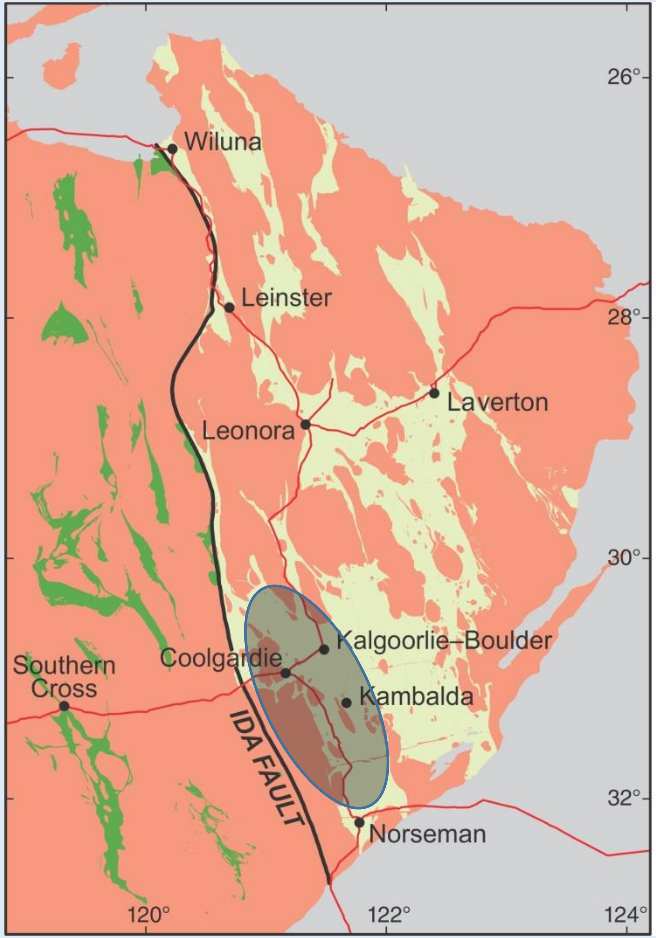
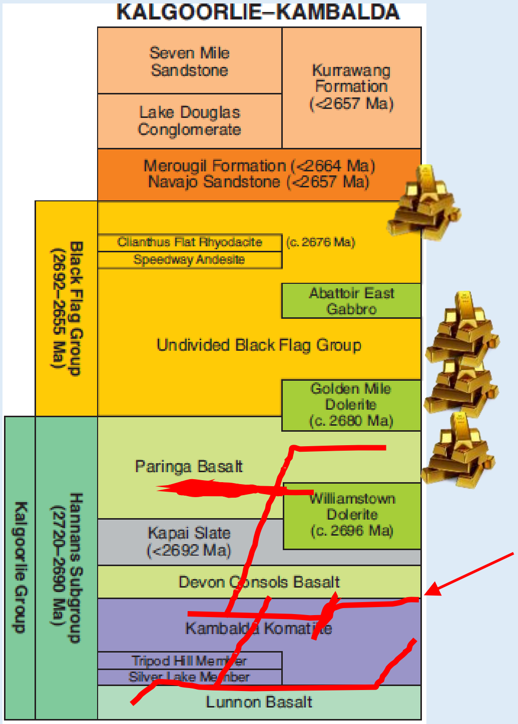
A new look at lamprophyres and sanukitoids and their relationships to the Black Flag Group and gold prospectivity

Presented by

Hugh Smithies

Kalgoorlie–Kambalda region of the Eastern Goldfields Superterrane, eastern Yilgarn Craton





- Black Flag Group felsic volcanic, volcaniclastic and clastic rocks + sub-volcanic intrusions
  ~2.69 – 2.66 Ga
- Au Mineralization ~2.66 – 2.64 Ga
- Compositionally specialized hbl–plag- to plag-porphyritic felsic intrusions (‘porphyries’)
  ~ 2.67 – 2.65 Ga
- Lamprophyres ~ 2.67 – 2.64 Ga

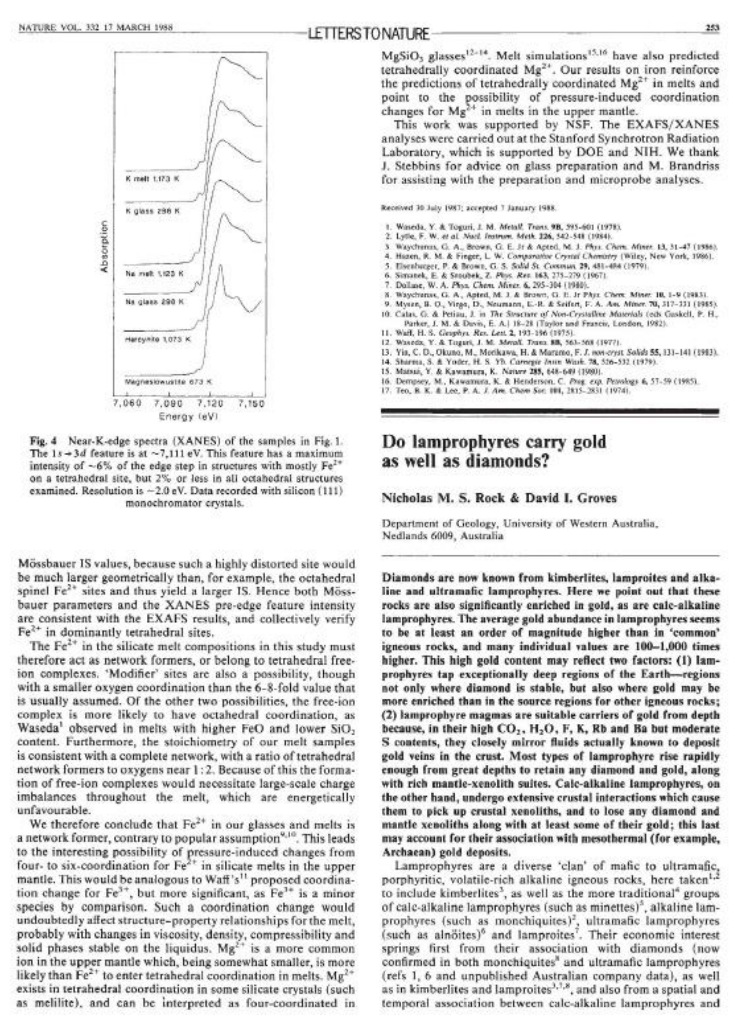


Fig. 4 Near-K-edge spectra (XANES) of the samples in Fig. 1. The $1s \rightarrow 3d$ feature is at ~7,111 eV. This feature has a maximum intensity of ~6% of the edge step in structures with mostly Fe^{2+} on a tetrahedral site, but 2% or less in all octahedral structures examined. Resolution is ~2.0 eV. Data recorded with silicon (111) monochromator crystals.

Mössbauer IS values, because such a highly distorted site would be much larger geometrically than, for example, the octahedral spinel Fe^{2+} sites and thus yield a larger IS. Hence both Mössbauer parameters and the XANES pre-edge feature intensity are consistent with the EXAFS results, and collectively verify Fe^{2+} in dominantly tetrahedral sites.

The Fe^{2+} in the silicate melt compositions in this study must therefore act as network formers, or belong to tetrahedral free-ion complexes. 'Modifier' sites are also a possibility, though with a smaller oxygen coordination than the 6–8-fold value that is usually assumed. Of the other two possibilities, the free-ion complex is more likely to have octahedral coordination, as Waseda[1] observed in melts with higher FeO and lower SiO_2 content. Furthermore, the stoichiometry of our melt samples is consistent with a complete network, with a ratio of tetrahedral network formers to oxygens near 1:2. Because of this the formation of free-ion complexes would necessitate large-scale charge imbalances throughout the melt, which are energetically unfavourable.

We therefore conclude that Fe^{2+} in our glasses and melts is a network former, contrary to popular assumption[9,10]. This leads to the interesting possibility of pressure-induced changes from four- to six-coordination for Fe^{2+} in silicate melts in the upper mantle. This would be analogous to Waff's[11] proposed coordination change for Fe^{3+}, but more significant, as Fe^{3+} is a minor species by comparison. Such a coordination change would undoubtedly affect structure–property relationships for the melt, probably with changes in viscosity, density, compressibility and solid phases stable on the liquidus. Mg^{2+} is a more common ion in the upper mantle which, being somewhat smaller, is more likely than Fe^{2+} to enter tetrahedral coordination in melts. Mg^{2+} exists in tetrahedral coordination in some silicate crystals (such as melilite), and can be interpreted as four-coordinated in $MgSiO_3$ glasses[12-14]. Melt simulations[15,16] have also predicted tetrahedrally coordinated Mg^{2+}. Our results on iron reinforce the predictions of tetrahedrally coordinated Mg^{2+} in melts and point to the possibility of pressure-induced coordination changes for Mg^{2+} in melts in the upper mantle.

This work was supported by NSF. The EXAFS/XANES analyses were carried out at the Stanford Synchrotron Radiation Laboratory, which is supported by DOE and NIH. We thank J. Stebbins for advice on glass preparation and M. Brandriss for assisting with the preparation and microprobe analyses.

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1. Waseda, Y. & Toguri, J. M. *Metall. Trans.* **9B**, 595–601 (1978).
2. Lytle, F. W. *et al. Nucl. Instrum. Meth.* **226**, 542–548 (1984).
3. Waychunas, G. A., Brown, G. E. Jr & Apted, M. J. *Phys. Chem. Miner.* **13**, 31–47 (1986).
4. Hazen, R. M. & Finger, L. W. *Comparative Crystal Chemistry* (Wiley, New York, 1986).
5. Eisenberger, P. & Brown, G. S. *Solid St. Commun.* **29**, 481–484 (1979).
6. Simanek, E. & Sroubek, Z. *Phys. Rev.* **163**, 275–279 (1967).
7. Dollase, W. A. *Phys. Chem. Miner.* **6**, 295–304 (1980).
8. Waychunas, G. A., Apted, M. J. & Brown, G. E. Jr *Phys. Chem. Miner.* **10**, 1–9 (1983).
9. Mysen, B. O., Virgo, D., Neumann, E.-R. & Seifert, F. A. *Am. Miner.* **70**, 317–331 (1985).
10. Calas, G. & Petiau, J. in *The Structure of Non-Crystalline Materials* (eds Gaskell, P. H., Parker, J. M. & Davis, E. A.) 18–28 (Taylor and Francis, London, 1982).
11. Waff, H. S. *Geophys. Res. Lett.* **2**, 193–196 (1975).
12. Waseda, Y. & Toguri, J. M. *Metall. Trans.* **8B**, 563–568 (1977).
13. Yin, C. D., Okuno, M., Morikawa, H. & Marumo, F. *J. non-cryst. Solids* **55**, 131–141 (1983).
14. Sharma, S. & Yoder, H. S. *Yb. Carnegie Instn Wash.* **78**, 526–532 (1979).
15. Matsui, Y. & Kawamura, K. *Nature* **285**, 648–649 (1980).
16. Dempsey, M., Kawamura, K. & Henderson, C. *Prog. exp. Petrology* **6**, 57–59 (1985).
17. Teo, B. K. & Lee, P. A. *J. Am. Chem. Soc.* **101**, 2815–2831 (1974).

