A-type granites: characteristics, petrogenesis and their contribution to the growth of the continental crust

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The A-type Granitoids

- Defined by Loiselle and Wones (1979)
- ***A*** stands for ***A***norogenic or ***A***nhydrous or the first letter of the alphabet. The last choice removes the necessity of debating the meaning of A.
- Magmas are emplaced in post-collisional or within plate settings, i.e., an extensional environment.

Characteristics of A-type Granitoids

1. Non-orogenic setting
2. Subaluminous to peralkaline, sometimes peraluminous
3. For rocks of intermediate silica content, A-type granitoids generally have higher total alkalis and lower CaO than other granitoids.
4. High FeO_T/MgO
5. A characteristic mineralogy consisting of iron-rich mafic silicates (annite, ferrohendenbergite, ferrohastingsite, fayalite), and in peralkaline suites alkali-rich mafic silicates (aegirine, arfvedsonite, reibeckite) and perthitic feldspars

The Alphabet Soup – is A-type granitoid a useful classification?

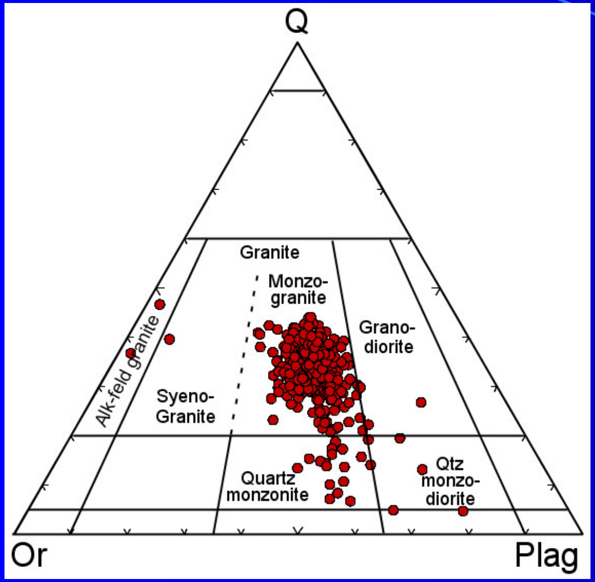
- Classifications are useful to the extent that they help us organize our observations/ideas.
- Classifications are a short-hand that can be used to convey a general description of geologic observations.
- One can define a group of granitoids, in terms of geologic setting and chemistry, that are distinct from other granitoids. In this instance the A-type classification is useful.
- However, a classification should not lead to rigid thinking.
- As geologists we still need to maintain our world view of multiple working hypotheses/processes.
- A-type granitoids, while similar in many respects, can apparently arise via different petrogenetic pathways. The challenge is to elucidate these pathways.

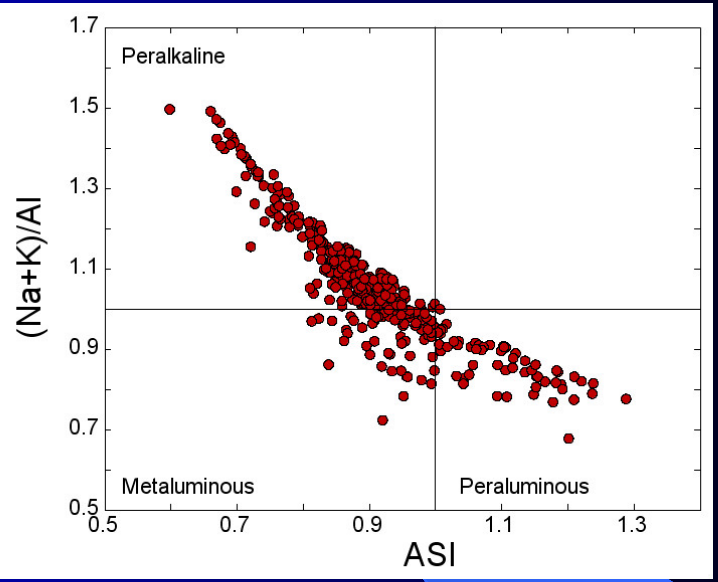
Summary of Chemical Characteristics for A-type Granitoids

The data base consists of 40 plutons/provinces and the A-type granitoids in the data base encompass a wide range of compositions.

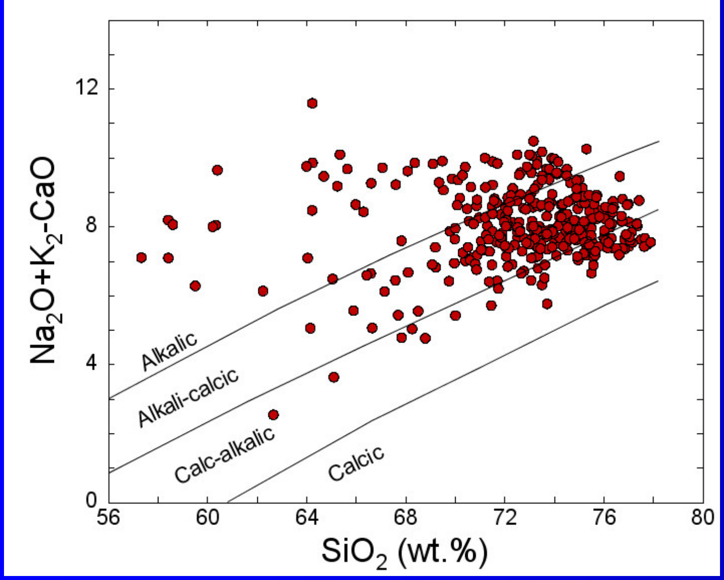
- All the granitoids plot in the Within Plate and A-type fields on standard discriminant diagrams.
- In terms of Al and alkalis, the granitoids are peralkaline, metaluminous, and peraluminous
- Most of the granitoids are alkali-calcic to alkalic
- Most of the granitoids are Ferroan, but some are Magnesian (Frost et al., 2001, classification)
- The granitoids show a wide range in T_{Zr} saturation temperatures, from 700 to 1000+ ^{o}C.

A-type granitoids: normative mineralogy and major element chemistry





Frost et al. 2001



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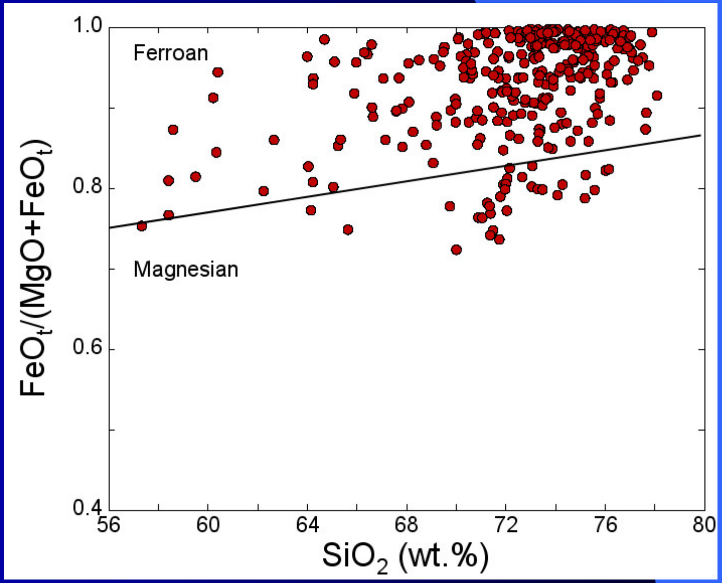
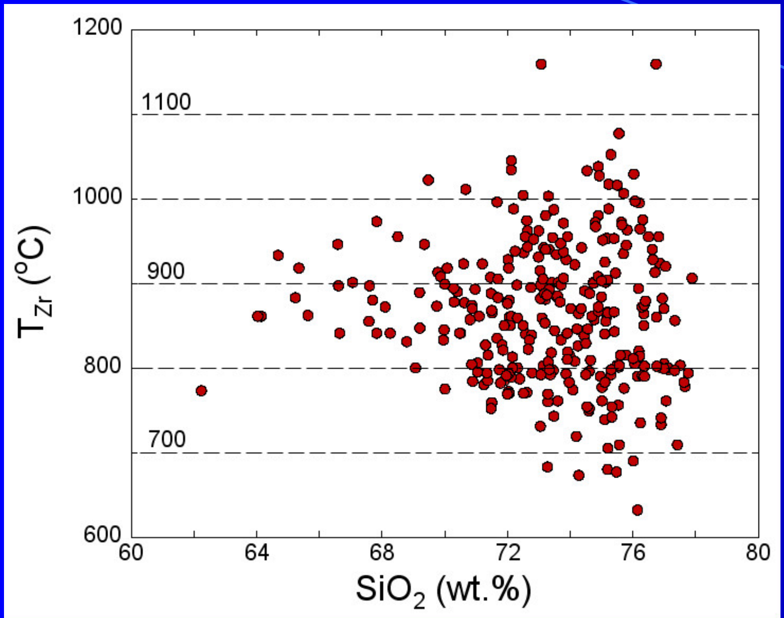
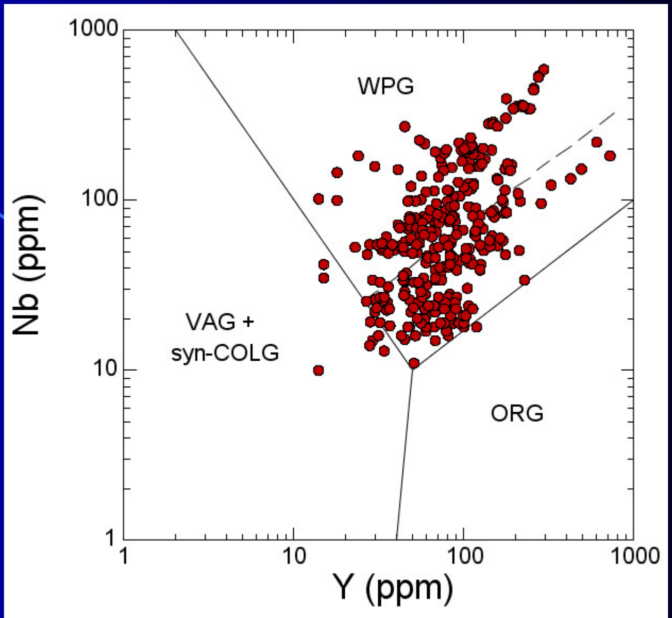


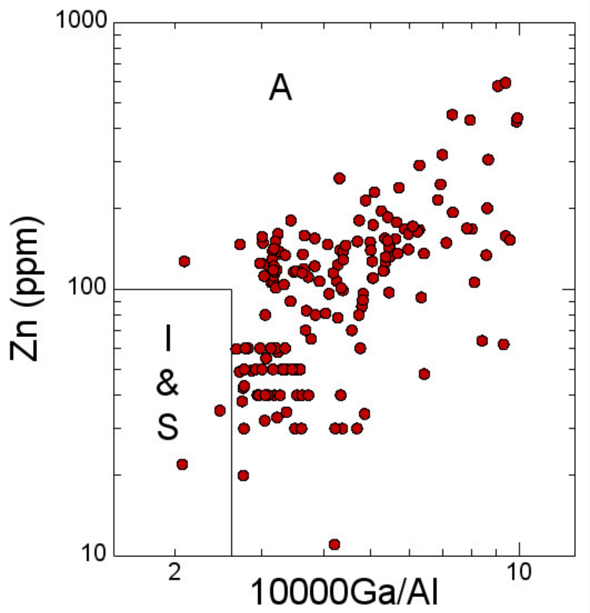
Frost et al. 2001

A-type granites: Zircon saturation temperatures and trace element characteristics

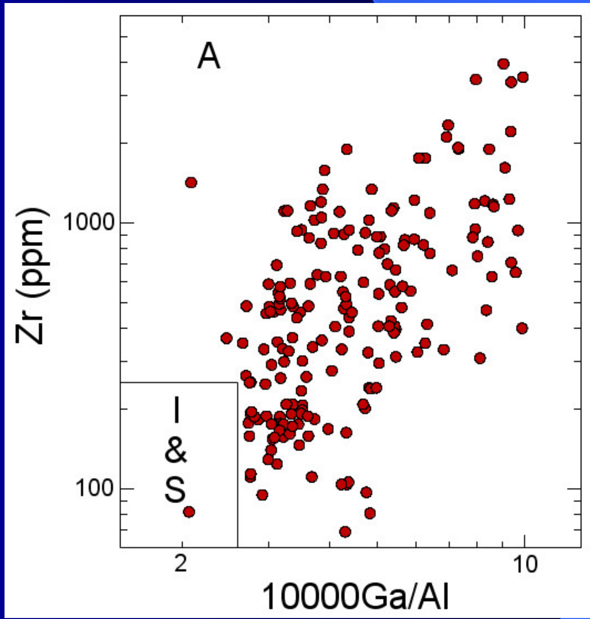




Pearce et al. 1984



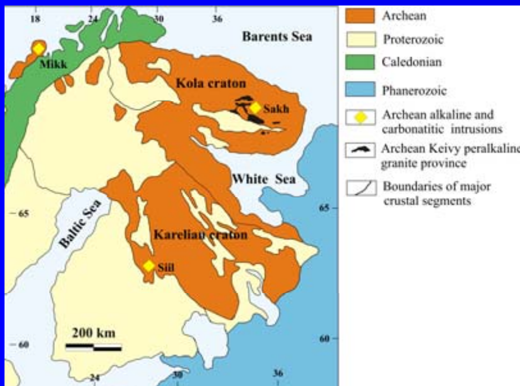
Whalen et al. 1987



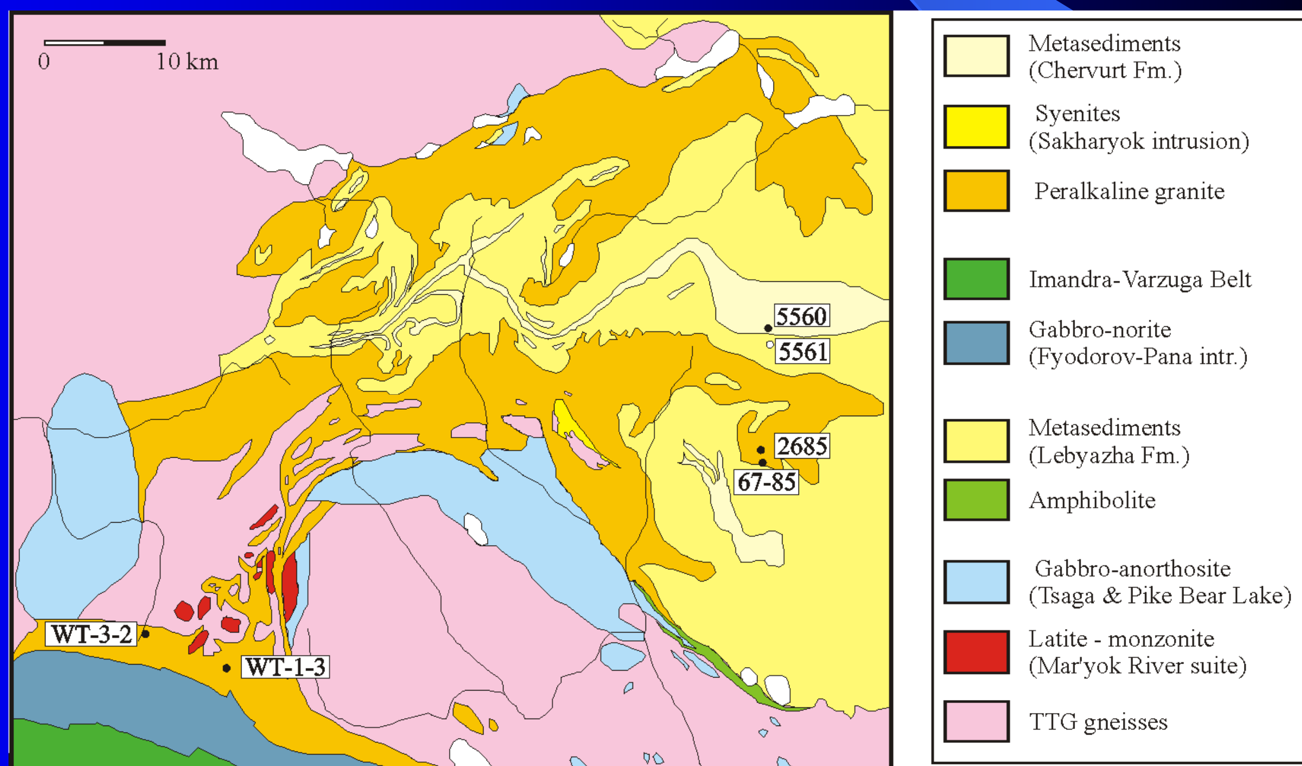
A-type granitoids - Examples

1) Keivy Alkaline Province. Peralkaline granites. Associated anorthosites. Late Archean. Probably a rift setting (Zozulya and Eby).
2) Chilwa Alkaline Province. Basanites, nepheline syenites, syenites and metaluminous to peralkaline granites. Cretaceous. Probably a rift setting (Eby and Woolley).
3) White Mountain Igneous Province. Basalts, andesites, rhyolites, syenites and metaluminous and peralkaline granites. Associated in space and time with the silica-undersaturated sequences of the Monteregian Hills Alkaline Province. Cretaceous. Has been linked to the Meteor hotspot (Eby).
4) Early Carboniferous granitoids of the proto-Andean Foreland (Sierras Pampeanas, Argentina). Metaluminous to peraluminous. Emplaced after a long period of orogenic magmatism. Extensive shearing and emplacement of the plutons is fault controlled (Dalhquist et al. 2010).

