FEMIC MAGMA:
A NEW PLAYER IN THE GAME

A few examples of alkaline complexes which, from my experience, are eloquent and worthy of close consideration

You will be able to judge on the relevance of femic magmas to ore deposits research

What on Earth are femic magmas???

DEFINITIONS……

- Mafic, adj., applied to a rock or a mineral, first defined by Henry Washington around 1900. Its root: ma for magnesium, f for ferrum, + ic, with the implication that Mg > Fe
- Femic, adj., defined at the same time, and applied to a rock or mineral by Washington, referring to the case where Fe > Mg
- Femic is rarely used these days, as “mafic” is applied loosely to all dark minerals… but is that acceptable if Mg is a trace element or absent?

MAJOR TREND IN FRACTIONAL CRYSTALLIZATION

- Mg-rich minerals crystallize early. The field of stability of these minerals extends to high T, and they are on or close to the liquidus
- Mg progressively becomes depleted in the melt, in all magmas
- One expects an Fe-enrichment trend
- Classic example: the Skaergaard complex, in eastern Greenland; another: the Bushveld complex in South Africa

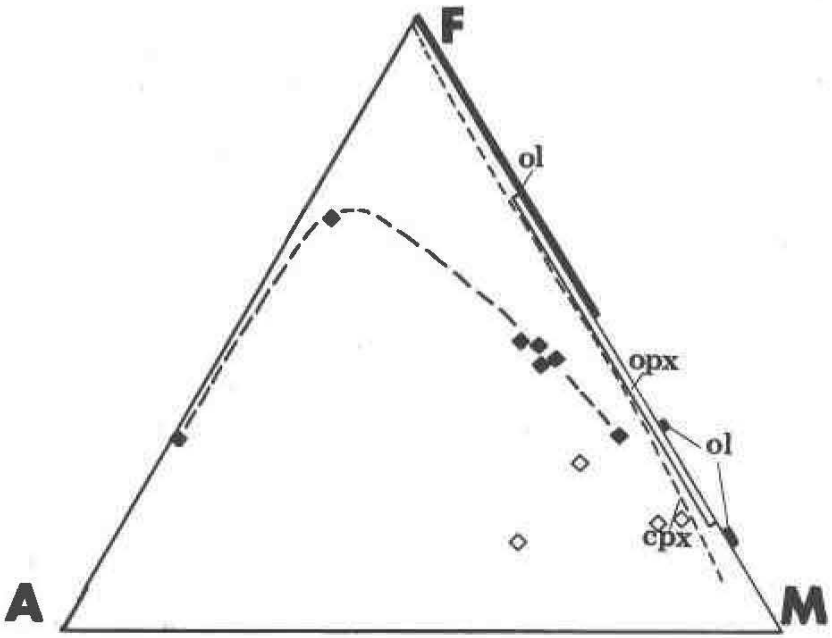


Fig. 4. AFM projection (molecular proportions) of rocks and cumulus minerals, Bushveld Complex, South Africa. Solid symbols represent noncumulus rocks (residual liquids); unfilled symbols represent cumulus rocks. Mineral abbreviations are those in Figure 2. Data are from Frick (1973); Wager and Brown (1967); Daly (1928); Gruenewaldt (1972); Van Zyl (1970); Atkins (1969).

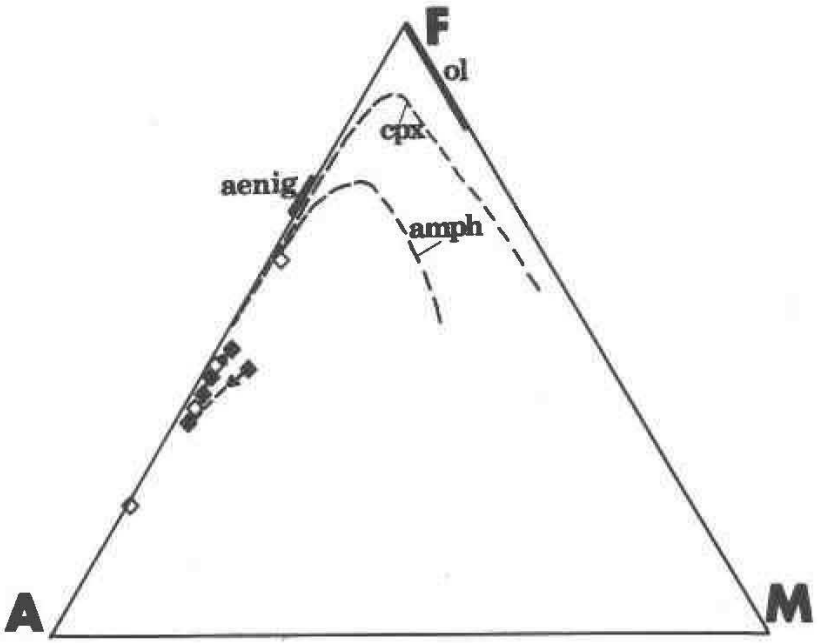


Fig. 5. AFM projection (molecular proportions) of rocks and cumulus minerals, Ilimaussaq Complex, southwest Greenland. Rock symbols as in Figure 4. Aenig = aenigmatite, amph = amphiboles. Other mineral abbreviations are those in Figure 2. Data are from Ferguson (1970); Larsen and Steenfelt (1974); Larsen (1976). Residual liquids evolved toward A, then toward F.

Bushveld, tholeiitic

Ilímaussaq, alkaline

Barker (1978, Figs. 4, 5)

AS A RESULT OF FRACTIONATION…

- The Mg content of the magma tends to zero
- The dark minerals approach the Fe end-member of their respective solid-solution series
- The upper thermal stability of the mineral drops progressively as the Fe end-member is approached (why might this be???)
- Arfvedsonite or annite or may well be the **last** mineral to crystallize…… or magnetite

Mont Saint-Hilaire complex, Quebec

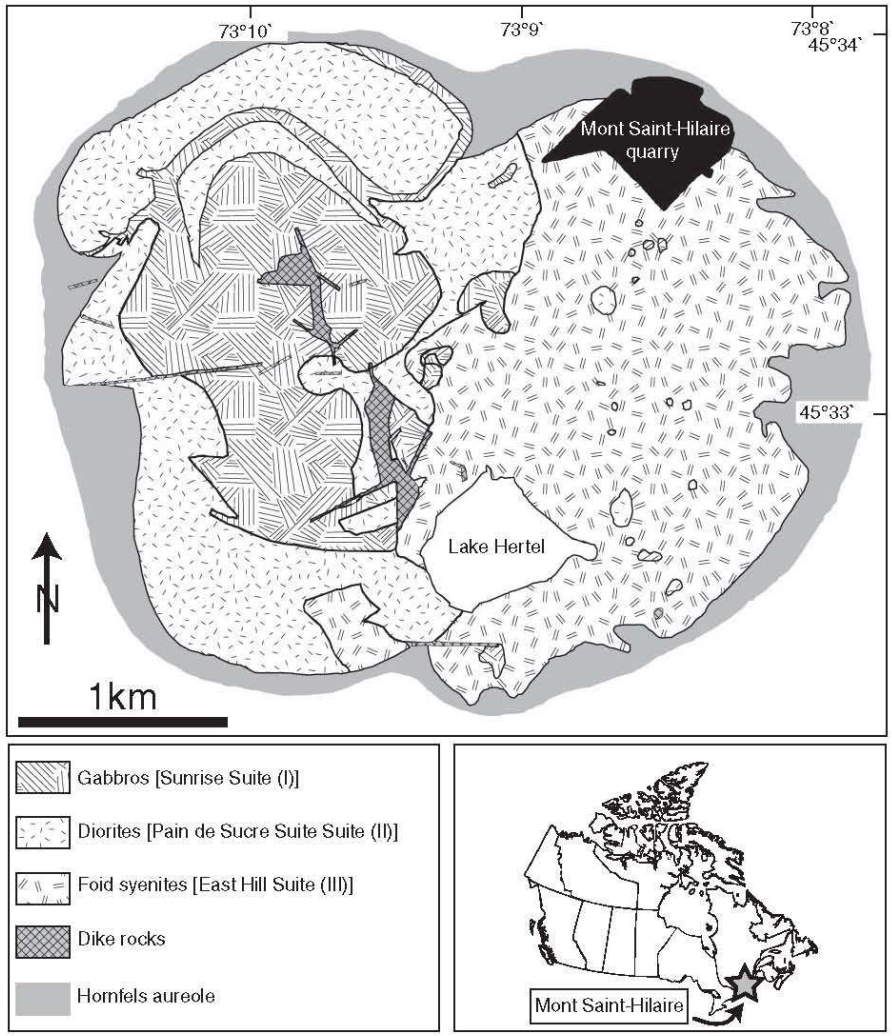


Fig. 1. Simplified geological map of the Mont Saint-Hilaire complex after Currie (1989). No further subdivision of the gabbro and diorite units can be undertaken owing to the poor outcrop in most parts of the complex. Sample coordinates are provided in the Electronic Appendix.

The nepheline–sodalite syenite exposed in the quarry is locally pegmatitic, and contains an array of fascinating textures …

Schilling et al. (2011)

Pegmatitic Ne–Sdl syenite, “naujaite”

How do you interpret this texture?

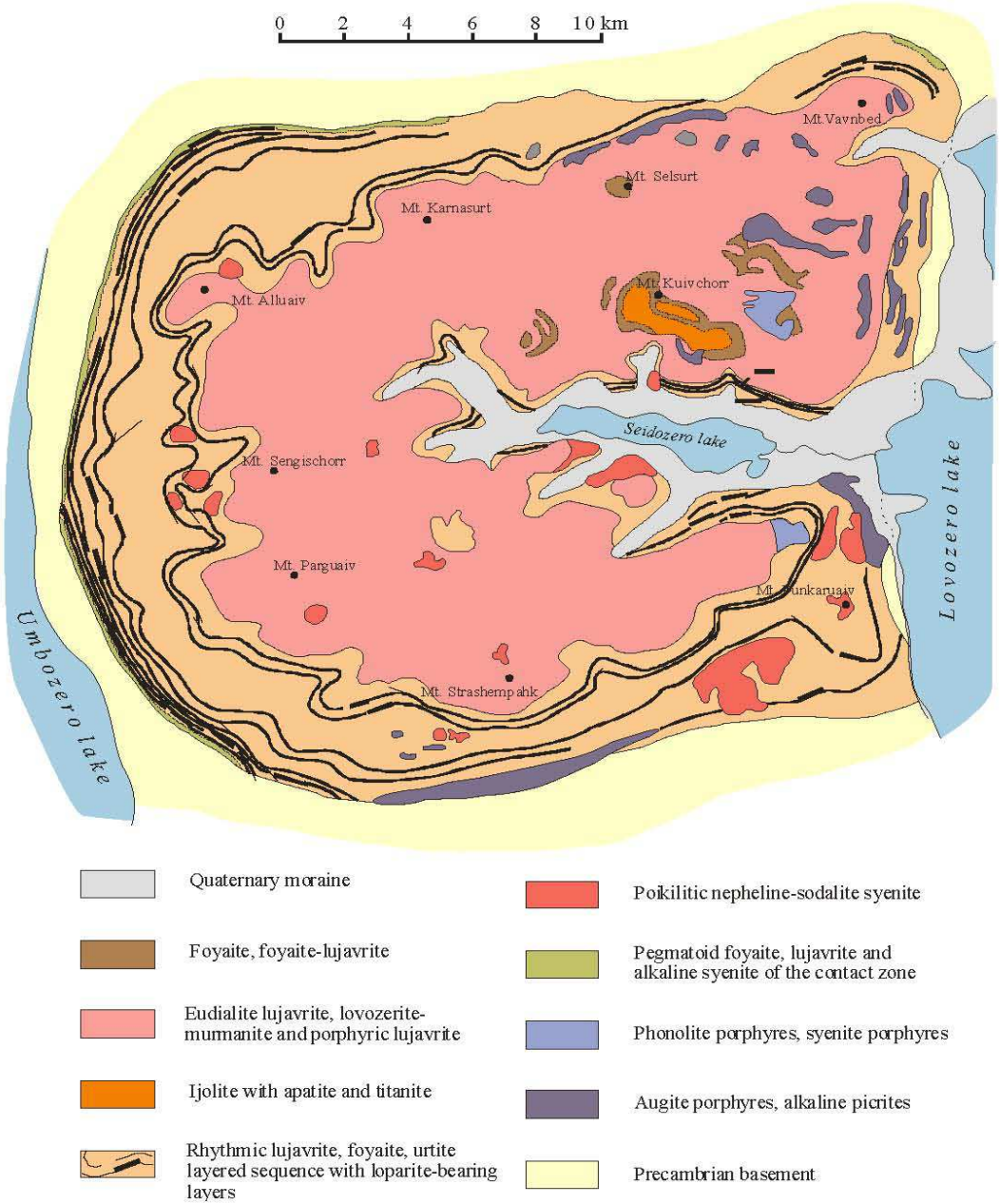


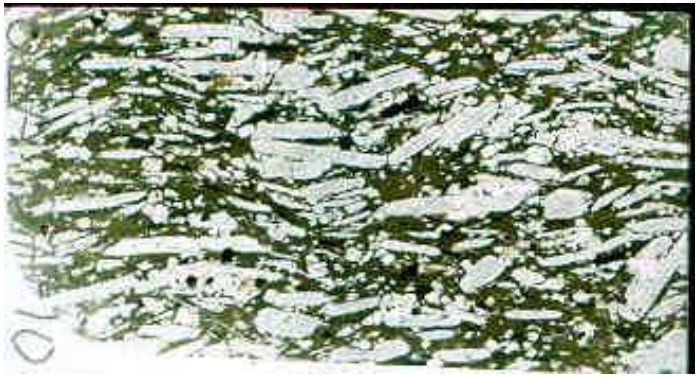
Fig. 5. Geological map of the Lovozero massif generalized from V.I.Gerasimovsky et al., 1966, I.V.Bussen and A.S.Sakharov (1972).

The Lovozero alkaline complex, Kola Peninsula, Russia

Lujavrite: a melanocratic nepheline syenite rich in Eud, Arf, Ae

Arzamastsev *et al*. (2008)

LUJAVRITE, LOVOZERO ALKALINE COMPLEX, RUSSIA



End-stage magmatic crystallization in an agpaitic igneous complex. Na-dominant arfvedsonitic amphibole forms a matrix to the alkali feldspars (subsolvus crystallization). The magma is becoming increasingly alkaline, Fe-rich, and highly enriched in REE and HFSE. The amphibole is on the solidus.