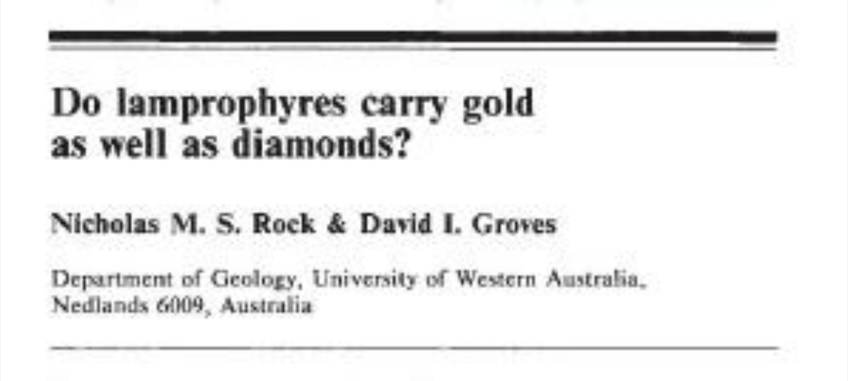
Do lamprophyres carry gold as well as diamonds?

Nicholas M. S. Rock & David I. Groves

Department of Geology, University of Western Australia, Nedlands 6009, Australia

Diamonds are now known from kimberlites, lamproites and alkaline and ultramafic lamprophyres. Here we point out that these rocks are also significantly enriched in gold, as are calc-alkaline lamprophyres. The average gold abundance in lamprophyres seems to be at least an order of magnitude higher than in 'common' igneous rocks, and many individual values are 100–1,000 times higher. This high gold content may reflect two factors: (1) lamprophyres tap exceptionally deep regions of the Earth—regions not only where diamond is stable, but also where gold may be more enriched than in the source regions for other igneous rocks; (2) lamprophyre magmas are suitable carriers of gold from depth because, in their high CO_2, H_2O, F, K, Rb and Ba but moderate S contents, they closely mirror fluids actually known to deposit gold veins in the crust. Most types of lamprophyre rise rapidly enough from great depths to retain any diamond and gold, along with rich mantle-xenolith suites. Calc-alkaline lamprophyres, on the other hand, undergo extensive crustal interactions which cause them to pick up crustal xenoliths, and to lose any diamond and mantle xenoliths along with at least some of their gold; this last may account for their association with mesothermal (for example, Archaean) gold deposits.

Lamprophyres are a diverse 'clan' of mafic to ultramafic, porphyritic, volatile-rich alkaline igneous rocks, here taken[1,2] to include kimberlites[3], as well as the more traditional[4] groups of calc-alkaline lamprophyres (such as minettes)[5], alkaline lamprophyres (such as monchiquites)[2], ultramafic lamprophyres (such as alnöites)[6] and lamproites[7]. Their economic interest springs first from their association with diamonds (now confirmed in both monchiquites[8] and ultramafic lamprophyres (refs 1, 6 and unpublished Australian company data), as well as in kimberlites and lamproites[3,7,8], and also from a spatial and temporal association between calc-alkaline lamprophyres and



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Department of Geology, University of Western Australia, Nedlands 6009, Australia

Nature 1988 v. 332 no 6161

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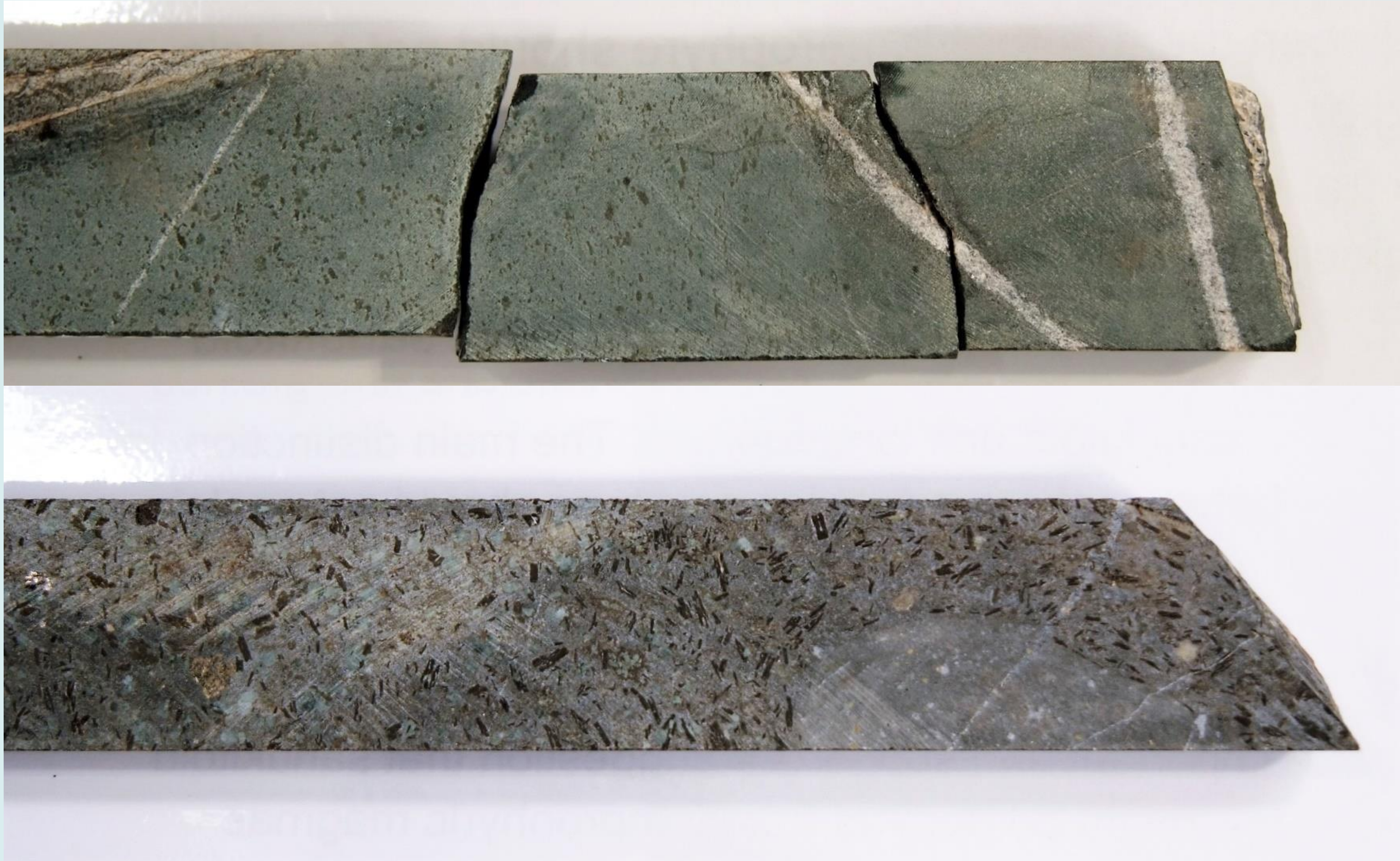
Lamprophyre – a textural / mineralogical term

- Phenocrysts or megacrysts of biotite and/or hornblende in an otherwise fine-grained or aphyric mafic to ultramafic groundmass

- From a compositional viewpoint (c.f. magmas with similar MgO) they are:
  - Hydrous
  - Alkali rich (high Na_2O and K_2O)
  - Enriched in LILE (e.g. Sr, Ba), LREE (e.g. La, Ce) and P_2O_5

- These features implicate an enriched or metasomatized lithospheric mantle source

- In the EGST, lamprophyres are calc-alkaline, not ‘highly’ alkaline, and probably better referred to as ‘appinites’, and form dykes intruded between c. 2.67 to 2.64 Ga



Sanukitoids

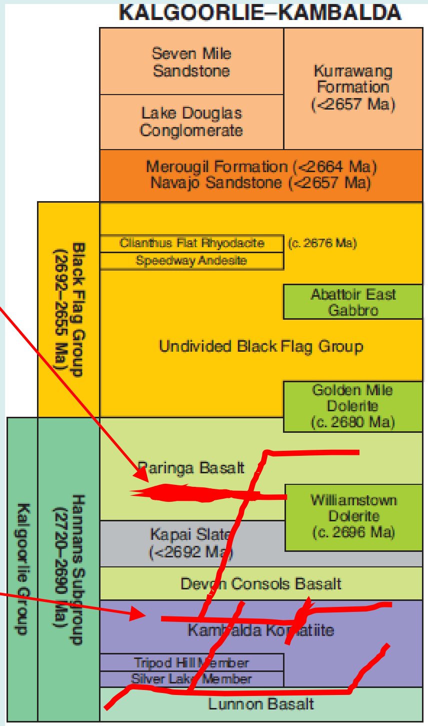
- Intrusive hornblende-bearing rocks in the compositional range of monzodiorite, diorite and granodiorite, typically with locally abundant cognate mafic enclaves (multiple intrusions)

- From a compositional viewpoint (c.f. magmas with similar SiO_2) they are;
  - Rich in MgO, Cr, Ni
  - Hydrous
  - Alkali rich (high Na_2O and K_2O)
  - Enriched in LILE (e.g. Sr, Ba), LREE (e.g. La, Ce) and P_2O_5

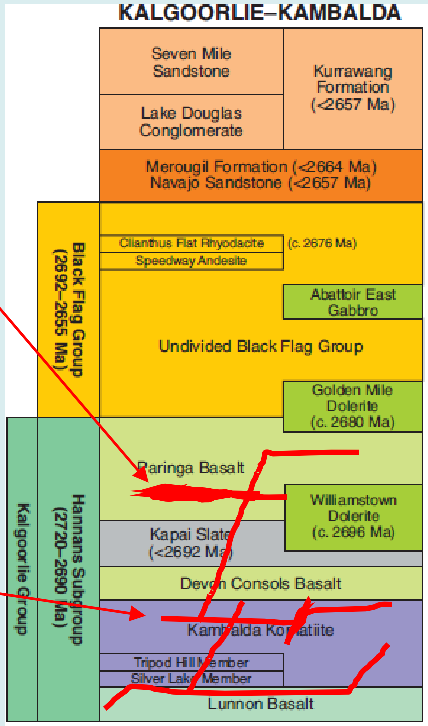
- These features make them very distinctive amongst Archean granite suites and, like lamprophyres, implicate an enriched or metasomatized lithospheric mantle source

- In the EGST, sanukitoids form a large proportion of what Champion and Cassidy and others refer to as the mafic granites, intruded between c. 2.67 to 2.65 Ga – along shears