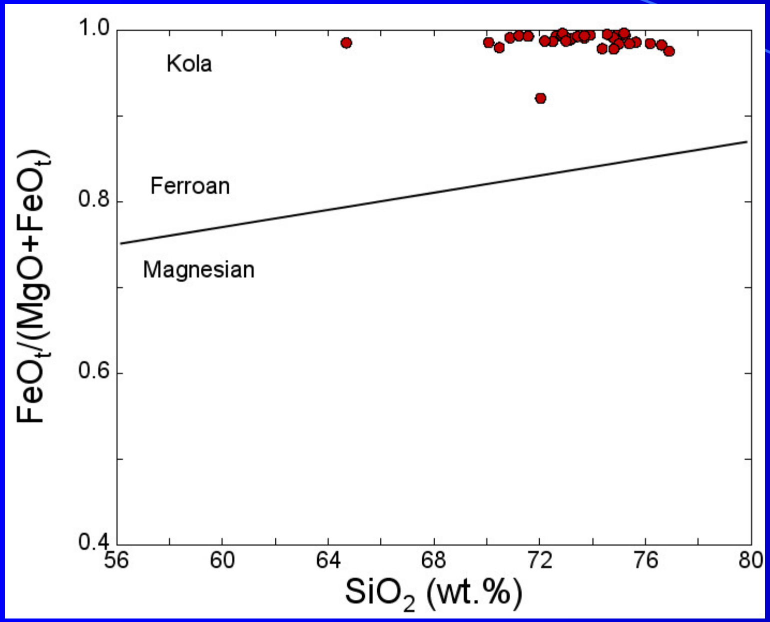
Geology of the Archean Keivy alkaline province

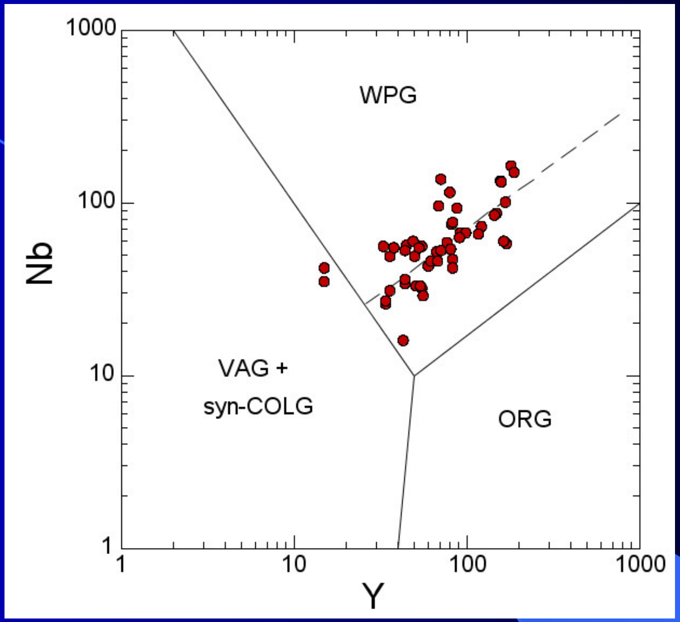


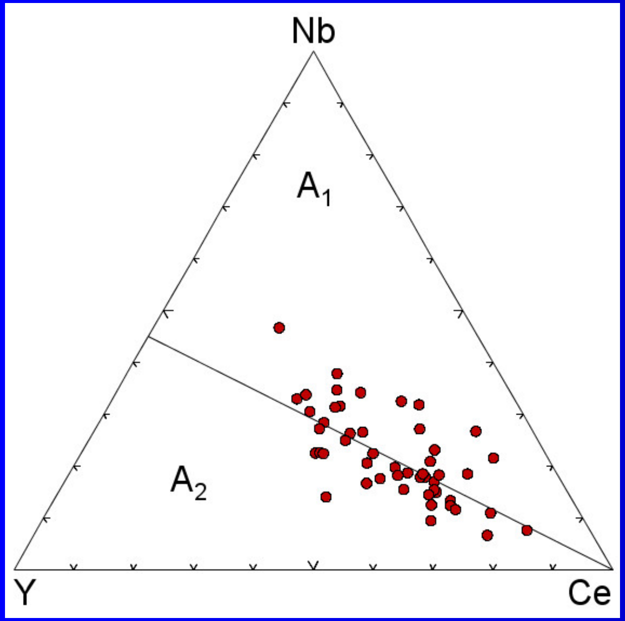
- Six peralkaline granite massifs, confined to the margins of the Keivy terrane
- Sheet-like bodies with thickness of a 100-500 m and of vast exposed areas (100-1300 km^2)
- Spatial and temporal association with massif-type anorthosite bodies

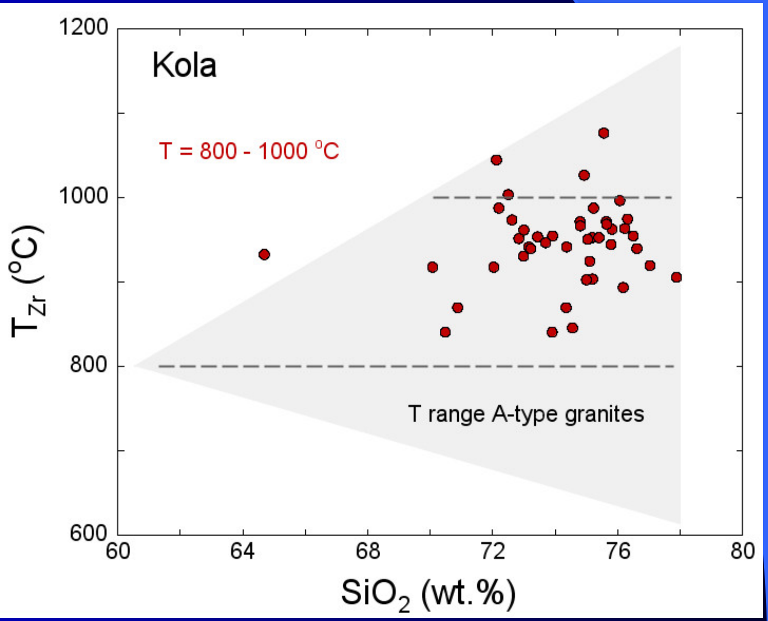


Chemical characteristics and T_{Zr} for the granitoids of the Keivy alkaline province





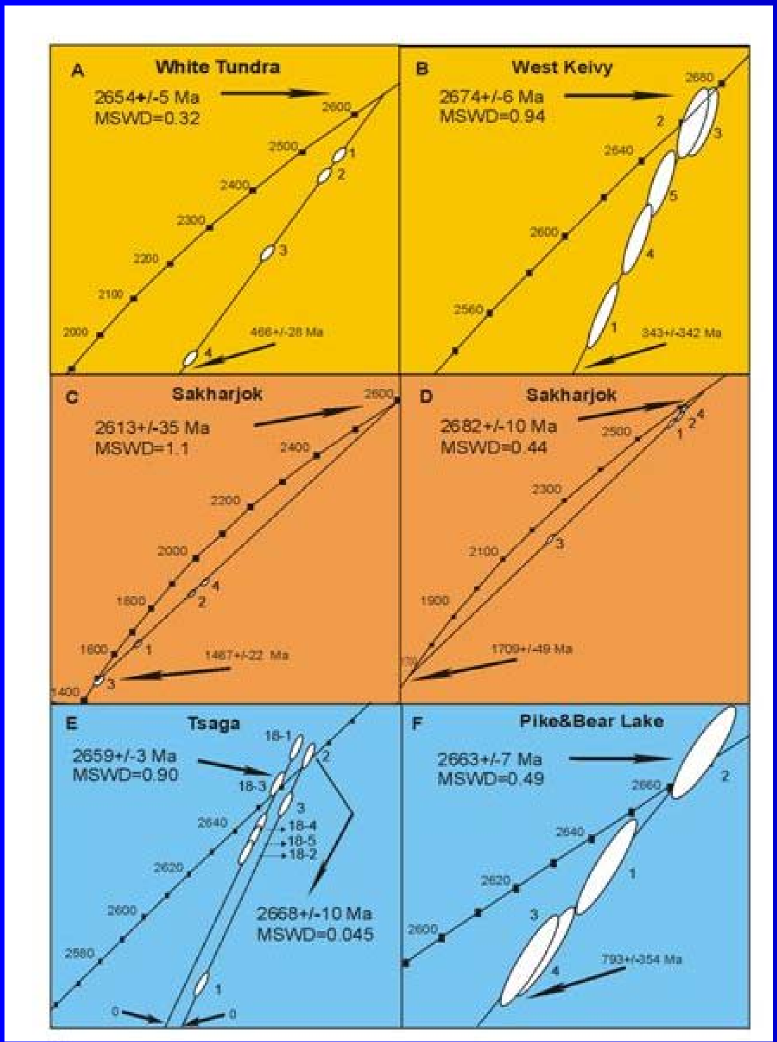


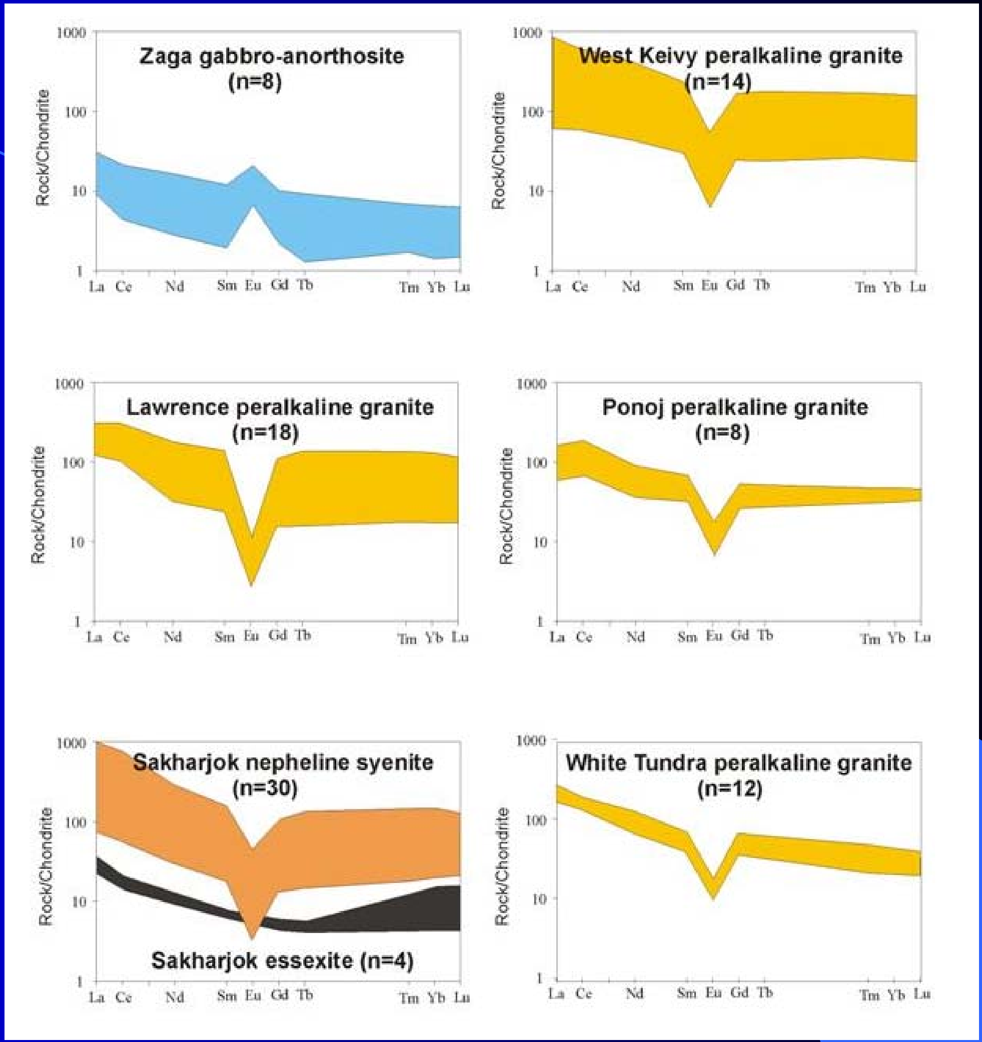


Granitoids 2654 – 2674 Ma

Anorthosites 2659 – 2663

Nepheline gabbro – 2682 Ma

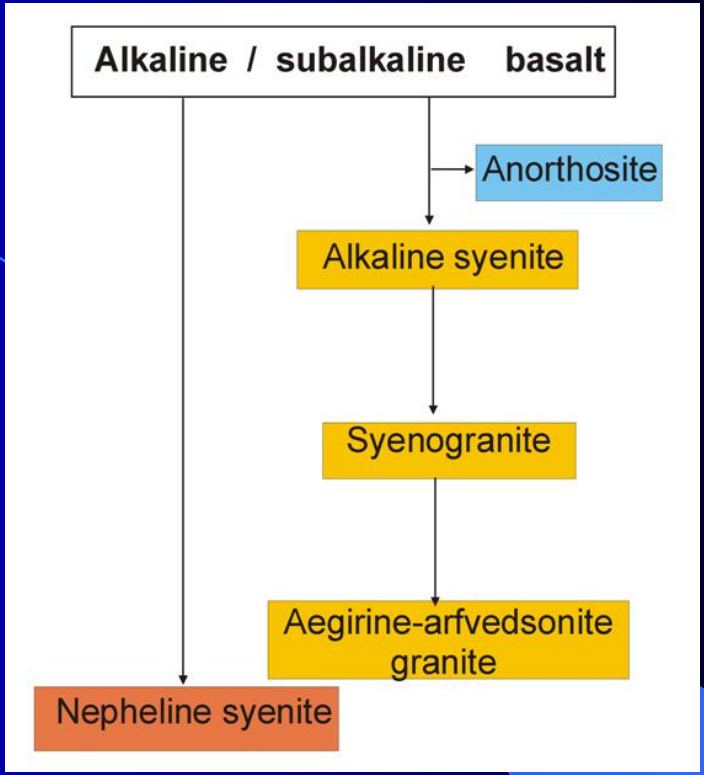


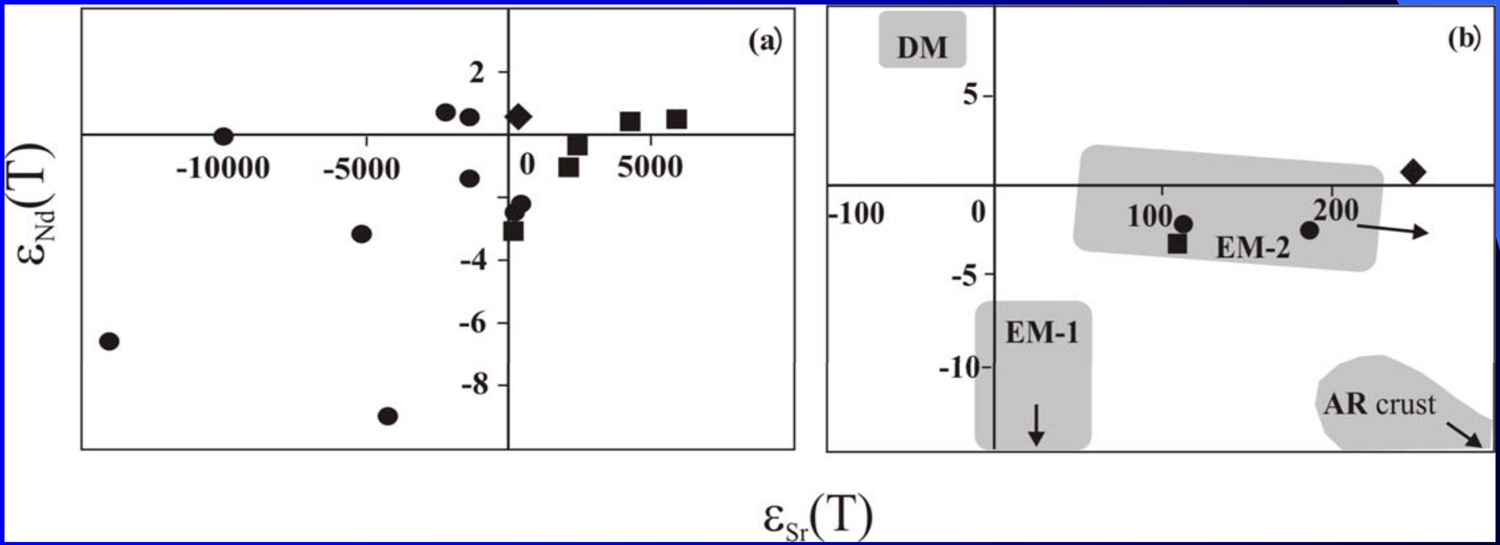


The feldspathic rocks and the gabbro-anorthosites show antithetical REE patterns which suggests they may represent evolved liquids and cumulates, respectively.

Zozulya and Eby (2008) proposed that the alkaline granitoids were the result of protracted fractional crystallization of a subalkaline/alkaline basalt magma. The anorthosites represent the cumulates.

Nd isotope data indicate that the basaltic magma(s) were derived from an enriched mantle source which was a result of the subduction process in the adjacent Kolmozero-Voron'ya greenstone belt which evolved in the period 2.92-2.83 Ga.



