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**From Core to Crust: Towards an Integrated Vision of Earth's Interior**

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**Constraints on mantle flow in subduction systems as inferred from petrological features of magmas and mantle xenoliths**

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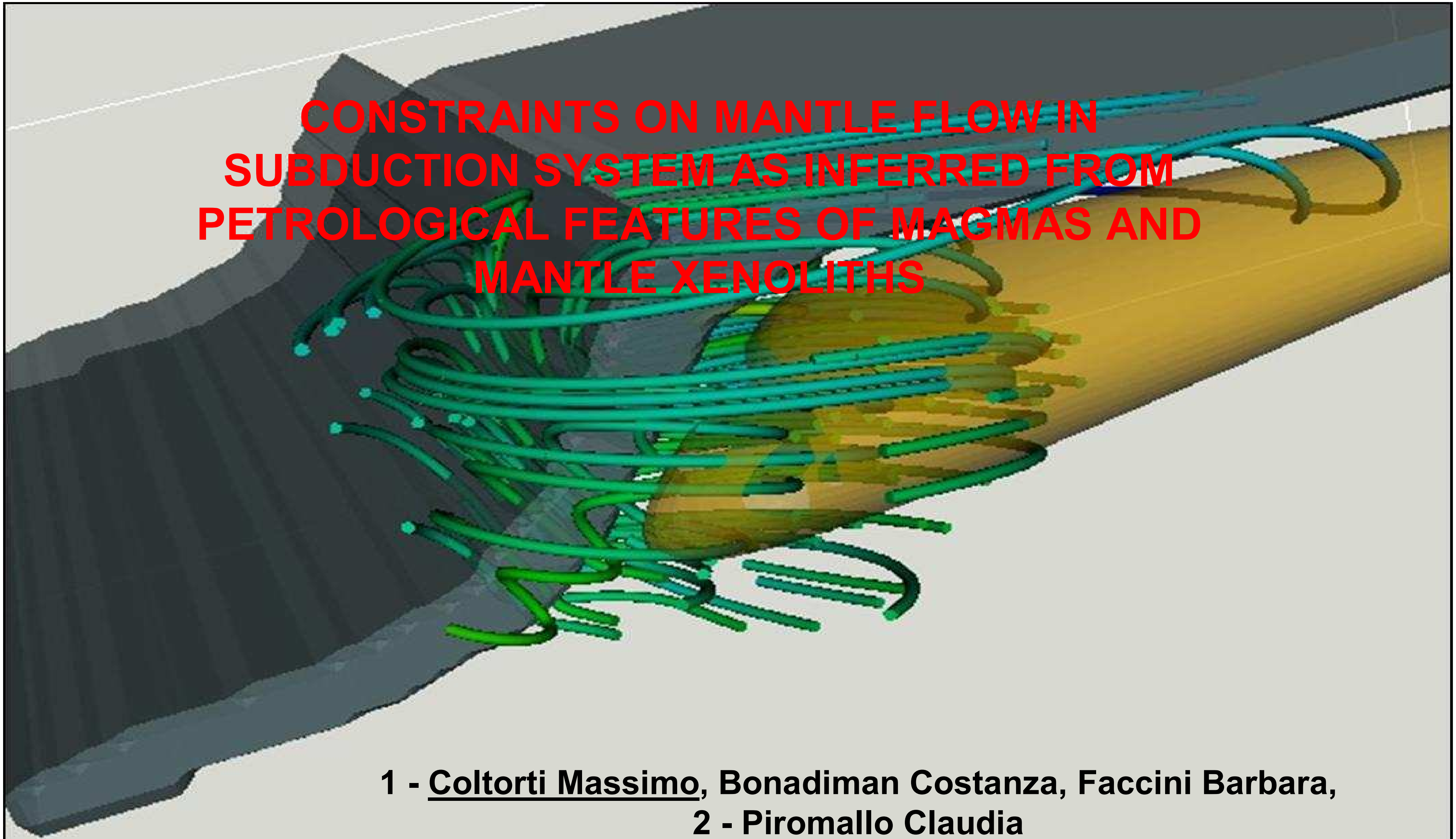


# CONSTRAINTS ON MANTLE FLOW IN SUBDUCTION SYSTEM AS INFERRED FROM PETROLOGICAL FEATURES OF MAGMAS AND MANTLE XENOLITHS


**1 - Coltorti Massimo, Bonadiman Costanza, Faccini Barbara,**
**2 - Piromallo Claudia**

1 - Department of Earth Sciences, Ferrara University, Italy
2 - Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

## A petrological approach to the study of the Earth's mantle

Two approaches are usually followed, which, hopefully should converge (sometime…):

**A backward approach**: the petrological features (T-P of formation and composition) of basic magmas (melt which were not affected by later modification during cooling and crystallization within the crust) are related to the chemical and physical characteristics of their sources, thus indicative of heterogeneity within the mantle.
**Advantage**: it allows a large space and time distribution
**Disadvantage**: you do not get a direct knowledge of the mantle

**A forward approach**: the petrological features of mantle materials recovered on the Earth' surface allow to directly asses and study the mineralogical and geochemical composition of the Earth's mantle, which could be similar to, or at least comparable with, the sources of basic magmas.
**Advantage**: you have the mantle in your hand
**Disadvantage**: but distribution is quite limited in both space and time

## Backward approach is based on the studies of the following Tectono-Magmatic Associations

- Mid-Ocean Ridge Volcanism
- Ocean (and continental) Intra-plate volcanism
- Continental Plateau Basalts
- Oceanic and Continental Subduction-related volcanism (and plutonism)

## Sources of mantle material for the forward approach

- Alpine peridotites
  - Slabs of continental crust entrapped in suture zones
- Ophiolites
  - Slabs of oceanic crust and upper mantle thrust onto edge of continent
- Dredge samples from oceanic fracture zones
- **Xenoliths in alkaline basalts**
- Xenoliths in Kimberlites

# Forward approach: xenoliths

We concentrate on xenoliths due to their rapid uprising which mantain almost unchanged the textural and chemical relationships between minerals **but:**

- Due to their small dimension relationships between different litothypes are difficult to asses

- Depth of provenance does not exceed few hundreds of km (in cratonic areas). The great majority of them are spinel-bearing, that is below 80km. Garnet-bearing samples are quite rare in off-craton areas (so far two-three localities are known). Thus all our study would be limited to the lithosphere

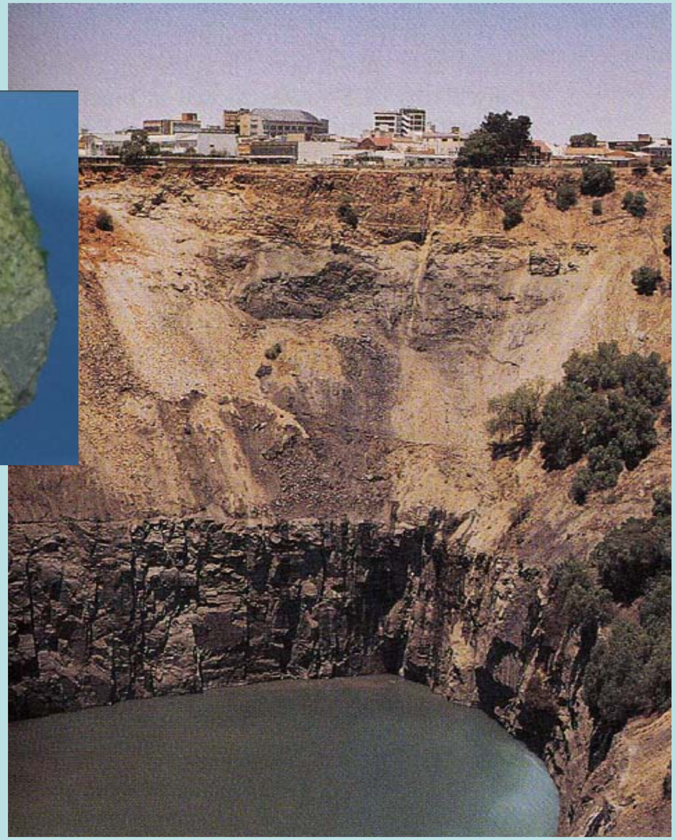
- As we said space (and time) distribution is limited. Moreover distribution within tectonic settings is uneven. The great majority of them come from intra-plate alkaline basalts. Few localities are known where these xenoliths are entrained in calc-alkaline s.l. basalts (Japan, Kamchatka, New Guinea).

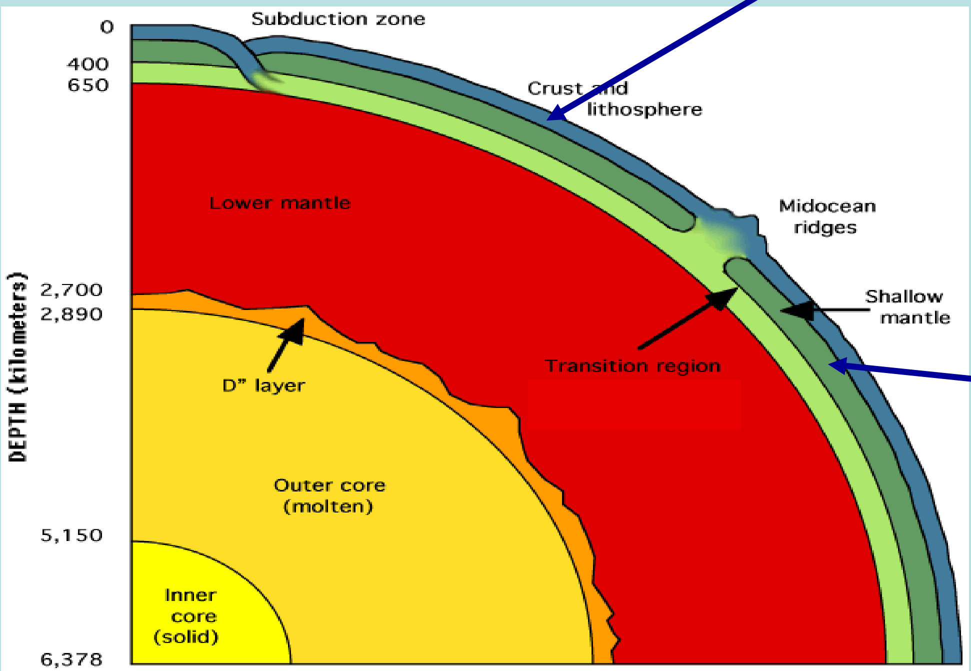
  - - As consequence a rather well-organized knowledge of the composition of the melt migrating through the intra-plate lithospheric mantle was acquired, together with their relationships with the kind of magmatism which ultimately transport the xenoliths on the surface.

  - - Viceversa, taking also into account the more complex physico-chemical and compositional constraints, much work has still to be carried out on mantle material from subduction zones.

# Forward approach: xenoliths

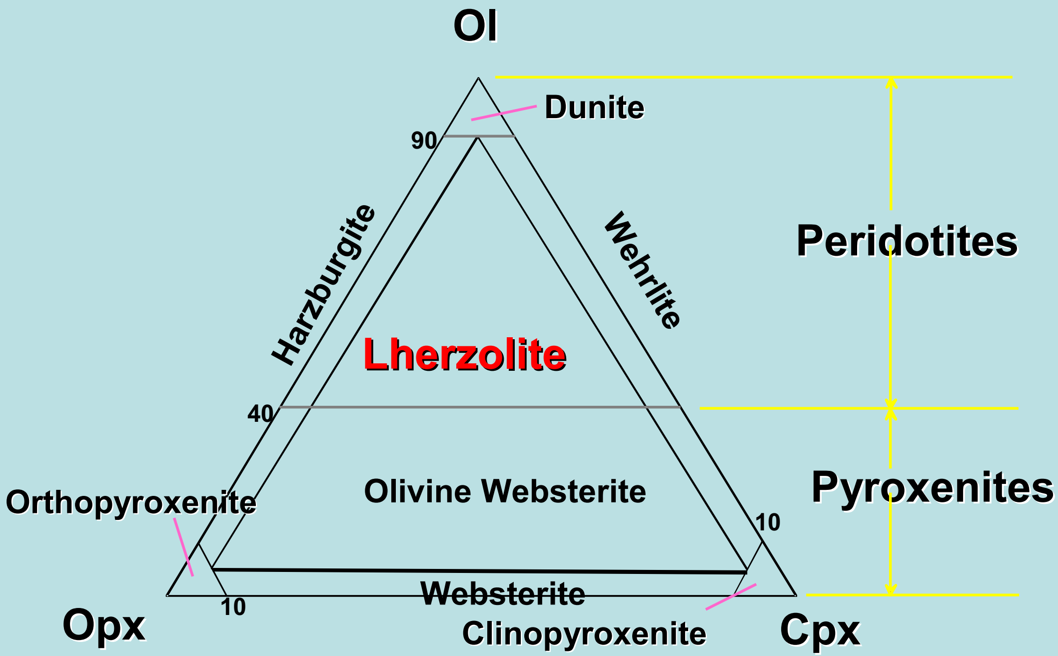


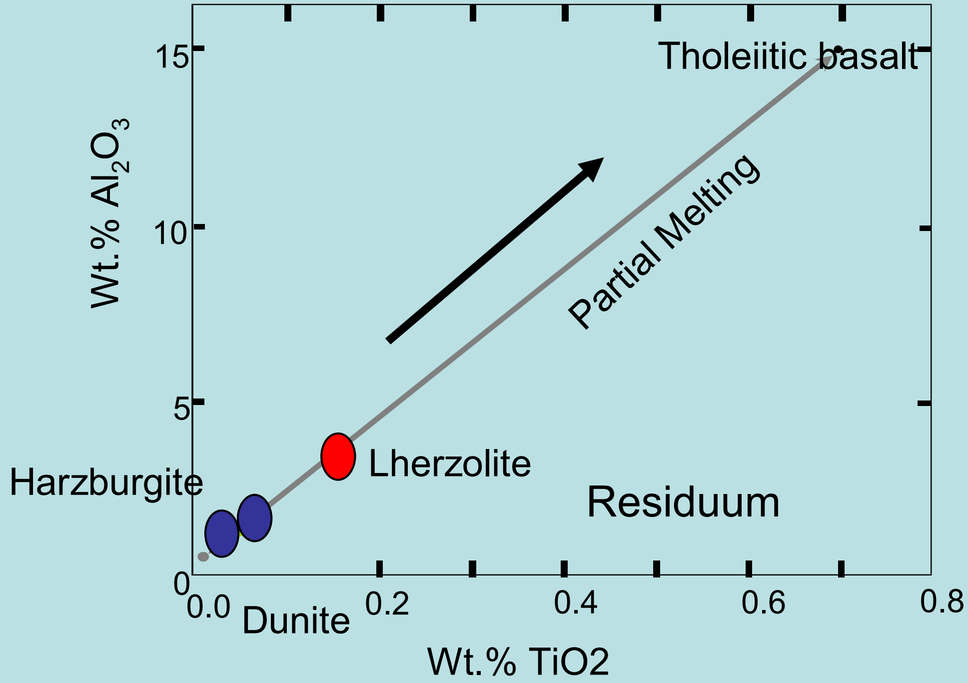






## Lherzolite: A type of peridotite with Olivine > Opx + Cpx




**Lherzolite is probable fertile mantle.**
**Dunite and harzburgite are refractory residuum after basalt has been extracted by partial melting**

## Mantle metasomatism

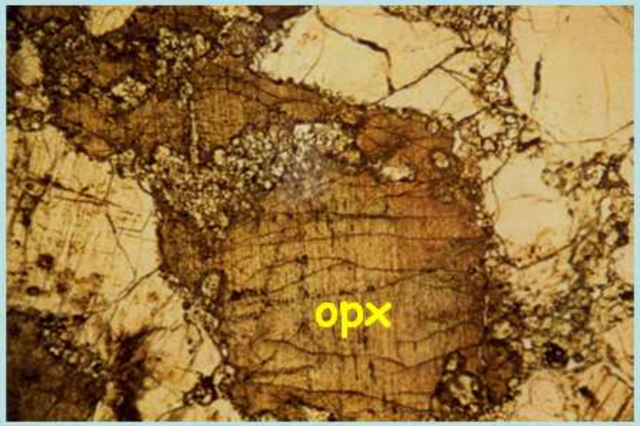
Mantle material can also be enriched by metasomatism whose evidence are textural (modal metasomatism) and chemical (criptic metasomatism)

- Comparing the composition and the textural relationships which allow to recognize **primary and secondary paragenesis** we can understand which is the composition of the percolating melt, what we called **metasomatizing agents** and, possibly, their provenance.