The ‘porphyries’ – very common in DDH in the Kalgoorlie–Kambalda region



The ‘porphyries’ – very common in DDH in the Kalgoorlie–Kambalda region



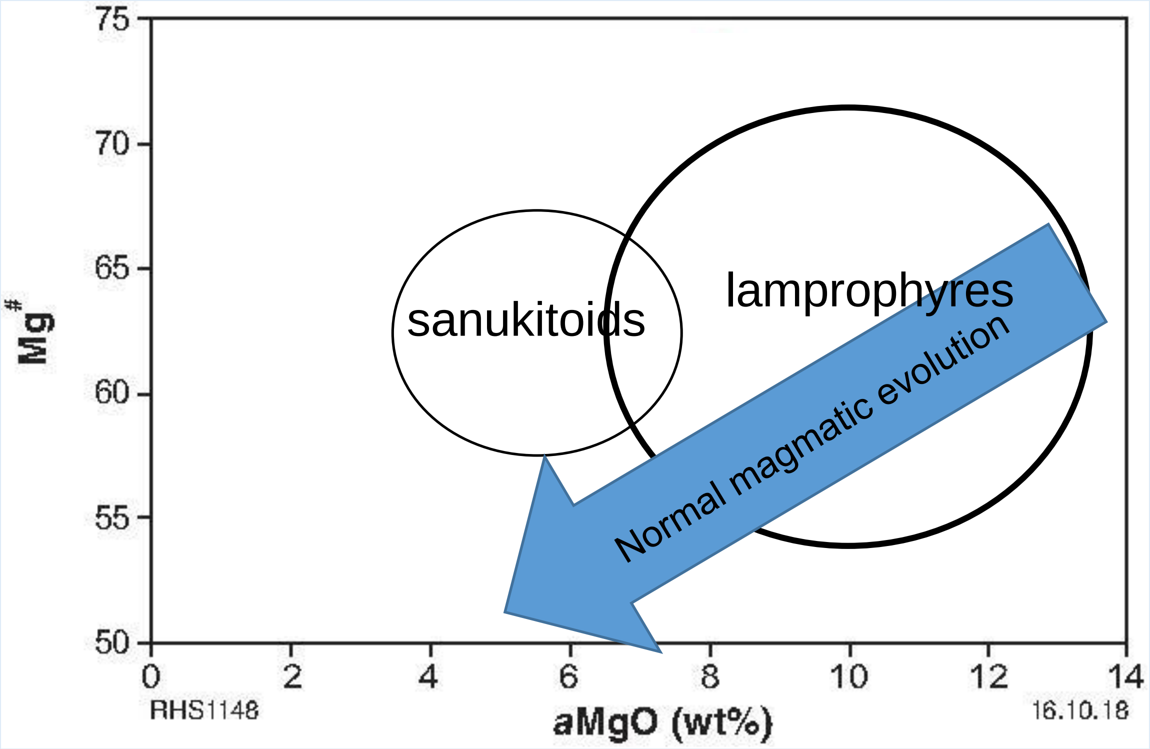
Calc-alkaline lamprophyre

MAFIC

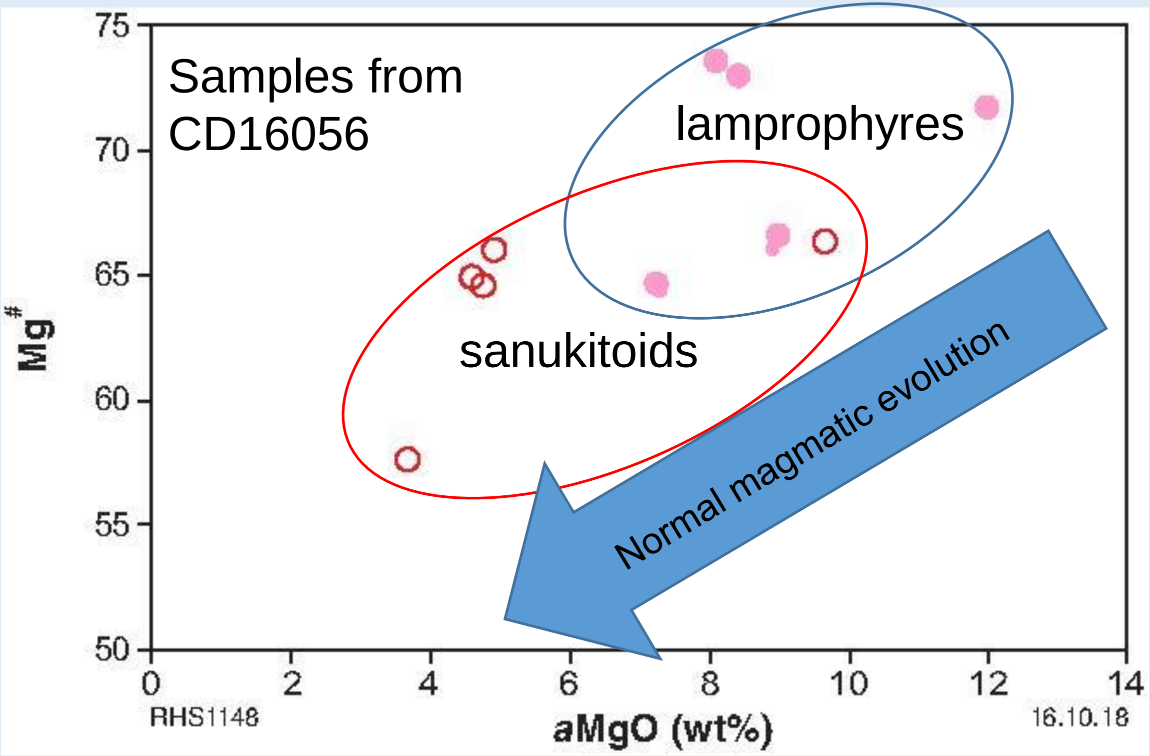
----------? Are they genetically related ----------

Sanukitoid

FELSIC

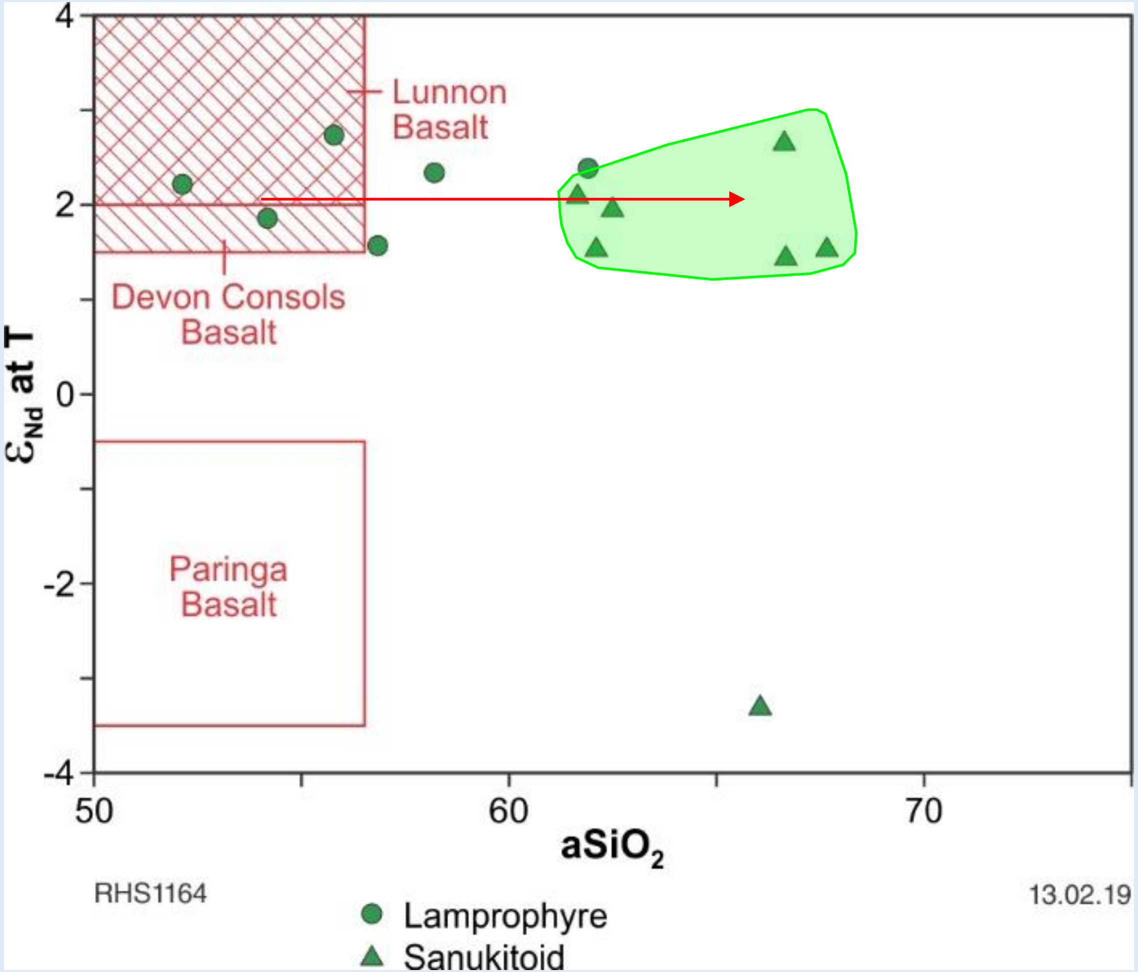


Early perspective – sanukitoids as primitive as regionally occurring lamrophyres and hence cannot be related. Thus the high-Mg# of sanukitoids must indicate direct derivation of these **felsic** rocks from the mantle (lithosphere)



Can show the same for samples from the nearby Kambalda DDH LD7006

For **GEOLOGICALLY RELATABLE** groups of lamprophyres and sanukitoids, the lamprophyres are clearly potential parental magmas to the sanukitoids.
So the sanukitoids we see are NOT direct melts of lithospheric mantle, they are the products of fractional crystallisation from primitive lamprophyre-like melts.



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ε_{Nd} at T
Lunnon Basalt
Devon Consols Basalt
Paringa Basalt
50
60
70
$aSiO_2$
RHS1164
13.02.19
Lamprophyre
Sanukitoid

Calc-alkaline lamprophyre → Sanukitoid

MAFIC (melting of lithospheric mantle) → Hornblende(–apatite) fractionation → FELSIC

EGST lamprophyres are probably genetically related to the sanukitoids (including the ‘porphyries’ that intrude the Kalgoorlie Group)……perhaps unsurprising!!

