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Discriminating between different types of ophiolitic basalts and their tectonic significance using a new method based on Th-Nb and Ce-Dy-Yb

Emilio Saccani

Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, sac@unife.it

Structure of this presentation:

1-The dataset and a review of the different types of ophiolitic basalts (*l.s.*)
2-The birth of the idea: a critical analysis of the existing discrimination diagrams (including mathematical problems)
3-The new proposal

Milano 10-12 Settembre 2014
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Part 1

-The dataset and a review of the different types of ophiolitic basalts (*l.s.*)

-The birth of the idea: a critical analysis of the existing discrimination diagrams (including mathematical problems)

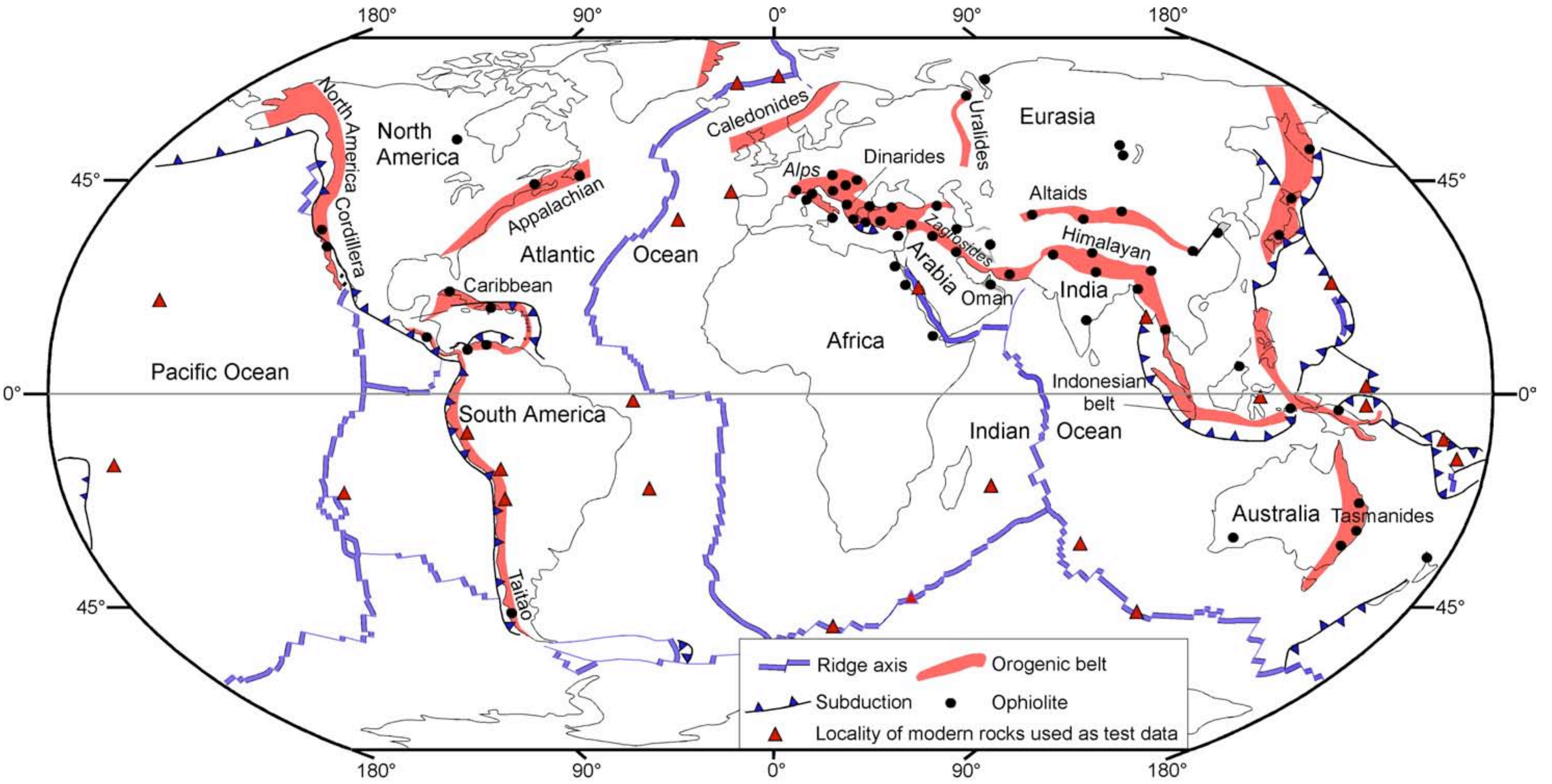
-The new proposal

The Database: Training and testing data

Training Data Age: Proterozoic-Paleogene (2500-30Ma) N. of samples = 2035

Testing Data Age: <10Ma N. of samples = 565

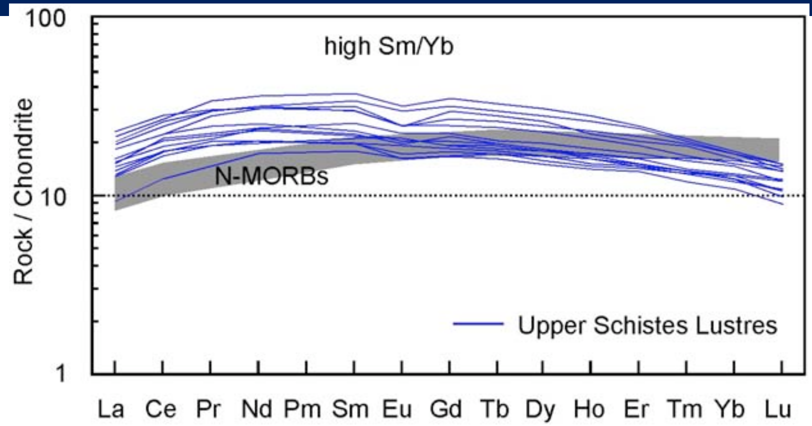