- Various diagrams can be used to discriminate **amph, cpx and glass** composition **in intraplate and suprasuduction settings**. Olivine cannot be used and opx have still limited use due to their low to very low trace element concentration, below detection limit of any up-to-date analytical instrument.

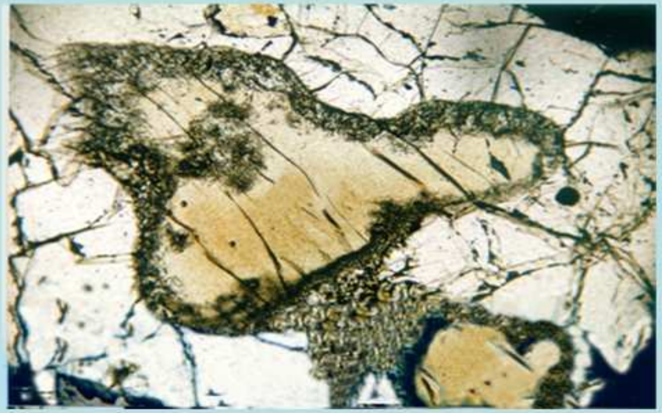
## **Petrographic** evidence of mantle metasomatism

- destabilized **orthopyroxene**




2 mm

# **Petrographic** evidence of mantle metasomatism



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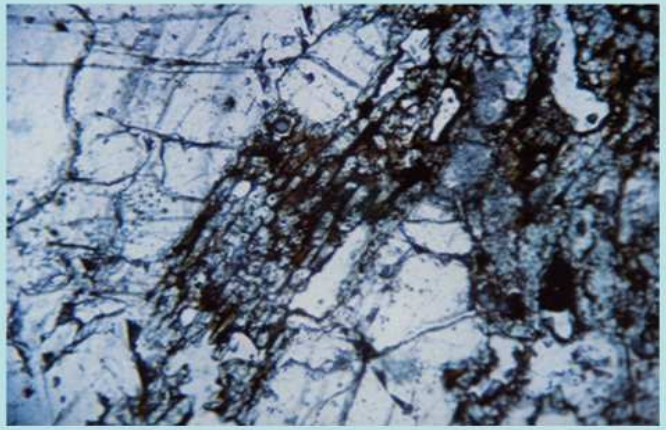
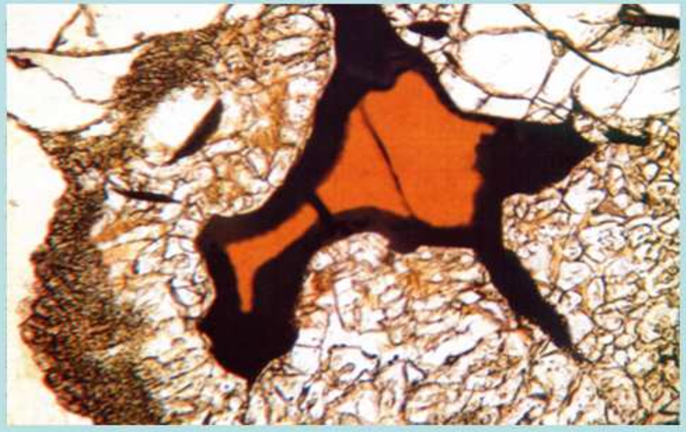
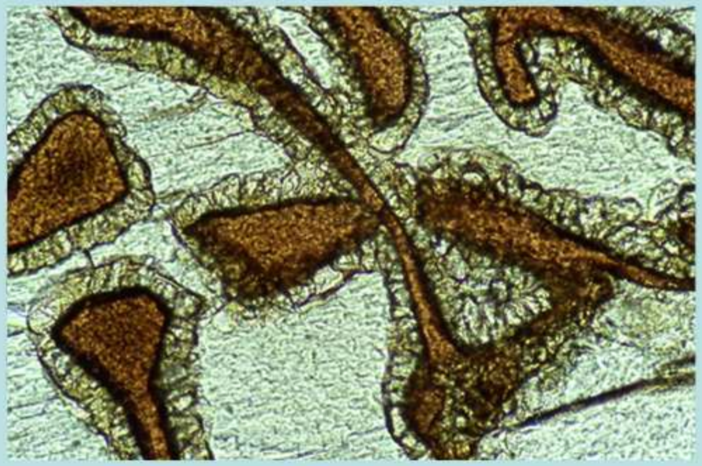


- destabilized **orthopyroxene**

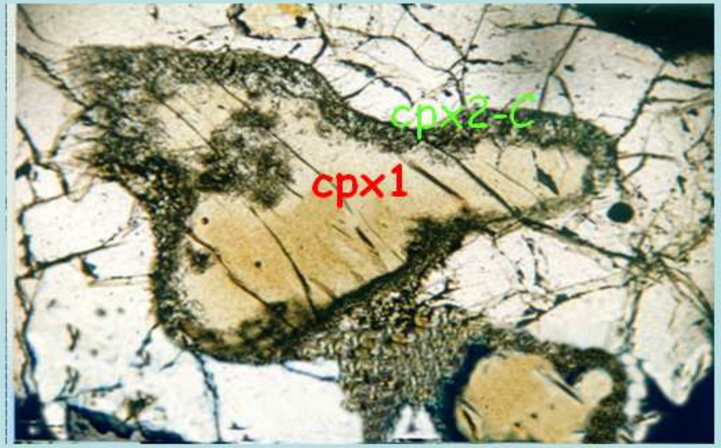
- **clinopyroxene** spongy and/or in reaction relations





## **Petrographic** evidence of mantle metasomatism

- destabilized **orthopyroxene**
- **clinopyroxene** spongy and/or in reaction relations
- reaction rims around **spinel**

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# **Petrographic** evidence of mantle metasomatism

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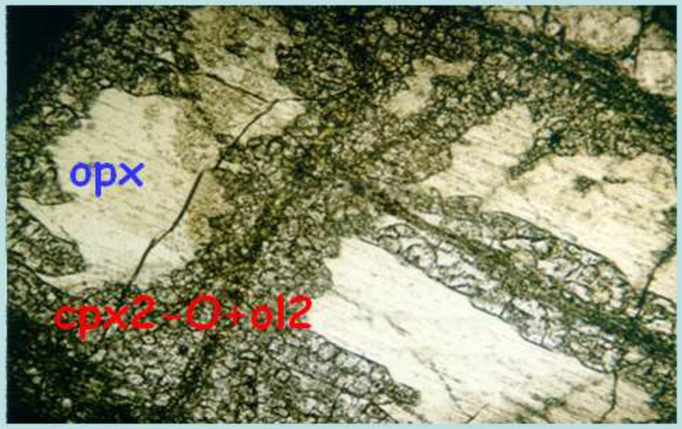
- re-crystallization of secondary phases (**ol, cpx, sp**) with different geochemical compositions

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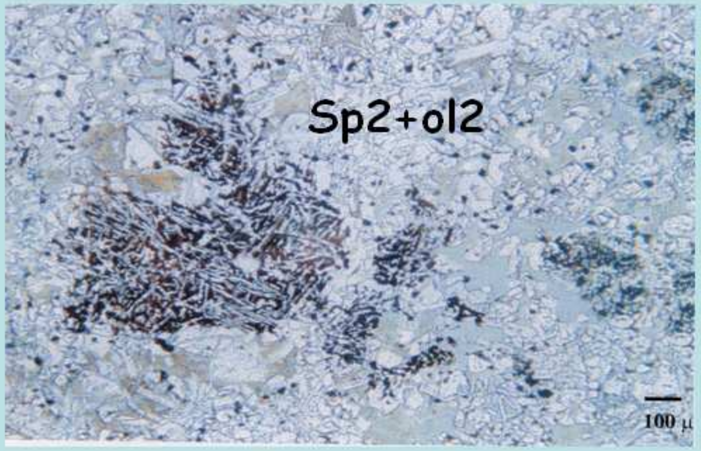


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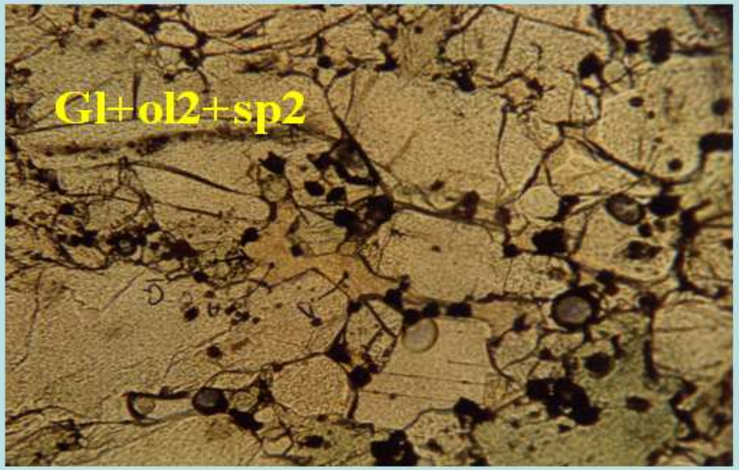


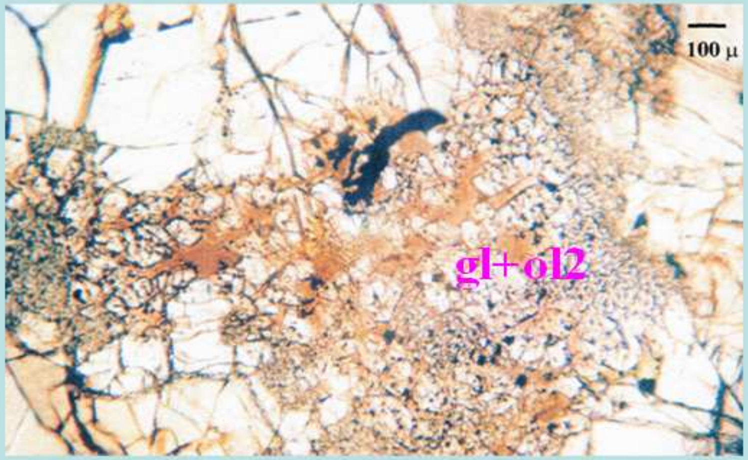


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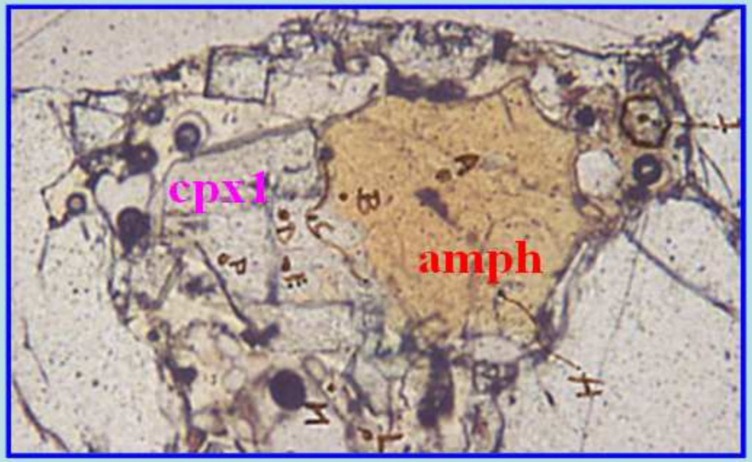
- formation of new phases (**glass**, amph, *phlog, ap, carb*)

# Petrographic evidence of mantle metasomatism

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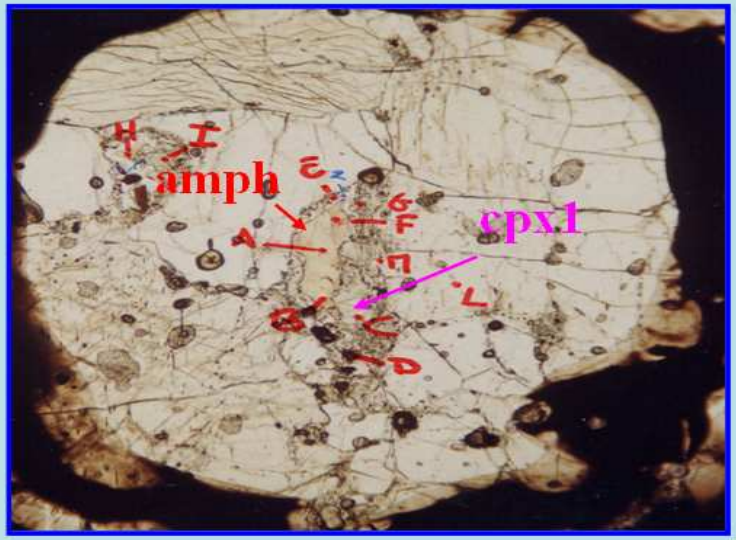



- re-crystallization of secondary phases (**ol, cpx, sp**) with different geochemical compositions

- formation of new phases (**glass**, amph, *phlog, ap, carb*)

- formation of new phases (glass, **amphibole**, *phlog, ap, carb*)

amph

# Trace element data

## Intraplate settings

**Northern Victoria Land, Antarctica**
10 analyses (Coltorti et al., 2004)

**Kerguelen Island, Indian Ocean**
43 analyses (Moine et al., 2001)

**Western Victoria, Australia,**
42 analyses (Powell et al., 2004; Yaxley et al., 1999; Coltorti, unpublished)

**Western Eifel, Germany,**
38 analyses
(Witt-Eickschen et al. 1998; 2003)

**Total of 133 analyses**

## Suprasubduction settings

**Ichinomegata, Japan**
20 analyses (Johnson et al., 1996; Coltorti et al., Lithos 2007)

**Avacha volcano, Kamchatka**
20 analyses (Ishimaru et al., 2007; Ishimaru & Arai, 2008)

**Lihir, Papua New Guinea,**
1 analyses (Gregoire et al., 2001)

**Finero, Italian Alps**
4 analyses (Zanetti et al., 1999)

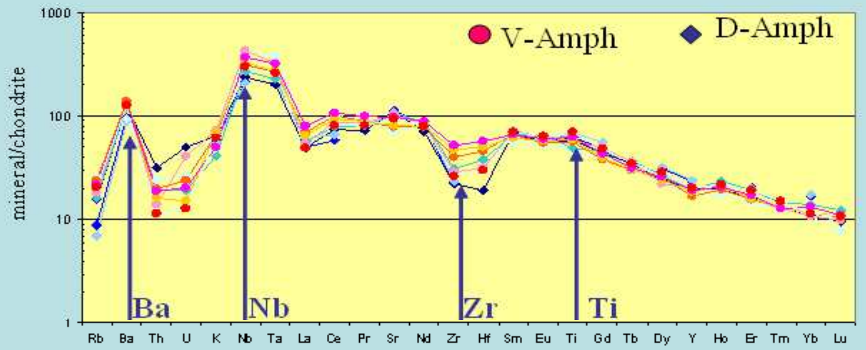
**Val d'Ultimo, Italian Alps**
20 analyses (Marocchi et al., 2009)