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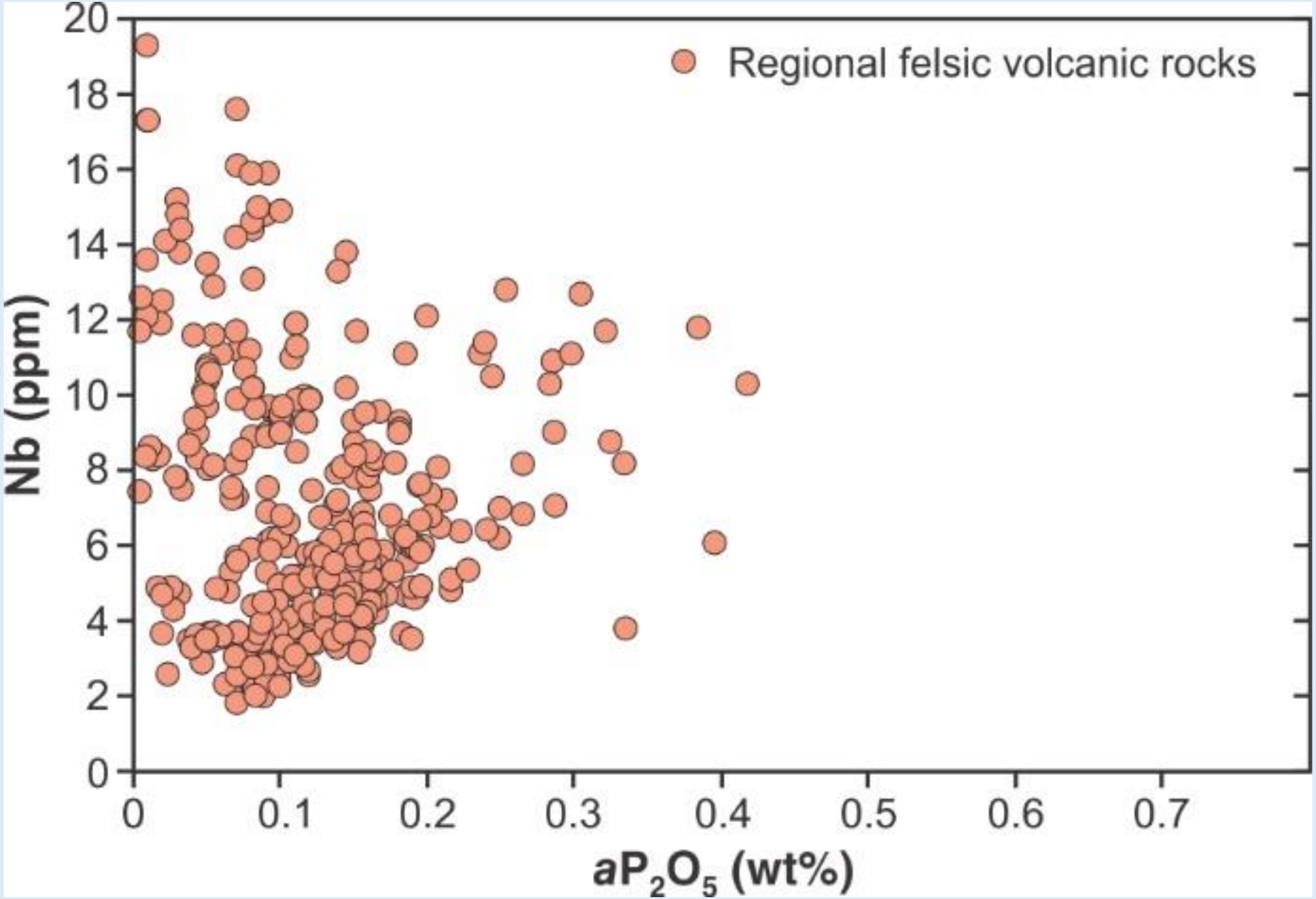
Compositional evolution within the sanukitoid series occurs within the crust !

Calc-alkaline lamprophyre → Sanukitoid

MAFIC (melting of lithospheric mantle) → Hornblende(–apatite) fractionation → FELSIC

Black Flag Group ???


Regional felsic volcanic rocks
Nb (ppm)
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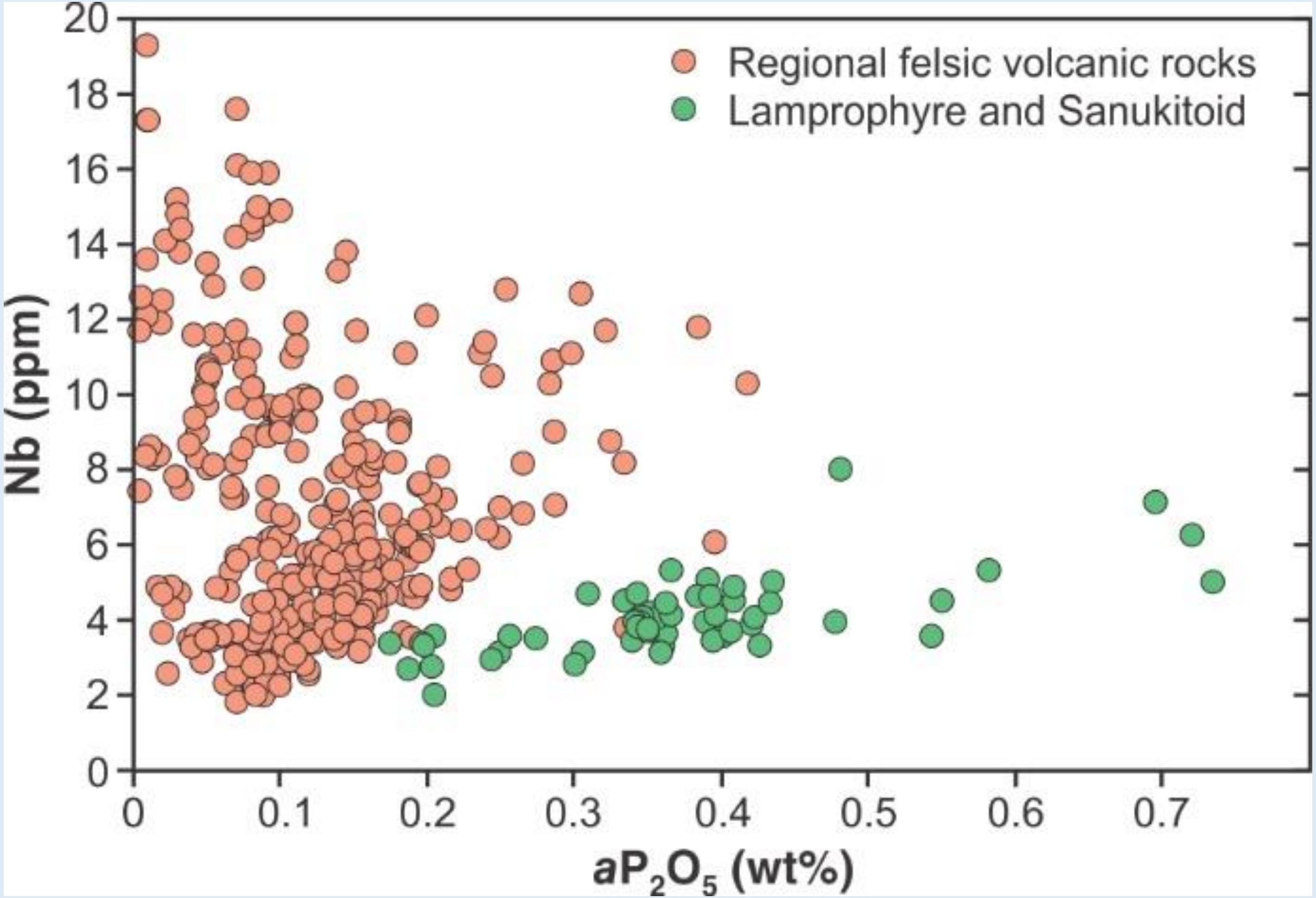
aP2O5 (wt%)



Regional felsic volcanic rocks
Lamprophyre and Sanukitoid
Nb (ppm)
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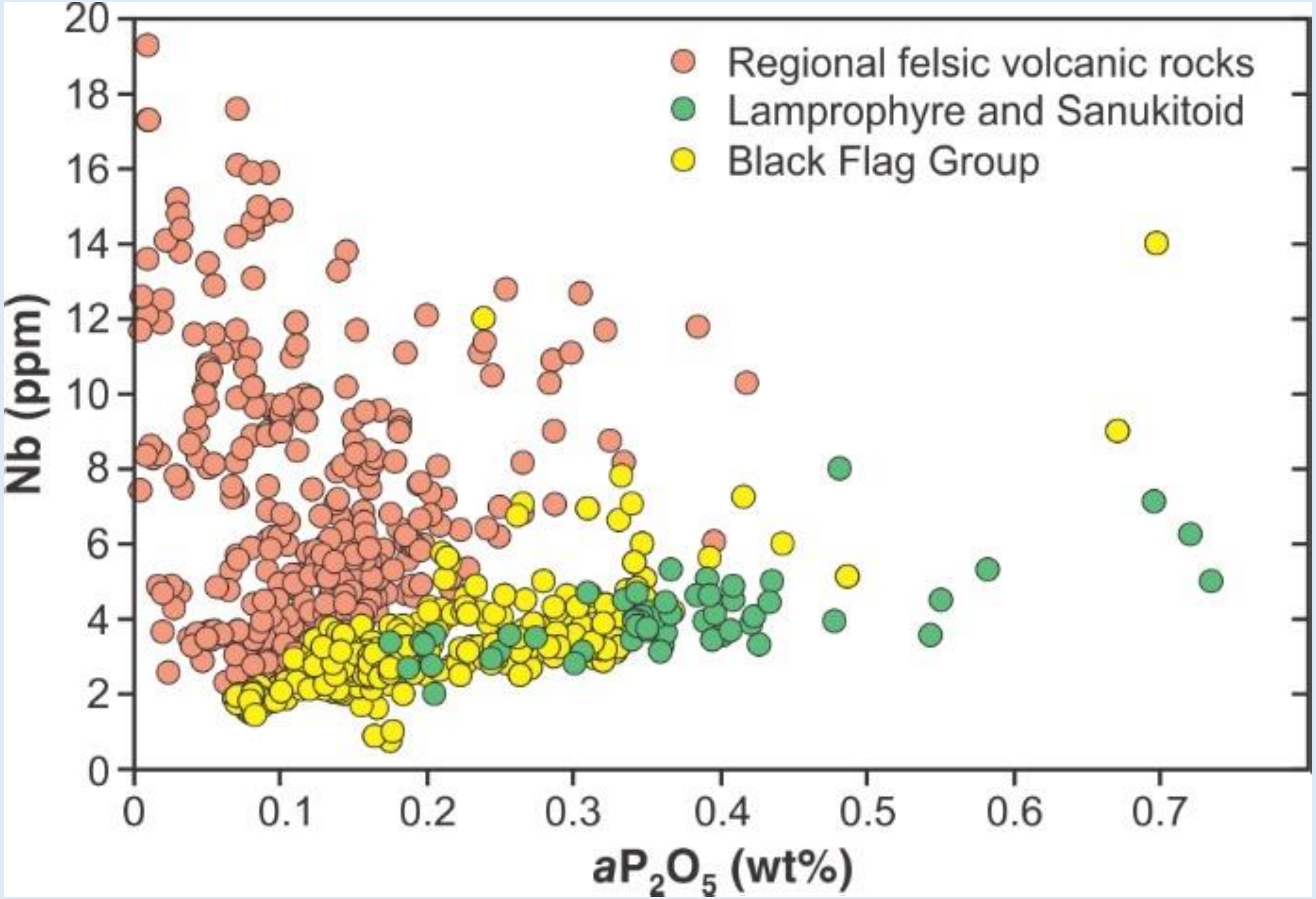