Only samples with well-defined and commonly accepted tectonic setting of formation were used



Basaltic rock-Types in Ophiolites (including mélanges) and their tectonic setting of formation

Rock-type	Tectonic Setting (Dilek & Furnes, 2011: *GSAB*)
G-MORB garnet-influenced MORB …..	Continental delamination / ”Alpine-type” ocean-continent TZ (C-MORB of Dilek & Furnes 2011)
N-MORB (high-Ti basalts) ………………	Mid-Ocean Ridge (plume-distal)
E-MORB (enriched MORB)…………...	Mid-Ocean Ridge (plume-proximal/plume-distal)
P-MORB (plume-type MORB) ………..	Mid-Ocean Ridge (plume-proximal/plume-distal)
OIB (alkaline ocean island basalts)…...	Continental rift / seamount (plume proximal)
IAT (low-Ti basalts)………………………	Intra-oceanic island arc
Boninite (very low-Ti basalts)…………..	Nascent intra-oceanic island arc / forearc / back-arc
CAB (calc-alkaline basalts)……………..	Island arc with polygenetic crust / cordilleran-type arc
MTB (medium-Ti basalts)………………...	Nascent intra-oceanic island arc / MOR subduction
BABB (backarc basin basalts)………….	Back-arc basin (either oceanic or ensialic)

New rock-term: garnet-influenced MORB (G-MORB)