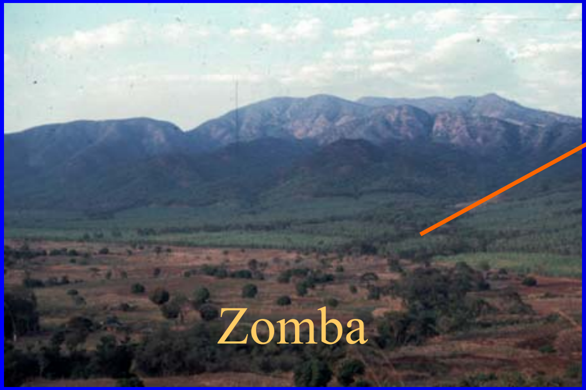


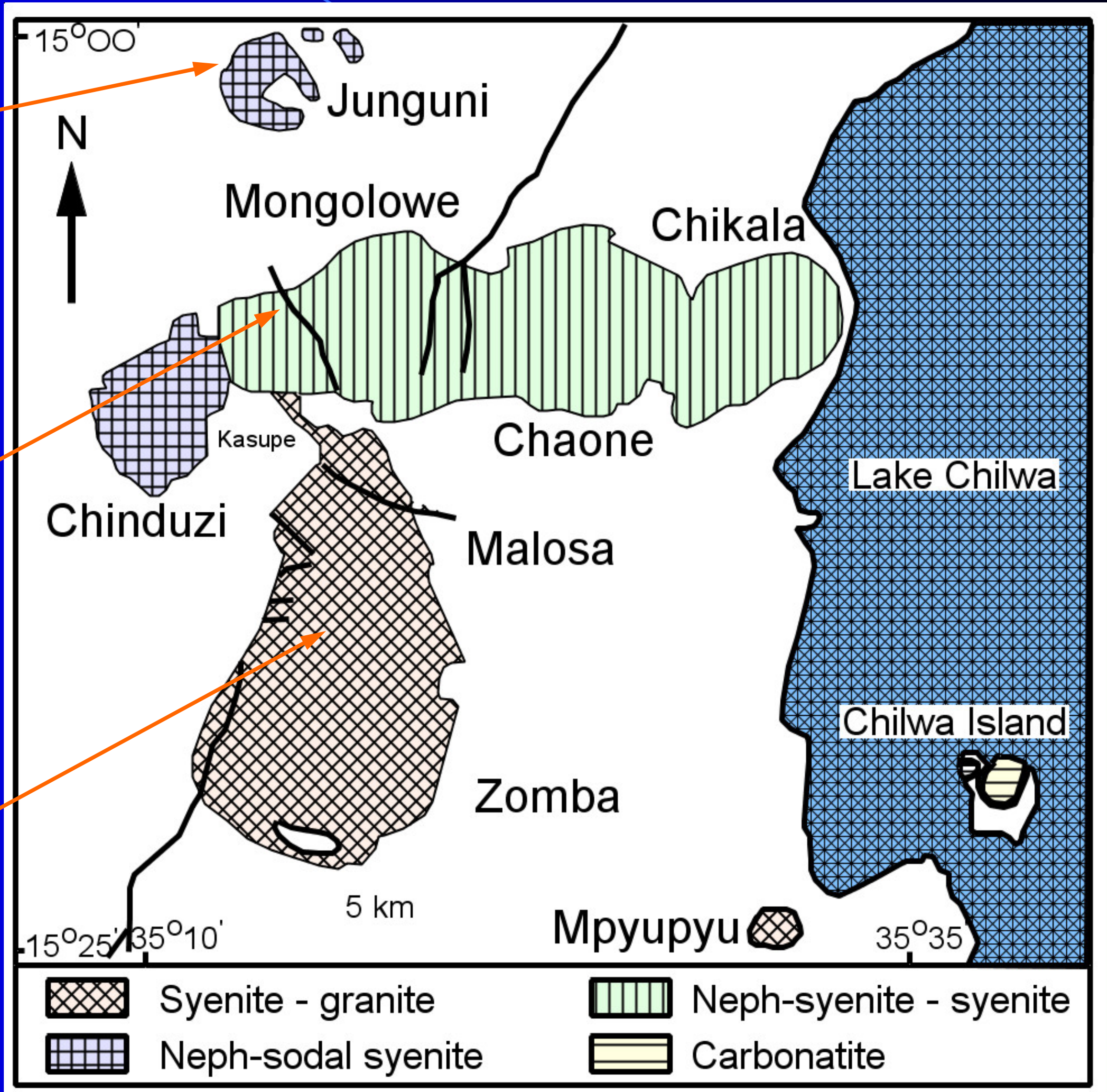
Petrogenesis of the Keivy Alkaline Province

- Extensional (rift) setting.
- The alkaline granites are the product of extended fractional crystallization of a basalt magma. Isotope data indicates that there was some crustal contamination.
- Zircon saturation geothermometry indicates temperatures of approximately 1000^{o}C for the peralkaline granites. The high temperatures of the magmas may be due to higher heat flow during the Archean.
- The magma source was enriched mantle. This enrichment occurred during an earlier period of subduction.
- The peralkaline granites represent a net addition of mantle derived material to the crust.

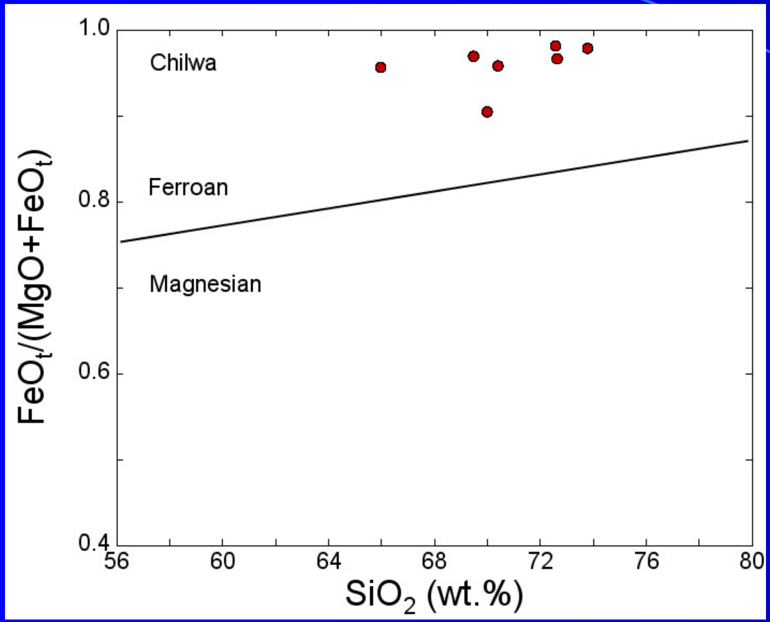
Geology of the Cretaceous Chilwa Alkaline Province

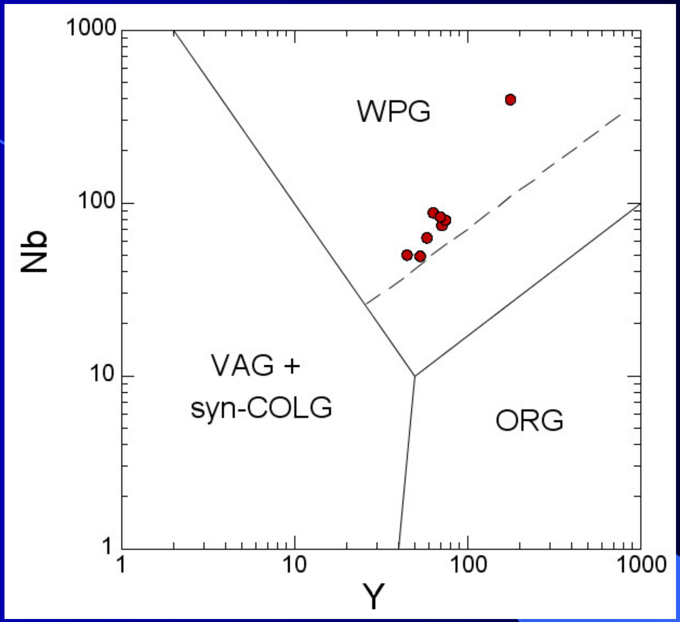
Lithologies: carbonatite, nepheline-sodalite syenite, nepheline syenite, syenite, granite

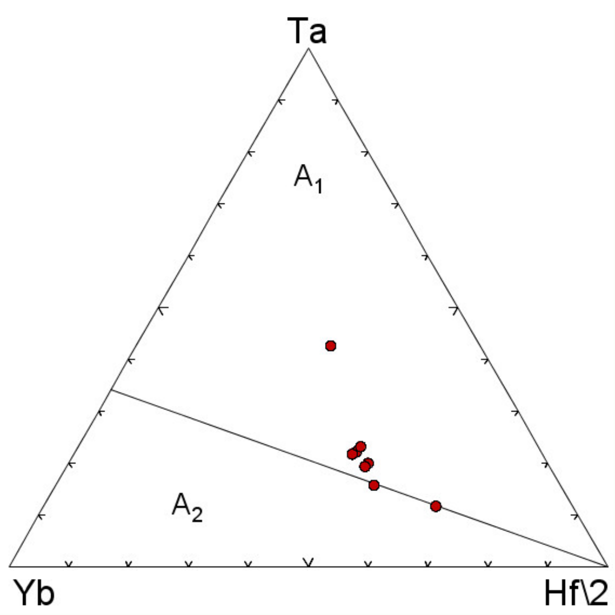


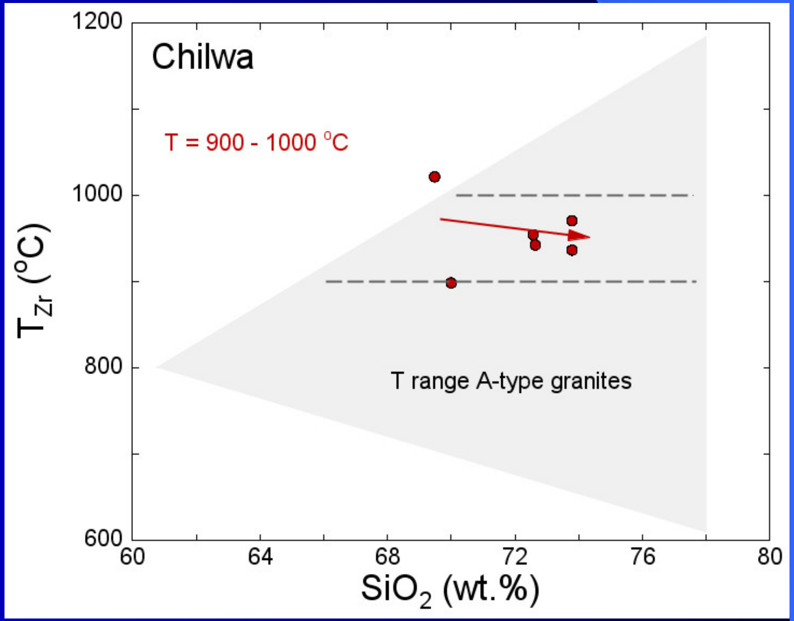


Chemical characteristics and T_{Zr} for the Chilwa syenites and granites





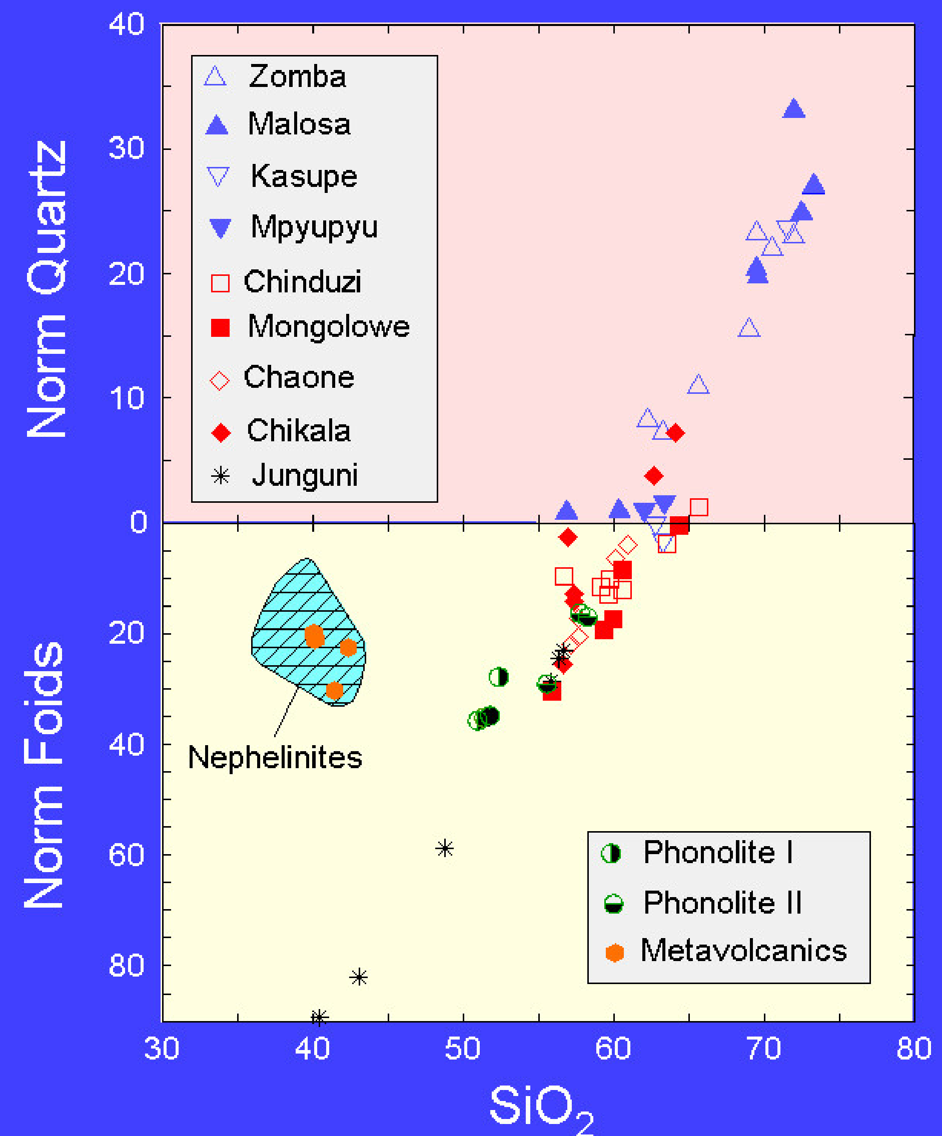




Degree of silica saturation for the major plutonic and volcanic units

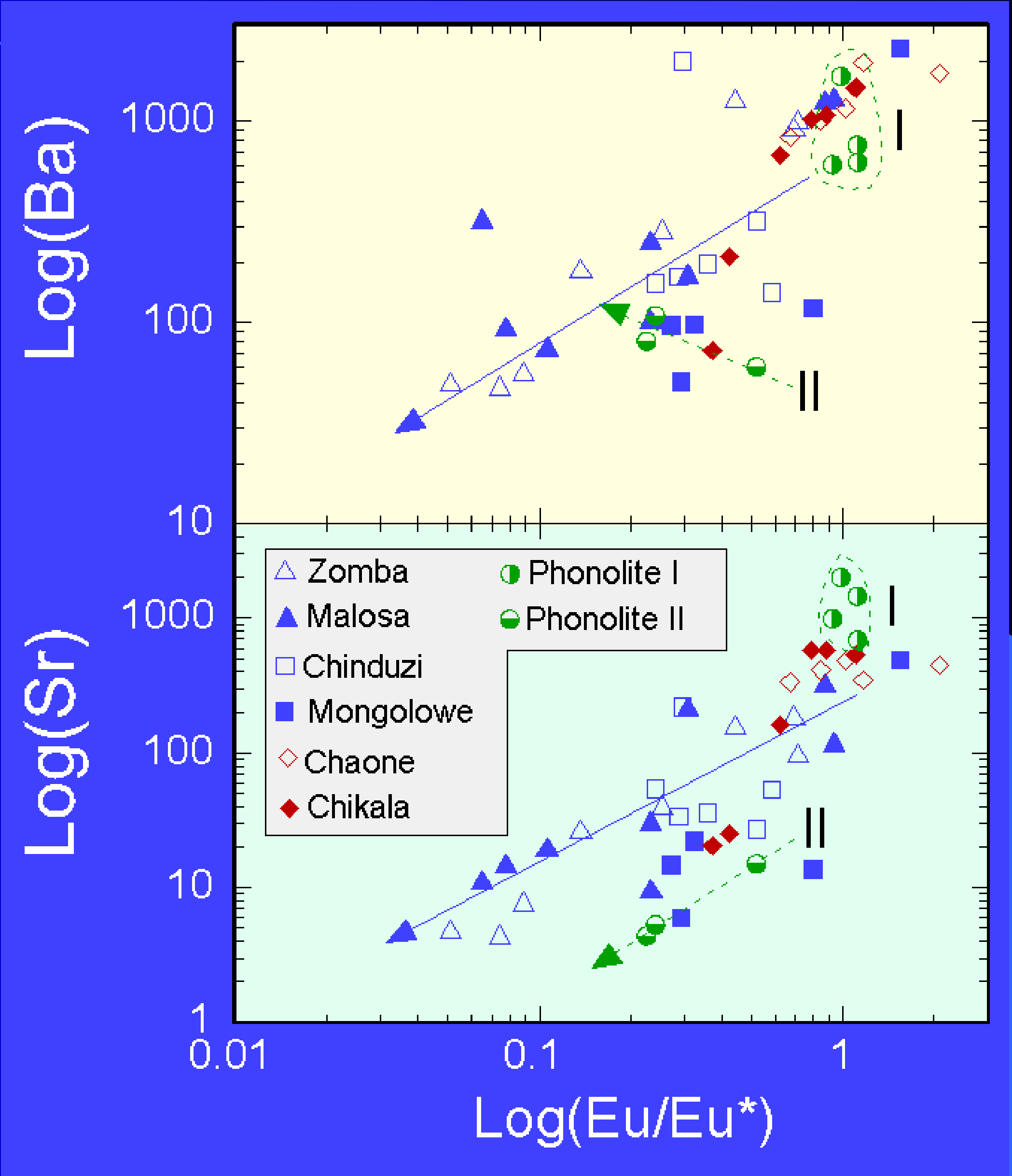
Felsic rocks vary from strongly silica-undersaturated nepheline-sodalite syenites to alkali granites.

Mafic rocks are silica-undersaturated basanites and nephelinites.