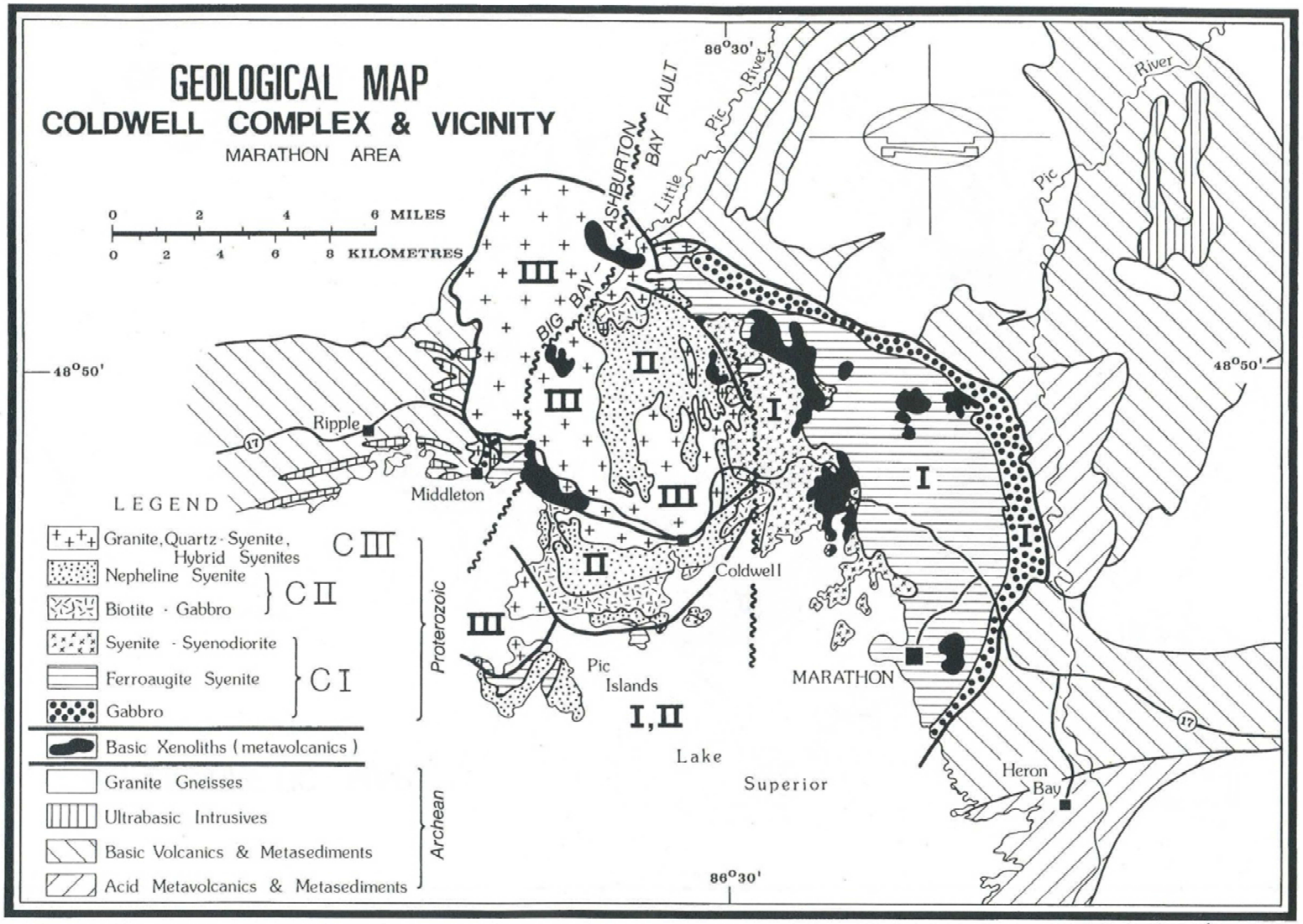


Figure 1. Geological map of the Coldwell complex based on Puskas (1967) together with our observations and interpretations of the sequence of magmatic events.

Mitchell & Platt (1994)

AGPAITIC NEPHELINE SYENITE, CENTER II

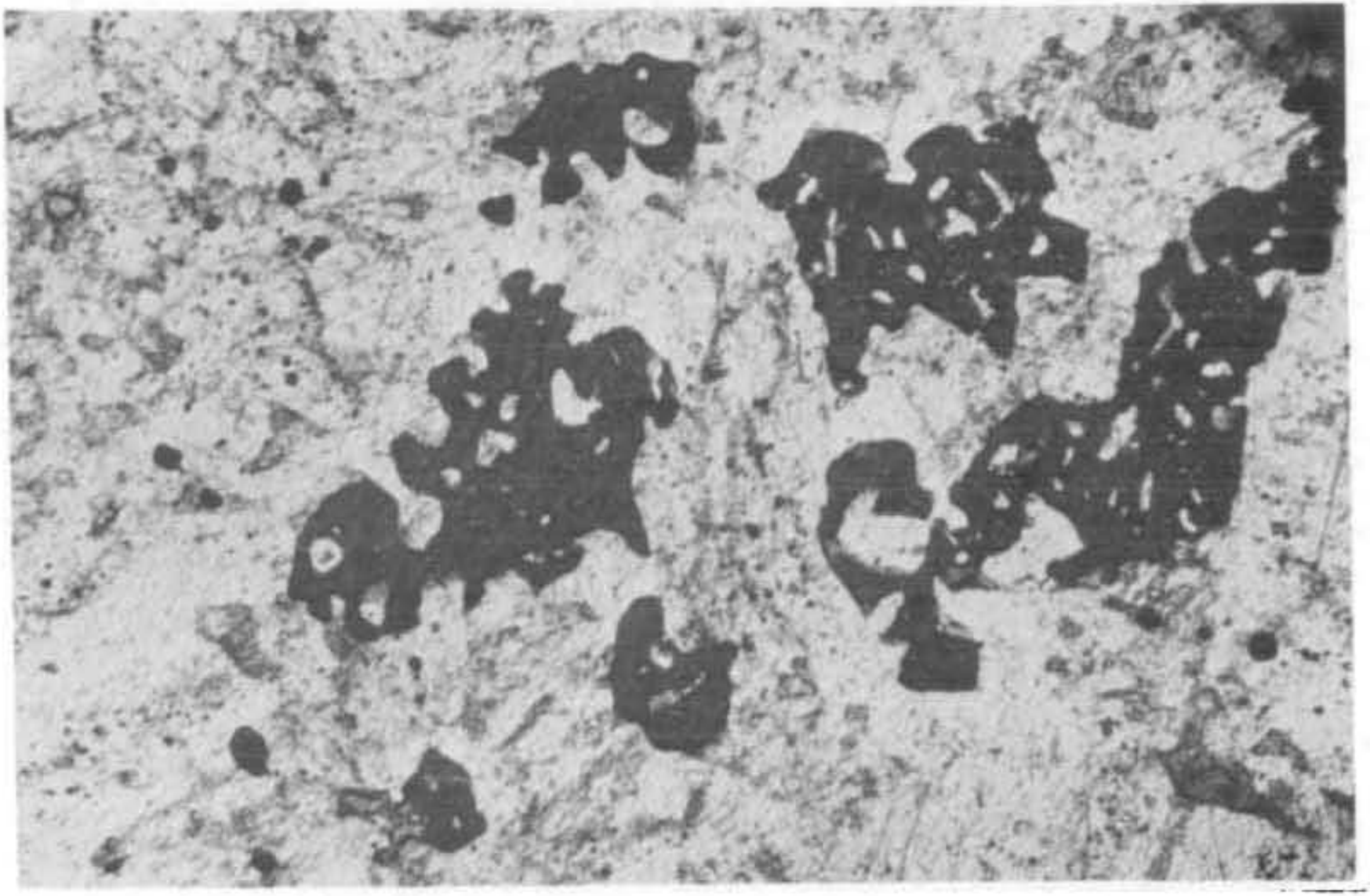
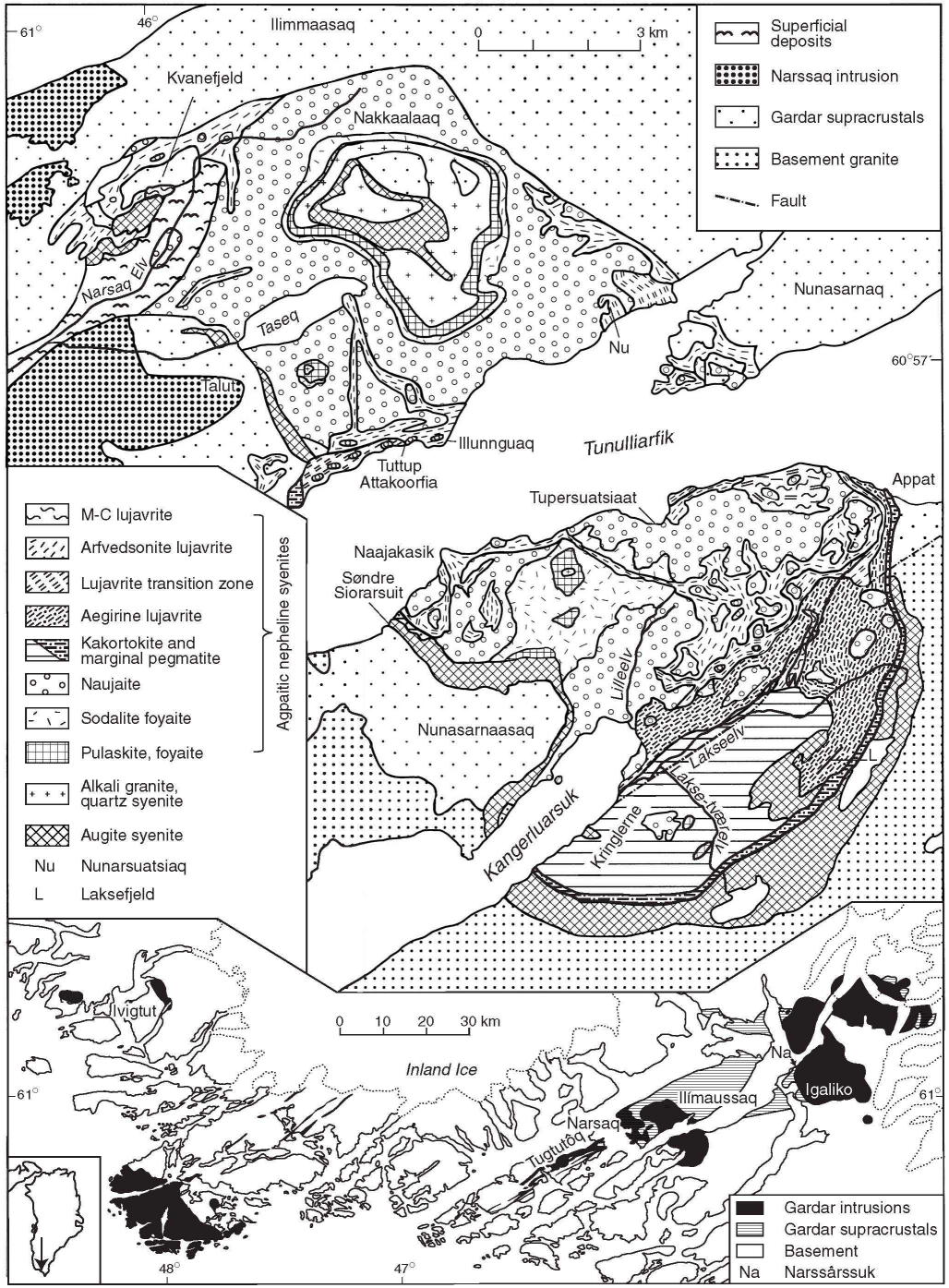


PLATE 3. Amphiboles disaggregated and modified in their habit by feldspar recrystallization (×62). Redsucker Cove.

Mitchell & Platt (1978)



The Ilímaussaq alkaline complex, southern Greenland

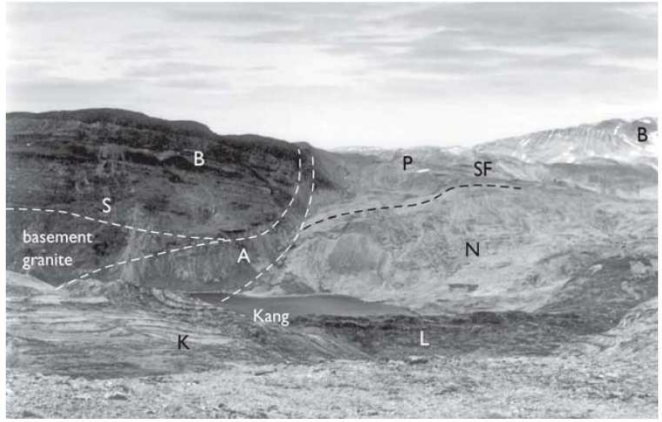
Naujaite: poikilitic agpaitic nepheline syenite, Sdl is early

Foyaite: hypersolvus nepheline syenite having a trachytic texture

Pulaskite: nepheline-bearing syenite

Sørensen (2001)

Fig. 3. A section through the complex viewed from Kringlerne plateau towards the north. Foreground layered kakortokites (**K**), the dark rocks in the middle ground belong to the intermediate sequence of lujavrites (**L**). The light grey rocks in the wall facing south towards the fjord Kangerluarsuk (**Kang**) are made up of the roof series with pulaskite-foyaite (**P**) and sodalite foyaite (**SF**) in the upper part, naujaite (**N**) in the lower part bordering the augite syenite shell (**A**). The contact between the roof zone and the basement granite and its overlying sandstone (**S**) with intercalated basalt (**B**) on the mountain Nunasarnaasaq (1442 m, on the left) is very sharp. The high mountains in the far distance (to the north of Tunulliarfik, see Fig. 1) have remnants of the volcanic roof (**B**) on top of the roof series (cf. Fig. 4). The distance to Kangerluarsuk is about 2 km.