Main feauture: High MREE/HREE ratios

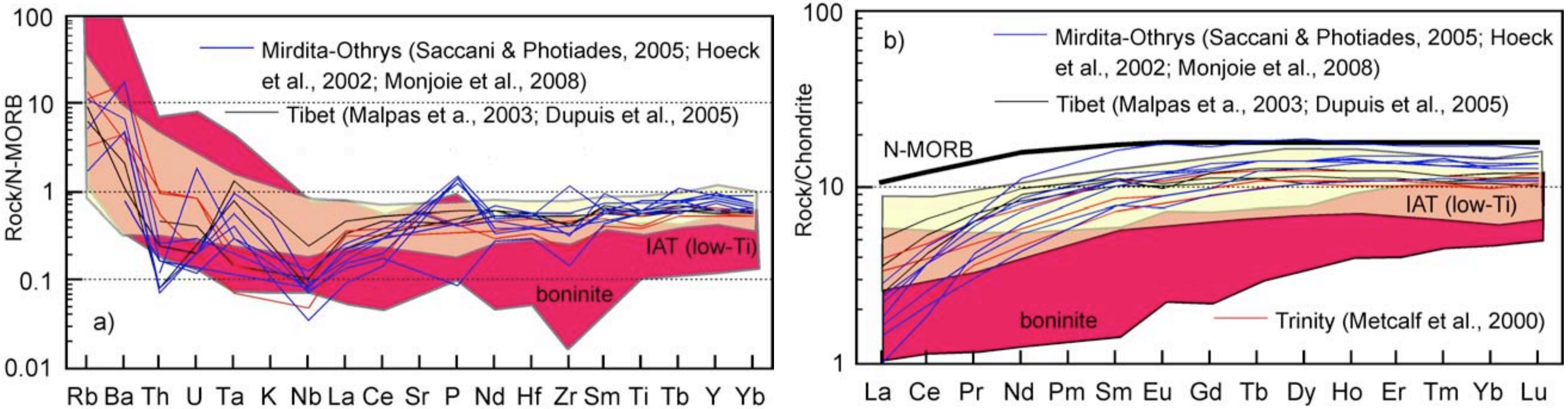
Where: Western Neo-Tethys (Alps, Apennine, Corsica), Turkey, Iranian Neo-Tethys, Iranian Paleo-Tethys

Previous names: High Sm/Yb MORBs of Montanini et al. 2008 *Lithos* - Saccani et al. (2008) *Ofioliti* - N-MORB with gt signature (Hirschmann & Stolper, 1996, *Contr.*) C-MORB (Dilek & Furnes, 2011, *Geol. Soc. Am. Bull.*)

Genesis of primary melts: from partial melting of DMM bearing Gt-Pyroxenite relics (see also Piccardo & co-workers) - from partial melting of DMM in the gt-facies + DMM in the sp-facies

Tectonic setting:
Alpine/Hiberian-type continental rift & Ocean-Continent Transition Zone (Saccani et al., 2013, *Gondw. Res.*) - Paleo-Tethys OCTZ (Saccani & Dilek, *Lithos*)

New rock-term: Medium-Ti Basalt (MTB)



Main feauture: Strong Th, Nb, (Zr), and LREE depletion

Where: Eastern Neo-Tethys (Albania, Greece), Luobusa, Altay, Hokkaido, New England (AUS), Cyclops, Nan-Uttaradit. ALWAYS STRATIGRAPHICALLY ASSOCIATED WITH (OFTEN INTERLAYRED WITHIN) N-MORBs

Previous names: MORB/IAT intermediate basalts (Bortolotti et al. 1996, *Ofioliti* ; 2002 *Geology*), Low Zr-high Cr basalts (Bébien et al., 2000, *Ofioliti*), Intermediate Ti basalts (Hoeck et al., 2002, *Lithos*), DEPLETED-MORB (rarely)

Genesis of primary melts: from partial melting of depleted mantle (Cpx-poor lherzolite) residual after MORB melt extraction (very hot thermal regime?)

New rock-term: MTB

MTB

Tectonic setting:

