Regional zoning of rare-element pegmatites: why understanding the distribution of LCT and NYF matters

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EGRI

CIMERA – DST-NRF
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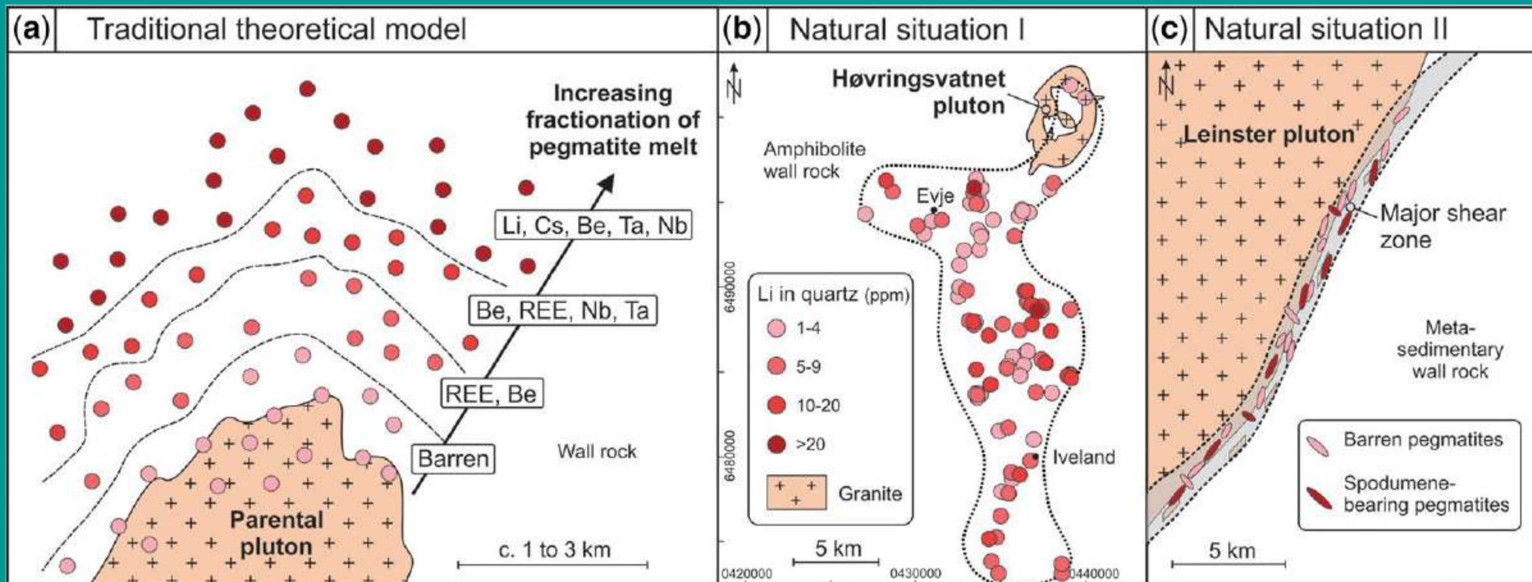
Integrated Mineral and Energy
Resource Analysis

Exploration / Economic Geology

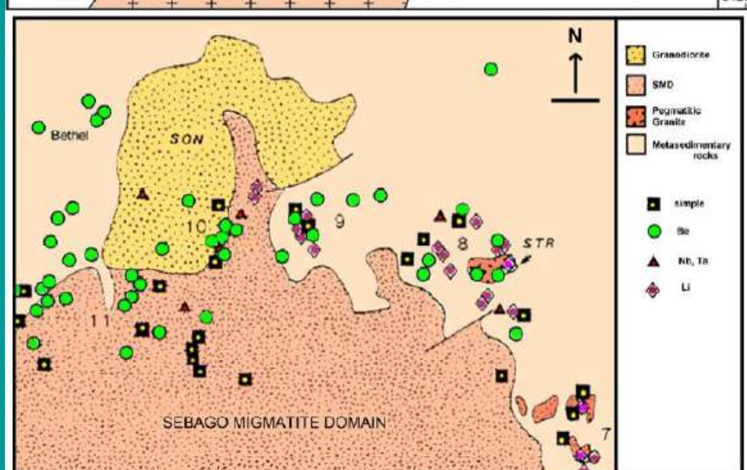
- The work presented today only applies, at the moment, to the Proterozoic and Phanerozoic. The Archaean may be very different.
- Granites and pegmatites do not just image their source, they can also image the conditions of partial melting under which the granitic magma formed.
- This is the same for both pegmatites produced by the fractionation of a large granite and for those produced by near in-situ anatexis

There are definitely examples where either the absence of granitic plutons or a lack of zonation with respect to a parental granite has been demonstrated.

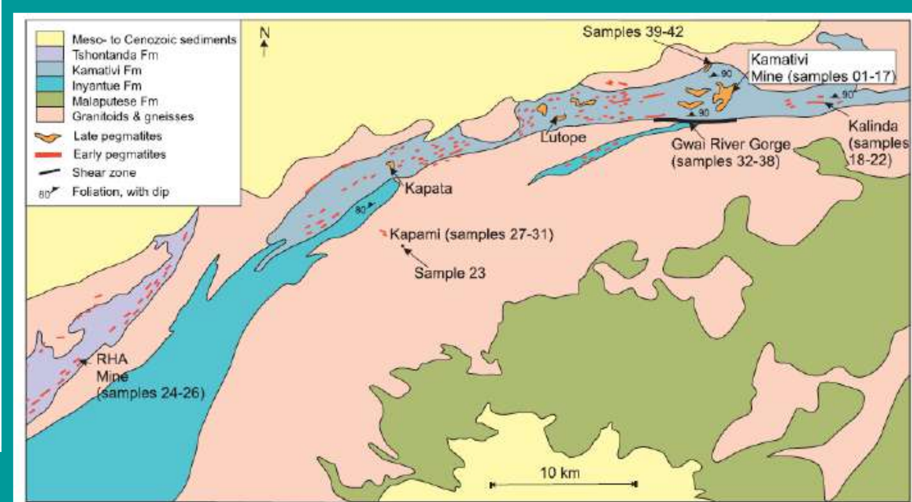


Muller et al (2023) GSL SP 526

Norway & Ireland



Simmons (2007) MAC SCN 37
New England

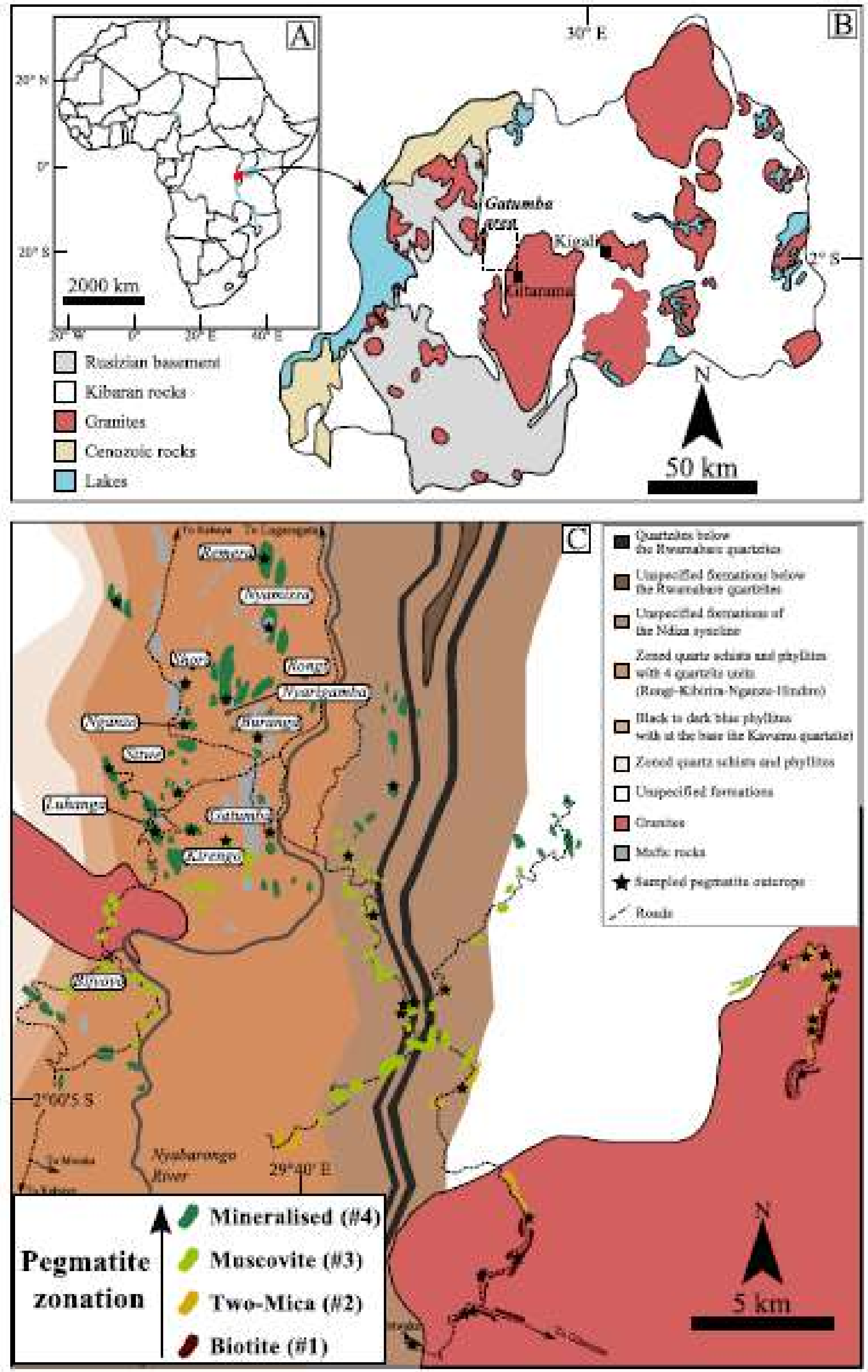


Shaw et al (2022) Can Min

Kamativi

And places where zonation with respect to parental granites is generally accepted.

