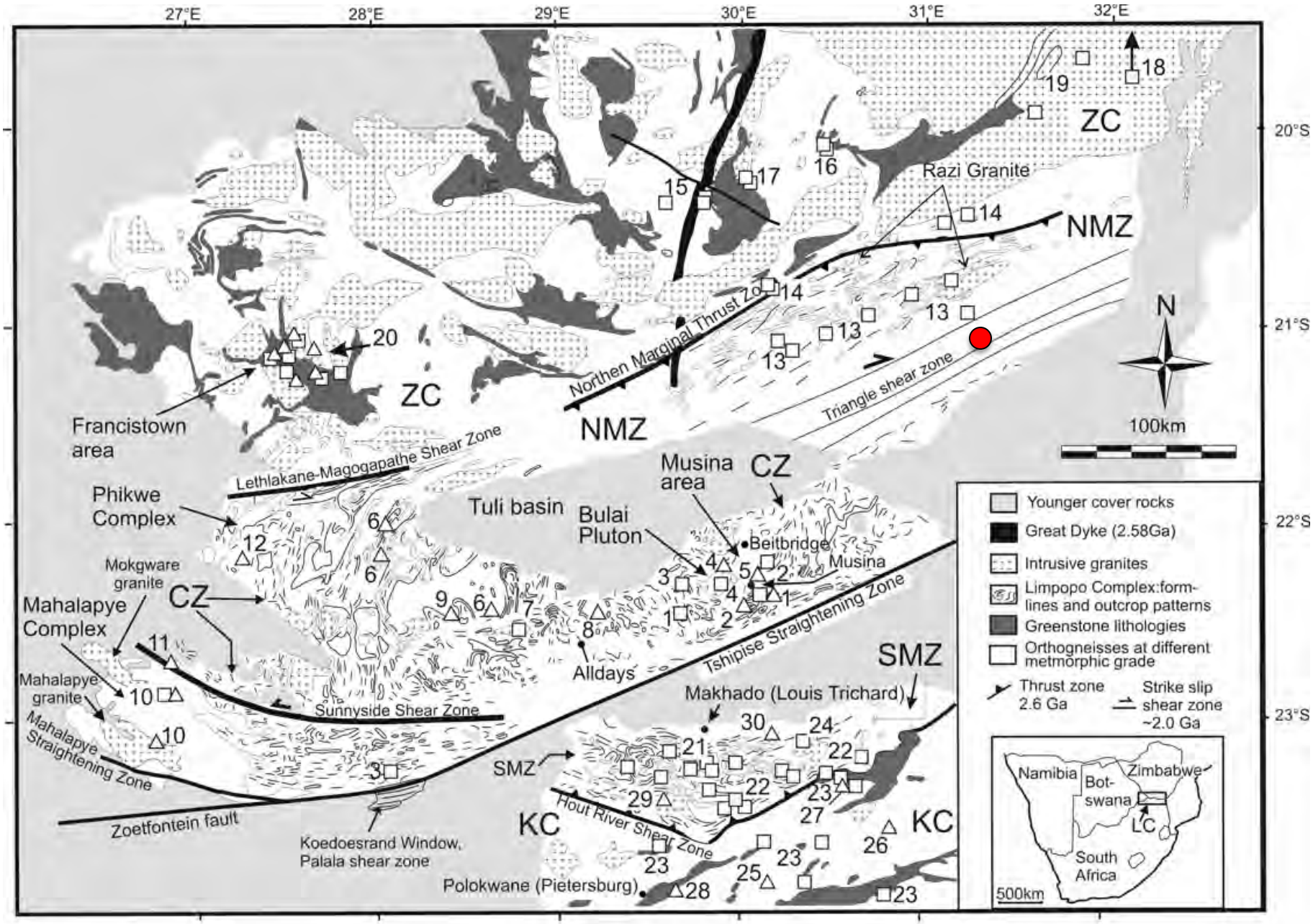

Sarahuru Quarry: magmatic enderbite (dark) with zones of rehydration and potassium metasomatism (pink)


detail

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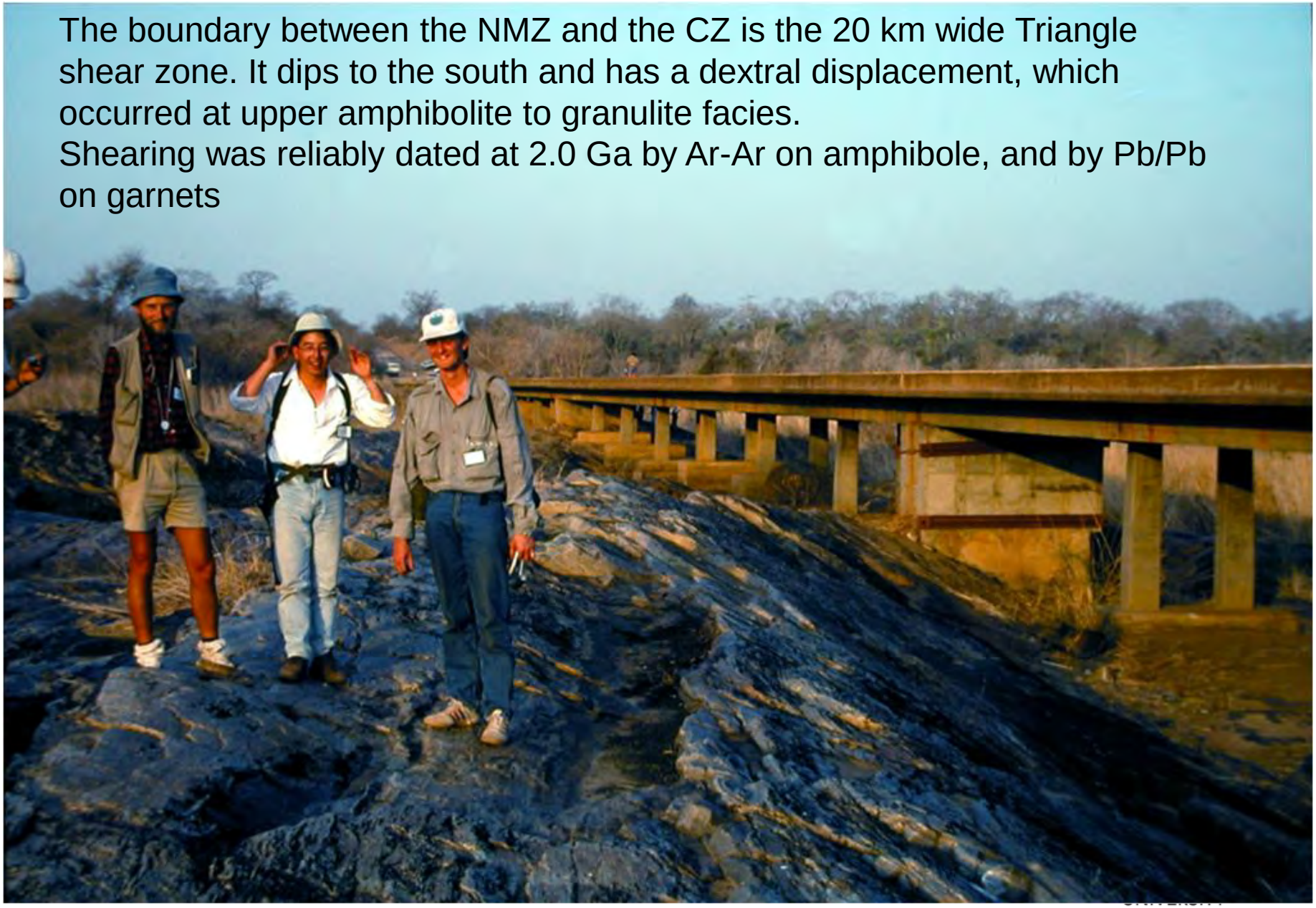
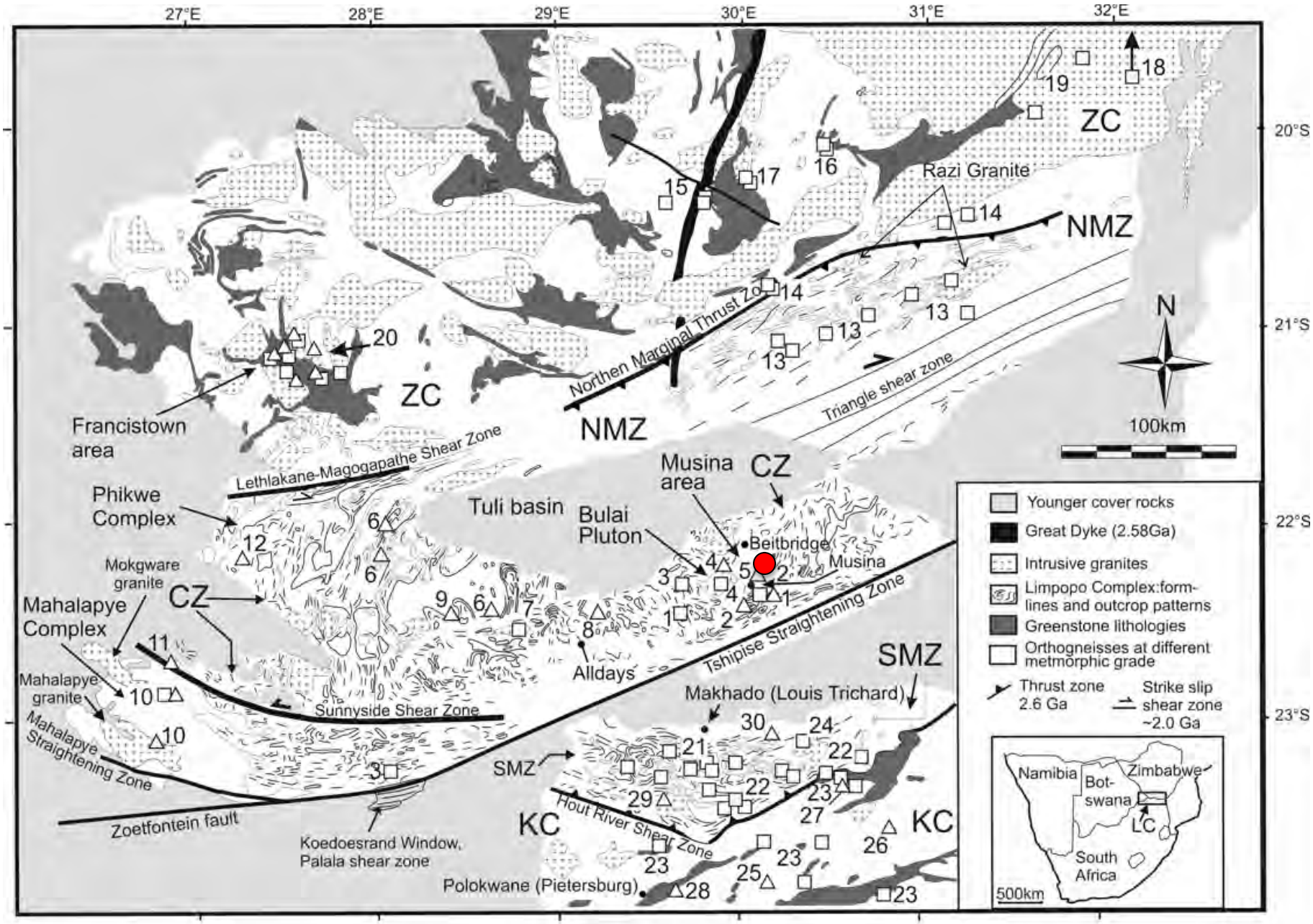
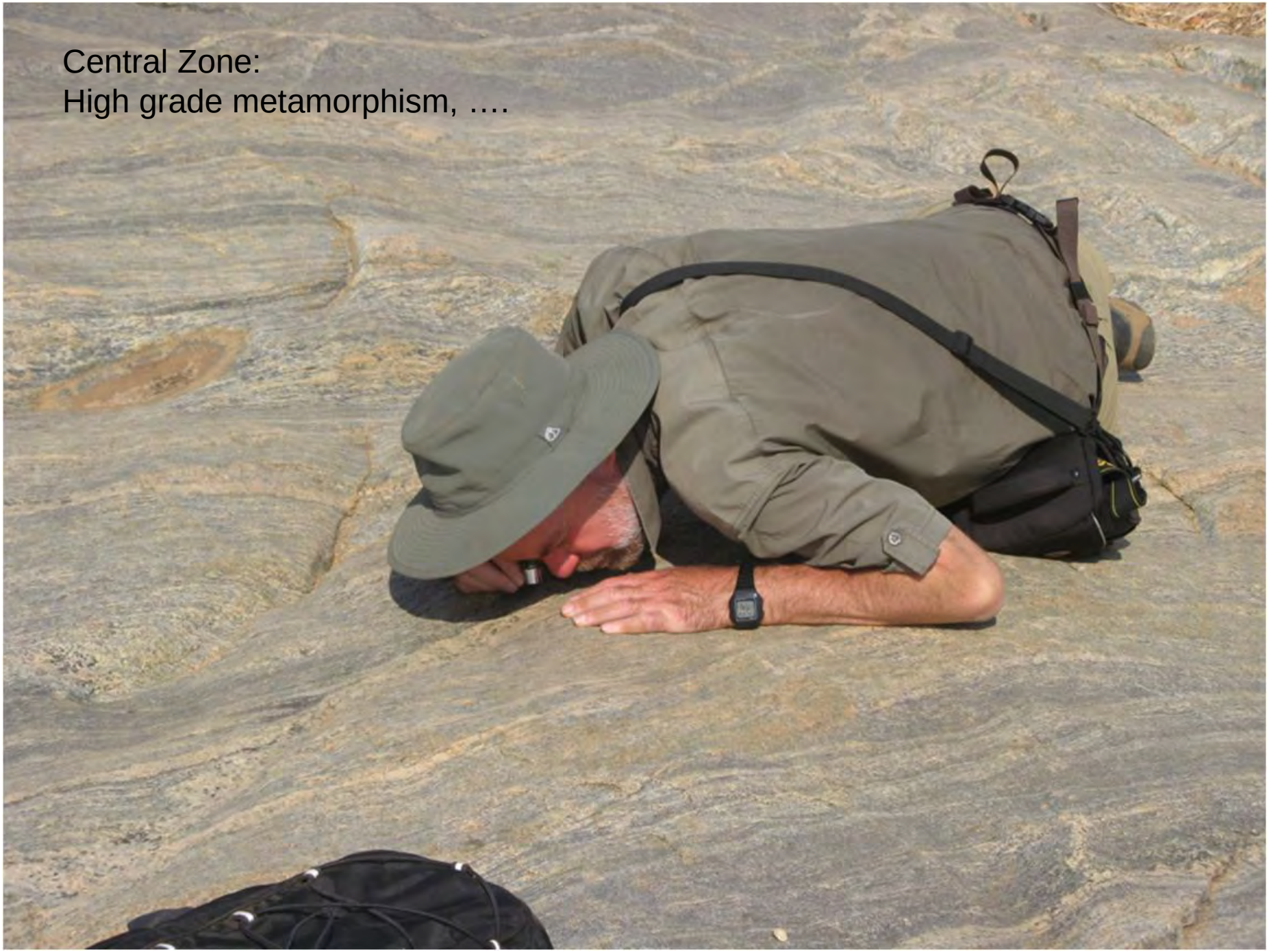
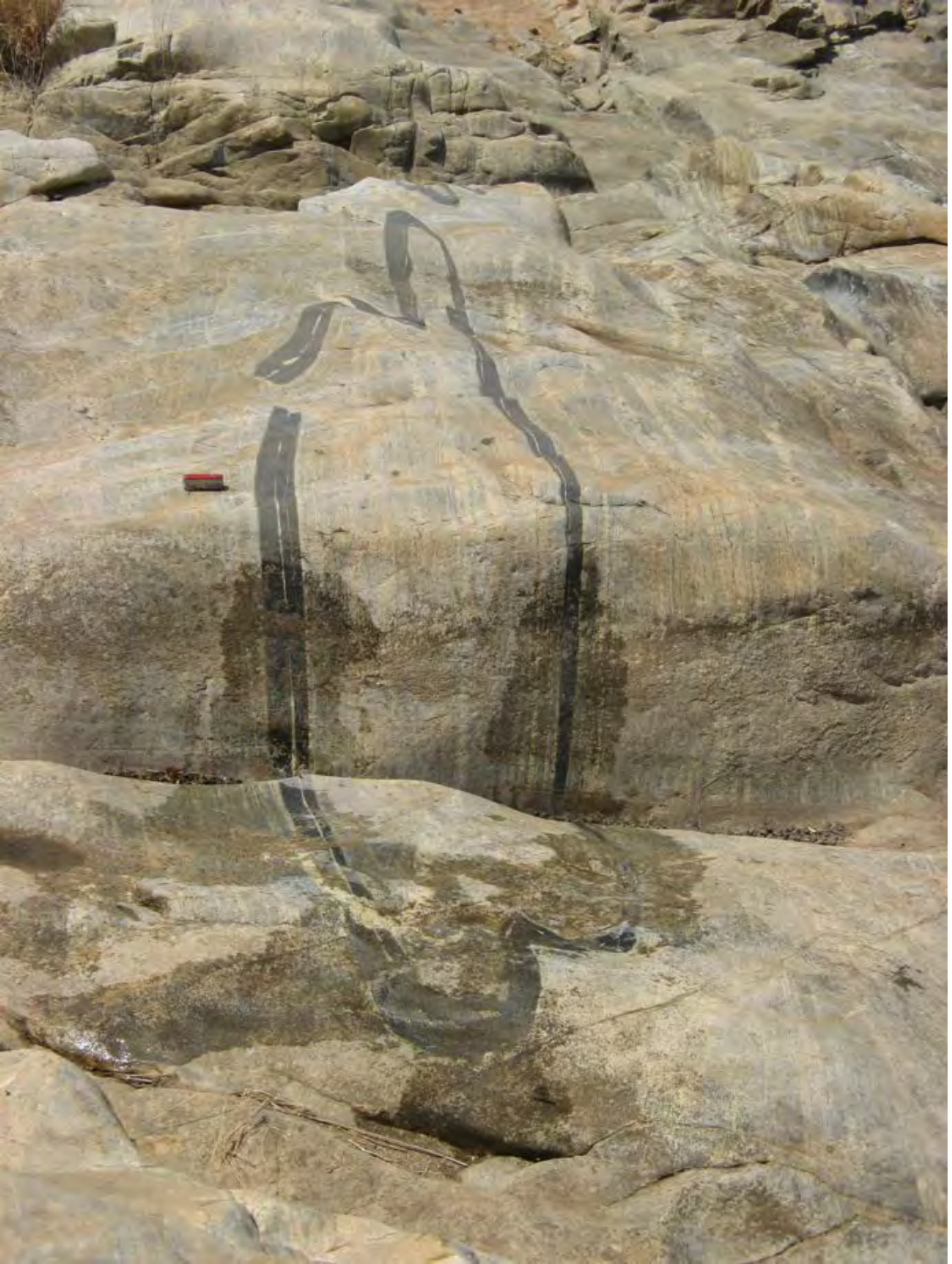
The boundary between the NMZ and the CZ is the 20 km wide Triangle shear zone. It dips to the south and has a dextral displacement, which occurred at upper amphibolite to granulite facies.
Shearing was reliably dated at 2.0 Ga by Ar-Ar on amphibole, and by Pb/Pb on garnets






Central Zone:
High grade metamorphism, ….



…. Highly complex structures such as sheath folds (here the famous bicycle wheel) ….

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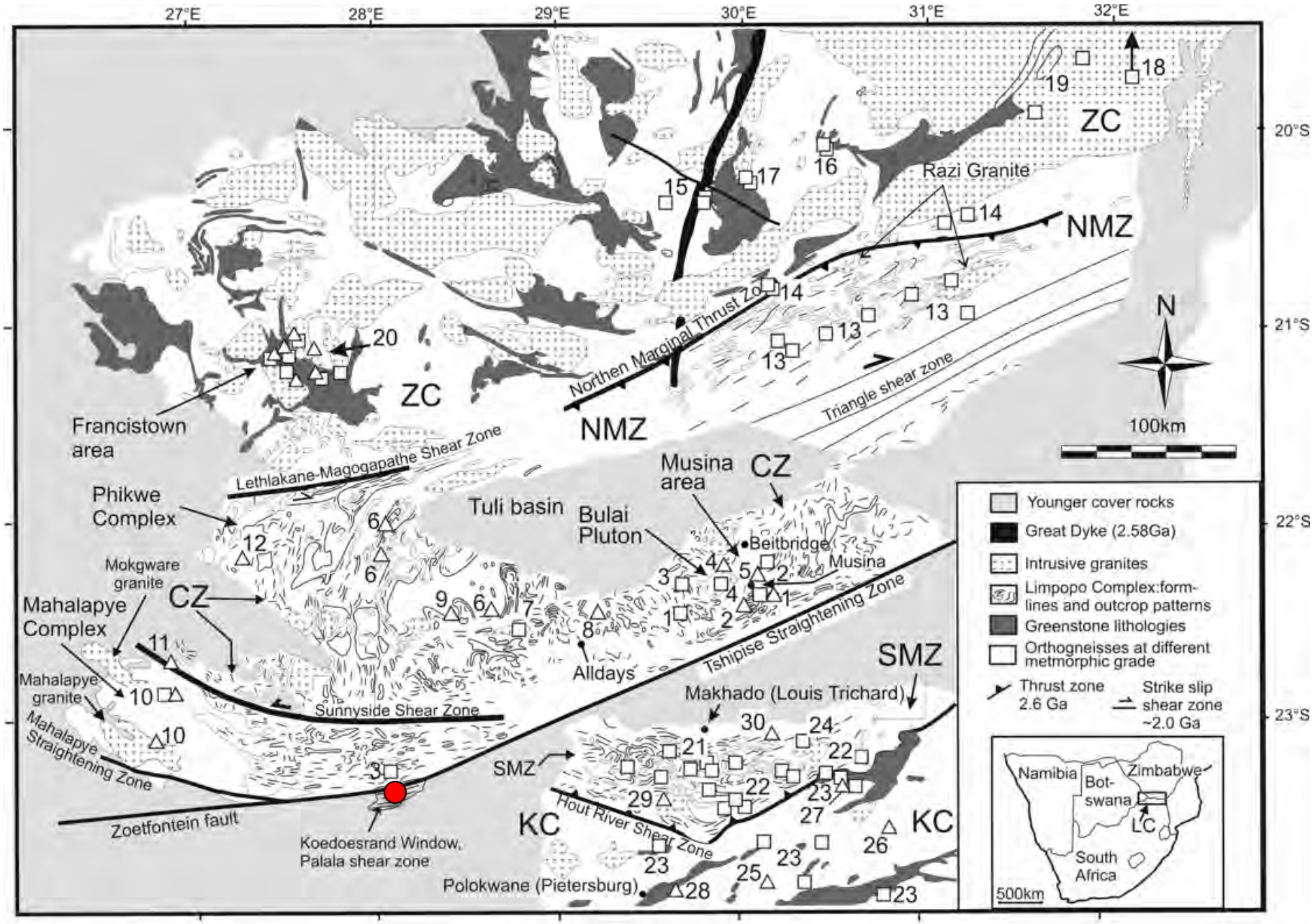
… abundant S-type granites,
here at Singelele type
locality and with xenolith of
metapelite

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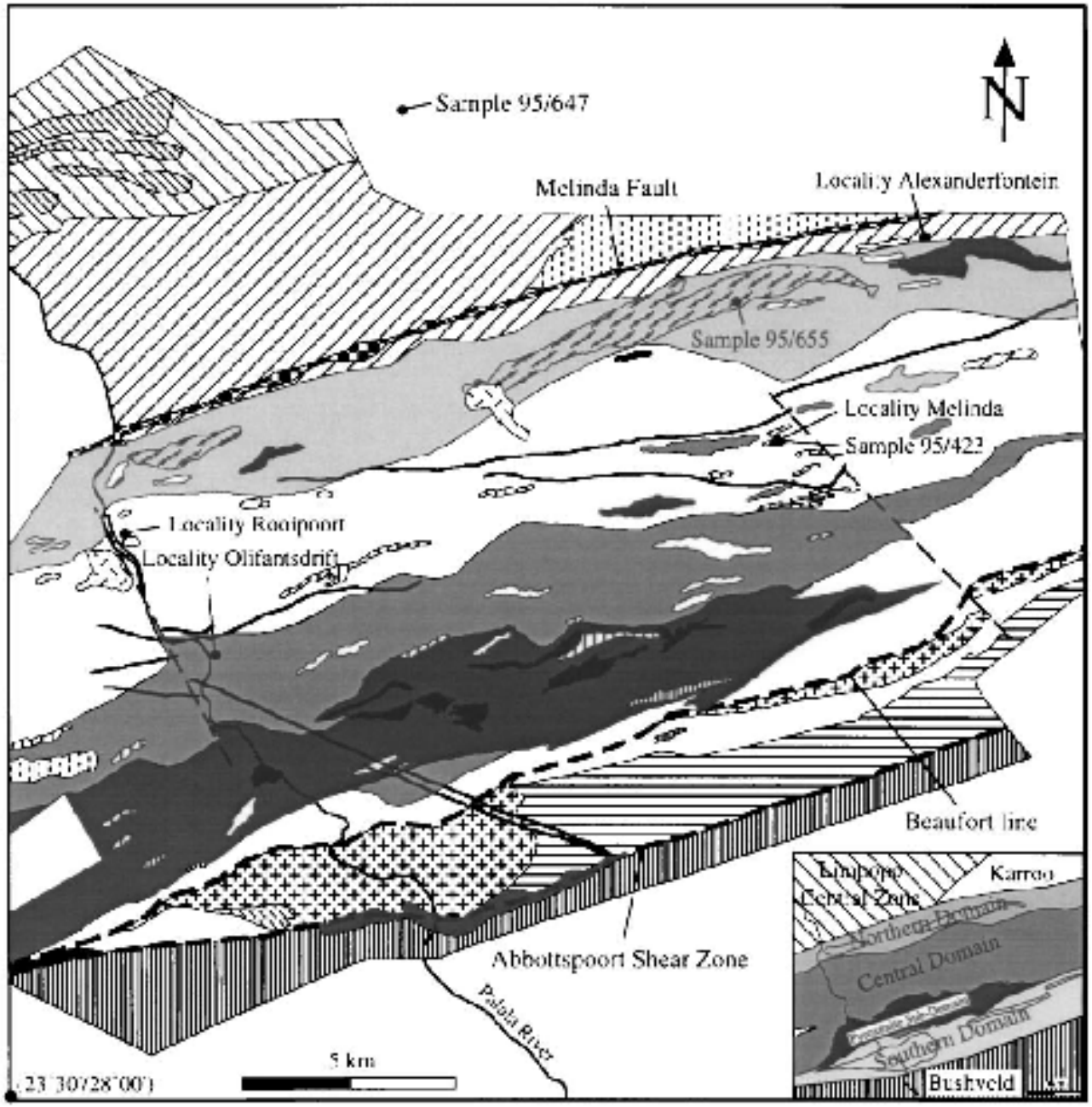


**Legend:**

**Palala Shear Zone:**

- Quartzo-feldspathic Gneiss
- Gabbro
- Pyroxenite
- Retrogressed Charnockite
- Palala Granite
- Northern Granite
- Mafic Mylonite
- Enderbitic Mylonite
- Felsic Mylonite
- Metapelitic and Calcsilicate Mylonite
- Intermediate Mylonite

**Limpopo Central Zone:**

- Quartzo-feldspathic Gneiss
- Calcsilicate and Marble
- Quartzite

**Other Units:**

- Gabbro and Anorthosite (Bushveld Igneo
- Dolerite Dyke
- Koedoesrand Sediment
- Undifferentiated undeformed Sediment
- Karroo Sediment
- Quartz Breccia
- Brittle Fault

Palala Shearzone in Abbotspoort Window

From Schaller et al. 1999, Prec. Res. 96: 266-288

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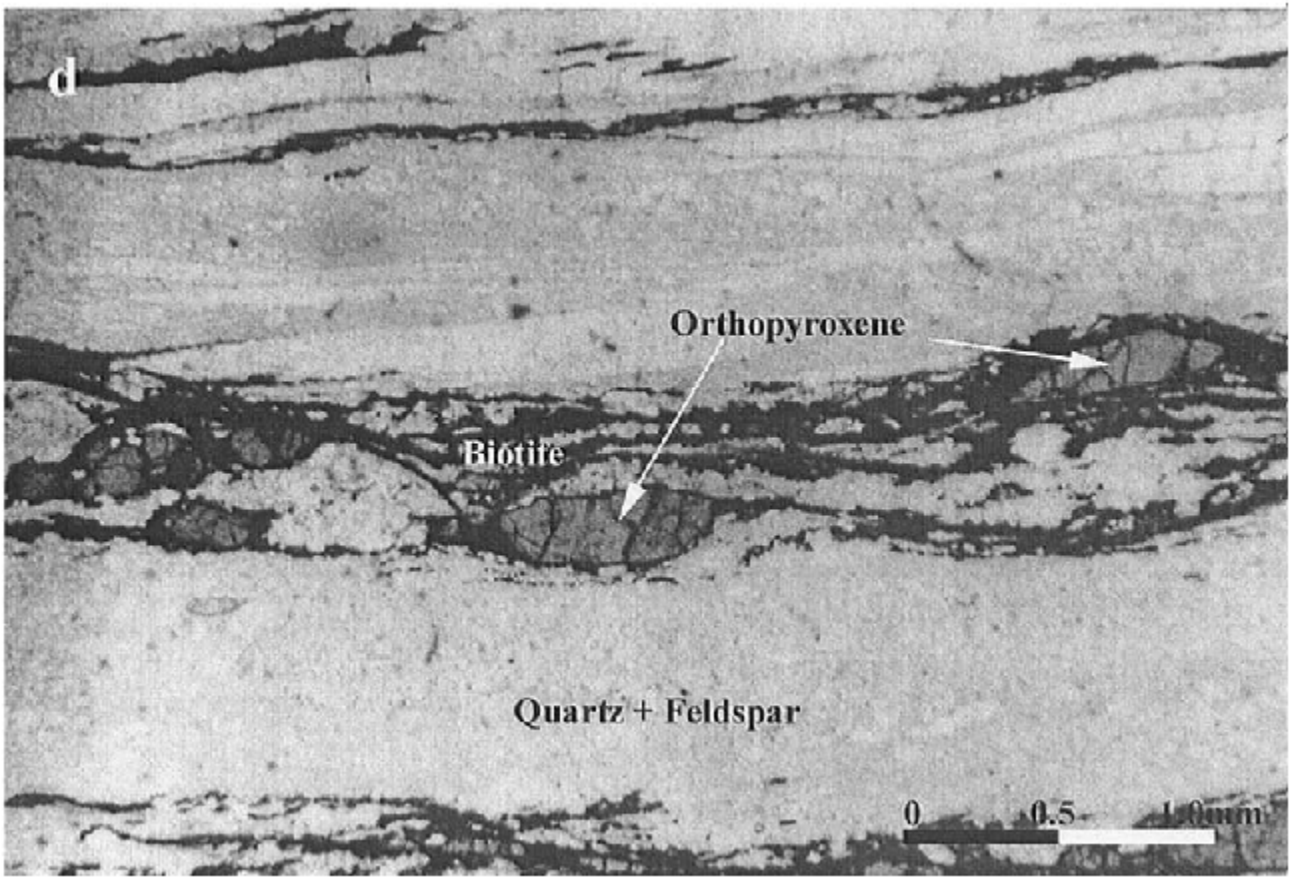


Rotated orthopyroxene clasts are embedded in an ultramylonitic matrix (feldspar, quartz and chlorite; sample 95/299 from the Central Domain).