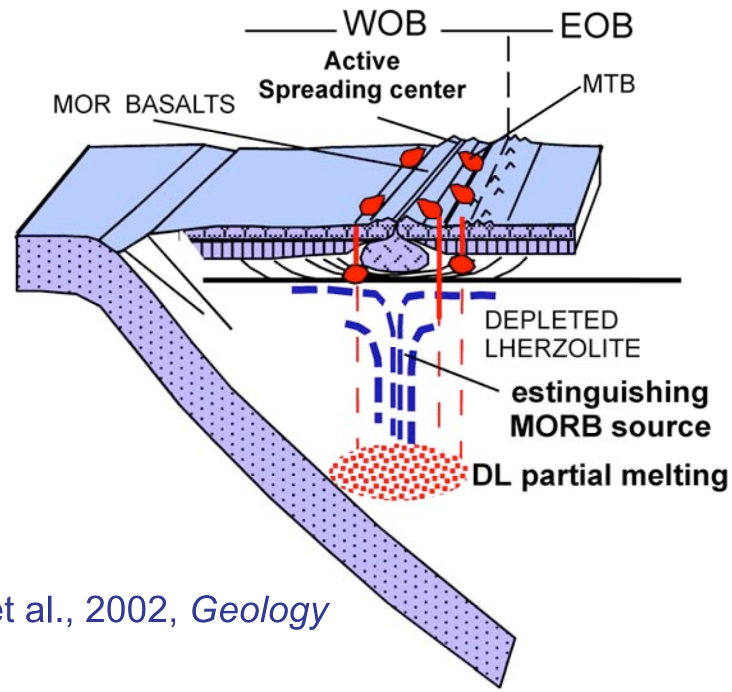
Subduction above a Mid-Ocean Ridge (Bébien & co-workers)

Subduction below a Mid-Ocean Ridge (Bortolotti, Saccani, Hoeck & co-workers)

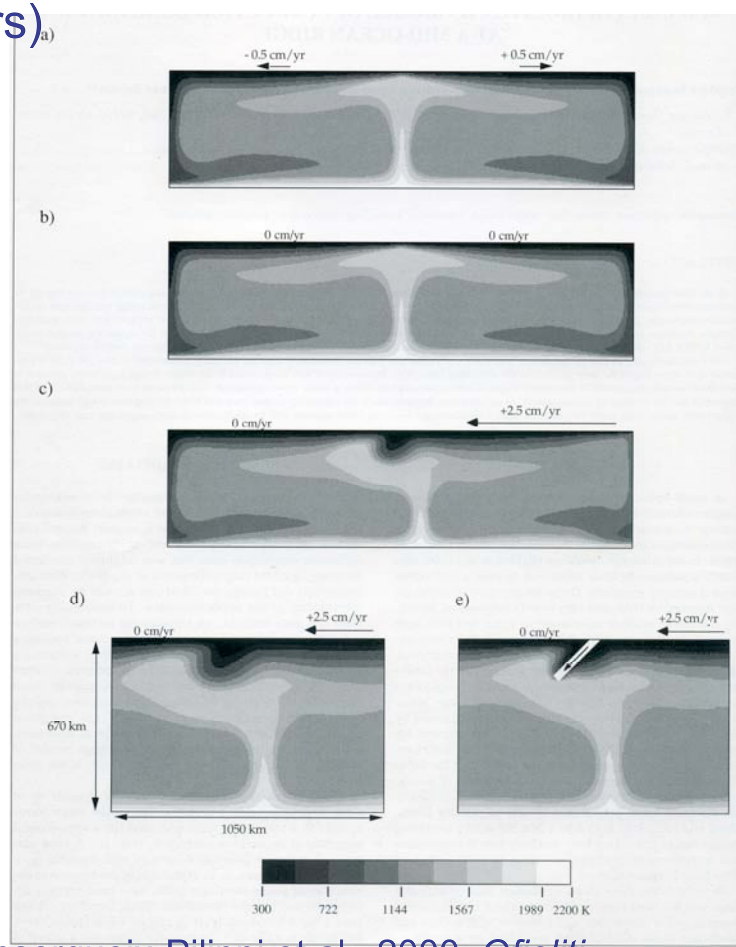
MOR-Subduction lateral transition (Dilek & co-workers)

Subduction oblique with respect to MOR
(several authors)

In any case: NASCENT INTRA-OCEANIC ARC



Bortolotti et al., 2002, *Geology*



Insergueix-Pilippi et al., 2000, *Ofioliti*

Part 2

-The dataset and a review of the different types of ophiolitic basalts

-The birth of the idea: a critical analysis of the existing discrimination diagrams (including the mathematical problems)