Regional felsic volcanic rocks
Lamprophyre and Sanukitoid
Black Flag Group
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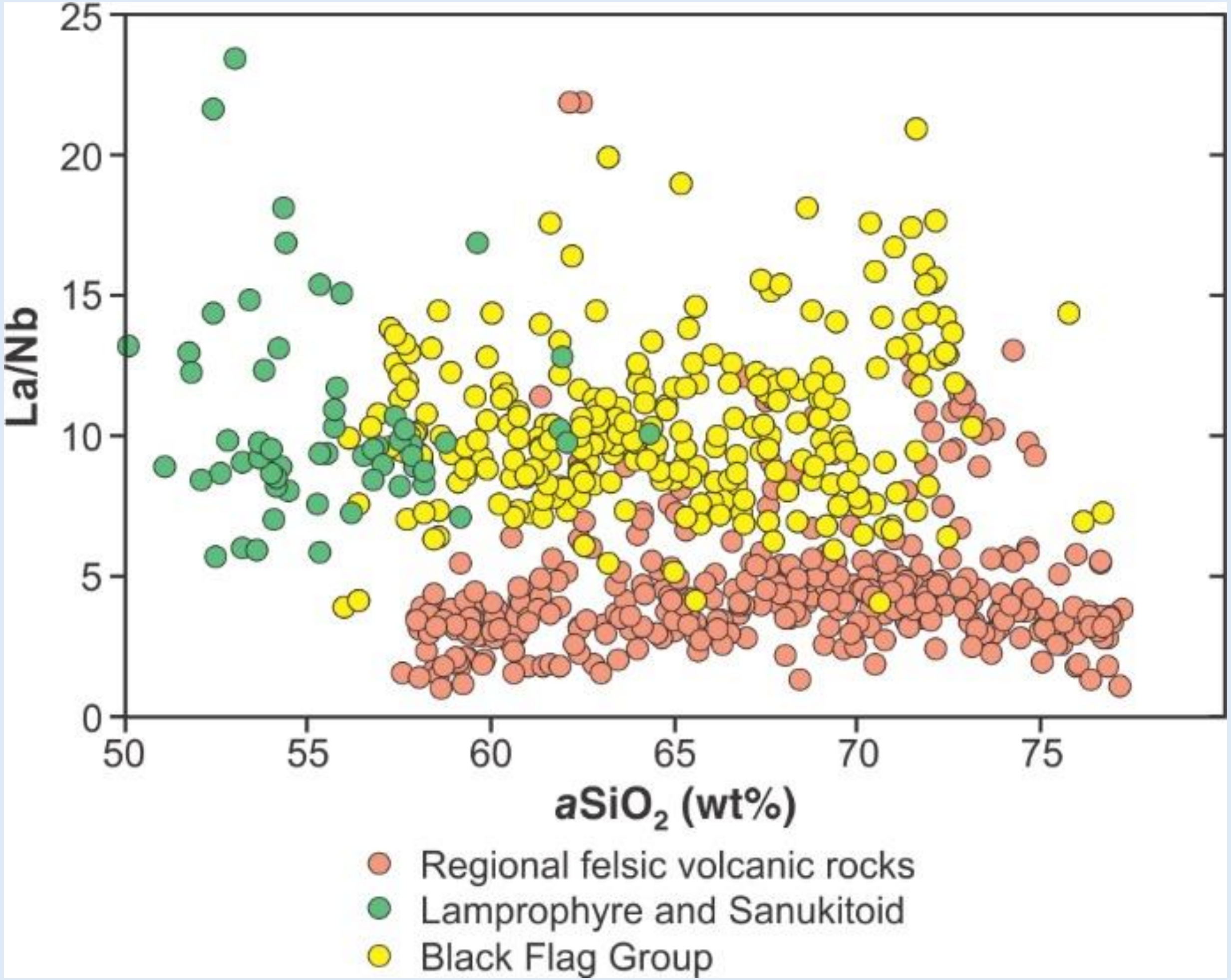

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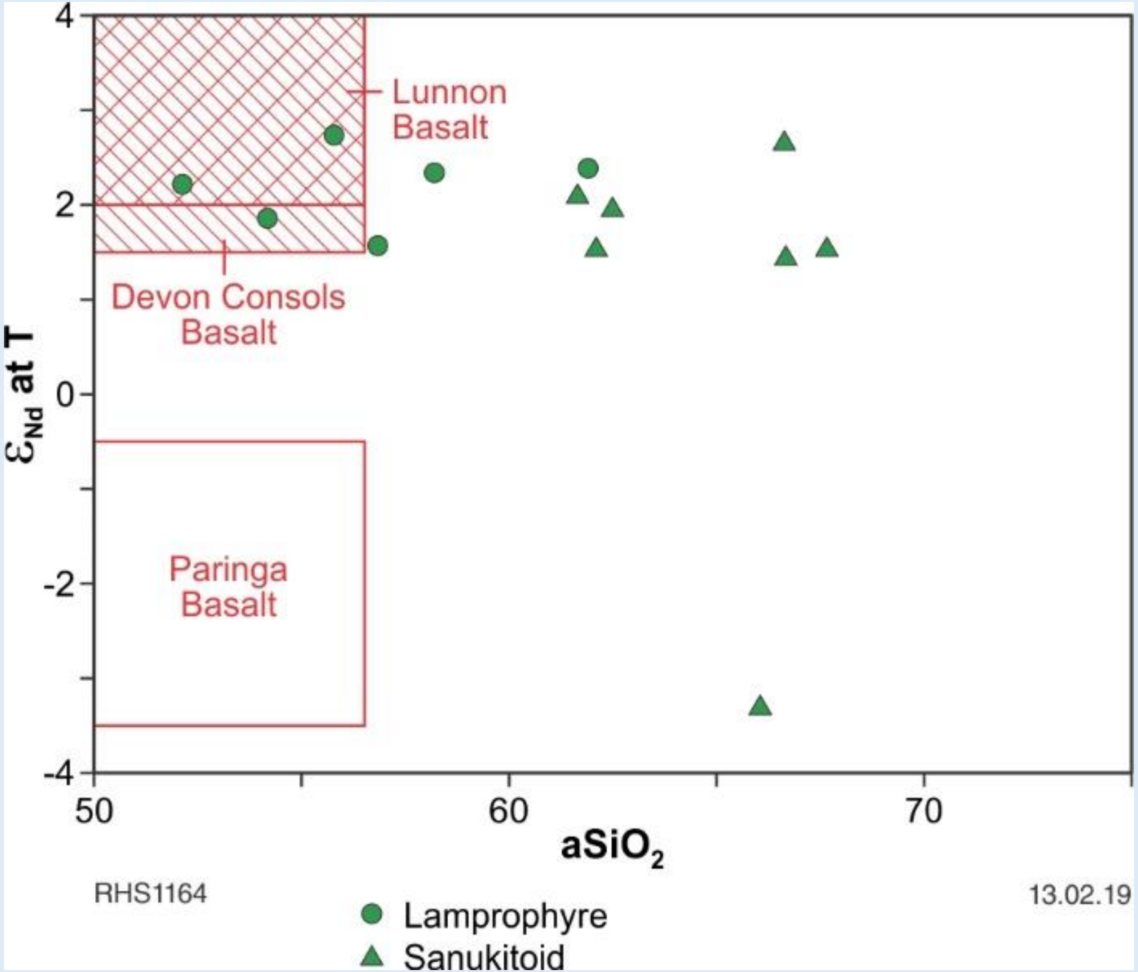
aSiO2 (wt%)
Regional felsic volcanic rocks
Lamprophyre and Sanukitoid
Black Flag Group



Lunnon Basalt
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Paringa Basalt
εNd at T
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Lamprophyre
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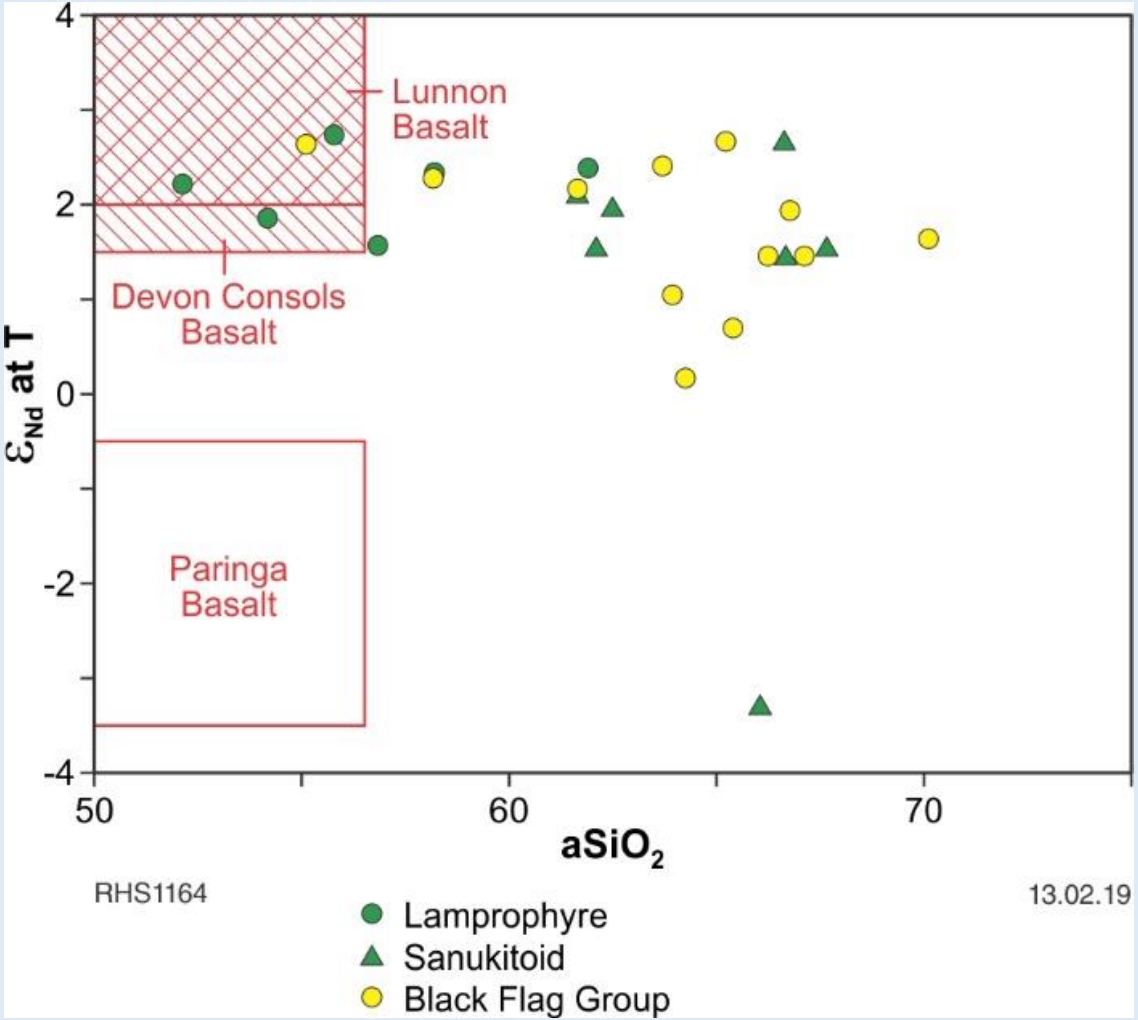