Kakortokite: agpaitic nepheline syenite displaying pronounced cumulate textures and igneous layering with a repetition of layers enriched in perthitic alkali feldspar (white), eudialyte (red) and arfvedsonite (black)

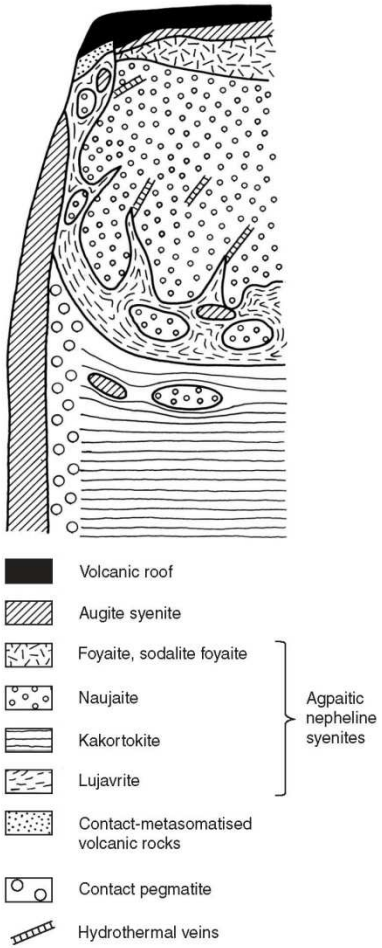


Fig. 4. Schematic section through the *c.* 1700 m of exposed stratigraphy of the Ilímaussaq alkaline complex.

Sørensen (2001)

Fig. 5. The lowermost exposed part of the complex, made up of thin layers of kakortokite with trough layering displaced by a minor fault (arrow, lower left). In the background the main series of kakortokite made up of a repetition of three-layer units, in which the black and white layers can be distinguished. The faulted white trough band is approximately 5 m wide and 15 cm thick.

Densities of minerals (g/cm^3)
Mi 2.56,
Ab 2.62
Ne 2.62
Arf 3.47
Eud 3.67

29 3-layer units, 10 m thick; Kfs + Ab + Ne (top) → Eud → Arf, then sharp contact

Sørensen (2001)

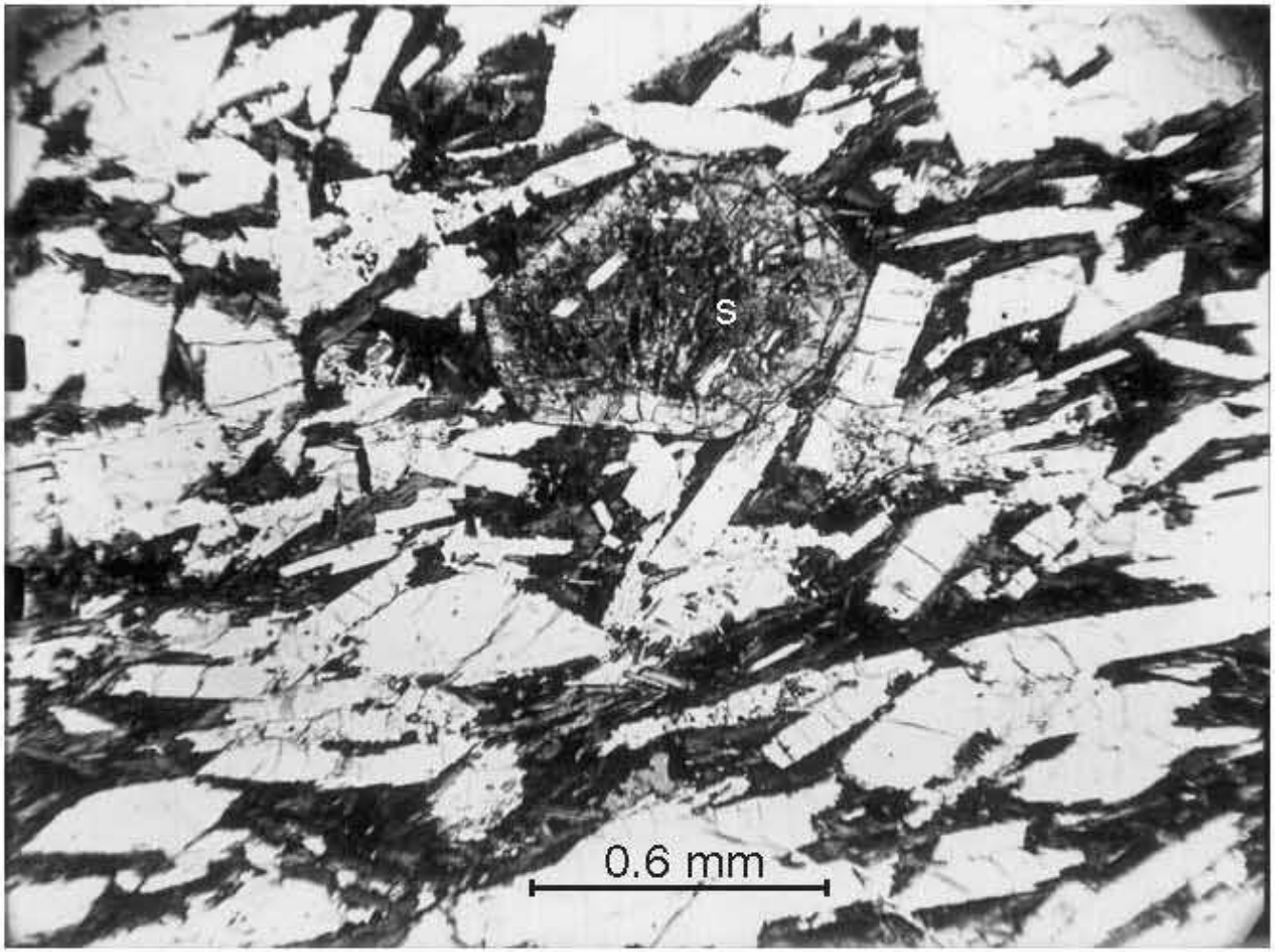


Fig. 3. Steenstrupine crystal (**s**) in lujavrite dyke made up of microcline (**light**) and arfvedsonite (**dark**). The central part of the steenstrupine crystal contains minute inclusions of microcline and arfvedsonite, much smaller than the grains of the matrix. The microcline inclusions in the marginal part of the crystal are intermediate in size. GGU 21154, head of Kangerluarsuk, plane polarised light.

Sørensen & Larsen (2001)

The hyper-agpaitic stage in the evolution of the Ilímaussaq alkaline complex, South Greenland

Henning Sørensen and Lotte Melchior Larsen

The term hyper-agpaitic covers mineral associations characterised by a wealth of Na-rich minerals such as natrosilite, zirsinalite, ussingite, vuonnemite, vitusite and lomonosovite. This mineral association clearly indicates a higher degree of alkalinity than for agpaitic rocks in general. In the Ilímaussaq complex hyper-agpaitic mineral associations occur not only in pegmatites and hydrothermal veins as in the Kola complexes, Khibina and Lovozero, but also in highly evolved lujavrites and in the fenitised volcanic rocks in the roof of the complex. This paper reviews the occurrences of hyper-agpaitic mineral associations in the Ilímaussaq complex. The mineral assemblages are determined by an interplay of temperature, pressure, oxygen fugacity, alkalinity, especially the concentration of Na, and contents of elements such as Zr, Ti, Nb, REE, Fe, Mn, U, Th, P, F, Cl and H_2O. Increasing and decreasing stages of alkalinity may be distinguished. At increasing alkalinity nepheline is for instance substituted by naujakasite, while at decreasing alkalinity and temperature naujakasite is substituted by analcime.

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Keywords: agpaite, Greenland, hyper-agpaite, Ilímaussaq

Mineral formulae

analcime: $NaAlSi_2O_6 \cdot H_2O$
catapleiite: $Na_2ZrSi_3O_9 \cdot 2H_2O$
chkalovite: $Na_2BeSi_2O_6$
epistolite: $Na_2(Nb,Ti)_2Si_2O_9 \cdot nH_2O$
eudialyte: $Na_4(Ca,Ce)_2Fe,Mn,Y)ZrSi_8O_{22}(OH,Cl)_2$
gerasimovskite: $(Mn,Ca)(Nb,Ti)_5O_{12} \cdot 9H_2O)(?)$
lomonosovite: $Na_5Ti_2O_2(Si_2O_7)_2(PO_4)_2$
lorenzenite: $Na_2Ti_2O_3(Si_2O_6)$
lovozerite: $Na_2Ca(Zr,Ti)Si_6(O,OH)_{18}$
microcline: $KAlSi_3O_8$
monazite: $(Ce,La,Nd,Th)PO_4$
murmanite: $Na_3(Ti,Nb)_4O_4(Si_2O_7)_2 \cdot 4H_2O$
natrosilite: $Na_2Si_2O_5$
naujakasite: $Na_6(Fe,Mn)Al_4Si_8O_{26}$
nenadkevichite: $Na(Nb,Ti)Si_2O_6(O,OH) \cdot 2H_2O$
nepheline: $(Na,K)AlSiO_4$
rhabdophane: $(Ce,La,Ca)PO_4 \cdot H_2O$
sodalite: $(NaAlSiO_4)_6 \cdot 2NaCl$
sorensenite: $Na_4Be_2Sn(Si_3O_9)_2 \cdot 2H_2O$
steenstrupine-(Ce): $Na_{14}Ce_6Mn_2Fe_2(Zr,Th)(Si_6O_{18})_2(PO_4)_7 \cdot 3H_2O$
tugtupite: $Na_4AlBeSi_4O_{12}Cl$
ussingite: $NaAlSi_3O_8 \cdot NaOH$
villiaumite: NaF
vinogradovite: $(Na,Ca)_4Ti_4Si_8O_{26} \cdot (H_2O,K_3)$
vitusite-(Ce): $Na_3Ce(PO_4)_2$
vuonnemite: $Na_5Nb_3Ti(Si_2O_7)_3O_2F_2 \cdot 2Na_3PO_4$
zircon: $ZrSiO_4$
zirsinalite: $Na_6CaZrSi_6O_{18}$

Hyper-agpaitic assemblages (Khomyakov 1995) are strongly deficient in Al; PO_4 tetrahedra become prominent in the structure of the melt, which is depolymerized because of so much Na

The Southern Bahia Alkaline Province

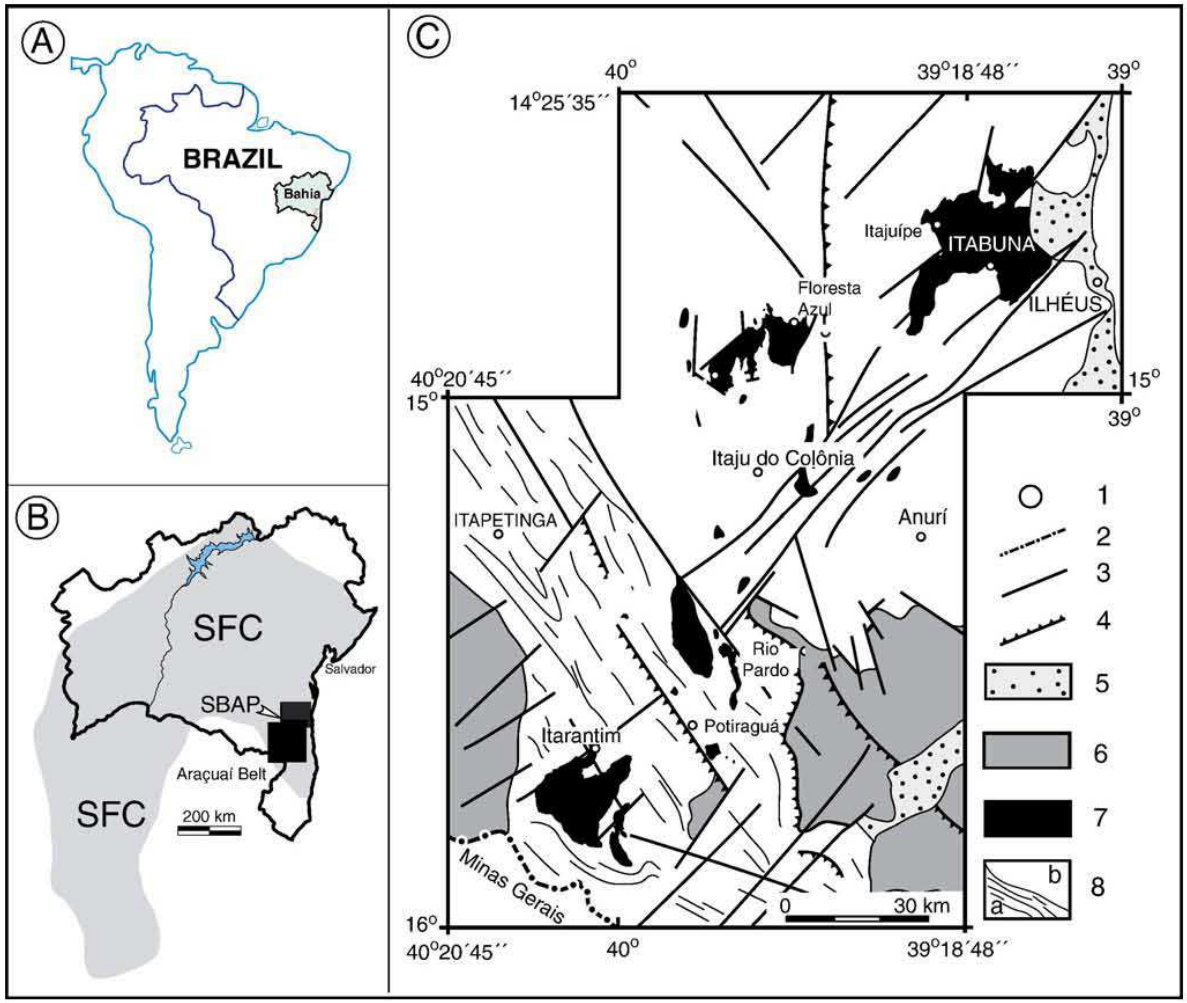

Fig. 1. Location of the State of Bahia in South America [A]. Geological sketch of Bahia with limits of the São Francisco craton (SFC) [B]. Location of the Southern Bahia Alkaline Province (SBAP) [C]: city [1], state divide [2], fracture or fault [3], thrust fault [4], recent sediments [5], Rio Pardo basin [6], alkaline rocks of the SBAP [7], gneiss–migmatite [8a] and granulite [8b] terrains.