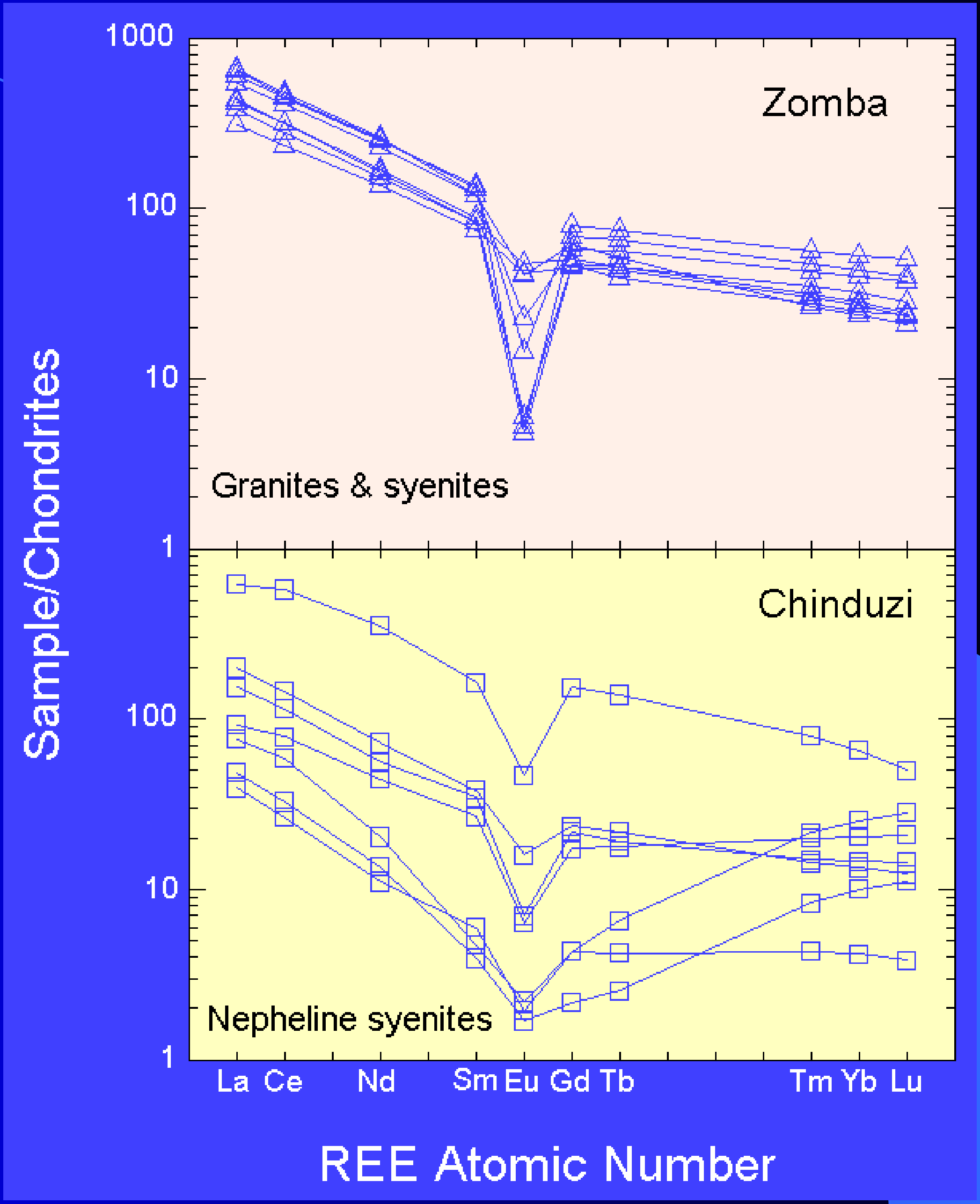
Log Eu* vs log Sr, Ba

- Two groups of phonolites can be distinguished, one that shows negative Eu anomalies, one that doesn't.
- The alkali granites and syenites (Zomba & Malosa) roughly fall along alkali feldspar + plagioclase fractionation vectors.
- Many of the nepheline syenites also show negative Eu anomalies indicating that feldspar fractionation played a role in their evolution.



REE patterns for Zomba are subparallel and show increasing negative Eu anomalies with increasing total REEs, typical of a feldspar fractionation trend.

REE patterns for Chinduzi are much more irregular and, in particular, the presence of U-shaped (or V-shaped) patterns suggests that there may have been postmagmatic redistribution of the elements by F- and/or CO_2-rich hydrothermal fluids.

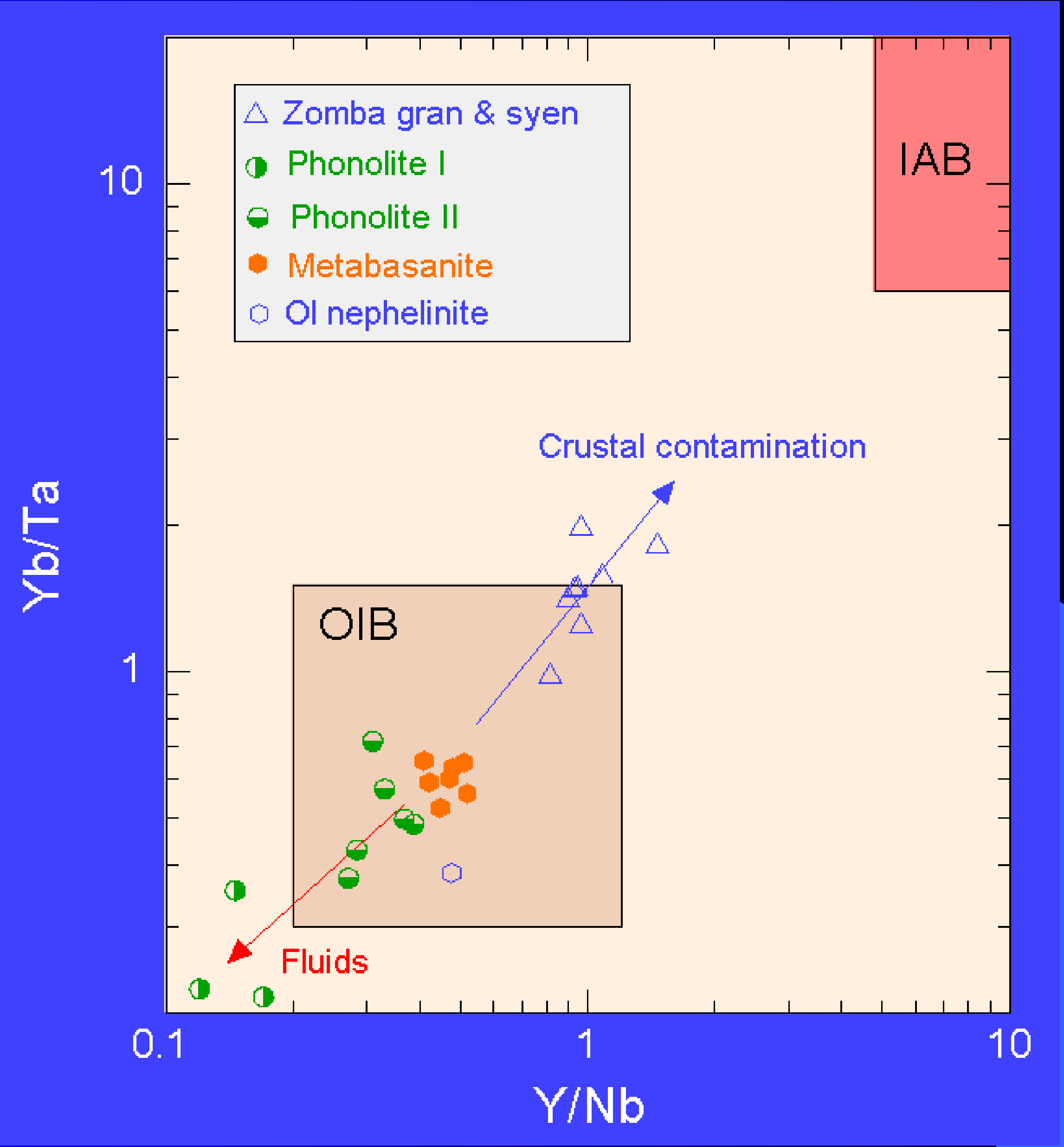


Y/Nb vs Yb/Ta diagram

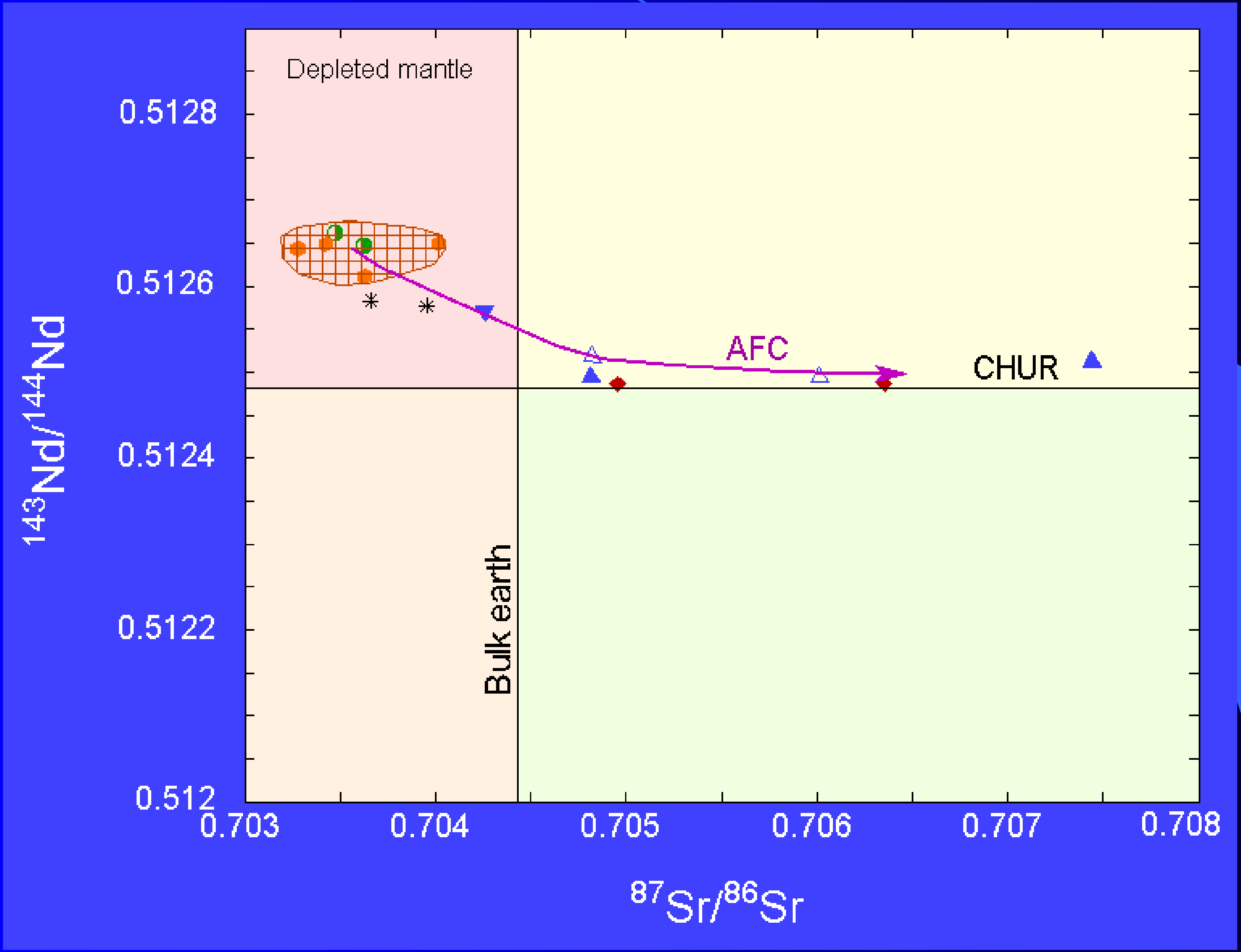
The metabasanites and olivine nepehlinites plot in the OIB field.

The blue vector indicates the effect that crustal contamination would have on these ratios.

The red vector indicates the effect that F- and/or CO_3-rich fluids would have on these ratios.



The majority of the CAP samples fall in the depleted mantle field. Samples that plot outside this field lie along a possible AFC curve.

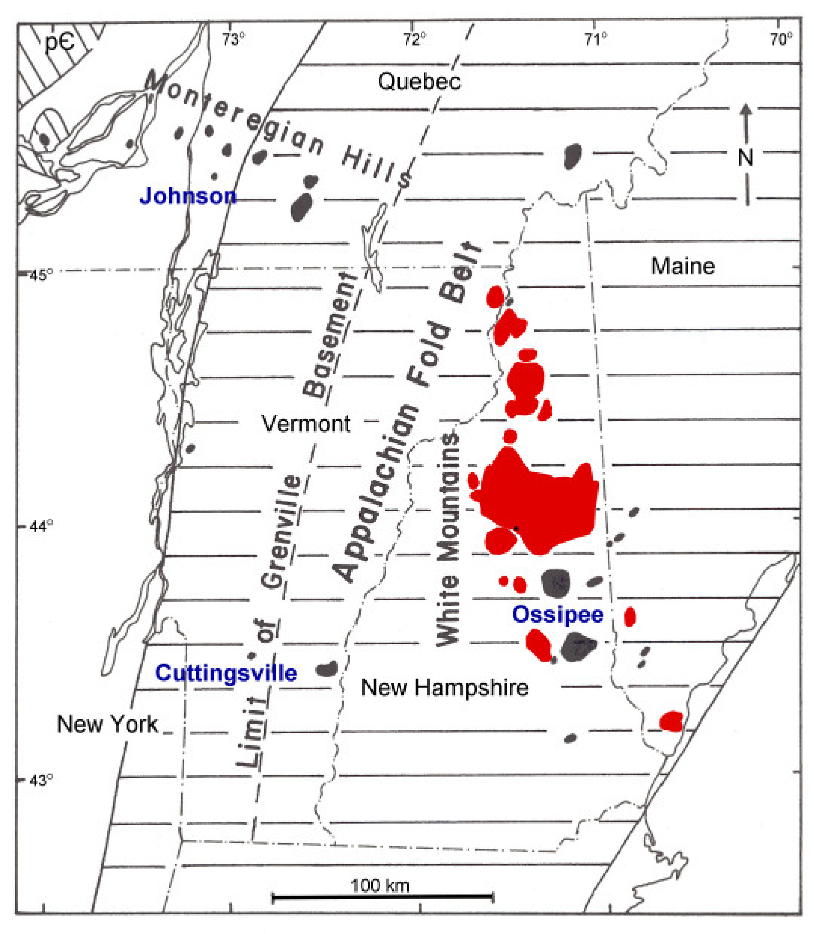


Petrogenesis of the Chilwa Alkaline Province

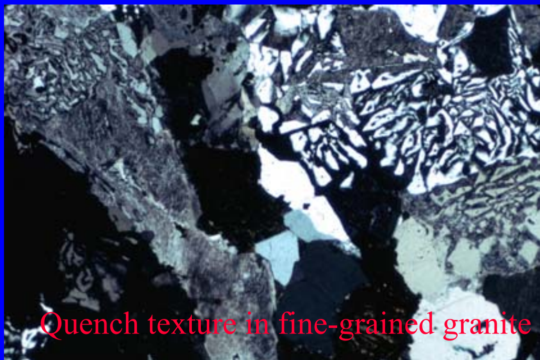
- Extensional (rift) setting.
- Both silica undersaturated and silica saturated sequences are associated in space and time.
- Nephelinites and basanites are part of the petrogenetic sequence.
- Zircon saturation geothermometry indicates temperatures of 900 - 1000^{o}C for the syenites and granites.
- An AFC model can be used to relate both the silica undersaturated and silica saturated rocks starting with a silica undersaturated mafic melt. The syenites and granites were emplaced last and show the greatest amount of crustal contamination.
- The magma source was depleted mantle that was enriched shortly before or simultaneously with the melting event.

The Cretaceous Monteregian Hills – White Mountain Igneous Provinces

There are two periods of anorogenic granitoid magmatism (White Mountain province) in New England, USA, at ~180 Ma and ~120 Ma. This magmatism is well after amalgamation of the North American craton and is precursor to the opening of the North Atlantic Ocean. Rocks of a correlative age to the younger period of White Mountain igneous activity, but forming a silica-undersaturated suite (Monteregian Hills), are found in proximal Quebec, Canada.



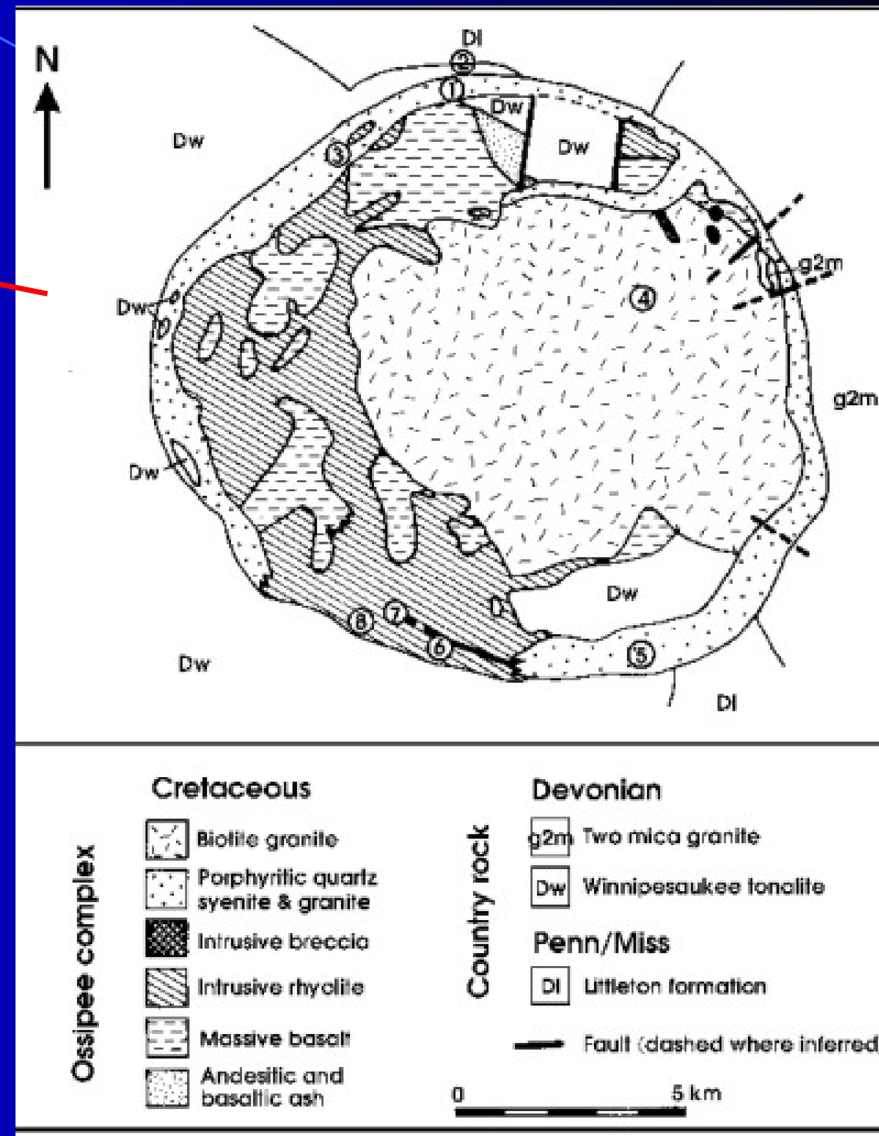
The Ossipee Ring Complex – an example of Cretaceous White Mountain magmatism