The Gatumba Pegmatite Field in Rwanda (Hulsbosch et al., 2014)



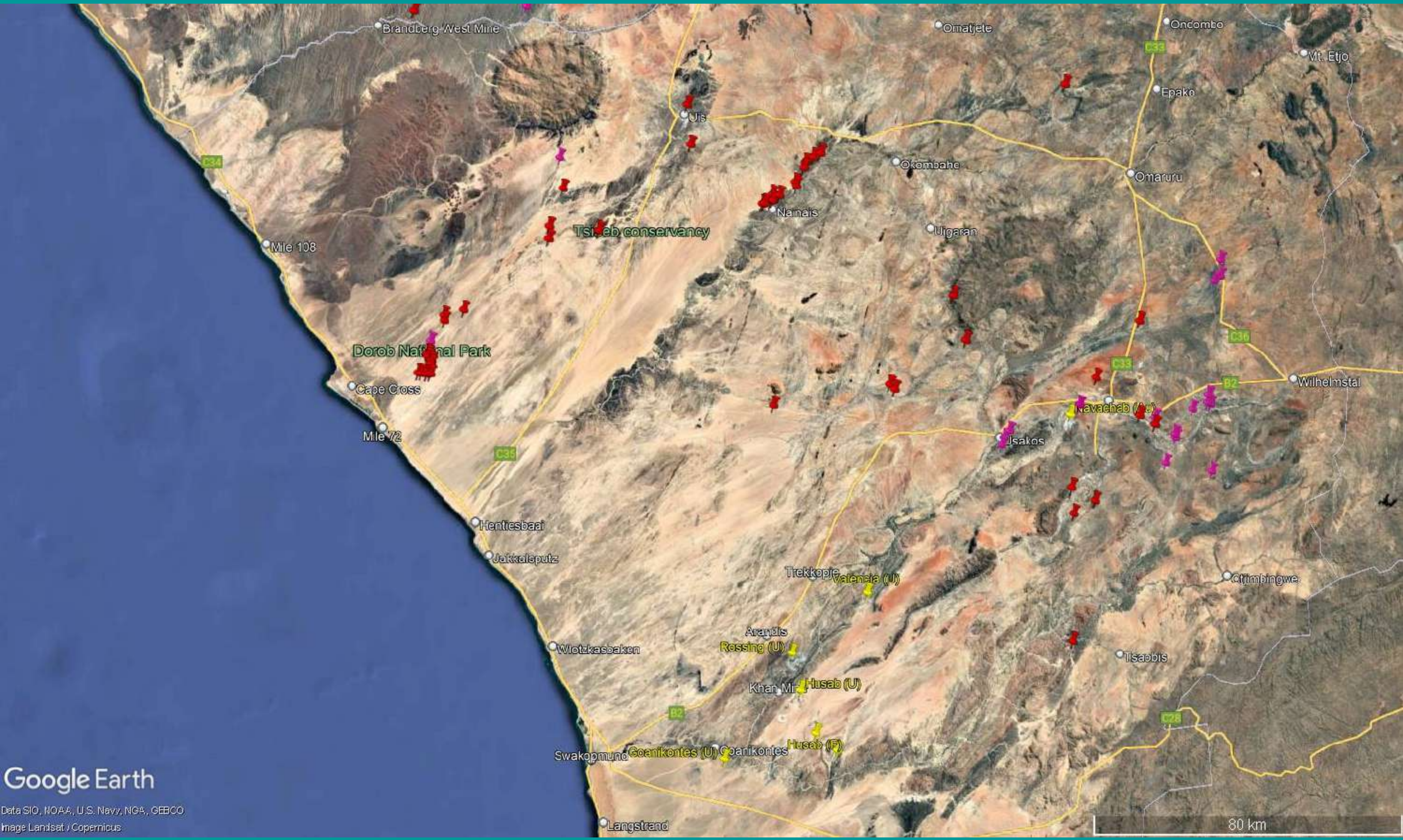
- Regional zoning of different types of pegmatite within pegmatite belts has not really been looked at in the same detail.

- Although, certainly for LCT pegmatites, it is established that they occur at the late stages, usually post-collisional, in orogenic belts (Bradley et al., 2017).

- Conversely NYF pegmatites are frequently intragranitic, in A-type granites (eg the Bushveld Complex, Pikes Peak Granite) although they also occur without any association with potentially parental granites (Norway, Muller et al., 2017).

- There are also places where LCT and NYF pegmatites co-exist:

The Distribution of different Pan-African, Late- / Post-Orogenic Mineralisation in Namibia is Zoned



Pegmatite classification: Globally it's in a bit of a mess!! (see Simmons, 2005)

Depth – what the current classifications are based on
Mineralogical- how many grains of beryl do we need?, rather subjective
Geochemical - complete suites of trace elements are rare in pegmatite studies
Economic – what was, is, or will be mined

Four Classes:

1. Abyssal

2. Muscovite

3. Rare-element

3. Miarolitic

Two or Three Families

Cerny & Ercit 2005

Family	Dominant subclass of pegmatites[§]	Geochemical signature	Bulk composition of pegmatites *	Associated granites	Bulk composition of granites *	Source lithologies **
LCT	REL-Li MI-Li	Li, Rb, Cs, Be, Sn, Ga, Ta>Nb, (B, P, F)	peraluminous to subaluminous	(synorogenic to) late-orogenic (to anorogenic); largely heterogeneous	peraluminous, S, I or mixed S + I types	undepleted upper- to middle-crust supracrustal rocks and basement gneisses
NYF	REL-REE MI-REE	Nb>Ta, Ti, Y, Sc, REE, Zr, U, Th, F	subaluminous to metaluminous (to subalkaline)	(syn-, late, post-) to mainly anorogenic; quasi-homogeneous	(peraluminous to) subaluminous and metaluminous; A and I types	depleted middle- to lower-crust granulites, juvenile granites, mantle-metasomatized crust
Mixed	Cross-bred LCT and NYF	mixed	(metaluminous to) moderately peraluminous	(postorogenic to) anorogenic; heterogeneous	subaluminous to slightly peraluminous	mixed protoliths or assimilation of supracrustal rocks by NYF granites

Loads of sub-divisions, sub-classes

- **Abyssal class**
  - K feldspar
  - corundum
- **Rare earth class**
  - beryl-columbite
  - beryl-columbite-U
  - beryl-columbite-P
  - chrysoberyl
  - emerald
- **Rare earth NYF**
  - allanite-monazite
  - monazite - Sc
  - bastnaesite
- **Complex LCT**
  - lepidolite
  - amblygonite
  - elbaite
  - danburite

(Pezzotta, 1999)

Possibly too much of a mineralogical focus

- How much of a particular mineral eg beryl before you can call it a beryl-pegmatite – is one 1 mm sized grain enough?
- Zoned pegmatites with large quartz cores are anomalous – most pegmatites are "simple", granitic, quartz + feldspar. But they shouldn't be forgotten.
- It does mean that there is an inherent bias in the dataset – mineralogically and geologically interesting pegmatites

- The pragmatic pegmatite perspective (P^3)
- Based on fieldwork in Namibia and Namaqualand

- If it contains Li-minerals (spodumene, lepidolite, petalite, amblygonite-montebrasite) it is most easily called a LCT-Li pegmatite
- If it contains tantalite, pollucite, cassiterite or coloured tourmaline (elbaite, liddicoatite) then it can also be called a LCT-(Sn) or LCT-(Tml) pegmatite. NB many pegmatites have been mined for Sn, Ta and then Li – economic definitions not geological.

- If it contains uraninite, gadolinite $(REE,Y)_2FeBe_2Si_2O_{10}$), samarskite $(Y,Fe,U,Th,Ca)_2(Nb,Ta)_2O_8$, fergusonite $(Y,REE)NbO_4$, fluorite, allanite $(Ce,Ca,Y,La)_2(Al,Fe)_3(SiO_4)_3(OH)$ topaz, columbite or amazonite it is probably a NYF pegmatite

- If it contains beryl, apatite, or ???? It could be either NYF or LCT

NYF-(U) pegmatites in the Damara Orogen

- Peraluminous-metaluminous, crustally derived, late-orogenic to post-orogenic sheeted pegmatitic leucogranites (SLG), unzoned and with an NYF affinity.
- Similar to the NYF (abyssal) pegmatites of Bancroft, Ontario (Grenvillian-age orogenic belt) and the older Wollaston domain pegmatites in Saskatchewan (Lentz /Annesley & co-workers).
- They are confined to a relatively
- small area within the sCZ of
- the Damara orogen and
- may contain economic
- uranium mineralization:
  - Rössing
  - Goanikontes (Etango)
  - Husab
  - Valencia

LCT pegmatites in the Damara Orogen

- Peraluminous-metaluminous, crustally derived, late-orogenic to post-orogenic with tin (cassiterite) tourmaline (elbaite, rubellite), lithium (spodumene, petalite).
- Similar to other orogenic-related occurrences of LCT pegmatites in any other orogenic belt.
- Spatially separate from the NYF
- pegmatites and in lower grade
- metamorphic areas of the belt.
- This coincides with the distribution
- of gold mineralization.

LCT and NYF pegmatites are broadly contemporaneous

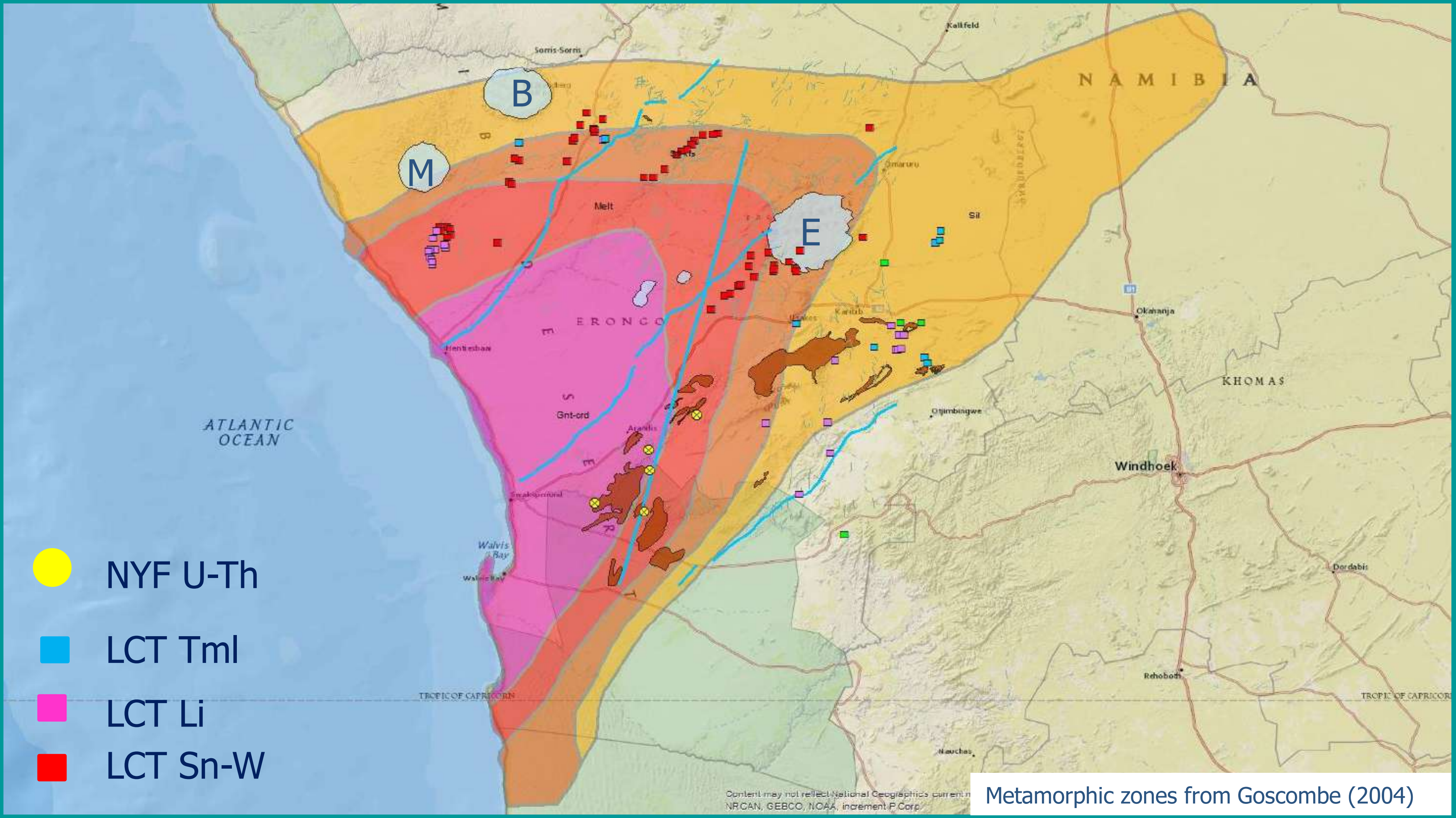
~575 Ma	Goas Suite		Milani et al (2014)
~550-540 Ma	Salem Granites		Milani et al (2014)
~530 Ma	Equigranular Red		Longridge (2012)
~520 Ma	Equigranular Grey		Longridge (2012)
Age	Location	Type	Source
524.2 ± 3.5 Ma	Neineis	LCT-Sn	Zhang et al (2017)
518.4 ± 7.7 Ma	Goantagab	Sn-W Vein	Zhang et al (2017)
516-514 Ma	Khan River Area	Skarns	unpublished
514 ± 22 Ma	Ida	NYF-U-Th	Longridge (2012)
513.0 ± 6.9 Ma	Uis	LCT-Sn	Zhang et al (2017)
509.9 ± 2.7 Ma	Goantagab	Sn-W Vein	Zhang et al (2017)
508 ± 2 Ma	Goanikontes	NYF-U-Th	Briqueu et al (1980)
507 ± 1 Ma	Gaudeanmus	NYF-U-Th	Zong et al (2015)
505 ± 2.6 Ma	Rubicon	LCT-Li	Melcher et al (2013)
503.8 ± 5.9 Ma	Uis	LCT-Sn	Zhang et al (2017)
500.9 ± 8.7 Ma	Arandis	LCT-Sn	Zhang et al (2017)
496.1 ± 4.1 Ma	Husab	NYF-U-Th	Cross et al (2011)