Rosa *et al*. (2007)


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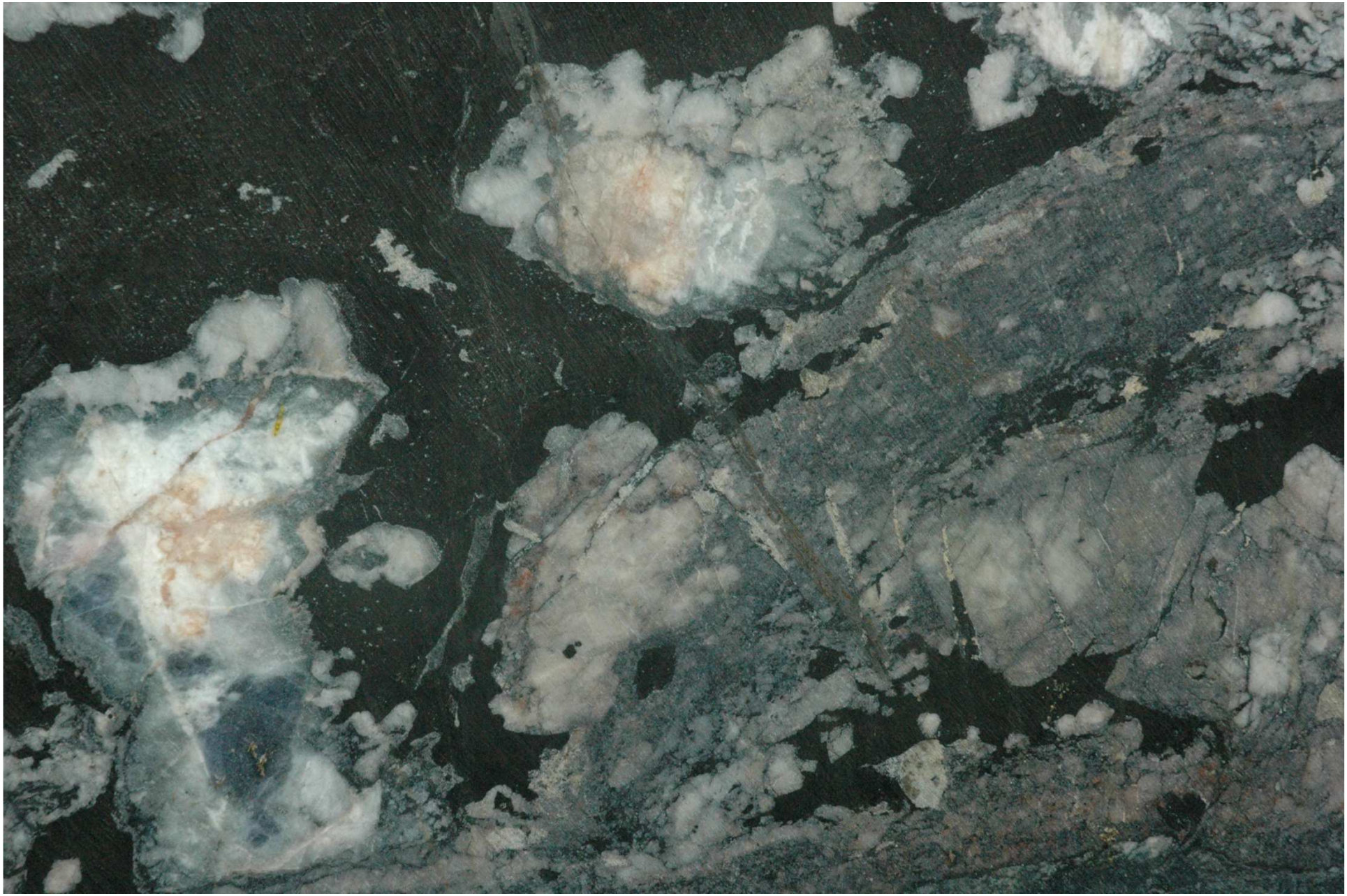
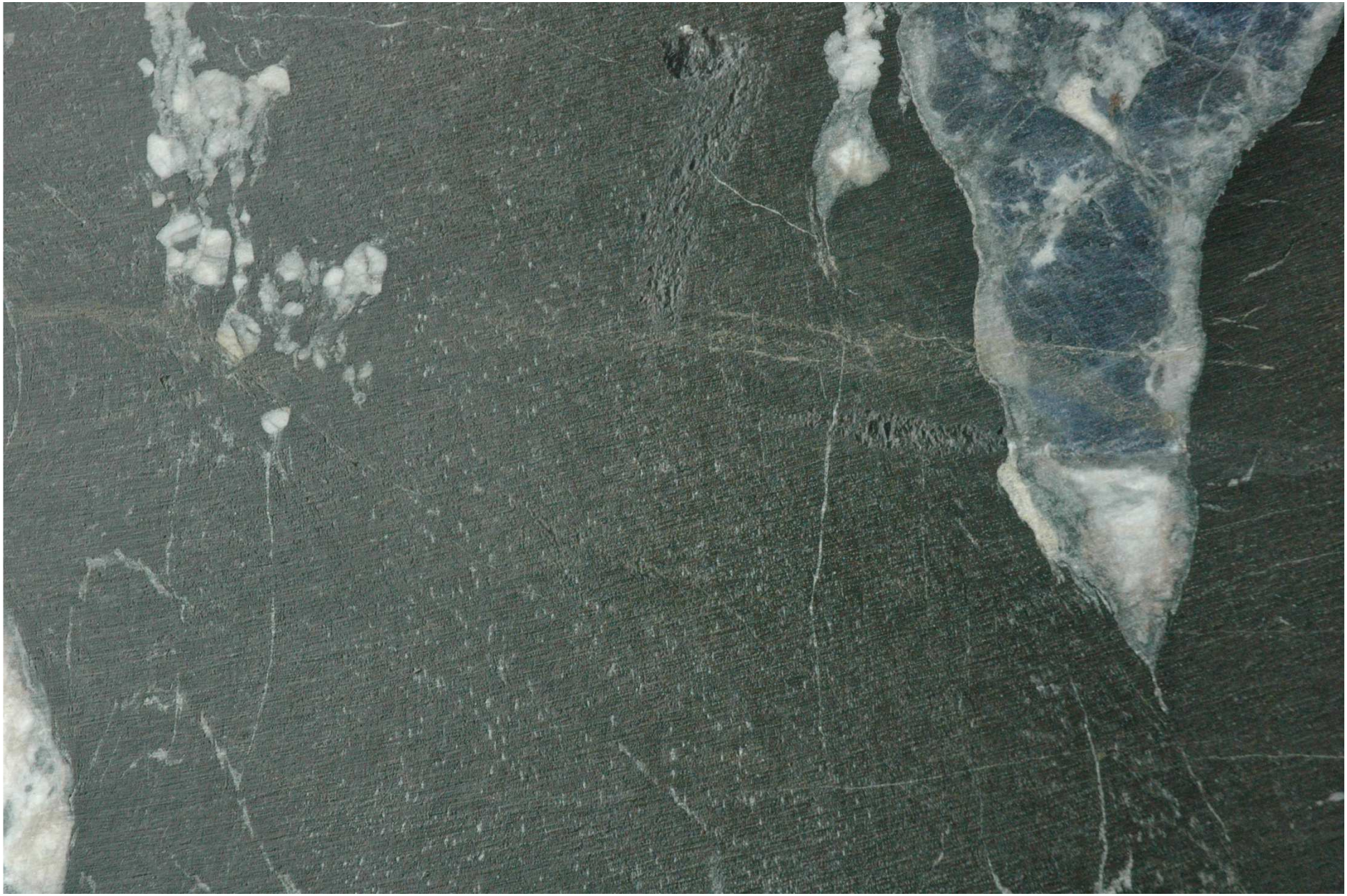
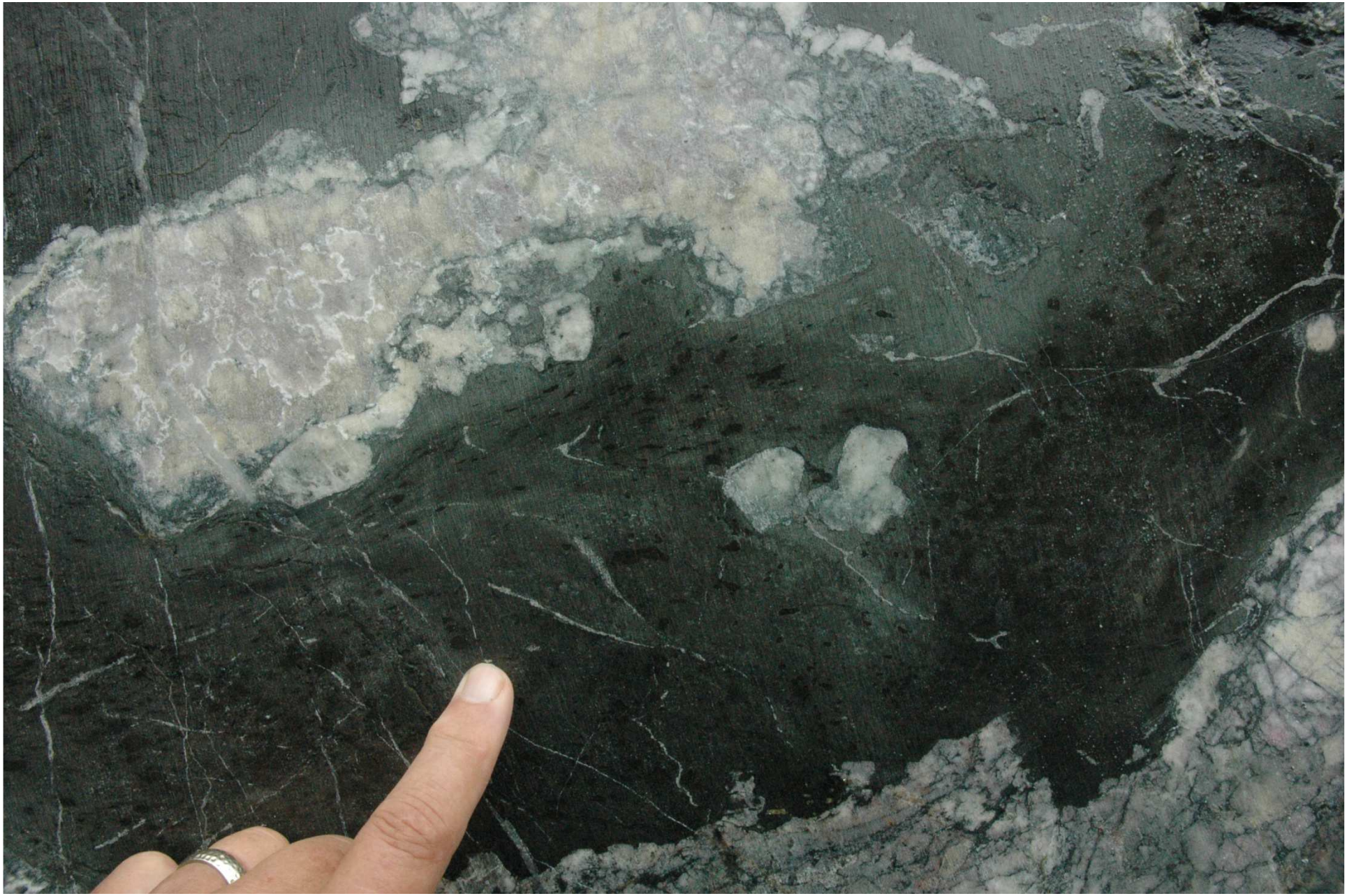
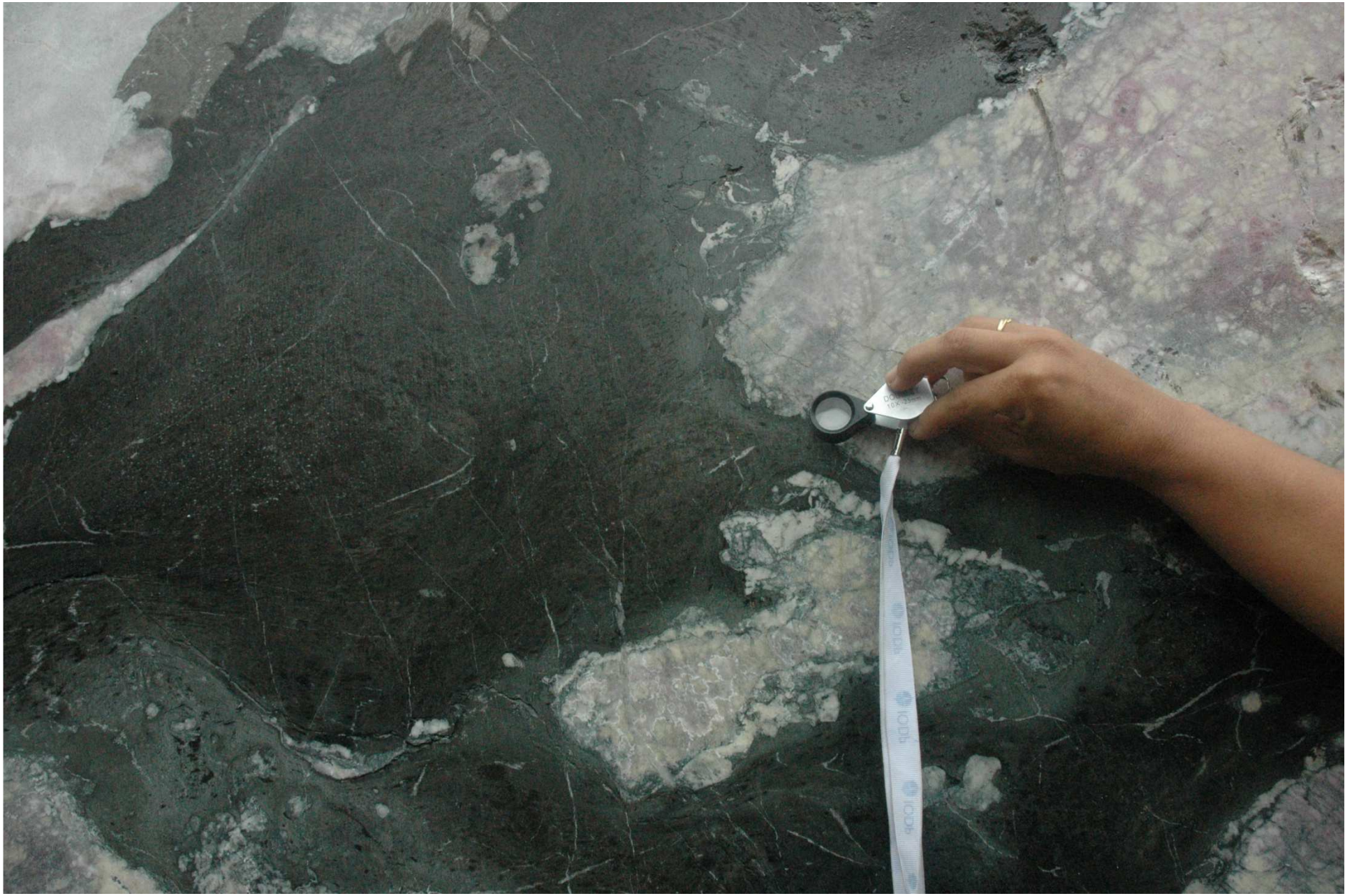