Quench texture in fine-grained granite

Fragmental rhyolite

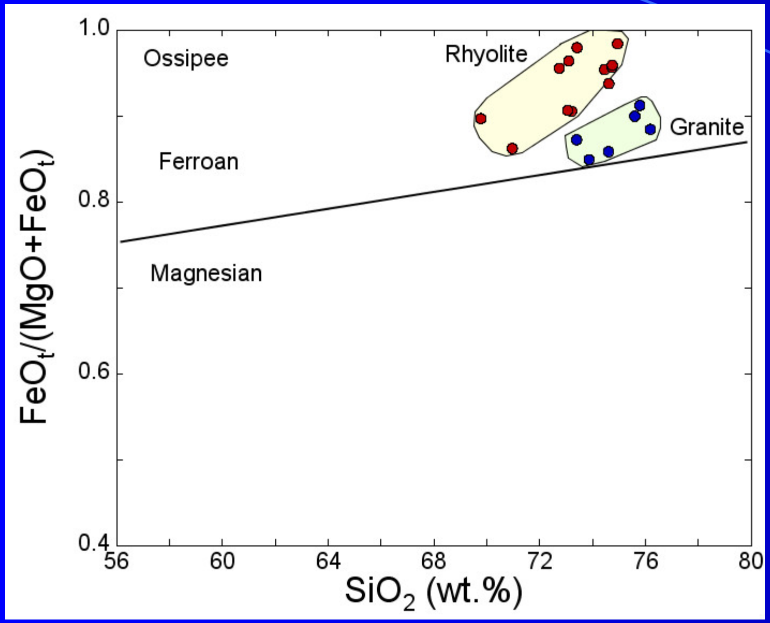
High level intrusion, classic ring-complex structure

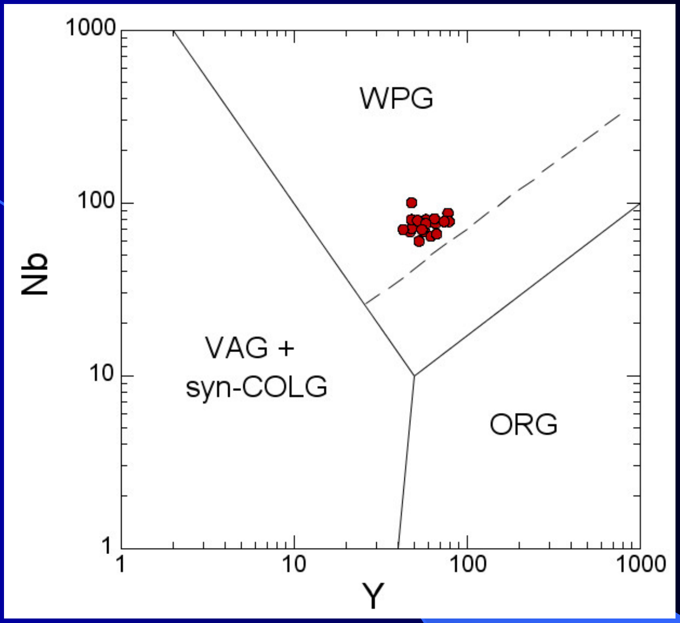


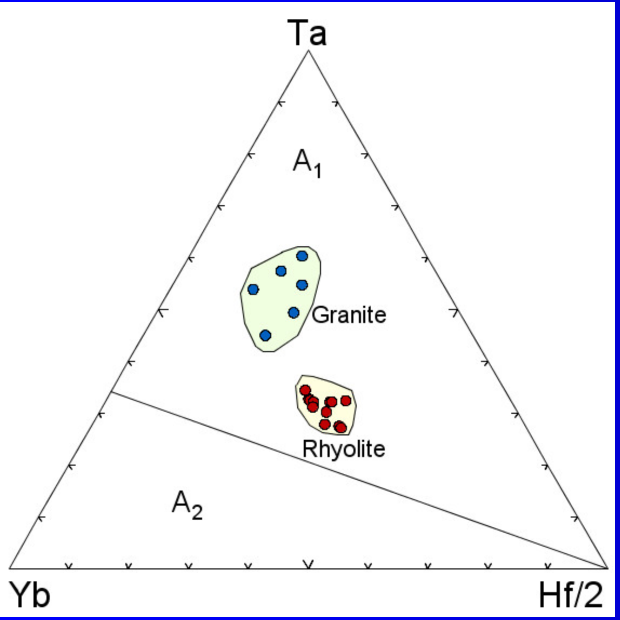
Bimodal volcanics + quartz syenites and granites

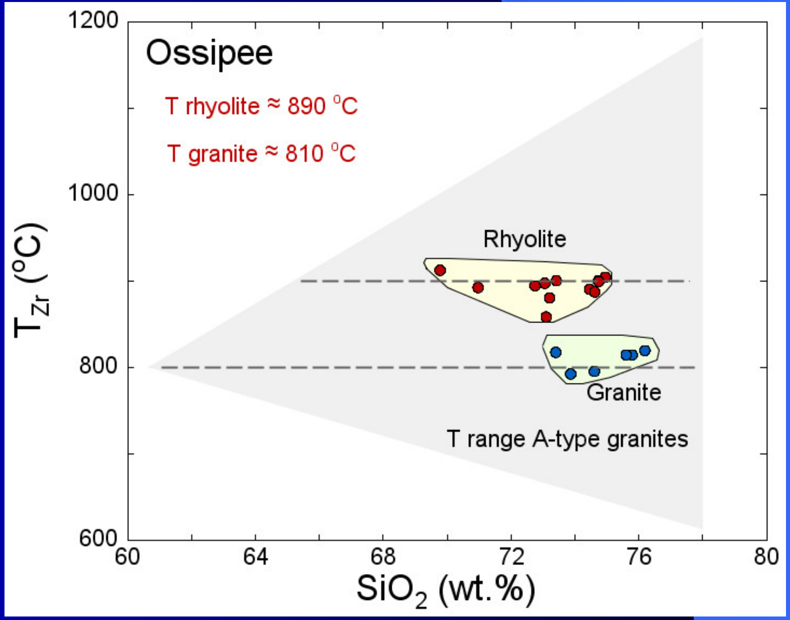
Coarse-grained biotite granite

Chemical characteristics and T_{Zr} for the Ossipee rhyolites and granites

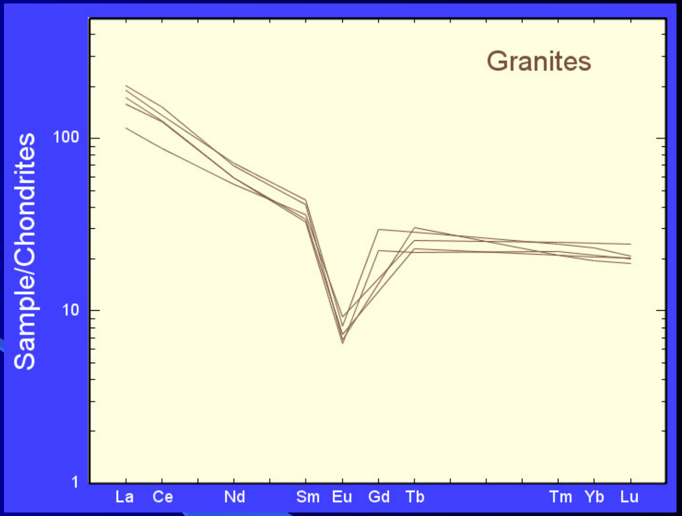


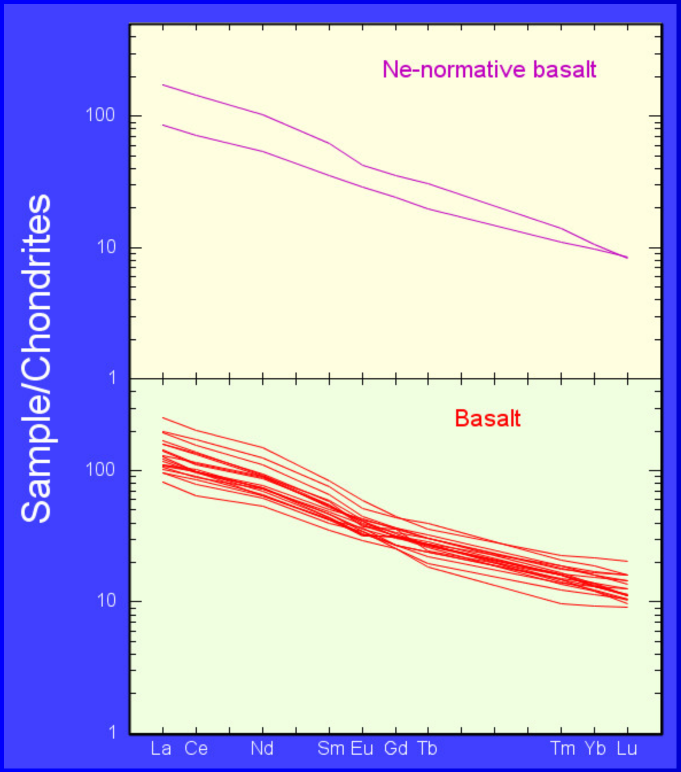


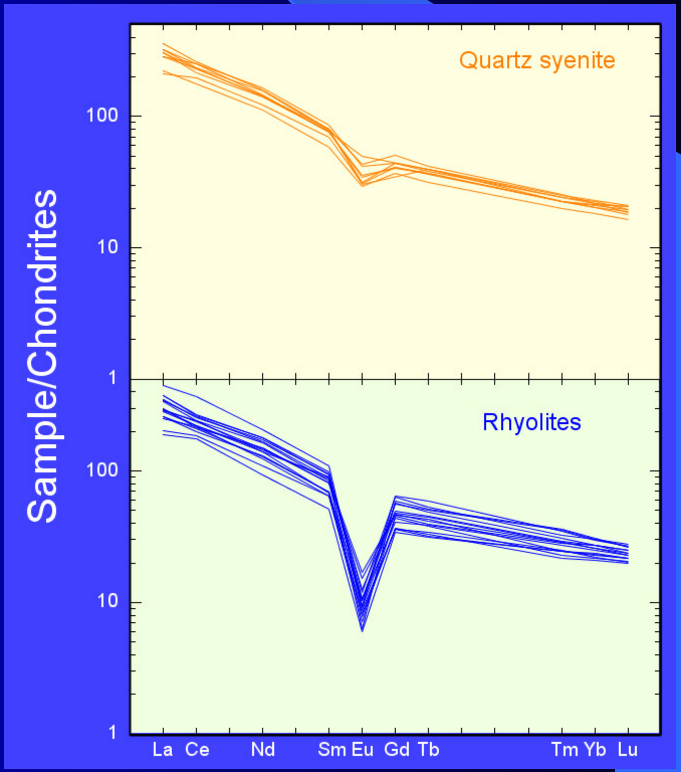




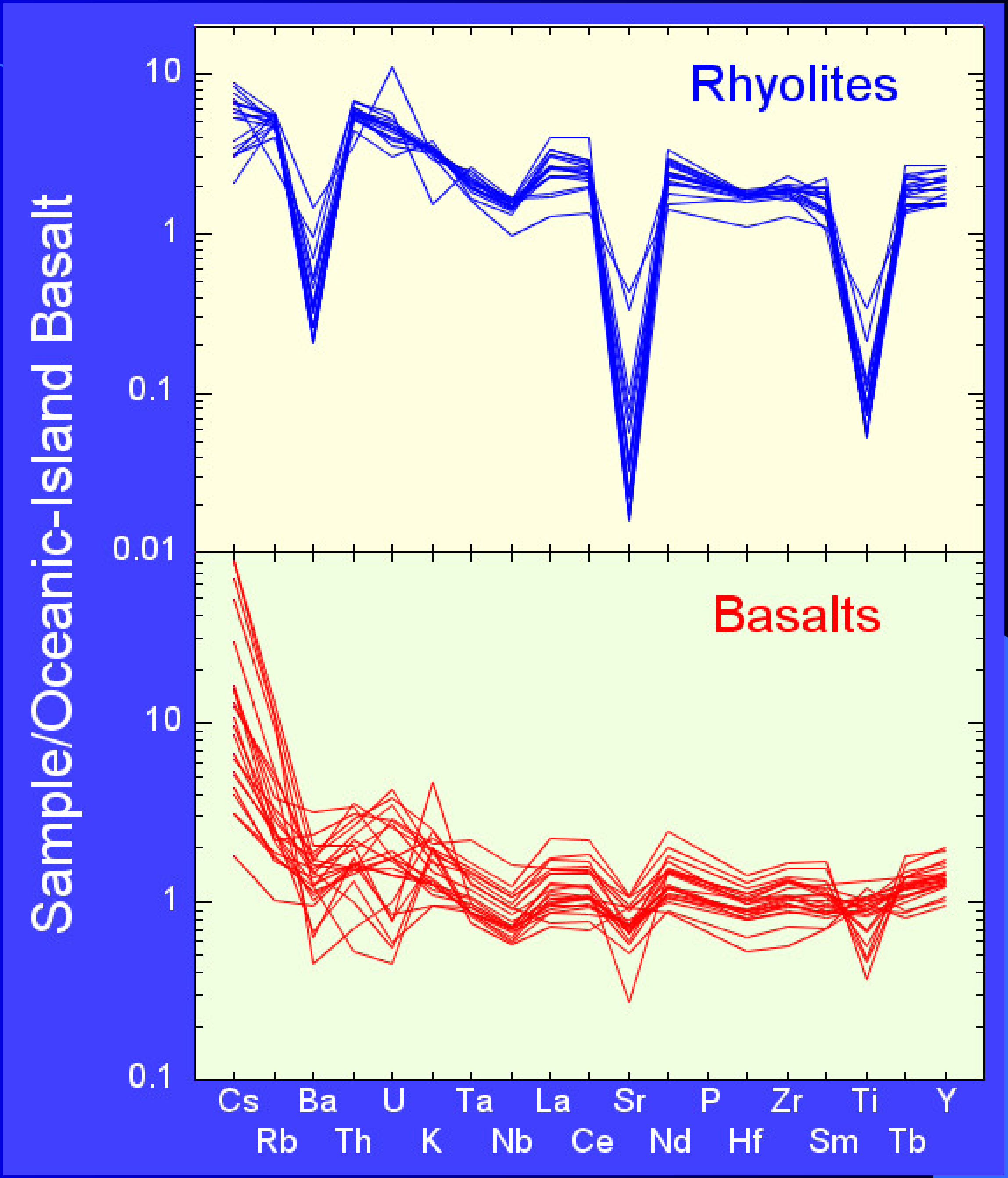
Chondrite normalized REE plots for the various lithologies of the Ossipee ring complex. Note the similar slopes of the REE patterns for all lithologies with the exception of the granite which shows a flattening at the HREE end.