**Total of 65 analyses**

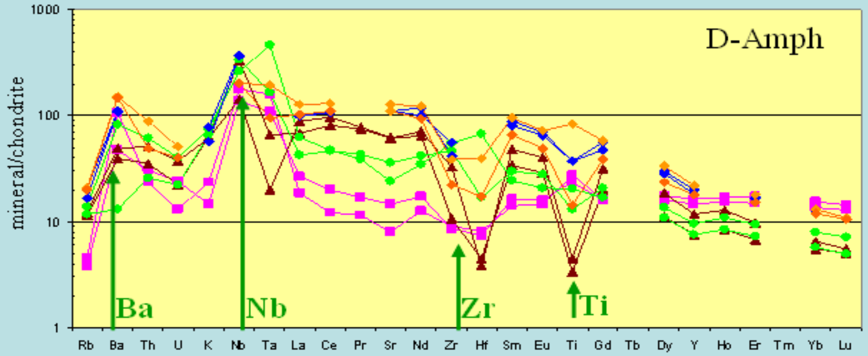
amph

# Intraplate settings

## Antarctica




## Australia

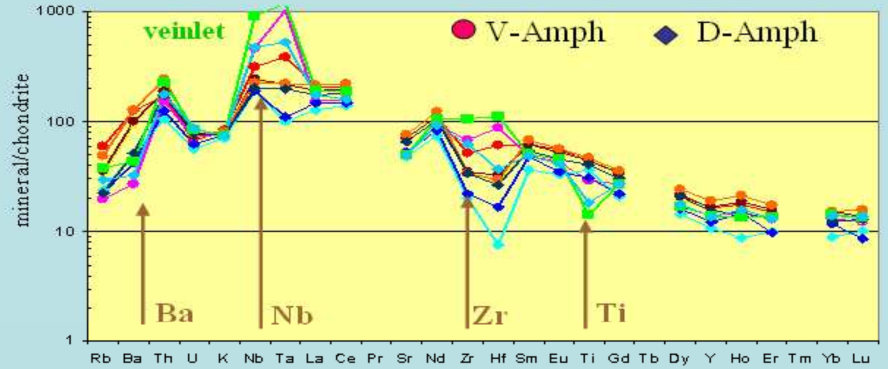


amph

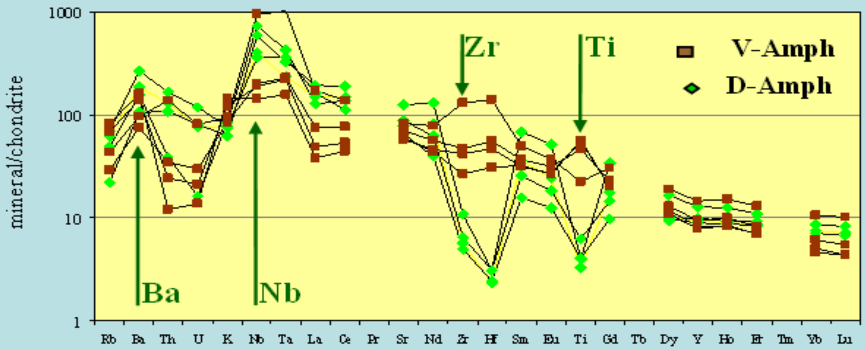
## Intraplate settings

## Suprasubduction settings

### Kerguelen

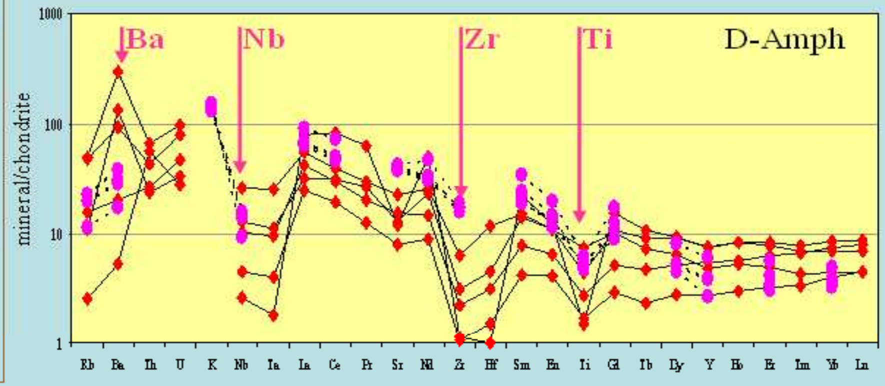



### West Eifel

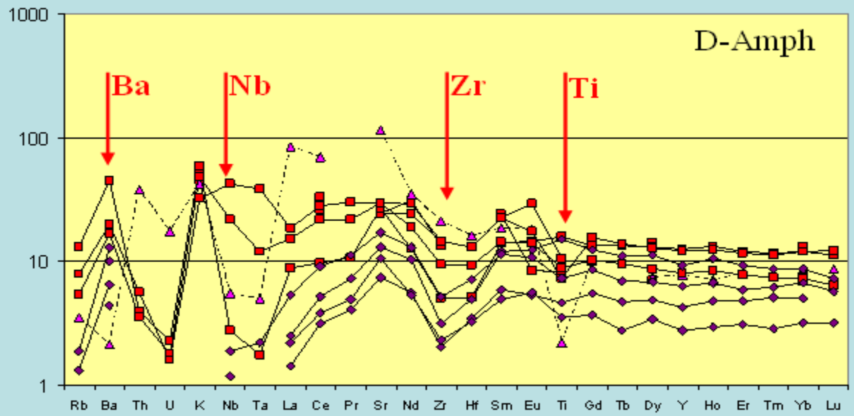



### Alpine Peridotite

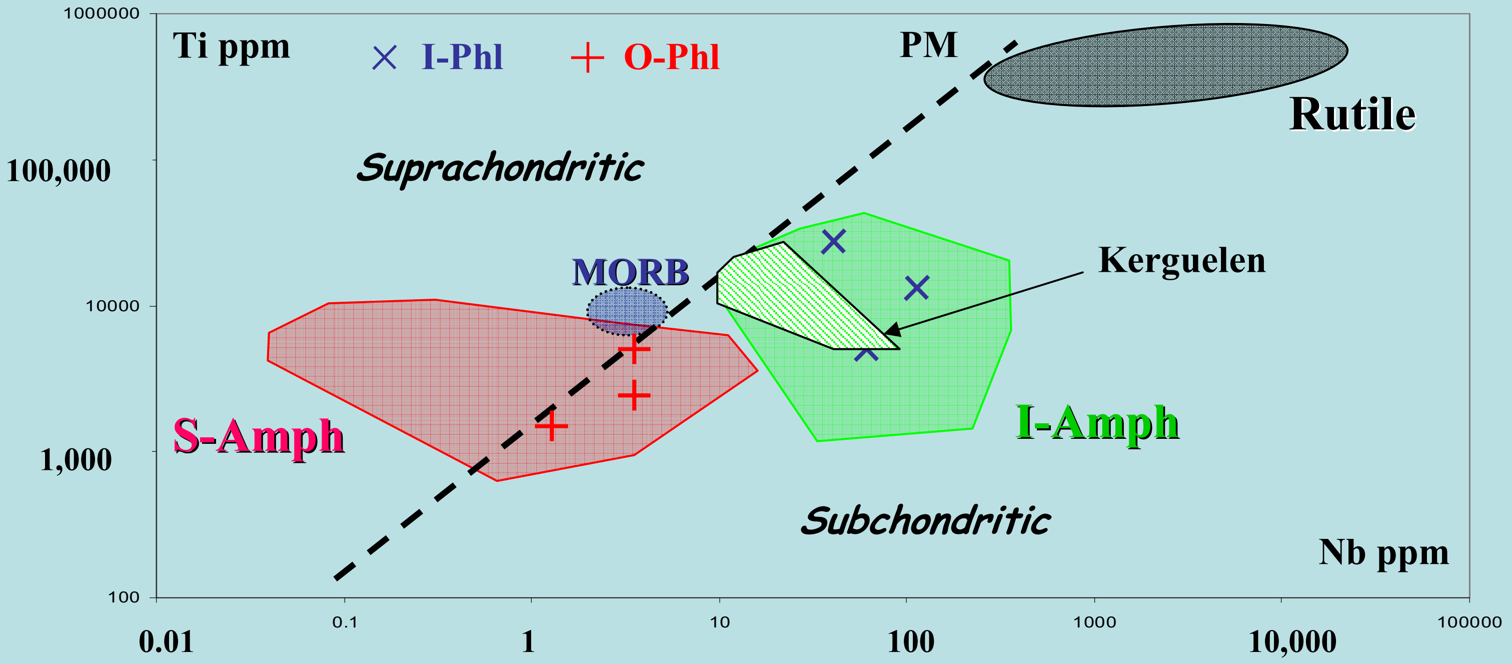
Val d'Ultimo Finero

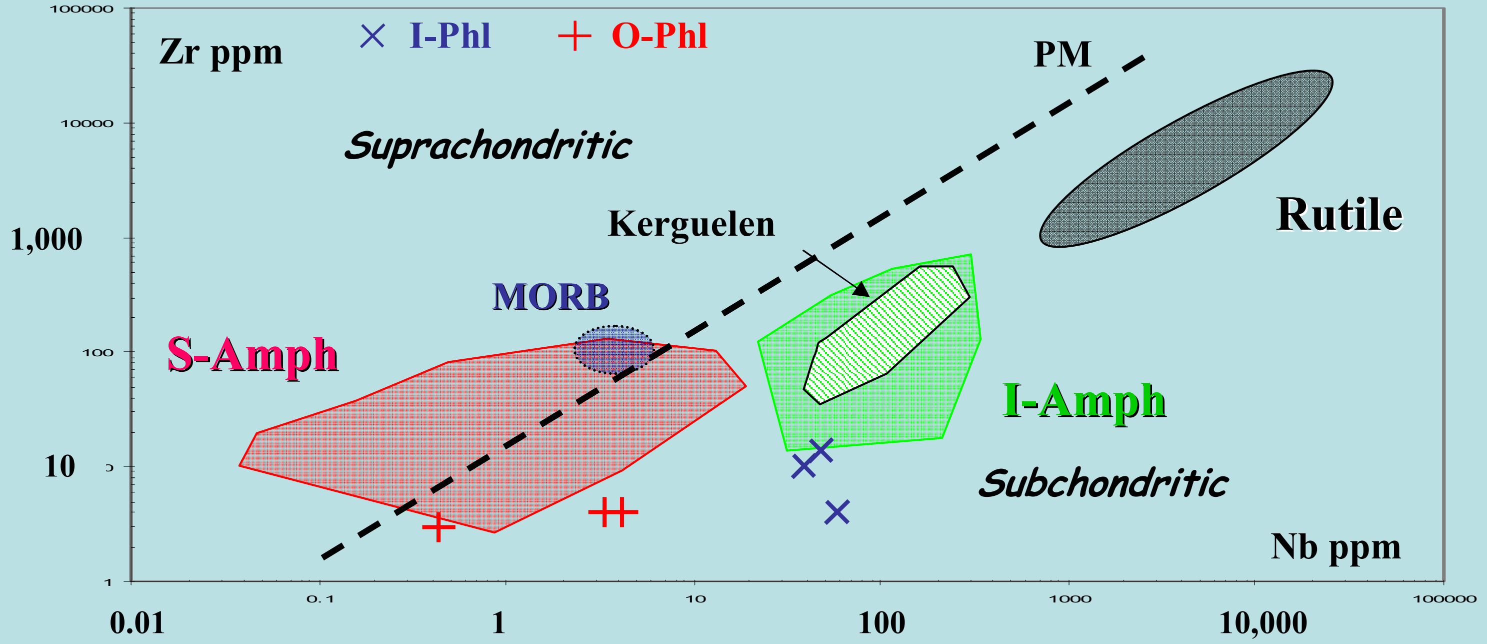



Japan Kamchatka Lihir

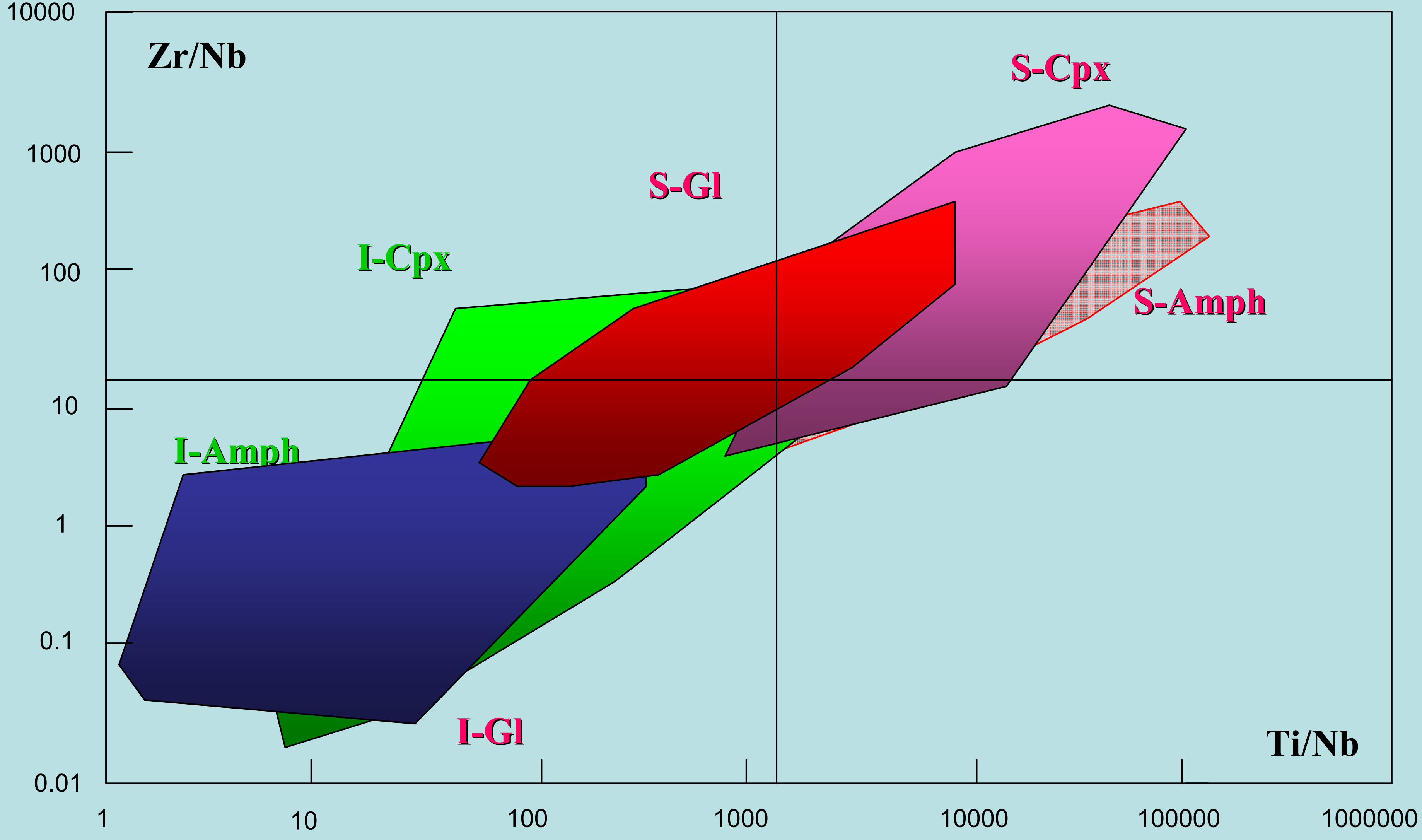


# amph


Ti ppm
I-Phl
O-Phl
PM
Rutile
Suprachondritic
MORB
Kerguelen
S-Amph
I-Amph
Subchondritic
Nb ppm
1000000
100,000
10000
1,000
100
0.01
0.1
1
10
100
1000
10,000
100000


Zr ppm
I-Phl
O-Phl
PM
Suprachondritic
Rutile
Kerguelen
MORB
S-Amph
I-Amph
Subchondritic
Nb ppm
100000
10000
1,000
100
10
1
0.01
0.1
1
10
100
1000
10,000
100000

# Amph, glass and cpx



Amph, Gl and Cpx from suprasubduction settings have Ti/Nb and Zr/nb ratios much higher than those observed in adakites. Thus we need other candidates as metasomatizing agents in the mantle wedge


Rutile can account for the Ti/Nb and Zr/Nb ratios observed in alkaline lavas

Only carbonatite magmas however can explain the very low ratios observed in some amph and glass.