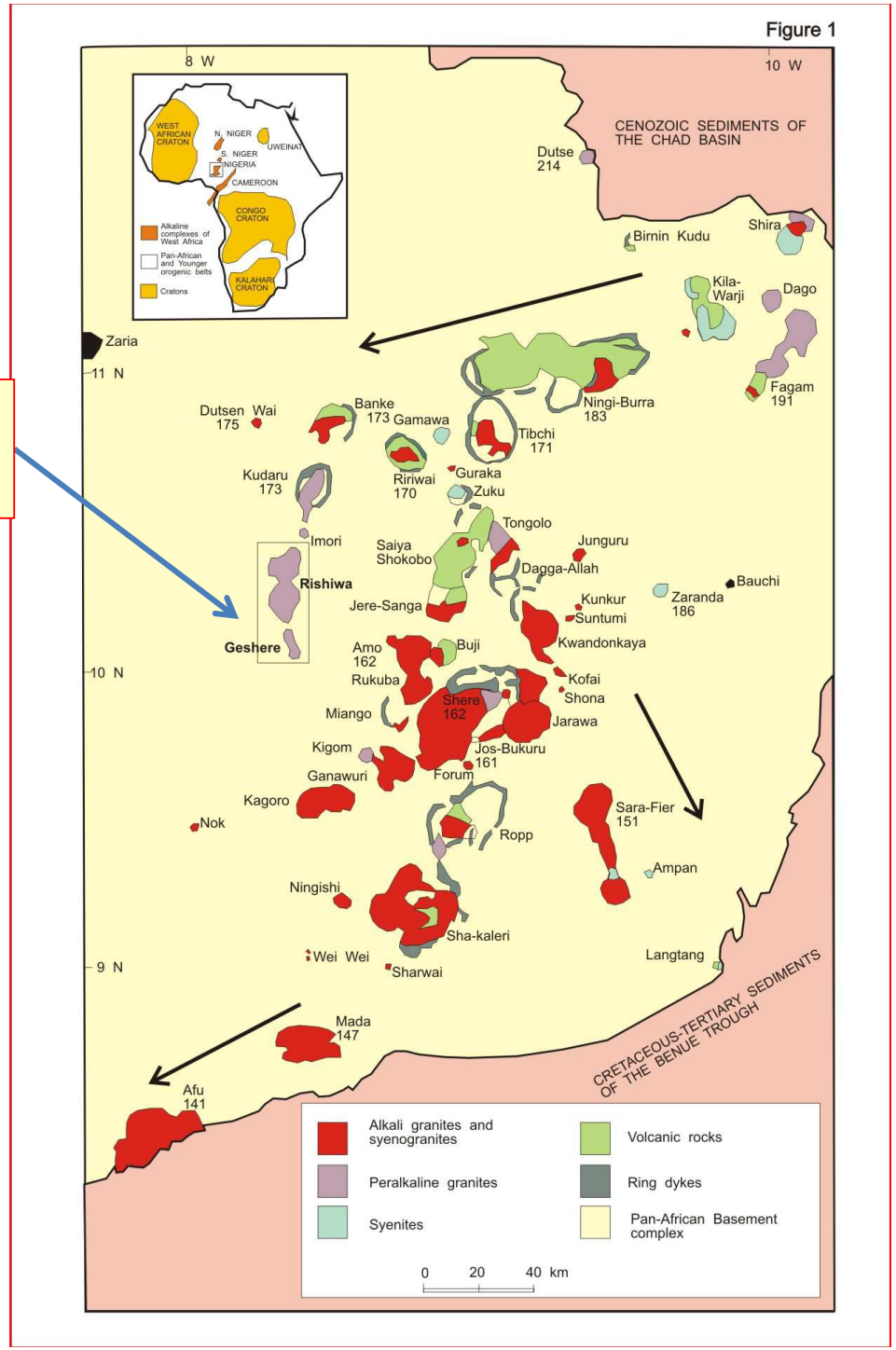


And now, something analogous in a silica-oversaturated complex: Geshere, Nigeria

- Geshere and Rishiwa are the two peralkaline syenite–granite plutons being studied by Shehu Magaji, Ahmadu Bello University
- There are over fifty Younger Granite plutons, some mineralized in Sn, Nb, REE, Zn, Be
- All are A-type (anorogenic) granites (Jurassic)

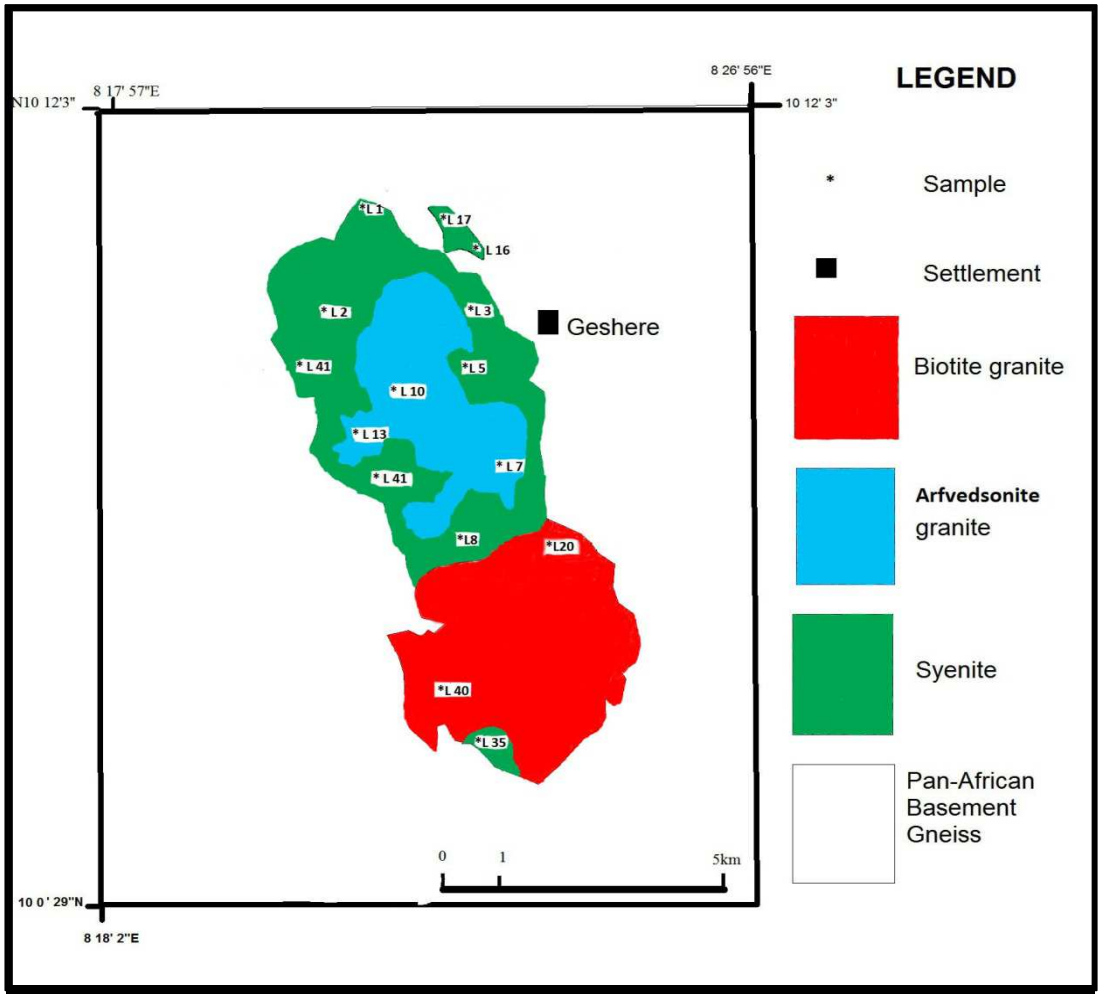
THE YOUNGER GRANITES OF NIGERIA: DISTRIBUTION

Location of the Geshere complex



Kinnaird (1985)