Combination of U-Pb columbite, tantalite, cassiterite, monazite, uraninite, titanite

Some ID-TIMS, mostly LA-ICP-MS

Range from 525 to 495 Ma

The distribution of rare element pegmatite types is more closely correlated with metamorphic grade / facies than any individual granite type or any single structure.



- Mozambique, Pan-African pegmatites in the Nampula Block

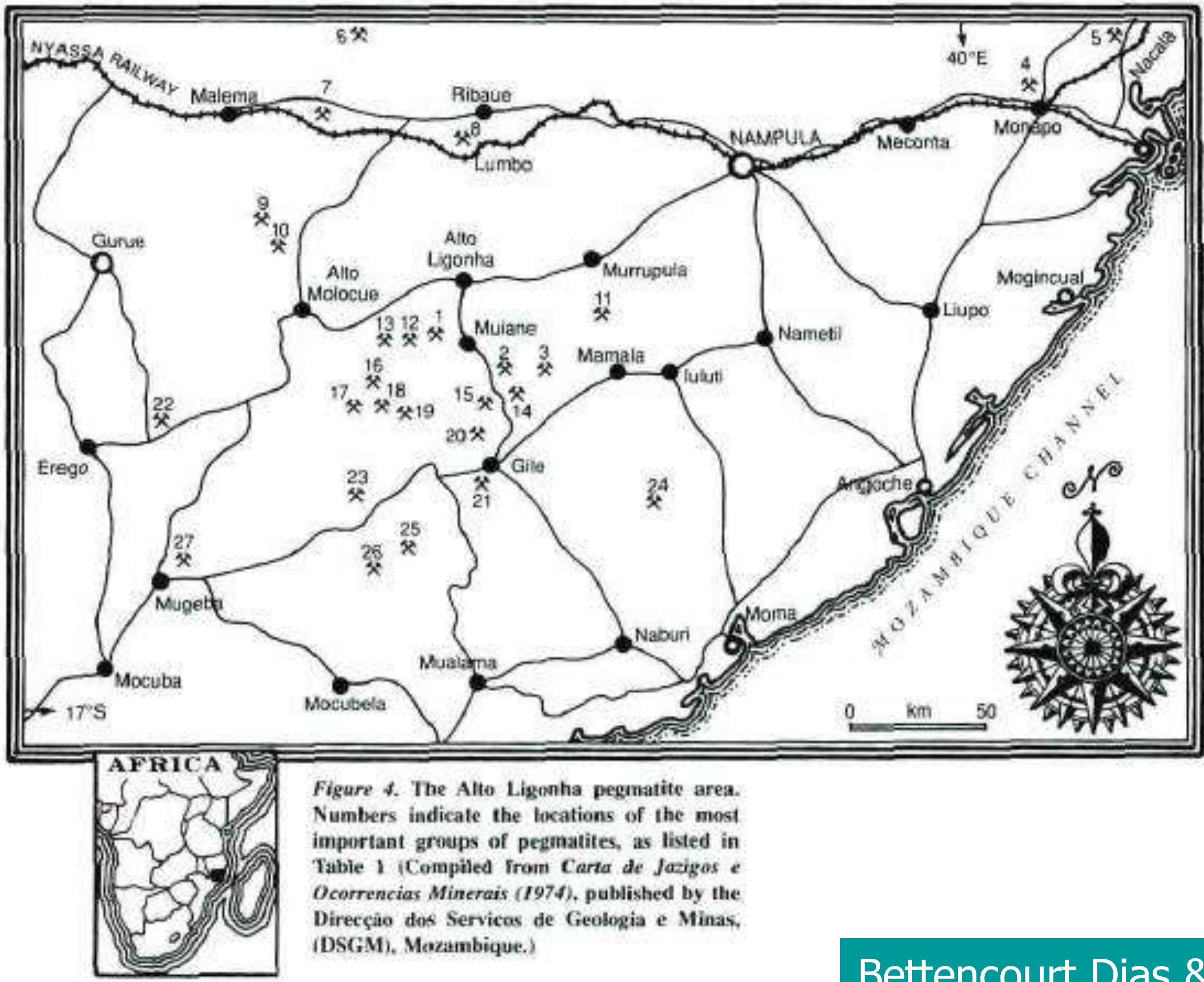
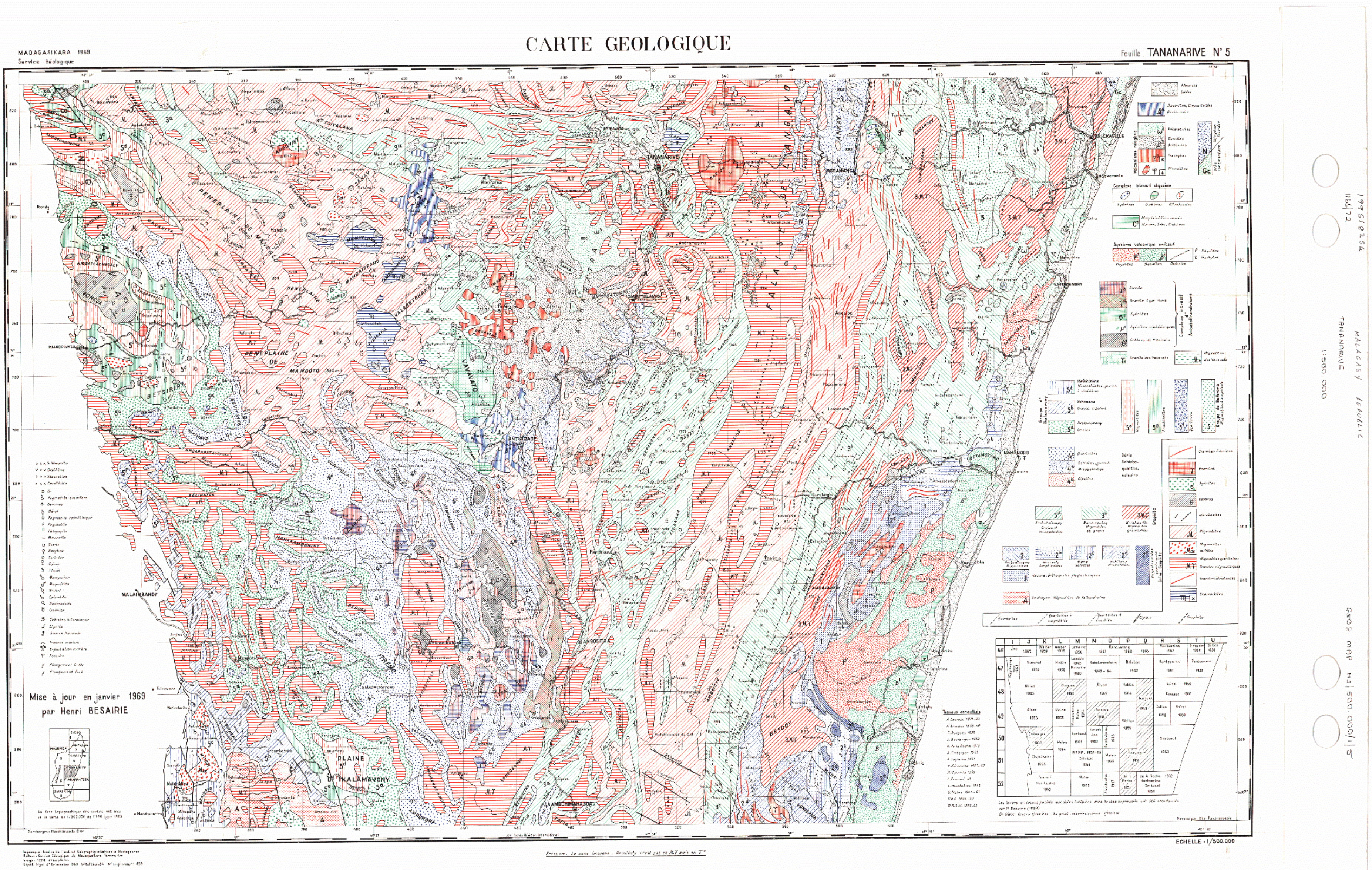


Figure 4. The Alto Ligonha pegmatite area. Numbers indicate the locations of the most important groups of pegmatites, as listed in Table 1 (Compiled from *Carta de Jazigos e Ocorrencias Minerais (1974)*, published by the Direcção dos Servicos de Geologia e Minas, (DSGM), Mozambique.)