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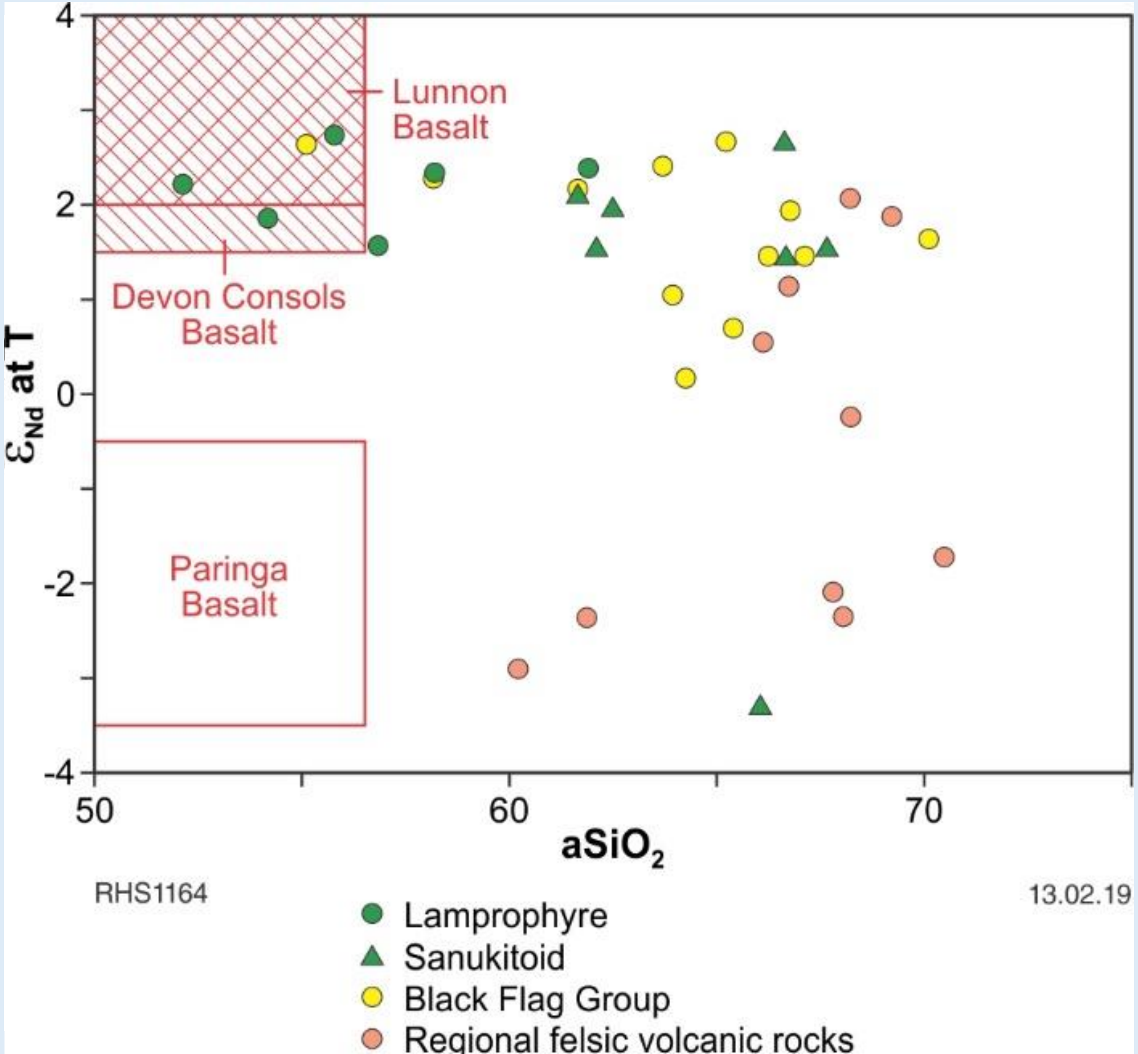

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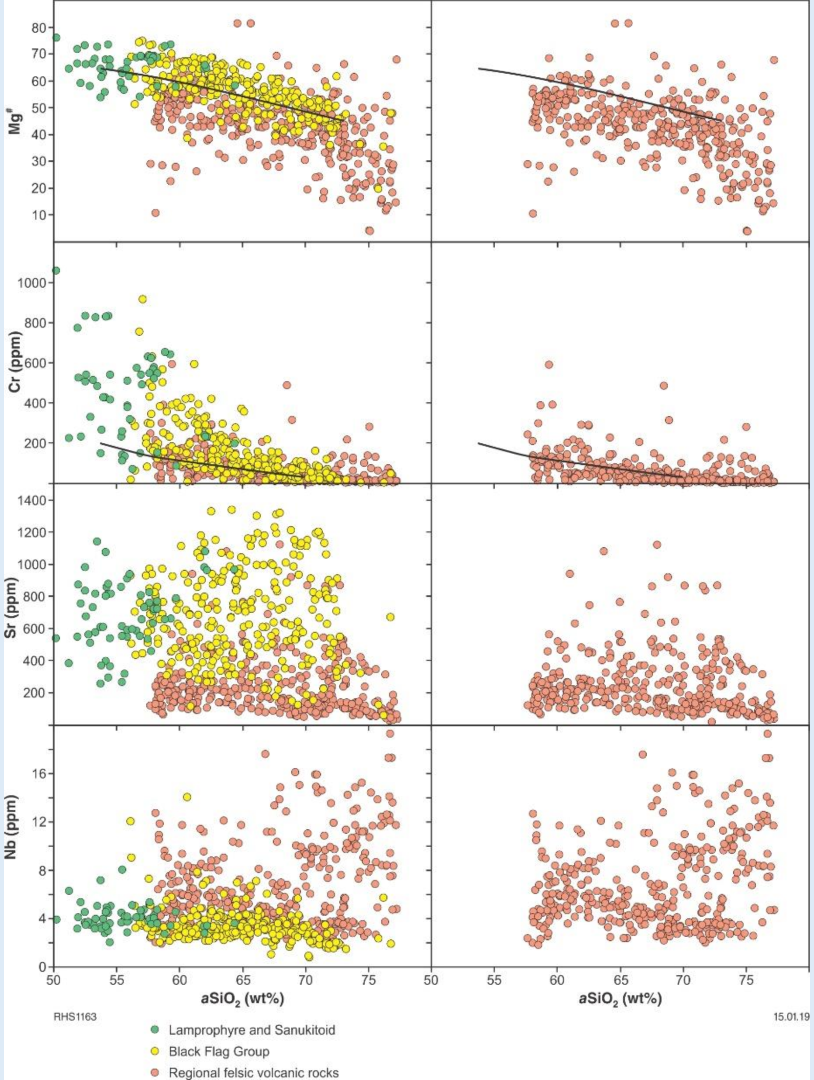
Regional felsic volcanic rocks



BFG volcanic and sub-volcanic rocks are:

- the eruptive or near eruptive equivalents of sanukitoid
- NOT TTG-like or ‘adakitic’ magmas
- distinct from typical Archean felsic suites of the EGST
- NOT derived through melting mafic crust
- derived through fractionation (in the crust) of lithospheric mantle melts.

We are looking at the highest level in a huge (crustal-scale), long-lived sanukitoid magmatic system.

Calc-alkaline lamprophyre → Sanukitoid

MAFIC (melting of lithospheric mantle) → Hornblende(–apatite) fractionation → FELSIC

Calc-alkaline lamprophyre → Sanukitoid

MAFIC (melting of lithospheric mantle) → Hornblende(–apatite) fractionation → FELSIC

Black Flag Group = sanukitoid – a massive, crustal-scale, multi-phased, sanukitoid magmatic system.

So what is, or why is there, this clear and significant relationship between these magmas and Au mineralization

?

Simple

Lamprophyres, sanukitoids and Au mineralization all like to hang around big cracks!

Petrological Constraints on Crystallization Conditions of Mesoarchean Sanukitoid Rocks, Southeastern Amazonian Craton, Brazil

MARCELO AUGUSTO DE OLIVEIRA[1,2]*, ROBERTO DALL'AGNOL[1,2] AND BRUNO SCAILLET[3]

[1]GROUP OF RESEARCH ON GRANITE PETROLOGY, INSTITUTO DE GEOCIÊNCIAS (IG), UNIVERSIDADE FEDERAL DO PARÁ (UFPA), CAIXA POSTAL 8608, 66075-900, BELÉM, PARÁ, BRAZIL

[2]PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA E GEOQUÍMICA (PPGG), IG, UFPA, 66075-900, BELÉM, PARÁ, BRAZIL

[3]CNRS/INSU, UNIVERSITÉ D'ORLÉANS, UNIVERSITÉ FRANÇOIS RABELAIS TOURS, INSTITUT DES SCIENCES DE LA TERRE D'ORLÉANS, 1A RUE DE LA FÉROLLERIE, 45071 ORLÉANS CEDEX 2, FRANCE

RECEIVED JULY 2, 2009; ACCEPTED AUGUST 6, 2010

We report petrological and geochemical data for the 2·87 Ga Rio Maria sanukitoid granodiorite and associated rocks from Mesoarchean granite–greenstone terranes of the eastern Amazonian craton, Brazil. The dominant rocks have granodiorite to subordinate monzogranitic compositions, with minor proportions of intermediate quartz diorites or quartz monzodiorites, in addition to mafic end-members occurring as layered rocks or as enclaves. The mineral assemblage is dominated by amphibole–plagioclase–biotite and epidote minerals, all of inferred magmatic origin, pyroxenes being notably absent. Textural and compositional criteria indicate that amphibole is a principal mineral on the liquidus of all the Rio Maria rocks. Crystallization conditions have been derived from a comparison between natural phase assemblages, proportions and compositions and experimental studies carried out on similar magma compositions. The comparison shows that the parental magmas were water-rich, with more than 7 wt % dissolved H_2O, with crystallization temperatures in the range 950–680°C. The Mg/(Mg + Fe) ratios of both amphibole and biotite indicate fO_2 conditions in the range NNO + 0·5 to NNO + 2·5 (where NNO is nickel–nickel oxide buffer), therefore pointing to both water-rich and oxidizing conditions for sanukitoid magmas. Amphibole compositions indicate emplacement at around 200 MPa and record a high-pressure stage of magma crystallization around 600–900 MPa. Sanukitoid magmas share two of the principal characteristics of modern arc magmas, elevated redox state and volatile contents, which suggest that they may have formed in a geodynamic environment broadly similar to present-day subduction zones.

KEY WORDS: *Amazonian craton; crystallization conditions; high-Mg granitoids; mineral chemistry; sanukitoid*

INTRODUCTION

Sanukitoid suites have been reported from several cratons (Stern & Hanson, 1991; Smithies & Champion, 2000; Bagai et al., 2002; Moyen et al., 2003; Halla, 2005; Kovalenko et al., 2005) and are now recognized as an important component of Archean terranes (Condie, 2005; Martin et al., 2005). Sanukitoids were formed during the late Archean (2·95–2·54 Ga) and are high-Mg rocks that display geochemical characteristics similar to both mantle- and crust-derived magmatic rocks. Extensive occurrences of sanukitoid rocks were recently identified in the Mesoarchean Rio Maria granite–greenstone terrane of the eastern Amazonian craton (Althoff et al., 2000; Leite, 2001; Souza et al., 2001; Oliveira et al., 2009). This terrane consists predominantly of greenstone belts, tonalite–trondhjemite–granodiorite (TTG) suites and sanukitoid rocks, with subordinate calc-alkaline leucogranites

The primary mineralogy and geochemistry shows us that even the most primitive sanukitoids are amongst the most volatile-rich Archean magmas that we know of.