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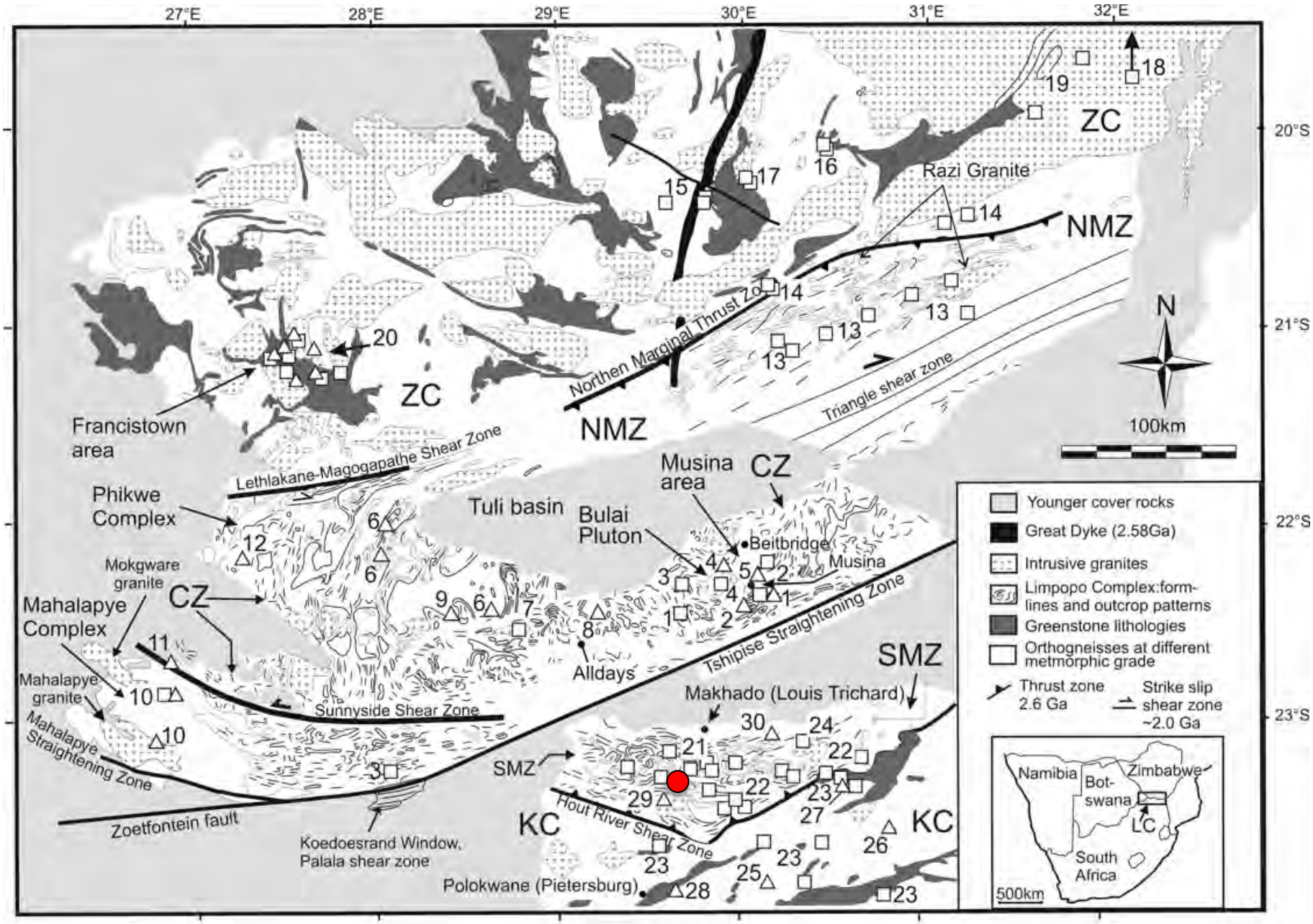
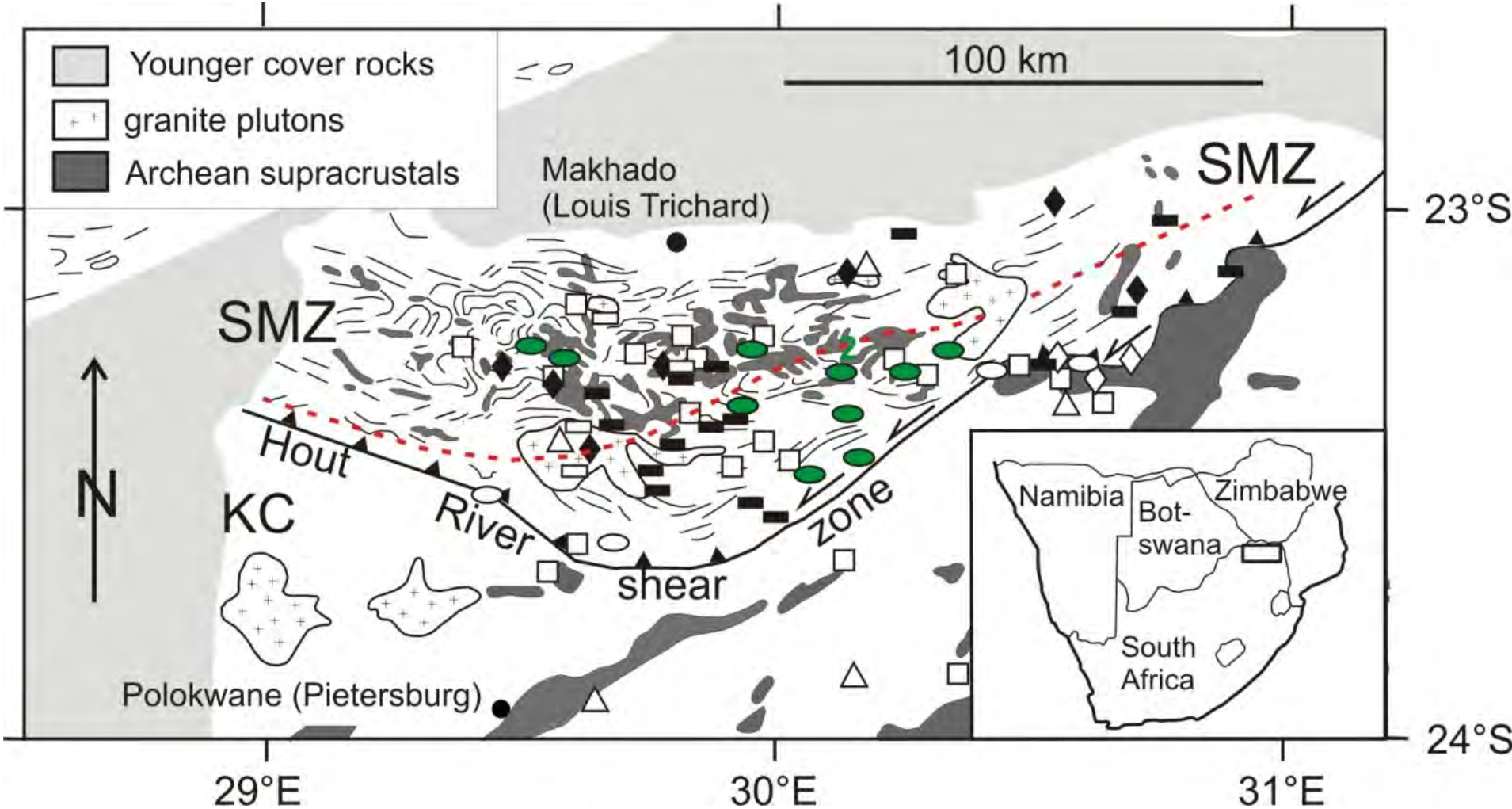
From Schaller et al. 1999, Prec. Res. 96: 263-288






orthoamphibole isograd (~ 2.65 Ga) almost coincides with the N'tabalala shear zone (~2.02 Ga)

Ar-Ar sample localities

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Southern Marginal Zone, granulite facies (northern) part:

Abundant greenstone belt remnants at high grade

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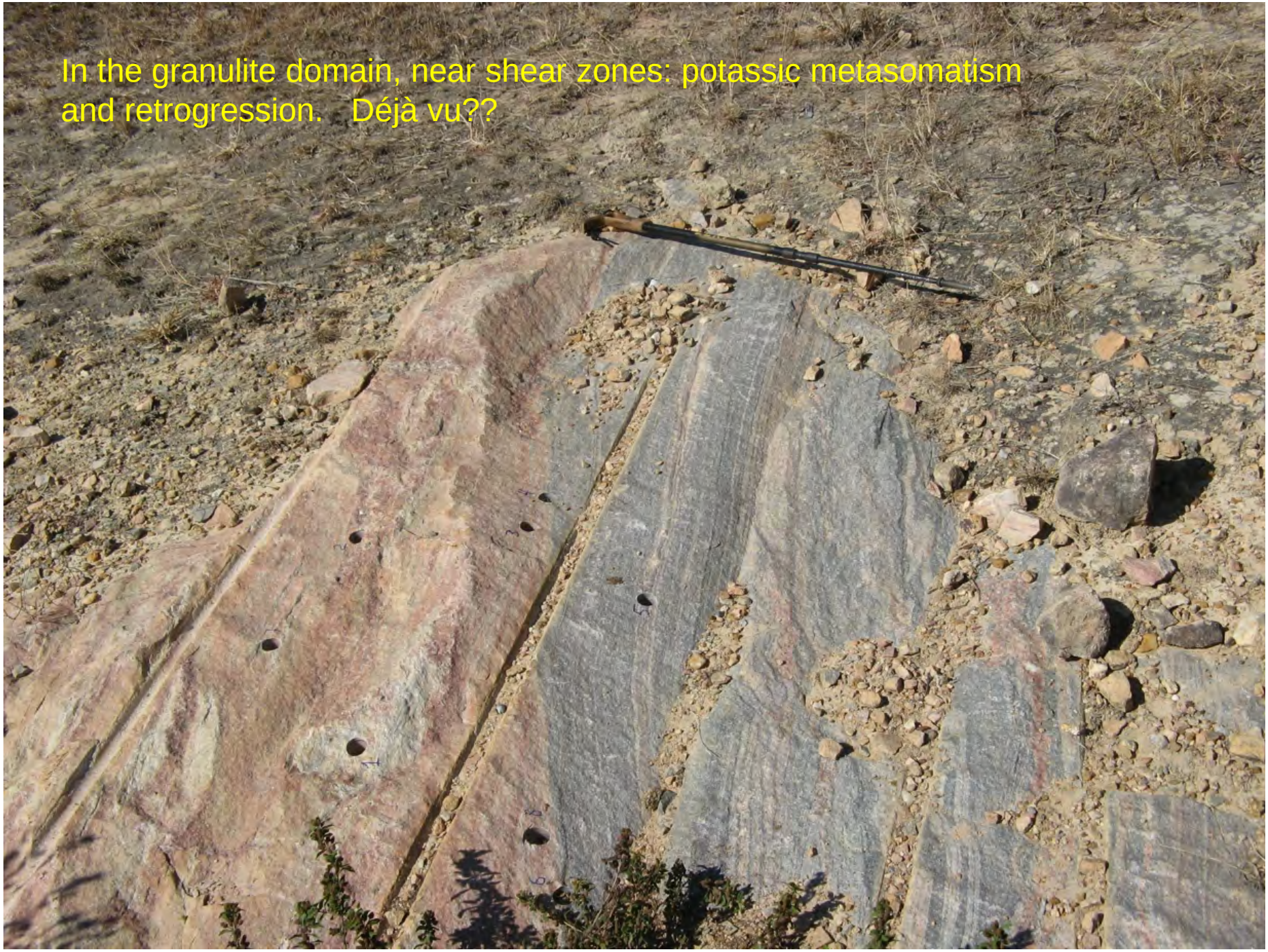
Partial melting of mafic and intermediary rocks

In the southern part (rehydrated zone):

Near horizontal ‘nappe’ structure, south-vergent.

Leucocratic (melt) bands – lubrication for the ‘nappe’ dynamcis?


In the granulite domain, near shear zones: potassic metasomatism
and retrogression. Déjà vu??

Early geochronology (Hickman, van Breemen and Dodson, 1970‘s):

- Whole rock Rb-Sr ages around 2.6 Ga

- Rb-Sr mica ages around 2.0 Ga

1980‘s and early 90‘s (mainly driven by Jay Barton)

- Using dates on intrusions to constrain the age of the orogenic event(s)

- Using Rb-Sr whole rock Rb-Sr muscovite, and U-Pb zircon geochronology

*The intrusive rocks (Matok in the SMZ, Bulai in the CZ, etc.) all came out at ca. 2.6-2.7 Ga.*

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1992:

Publication of Precambrian Research Volume 55, dedicated to the Limpopo Belt (driven by the RAU Geology Department).

*Concept of the Limpopo Belt as a late Archean orogen, product of a collision between the Zimbabwe and Kaapvaal Cratons, is presented and elaborated.*

and

*2.0 Ga ages are explained as late uplift or later thermal event*

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*2.0 Ga ages are explained as late uplift or later thermal event*

*But then the ages on high temperature metamorphic minerals started coming in …*

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*1981: first garnet Sm-Nd date ever, on a garnet from the Triangle Shearzone: close to 2 Ga (van Breemen and Hawkesworth)*

*This young age was confirmed by further Sm-Nd and by Pb/Pb dating (Kamber et al. Prec. Res.1995)*

*2.0 Ga ages not just cooling, but*

*Documenting a high grade event at 2.0 Ga with tectonics*

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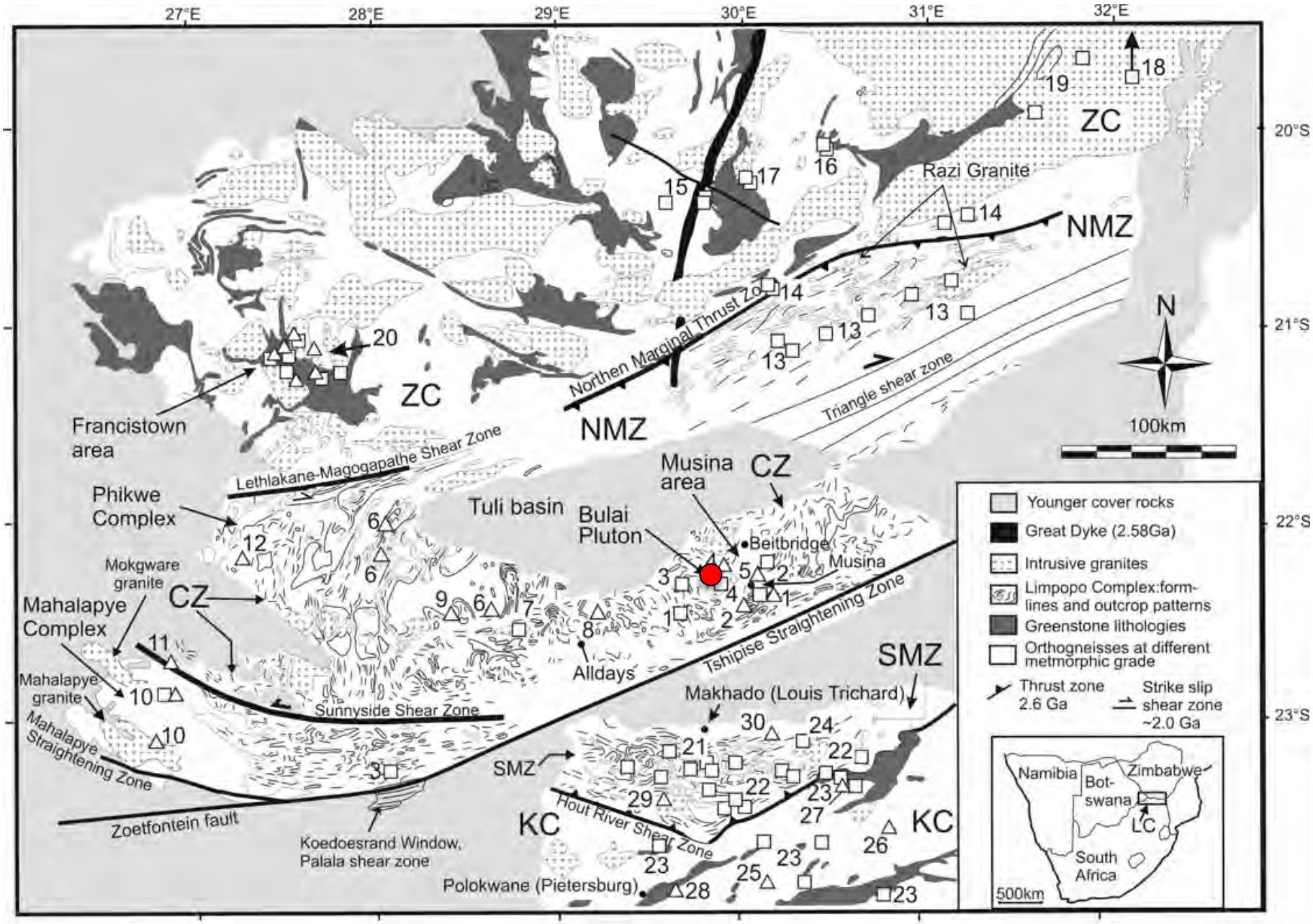


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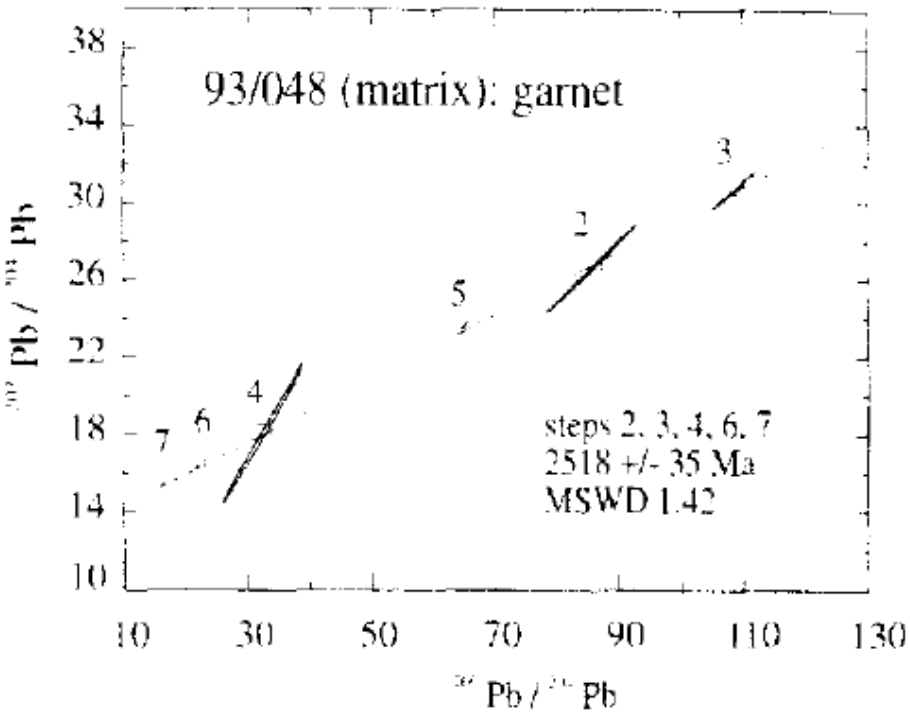
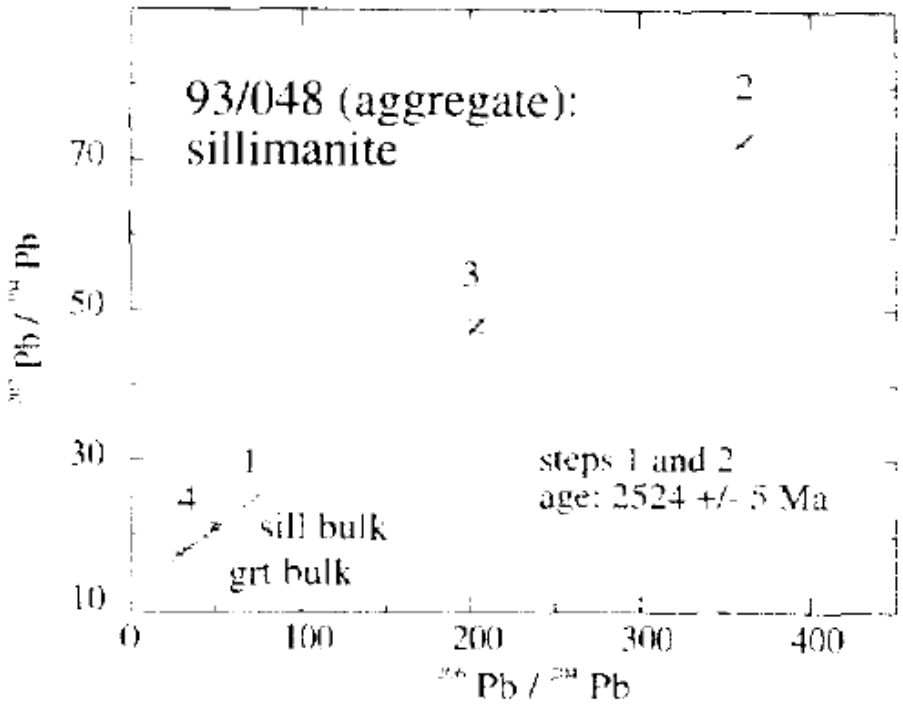
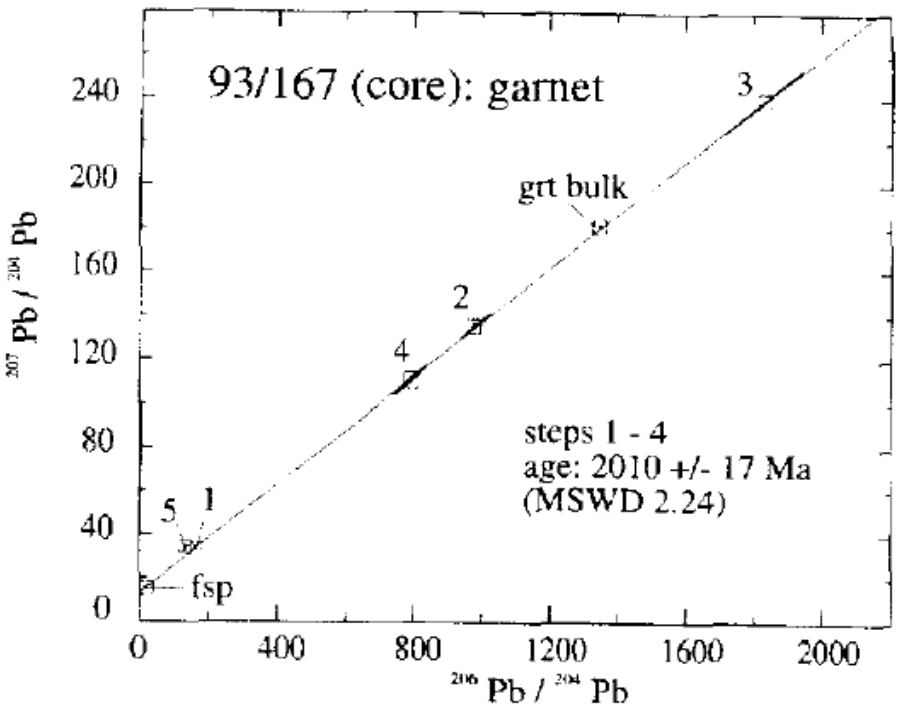
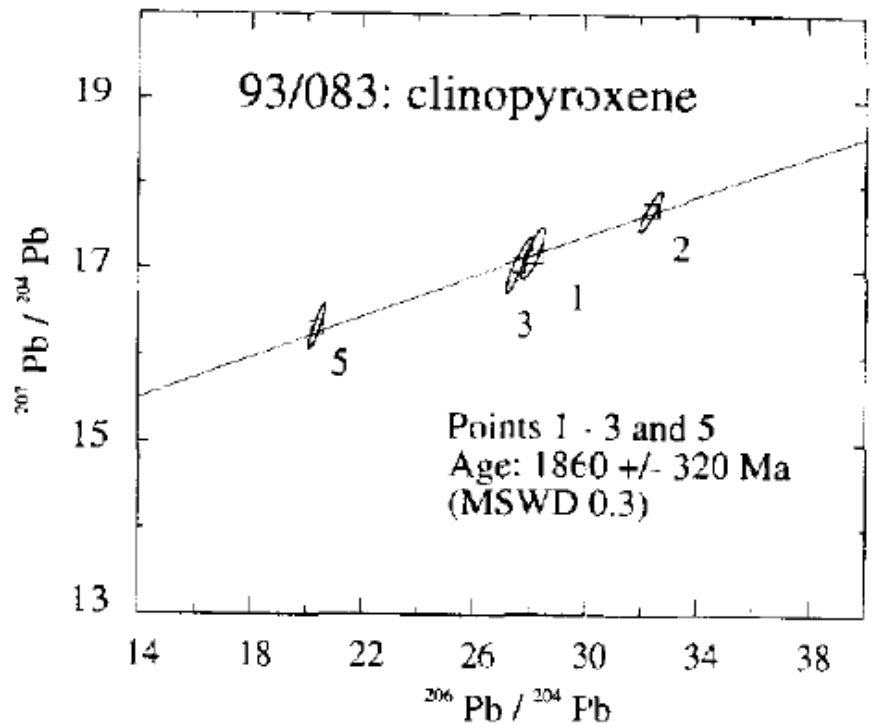



Garnet and sillimanite from a metapelitic inclusion in the Bulai granite give ages around 2.52 Ga, *but...*

*From Holzer et al., 1998. Prec. Res. 87: 87-115*




.... garnet (and clinopyroxene) in high grade Mg-rich metapelites in a large fold, the Campbell structure, only 5 km away, gives 2.0 Ga. If this dates the high grade metamorphism, *then .....*

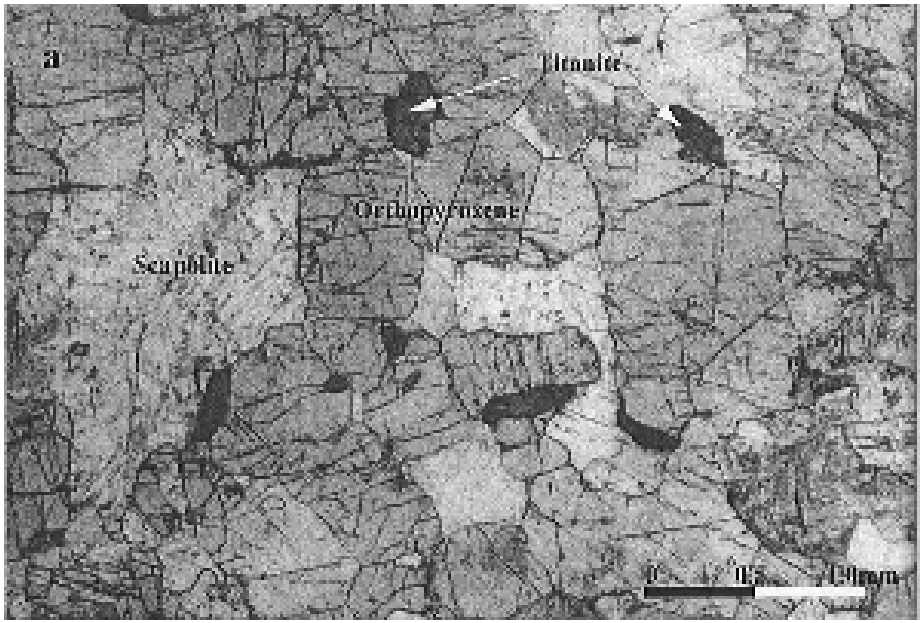
*From Holzer et al., 1998. Prec. Res. 87: 87-115*

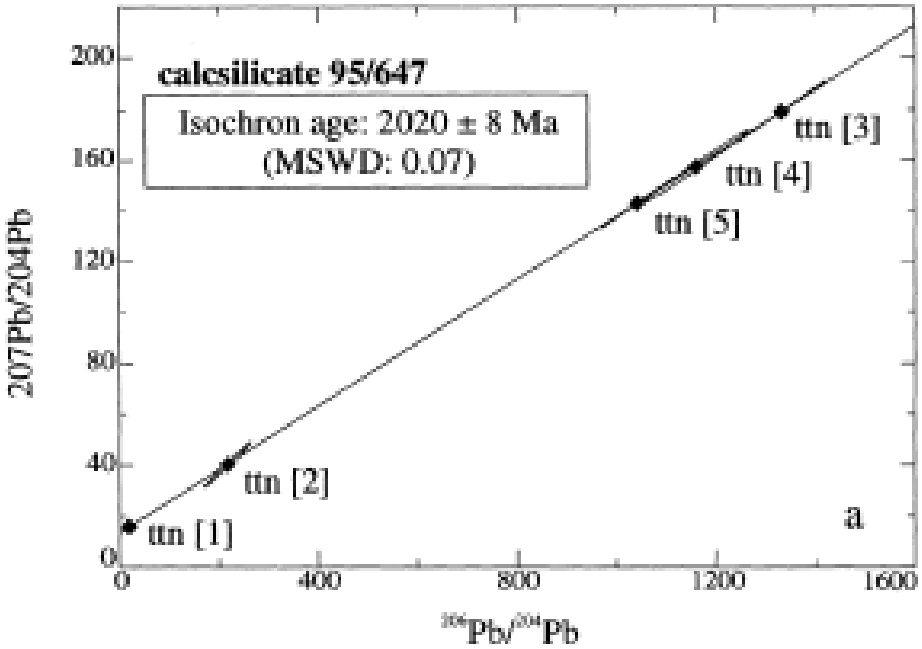
Koedoesrand Window.

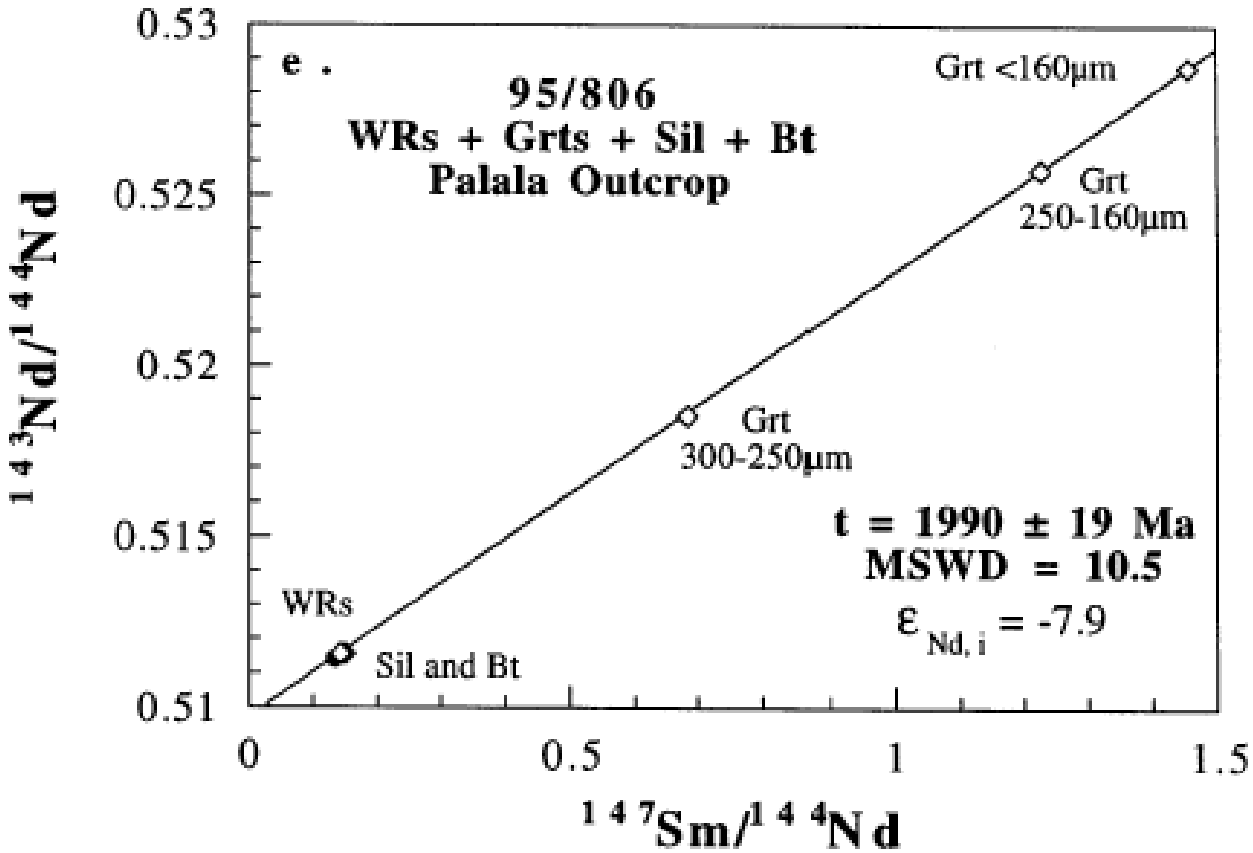
Top: Thin section showing the granoblastic texture of a granulite facies, titanite-bearing calcsilicate (sample 95/645) from the Limpopo Central Zone just N of the Palala shear zone

Bottom: $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ isochron diagram obtained by step-leaching the titanite.

*From Schaller et al. 1999, Prec. Res. 96: 263-288*






Sm-Nd isochron diagram: Metapelite coexisting with calc silicate just N of Melinda Fault: Central Zone section of Koedoesrand (Abbotspoort) Window.

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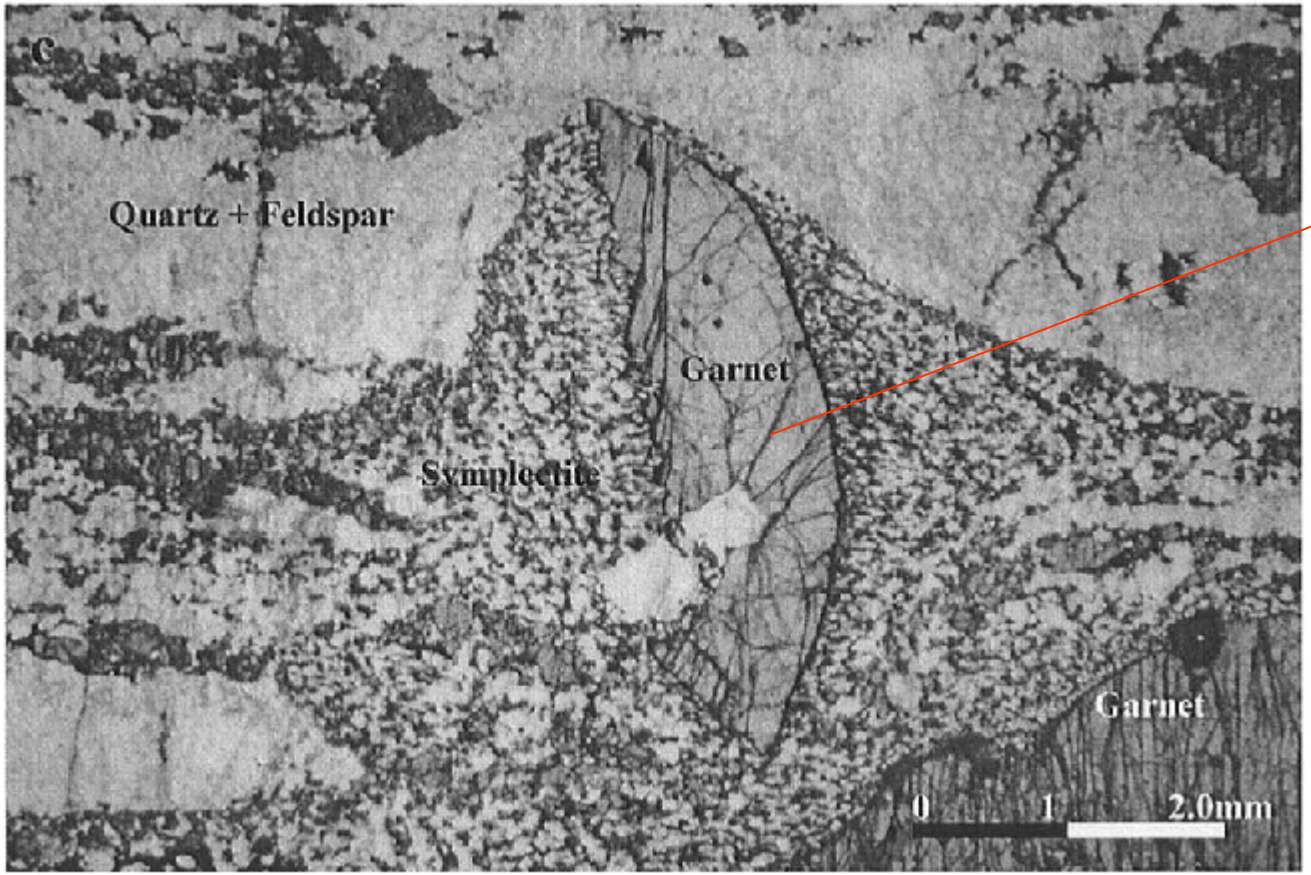
From Chavagnac et al. 2001, Prec. Res. 112: 51-86




Garnet PbSL age:

**2602 ± 20 Ma**

(Schaller et al. 1997. SMPM 77: 113-121)

Symplectites consisting of cordierite and orthopyroxene formed at the expense of resorbed garnet in a metapelitic mylonite (sample 95/609) from the Central Domain. The symplectite texture indicates pressure decrease at high temperatures.