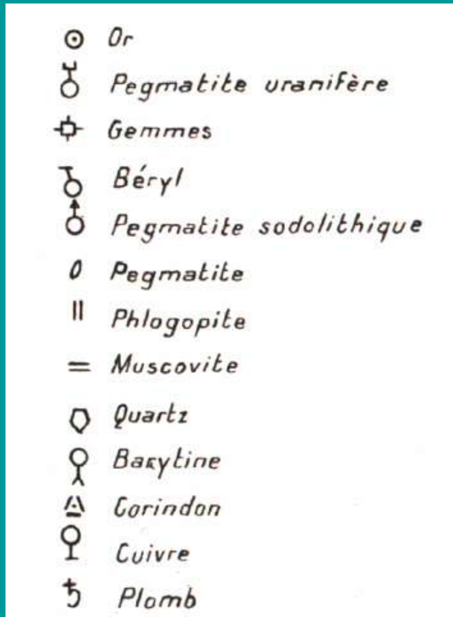
Bettencourt Dias & Wilson, (2000)

Although in separate areas, not clear what this relates to. Very little age data so may or may not be contemporaneous

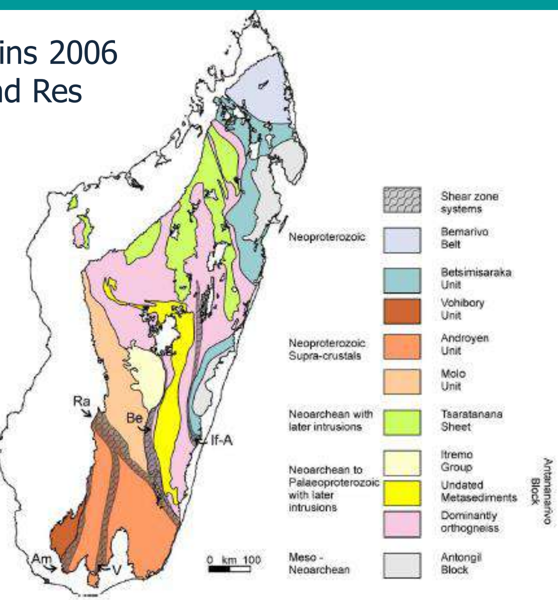
Madagascar

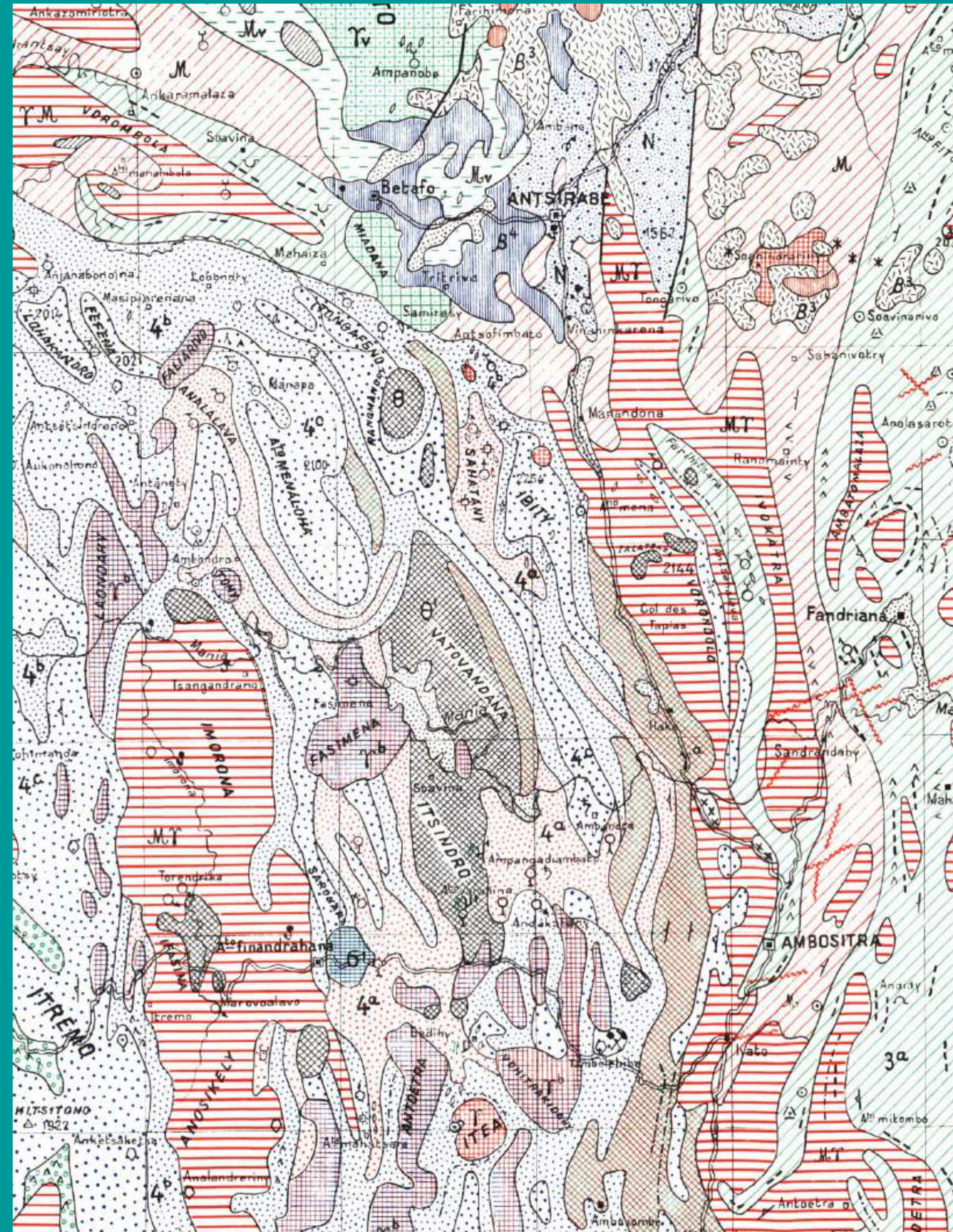


1969 1:500,000 Geological Map Sheet 5, Tananarive



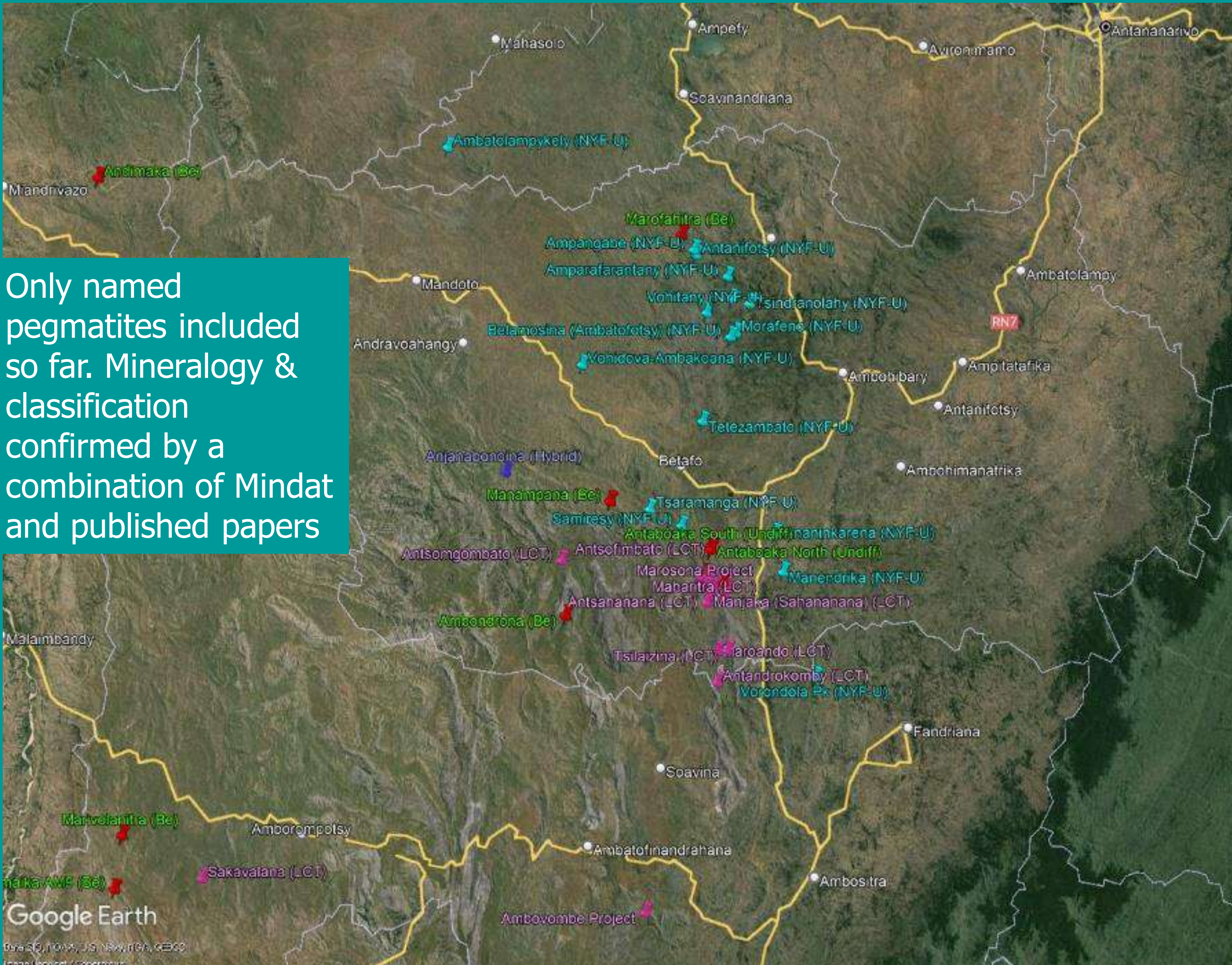
Collins 2006
Gond Res





Pan-African pegmatites although very little age data.