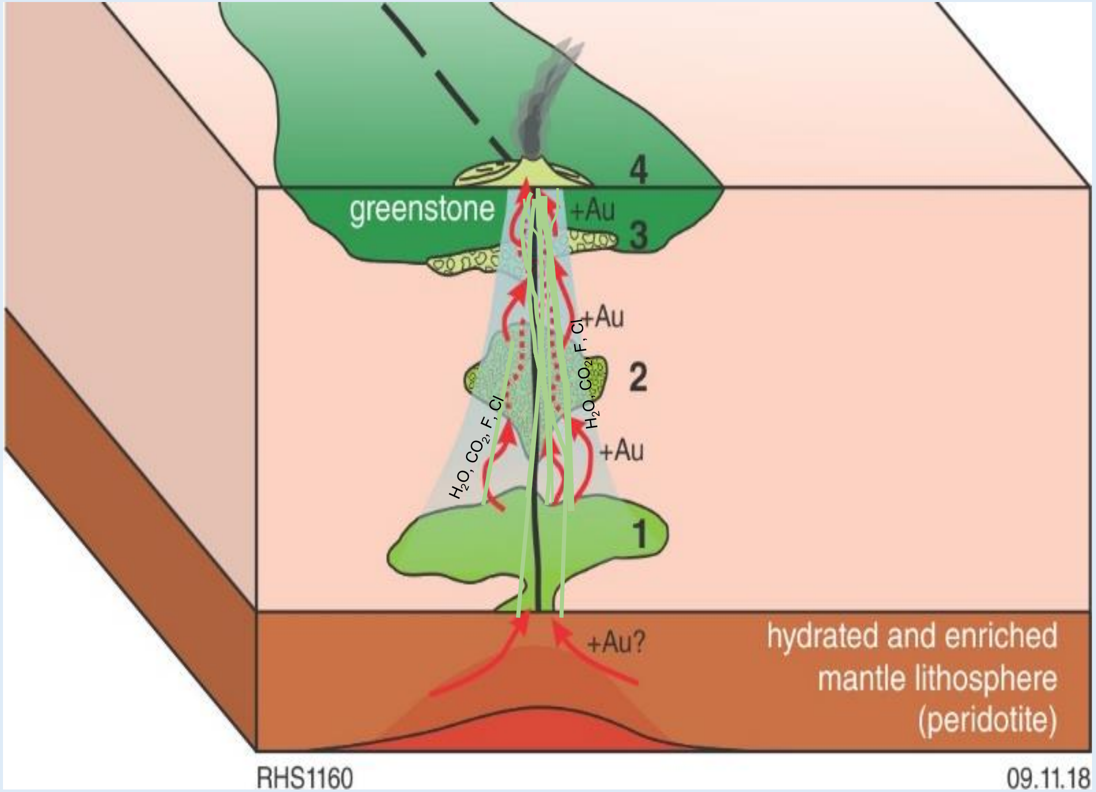
Journal of Petrology, 2010

Parental magmas

- 7 wt% dissolved H_2O
- Up to 950ºC
- fO_2 ~ *NNO*+0.5 to 2.5

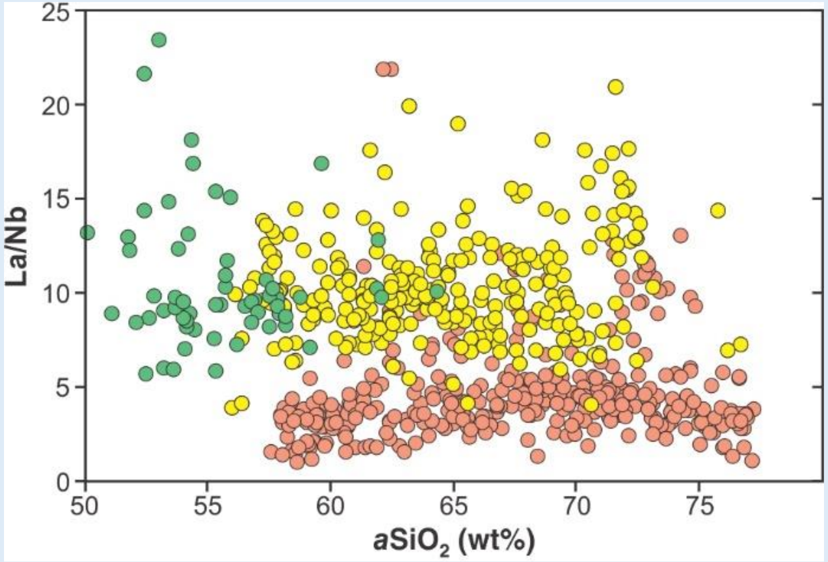
1) Explicitly implicate close proximity to a translithospheric crack, that has tapped volatile-rich mantle

2) Primitive magmas derived from the mantle but sanukitoid/BFG series represents **fractionation in the crust**



- Very wet and oxidized primitive magmas fractionating to the dacitic (and even rhyolitic) compositions of the BFG reduce in volume but give off a large amount of volatiles.

- Even if primitive magmas (i.e. lamprophyres in dykes!!) don't carry Au, there is the huge potential for net transfer of metals towards the surface in a series of punctuated and overlapping magmatic/hyrothermal events.



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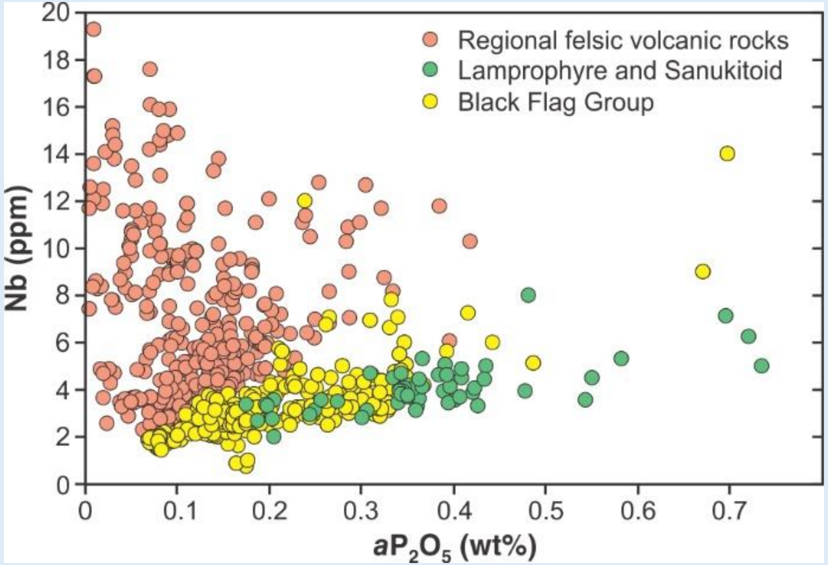
aSiO2 (wt%)



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Nb (ppm)
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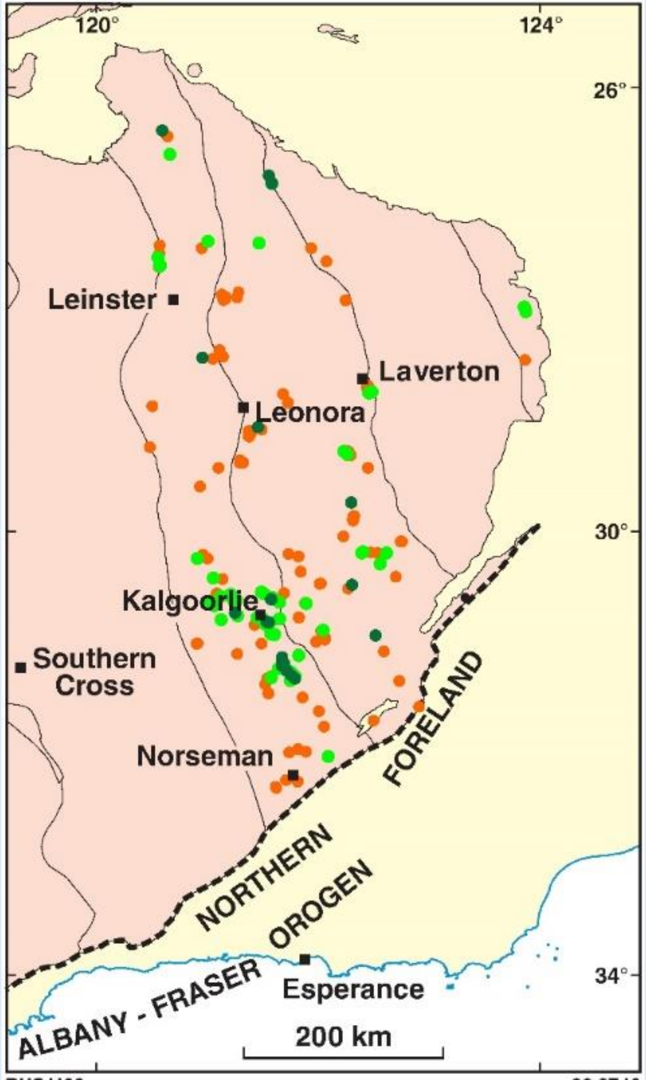
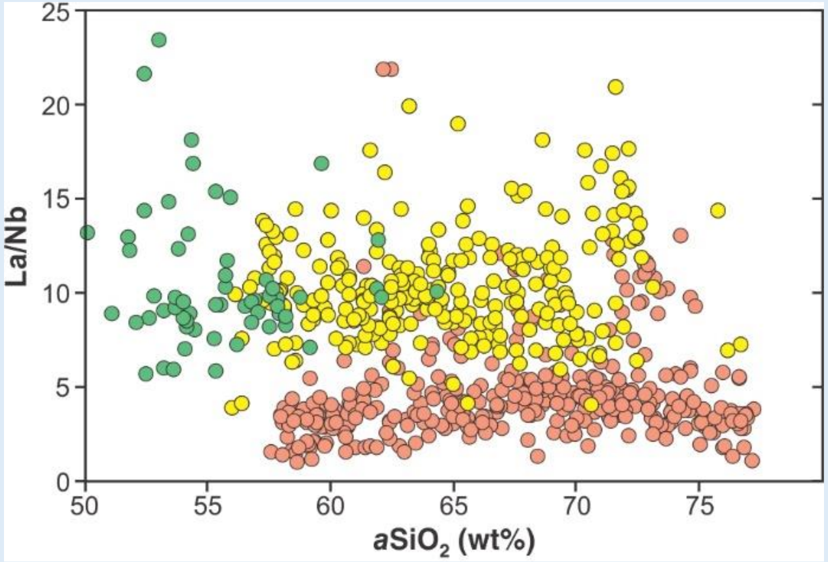
aP2O5 (wt%)



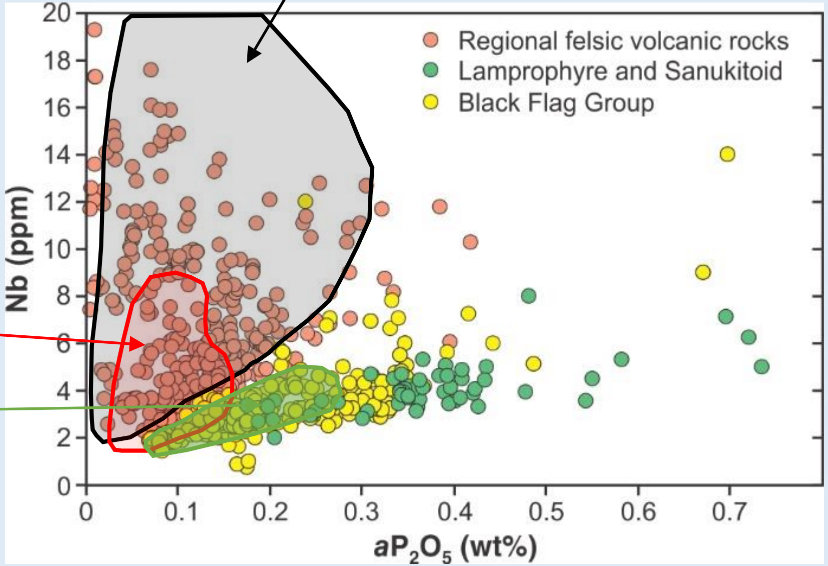
- Regional felsic volcanic rocks and sub-volcanic porphyritic intrusions
- BFG and compositionally similar high-Mg andesites and dacites
- Lamprophyres and sanukitoids