# Summary part 1…

- S-Amph tend to have higher Zr/Nb and Ti/Nb ratios, whereas I-Amph show Zr/Nb and Ti/Nb ratios lower. The same apply to Gl and, although with a larger overlap, to Cpx

- Supra-subduction metasomatism is characterized by silica-, (and water-)rich fluids. Since no Ti(and HFSE)-bearing phase are commonly reported from orogenic xenoliths (as far as author’s knowledge) these fluids has to be already depleted in Nb, Ti and Zr

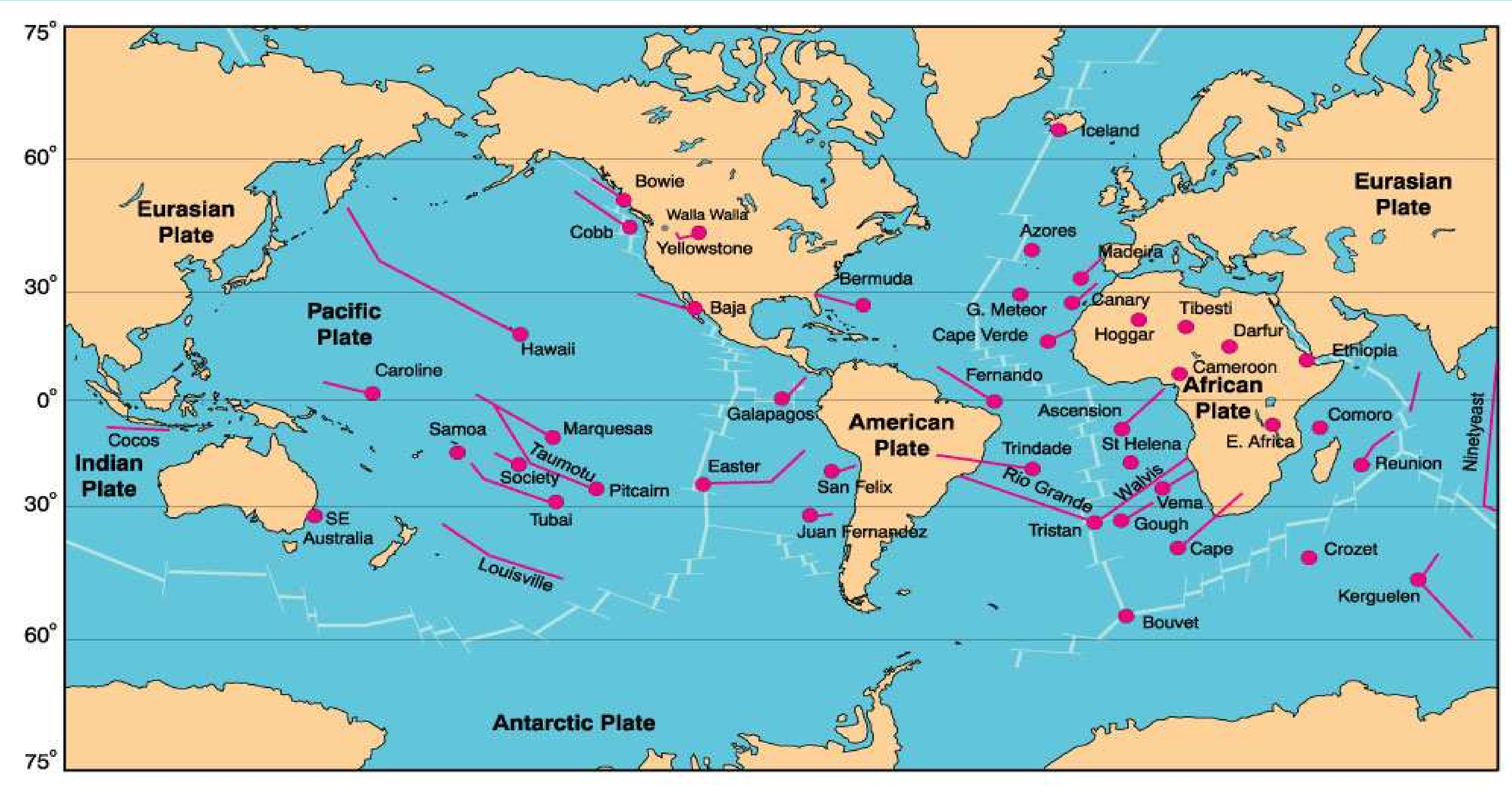
## Summary part 1

- If this is the case a Ti(and HFSE)-bearing phase should remain in the downgoing slab

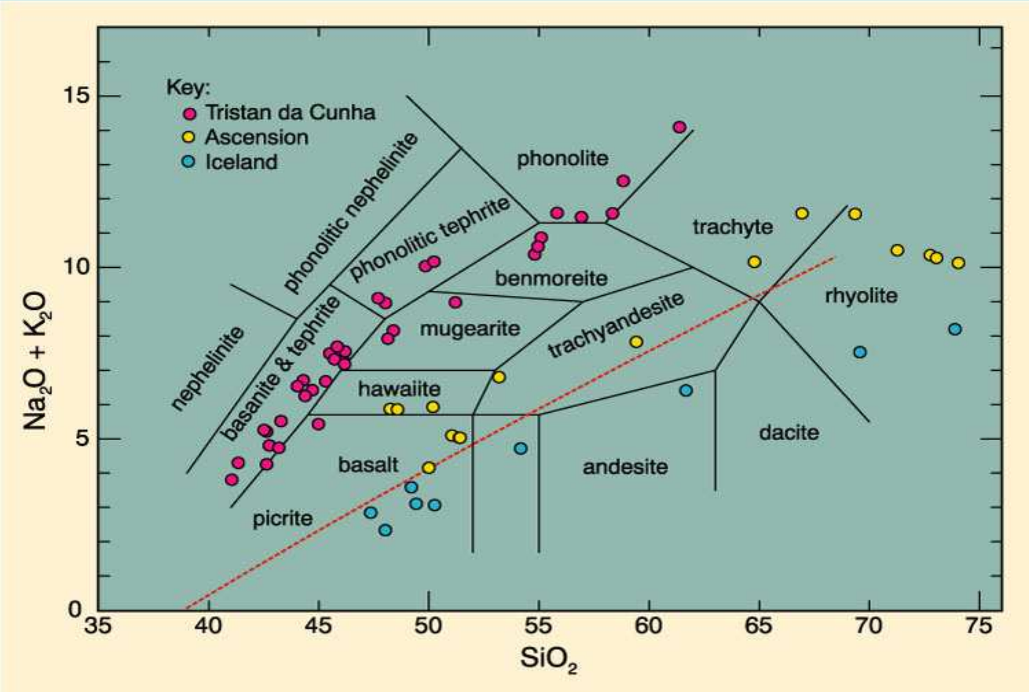
- Rutile is a good candidate for retaining HFSE in the subducting slab. It can effectively fractionate Nb with respect to Ti and Zr, thus moving released fluids toward higher Zr/Nb and Ti/Nb ratios. On the other hand it cannot fractionate Ti from Zr, since its composition span from supra-chondritic to sub-chondritic values, that is the Zr budget is not controlled by rutile!

- Rutile may afterward play an important role in the genesis of I-Amph, suggesting a link between eclogite recycling and intraplate magmatism

# Backward approach: Ocean Intraplate Volcanism



## Types of OIB Magmas




Two principal magma series

- Tholeiitic series (dominant type)
- Alkaline series (subordinate)

### Trace Elements

- HFS elements (Th, U, Ce, Zr, Hf, Nb, Ta, and Ti) are enriched in OIBs > MORBs
- Ratios of these elements are also used to distinguish mantle sources
  - The Zr/Nb ratio

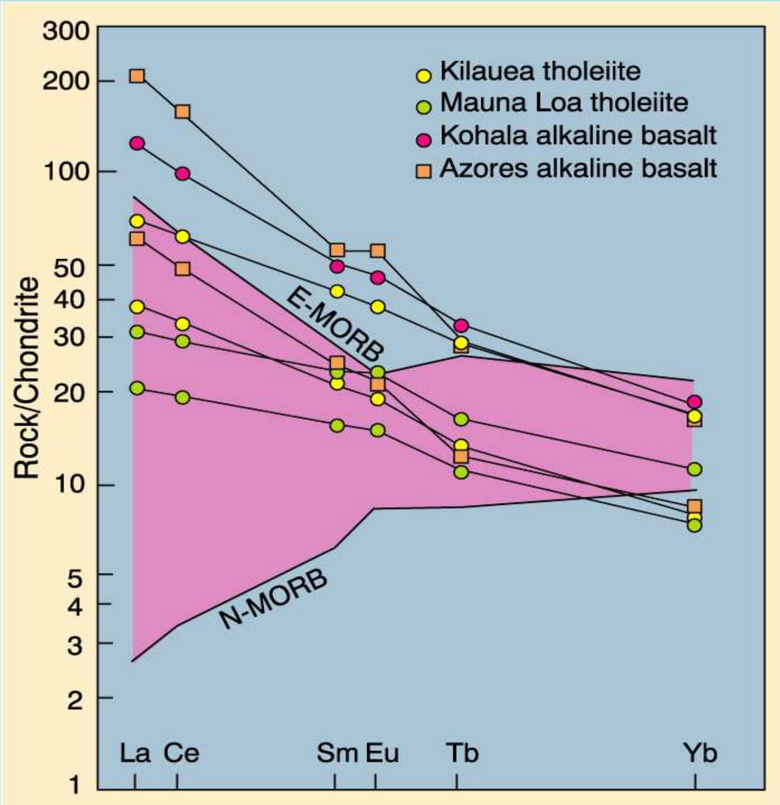
N-MORB generally quite high (>30)

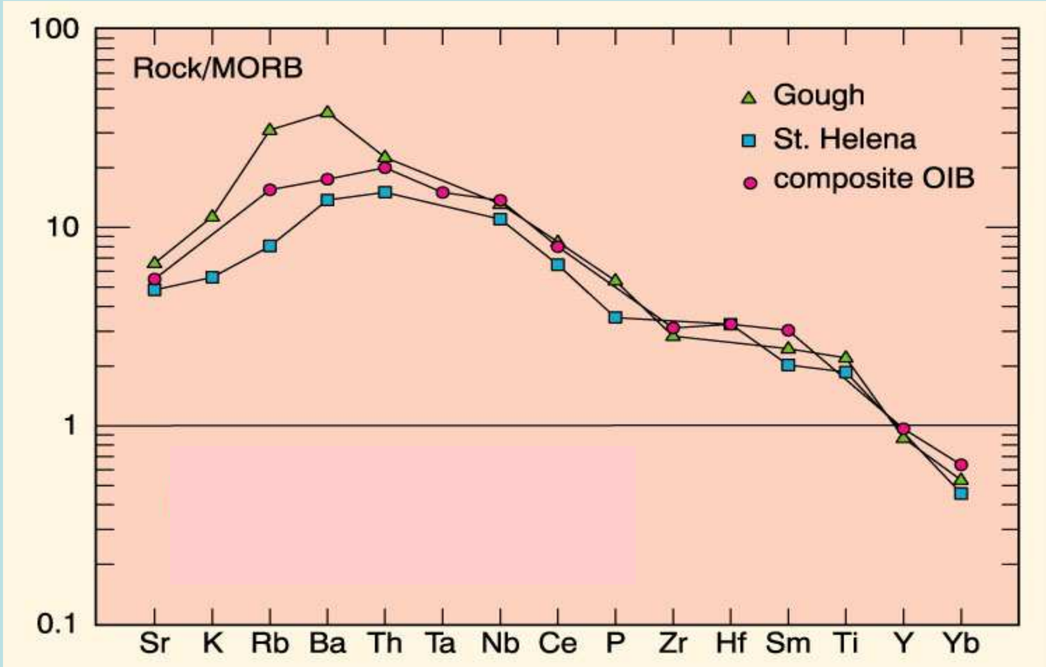
OIBs are low (<10)

La/Yb (REE slope) correlates with the degree of silica undersaturation in OIBs

- Highly undersaturated magmas: La/Yb > 30
- Alkaline series: closer to 12
- Tholeiite series: ~ 4
- (+) slopes $\rightarrow$ E-MORB and all OIBs $\neq$ N-MORB