Only named pegmatites included so far. Mineralogy & classification confirmed by a combination of Mindat and published papers



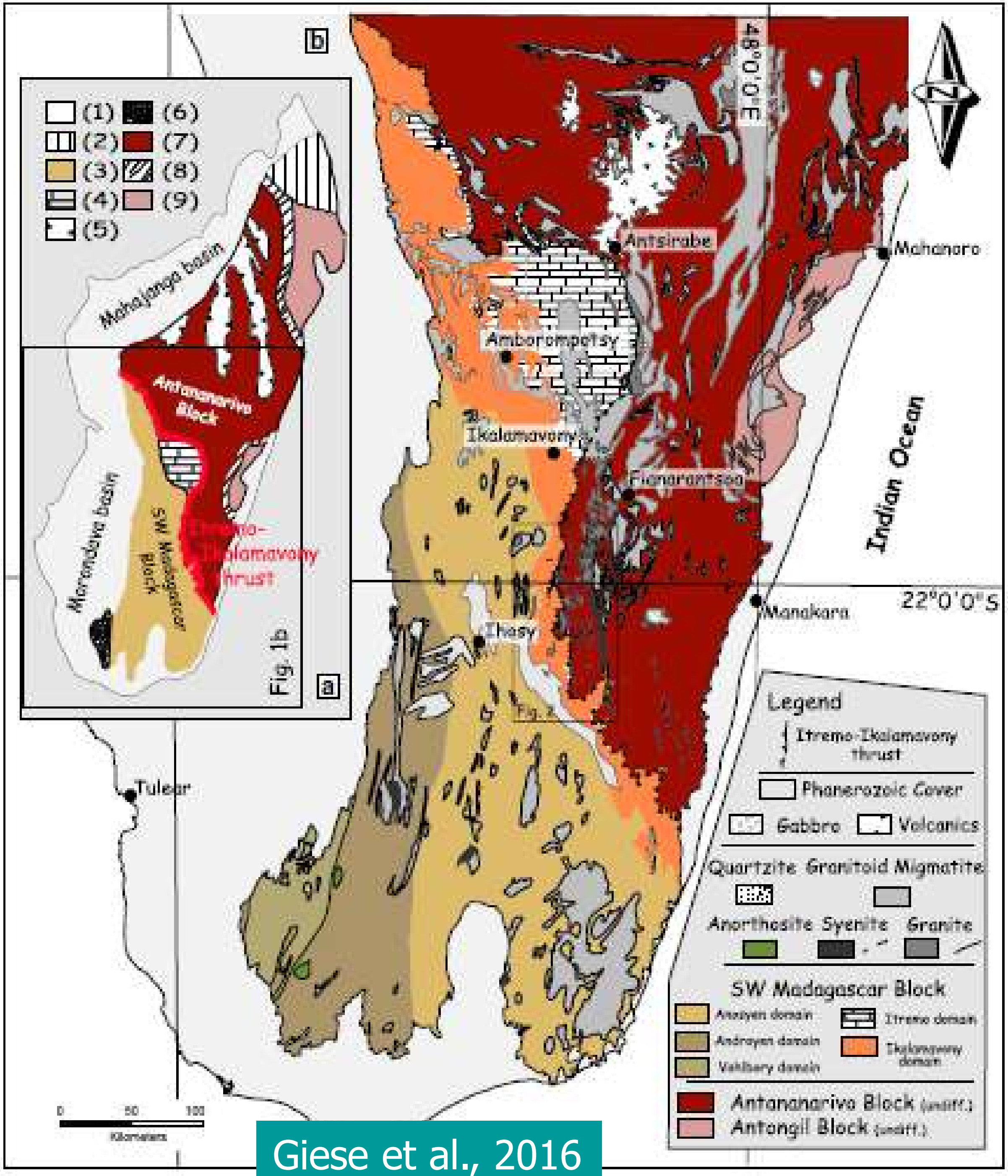
The boundary between domains of LCT and NYF pegmatites is coincident with the boundary between the Itremo Gp and the Antananarivo Block.

Itremo Gp: Proterozoic metasediments metamorphosed at greenschist-amphibolite facies.

Antananarivo Block: Late Archaean granulite facies rocks

The Itremo-Ikalamavony Thrust separates the two.

Also complicated by a number of "Hybrid" pegmatites with characteristics of both NYF and LCT



Giese et al., 2016

Namaqualand

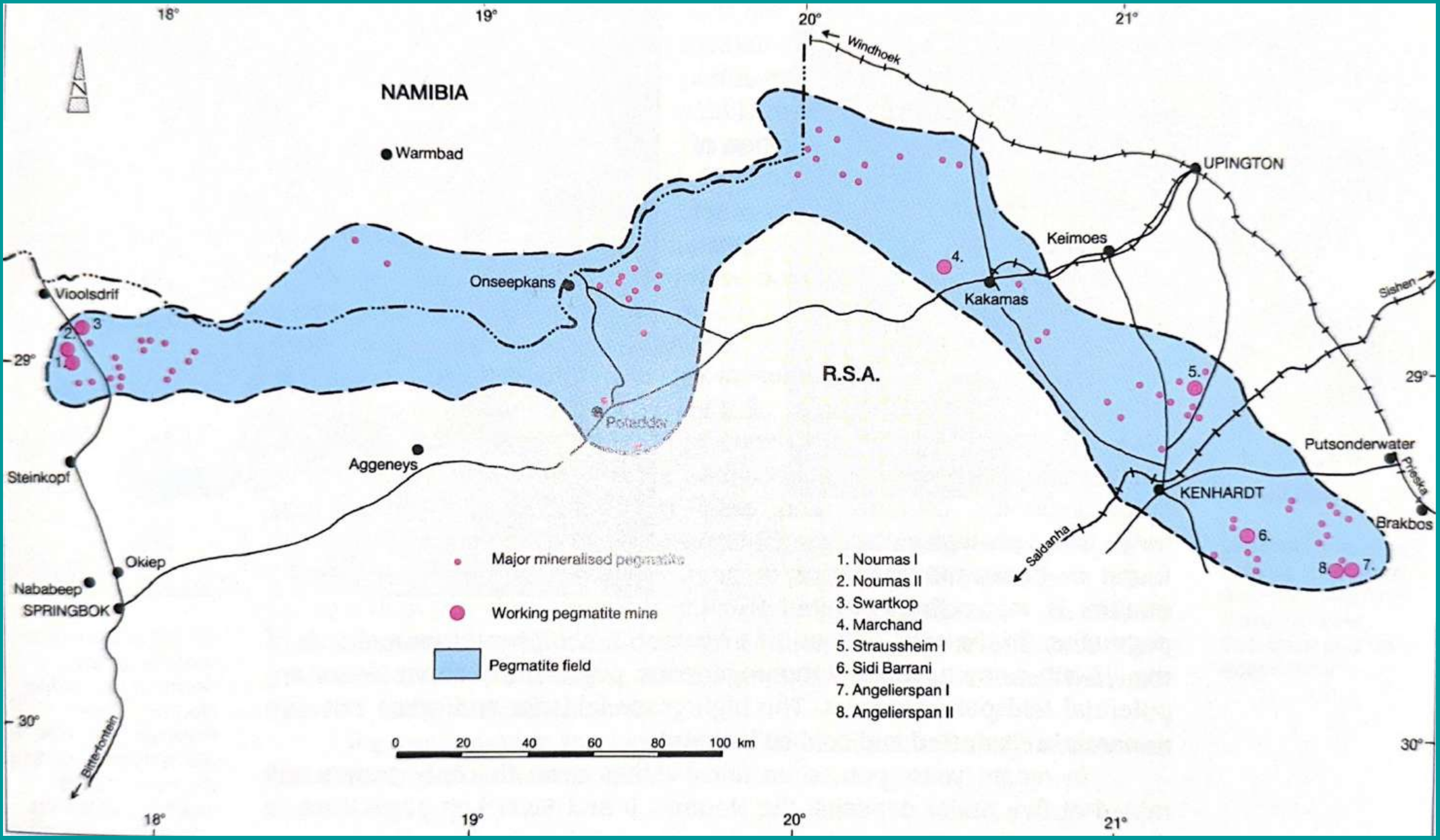


Daberas & Baviaanskloof

Norrabees & Witkop (Miller & Wicht, 2007)

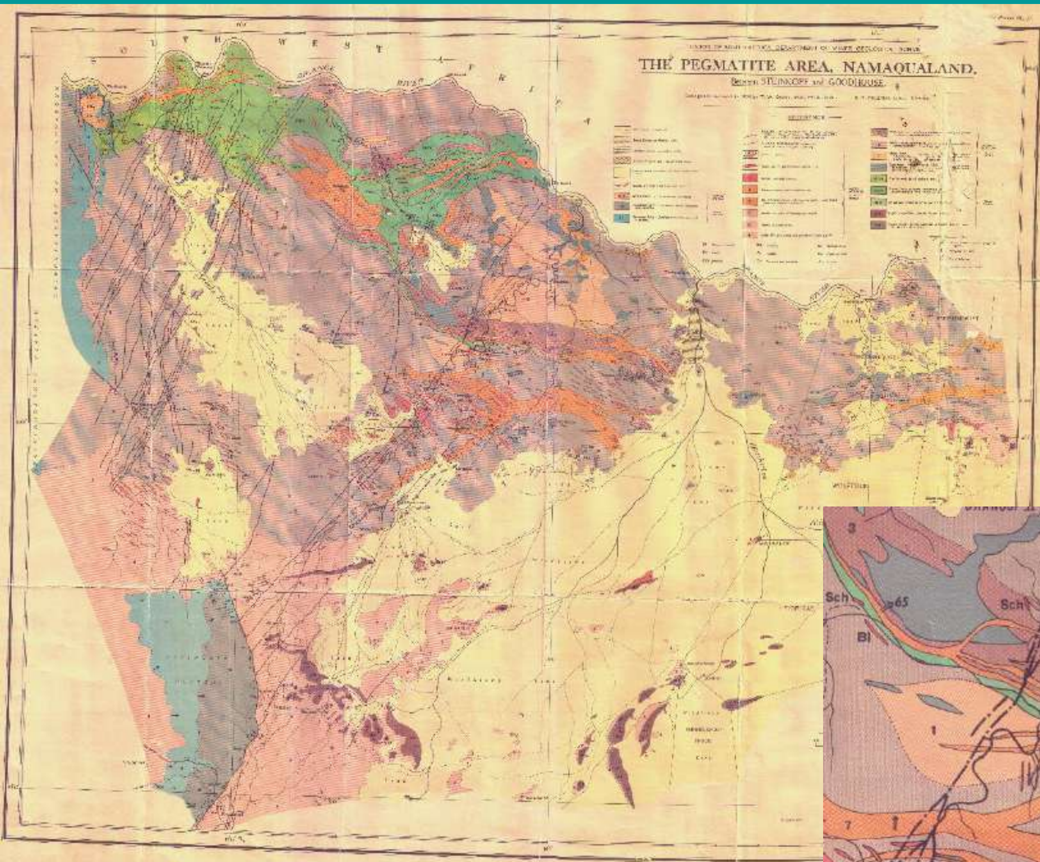

Crieff ~1027 Ma

The Mesoprotererozoic Namaqua-Natal orogen hosts the Orange River Pegmatite Belt in the Northern Cape, South Africa