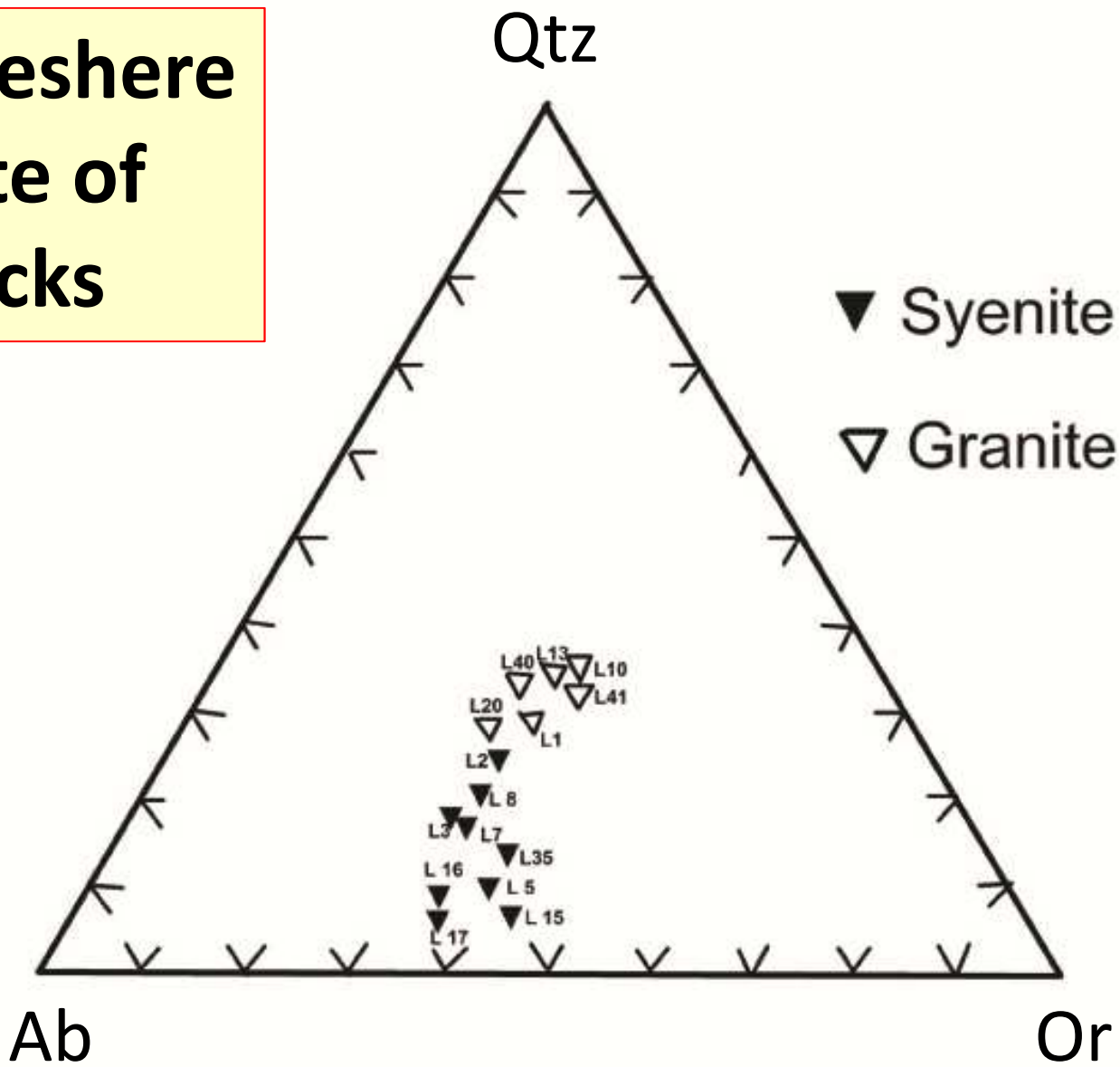
THE GESHERE SYENITE–PERALKALINE GRANITE COMPLEX



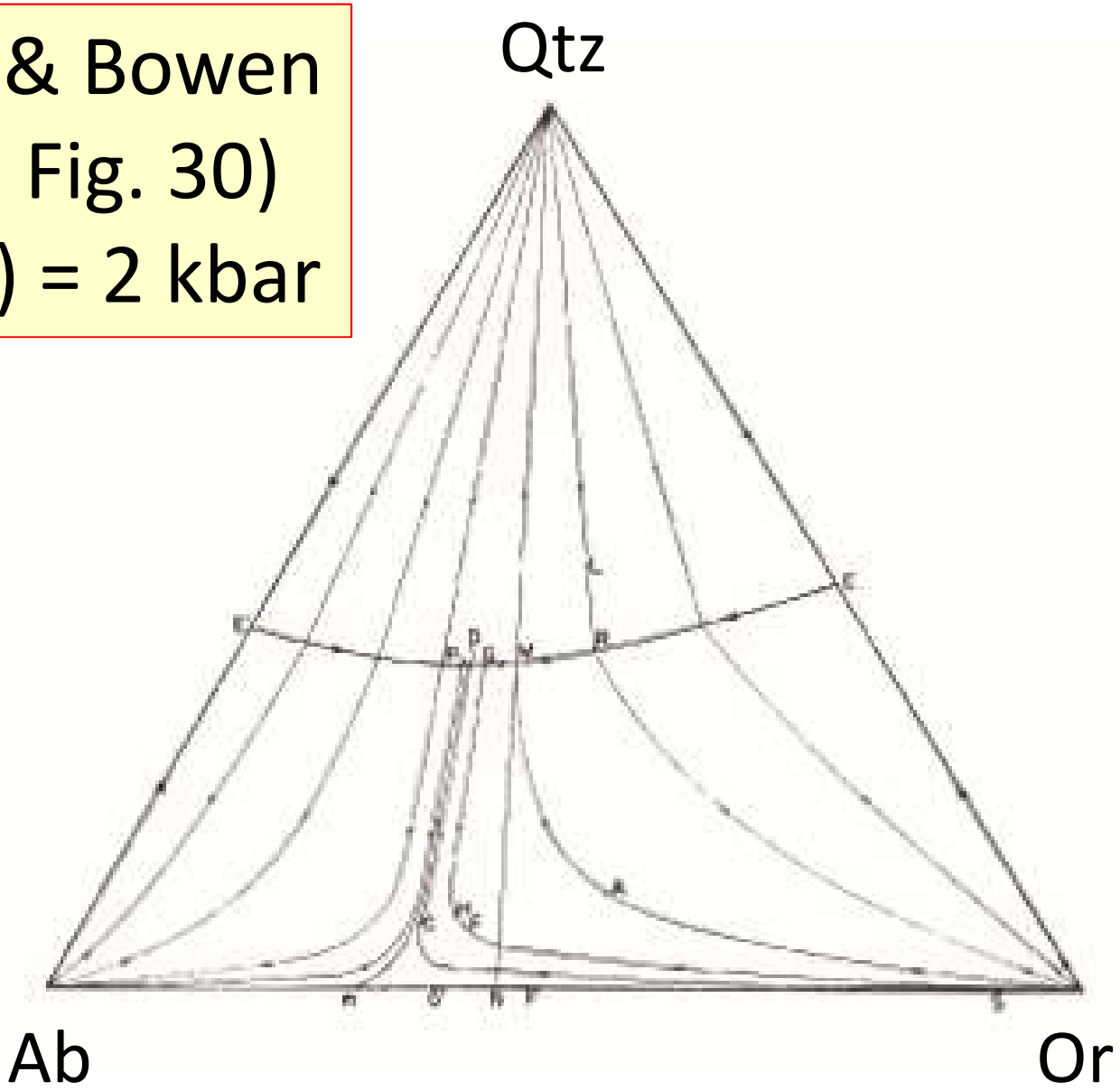
Mapping by Shehu S. Magaji, 2010

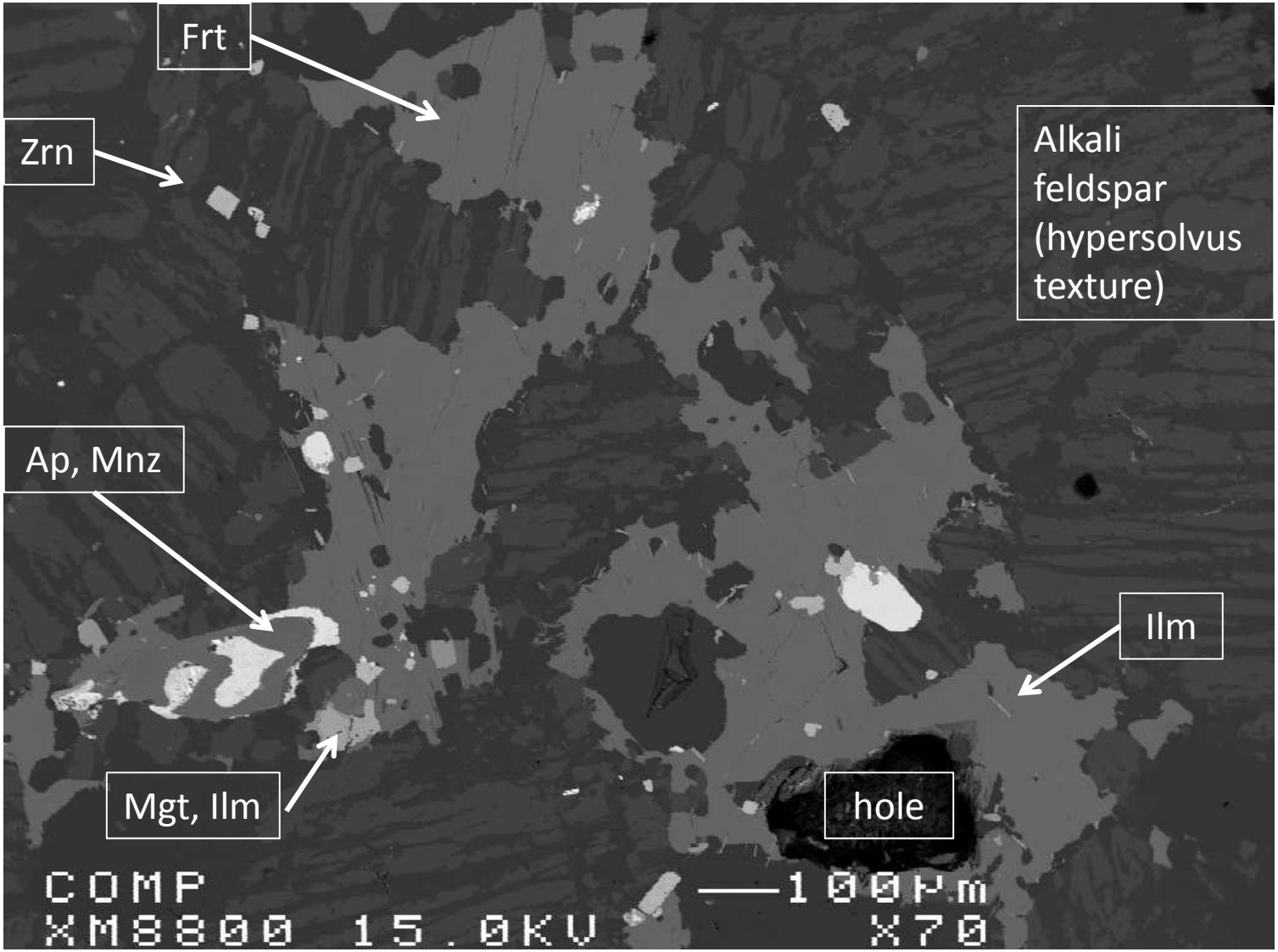
Arfvedsonite granite, Rishiwa complex

The Geshere suite of rocks



Tuttle & Bowen (1958, Fig. 30)
$P(H_2O) = 2$ kbar





Quartz syenite L2

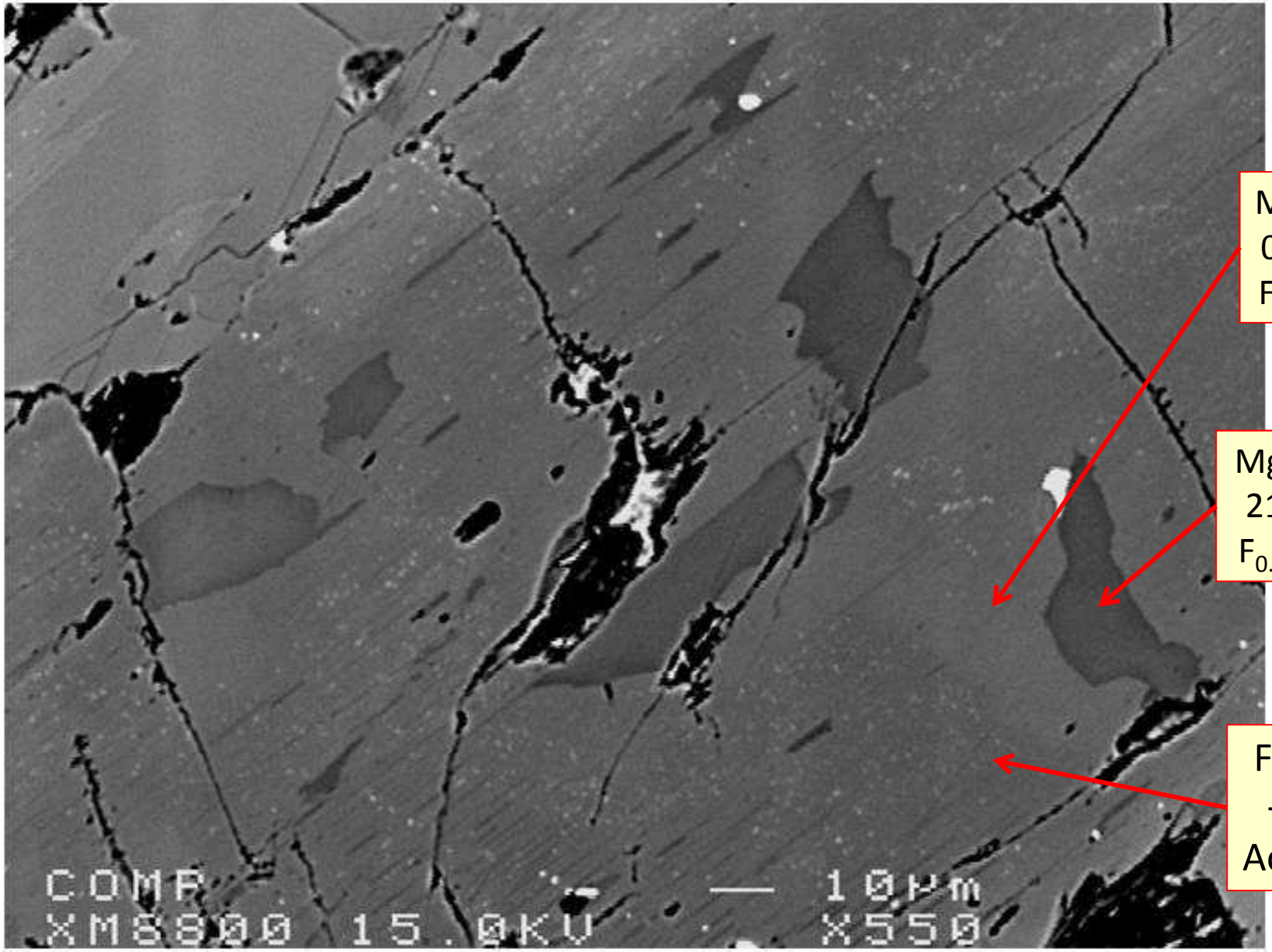
JUST HOW FEMIC ARE THE AMPHIBOLE (Frt) AND MICA (Ann)???

- Frt: Mg# = 0.5 on a scale of 100!

$^{A}(K_{0.22}Na_{0.28}\square_{0.50})\ ^{X}(Na_{0.94}Ca_{1.06})_{\Sigma 2.00}$
$^{Y}(Ti_{0.17}Fe^{3+}_{0.73}Fe^{2+}_{4.05}Mn_{0.10}Mg_{0.05})_{\Sigma 5.00}$
$(Si_{7.78}Al_{0.14})_{\Sigma 7.92}\ O_{22}(OH_{1.93}F_{0.07})$

- Ann:

$(K_{1.90}Na_{0.03}\square_{0.07})_{\Sigma 1}\ (Ti_{0.39}Fe_{5.21}Mn_{0.04}Mg_{0.06}\square_{0.30})_{\Sigma 6}$
$(Si_{6.25}Al_{1.32}Fe_{0.43})_{\Sigma 8}\ O_{10}[(OH)_{3.83}F_{0.04}Cl_{0.13}]_{\Sigma 2}$



Mg# 0.5, $F_{0.18}$

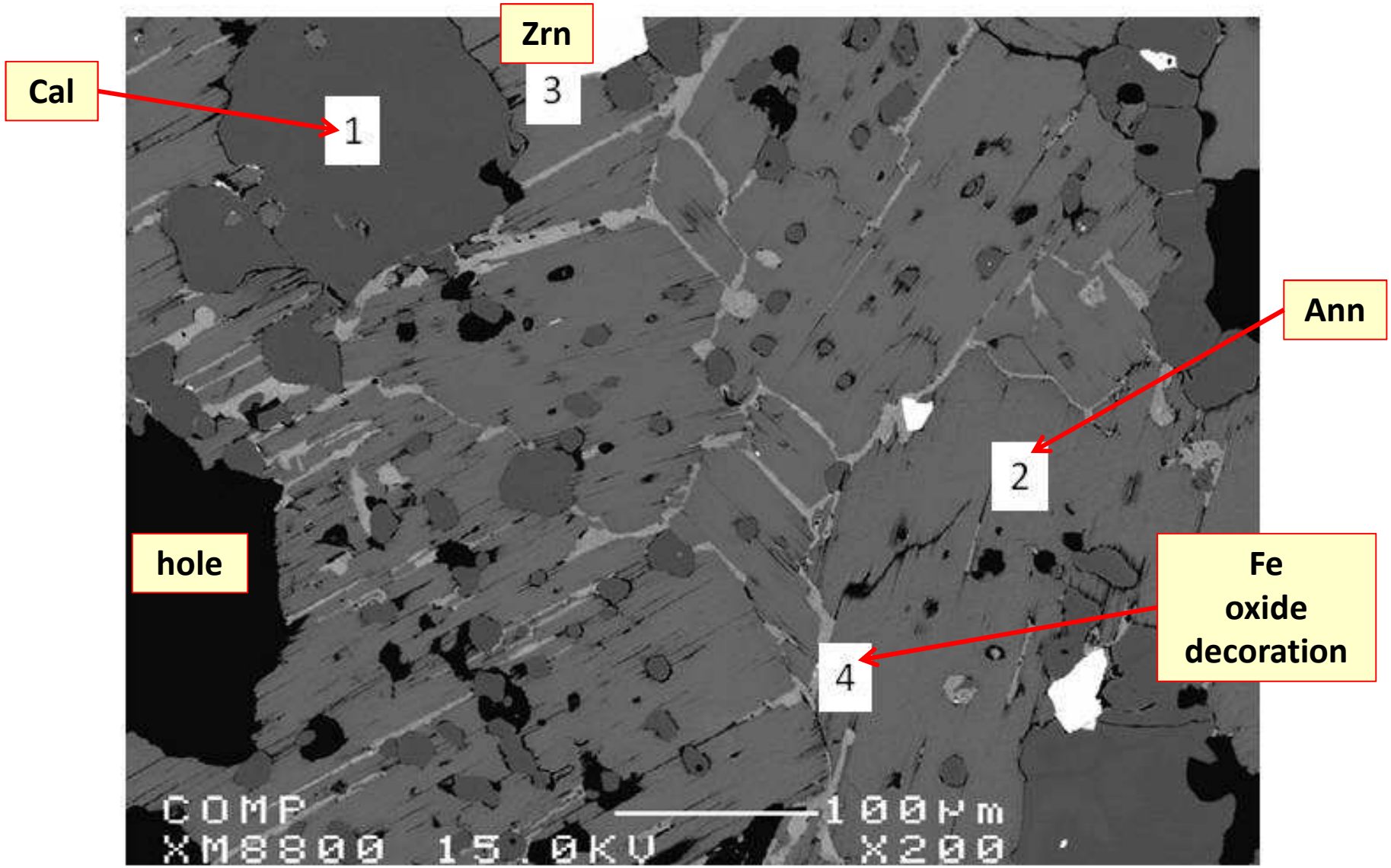
Mg# 21, $F_{0.76}$

Frt + Acc.