# Trace Elements



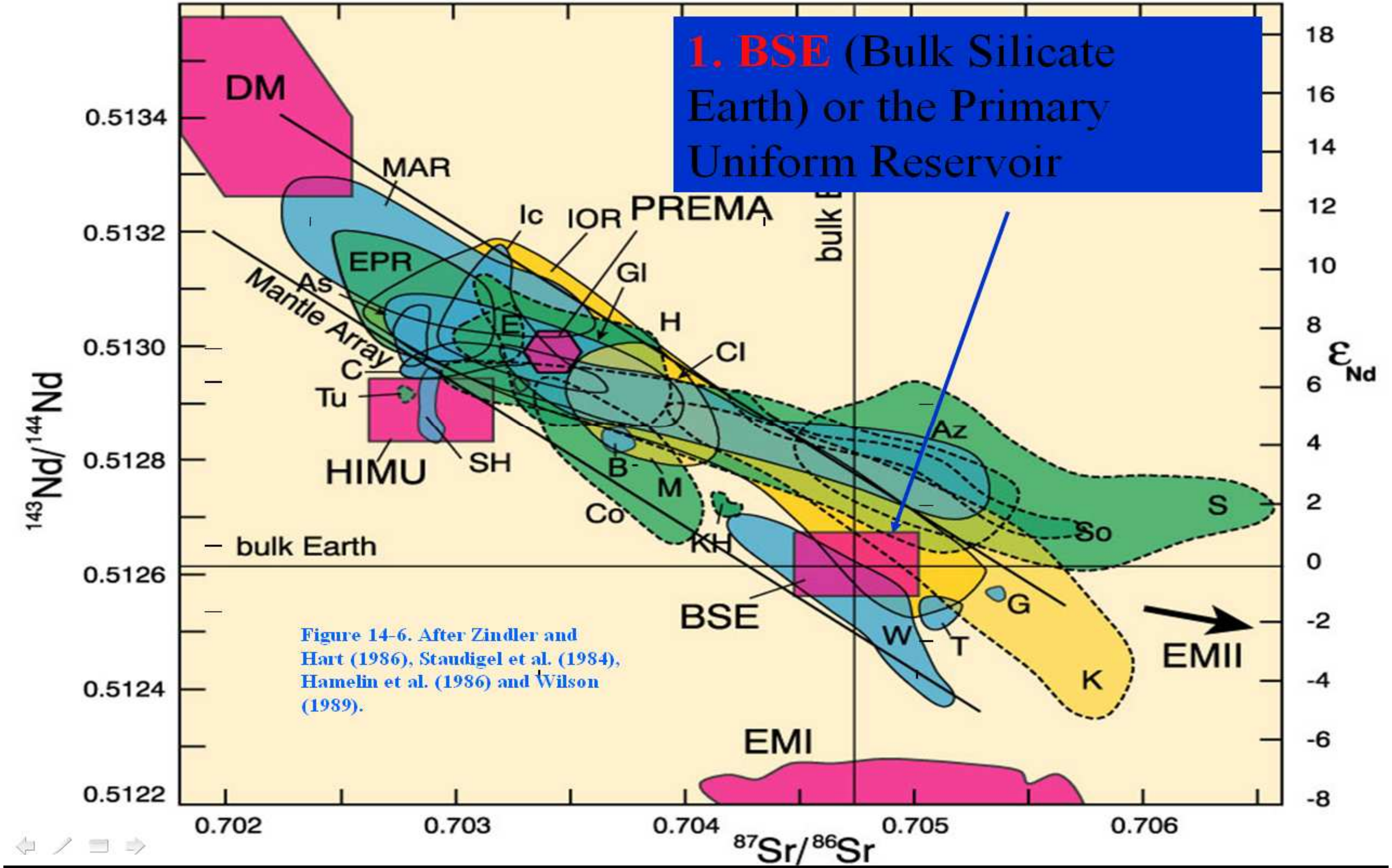



# Isotope Geochemistry

- Isotopes do not fractionate during partial melting of fractional melting processes, so will reflect the characteristics of the source

- OIBs, which sample a great expanse of oceanic mantle in places where crustal contamination is minimal, provide incomparable evidence as to the nature of the mantle

- Isotopically enriched reservoirs (EMI, EMII, and HIMU) are too enriched for any known mantle process, and they correspond to crustal rocks and/or sediments recycled within the mantle




**1. BSE** (Bulk Silicate Earth) or the Primary Uniform Reservoir

Figure 14-6. After Zindler and Hart (1986), Staudigel et al. (1984), Hamelin et al. (1986) and Wilson (1989).

**2. DM** (Depleted Mantle) = N-MORB source

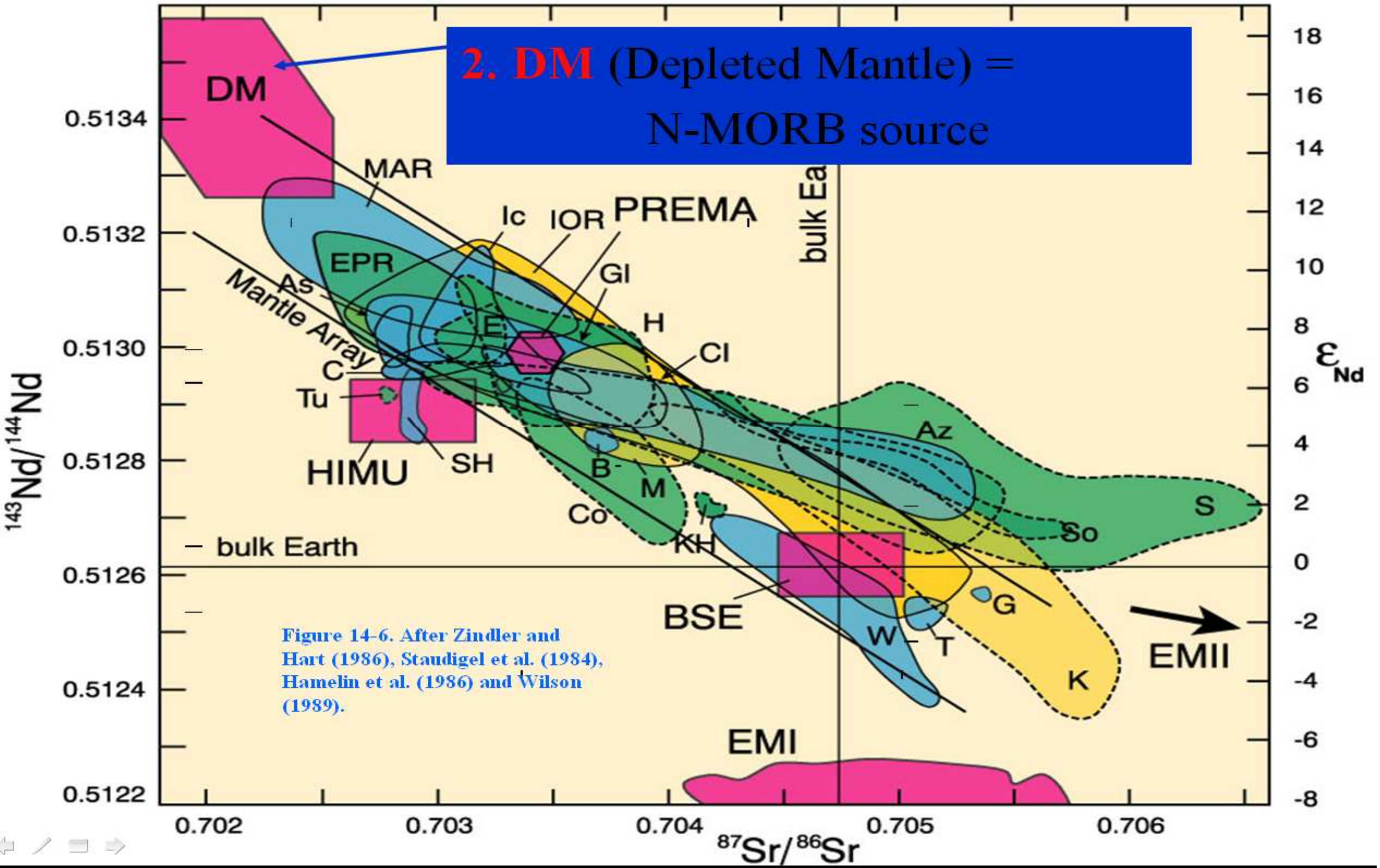
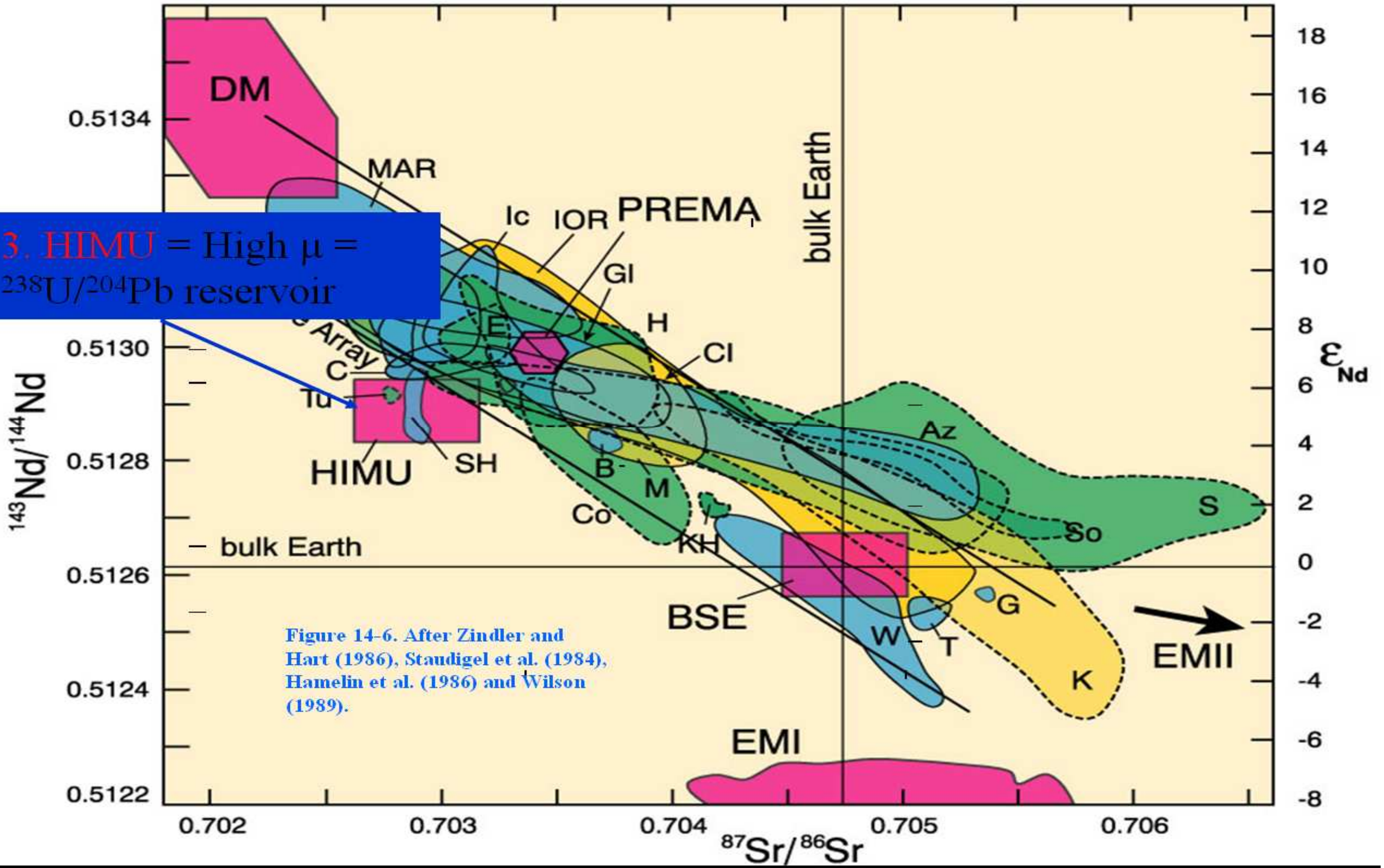



Figure 14-6. After Zindler and Hart (1986), Staudigel et al. (1984), Hamelin et al. (1986) and Wilson (1989).

3. HIMU = High $\mu$ = $^{238}U/^{204}Pb$ reservoir

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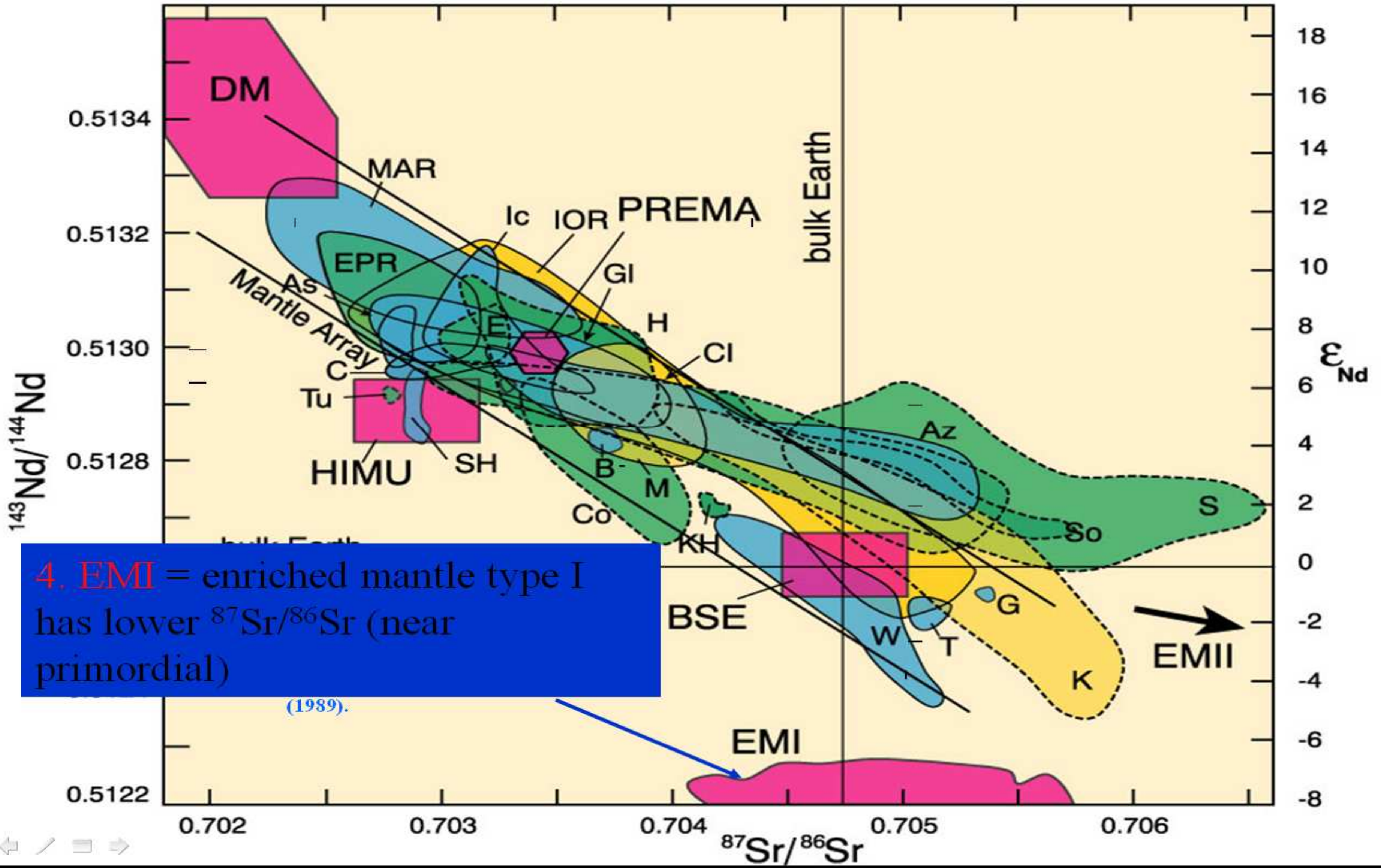



(1989).