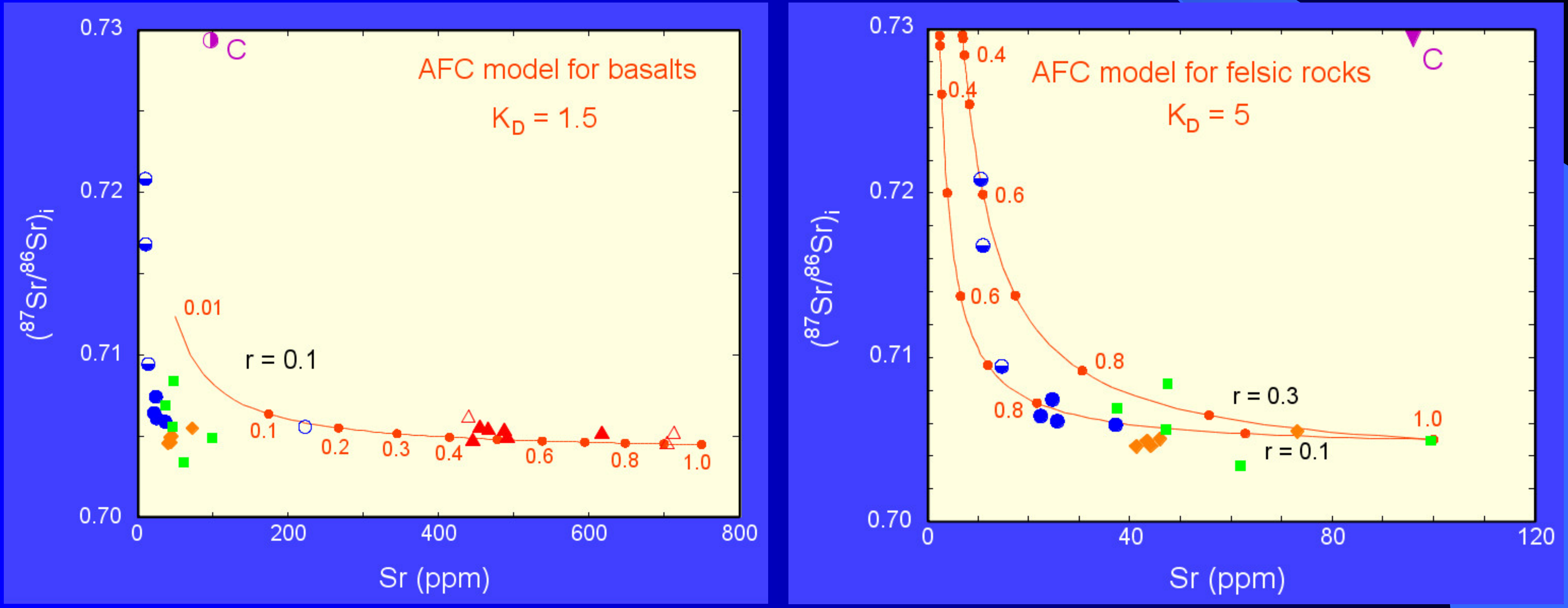




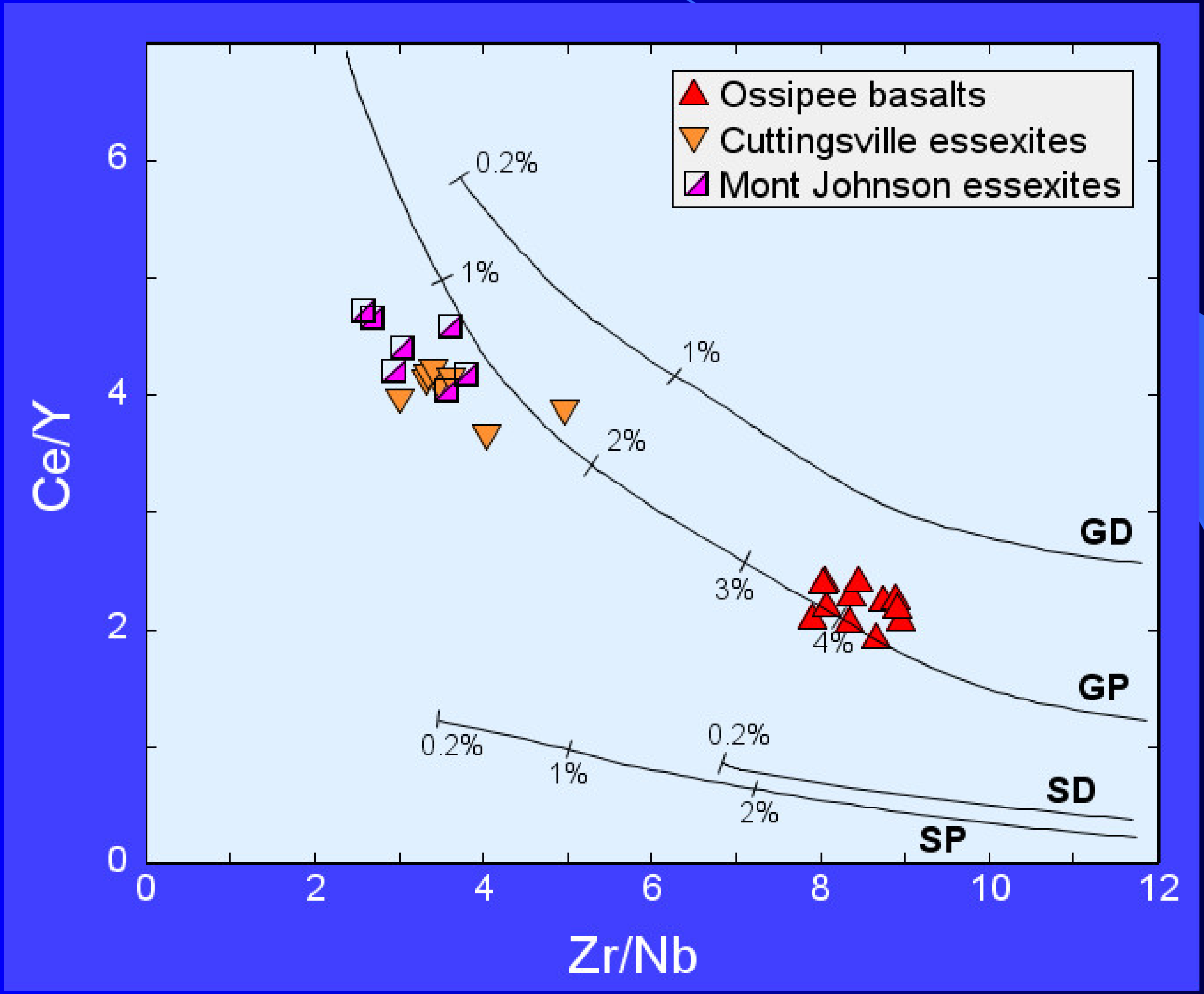
OIB normalized spider diagrams for Ossipee rhyolites and basalts. Note the similarity of both lithologies to OIB. Variations can be explained by the fractionation of alkali feldspar and opaque oxide minerals. Cs enrichment in basalts is due to late-stage hydrothermal alteration as evidence by the partial replacement of plagioclase by epidote.



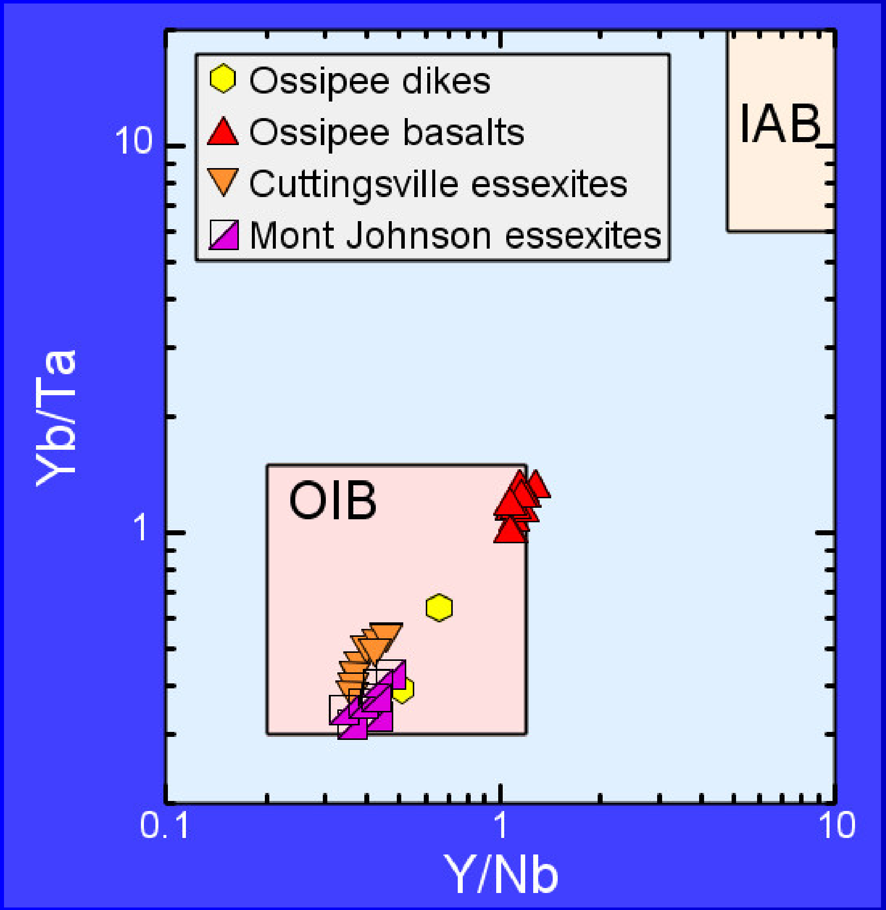
AFC models for basalts and felsic rocks. The isotopic variations require only minor contamination of the melts by country rock.

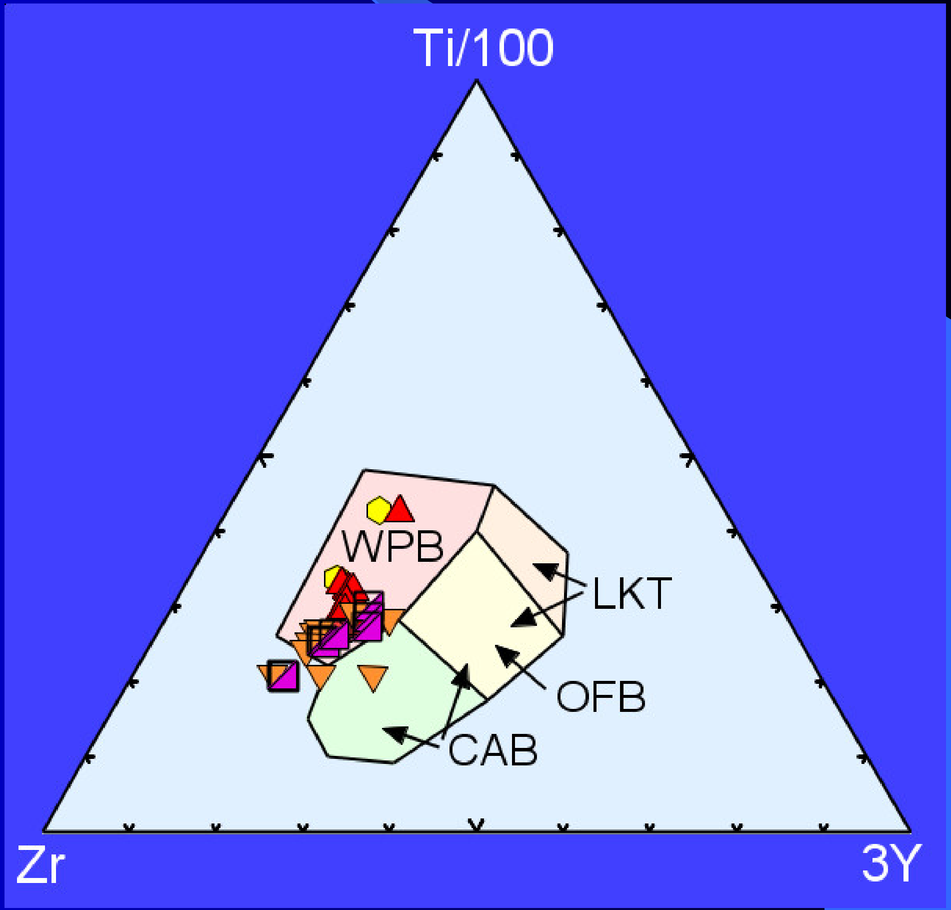


Melting models for various mantle sources. Note that the MHWM mafic rocks fall along the Garnet Peridotite (GP) curve and are apparently related by variable degrees of melting of the source.

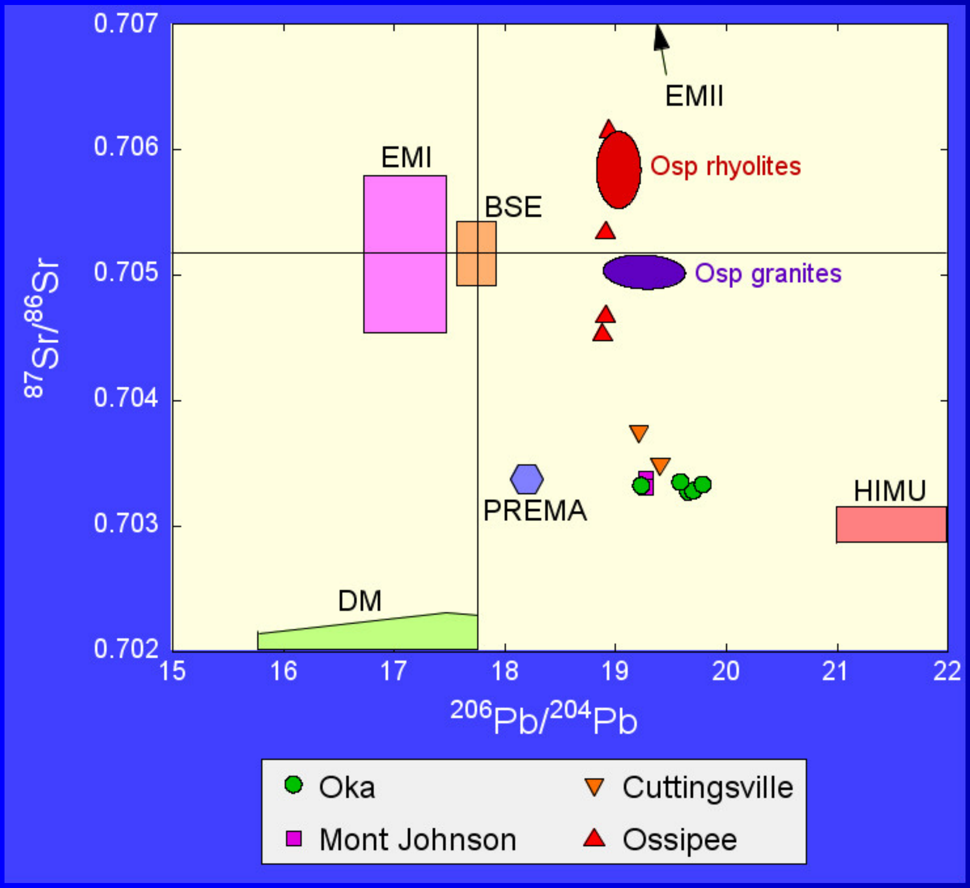


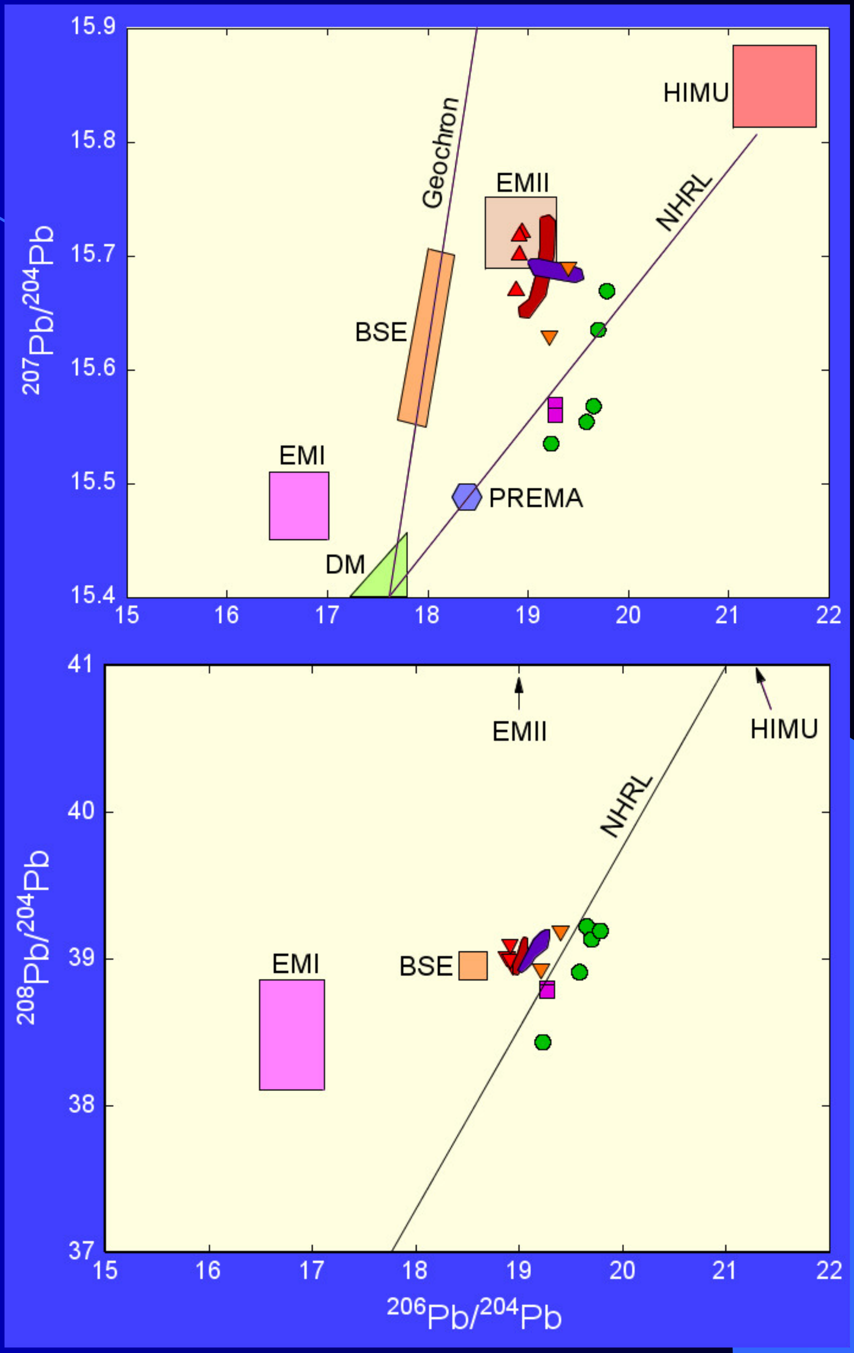
The mafic rocks plot in the OIB and WPB fields on various discrimination diagrams. In the Y/Nb vs Yb/Ta diagram the Ossipee basalts plot towards the IAB field (but still within the OIB field), an indication of minor crustal contamination.





Sr and Pb isotopic relationships for the mafic silicate rocks and the Oka sovites.



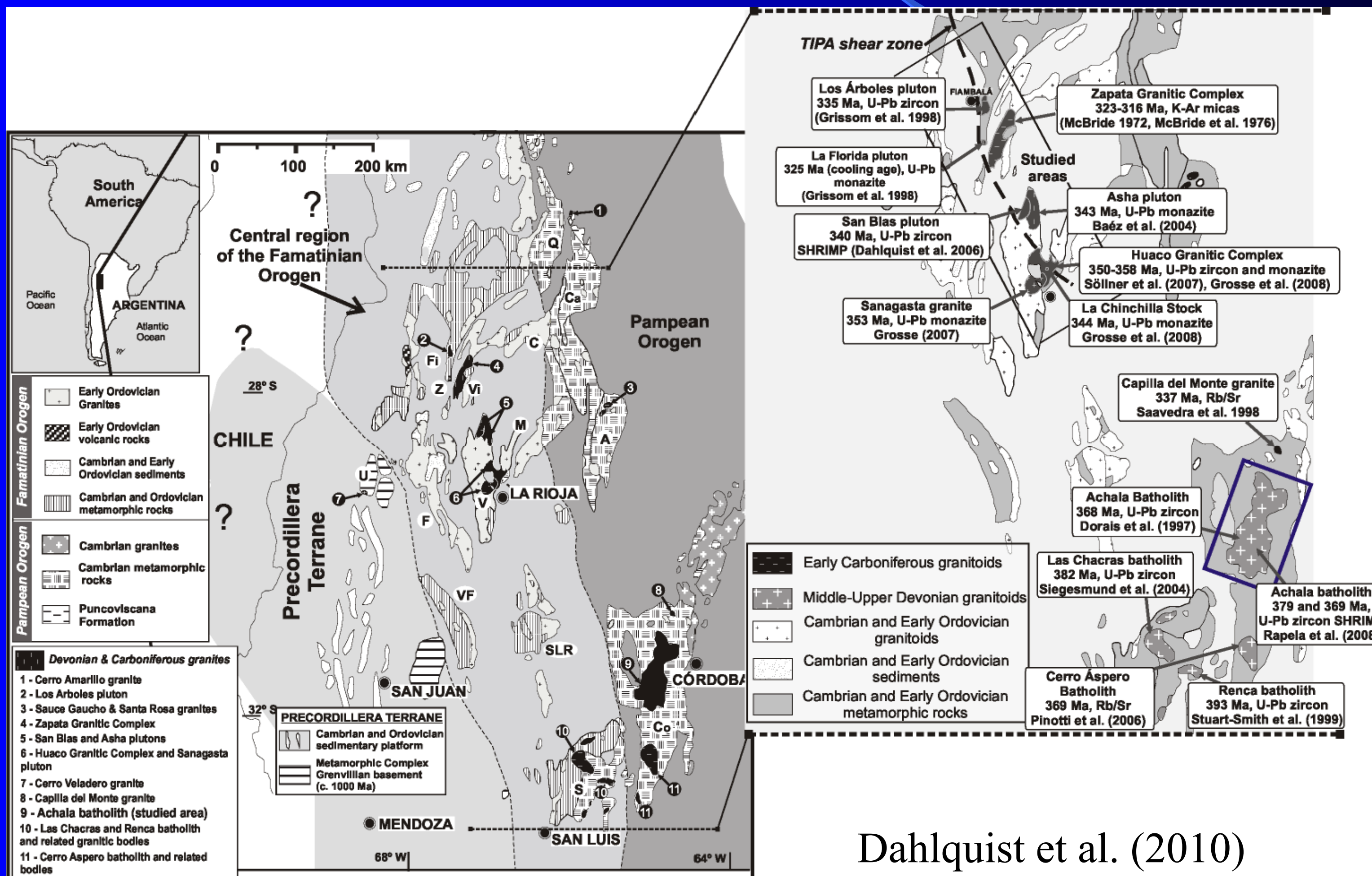


Petrogenesis of the Ossipee Ring Complex

- The Monteregian Hills – White Mountain magmatism has been related to a hotspot trace. This trace continues with the New England Seamount Chain.
- In a west to east direction the magmatic activity changes from silica undersaturated magmas to silica saturated magmas. This transition corresponds with an increase in crustal thickness.
- Mafic magmas associated with the Cretaceous White Mountain plutons show isotopic evidence of crustal interaction.
- Zircon saturation geothermometry indicates temperatures of ~900^{o}C for the rhyolites and ~ 800^{o}C for the granites.
- An AFC model can be used to relate the basalts and rhyolites. The granites show isotopic evidence of a greater amount of crustal interaction than the rhoylites.
- The basaltic magma were derived from an OIB-like source.