From Schaller et al. 1999, Prec. Res. 96: 263-288

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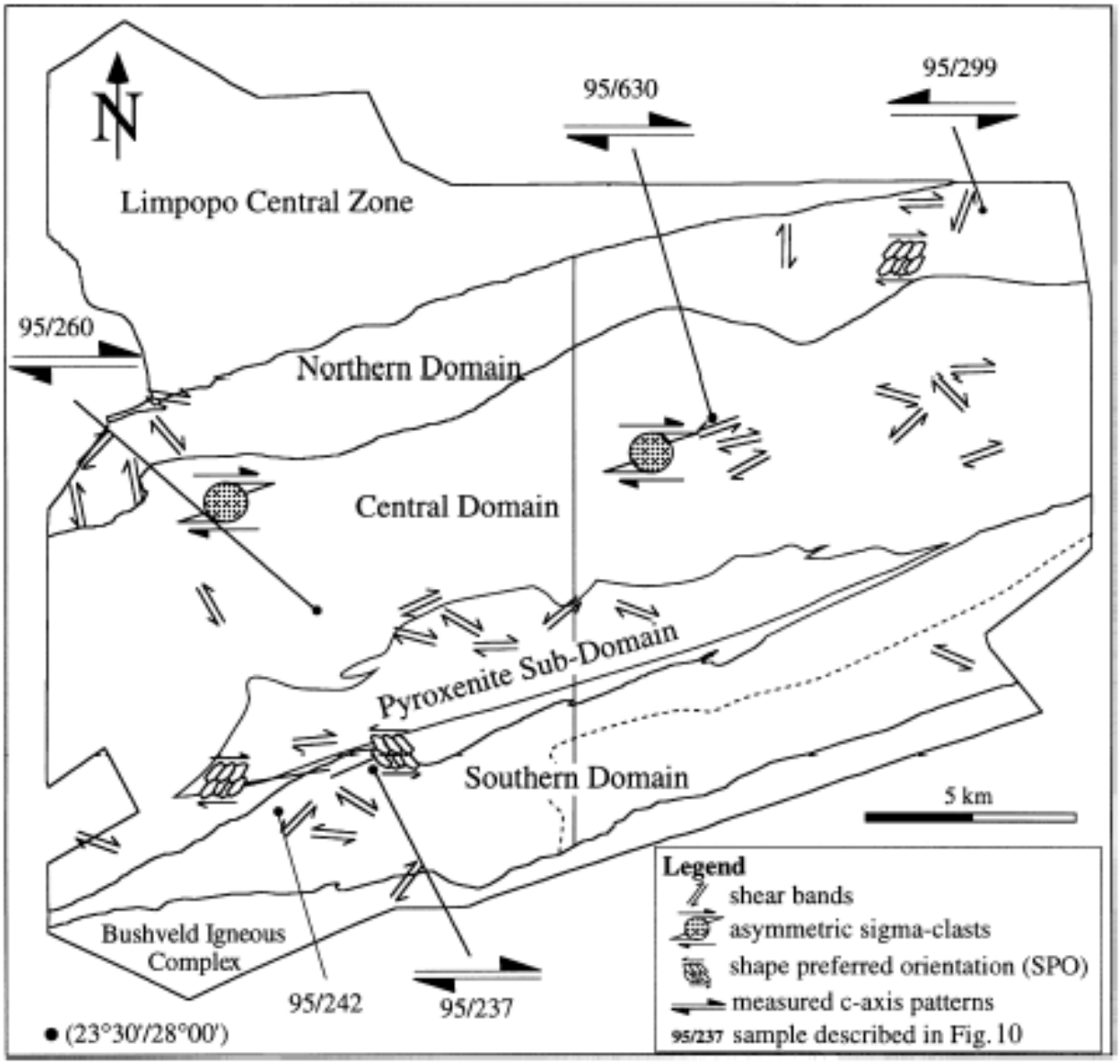


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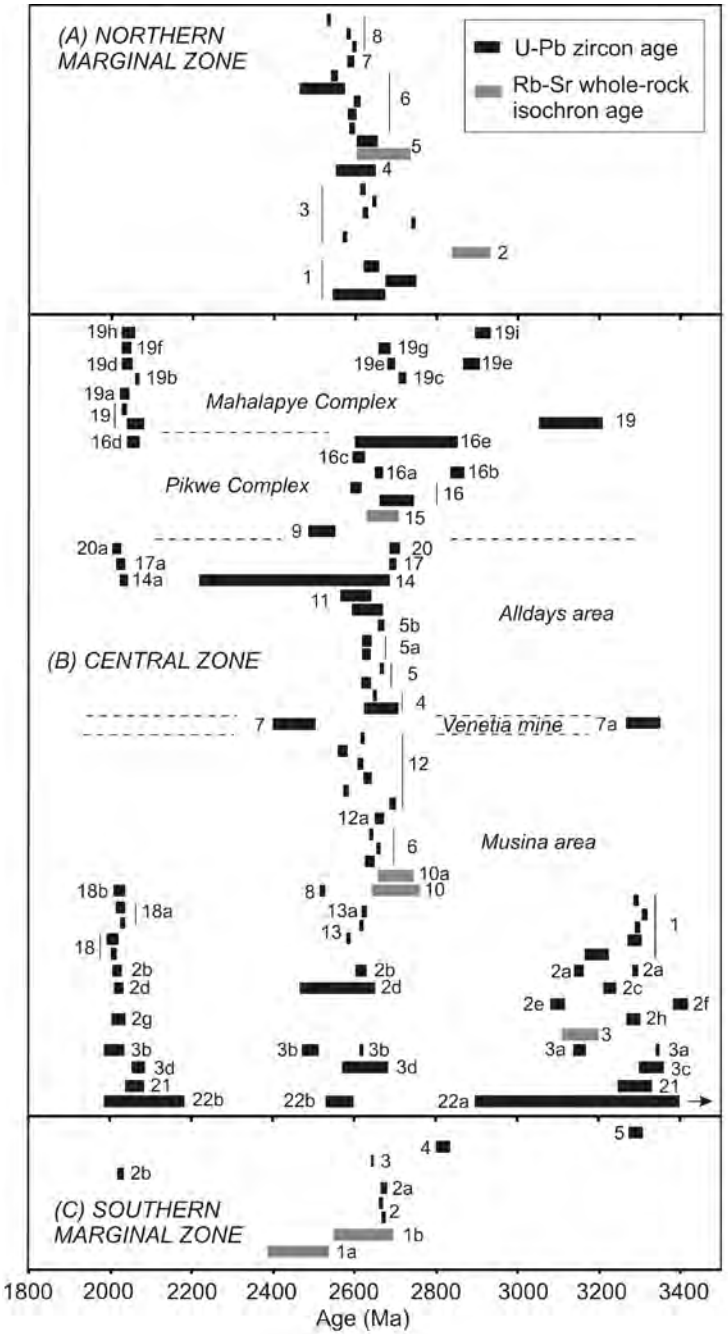
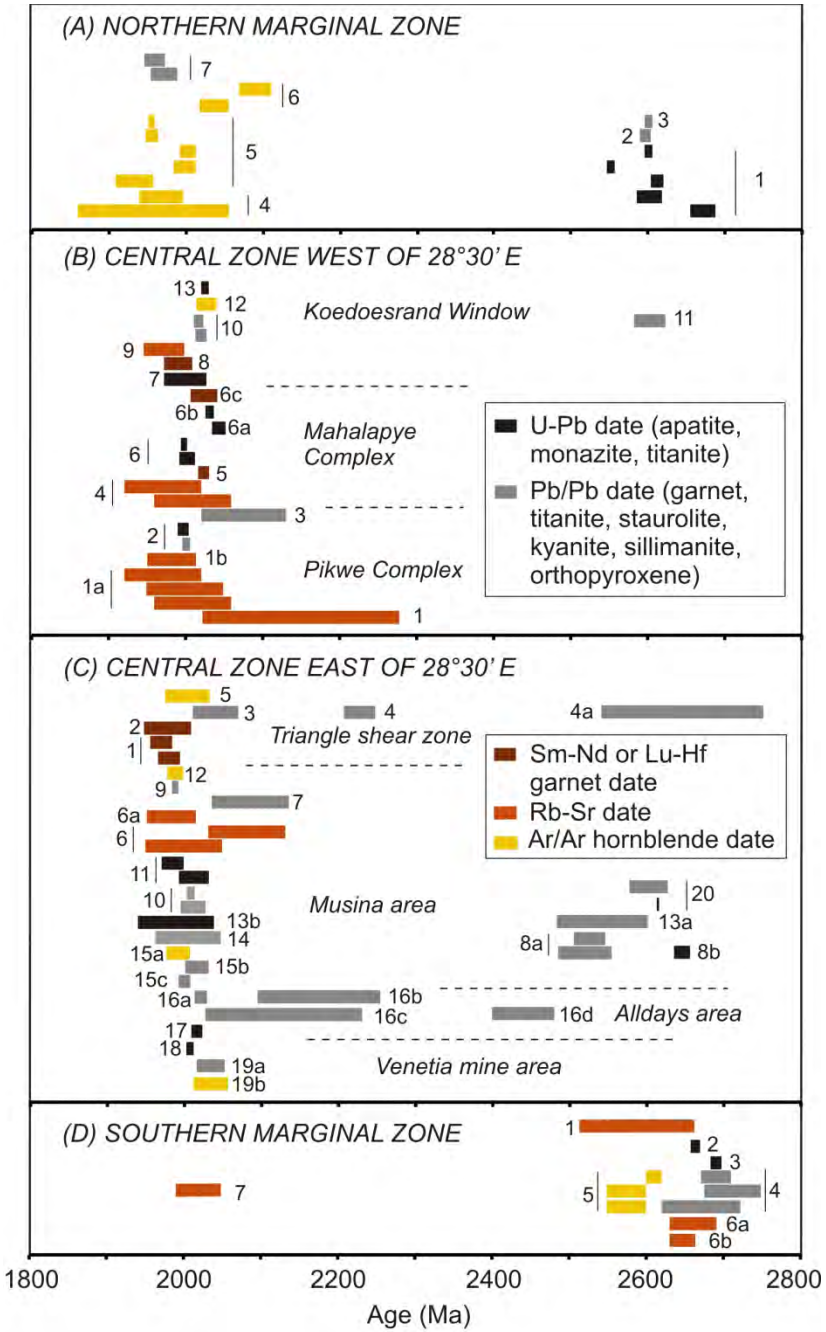
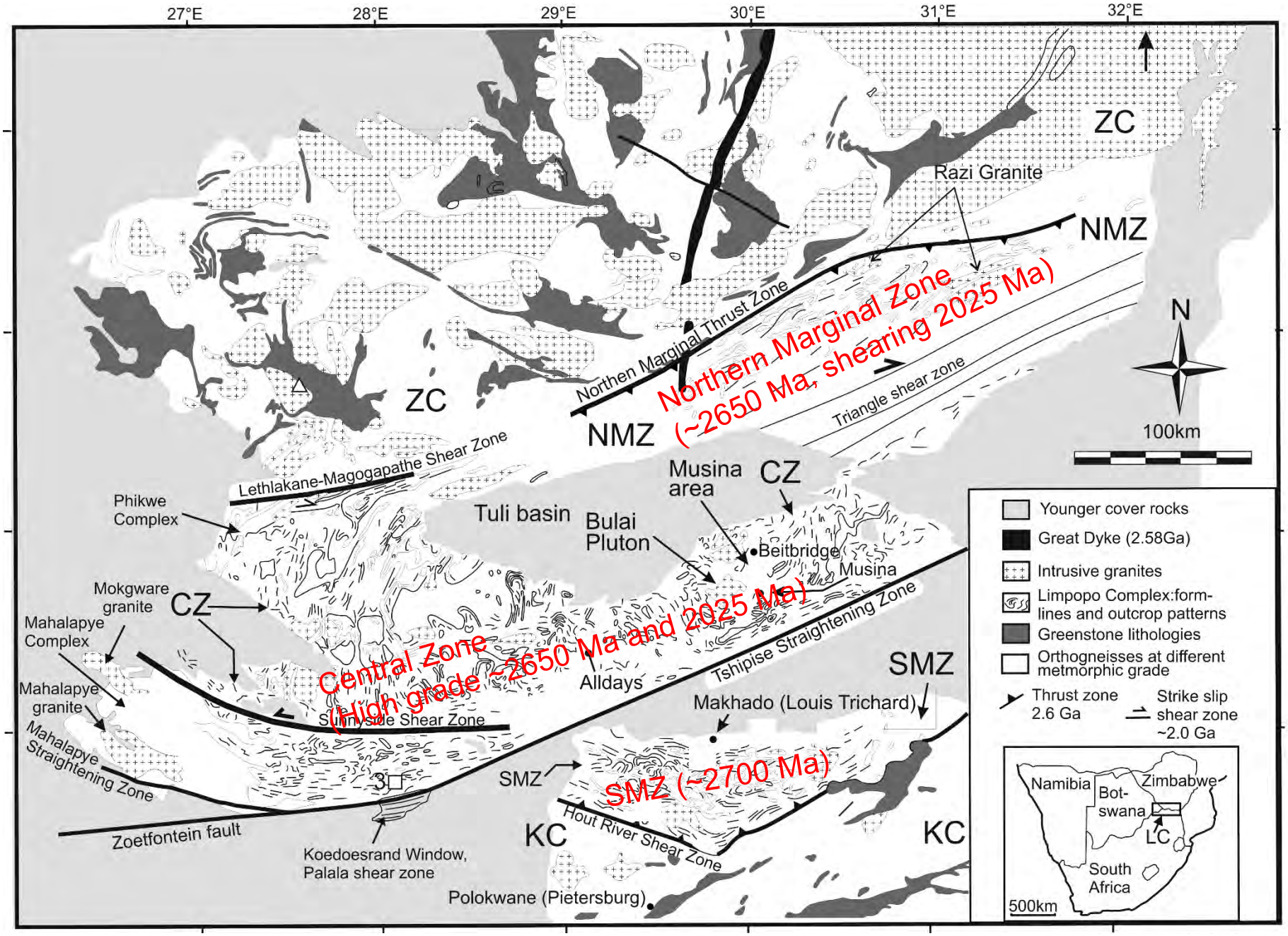
From Schaller et al. 1999, Prec. Res. 96: 263-288

Overview of geohronological data. Left, (mainly) rock formation; right, (mainly) metamorphism

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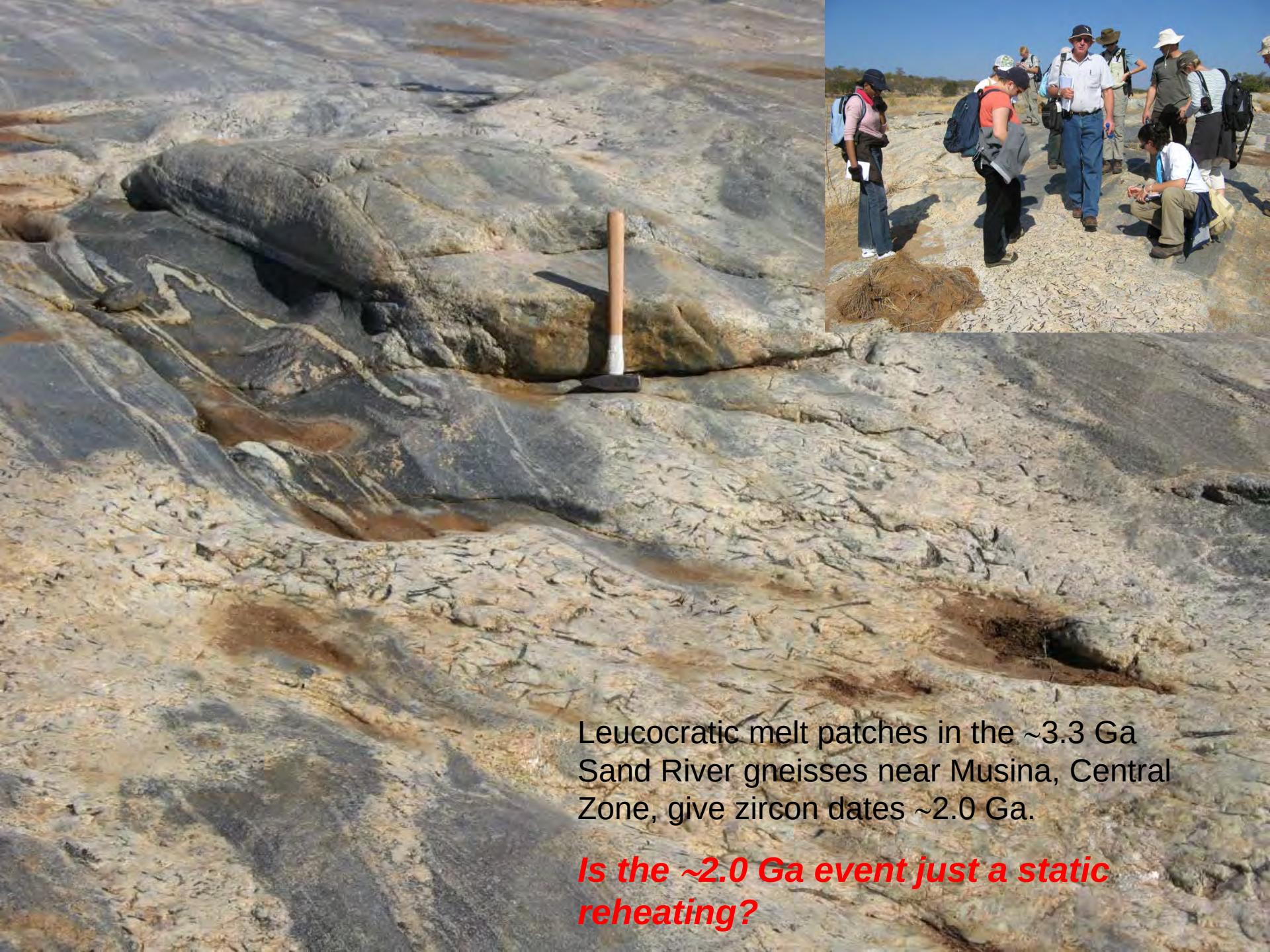
~2.0 Ga
Namibia
Bot-
swana
Zimbabwe
LC
South
Africa
500km



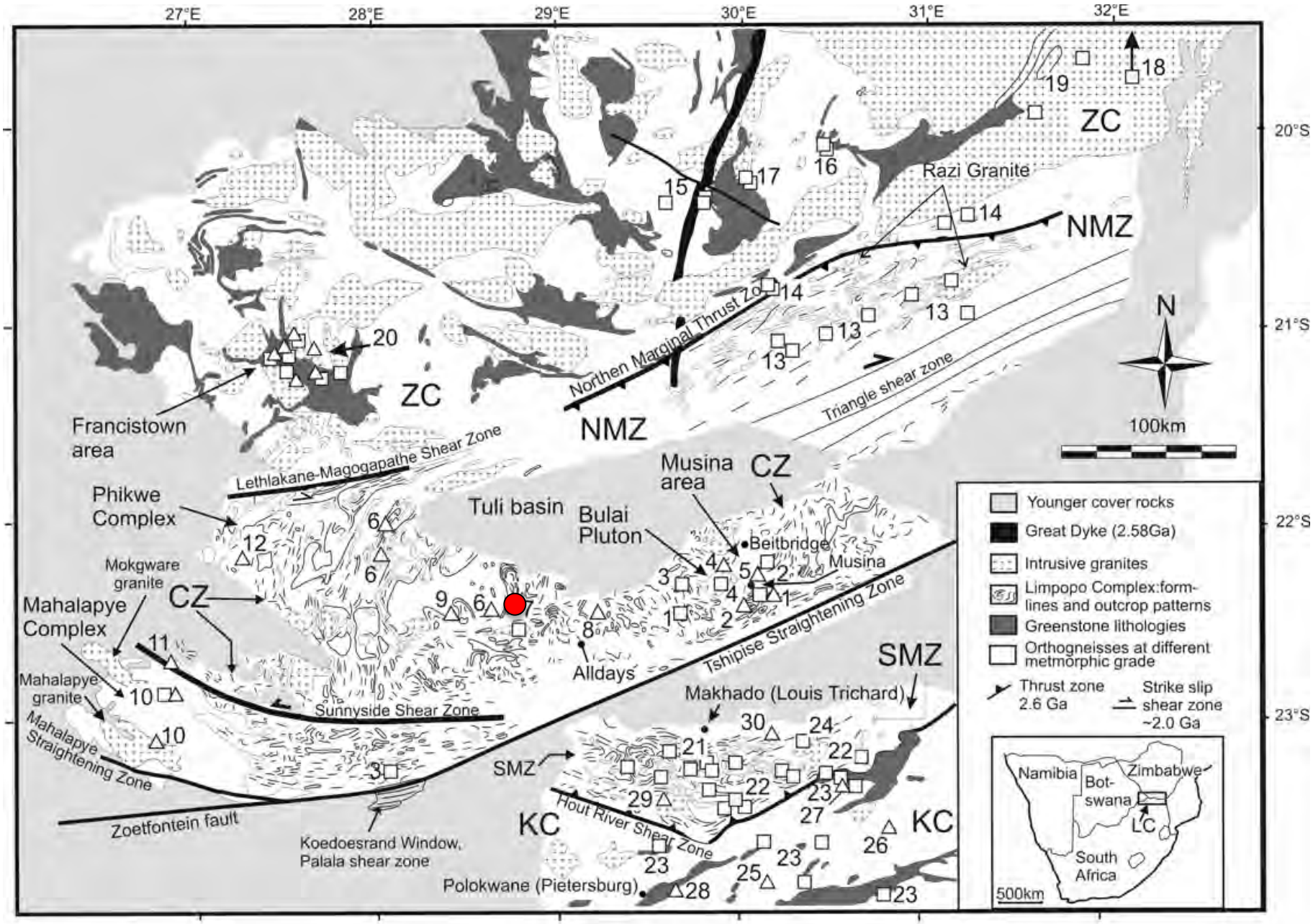
Leucocratic melt patches in the ~3.3 Ga Sand River gneisses near Musina, Central Zone, give zircon dates ~2.0 Ga.

***Is the ~2.0 Ga event just a static reheating?***

NO.

Outcrop in Sand River close to N1 bridge; melting in dynamic regime.


In Sand River 50 km W N1 bridge: also
definitely not static. Intensive shearing

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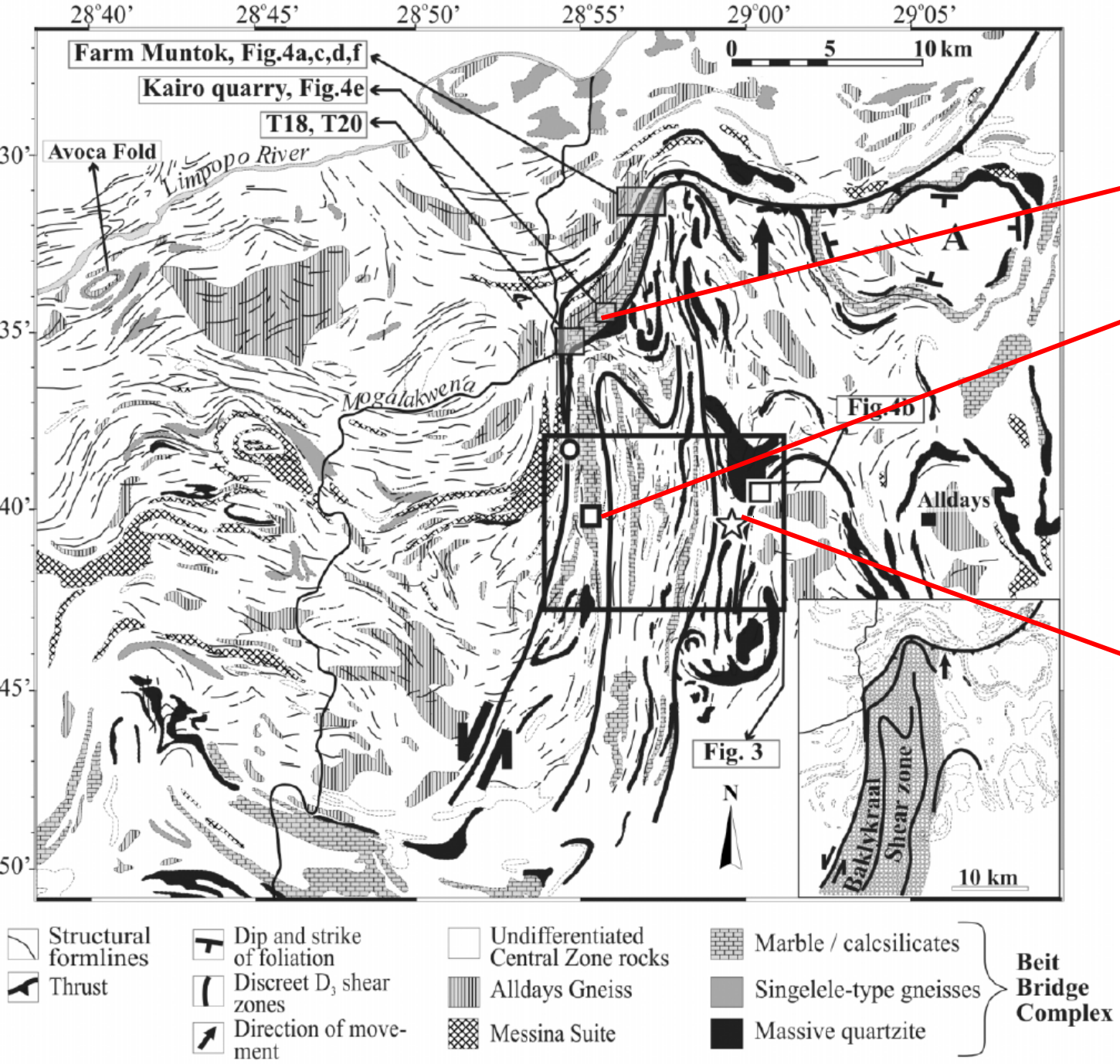


Kairo quarry, next 2 slides

Sample T73, a single syntectonic metamorphism at 2.02 Ga

Sample RB1, mix of 2.0 Ga and older structures, >1 metamor-phism and poorly defined metamorphic dates

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# *Kairo quarry*

W side:

Calc silicates and shales, intensely sheared, apparently monometamorphic

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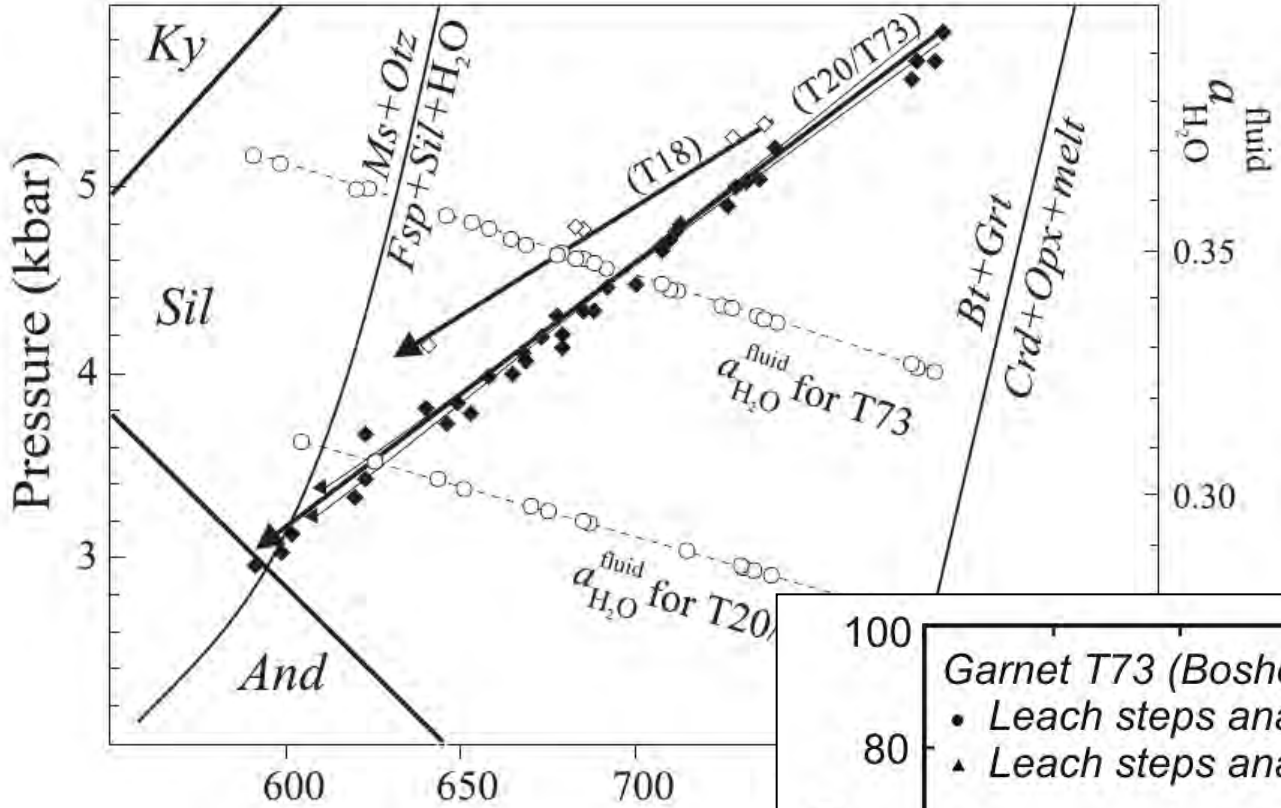
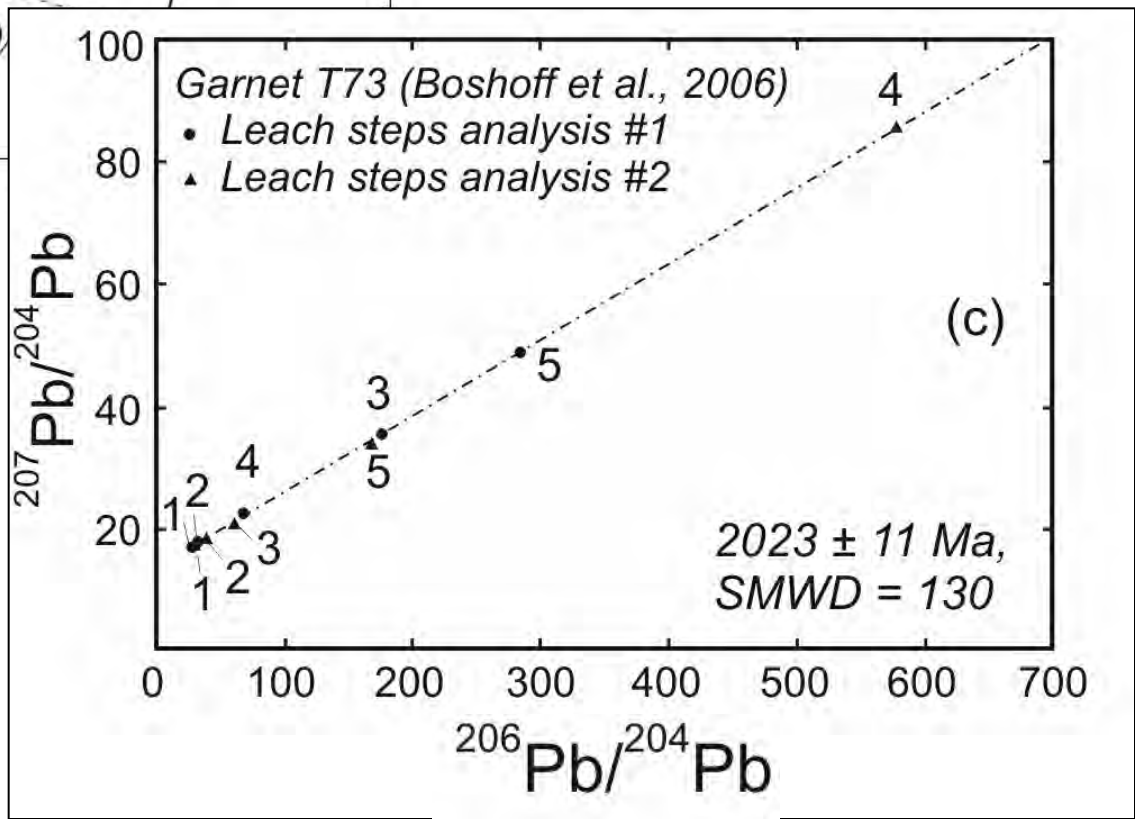
Kairo quarry

# Sample T73




- A single metamorphism (*van Reenen et al., 2004, J.Pet. 44, 1413-1439*) and....

- a well defined paleoproterozoic age (*Boshoff et al., 2006, J. Geol., 114, 699–716*)

RB1 sample locality

E side of structure: Singelele-type 2.65 Ga quartzofeldspathic gneisses are re-folded and boudinaged; later shearing.