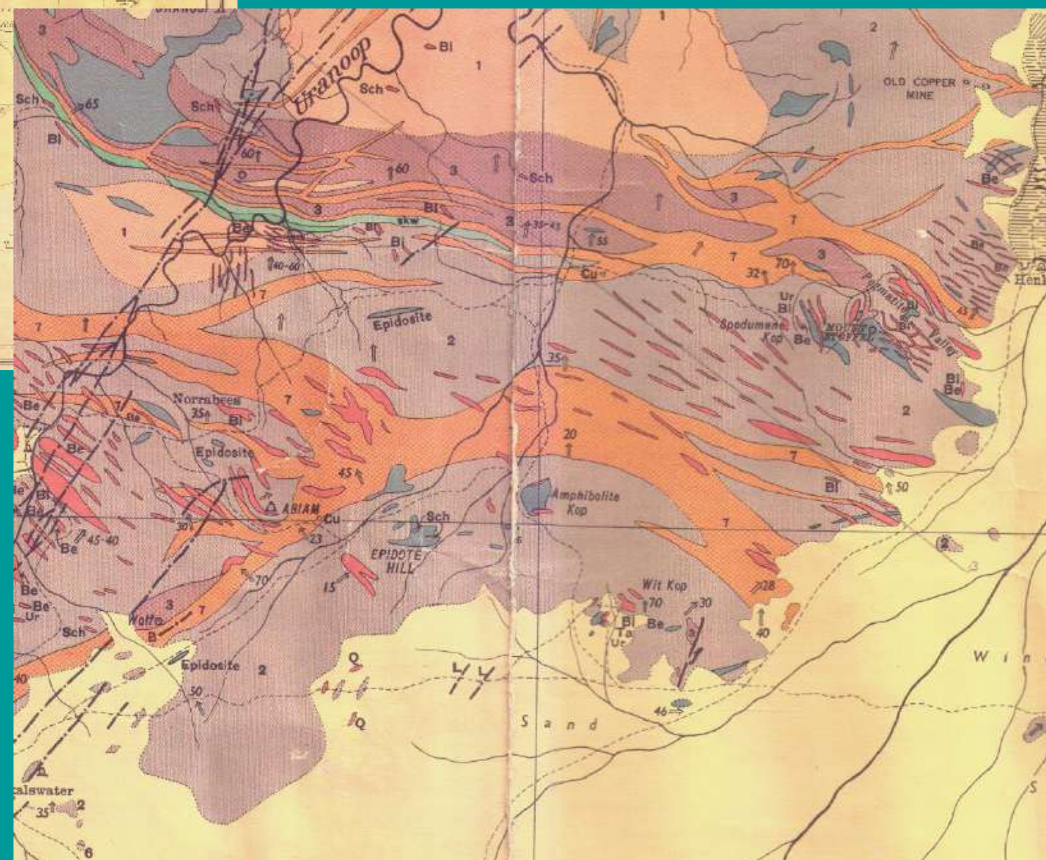


Cairncross & Dixon, 1995

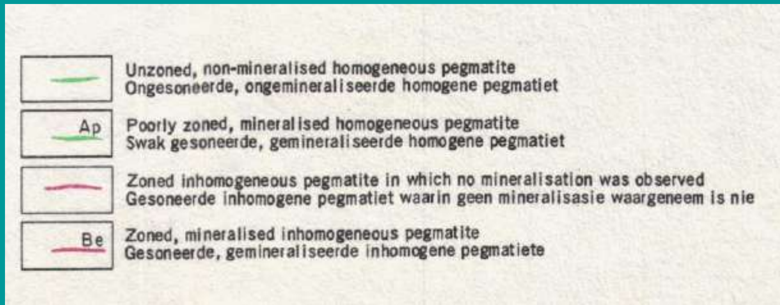
The western side

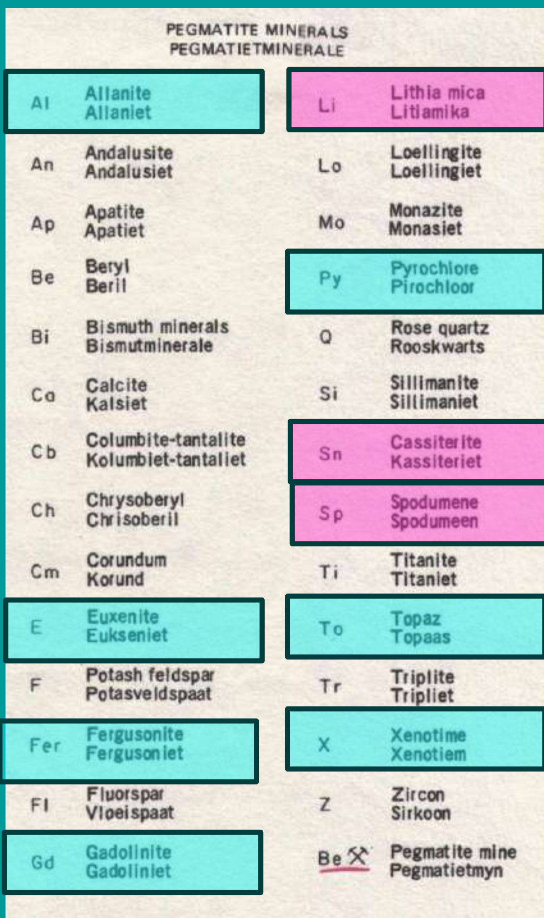


Gevers et al., 1937

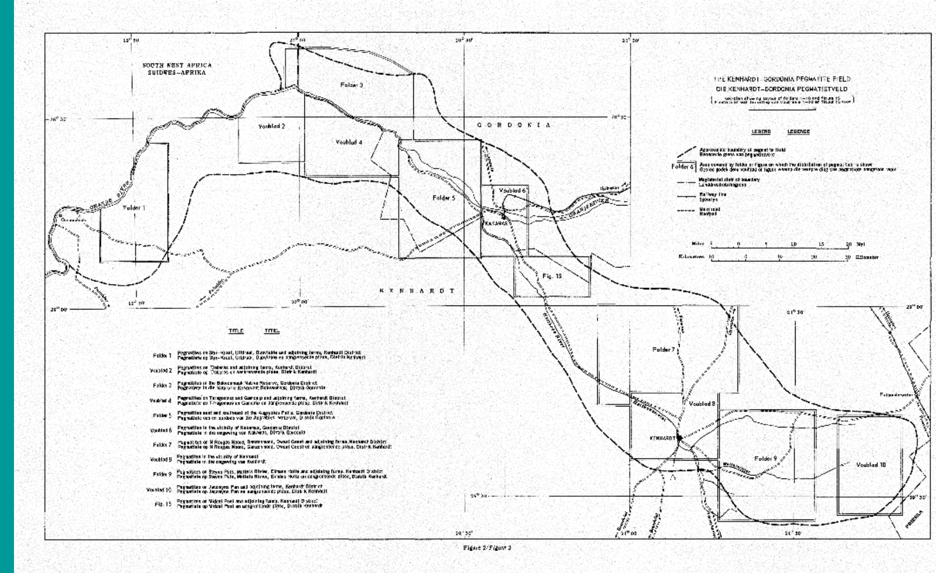


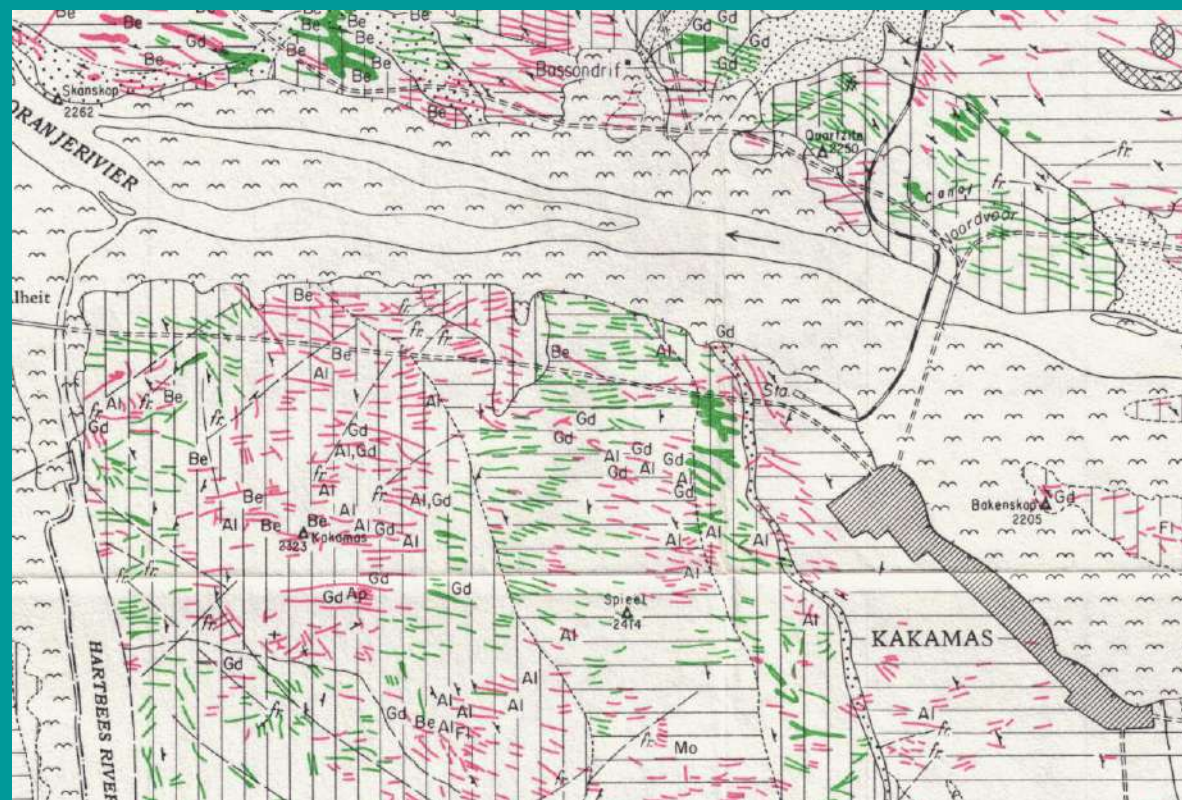
Central & eastern areas



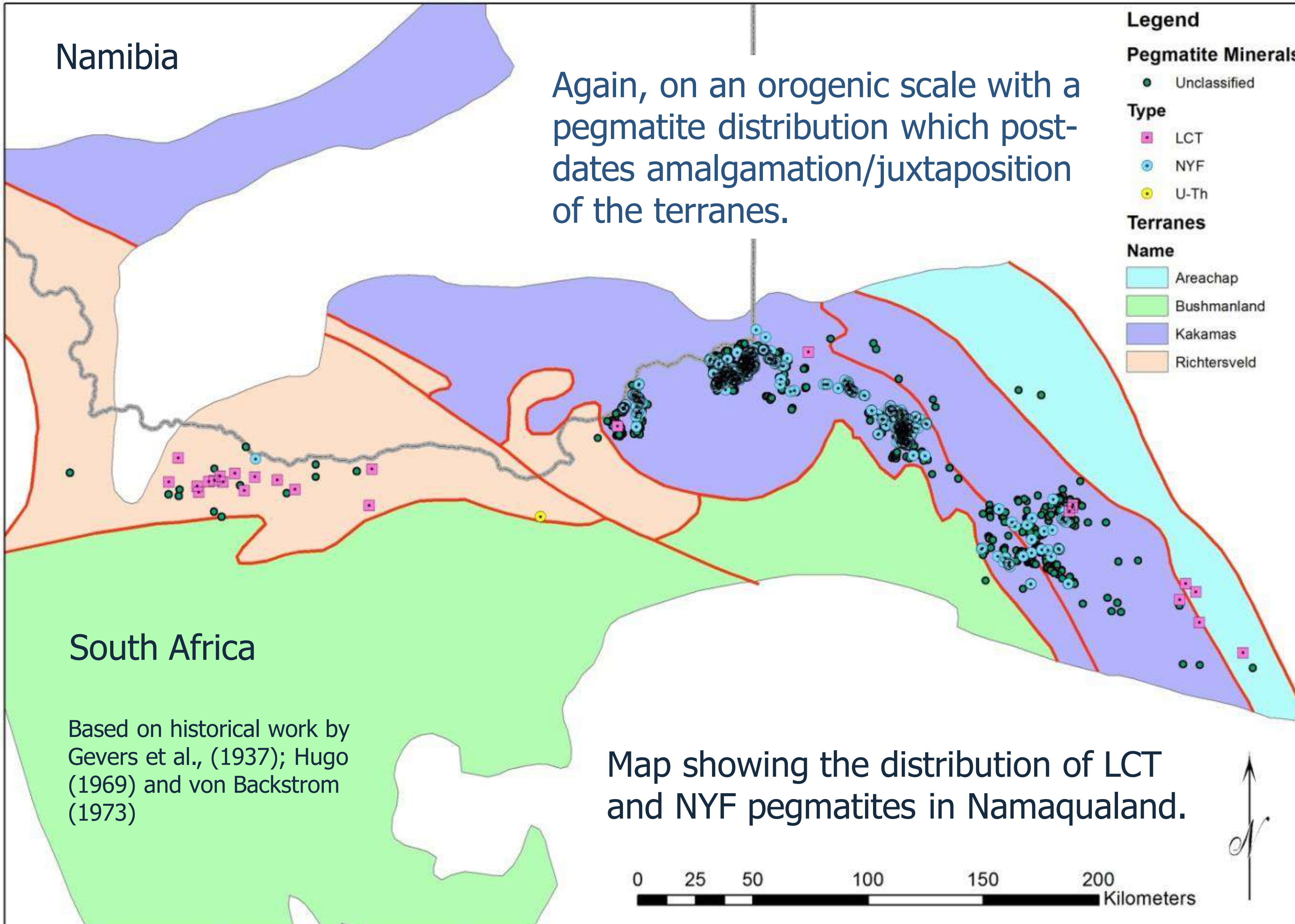


Hugo, 1970



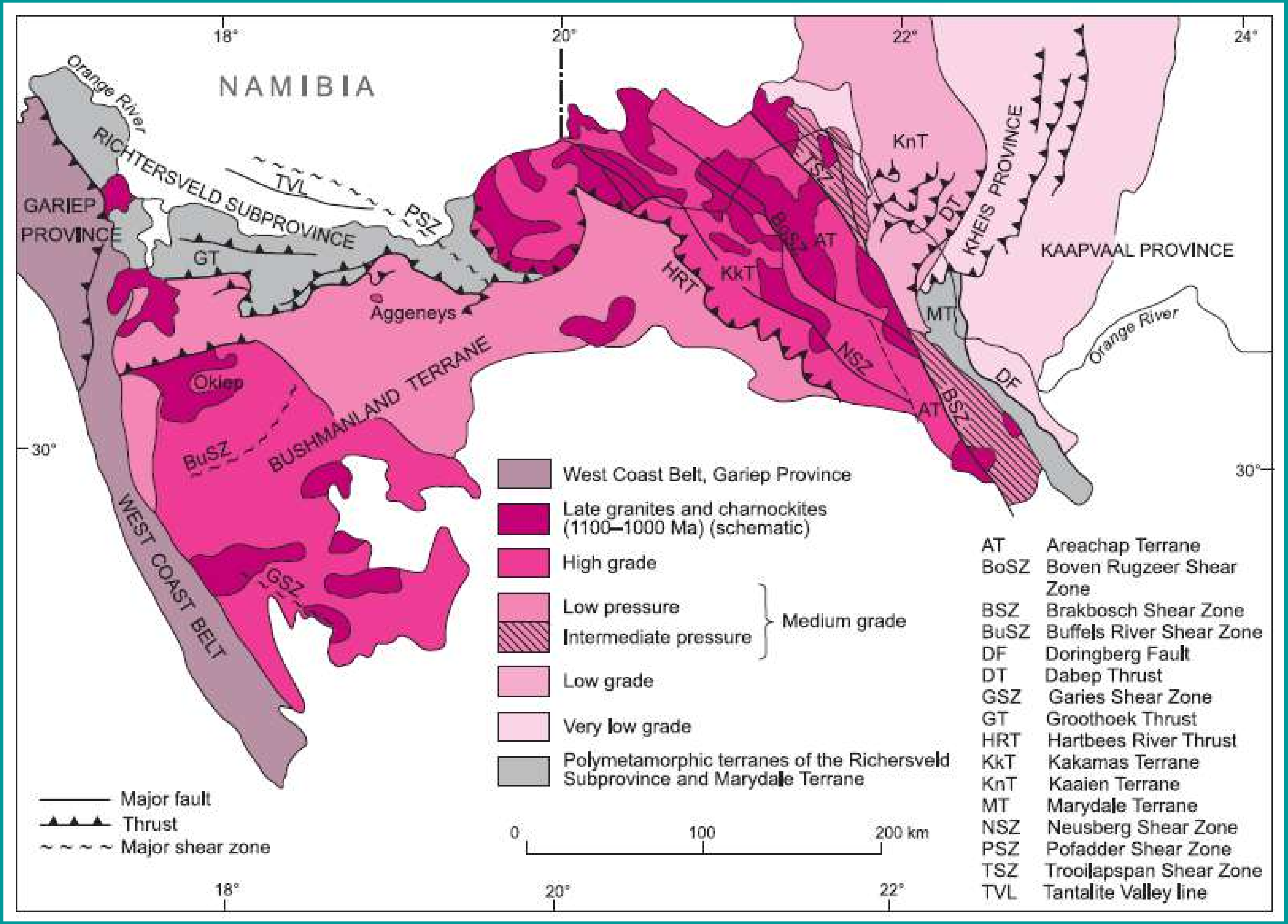


Again, on an orogenic scale with a pegmatite distribution which post-dates amalgamation/juxtaposition of the terranes.



Map showing the distribution of LCT and NYF pegmatites in Namaqualand.

Based on historical work by Gevers et al., (1937); Hugo (1969) and von Backstrom (1973)



The metamorphic facies map of Cornell et al., (2006) for Namaqualand does not provide as convincing a relationship between metamorphic facies and pegmatite types as the Damara Orogen. However, LCT pegmatites in the west and central parts are coincident with the medium grade facies.

Partial Melting

- Pegmatitic magma must have formed from low degrees of partial melting or be highly fractionated.
- Cuney, 1981, 1982; Friedrich et al, 1987 consider that the magma which formed the NYFs in Namibia was a low-volume partial melt of metasediments and/or acid metavolcanics – potentially pre-Damaran Abbabis Basement and / or the lower part of the Damara Sequence
- Generalised partial melting (anatexis) reactions (vapour-absent) :
- Muscovite dehydration anatexis (MDA ~:amphibolite facies)
  - Muscovite + plagioclase + quartz = Al-silicate + melt (NB other phases may be present in restite, eg biotite)
- Biotite dehydration anatexis (BDA ~: upper amphibolite-granulite facies)
  - Biotite + plagioclase + Al-silicate + quartz = Gnt +/- Crd +/- Kfsp + melt (NB other phases may be present eg ilmenite and rutile)
- The "other phases" may actually be quite important as they have the capacity to sequester our elements of interest.

The release of trace elements from muscovite and biotite into the melt is important and so is partitioning of elements between melt and restite. Routine measurement of multiple trace elements in micas by LA-ICP-MS is relatively recent.