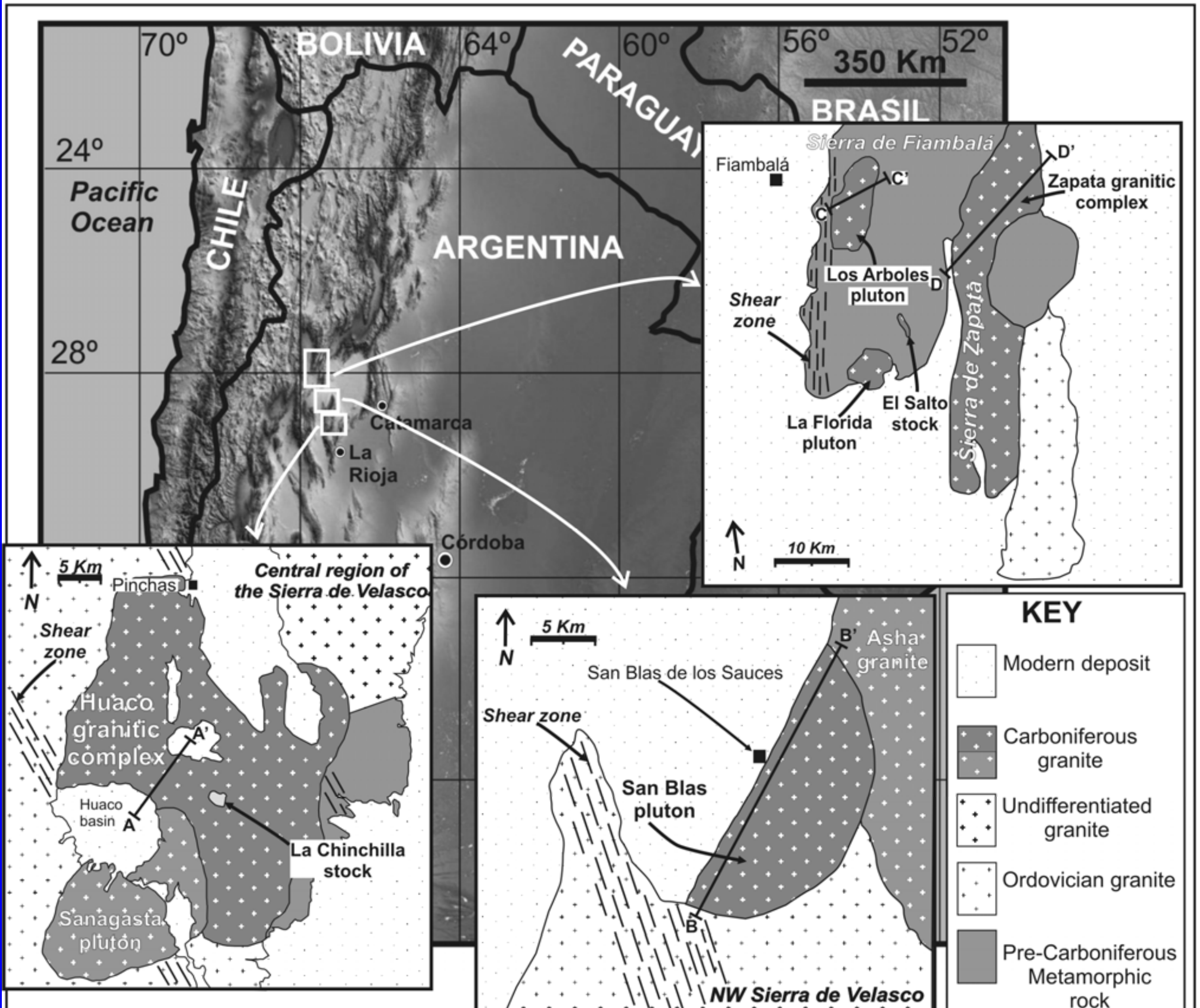
Post-Orogenic Carboniferous granitoids in the proto-Andean Foreland, Western Argentina

These A_2 granitoids are slightly to strongly peraluminous, are associated with shear zones, and are emplaced shortly after a long period of orogenesis.



Dahlquist et al. (2010)

Geology of the individual plutons and their relationship to the TIPA shear zone



Dahlquist et al. 2010

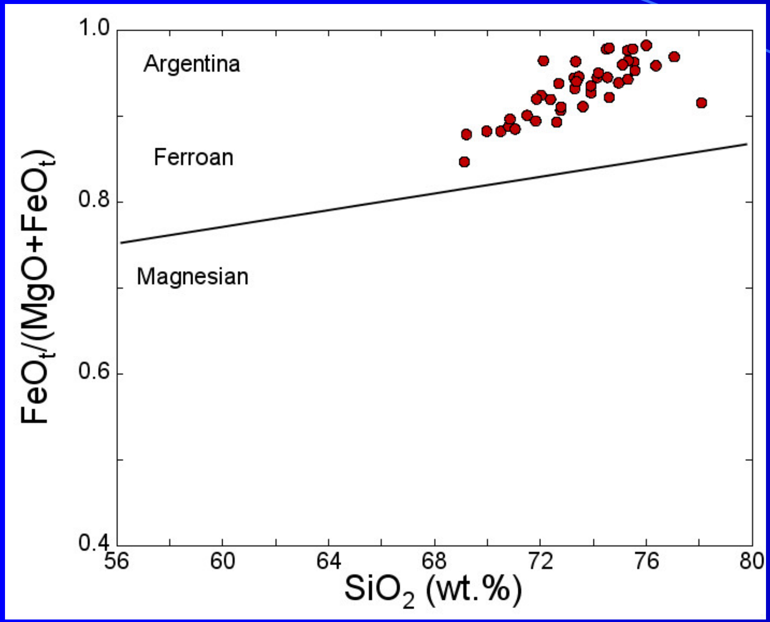
TIPA shear zone. Large feldspars in mylonite. Fractured feldspar indicates right lateral shear.

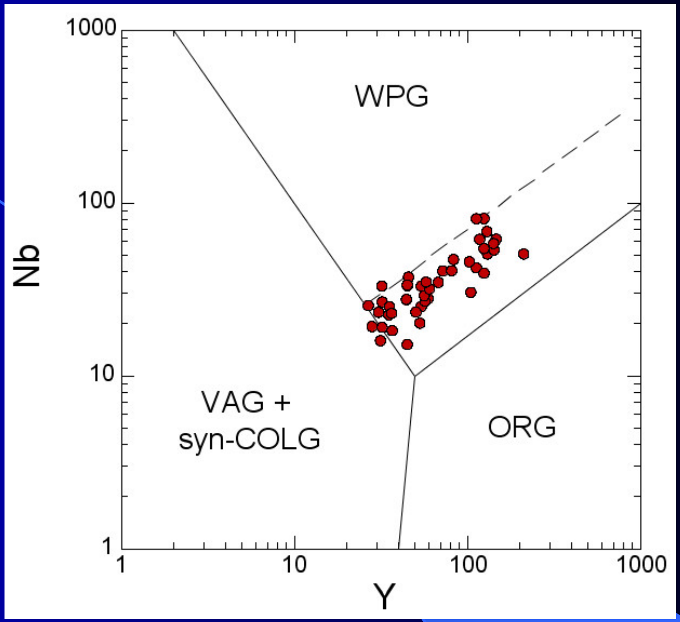
TIPA shear zone. Well-developed mylonitic fabric

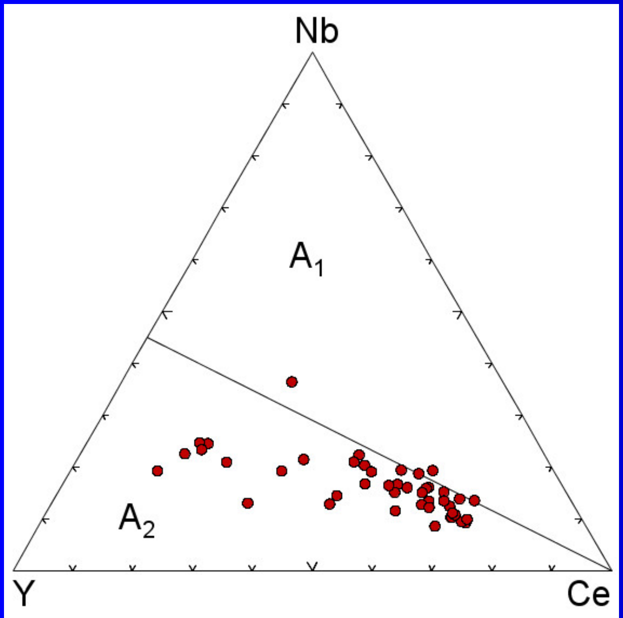
San Blas pluton. Large feldspar phenocrysts in a dark matrix.

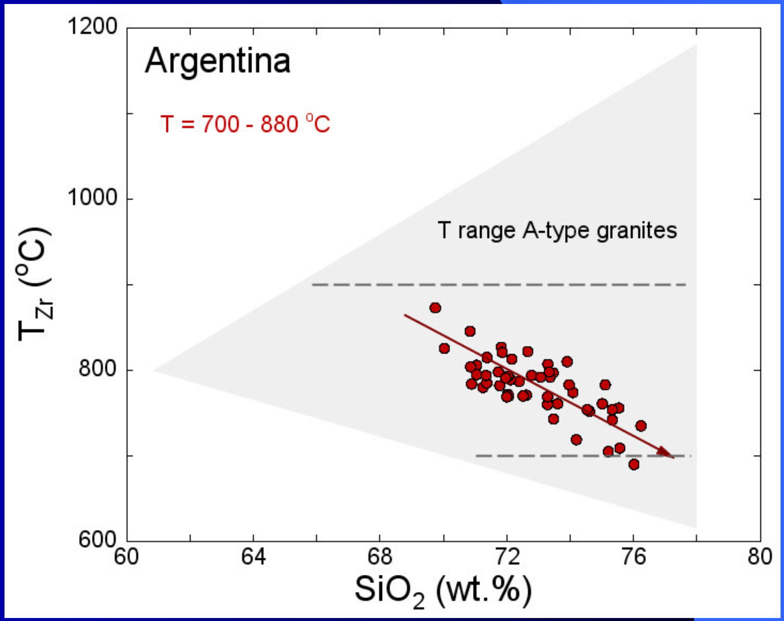
Huaco complex, about 2000 m from contact with San Blas pluton. Feldspar phenocrysts show primary igneous flow alignment.

Chemical characteristics and T_{Zr} for the Argentina granitoids

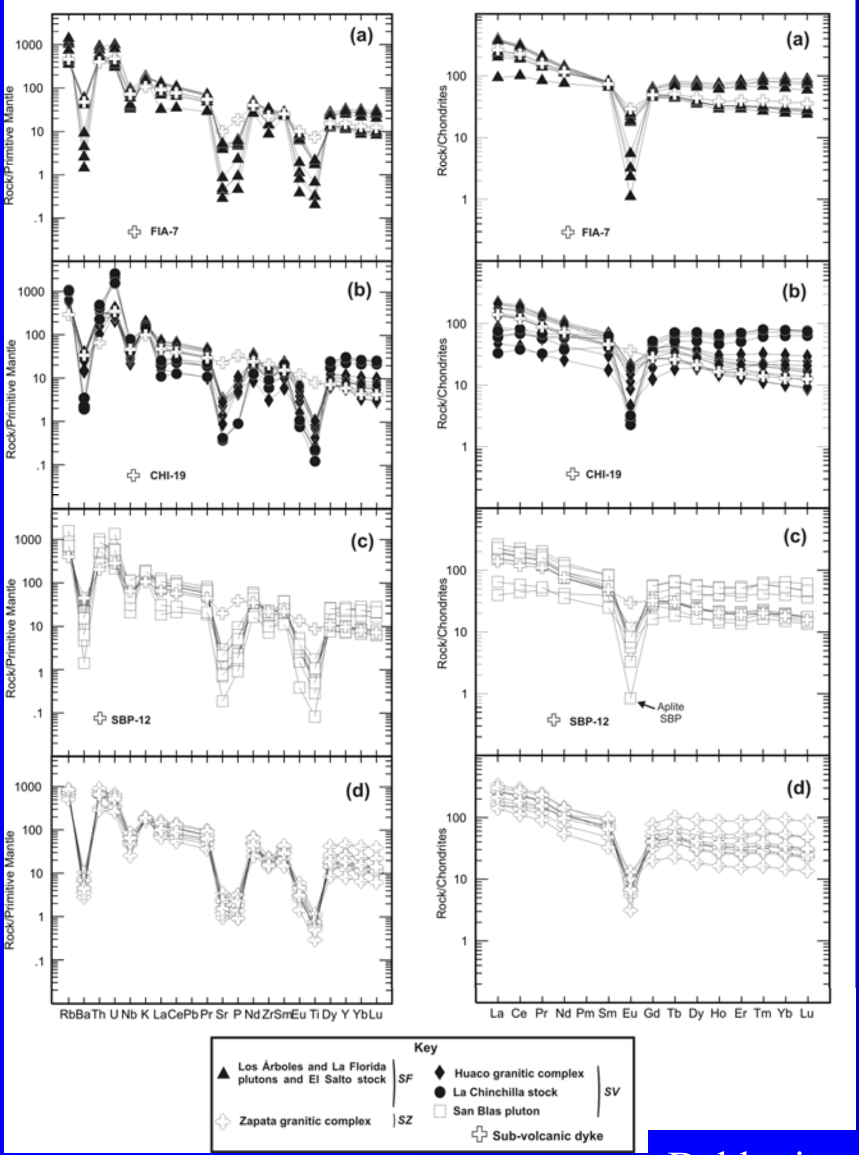


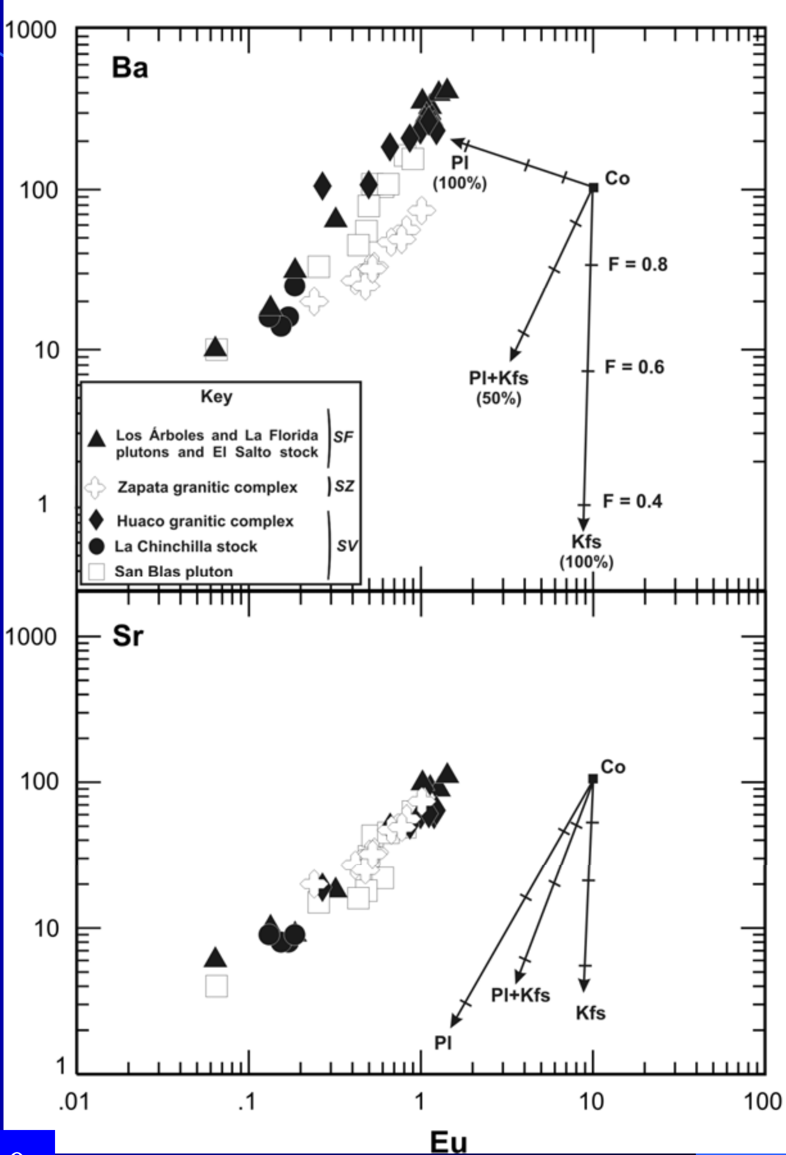






Trace (and major) element data indicate that the individual plutons evolved through fractionation of alkali feldspar, apatite, and FeTi oxide.