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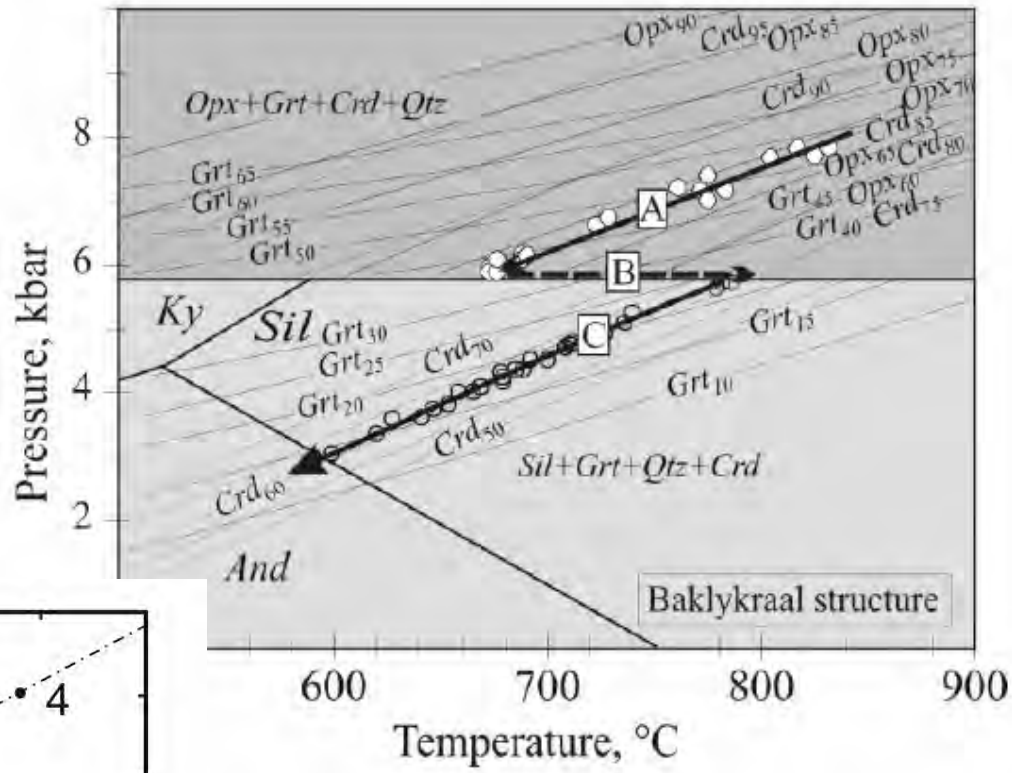
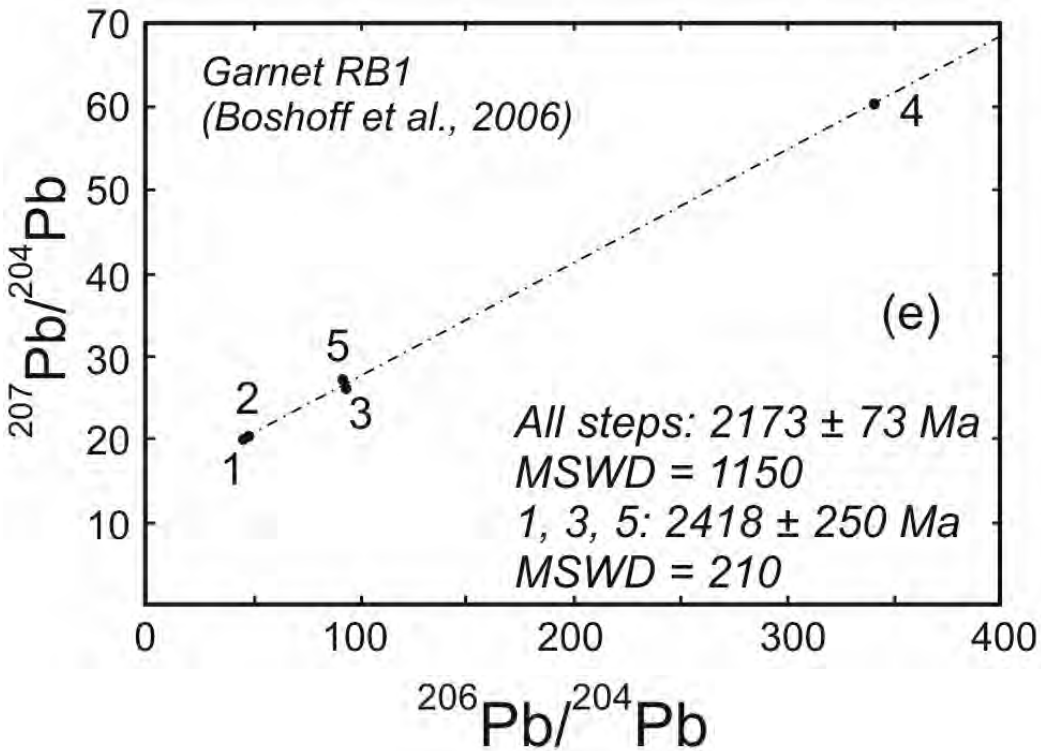
RB1 sample
locality

Higher-pressure early P-T path, followed by re-heating and second cooling (assembled from several samples in same area, (*Boshoff et al., 2006, J. Geol., 114, 699–716*) ....




... and an intermediate garnet Pb-Pb age with a large error and scatter of the data *(ibid.) in the samples with the hotter and higher P garnets*

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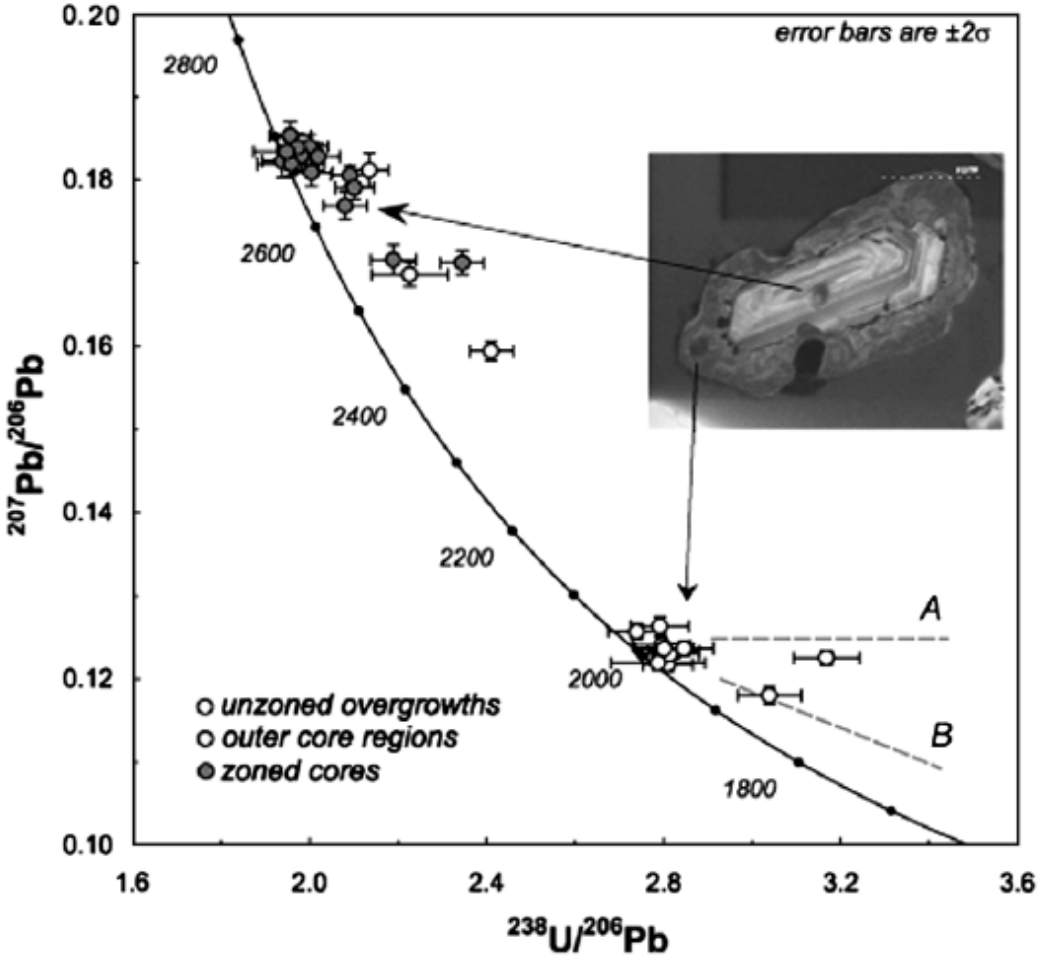
For those who do not believe ages on metamorphic minerals:




*2000 Ma age is also seen in many zircon overgrowths, produced by metamorphism Example Opx-gedrite bearing granulite, Central Zone (Mouri et al., JAES, 2008).*

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## Lorenz Holzer's Paleoproterozoic Transpression Orogeny Model

Based on the following points:

1. High grade metamorphism in the Central Zone occurred at around 2.0 Ga
2. This high grade metamorphism marks an orogeny (far to hot to be some vague thermal resetting)
3. For the purpose of thinking about this 2.0 Ga orogeny, the Northern and Southern Marginal Zones are pars of the Zimbabwe and Kaapvaal Cratons, respectively

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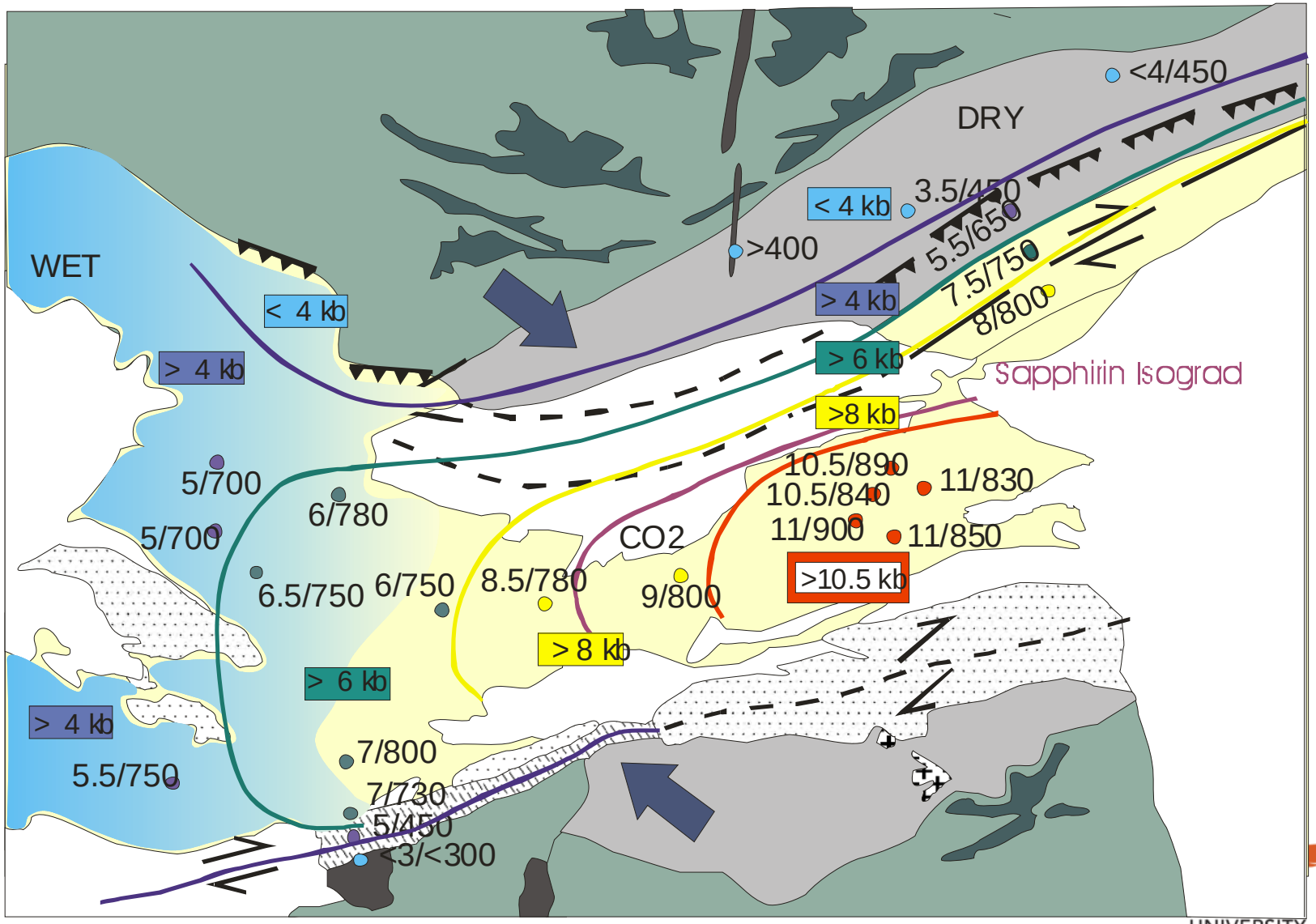
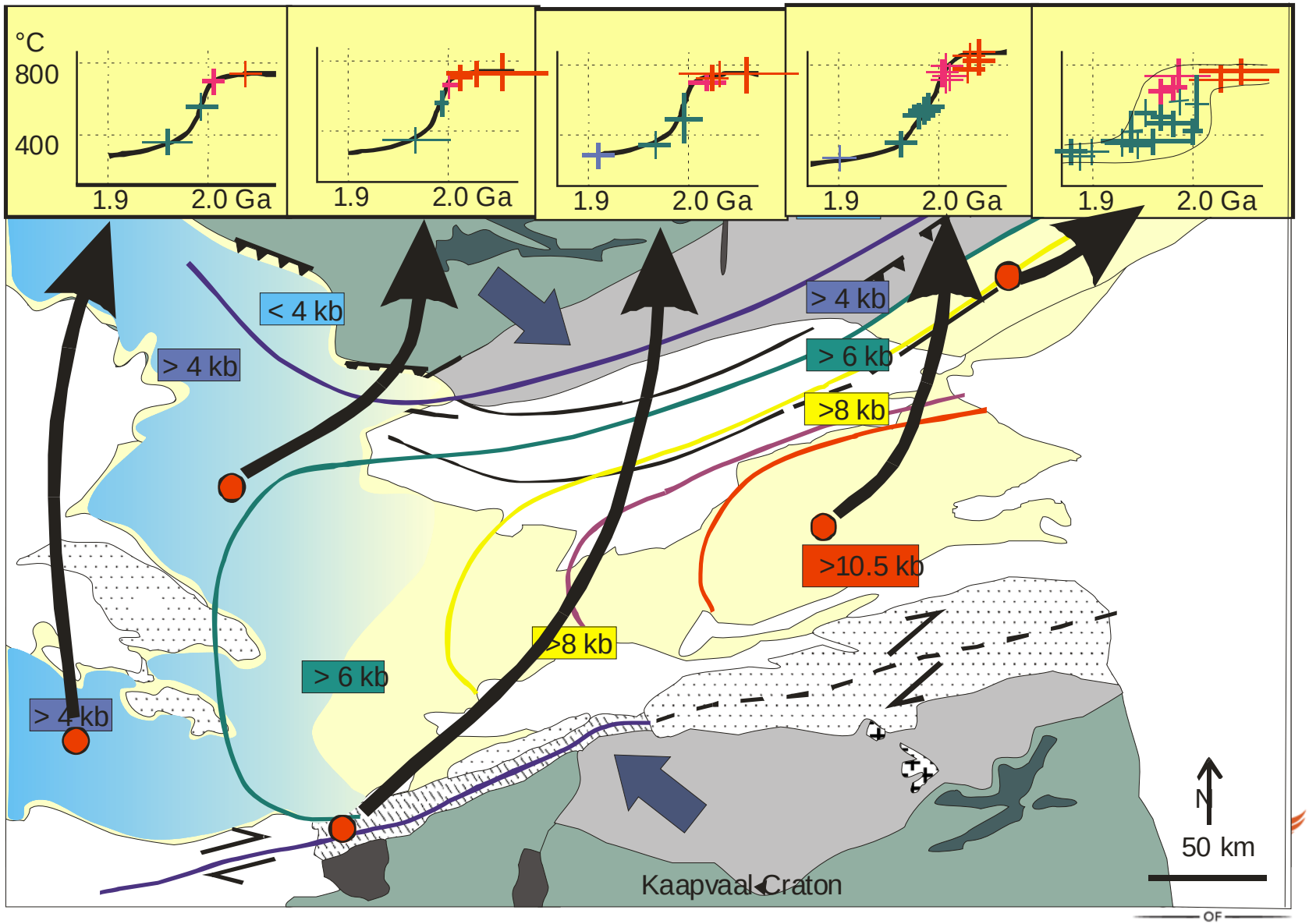
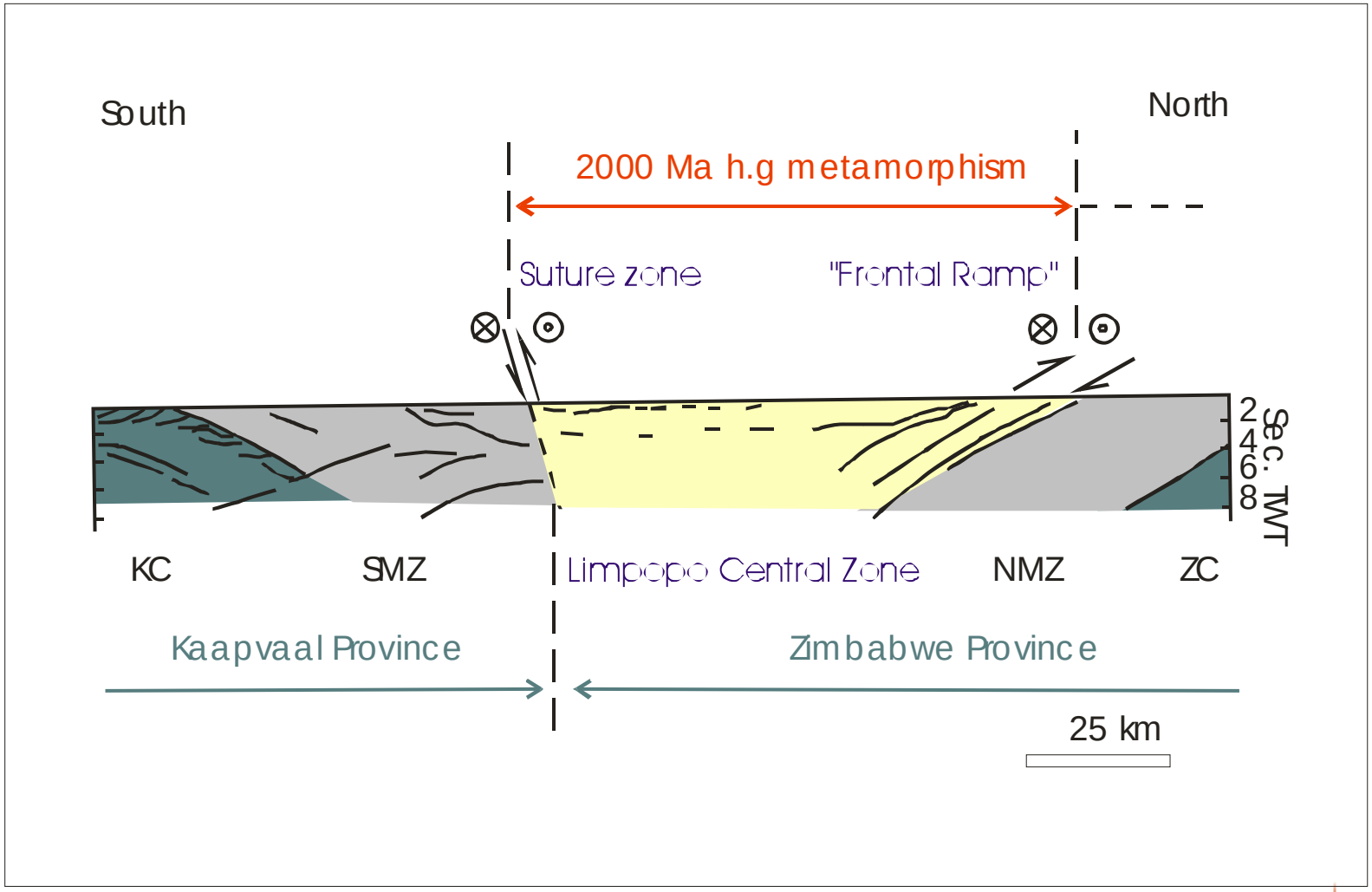



Metamorphic P- map of the Central Zone, compiled by Lorenz Hölzer




Metamorphic map with time markers

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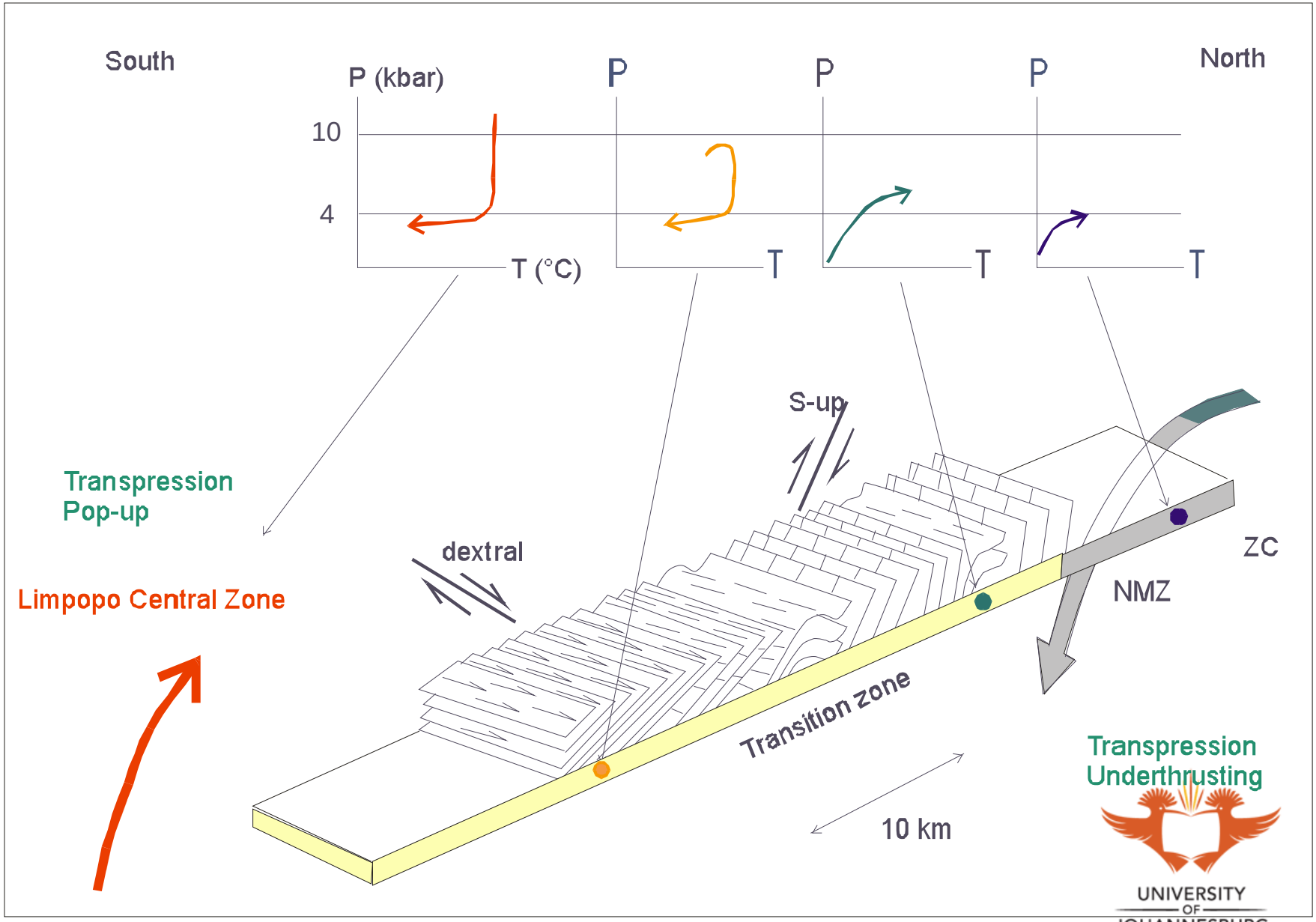
South
North
P (kbar)
P
P
P
10
4
T (°C)
T
T
T
S-up
Transpression
Pop-up
dextral
Limpopo Central Zone
ZC
NMZ
Transition zone
10 km
Transpression
Underthrusting
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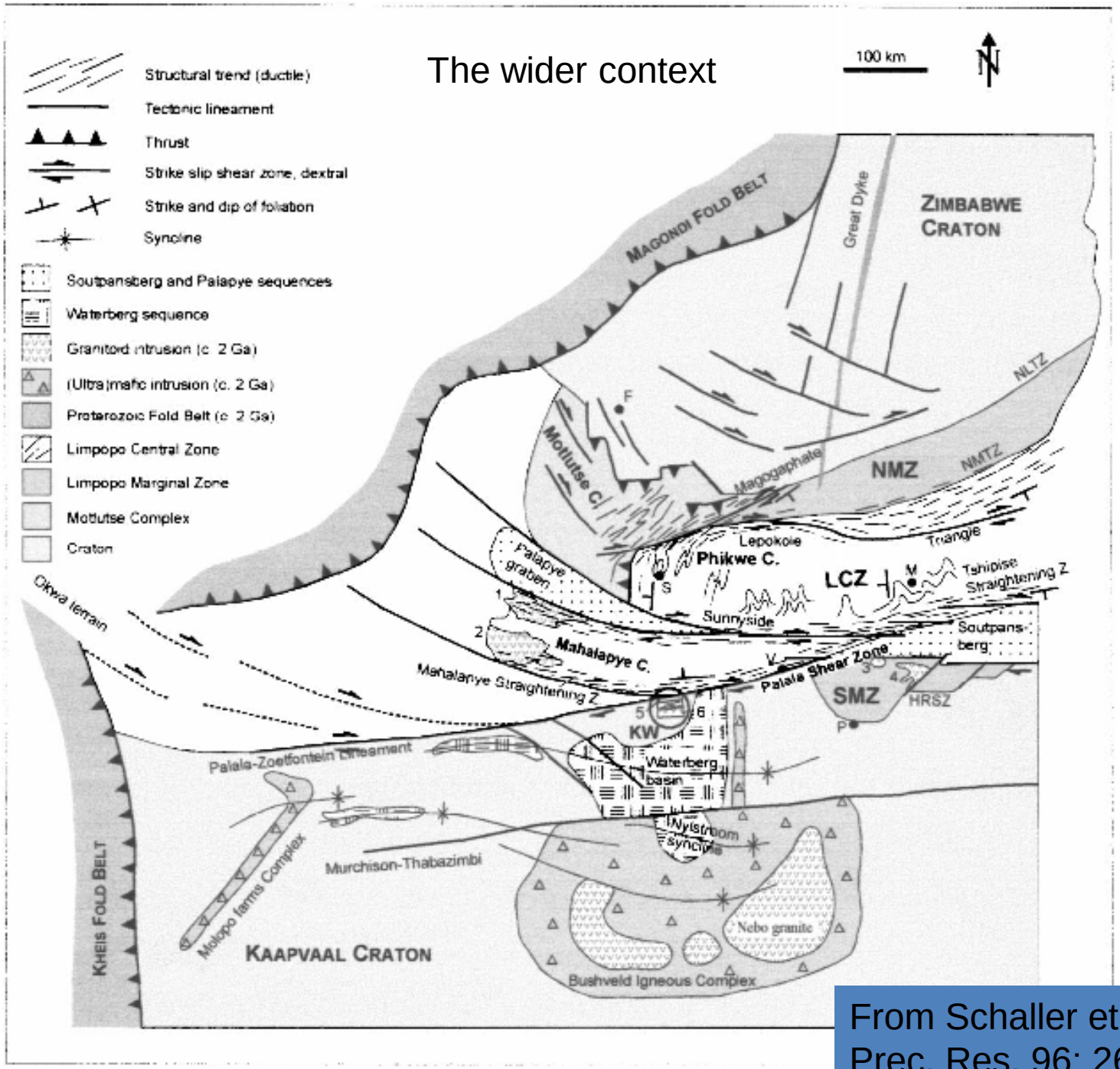
# The wider context




From Schaller et al. 1999, Prec. Res. 96: 263-288

This model is self consistent but:

- Does not consider the evidence for Neoarchean tectonometamorphism
- Can it be superimposed on a Neoarchean continent collision model?

*We need to consider age data for the Southern Marginal Zone*

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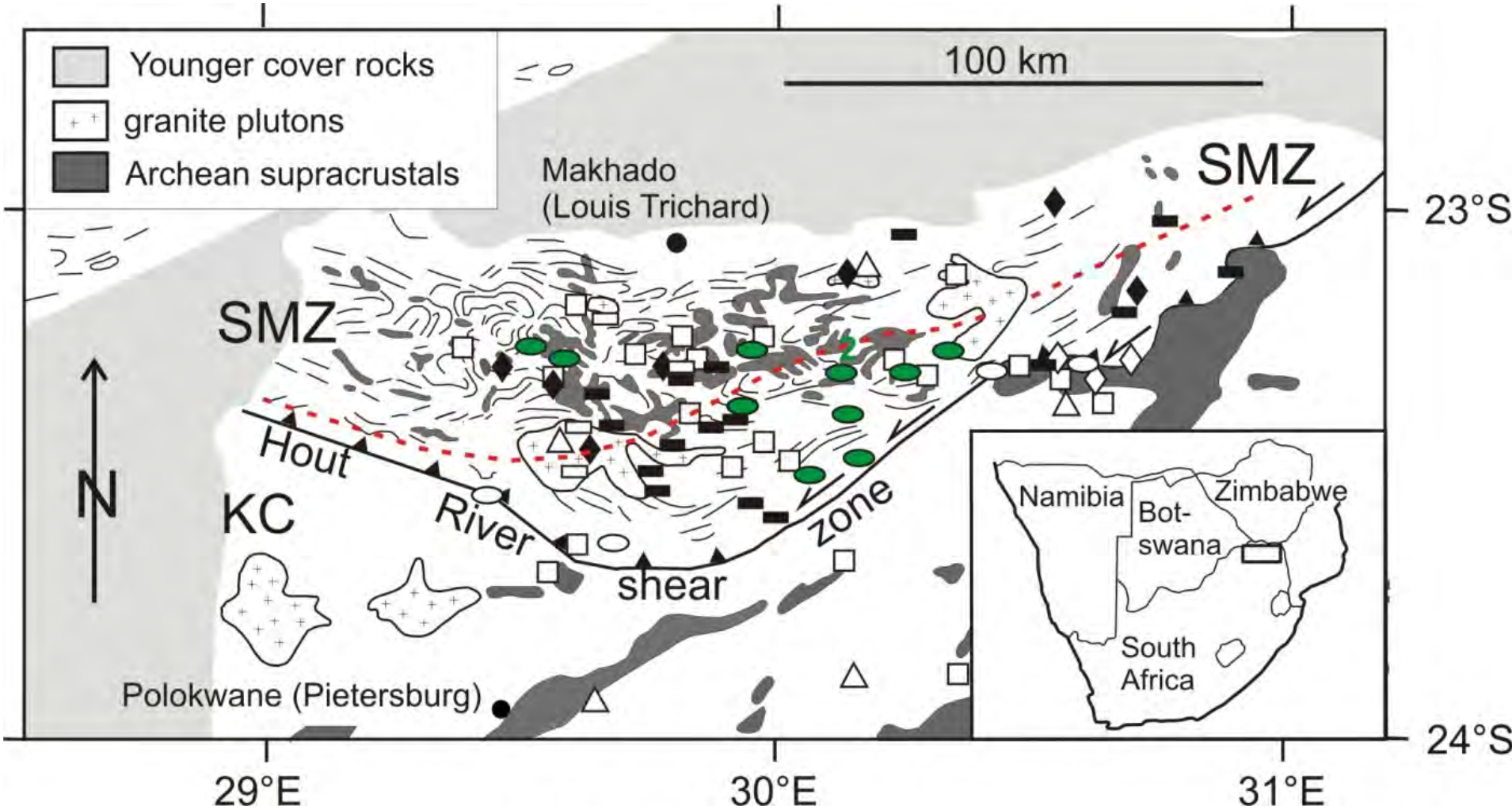


orthoamphibole isograd (~ 2.65 Ga) almost coincides with the N'tabalala shear zone (~2.02 Ga)

Ar-Ar sample localities

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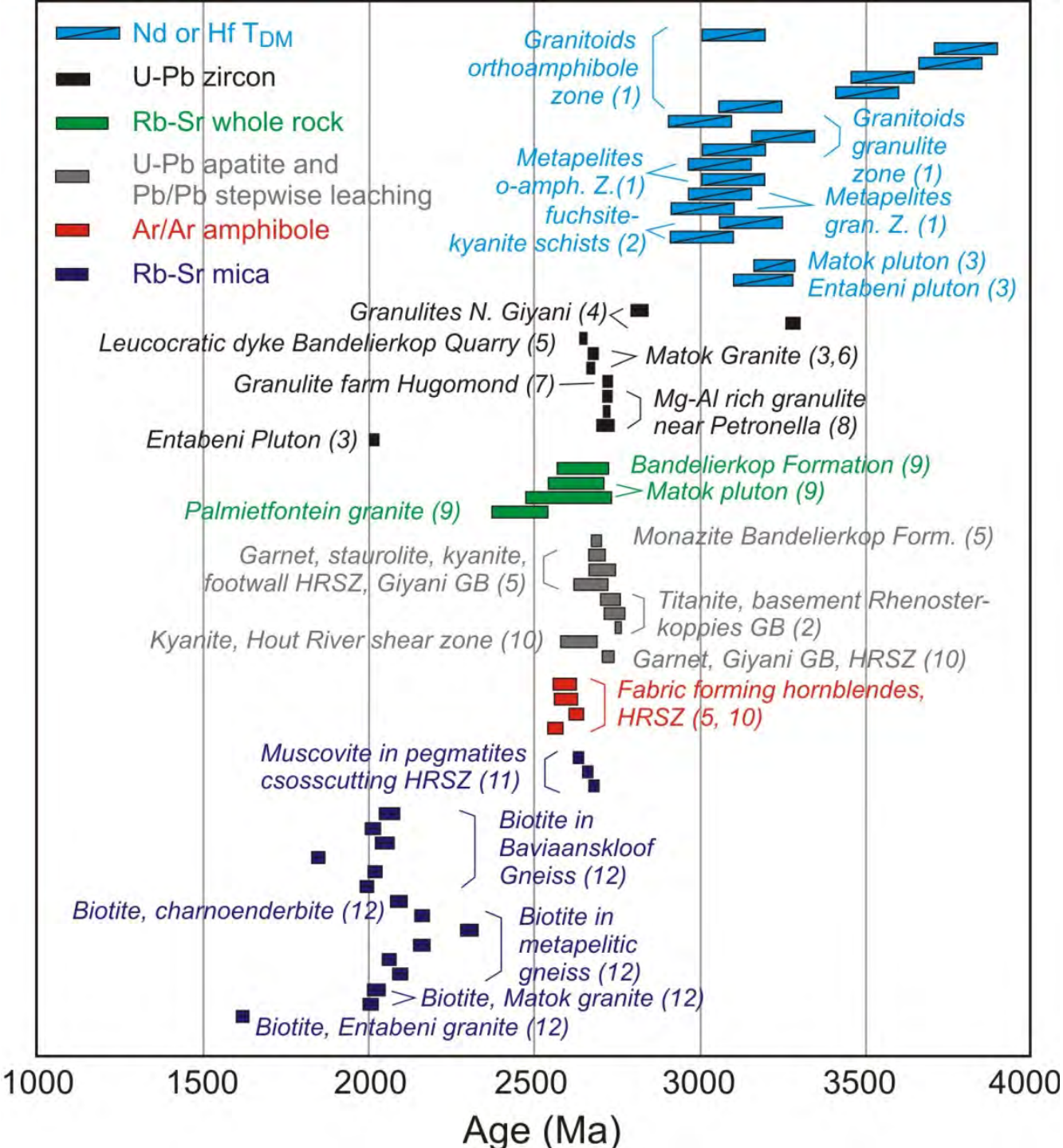