4. EMI = enriched mantle type I has lower $^{87}Sr/^{86}Sr$ (near primordial)

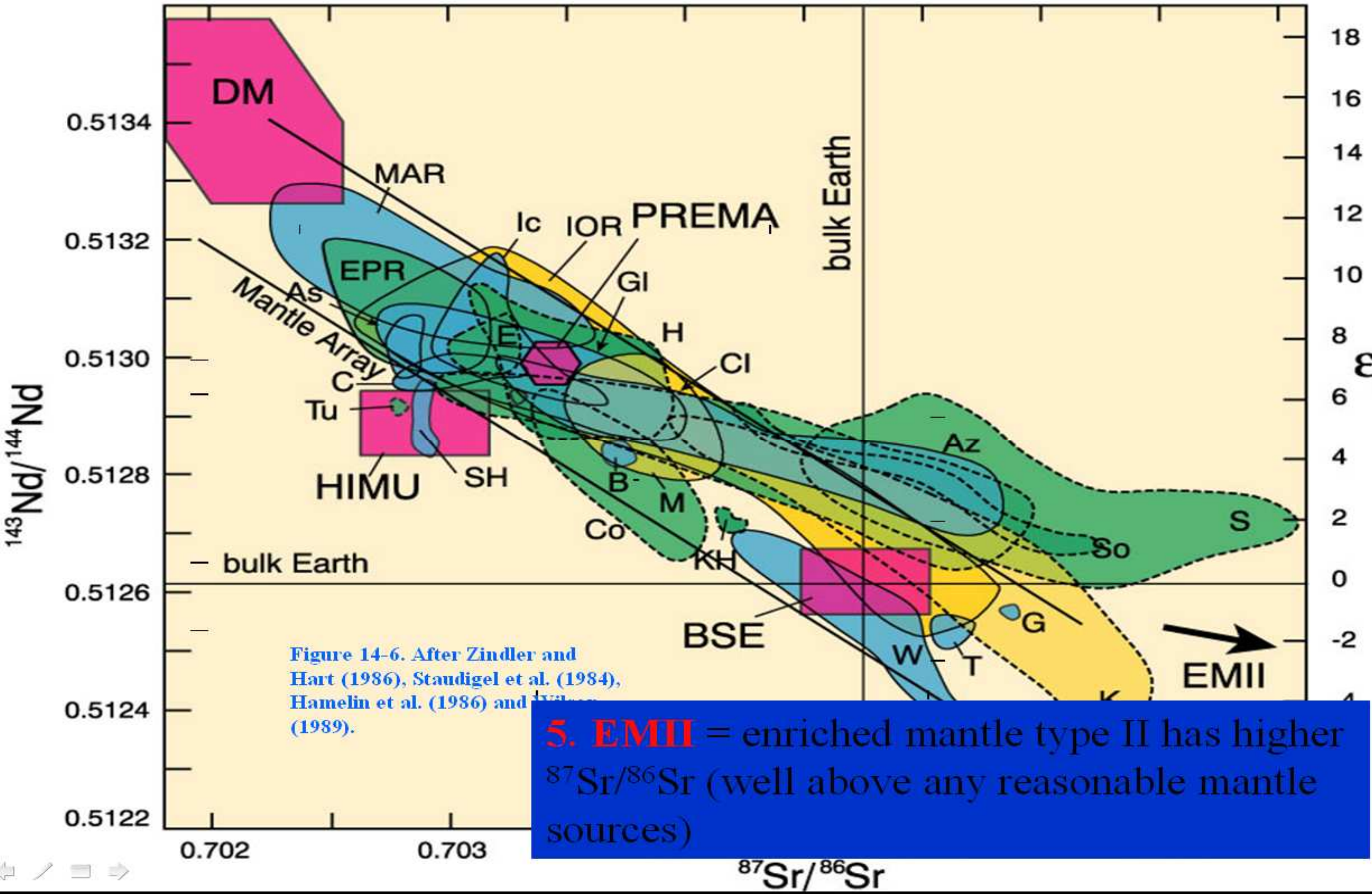



Figure 14-6. After Zindler and Hart (1986), Staudigel et al. (1984), Hamelin et al. (1986) and Wilson (1989).

**5. EMII** = enriched mantle type II has higher $^{87}Sr/^{86}Sr$ (well above any reasonable mantle sources)

# 6. PREMA (PREvalent MAntle)

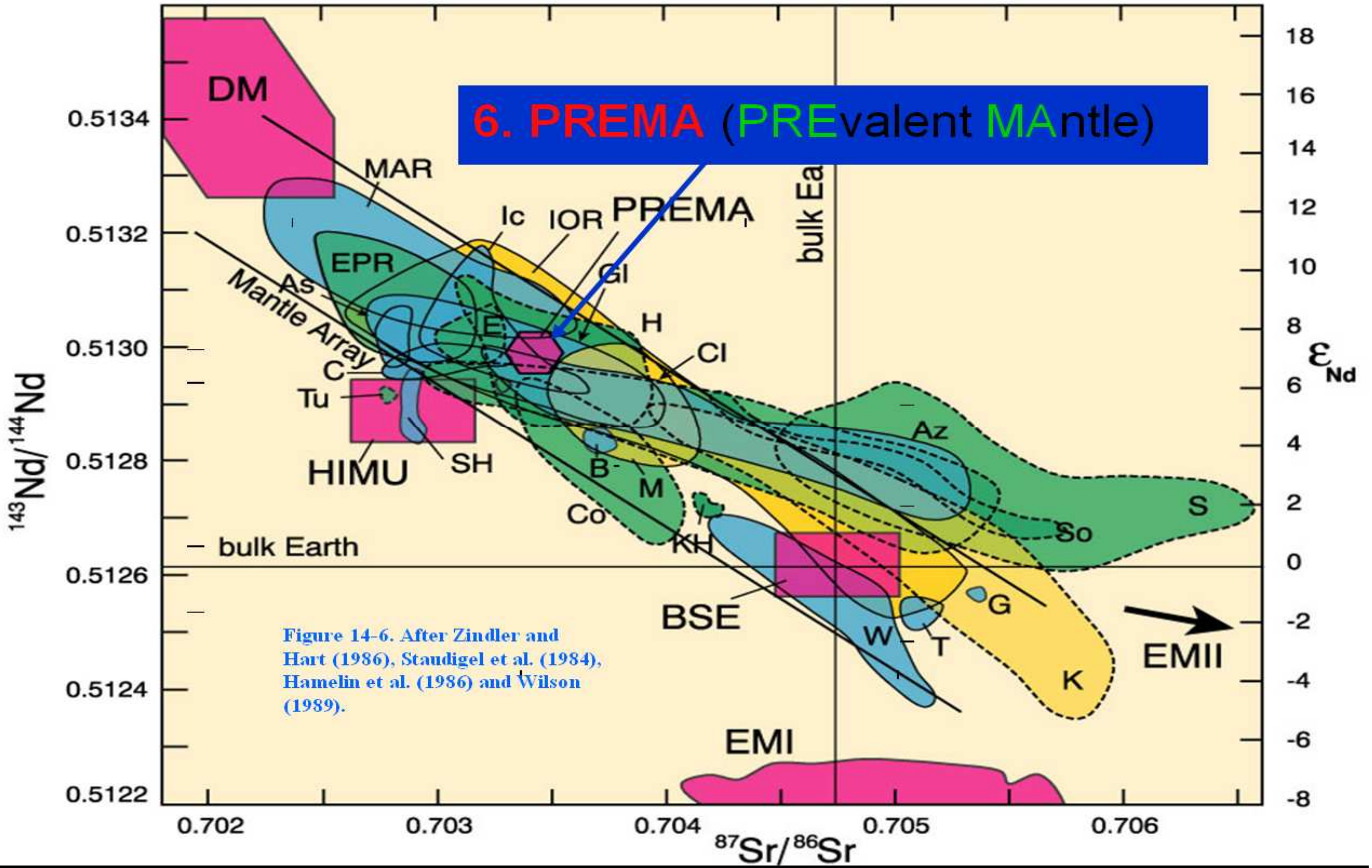


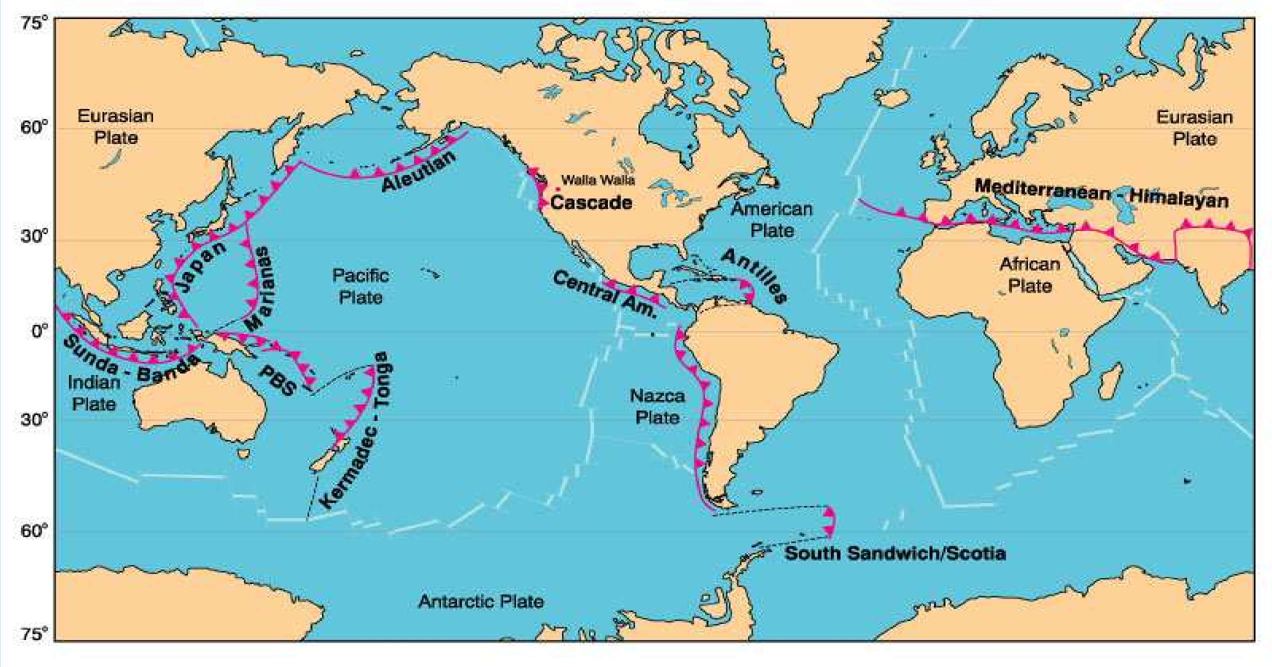

Figure 14-6. After Zindler and Hart (1986), Staudigel et al. (1984), Hamelin et al. (1986) and Wilson (1989).

## Island and Continental Arc Magmatism

- Activity along arcuate volcanic island chains along subduction zones
- Distinctly different from the mainly basaltic provinces
  - Composition more diverse and richer in $SiO_2$
  - Basalt generally occurs in subordinate quantities
  - Also more explosive than the quiescent basalts
  - Strato-volcanoes are the most common volcanic landform

Ocean-ocean → Island Arc (IA)

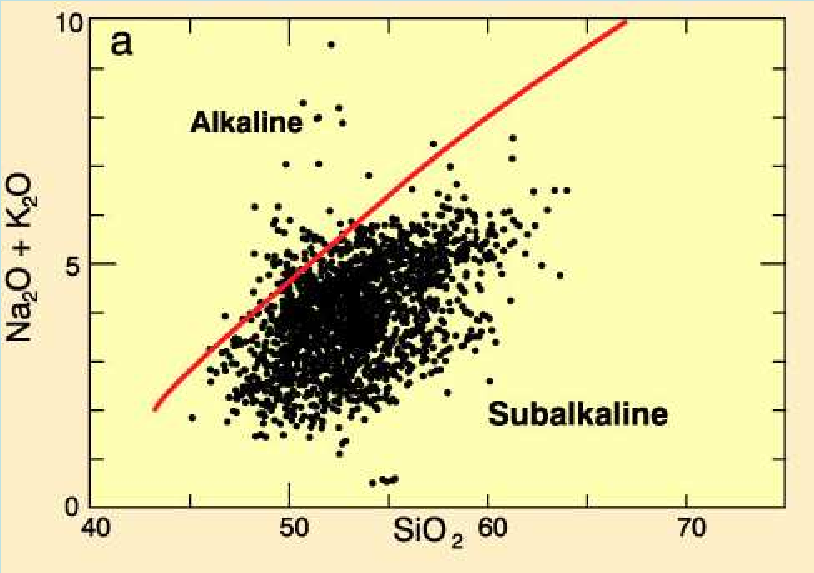
Ocean-continent → Continental Arc or Active Continental Margin (ACM)




As for Intraplate oceanic magmatism the island arc magmatism has the advantage to not consider the effect of thick crust through which the magma have to pass before reaching the surface

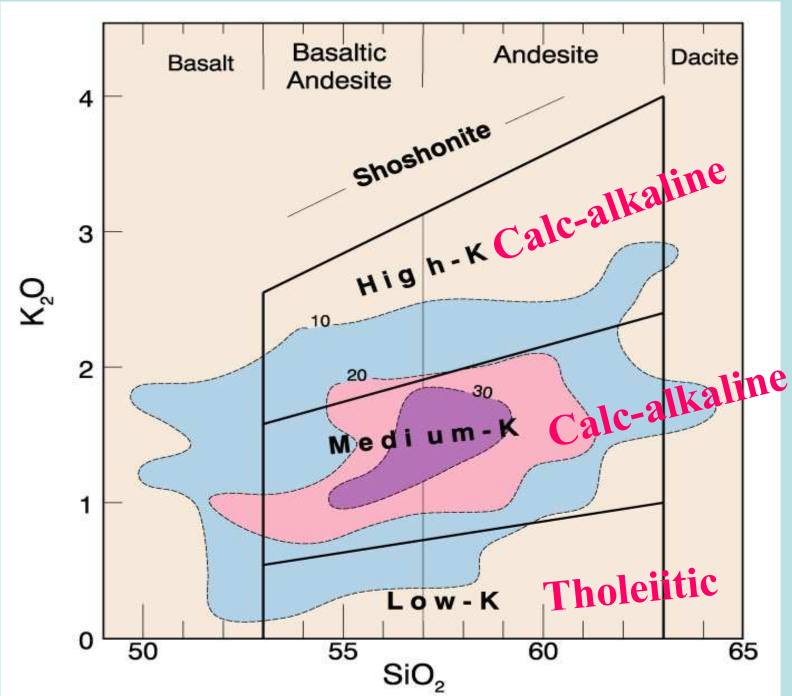
# Major Elements and Magma Series

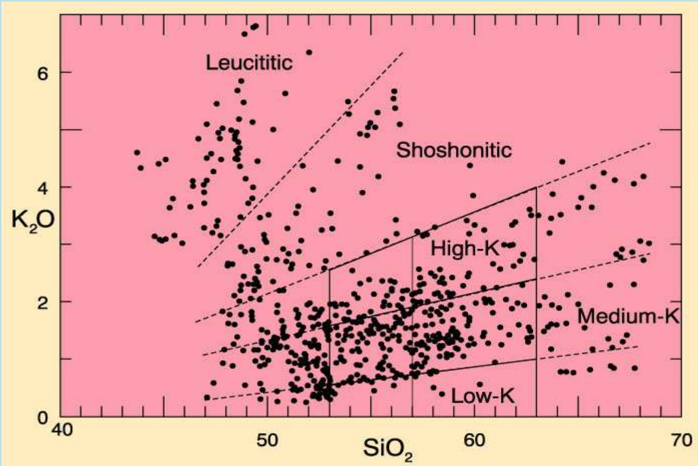
- Tholeiitic (MORB, IAT)
- Boninitic magmas
- Alkaline (HK-CA, Sh, Leuc)
- Calc-Alkaline (~ restricted to SZ)