Dahlquist et al. 2010

Nd isotope data for Carboniferous granites

Pluton/complex	ε_{Nd}	T_{DM} (Ga)
Los Árboles	-0.8 to -2.6	0.96 – 1.30
Huaco	-2.4 to -3.2	1.25 – 1.40
San Blas	0.6 to -4.8	1.04 – 1.38
Zapata	-2.6 to -3.9	1.20 – 1.70
Early Ordovician granites	-4.8 to -8.5	1.5 – 1.7

A simple isotope mixing model, using as one end member the Early Ordovician granites as a potential crustal protolith and as the other end member asthenospheric mantle (CHUR) gives the following result:

63% asthenospheric mantle and 37% continental lithosphere

(Dahlquist et al. 2010)

Petrogenesis of Argentina Carboniferous Granitoids

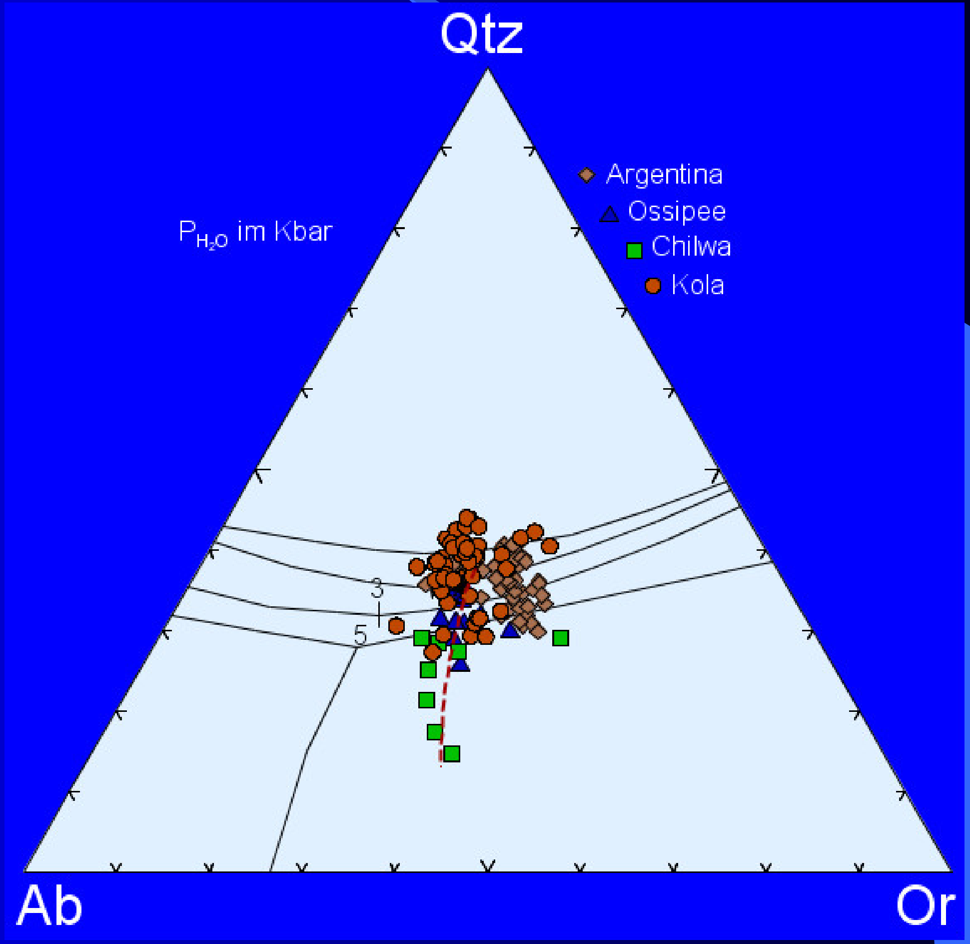
- The granitoids were emplaced at the end of a long period of orogenic activity which ended with an extensional phase
- The extension led to ensialic back-arc rifting with asthenospheric upwelling and melting of underplated basaltic material (Alasino et al. 2011, Hutton VII)
- Emplacement was controlled by a pre-existing shear zone.
- Zircon saturation geothermometry indicates temperatures of 880^{o}C to 700^{o}C and there is an excellent correlation between decreasing T_{Zr} and increasing SiO_2.
- Magmatic evolution of each pluton was controlled by fractional crystallization of alkali feldspar, apatite, and Fe-Ti oxides.
- Simple isotopic mixing calculations indicate that the magmas were mixtures of asthenospheric (63%) and crustal (37%) material. Hence there is a significant mantle component.

Summarized from Dalhquist et al. 2010.

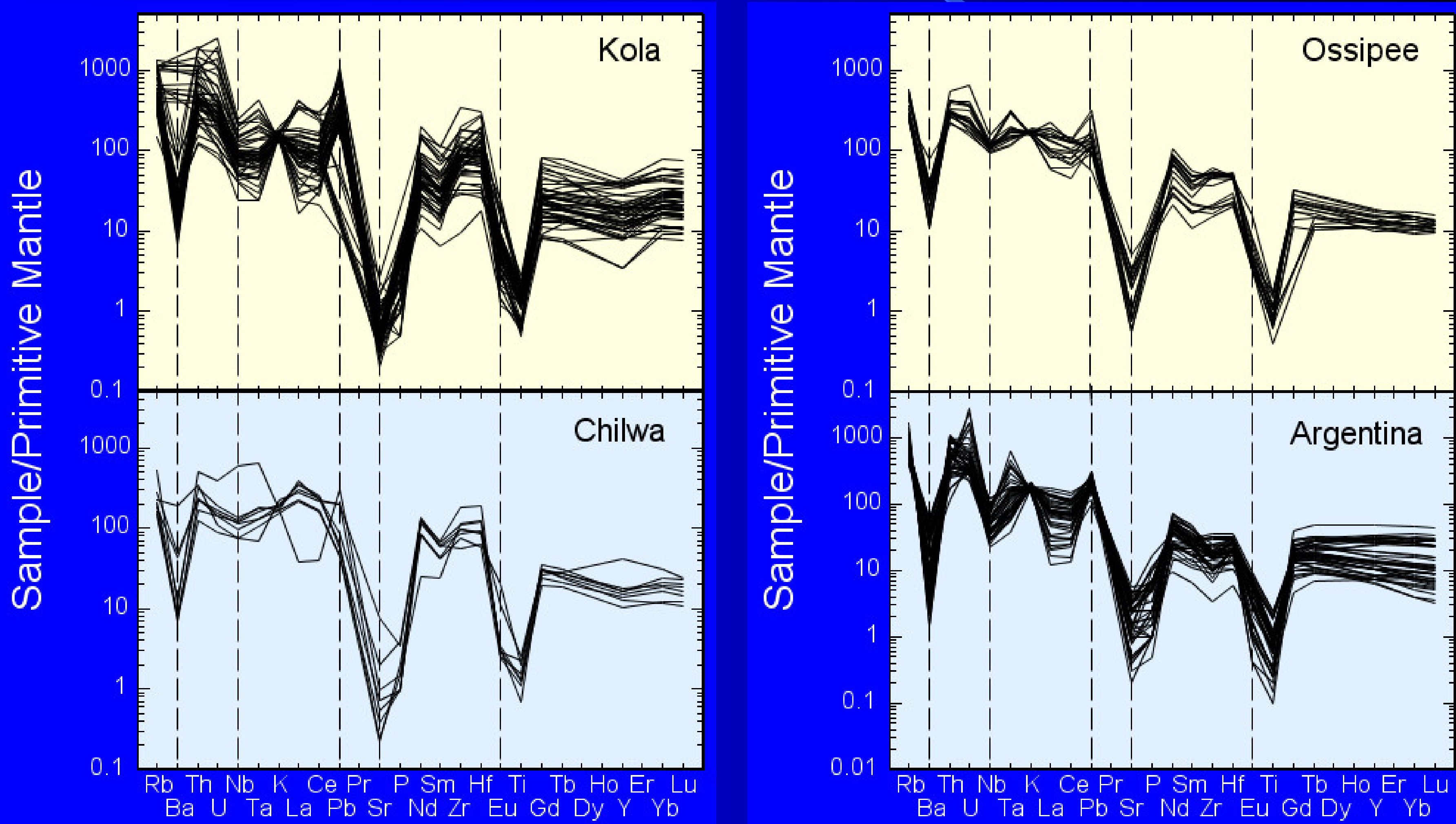
Summary Comments on the Petrogenesis of A-type Granites

The previous 4 examples represent the variety of granitoids that fall in the A-type category. Several generalities can be derived from these examples.

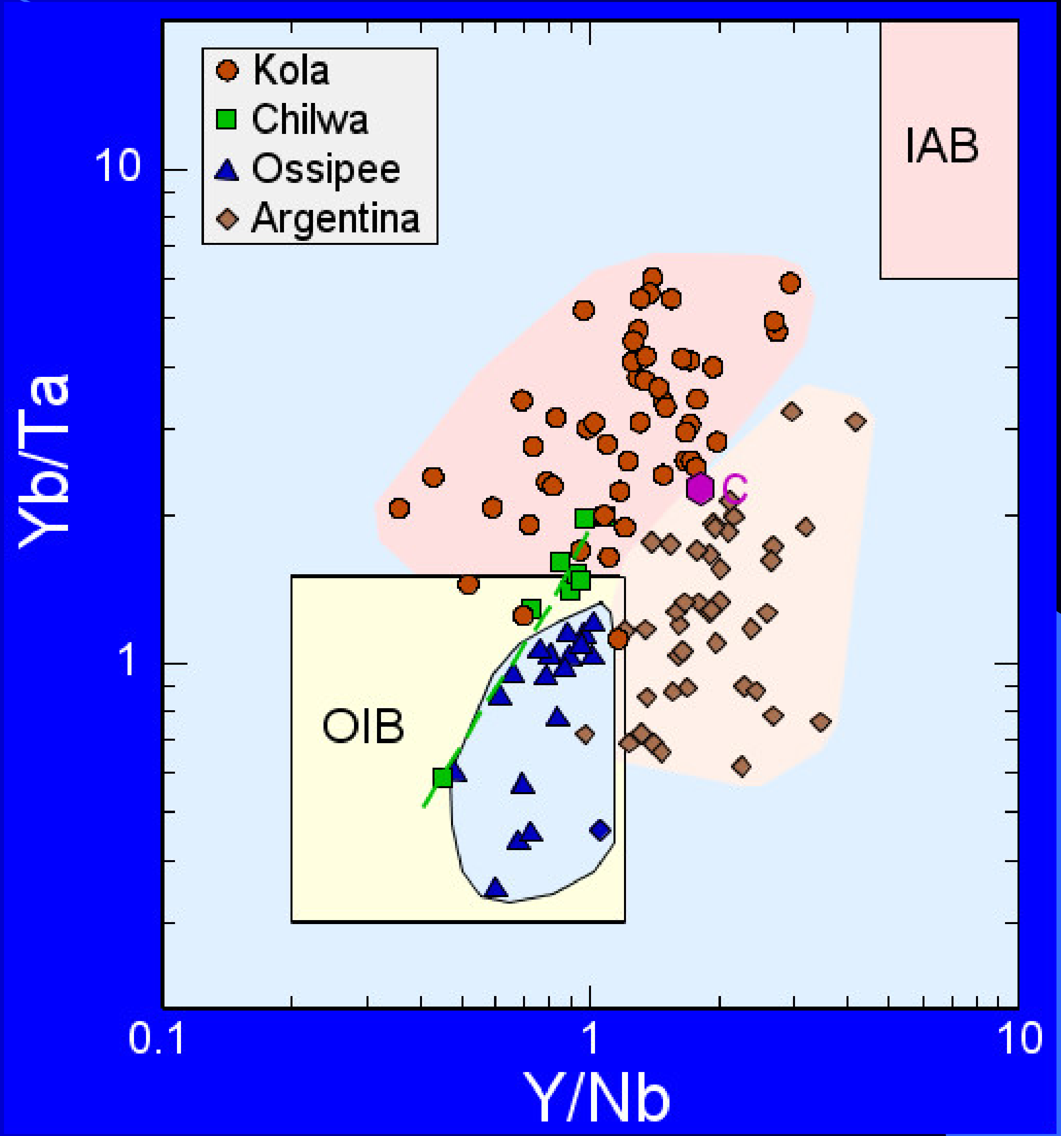
1) Zircon saturation temperatures range between 800 and 1000°C. Hence these are high temperature melts with low water content. This is illustrated by the projection of the compositions for the granitoids into the haplogranite system. The compositions of the granitoids from the four examples fall well off the water saturated minima.



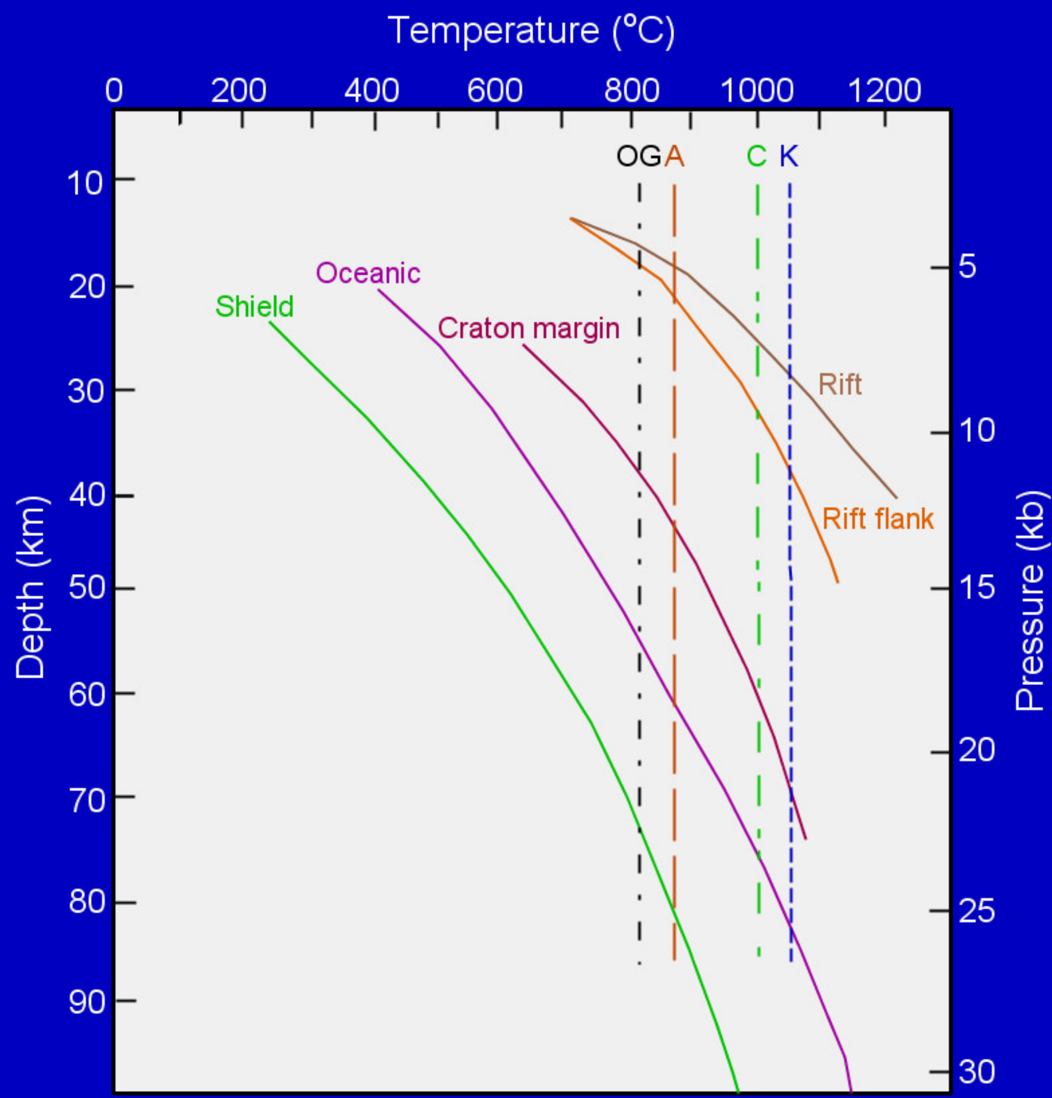
2) Primitive mantle normalized spider diagrams indicate that (a) feldspar (negative Ba, Sr and Eu anomalies), apatite (negative P anomaly) and Fe-Ti oxides (negative Ti anomaly) were fractionated from the magmas; (b) the presence of small to relatively significant positive Pb anomalies indicate that crustal contamination played a role; and (c) Nb-Ta and Zr-Hf anomalies indicate an enriched mantle source for the mafic melts that played a role in the petrogenesis of the granites.



3) The hotspot and rift related Ossipee and Chilwa granitoids show clear evidence of an OIB-like source. In the case of the Argentina granites there is evidence of a significant crustal component. The Archean rift-related Kola granitoids overlap with the OIB field, but largely fall in the area dominated by crustal compositions. Note that in the case of both the Kola and Argentina granitoids there is also a possible IAB-like end-member. In all of these cases, the data suggest the involvement of both mantle and crustal material, to varying degrees, in the petrogenesis of the granitoids.



4) Maximum T_{Zr} for Ossipee granites (OG), Ossipee rhyolites and Argentina granitoids (A), Chilwa syenites and granites (C), and Kola peralkaline granites (K) plotted versus a variety of geotherms. Matching the tectonic setting to the appropriate geotherm and magma temperature shows that the required melting temperatures exceed those that could be reasonably expected at an appropriate depth. Hence the role of mantle derived mafic magmas, to provide heat and/or material seems essential in the generations of these A-type granitoid melts.



From O'Reilly and Griffin

Conclusions

- The A-type granites define a distinct group within the granite family.
- They are, essentially without exception, crystallized from high temperature melts. This requires high temperatures in the source regions and such high temperatures are not normally achieved in the crust. Hence, the involvement of mafic magmas, or high mantle heat flow, is a necessity.
- A variety of chemical parameters indicates that the granitic magmas are derived by fractional crystallization of feldspars, apatite, and FeTi oxides from more primitive melts. The high Ga/Al ratios that are typical of A-type granites may be a result of extensive feldspar fractionation.
- In most cases a satisfactory petrogenetic model involves AFC processes starting with relatively mafic magmas. These mafic melts can be derived directly from the mantle or by re-melting of underplated mafic material.
- No single petrogenetic model can be used to describe the formation of A-type granites.

With special thanks to the following colleagues

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