Quartz syenite L2

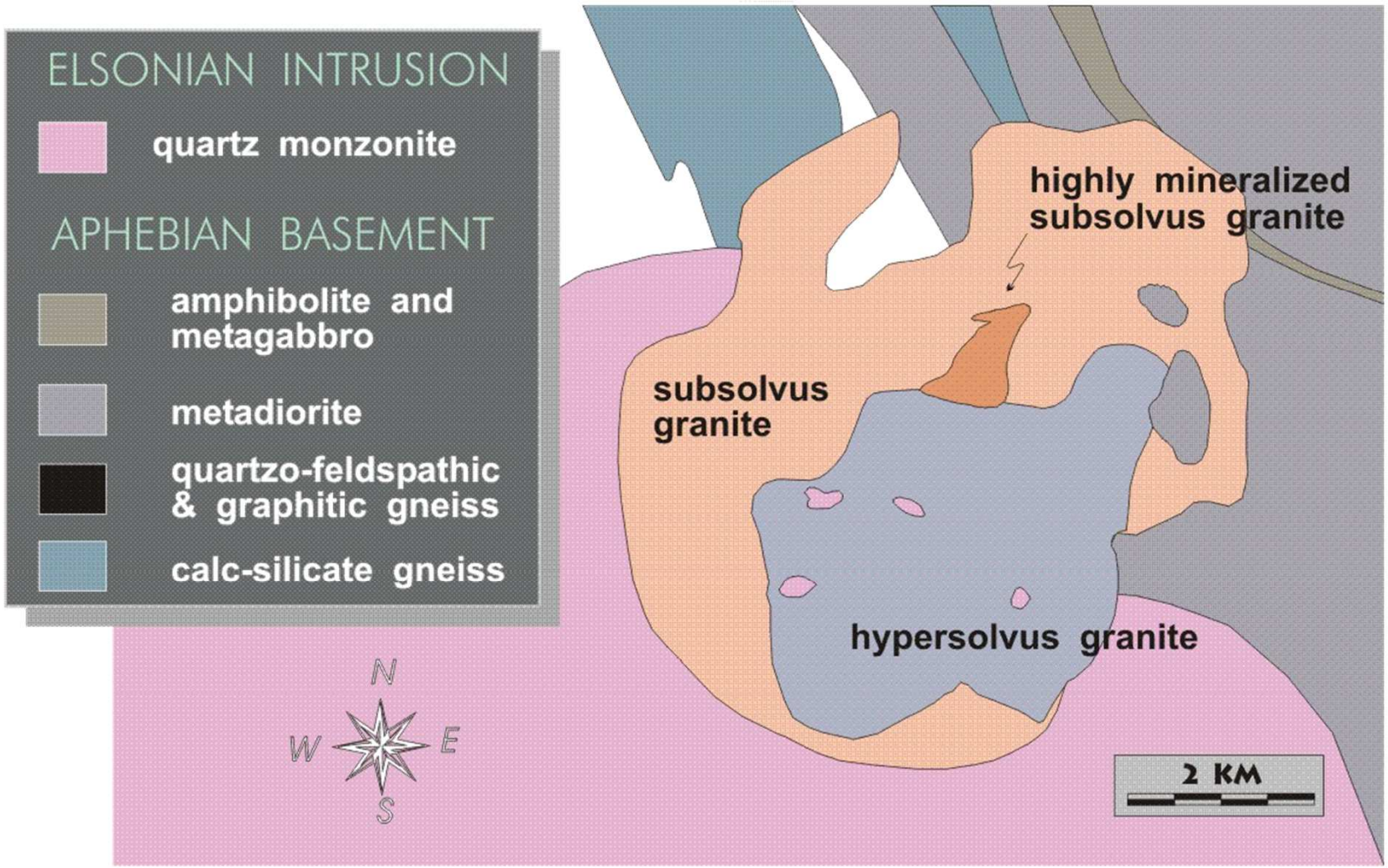
Myriads of specks in the femic minerals

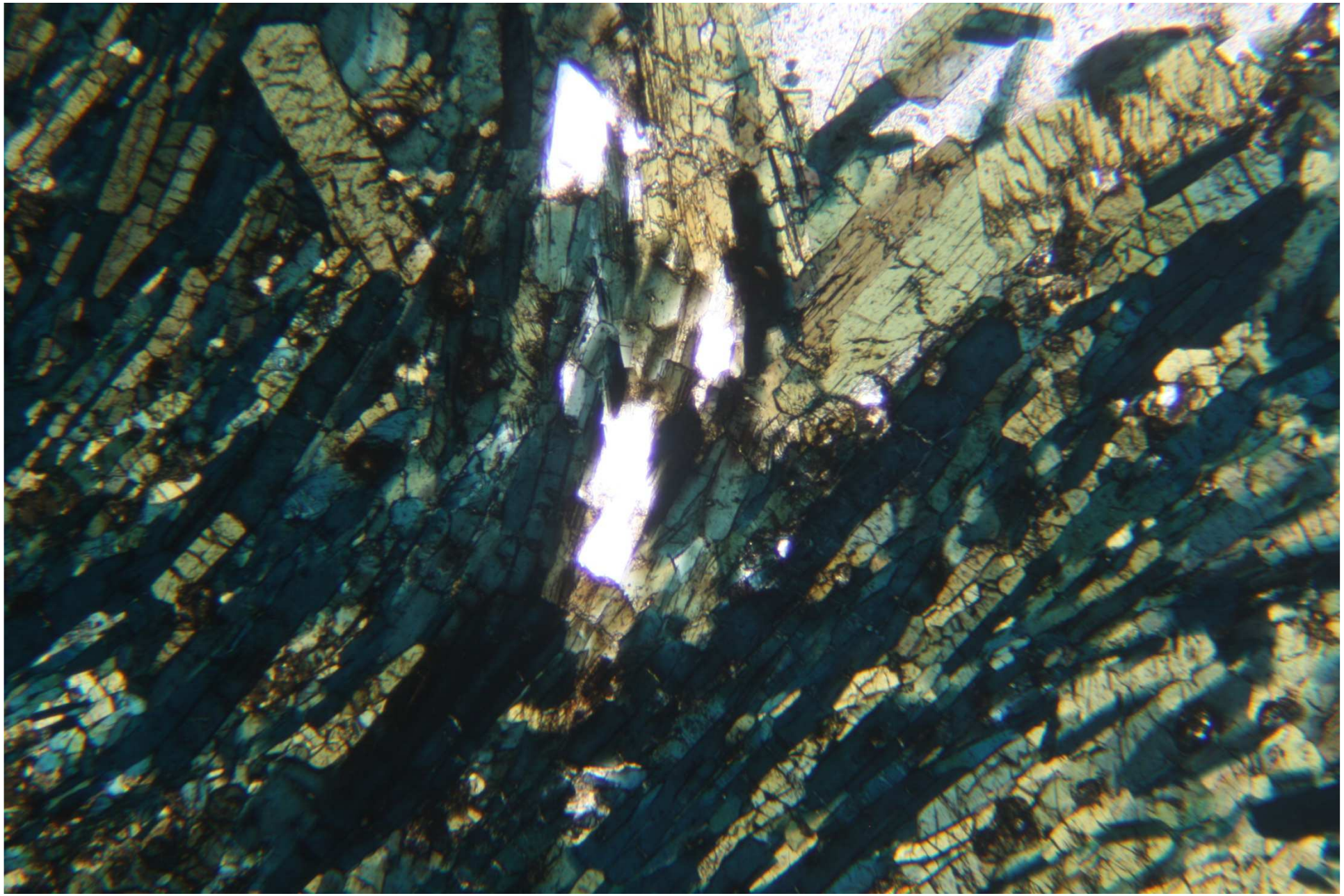
- Ilmenite (partly in perthite)
- Magnetite
- Perrierite-(Ce) or chevkinite-(Ce)
- Monazite-(Ce)
- Apatite, vestiges of britholite
- Zircon (partly in perthite)
- Sphalerite
- Bastnäsite-(Ce)

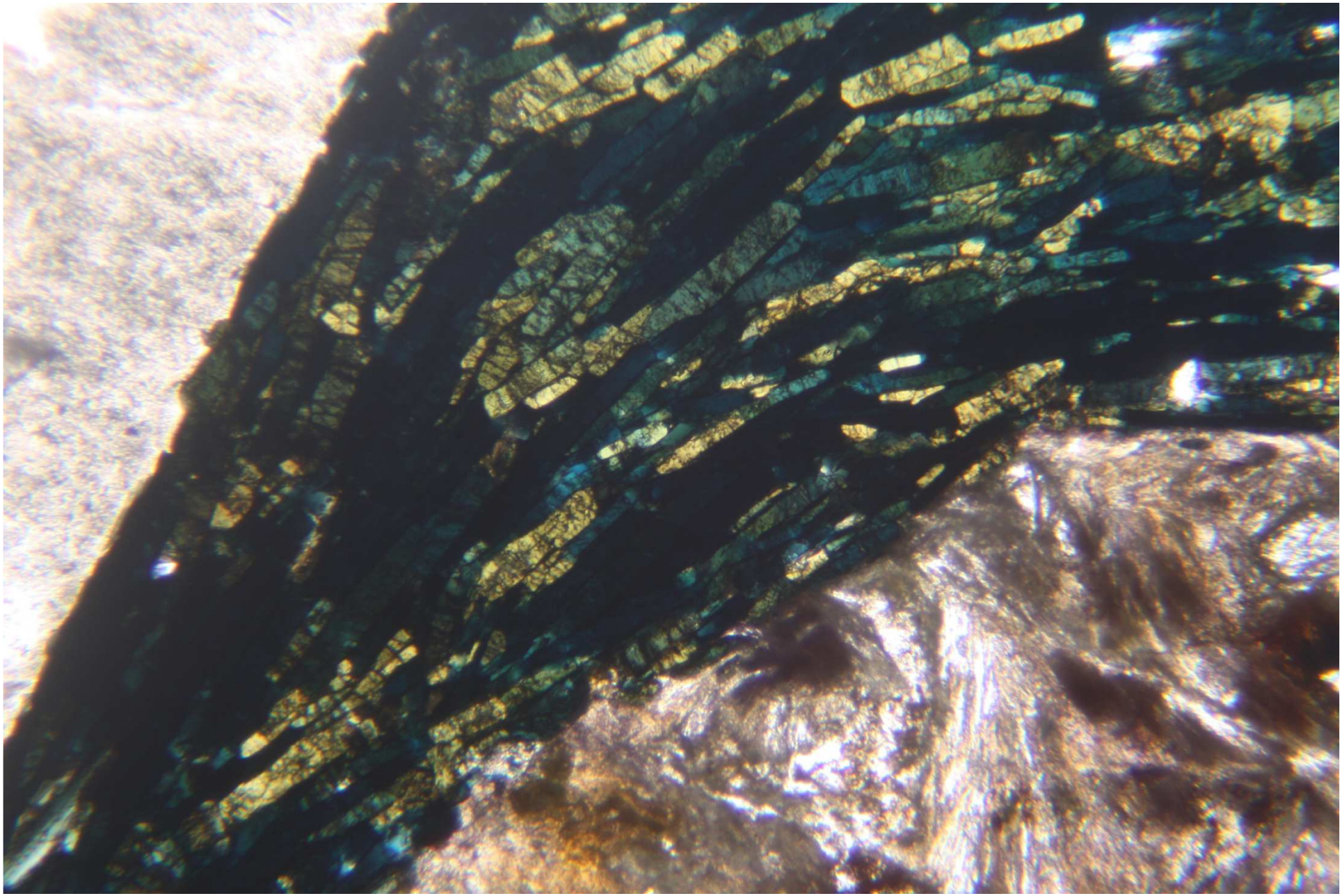


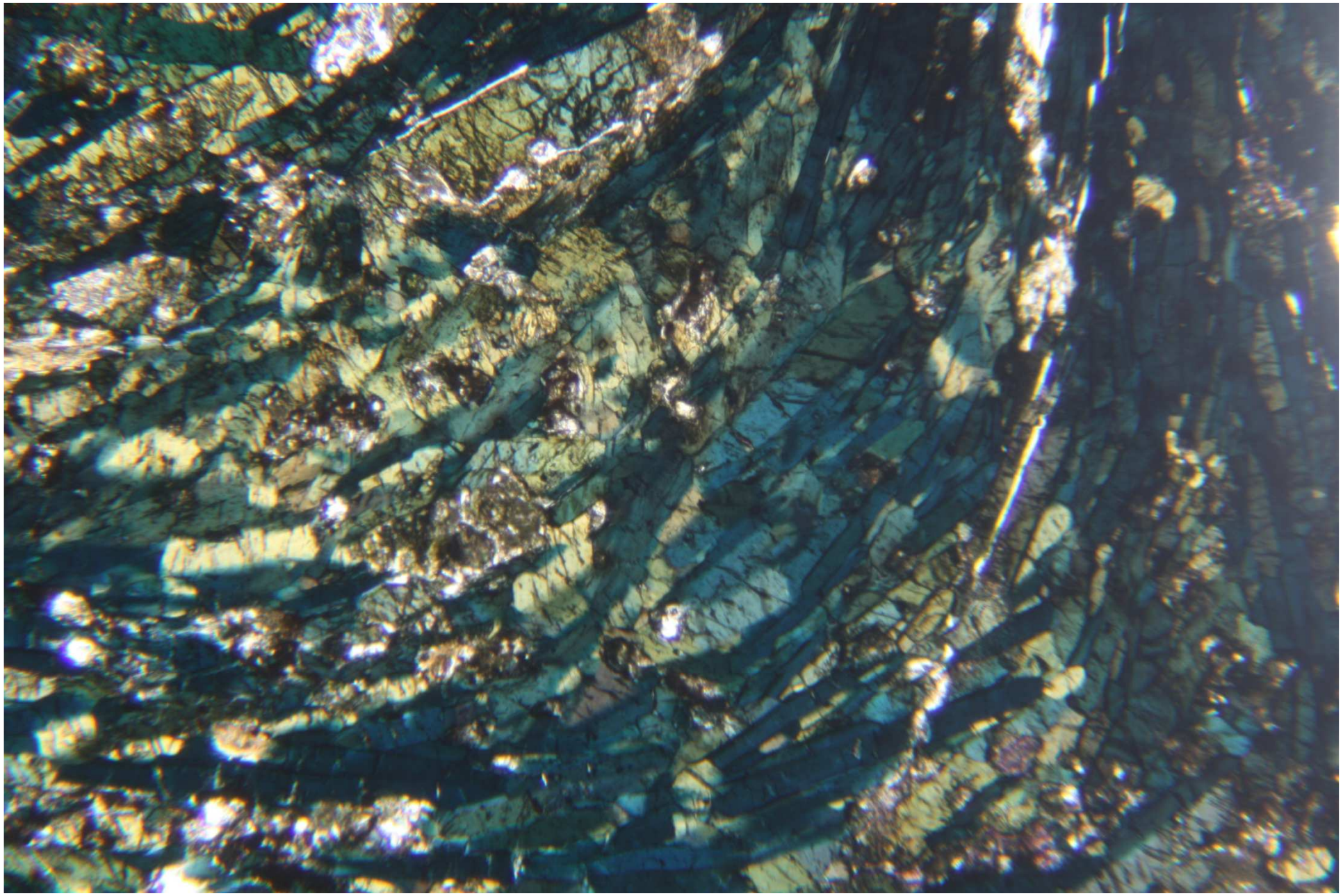
Emulsion texture in annite in quartz syenite L35