## Sub-series of Calc-Alkaline

- $K_2O$ is an important discriminator → 3 sub-series

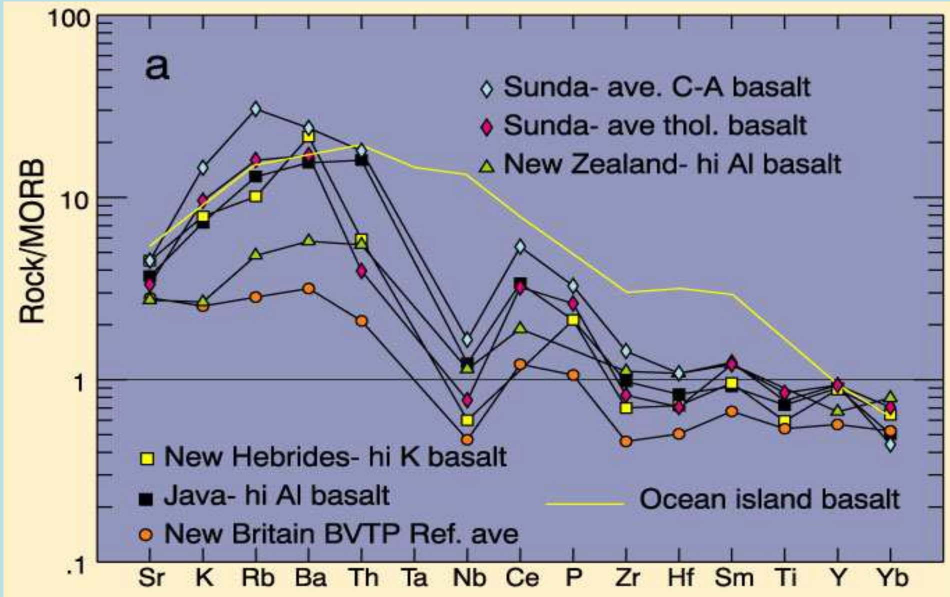


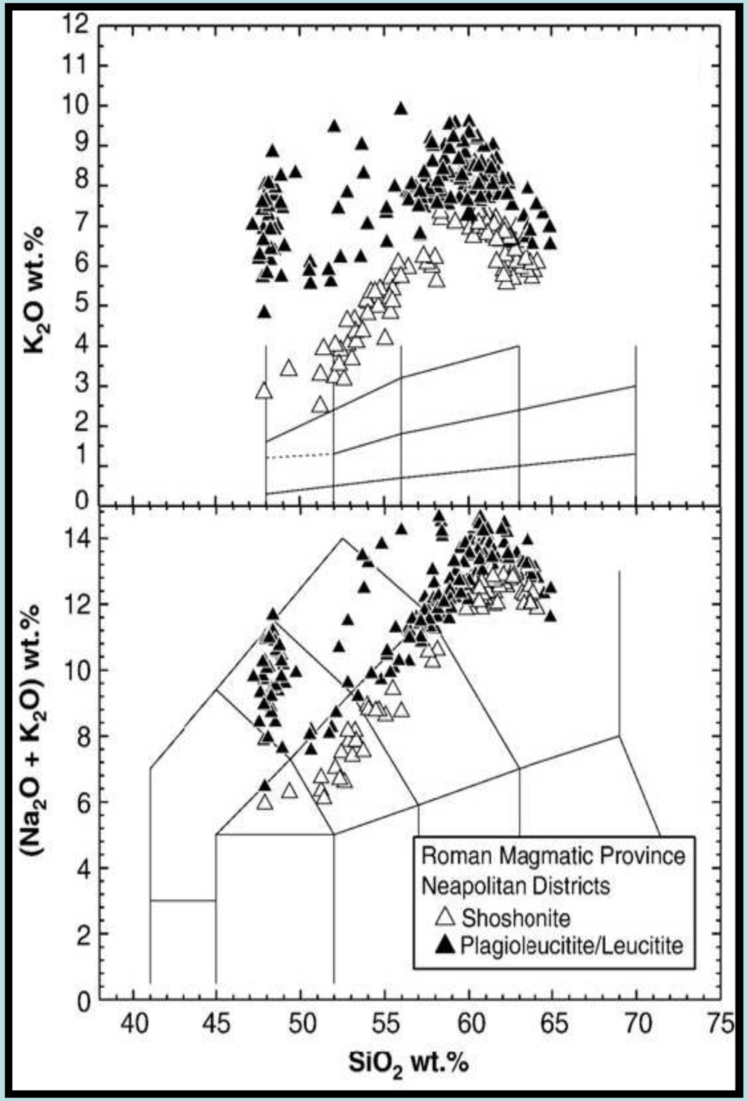




Ultrapotassic magmatism are practically absent in intra-oceanic environment.
It requires the subduction of continental material.
They usually occur after the subduction took place

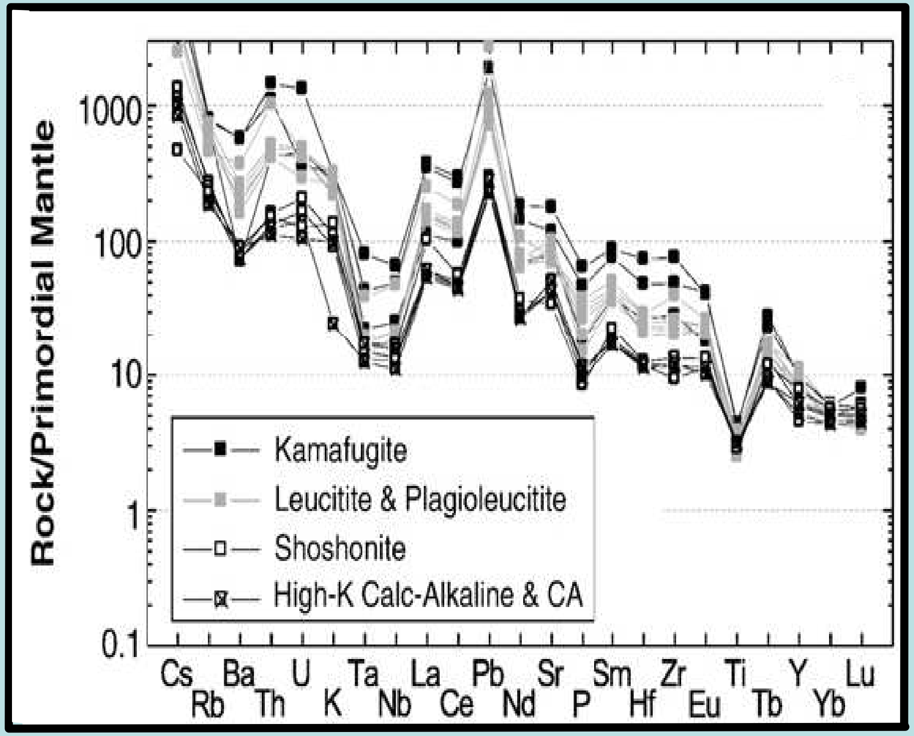
# Trace element

CA



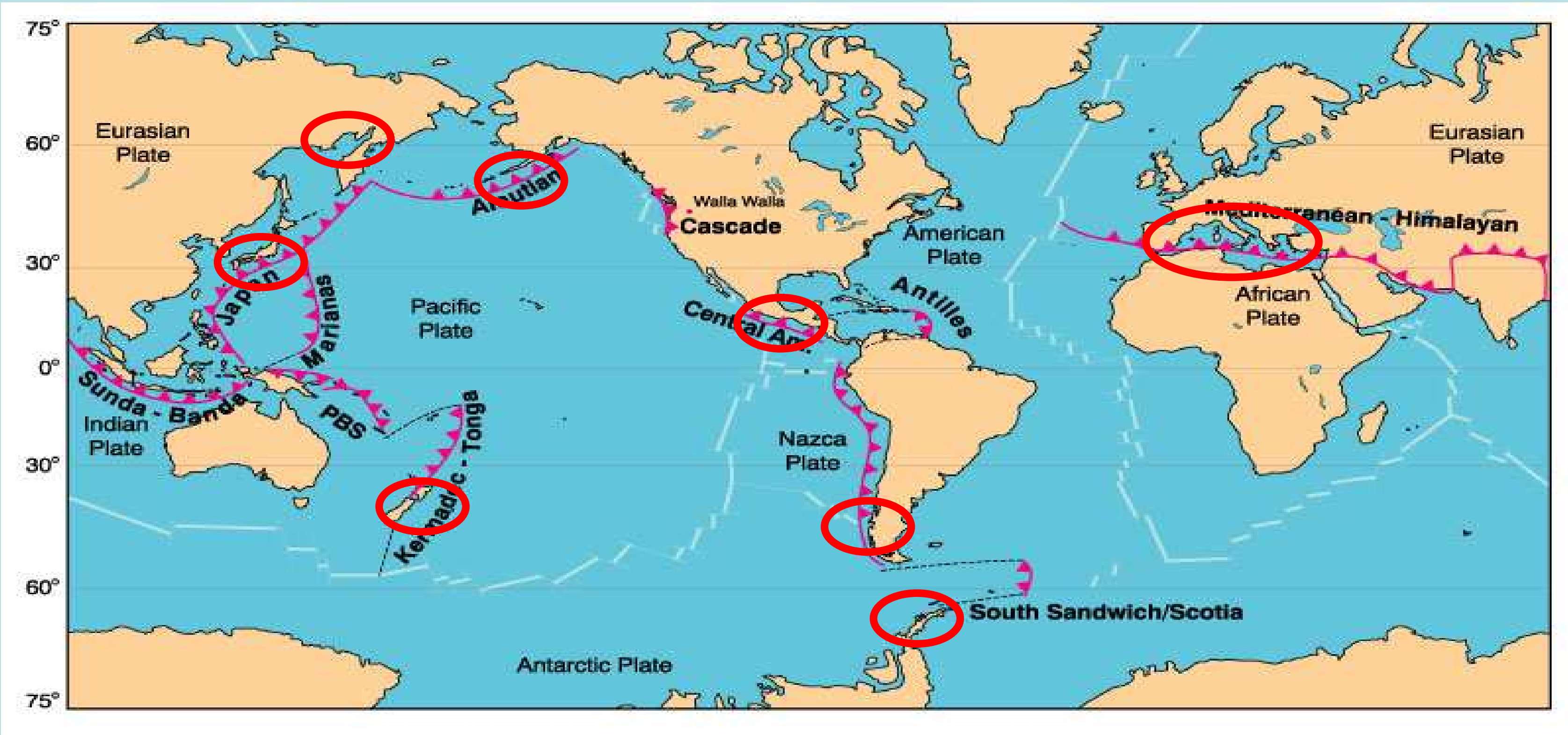




HK



**Are the two magmatic series so well separated?**
**Calc-Alkaline to Na-Alkaline succession; CA-NA succession**

In many localities worldwide we can observe a sequence of Calc-alkaline magmatism followed in a time span of 5 to 15 Ma by alkali basalts, which often carry mantle xenoliths.
They are perfectly comparable to intraplate alkaline basalts.



# Distribution of Tertiary-Quaternary volcanism

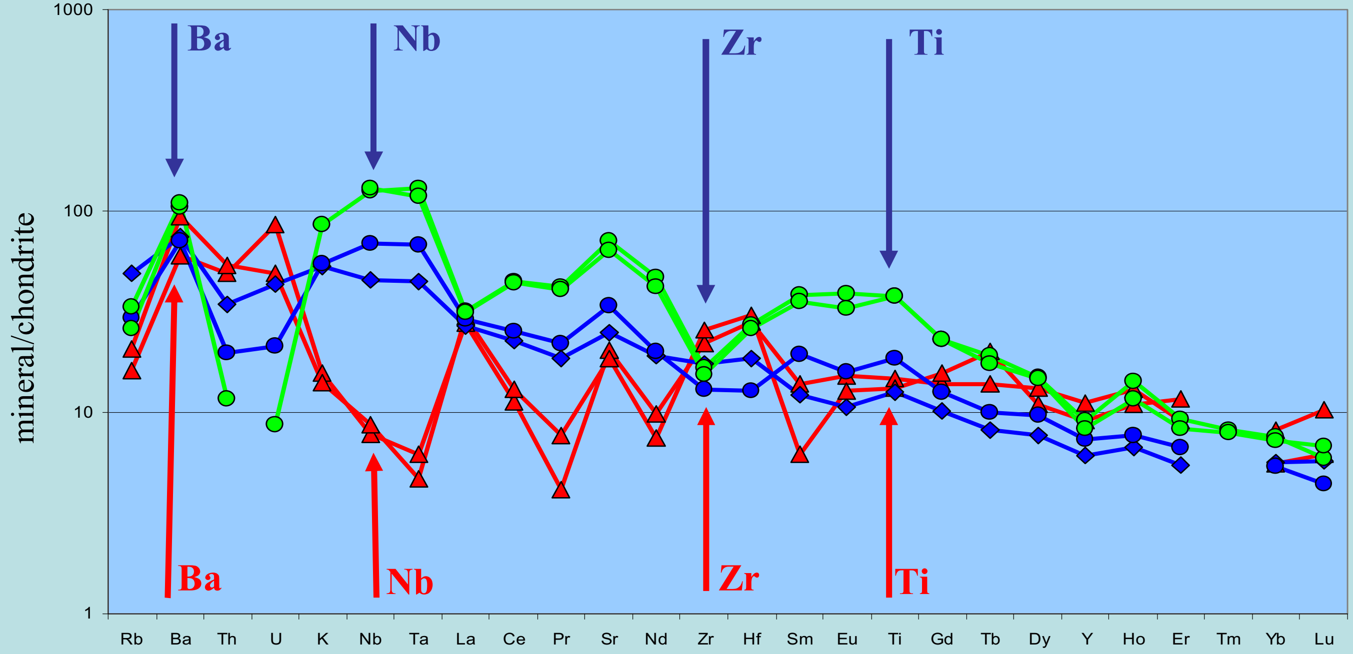

Within the Mediterranean this sequence can be observed in Sardinia, Pannonian Basin, Turkey, Algeria, Marocco, Tunisia, Spain.
Rarely the two magmatism are contempora-neous as for Transilvania and New Zealand

Stars also indicate the presence of mantle xenoliths

## Calc-Alkaline to Na-Alkaline succession; CA-NA succession

Similar sequences has been observed in the metasomatic style of mantle xenoliths from Tallante (Spain) and Kapfenstein (Western Pannonian Basin). Time constrains in this case are impossible to decipher, but alkaline metasomatism always follow the subduction metasomatism.