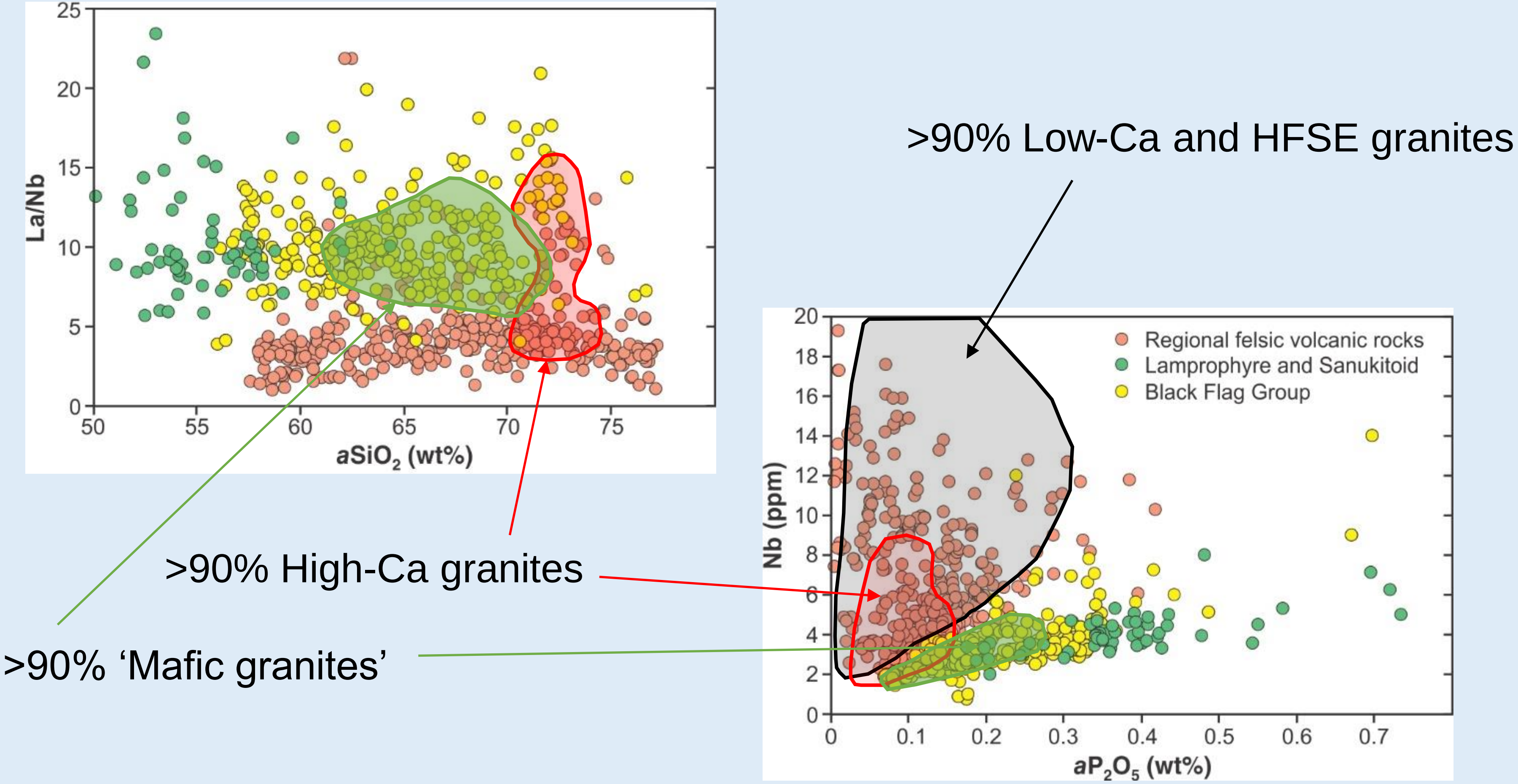


>90% Low-Ca and HFSE granites

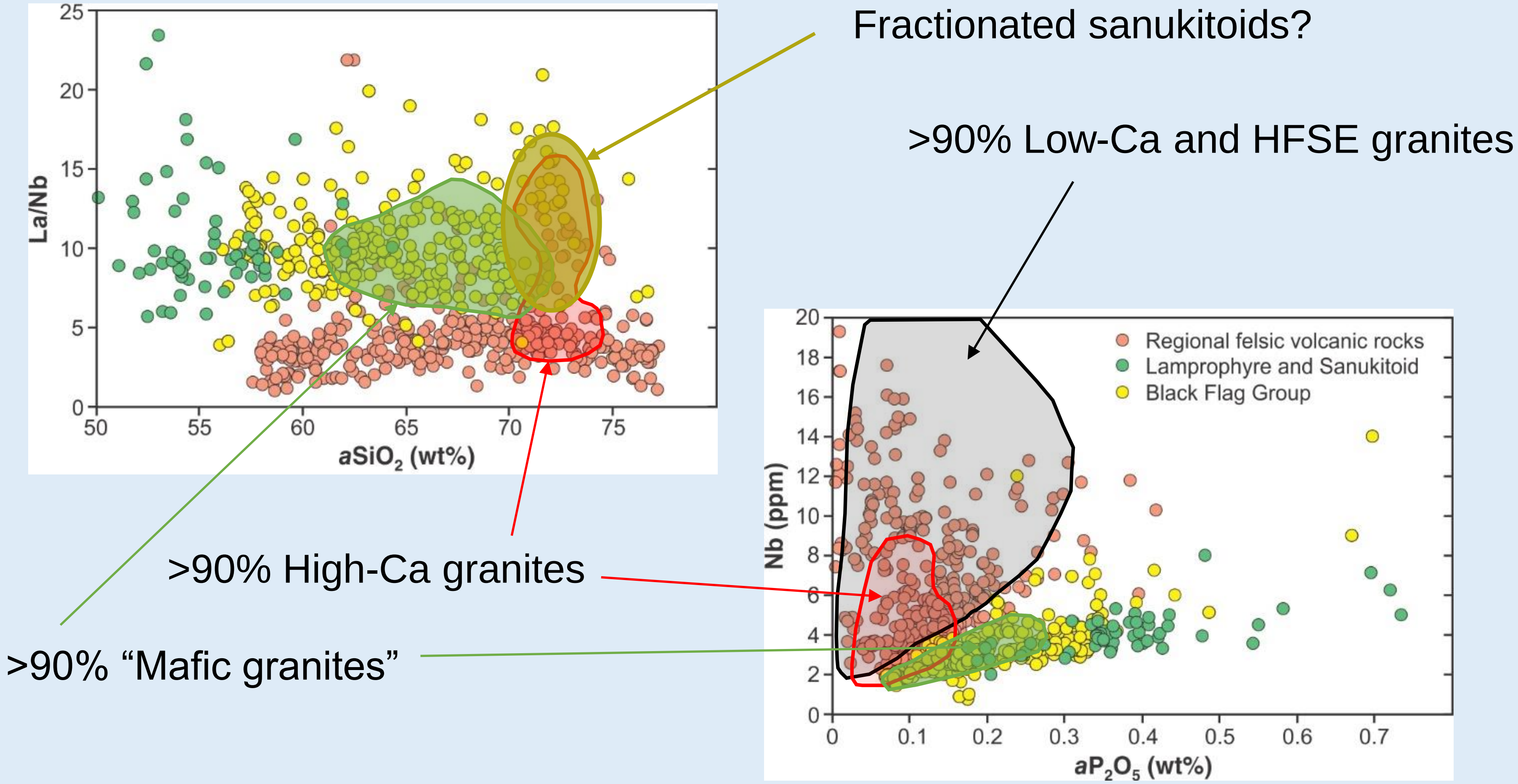
>90% High-Ca granites

>90% ‘Mafic granites’



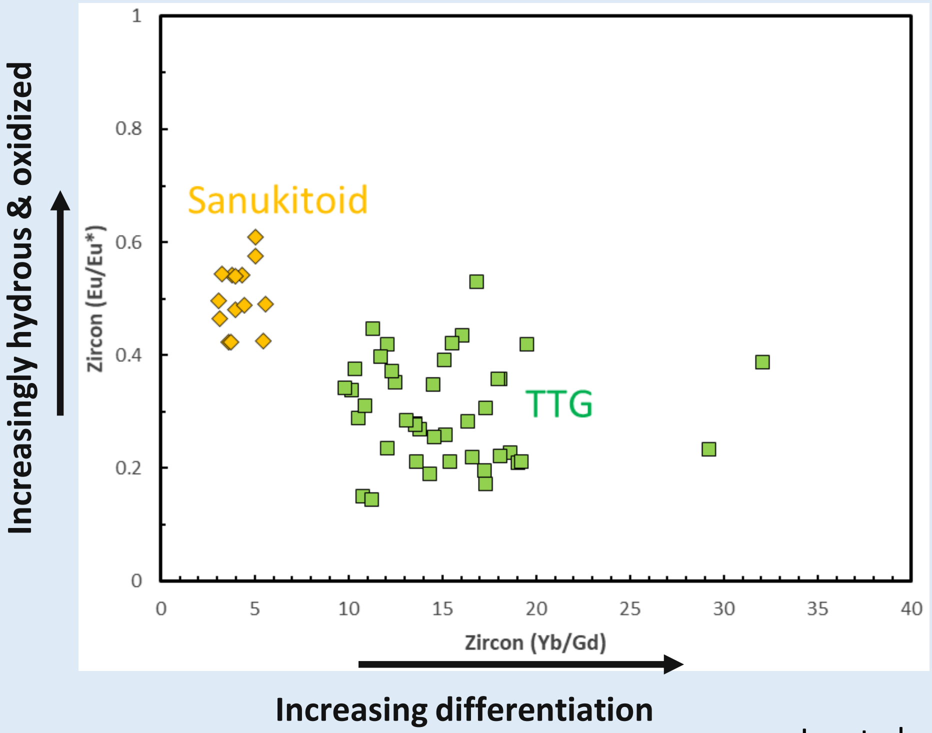


>90% Low-Ca and HFSE granites
>90% High-Ca granites
>90% 'Mafic granites'
La/Nb
25
20
15
10
5
0
50
55
60
65
70
75
aSiO2 (wt%)
Nb (ppm)
20
18
16
14
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
aP2O5 (wt%)
Regional felsic volcanic rocks
Lamprophyre and Sanukitoid
Black Flag Group



Fractionated sanukitoids?
>90% Low-Ca and HFSE granites
>90% High-Ca granites
>90% “Mafic granites”
La/Nb
25
20
15
10
5
0
50
55
60
65
70
75
aSiO$_2$ (wt%)
Nb (ppm)
20
18
16
14
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
aP$_2$O$_5$ (wt%)
Regional felsic volcanic rocks
Lamprophyre and Sanukitoid
Black Flag Group

Zircon compositions preserve magmatic heritage



Lu et al., 2019 submitted to Nature Geoscience