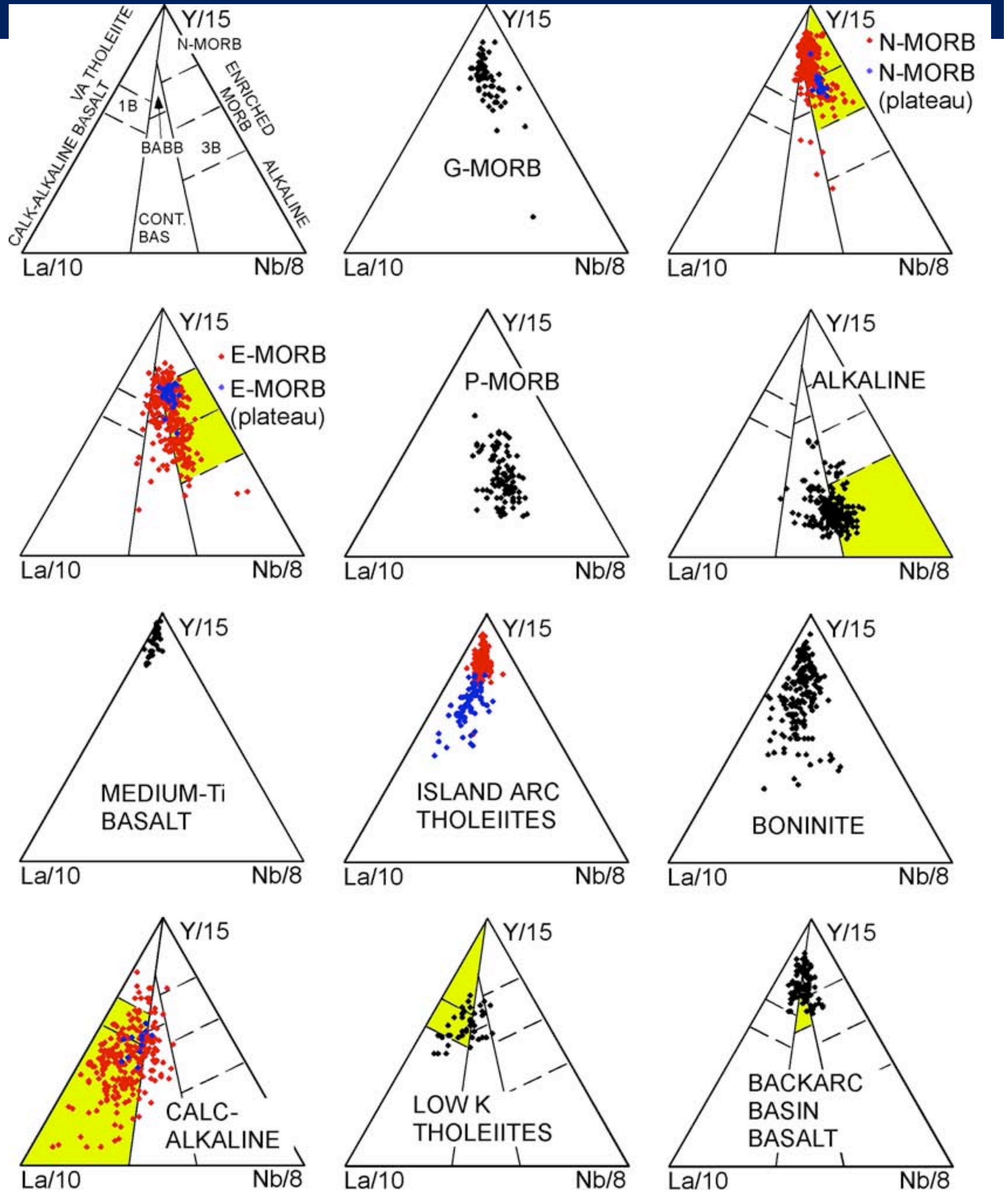
-The new proposal

The body of evidence: in (too) many cases, the commonly used diagrams fail in discriminating among different tectonic setting of formation of ophiolitic basalts.
They are more reliable when used in combination.