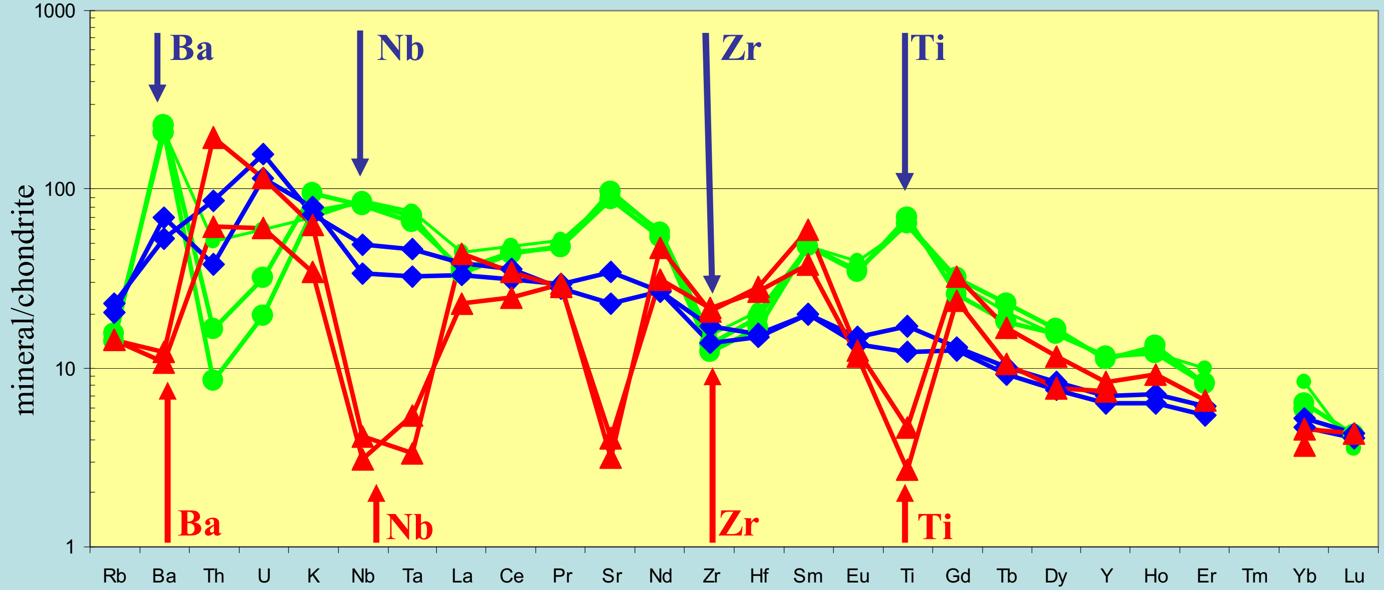
# amph




## Kapfenstein

## (Austria)

- Intraplate V-Amph
- Intraplate D-Amph
- Orogenic D-Amph




## Tallante

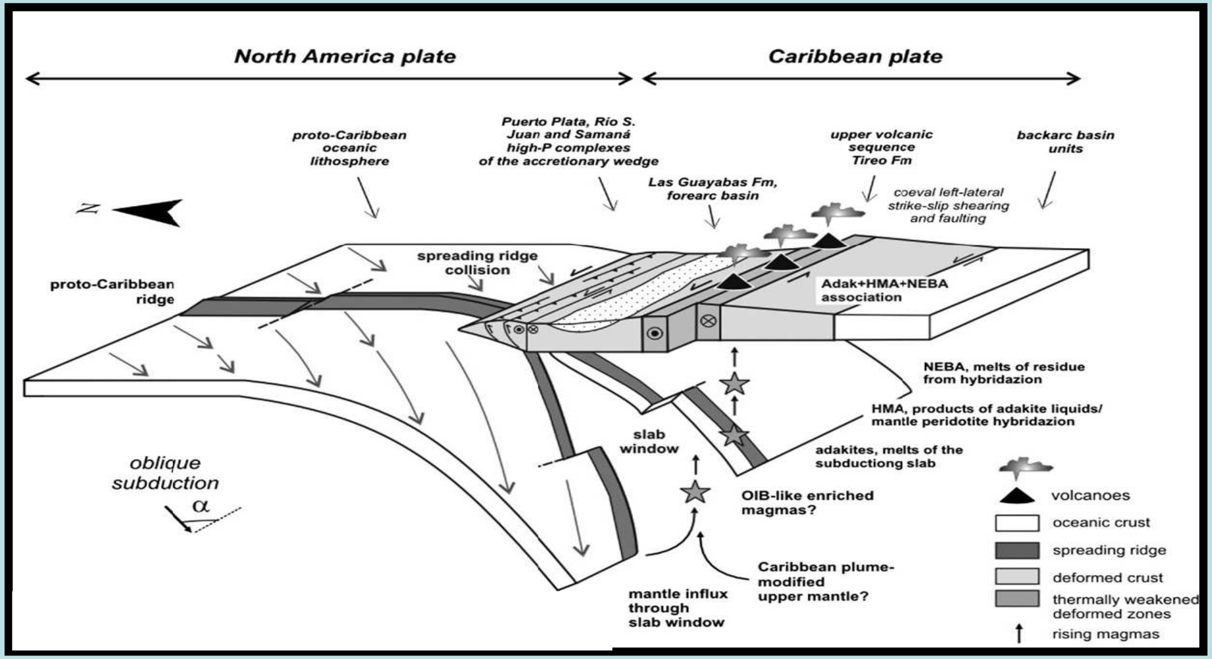
## (Spain)

- Intraplate V-Amph
- Intraplate D-Amph
- Orogenic D-Amph

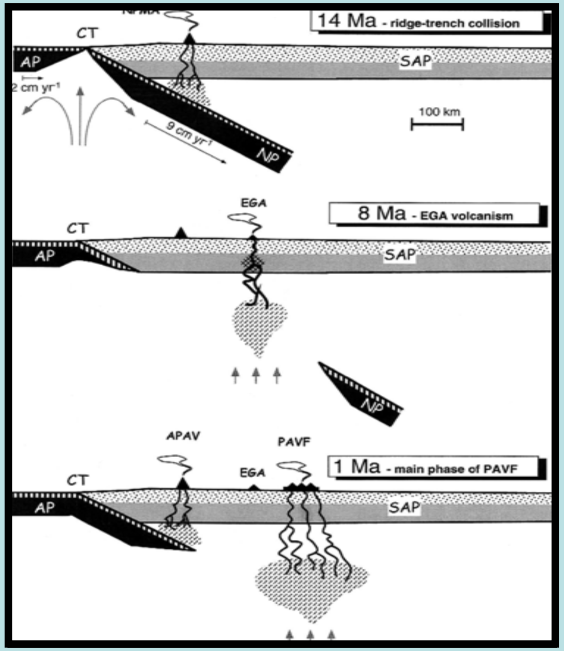
## Calc-Alkaline to Na-Alkaline succession; CA-NA succession

In order to generate Na-alkaline basalts, analogous in every respect to those from pure, intraplate (hot spot?) setting, and the two kind of metasomatism observed, we have to completely substitute the mantle sources of calc-alkaline magmas with those necessary to create Na-alkaline basalts in a very short time span.

The most common models invoke slab-window or return flow around the slab edge, in order to introduce fresh material from behind the subducting plate

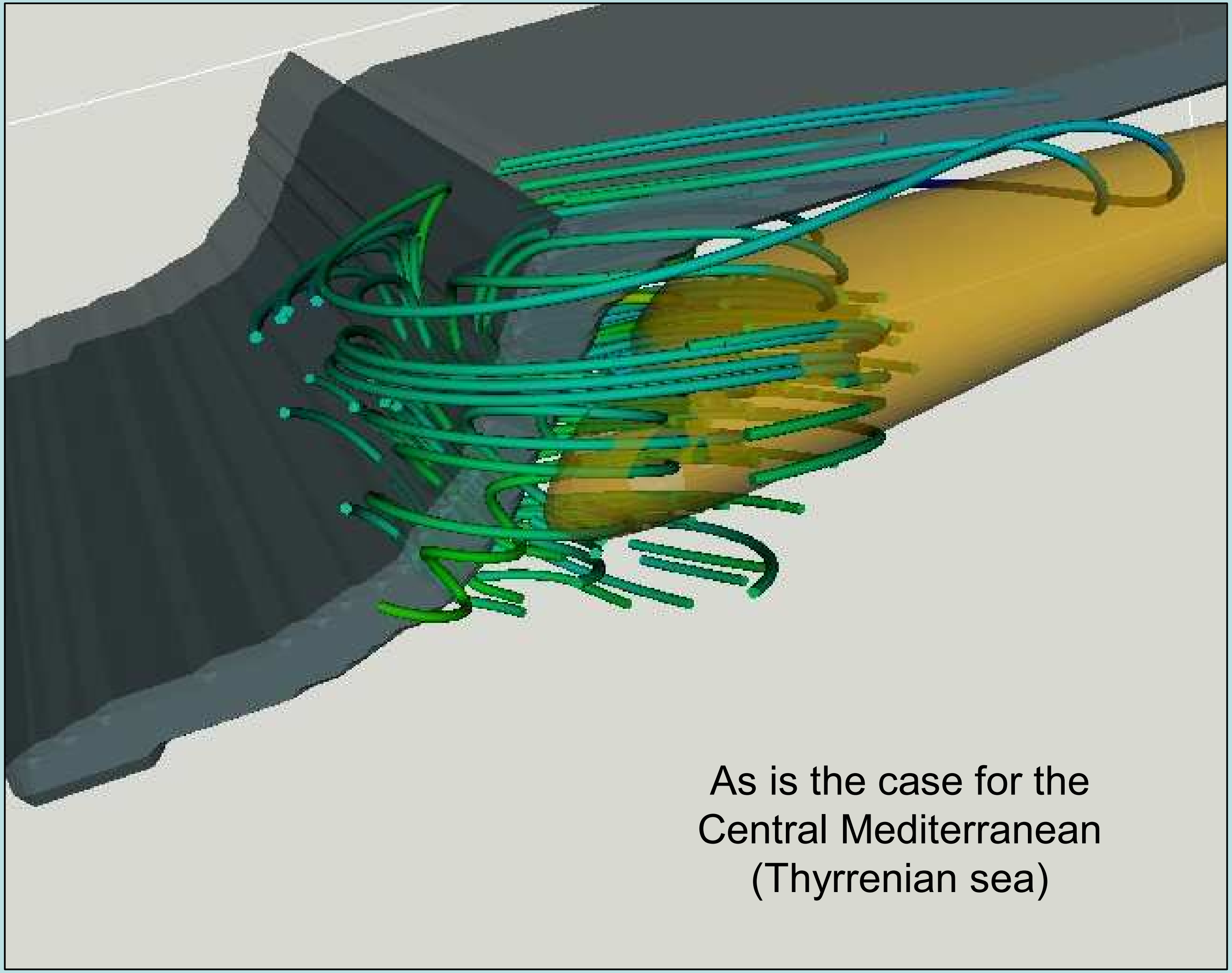



Viruete et al. (2007)




D’Orazio et al. (2001)

# Return flow at slab edge during slab retreating



## Calc-Alkaline to K-Alkaline or High K-Alcaline succession
## CA-KA-HK succession

- In this case a continuous production of progressively K-enriched magmatic products is observed without solution of continuity. The two most famous localities in Central-Western Mediterranean are Central Italy and South-eastern Spain

- In this case no substitution of mantle source may be invoked, but, viceversa, we need a progressive enrichment of the same source. Thus mantle circulation should be completely different, but

- In Central Mediterranean Ca-NA and CA-KA-HK successions are present within a distance of few tens of kilometers (Sardinia, Corsica and Tuscany)

- Thus it is going to be difficult to take into account for two so different behaviours with the same model

- So far evidence of this succession has not been recorded in mantle xenoliths

**More questions than answers, as usual…**

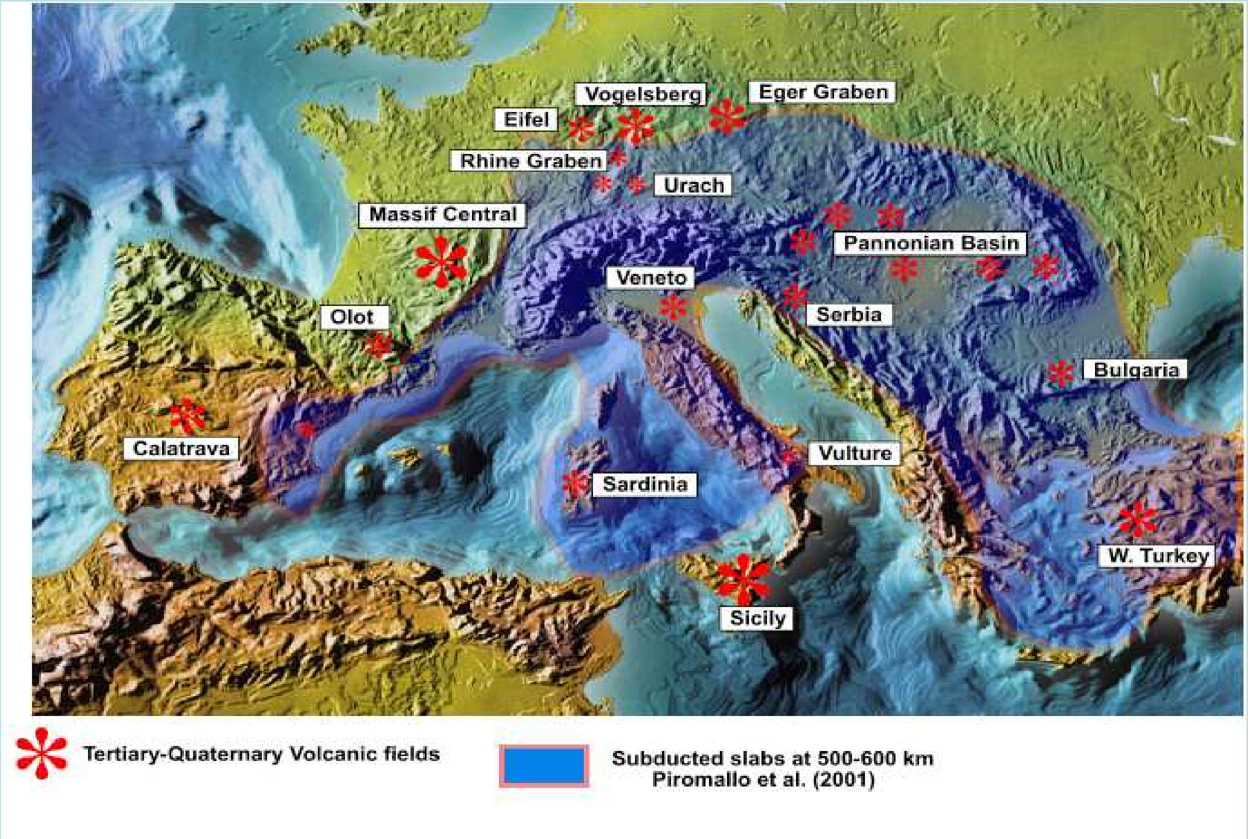
- the two models (slab-window or flow around the edge) require that astenospheric material (or deeper, down to 670 discontinuity) behind the subducting plate would be different, that is enriched to generate Na-Alkaline basalts, with respect to that present on its front

- In the CA-NA sequence time constraints between the two kind of magmatism (and metasomatism) is very restricted. In few cases even contemporaneous, thus mantle circulation has to be very, probably unreasonable, quick.

- The two magmatic sequences, CA-NA and CA-KA-HK, require completely different mantle circulation

On the other hand there are increasing evidence of the role that eclogite material may play in the alkaline basalt petrogenesis.
And this cannot come from behind…

**Base of the upper mantle (410-660 km) is seismically FAST - this could be a region of subducted slabs - SLAB GRAVEYARD**




**Intra-plate magmatism occurs just ad the edges of this Slab Graveyard**

## Not conclusions, but suggestions

- As indicated by the petrological features of metasomatized material in both intraplate and suprasubduction settings, coupled with the complementarity of CA and Na-alkaline basalts I would favour the hypothesis of eclogite material, on the front of the subducting plate, being involved during the subduction or soon after in the genesis of alkaline basalts.

- We should better take into account what is the composition of the material brought down and how this material is going to be transformed after deydration and/or melting in the upper part of the slab.

- Slab-window probably exist but we do not need them in order to explain geochemical features

- For the K-HK series subduction of continental crustal material is required, together with the absent of mantle circulation to allow the progressive enrichment of the mantle sources

- A compelling synergy between mantle flow numerical simulations, tomographic and petrological studies would be essential to arrive to a satisfactory comprehension of the nature of the material as well as to their rheological and geodynamical behaviour of the upper mantle in the subduction setting.


That's the end ?
?
?
?
?
?
Thanks for your attention

Vulture vulcano represents another peculiar locality where Na-alkaline magmatism is followed by K-subduction-related magmatism

Again a slab-window model is invoked, although, in this case mantle influx is from the strongly metasomatized, K-enriched mantle wedge