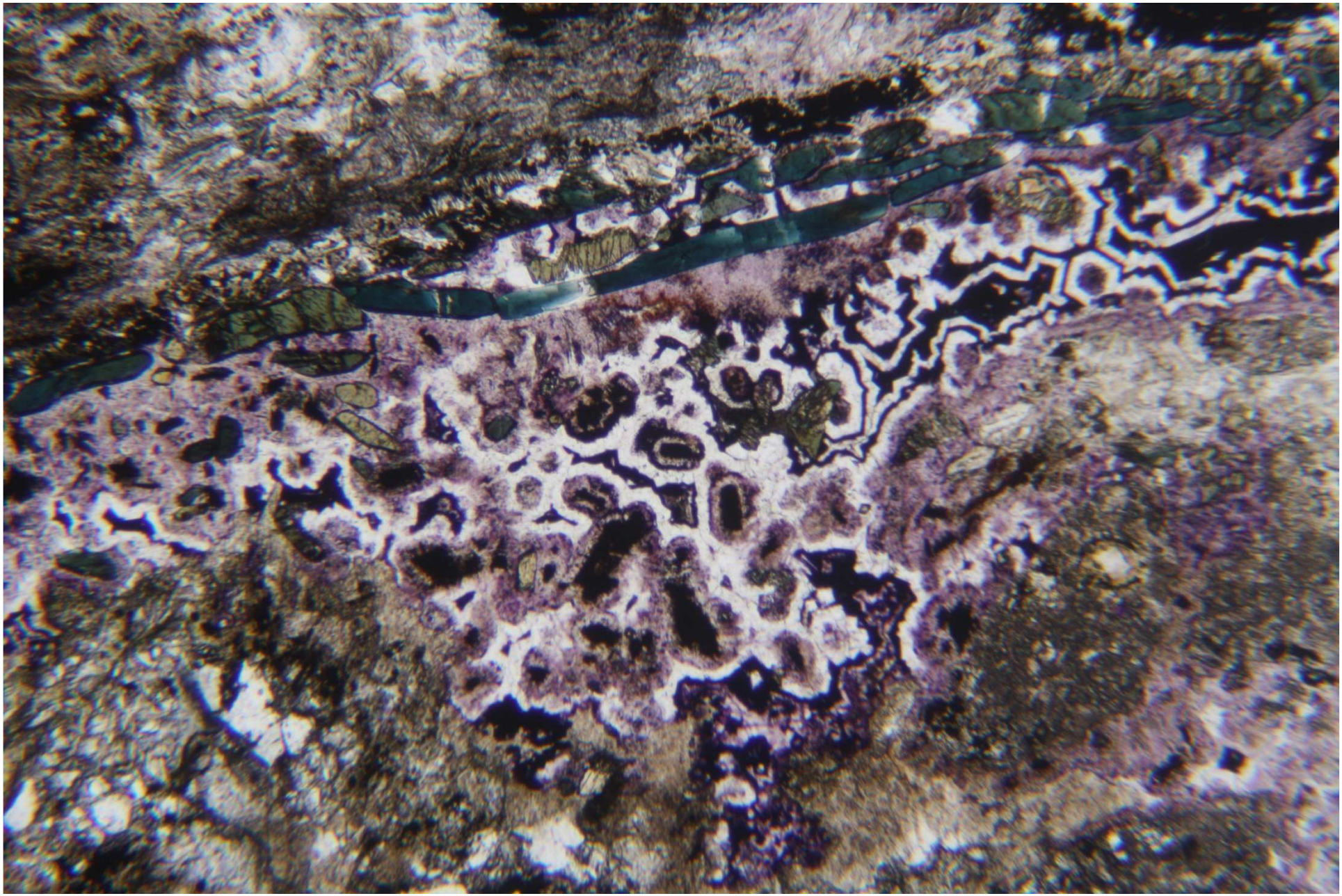
The Strange Lake pluton, Quebec–Labrador

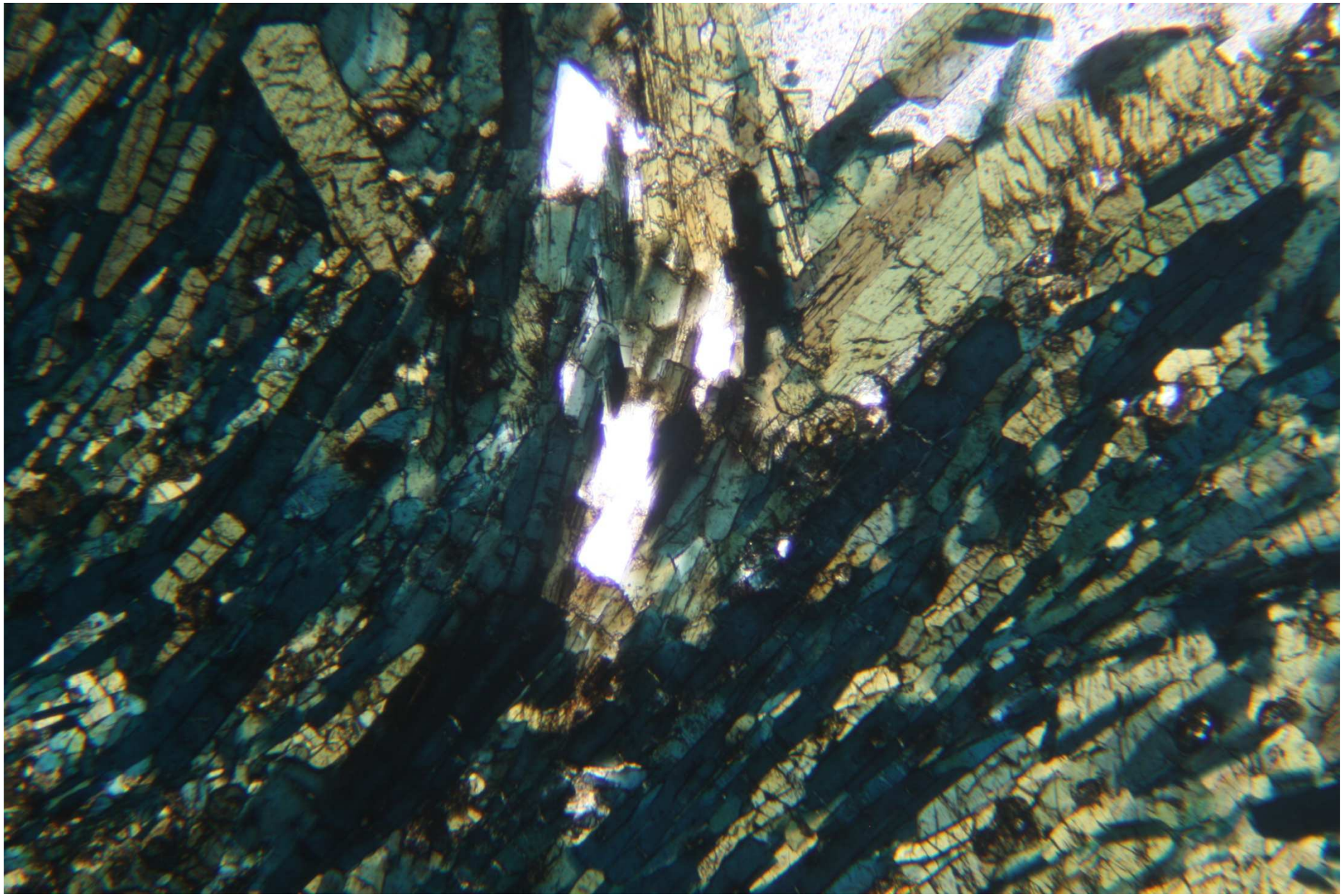












Fractionation revealed in amphibole compositions

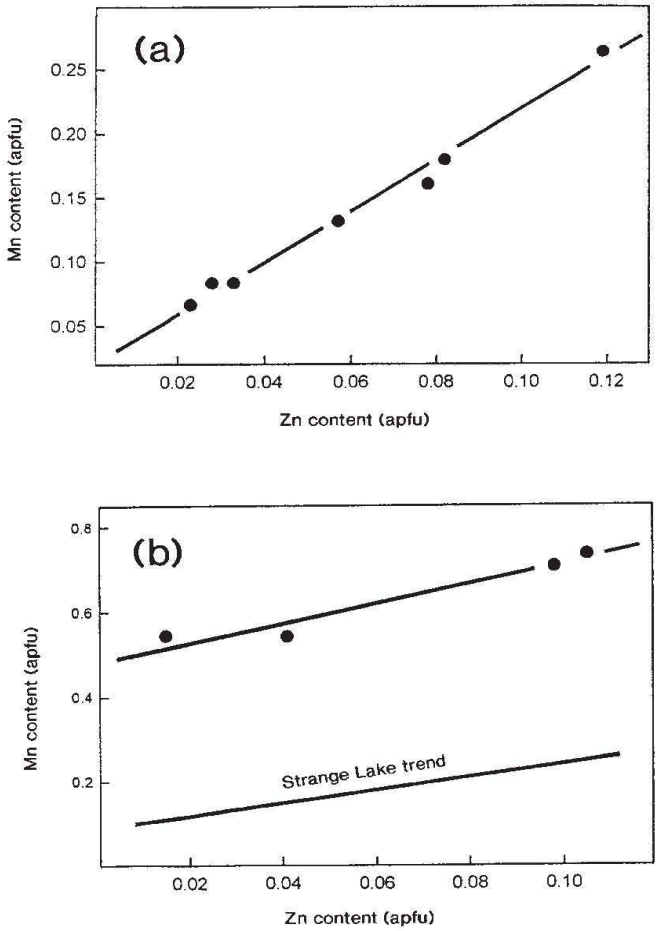


FIG. 5. Variation in the contents of Zn and Mn in cogenetic sodic–calcic and sodic amphiboles: (a) Strange Lake; (b) Virgin Canyon (Hawthorne *et al.* 1993); the lower line in (b) shows the Strange Lake trend.

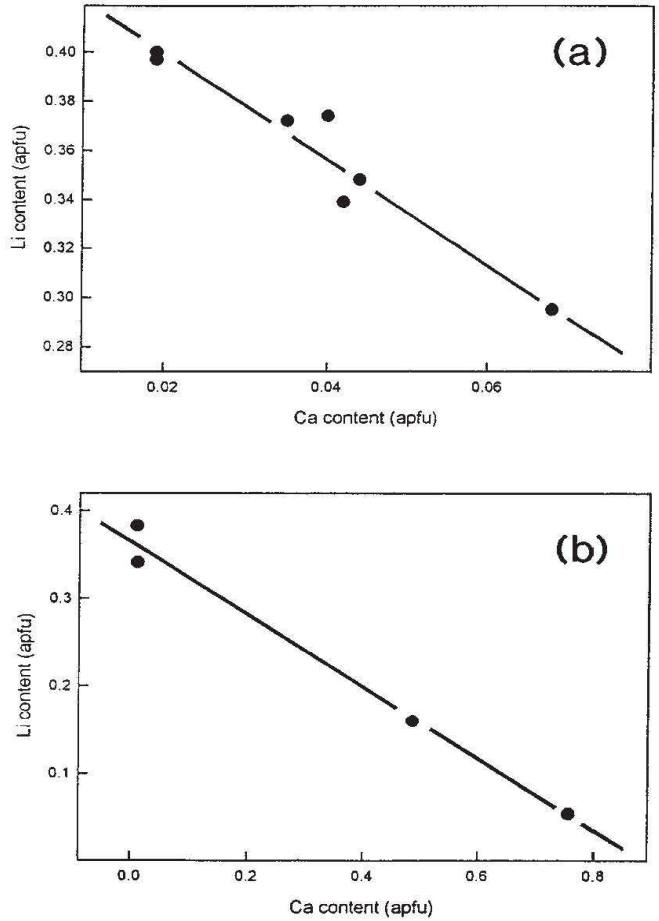


FIG. 6. Variation in the contents of Li and Ca in cogenetic sodic–calcic and sodic amphiboles: (a) Strange Lake pluton; (b) Virgin Canyon pluton.

Hawthorne *et al.* (2001)

A FEW CONCLUSIONS….

- A femic melt is expected to appear at the late stage of evolution of alkaline complexes
- Overall trend is thus mafic → felsic → femic → hyperagpaitic melt
- The femic melt is “loaded” with REE, Zr, Nb, Ta, U, Th, Be and, of course, Na, K, Li ……..
- A Na–Ca or Na amphibole is a main product of crystallization, ± annite

A FEW MORE CONCLUSIONS…

- The ore constituents are commonly in secondary minerals formed upon oxidation and destabilization of the primary minerals
- Late in the evolutionary sequence, products of a felsic melt may be engulfed in a femic melt
- Not an immiscibility relationship!
- An immiscible carbonate melt may be present
- Primary magnetite: upper stability limit of the amphibole or annite BELOW the solidus


Thank you
for your
attention!!!