Published age data in the Limpopo SMZ Status 2014

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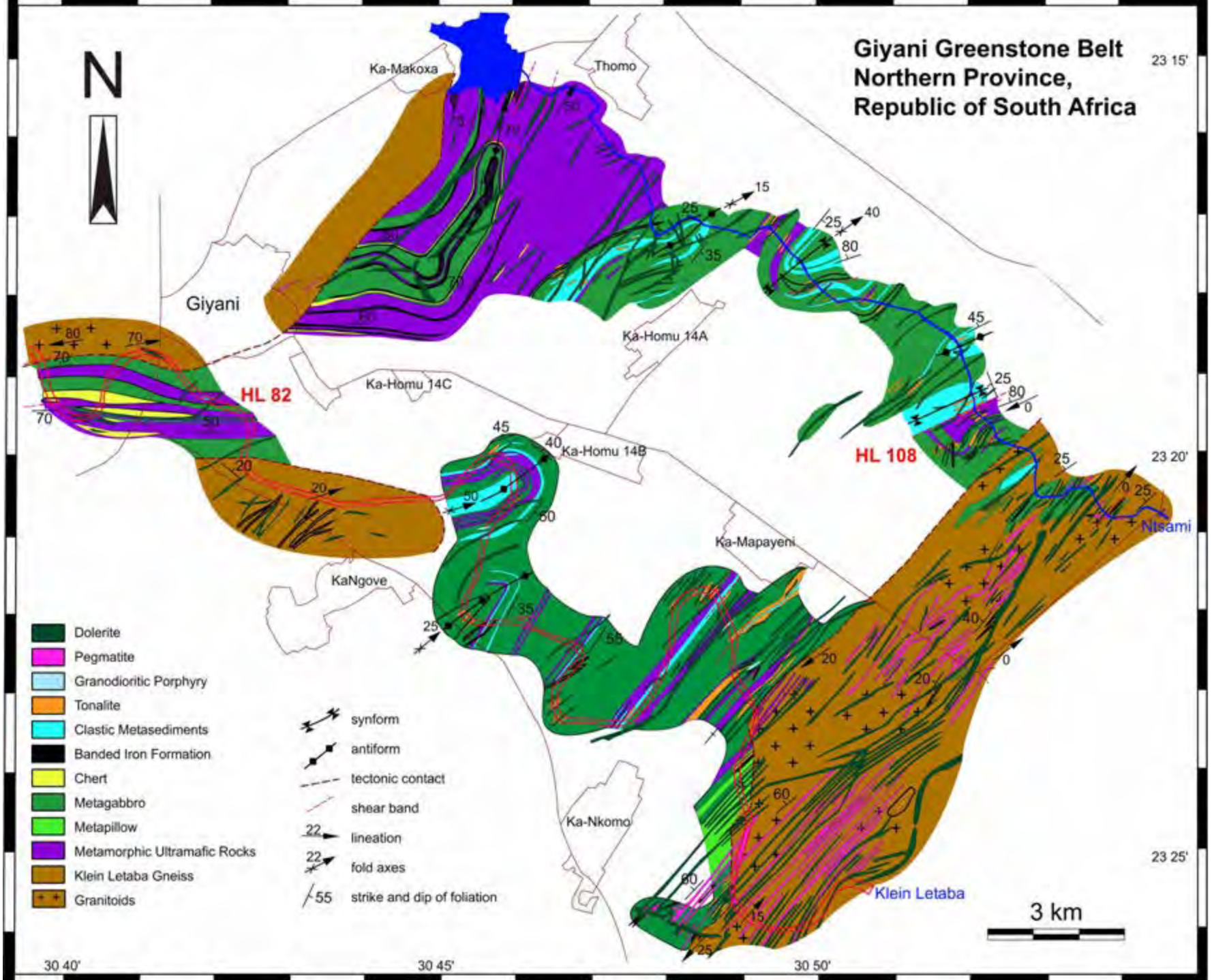
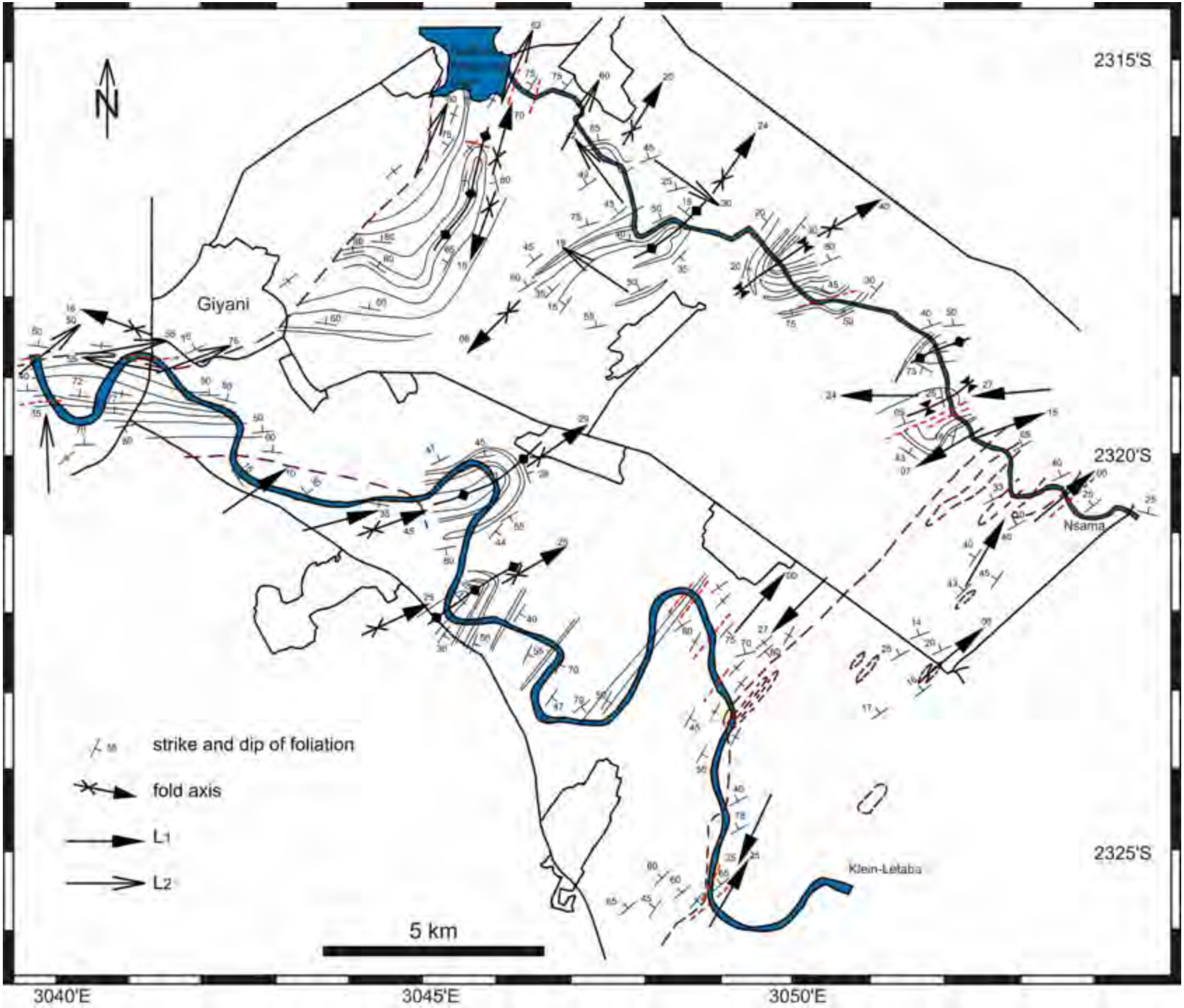
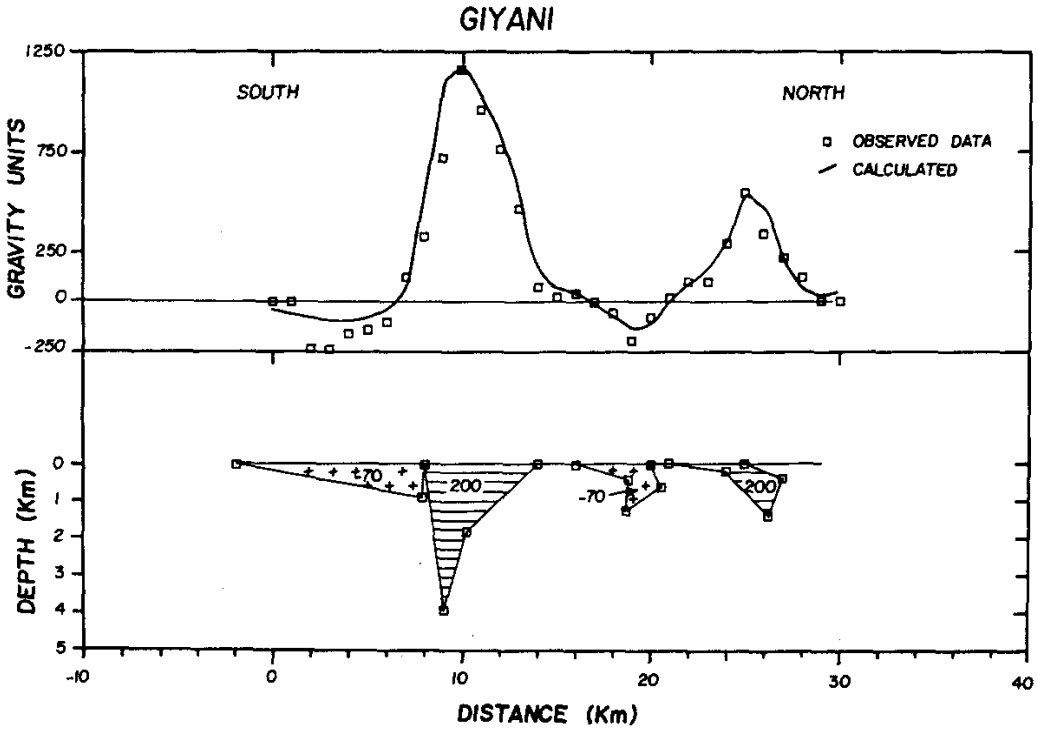

Giyani Greenstone Belt
Northern Province,
Republic of South Africa
N
Ka-Makoxa
Thomo
Giyani
Ka-Homu 14A
Ka-Homu 14C
Ka-Homu 14B
HL 82
HL 108
Ka-Mapayeni
KaNgove
Ka-Nkomo
Klein Letaba
Ntsami
3 km
23 15'
23 20'
23 25'
30 40'
30 45'
30 50'
Dolerite
Pegmatite
Granodioritic Porphyry
Tonalite
Clastic Metasediments
Banded Iron Formation
Chert
Metagabbro
Metapillow
Metamorphic Ultramafic Rocks
Klein Letaba Gneiss
Granitoids
synform
antiform
tectonic contact
shear band
lineation
fold axes
strike and dip of foliation


2315'S
2320'S
2325'S
3040'E
3045'E
3050'E
Giyani
Nsama
Klein-Letaba
strike and dip of foliation
fold axis
L1
L2
5 km

Gravity profile across Giyani Belt, de Beer & Stettler, 1992.

Suggestion: Anticline

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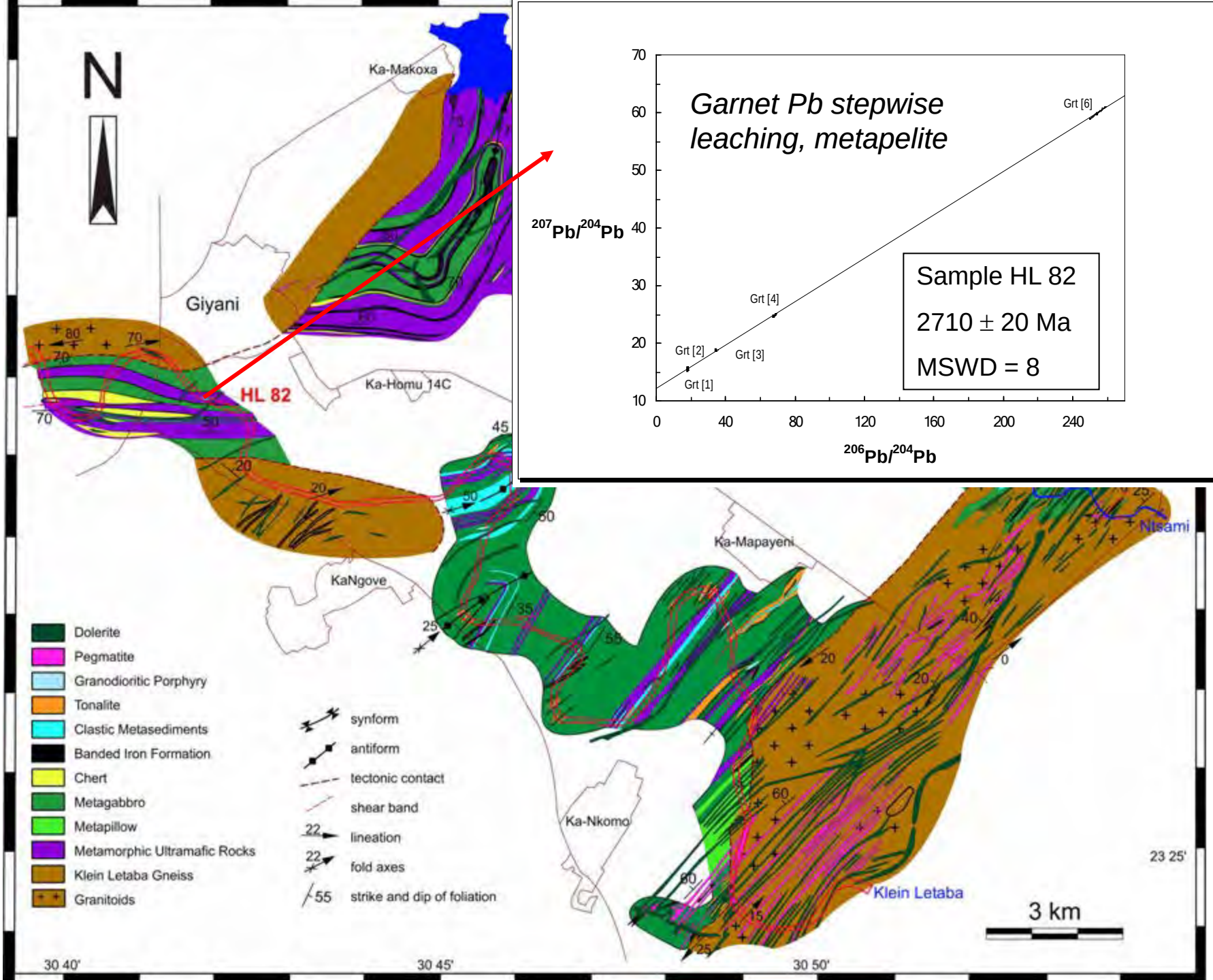
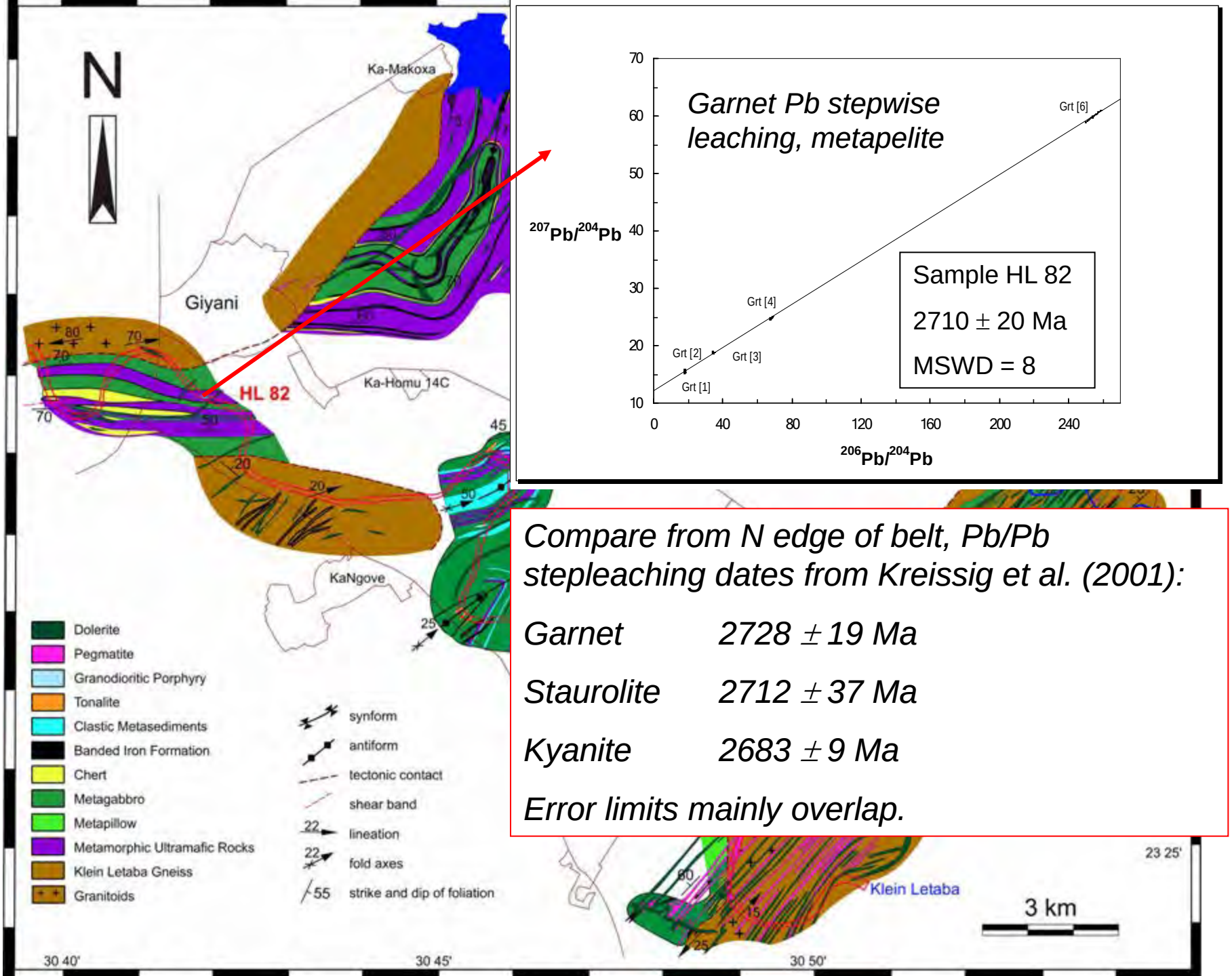
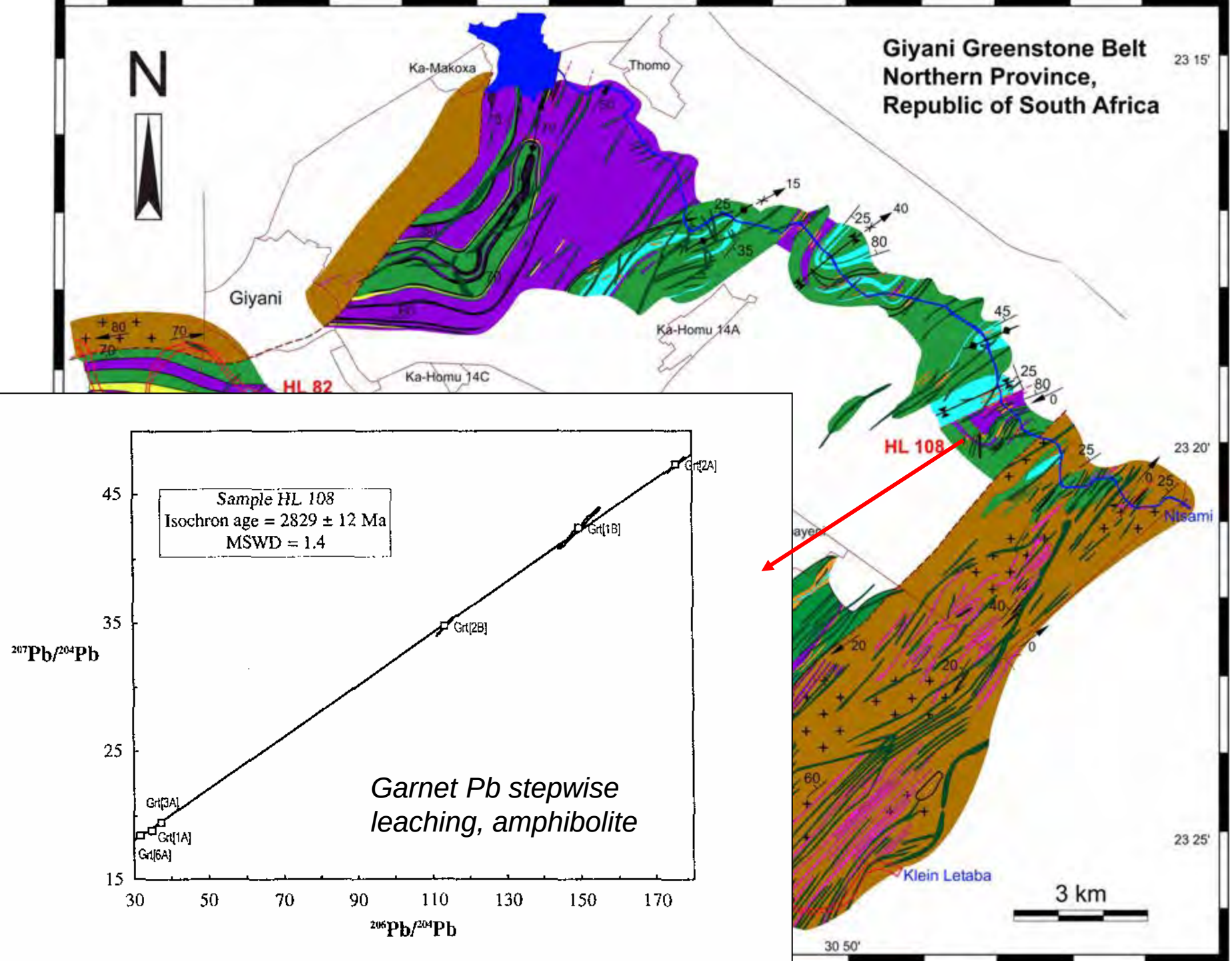
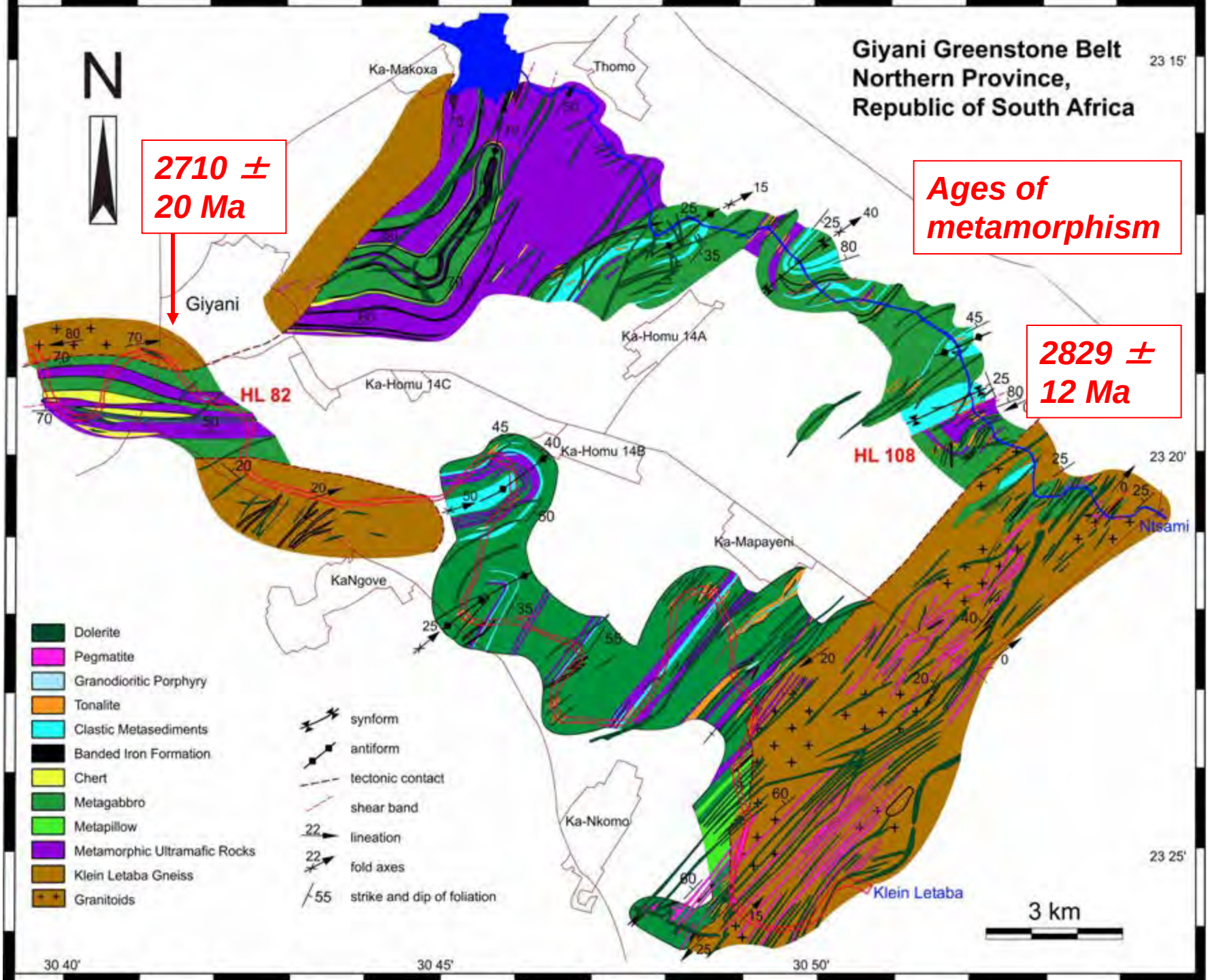

N
Ka-Makoxa
Giyani
HL 82
Ka-Homu 14C
KaNgove
Ka-Mapayeni
Ntsami
Ka-Nkomo
Klein Letaba
3 km
30 40'
30 45'
30 50'
23 25'
Dolerite
Pegmatite
Granodioritic Porphyry
Tonalite
Clastic Metasediments
Banded Iron Formation
Chert
Metagabbro
Metapillow
Metamorphic Ultramafic Rocks
Klein Letaba Gneiss
Granitoids
synform
antiform
tectonic contact
shear band
lineation
fold axes
strike and dip of foliation
Garnet Pb stepwise leaching, metapelite
Sample HL 82
2710 ± 20 Ma
MSWD = 8
Grt [1]
Grt [2]
Grt [3]
Grt [4]
Grt [6]
207Pb/204Pb
206Pb/204Pb


N
Ka-Makoxa
Giyani
HL 82
Ka-Homu 14C
KaNgove
Klein Letaba
3 km
30 40'
30 45'
30 50'
23 25'
Dolerite
Pegmatite
Granodioritic Porphyry
Tonalite
Clastic Metasediments
Banded Iron Formation
Chert
Metagabbro
Metapillow
Metamorphic Ultramafic Rocks
Klein Letaba Gneiss
Granitoids
synform
antiform
tectonic contact
shear band
lineation
fold axes
strike and dip of foliation
Garnet Pb stepwise leaching, metapelite
Sample HL 82
2710 ± 20 Ma
MSWD = 8
Grt [1]
Grt [2]
Grt [3]
Grt [4]
Grt [6]
207Pb/204Pb
206Pb/204Pb
Compare from N edge of belt, Pb/Pb stepleaching dates from Kreissig et al. (2001):
Garnet 2728 ± 19 Ma
Staurolite 2712 ± 37 Ma
Kyanite 2683 ± 9 Ma
Error limits mainly overlap.


Giyani Greenstone Belt
Northern Province,
Republic of South Africa
N
Ka-Makoxa
Thomo
Giyani
Ka-Homu 14A
Ka-Homu 14C
HL 82
HL 108
Ntsami
Klein Letaba
3 km
23 15'
23 20'
23 25'
30 50'
Sample HL 108
Isochron age = 2829 ± 12 Ma
MSWD = 1.4
Grt[2A]
Grt[1B]
Grt[2B]
Grt[3A]
Grt[1A]
Grt[6A]
Garnet Pb stepwise leaching, amphibolite
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
15
25
35
45
30
50
70
90
110
130
150
170


Giyani Greenstone Belt
Northern Province,
Republic of South Africa
N
2710 ± 20 Ma
Ages of metamorphism
2829 ± 12 Ma
Ka-Makoxa
Thomo
Giyani
HL 82
Ka-Homu 14C
Ka-Homu 14A
Ka-Homu 14B
HL 108
Ka-Mapayeni
KaNgove
Ka-Nkomo
Klein Letaba
Ntsami
3 km
23 15'
23 20'
23 25'
30 40'
30 45'
30 50'
Dolerite
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Clastic Metasediments
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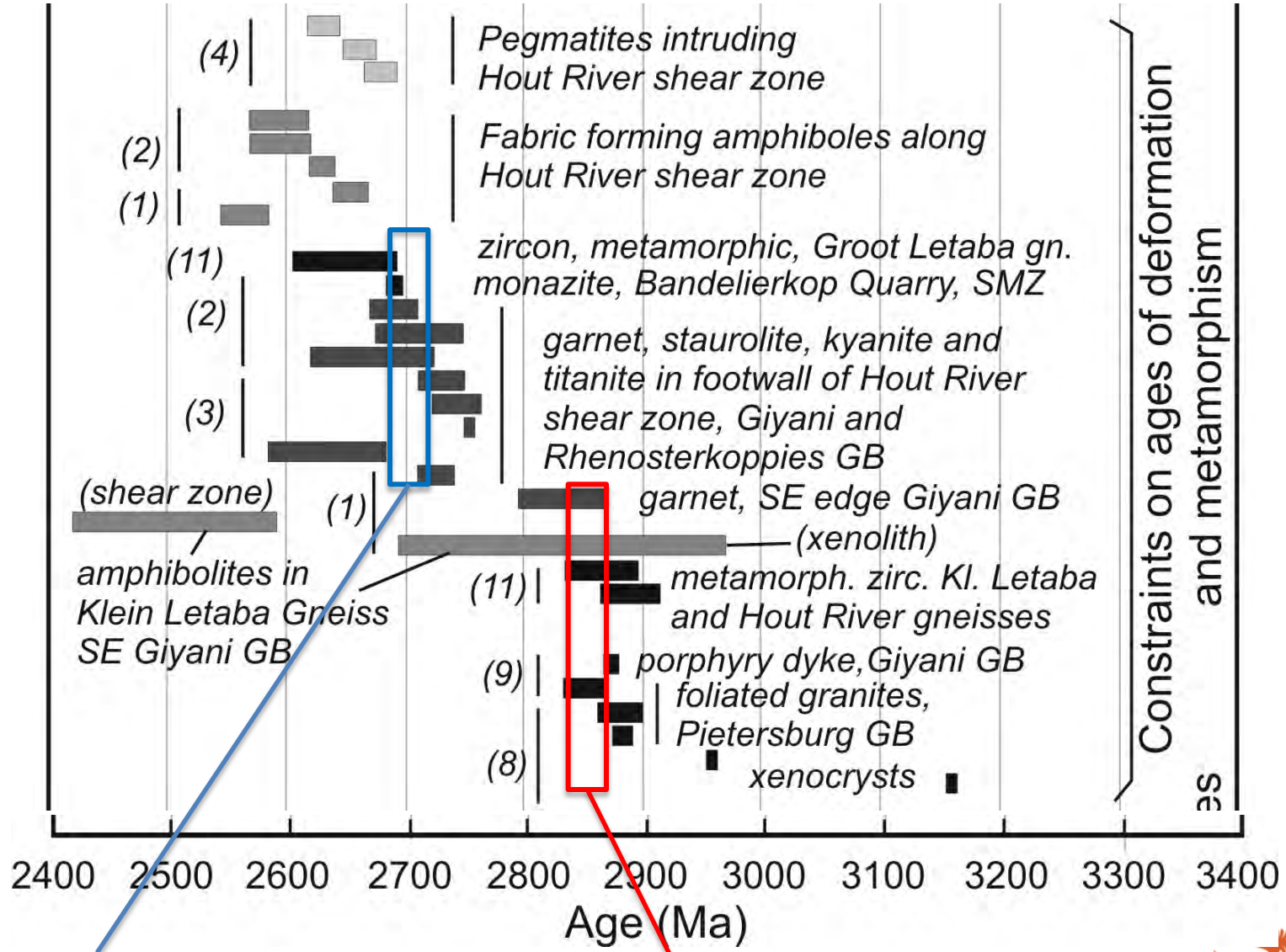
Chert
Metagabbro
Metapillow
Metamorphic Ultramafic Rocks
Klein Letaba Gneiss
Granitoids
synform
antiform
tectonic contact
shear band
lineation
fold axes
strike and dip of foliation