Derivation of partition coefficients can be either from analysis of experimental products or from natural rocks – such as migmatites.

Compilation of partition coefficients

	Qtz[a]	Kfs	Pl	Bt	Msc	Grt	Sil	Crd
Li	0	0	0	1.65[1]	0.80[1]	0	0	0.44[2]
Be	0	0.26[2]	0.10[2]	0.39[2]	1.35[2]	0	0	30.698
Ga	0	0.20[3]	0.59[3]	3.10[3]	5.04[a]	0	0	0
Nb	0	0.04[3]	0.07[3]	1.96[5]	0.15[5]	0	0	0.01[1]
In	0	0[a]	0[a]	1.87[a]	5.21[a]	10.3[4]	0	0
Sn	0	0.05[a]	0.60[a]	2.32[a]	4.14[a]	0.86[4]	0	0
Sb	0	0	0	0.0013[4]	0	10[4]	0	0
Ta	0	0.025[6]	0.063	0.16–0.91[5]	0.06–0.45	0.0017[4]	0	0
W	0	0[a]	0[a]	0.4[a]	10.71[a]	0.0008[4]	0	0
Bi	0	0	0	0	0	0	0	0

Simons et al 2017 (mainly from experimental data)

Stepanov & Herman (2013), Wolf et al (2018), Kunz et al (2022), Zhao et al (2022) have all published new trace element data from biotite- and/or muscovite-bearing natural samples which include trace elements and show that MDA in the presence of biotite produces a restitic biotite with high Li and Sn.

Critical metal enrichment in crustal melts: The role of metamorphic mica

Barbara E. Kunz*, Clare J. Warren, Frances E. Jenner, Nigel B.W. Harris and Tom W. Argles

Low-temperature MDA and high-temperature BDA has been shown to result in different rare-element enrichment.

Economic Geology, v. 117, no. 3, pp. 667–682

Temporal Separation of W and Sn Mineralization by Temperature-Controlled Incongruent Melting of a Single Protolith: Evidence from the Wangxianling Area, Nanling Region, South China

Panlao Zhao,[1,2] Shunda Yuan,[1,†] Anthony E. Williams-Jones,[3] Rolf L. Romer,[4] Chen Yan,[2] Shiwei Song,[1] and Jingwen Mao[1,2]

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It is suggested that W mineralization occurs as a result of MDA while Sn mineralization is a result of BDA, NOT differential fractionation or magmatic-hydrothermal processes. Early MDA resulted in Sn sequestration in biotite until later BDA. In this example there is a temporal difference.

Parameters that discriminated between include MDA and BDA included Pb/Ba and Al_2O_3/TiO_2 ratios.