Hout River Shear Zone
Peak metamorphism

Giyani & Polokwane GB,
N-vergent thrusting

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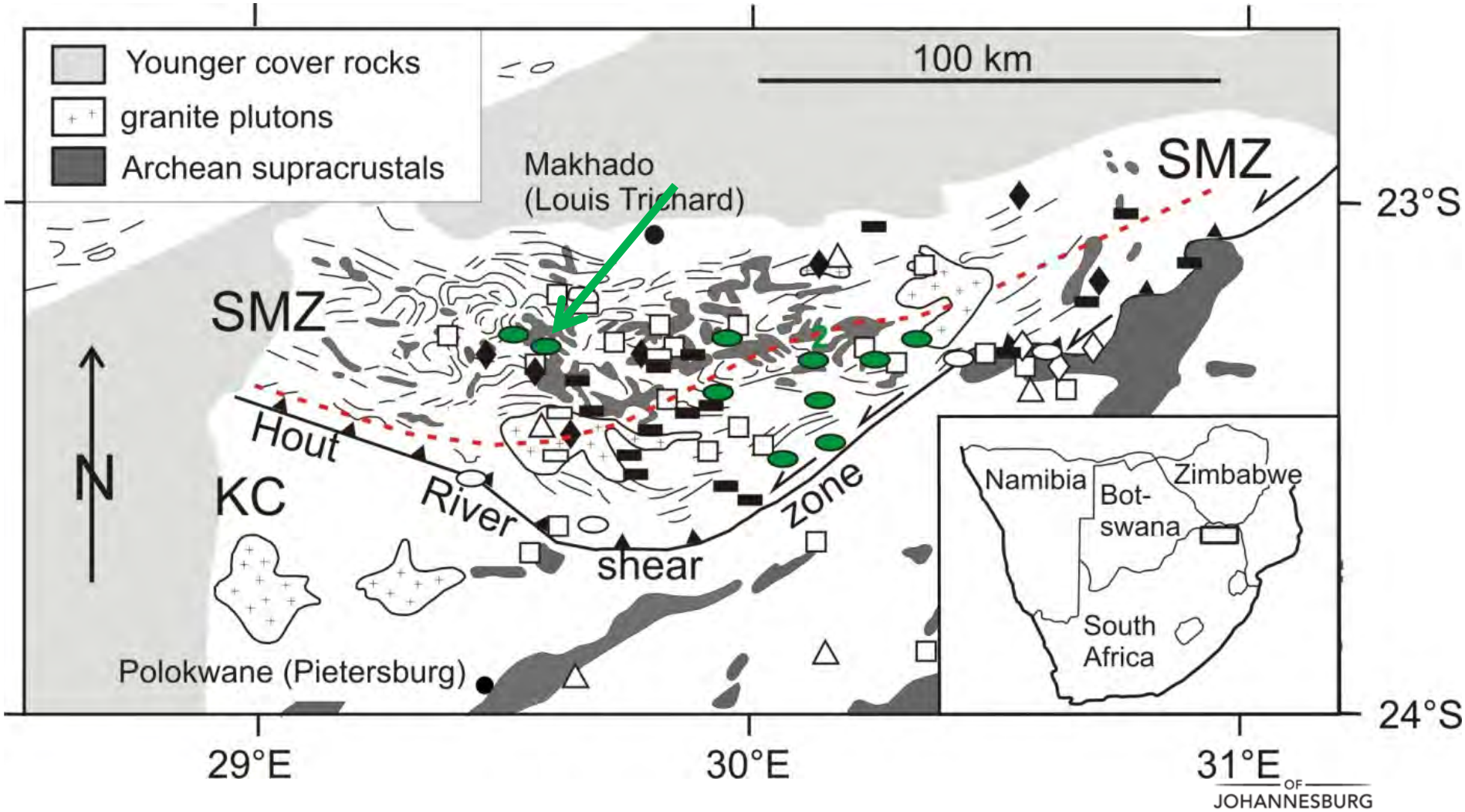
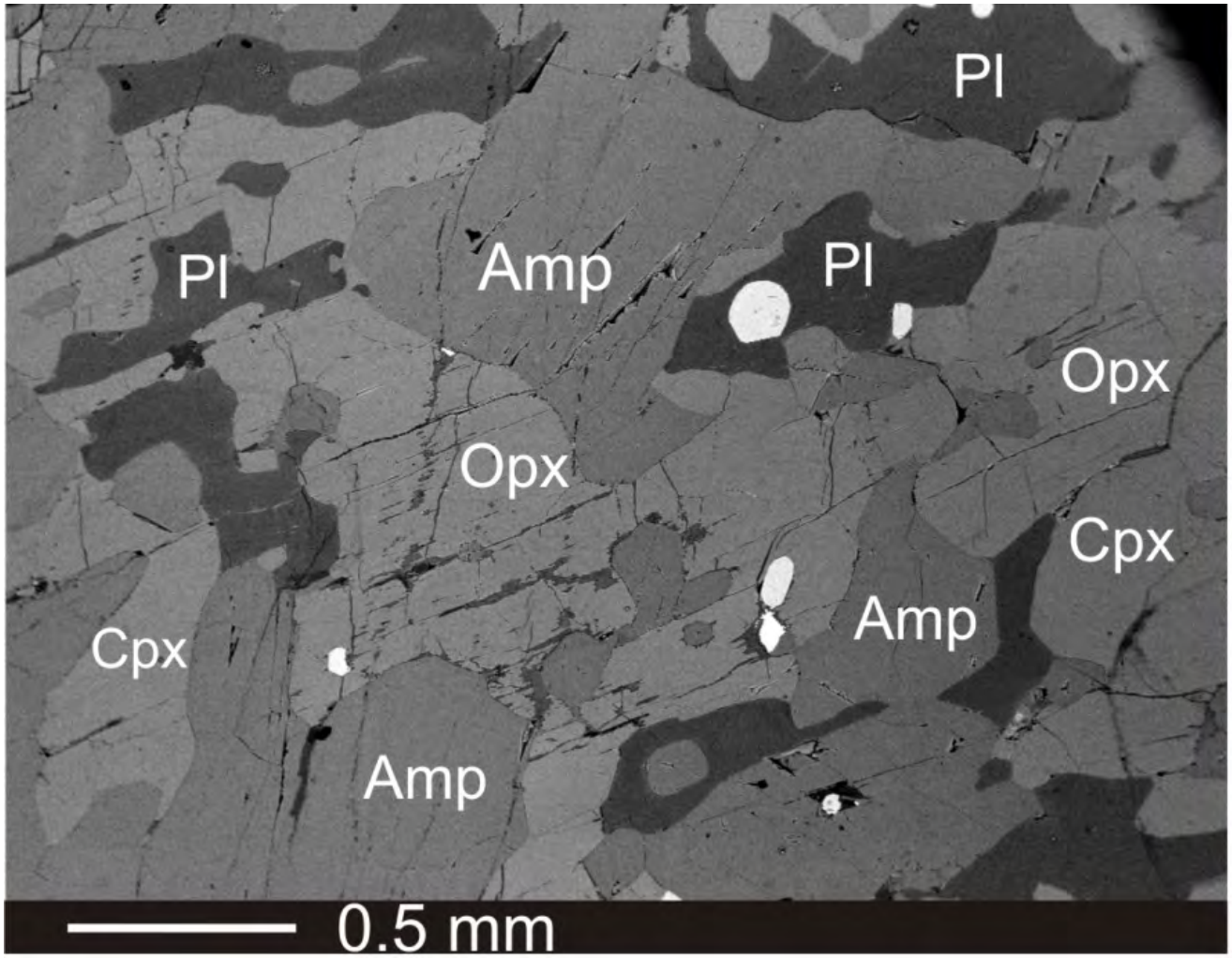
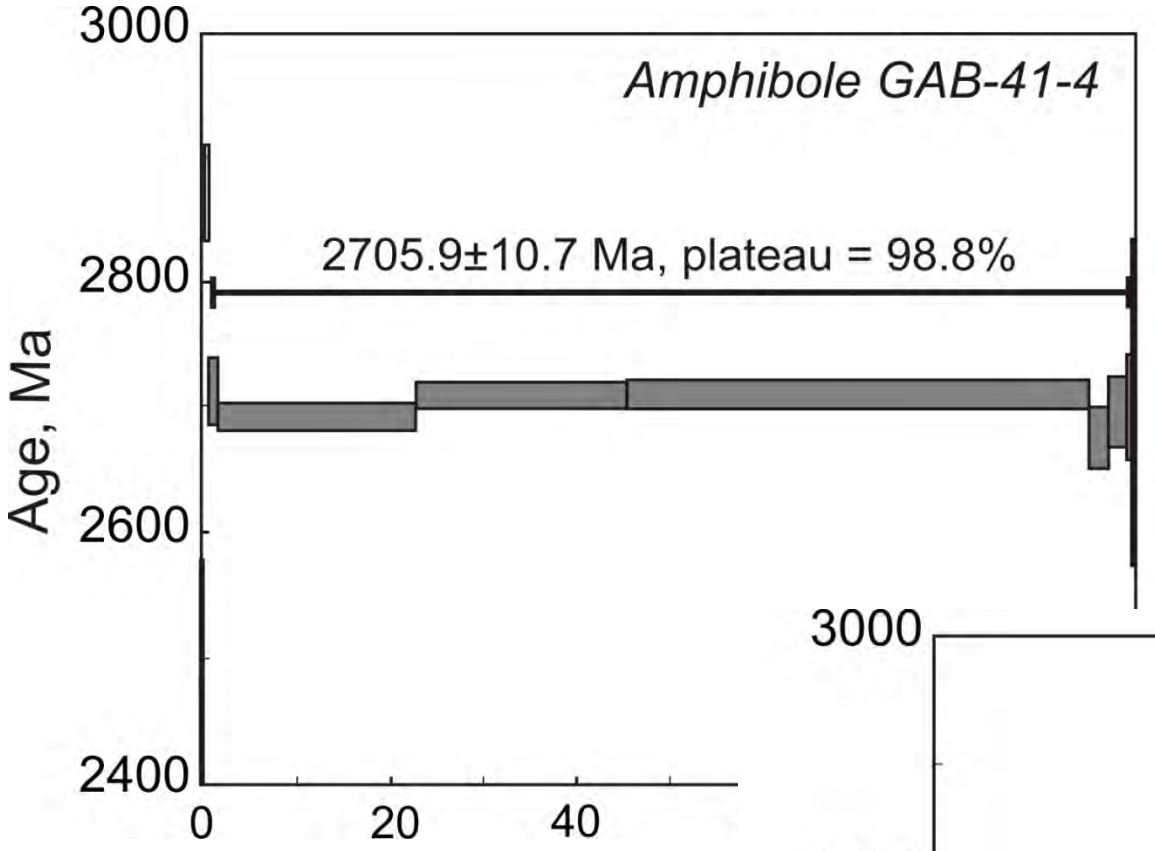
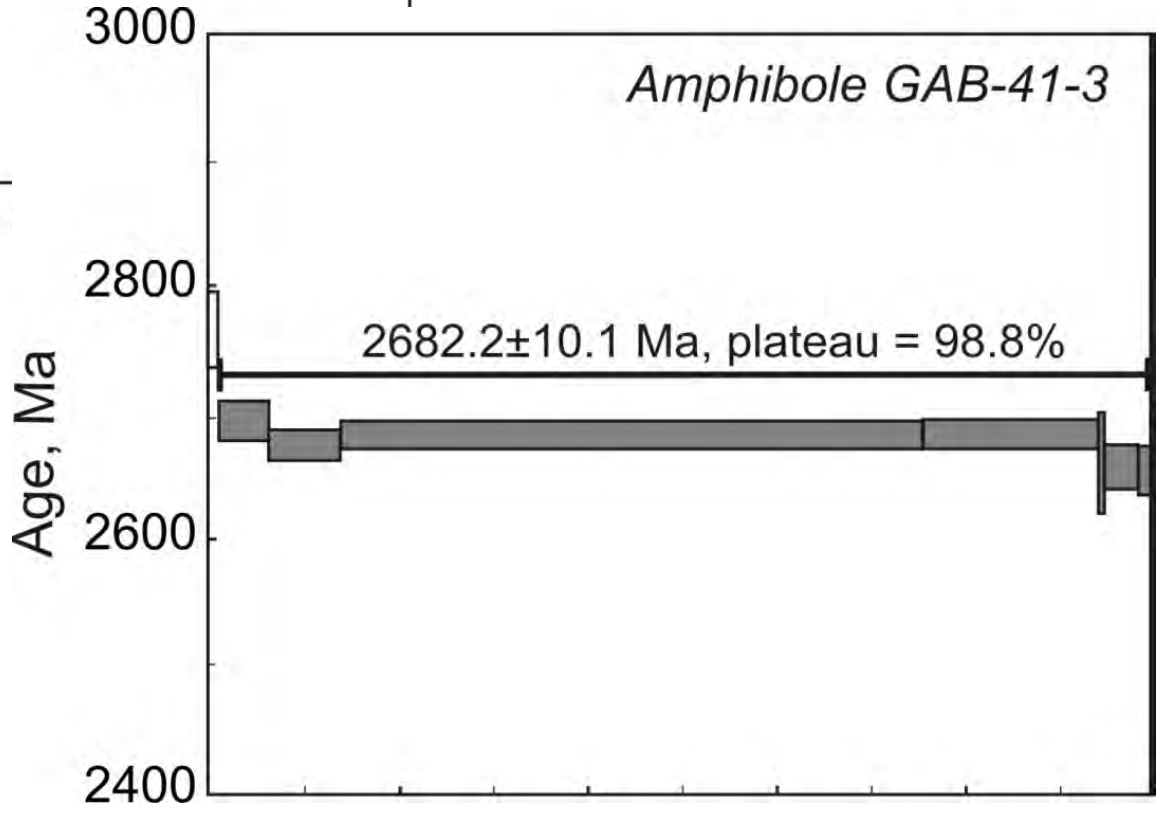
# Mafic granulite from the non-rehydrated zone



# Mafic granulite from the non-rehydrated zone





Amphibole GAB-41-4
2705.9±10.7 Ma, plateau = 98.8%
Age, Ma
3000
2800
2600
2400
0
20
40


Amphibole GAB-41-3
2682.2±10.1 Ma, plateau = 98.8%
Age, Ma
3000
2800
2600
2400

# Amphibolites from the rehydrated zone


DR 168


DV 170

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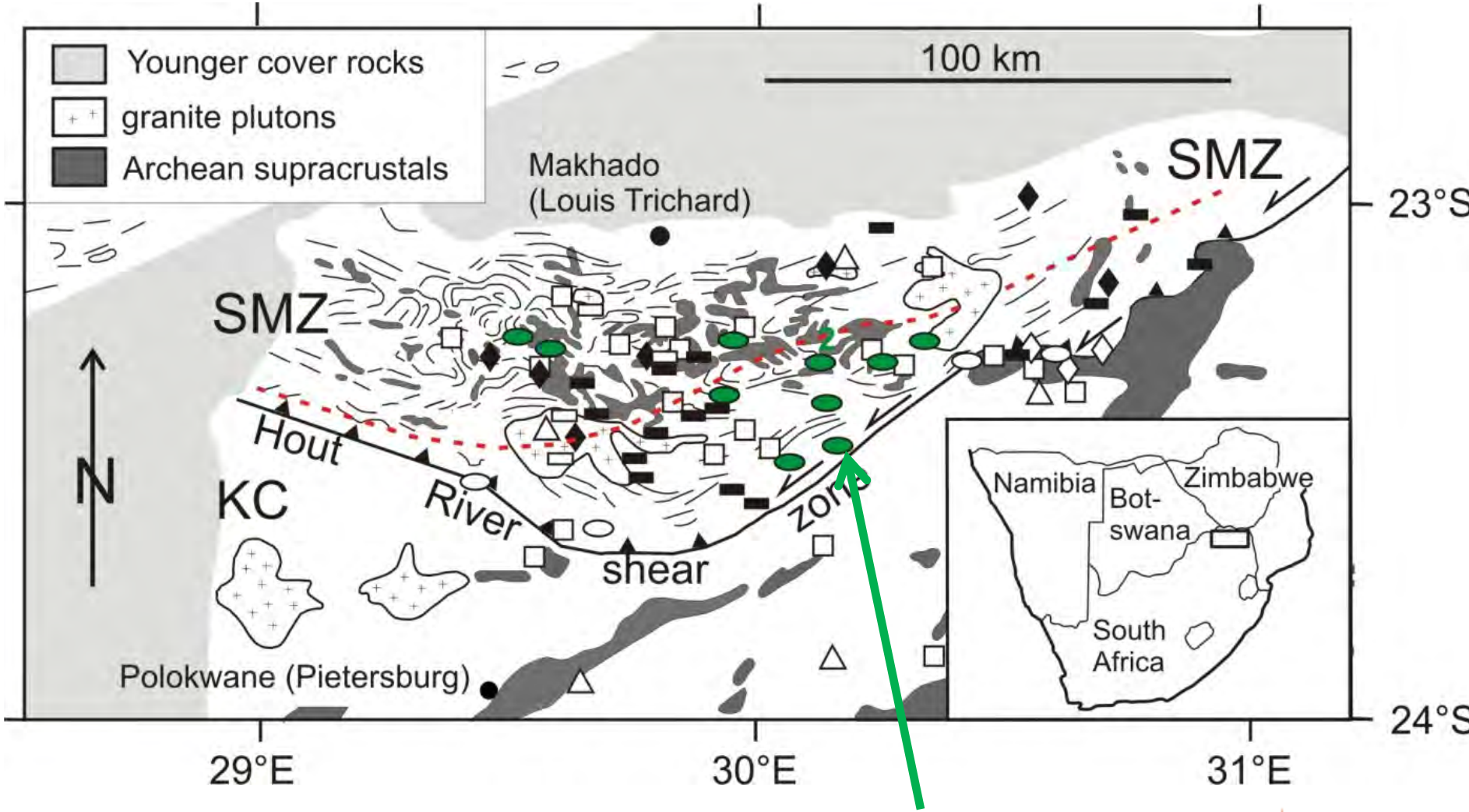


DR 168 in the horizontal "nappe"

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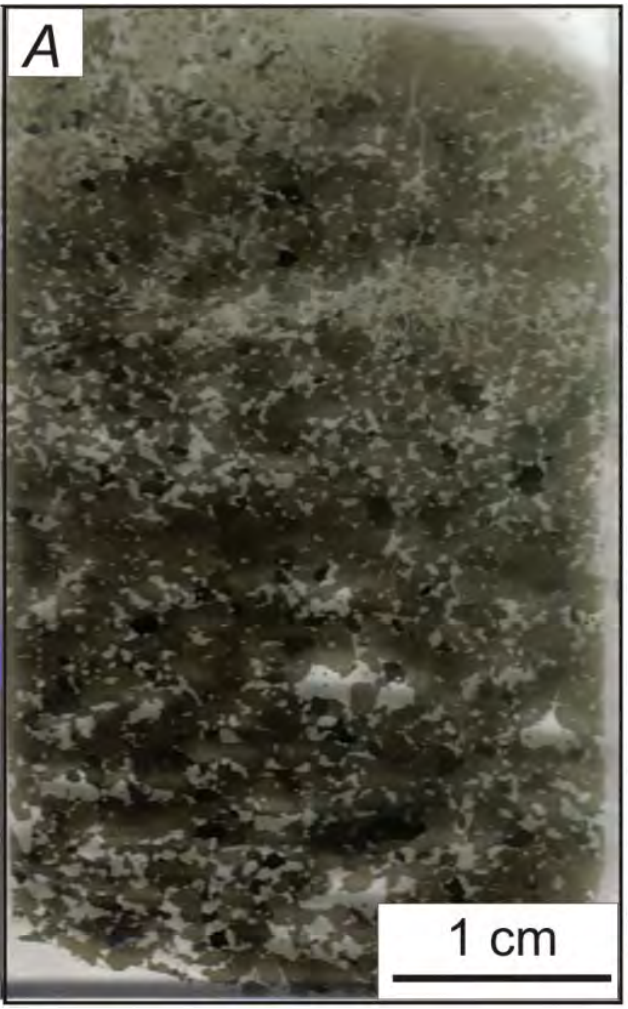
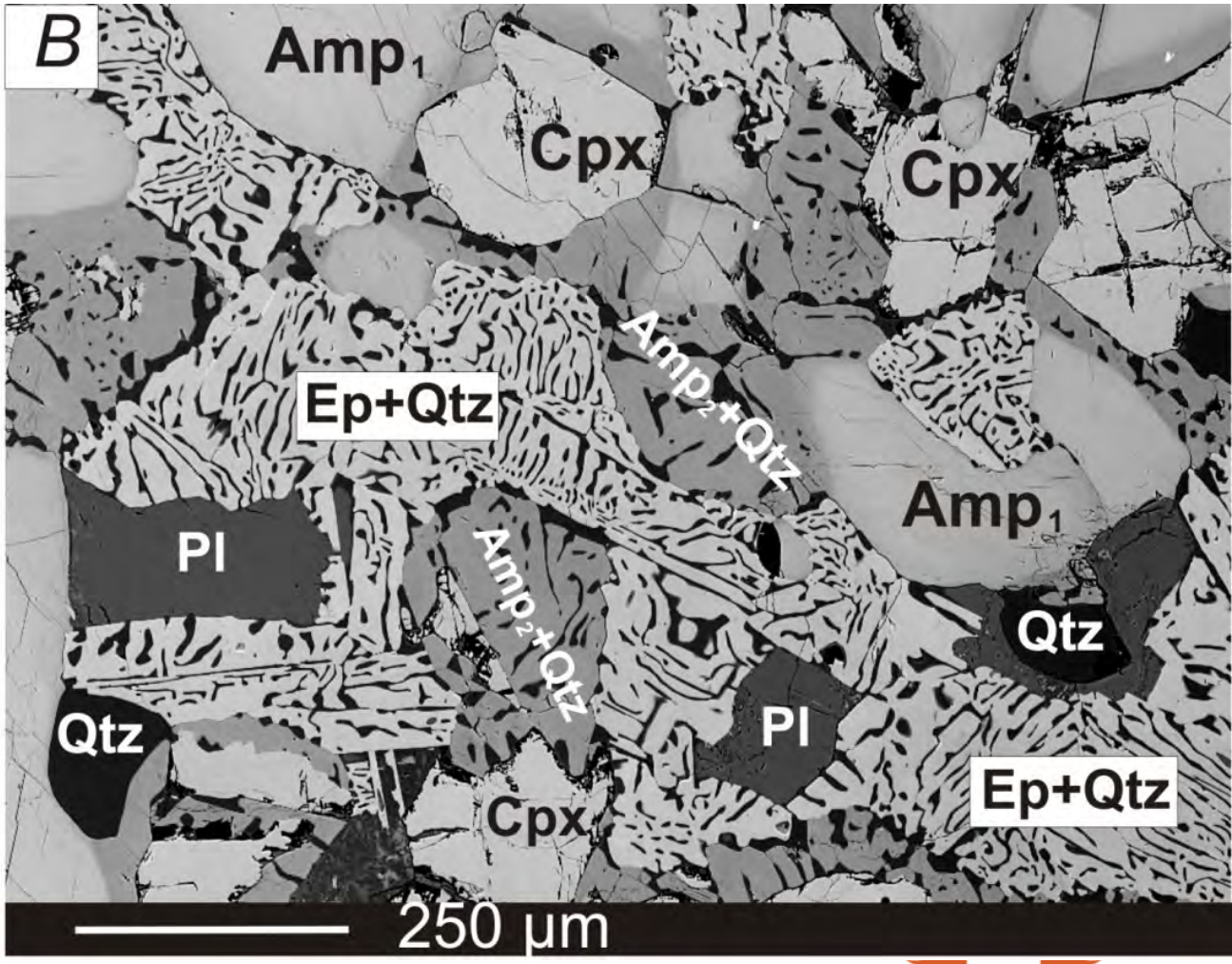
# Amphibolite DR 168

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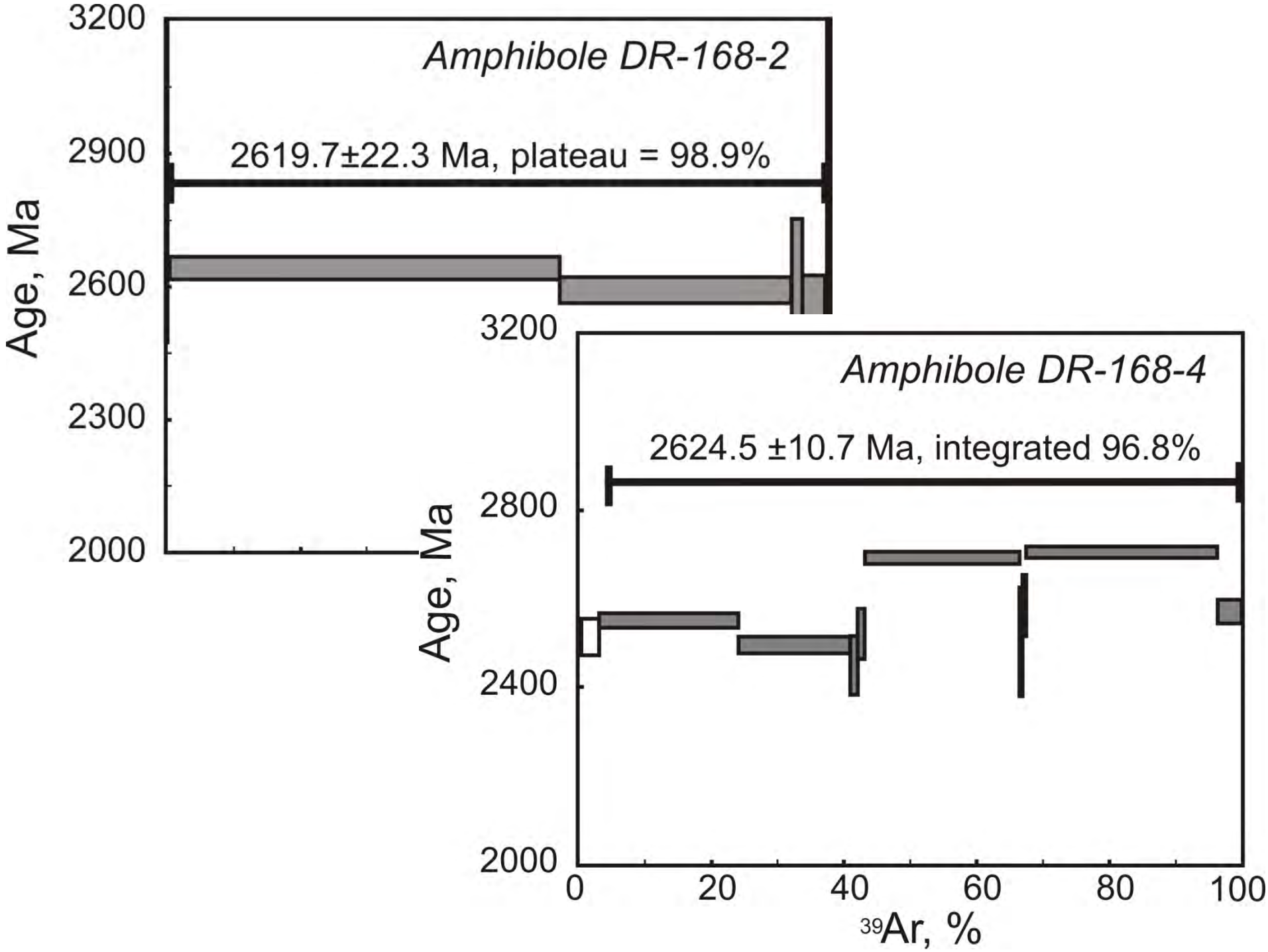
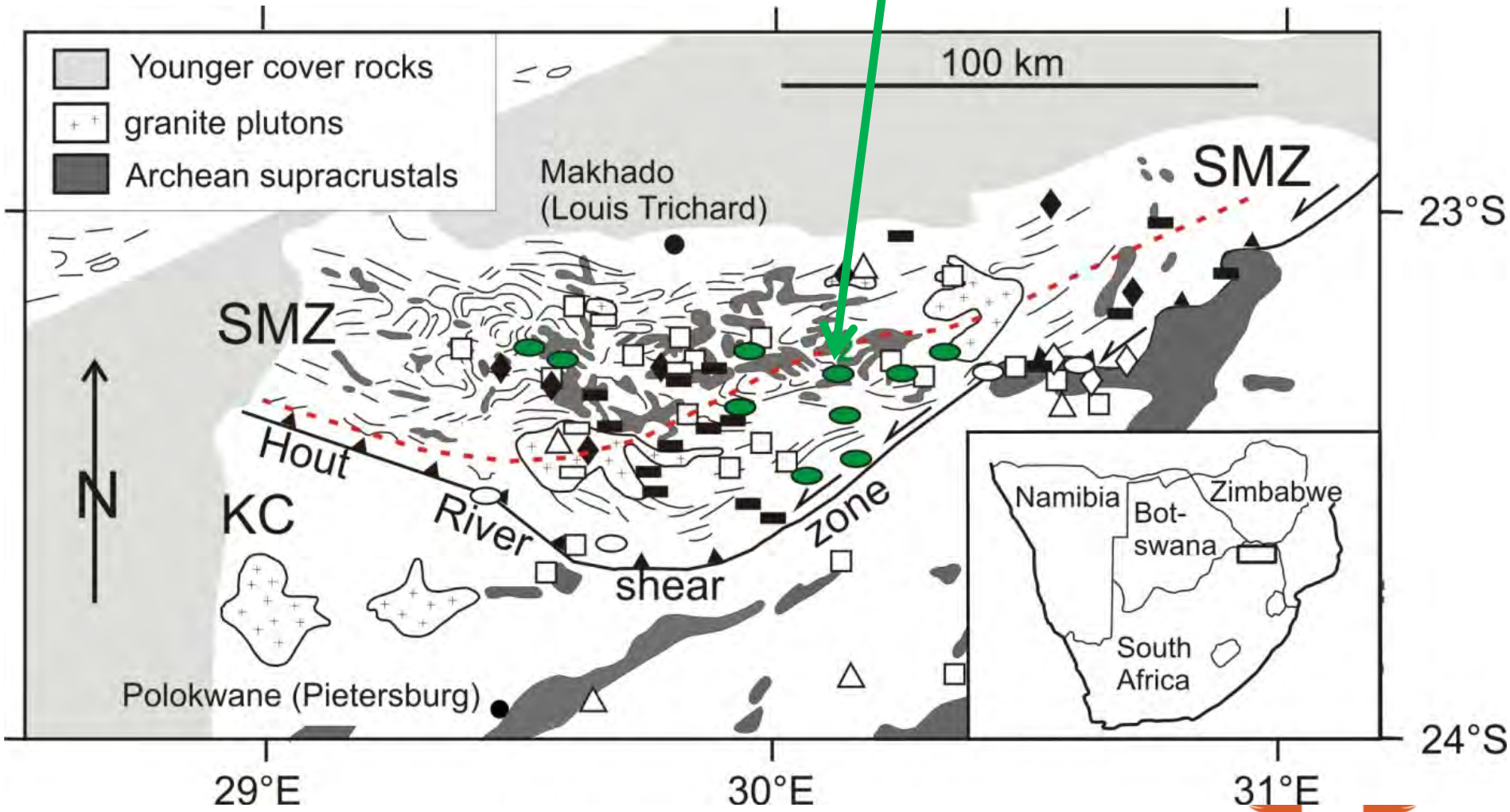

Amphibole DR-168-2
2619.7±22.3 Ma, plateau = 98.9%
Age, Ma
3200
2900
2600
2300
2000
Amphibole DR-168-4
2624.5 ±10.7 Ma, integrated 96.8%
Age, Ma
3200
2800
2400
2000
0
20
40
60
80
100
39Ar, %

DV 170 in region of steep foliations

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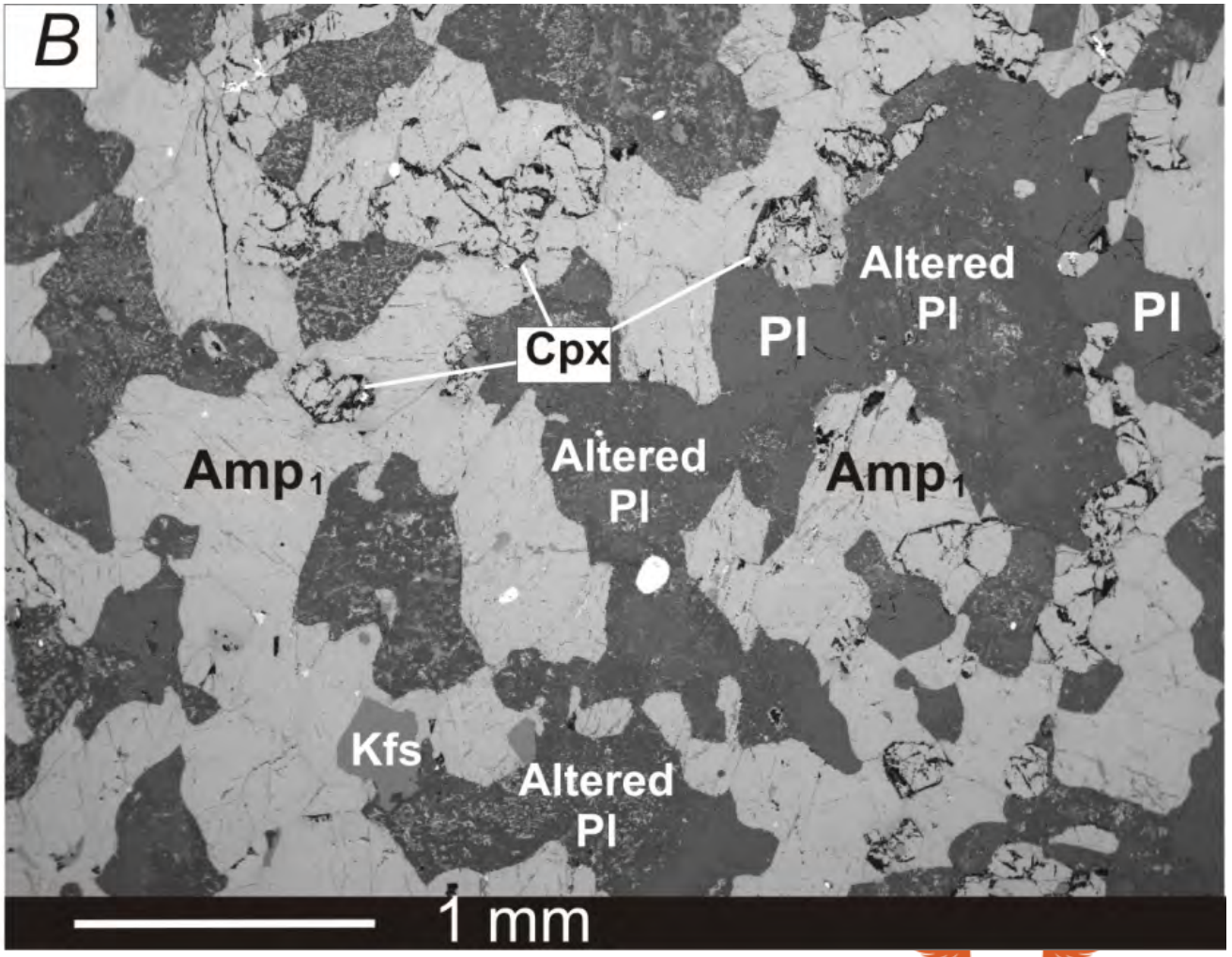