Zhao et al (2022)

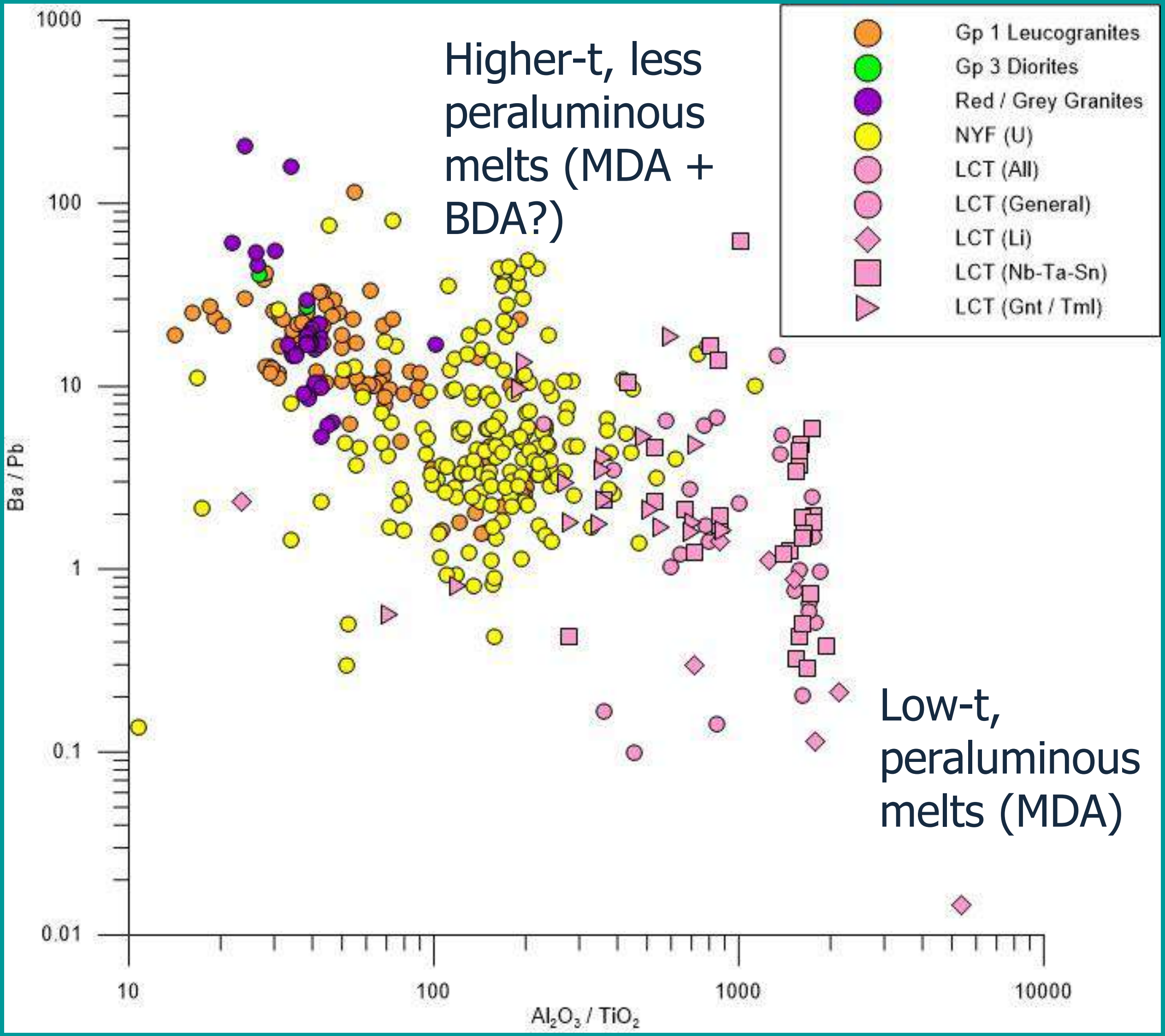
1. Pb partitions into muscovite>>biotite.
2. Muscovite contains >> Al_2O_3 than biotite
3. Ba has high mineral-melt partition coefficients

Therefore:

MDA will release more Pb and Al_2O_3 into early low-T peraluminous melts.

Ba is not released to the melt until higher temperatures.

Breakdown of Ti-containing phases (ilmenite, rutile & biotite) which contain HFS elements takes place at higher temperatures than MDA



Sequential anatexis (episodic or continuous) will release different trace element contents into partial melts at different times. Should we consider M_1 and M_2 or $M_{(start)}$ and $M_{(finish)}$

What do we really mean by source?

THIS IS NOT NEW

Applied Geochemistry, Vol. 7, pp. 393–416, 1992
Printed in Great Britain

0883–2927/92 $5.00+.00

Geochemical and petrogenetic features of mineralization in rare-element granitic pegmatites in the light of current research

P. ČERNÝ

"Peraluminous fertile (S-)granites generating LCT pegmatites are derived by partial melting of upper/middle crustal rocks undergoing their first anatexis, and the pegmatites commonly show regional zoning.

Metaluminous granites yielding poorly zoned groups of NYF pegmatites are largely of the A type, generated by second melting of short-lived, depleted lower-crustal protoliths."

Although relating it to the regional distribution of different pegmatite types within an orogen might be.

This may therefore solve the long-standing puzzle that Andreoli et al (2006) described regarding the association of U and Th with granulite, rather than lower metamorphic grade terrains. It is only at higher-T biotite dehydration melting that U is released from monazite and zircon into the melts when in addition F stabilizes biotite to higher temperatures and leads to the F component of the NFY signature.

Supporting evidence – biotite selvedge – fluorite –U veins, fluorite common at Rossing

CONCLUSIONS (1)

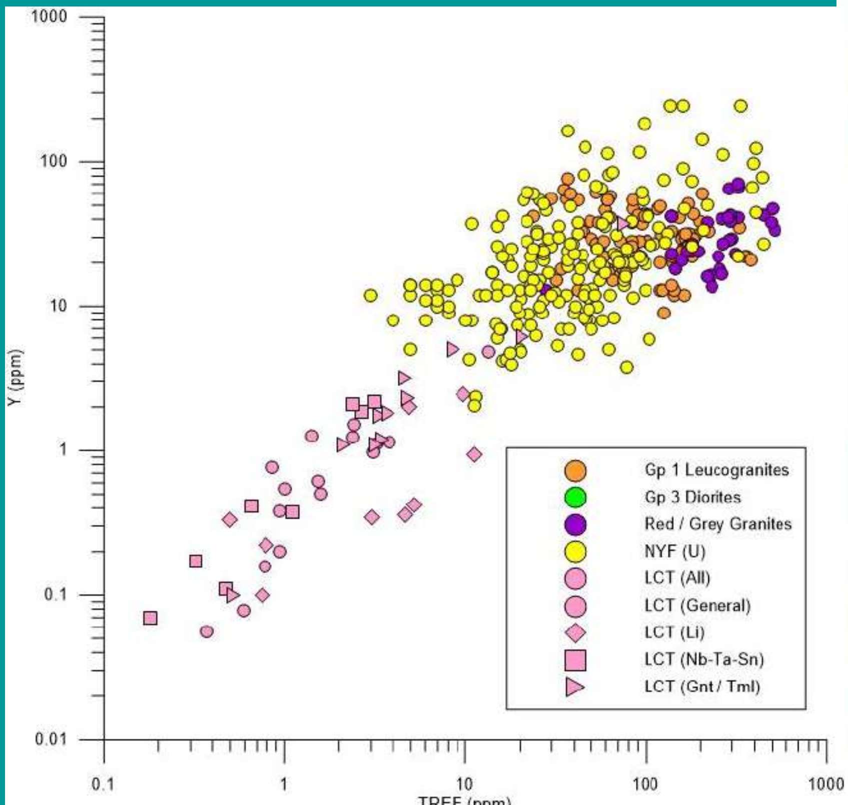
Multiple discrete or progressive anatexis is NOT new, several workers have suggested that it can occur and may be particularly important in rare metal granite systems (see especially Romer & Pichavant, 2020 and references therein)

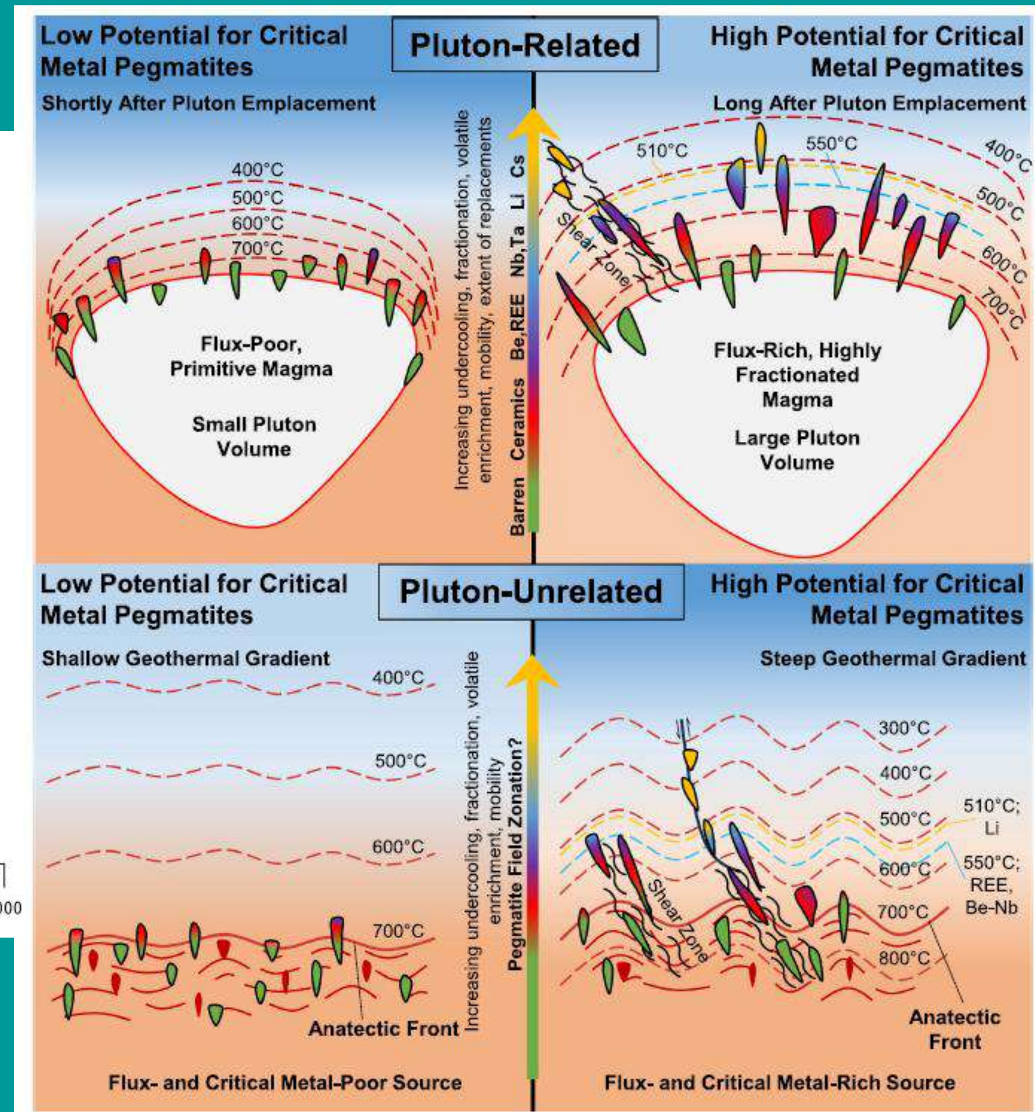
It does NOT invalidate other occurrences where there IS pegmatite zoning around a parental granitic pluton.

It does NOT invalidate the concept that pegmatites can form from the fractionation of a large body of granite.

Anatexis of a pre-existing granite is another possibility (see Koopmans et al 2023)

And whole-rock geochemical discrimination may be possible





McCaffrey & Jowitt, (2023)


Thank you