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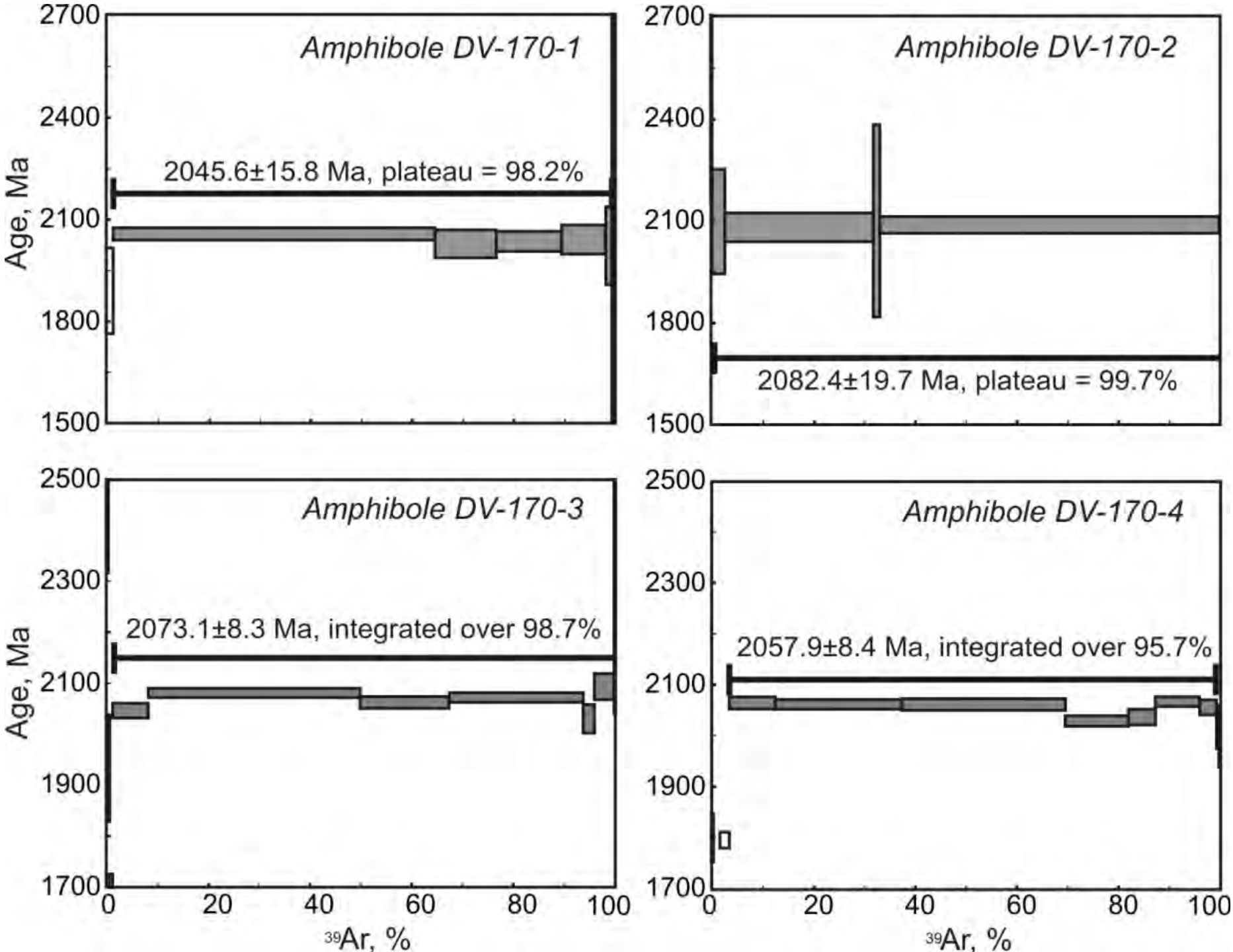
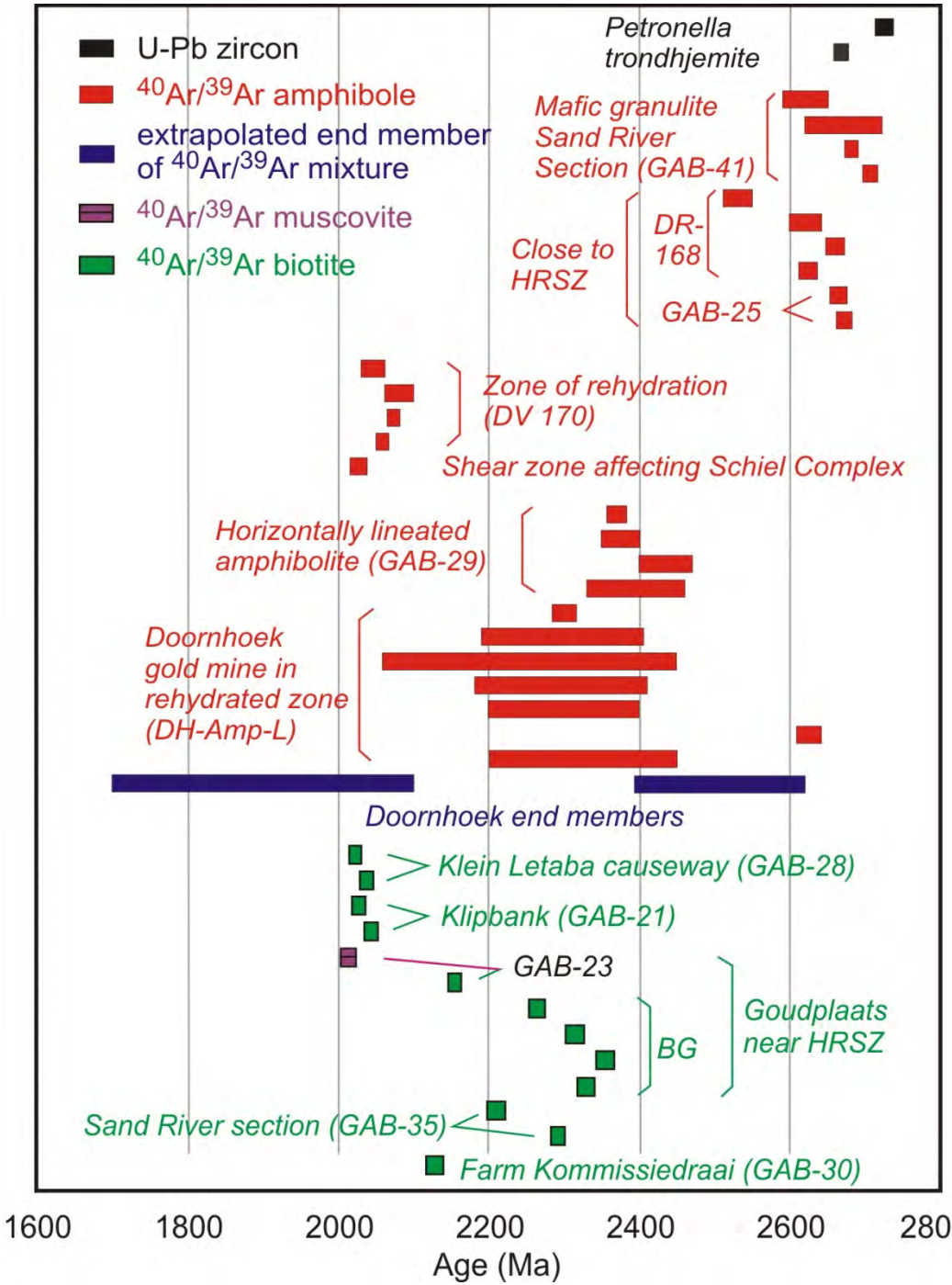

Amphibole DV-170-1
2045.6±15.8 Ma, plateau = 98.2%
Amphibole DV-170-2
2082.4±19.7 Ma, plateau = 99.7%
Amphibole DV-170-3
2073.1±8.3 Ma, integrated over 98.7%
Amphibole DV-170-4
2057.9±8.4 Ma, integrated over 95.7%
Age, Ma
39Ar, %
2700
2400
2100
1800
1500
2500
2300
1900
1700
0
20
40
60
80
100

**Amphiboles in the non-rehydrated zone yield close to peak metamorphic ages around 2700 Ma.**

**Amphiboles within the Zone of Rehydration yield the same age range as those previously recorded in the Hout River Shear Zone (~2.62-2.65 Ga).**

**There are amphibole ages close to 2050 Ma in zones of K metasomatism (mostly associated with shear zones) within the Southern Marginal Zone.**



*Consider crust formation stories as told by Nd and Hf isotopes.*

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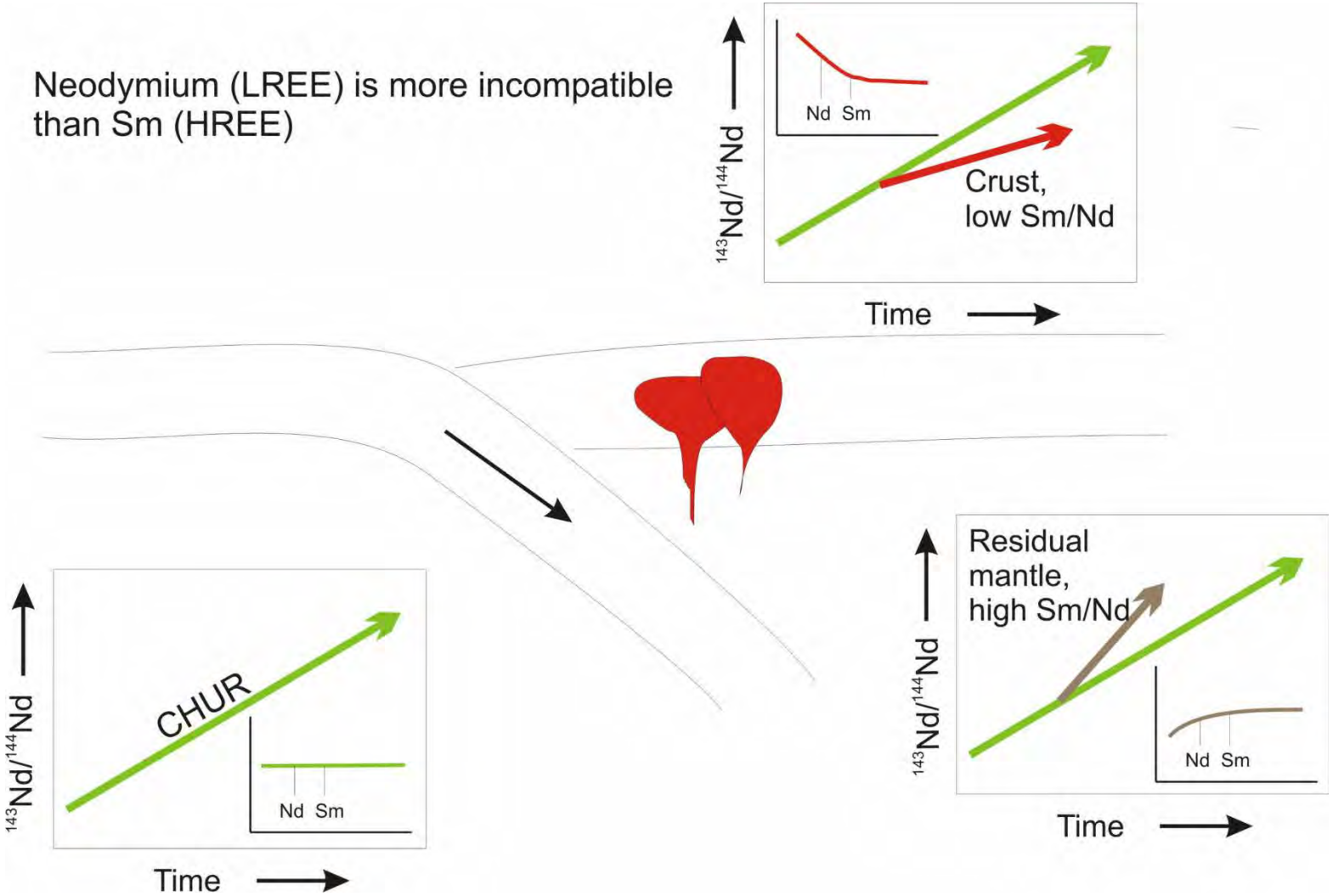
Neodymium (LREE) is more incompatible than Sm (HREE)

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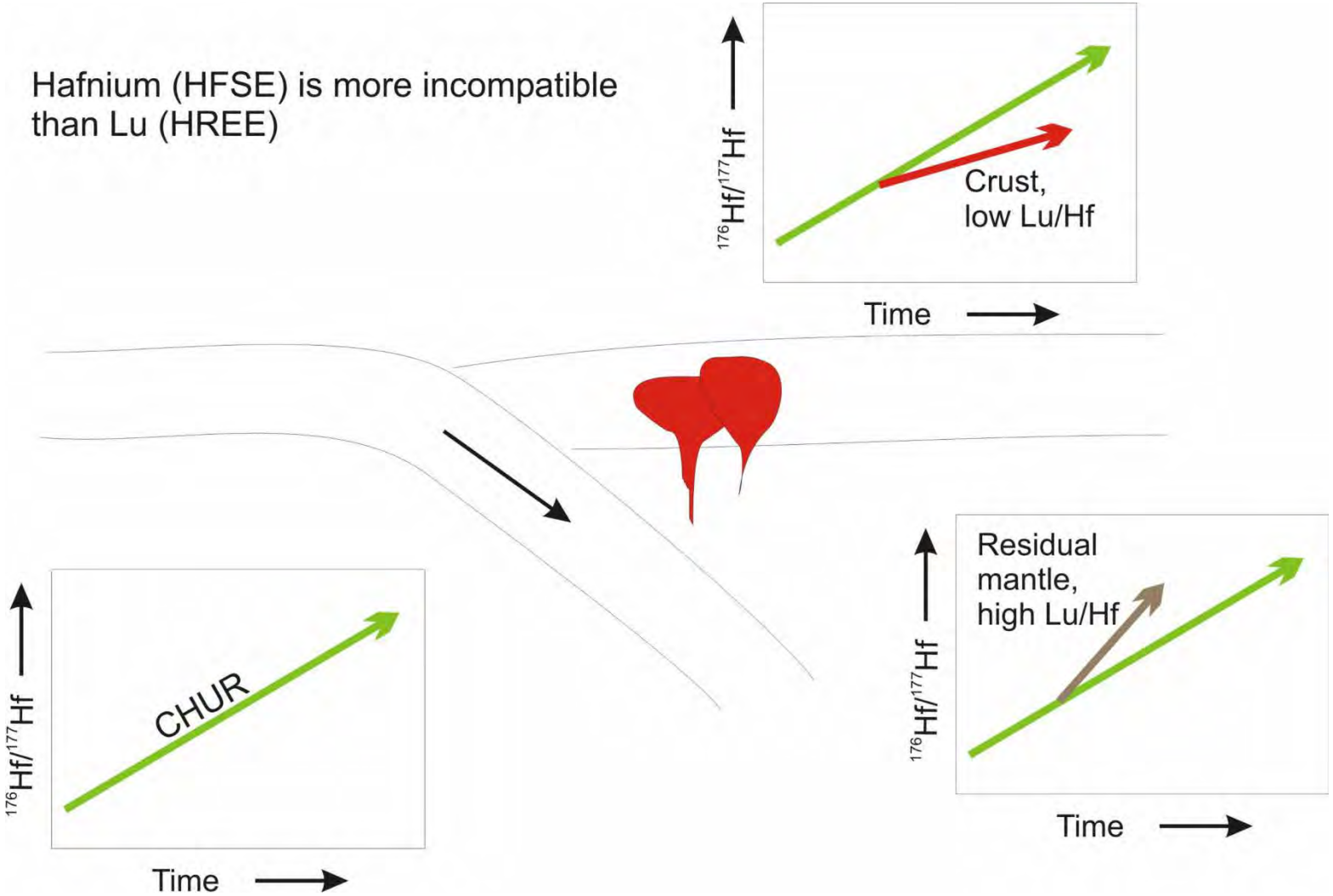
Hafnium (HFSE) is more incompatible than Lu (HREE)

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ε Notation is used in the diagrams in this talk, with the time axis going from right to left (age from left to right).

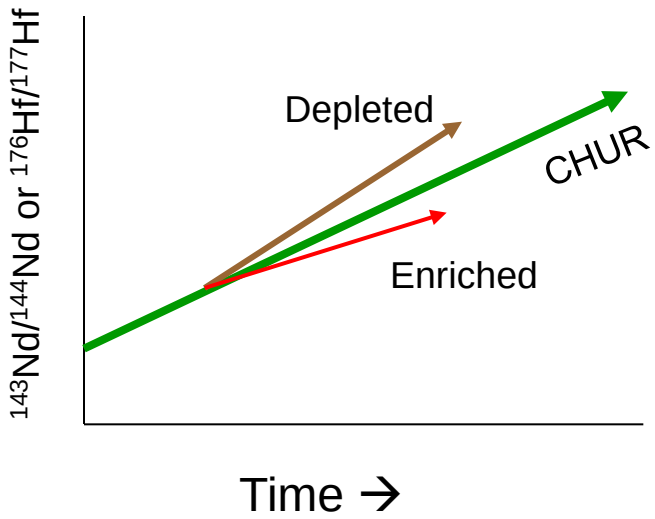
# The ε notation:

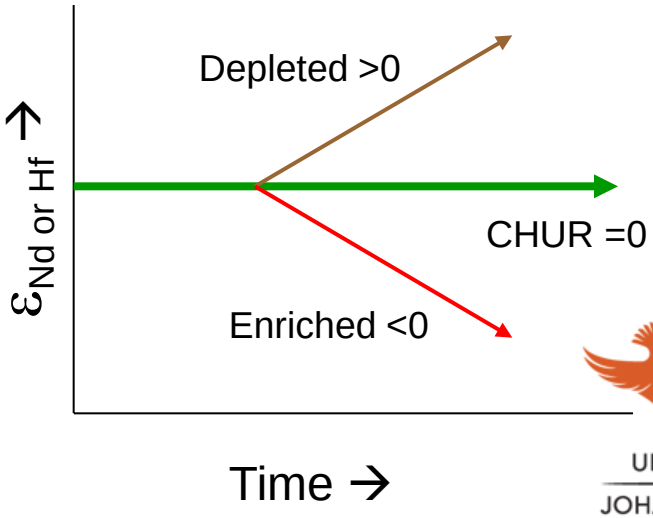
Normalizing Nd or Hf isotope ratios to those of the Uniform Chondritic Reservoir (CHUR)

Purpose: to reveal the fine structure of deviations (enrichment or depletion history).

$$\varepsilon_{Nd} = ({}^{143}Nd/{}^{144}Nd_{init}/{}^{143}Nd/{}^{144}Nd_{CHUR} - 1) \times 10^4$$

$$\varepsilon_{Hf} = ({}^{176}Hf/{}^{177}Hf_{init}/{}^{176}Hf/{}^{177}Hf_{CHUR} - 1) \times 10^4$$

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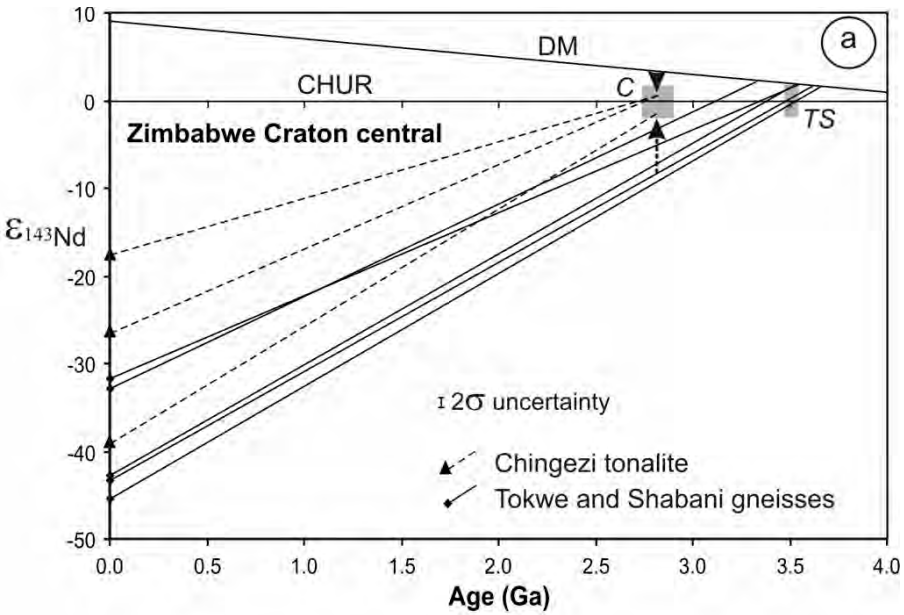


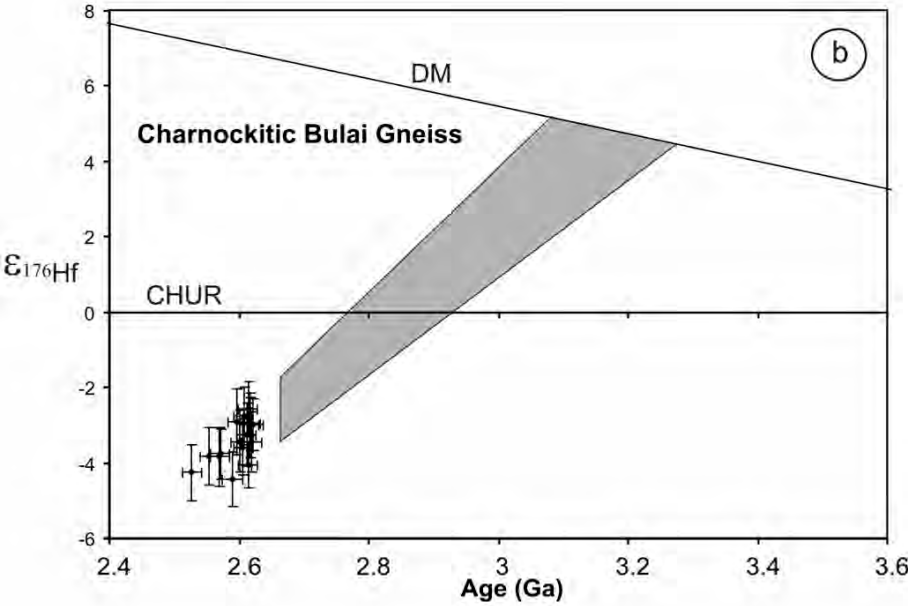


Examples of the diagrams and what they tell us.

Top: Nd diagram. ε values measured in the rocks today are plotted on the vertical axis on the left.

Lines going up to the right from these points show the evolution of ε over geological time.

The evolution lines intersect the depleted mantle (DM) evolution line at the $T_{DM}$ model age - about 3.5 Ga in the case of the Tokwe and Shabani gneisses.

Hf (bottom) is highly concentrated in zircons and can be measured *in situ* in dated zircons. The ε evolution prior to zircon crystallization (grey band) intersects the DM line at $T_{DM}$.

The 2.6 Ga Bulai Charnockite was derived by remelting of crust that was originally formed from the mantle at >3 Ga.

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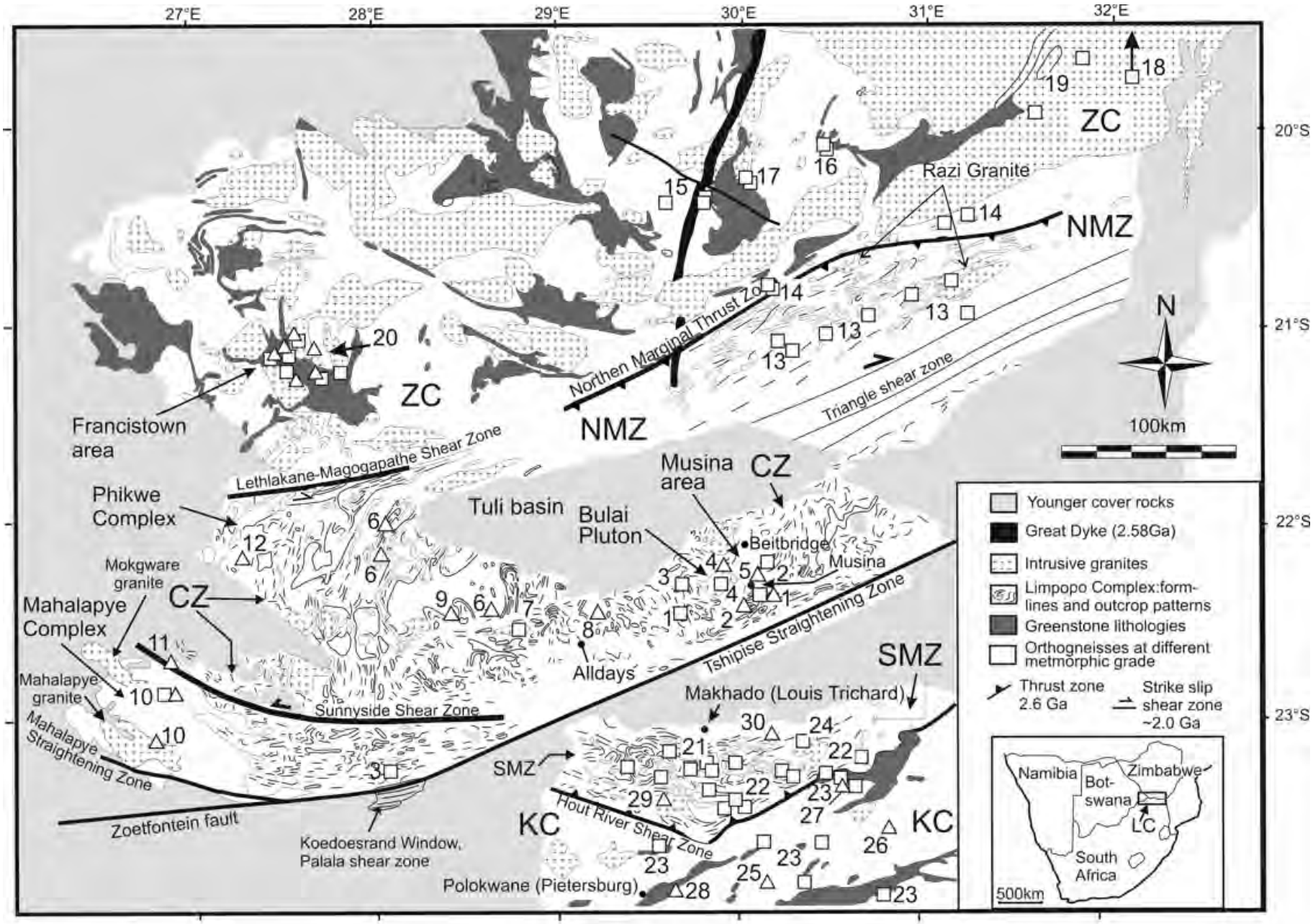
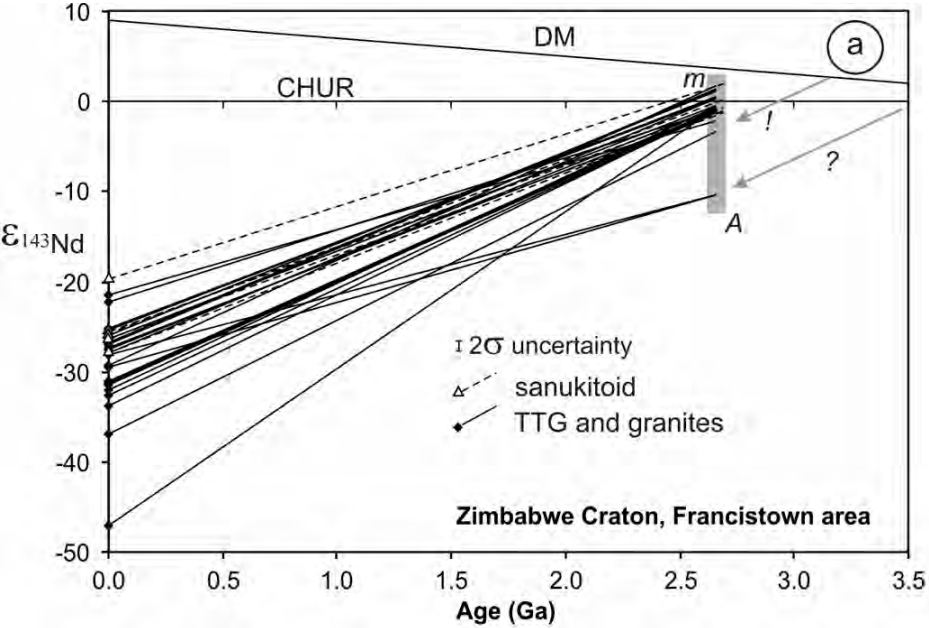
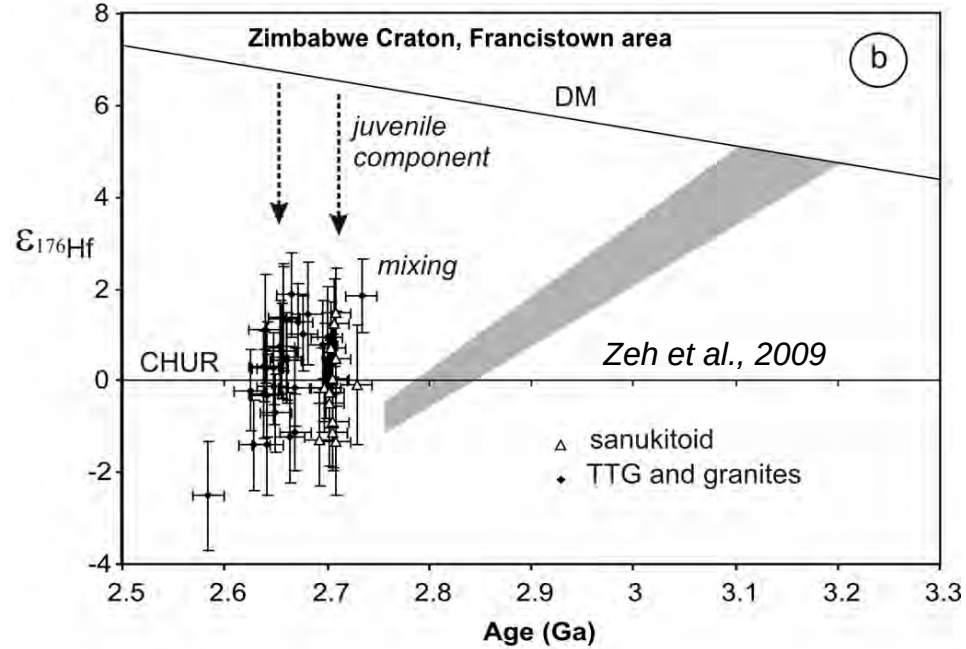



*Regional studies can reveal patterns of crust ages, relevant to tectonic models.*

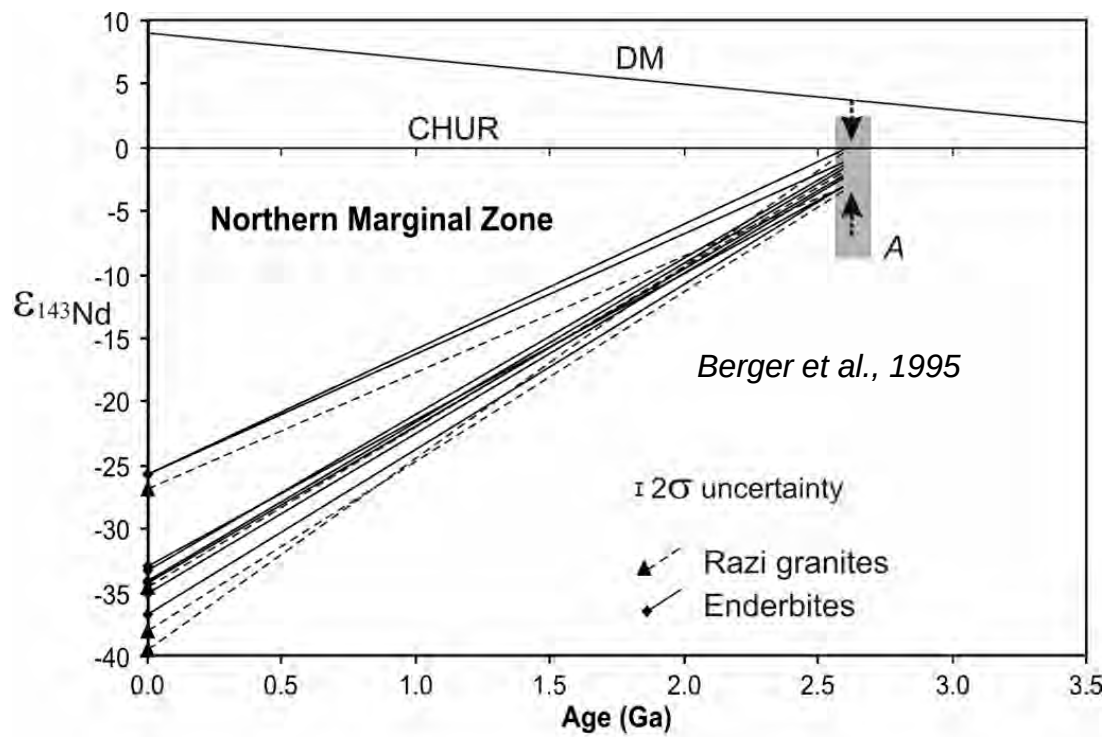
*Squares: Sm-Nd localities, triangles: Lu-Hf zircon localities*

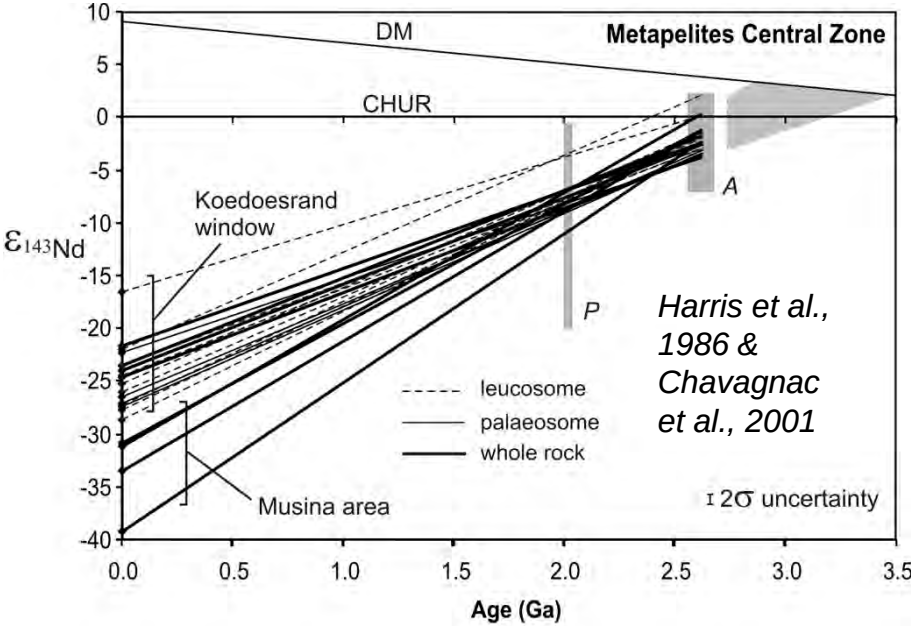



Hf-isotopes of ***Francistown area*** agree with Nd-isotopes, suggesting a magmatic arc

Comparison Nd isotopes of ***Northern Marginal Zone*** with Francistown arc indicates that NMZ is the eastward continuation of the same arc, or accretionary margin – seen at deeper crustal level. Grey rectangles *A* in both localities: the zircon dates.

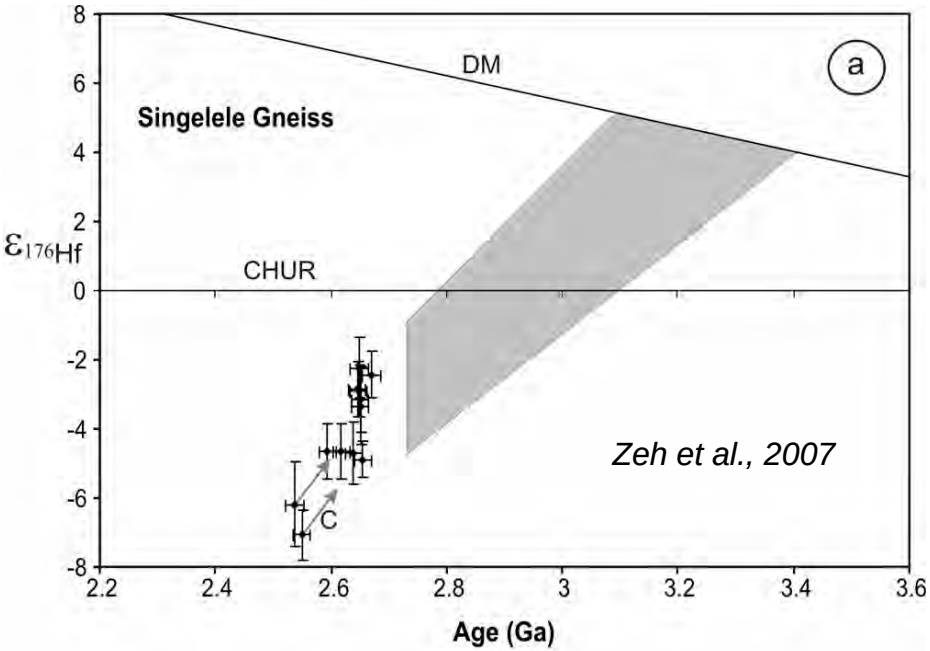




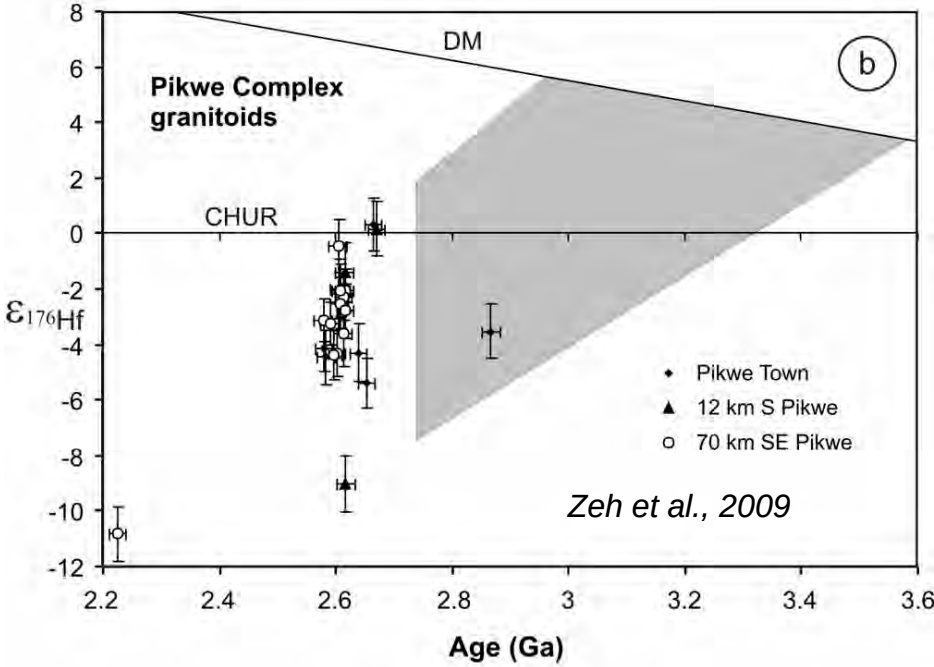

*Harris et al., 1986 & Chavagnac et al., 2001*

Analyzed metapelites from Central Zone reveal derivation from crust older than 3.0 Ga (such as Sand River gneisses)

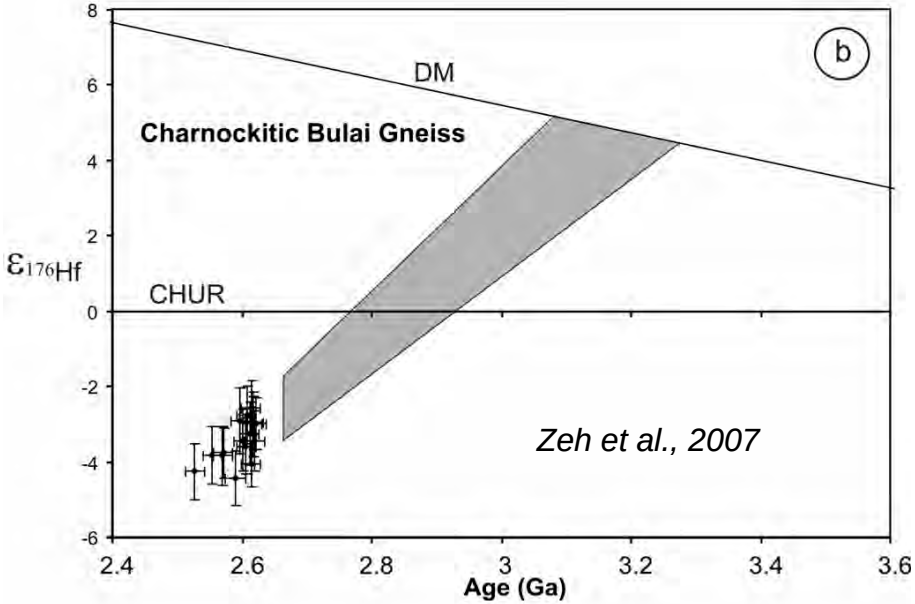
Combined comparison of Nd and Hf isotopes of metapelites, Singelele and Pikwe complex gneisses show that the latter two may be derived purely by anatexis of the metapelites.




*Zeh et al., 2007*

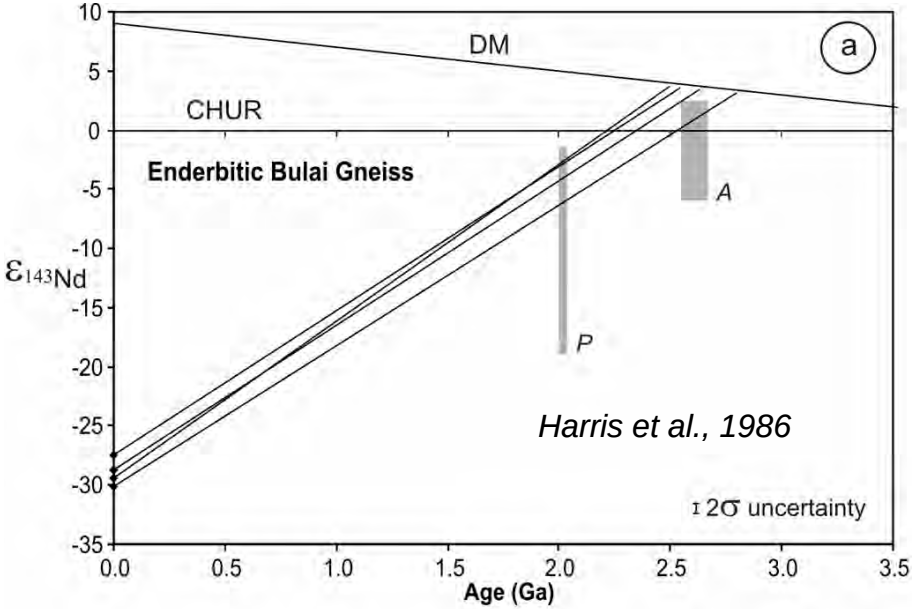


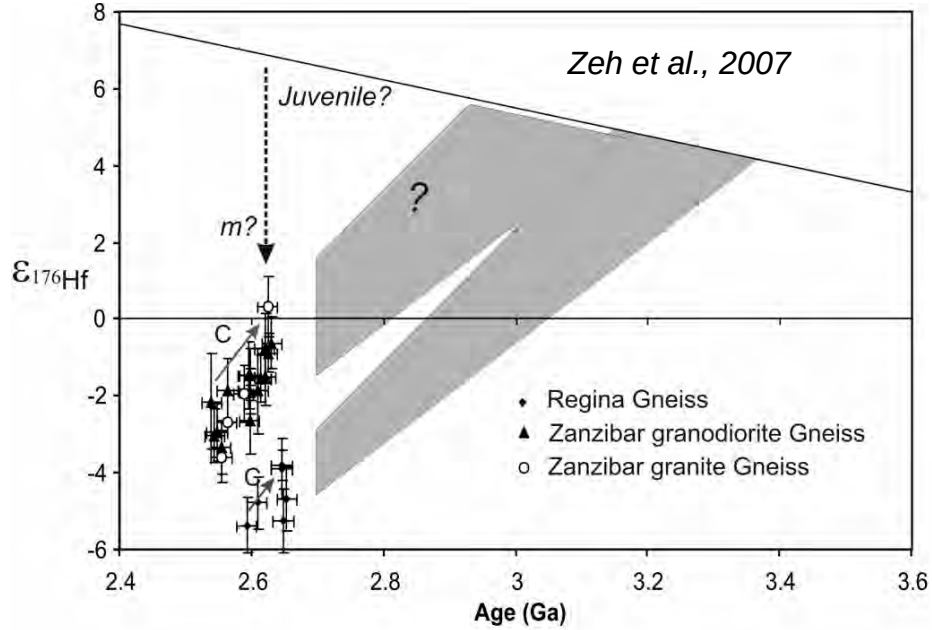

*Zeh et al., 2009*

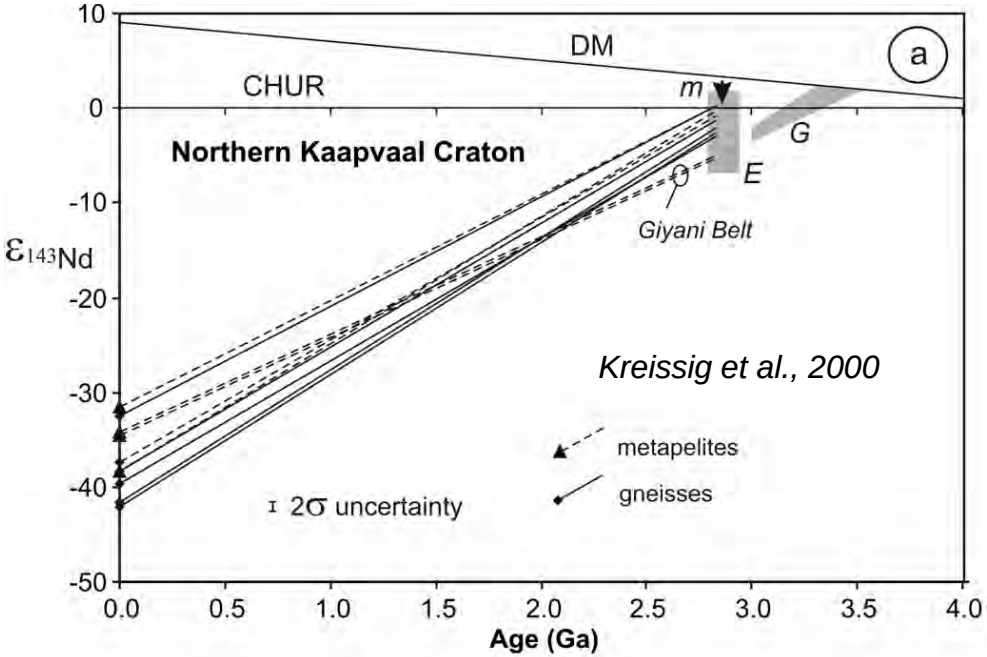


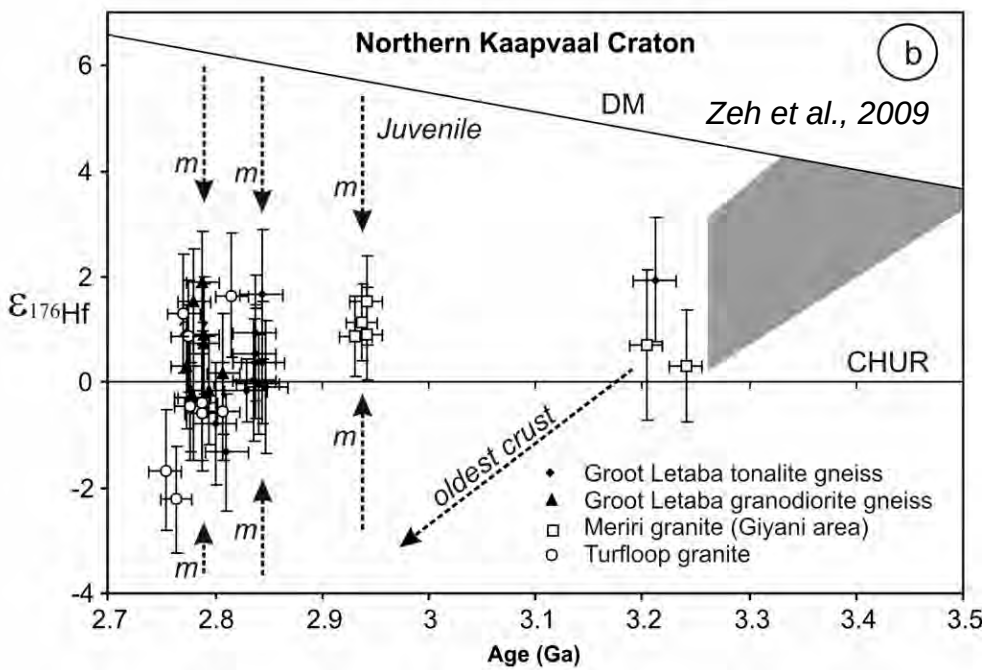

Charnockitic Bulai Gneiss and regina Gneiss (at Venetia) appear purely crustally derived.

Enderbitic Bulai Gneiss and Zanzibar Gneiss look like they have a juvenile mantle derived component „pulling up“ the Nd and Hf isotope ratios in the graph, relative to old crust alone.



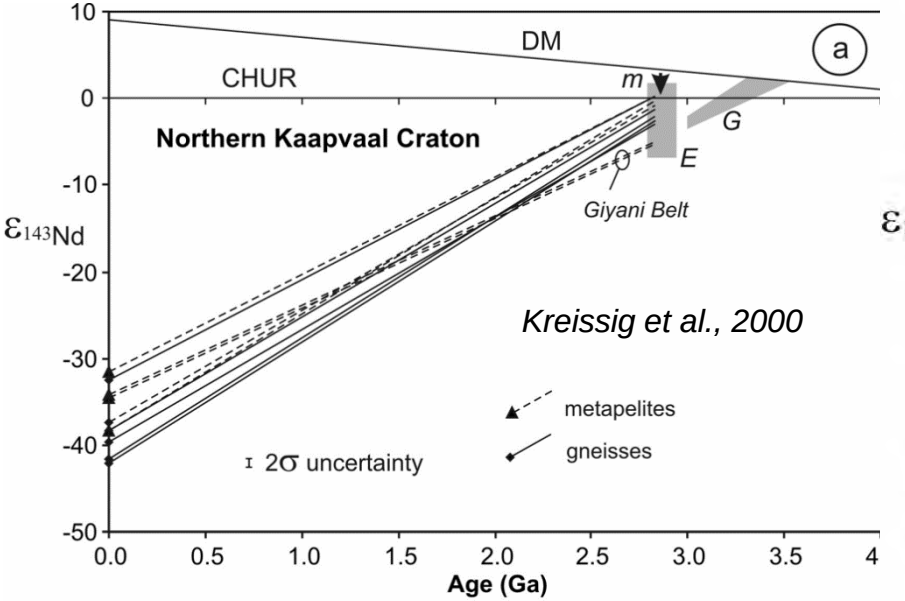



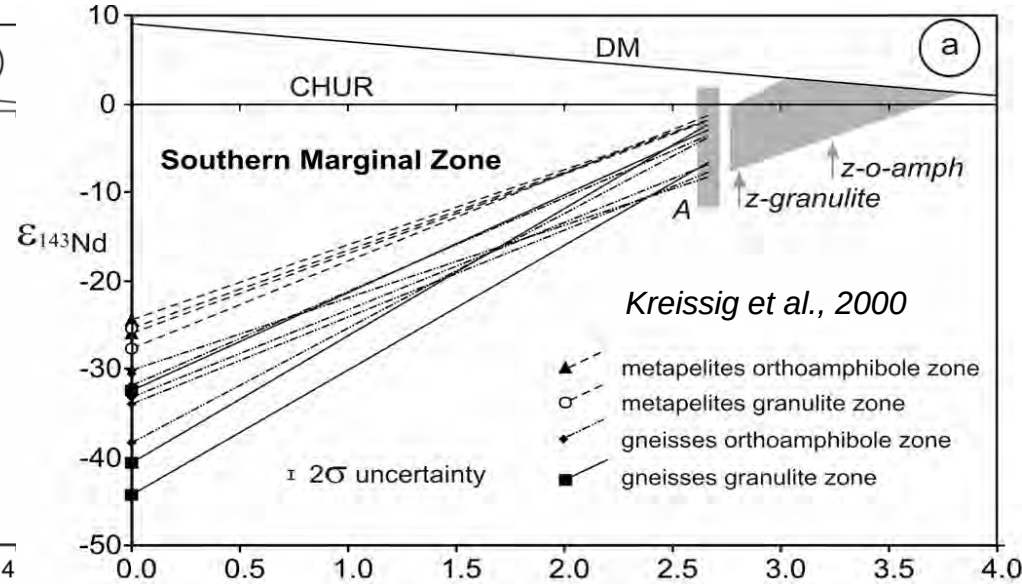


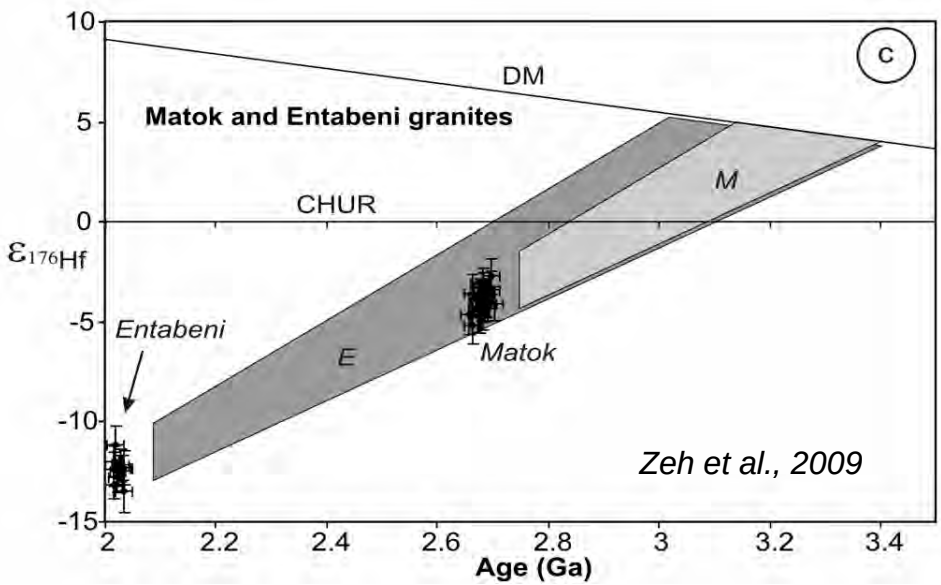




The Northern Kaapvaal Craton probably contains a mid- to early Archean nucleus, located near the Giyani Greenstone Belt ($T_{DM}$ ages up to around 3.5 Ga, even if no such old zircon ages appear)

It also has units that look like they were formed in accretionary margins at 2.93-2.78 Ga (see up and down stippled black arrows *m*)



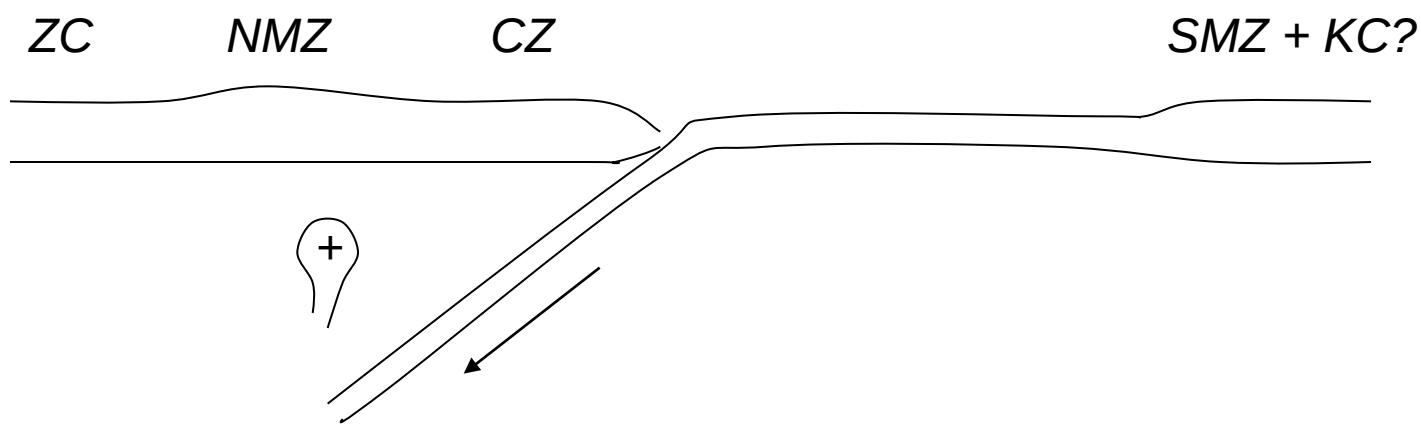

The Southern Marginal Zone looks very similar to the northern Kaapvaal Craton in its Nd-isotopes. It was NOT an accretionary margin at the time of the high grade metamorphism.

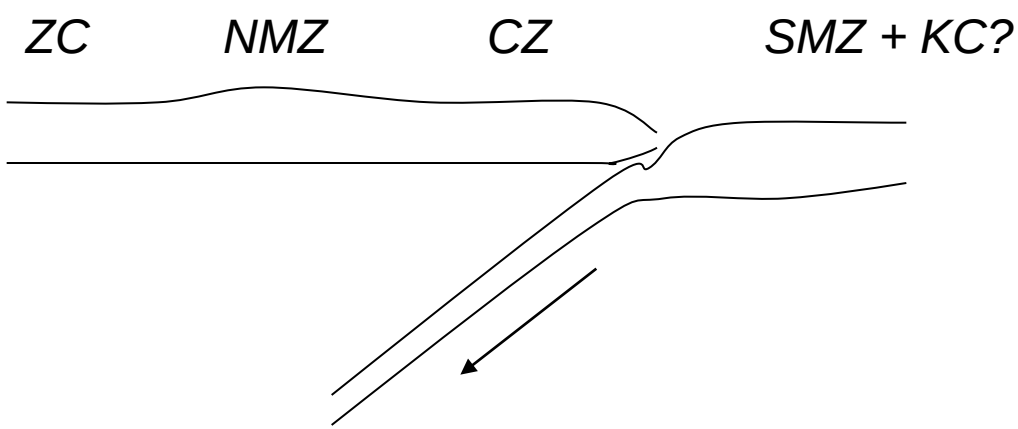
Also, the syntectonic Matok pluton was entirely derived by crustal anatexis.

*If the Northern Marginal Zone is an accretionary margin, and the Southern Marginal Zone is not… Subduction should have been to present North*

Present NNW

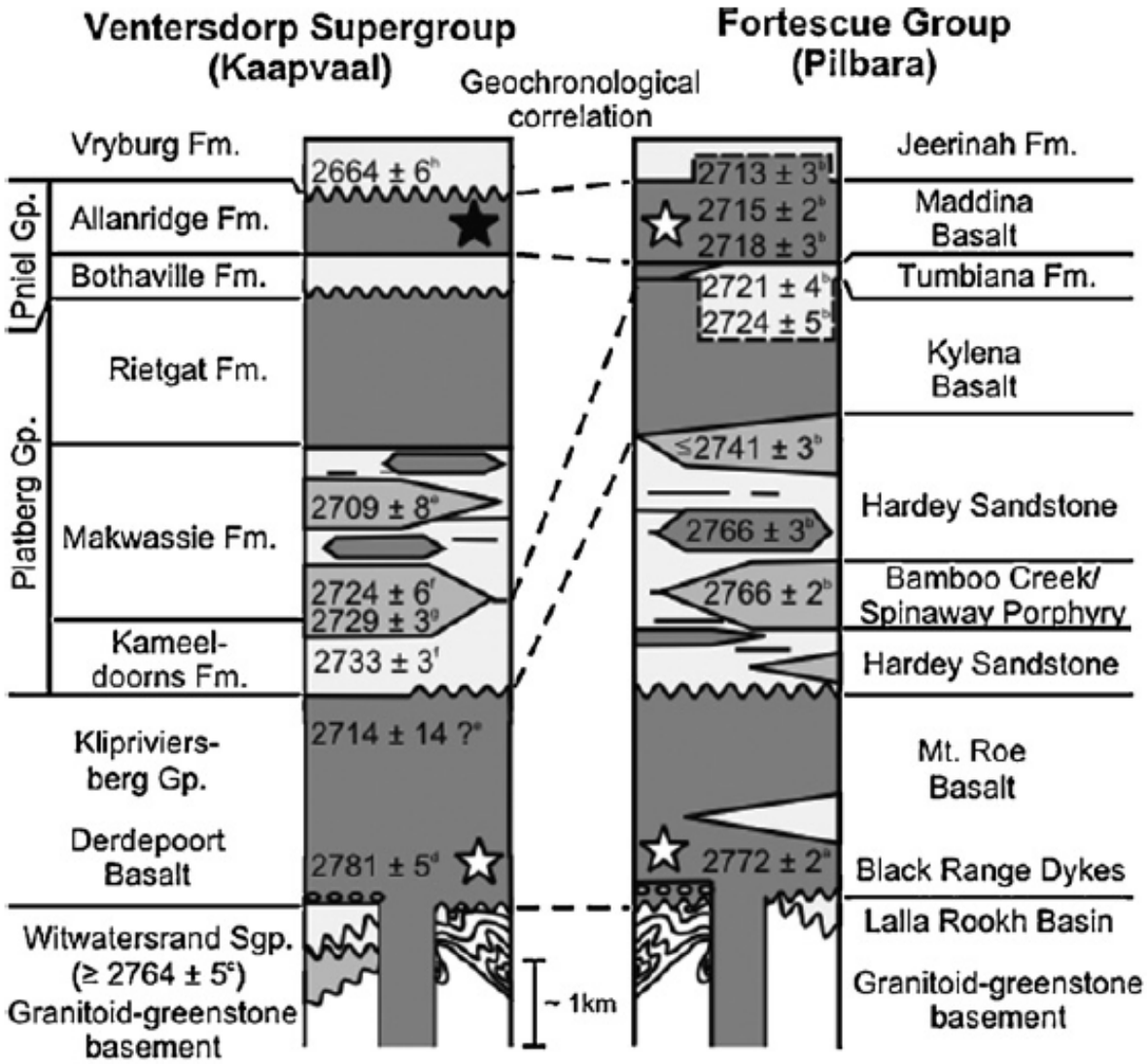
Present SSE



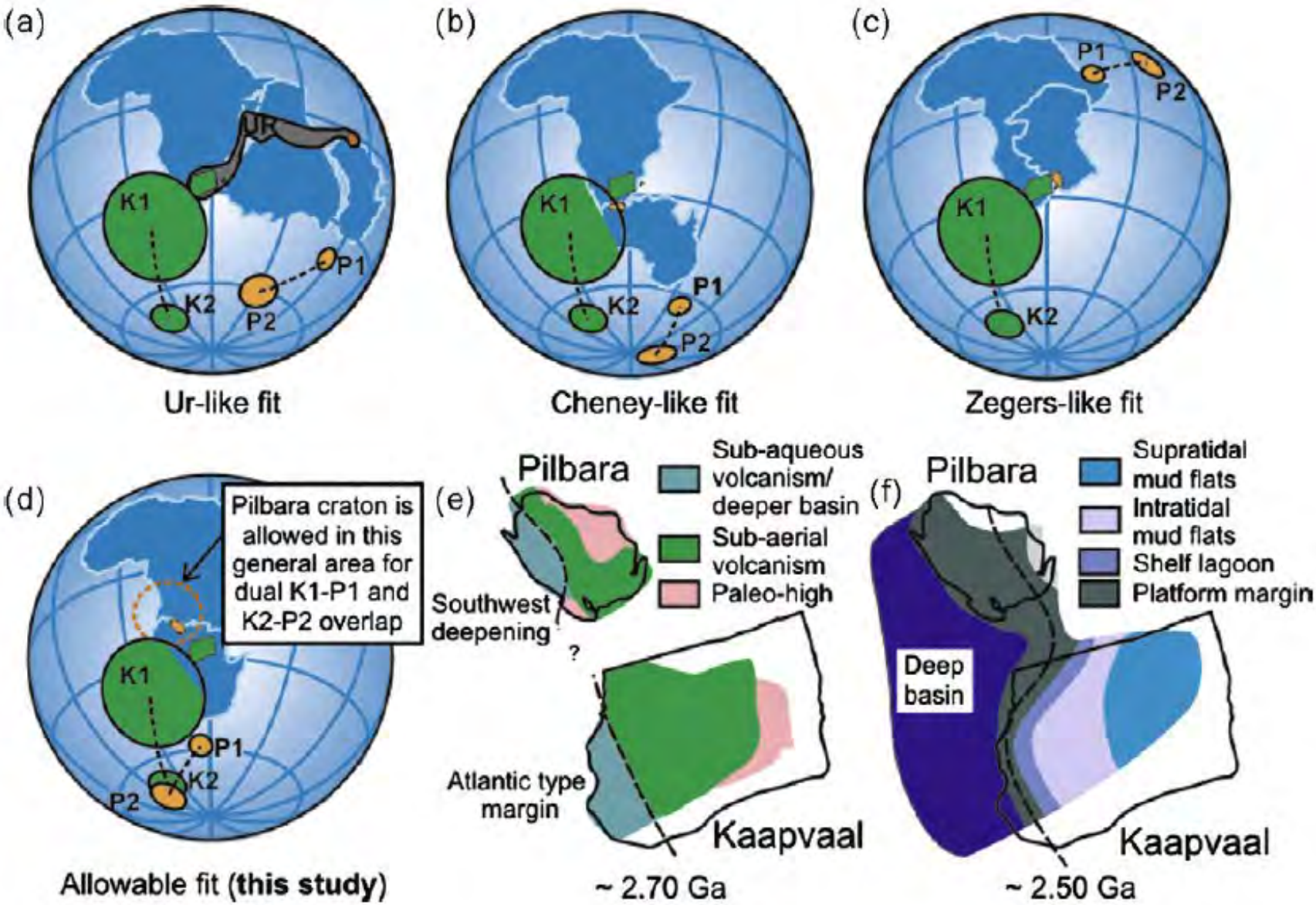



This would lead to a mismatch in time: Ages in the NMZ should be older than peak metamorphism in the SMZ. Instead, they are younger.

*Further, paleomagnetic and paleogeographical reconstructions of the Kaapvaal and Pilbara Cratons point to another problem.*




Paleomagnetic poles for the Ventersdorp Sgp. (this study ★ and Wingate, 1998☆)
and the Fortescue Gp. (Strik et al. 2003☆)


(a)
UR
K1
K2
P1
P2
Ur-like fit
(b)
K1
K2
P1
P2
Cheney-like fit
(c)
P1
P2
K1
K2
Zegers-like fit
(d)
Pilbara craton is allowed in this general area for dual K1-P1 and K2-P2 overlap
K1
P1
K2
P2
Allowable fit (this study)
(e)
Pilbara
Sub-aqueous volcanism/ deeper basin
Sub-aerial volcanism
Paleo-high
Southwest deepening
?
Atlantic type margin
Kaapvaal
~ 2.70 Ga
(f)
Pilbara
Supratidal mud flats
Intratidal mud flats
Shelf lagoon
Platform margin
Deep basin
Kaapvaal
~ 2.50 Ga

Where to from here?

- The model of a Neoarchean continent collision between the Zimbabwe and Kaapvaal Cratons is incompatible with new data.

- A c. 2 Ga transpressive orogeny between the Zimbabwe and Kaapvaal Cratons remains a possibility.

- This can be superimposed on a Neoarchean accretionary margin to the north (the CZ and NMZ), and a passive craton margin to the south, but they cannot have had a prior connection in any way.

- What caused the high grade metamorphism in the Southern Marginal Zone remains a mystery.

*THANK YOU FOR LISTENING……*