Just some examples:

Cabanis & Lécolle (1989)
C. R. Acad. Sci. Paris, 309: 2023-2029

n > 2000 samples



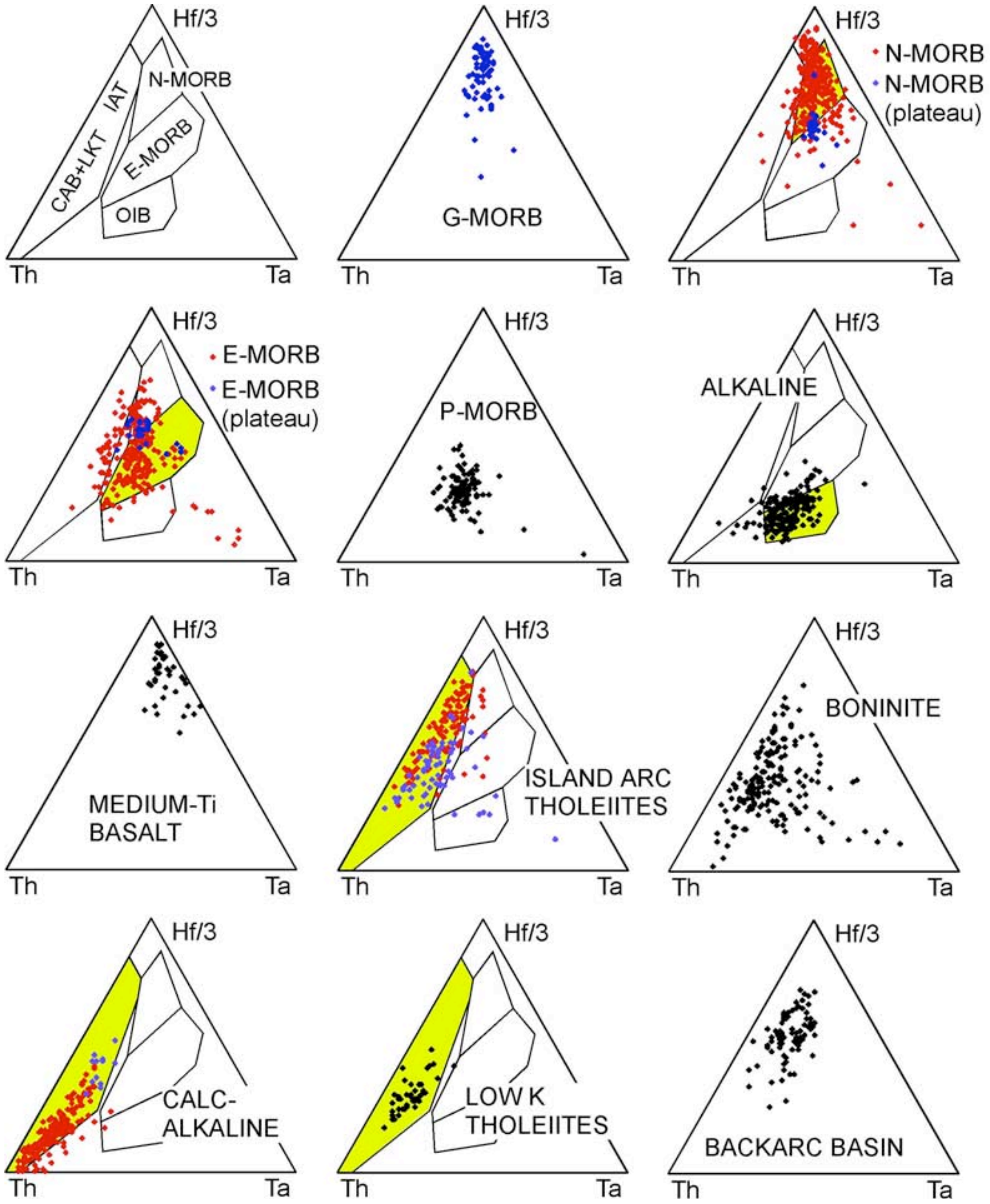
Yellow: proper fields for each rock-type

No fields: rock-type not considered in this discrimination

Just some examples:

Wood (1980)
Earth Plan. Sci. Lett., 50: 11-30

n > 2000 samples



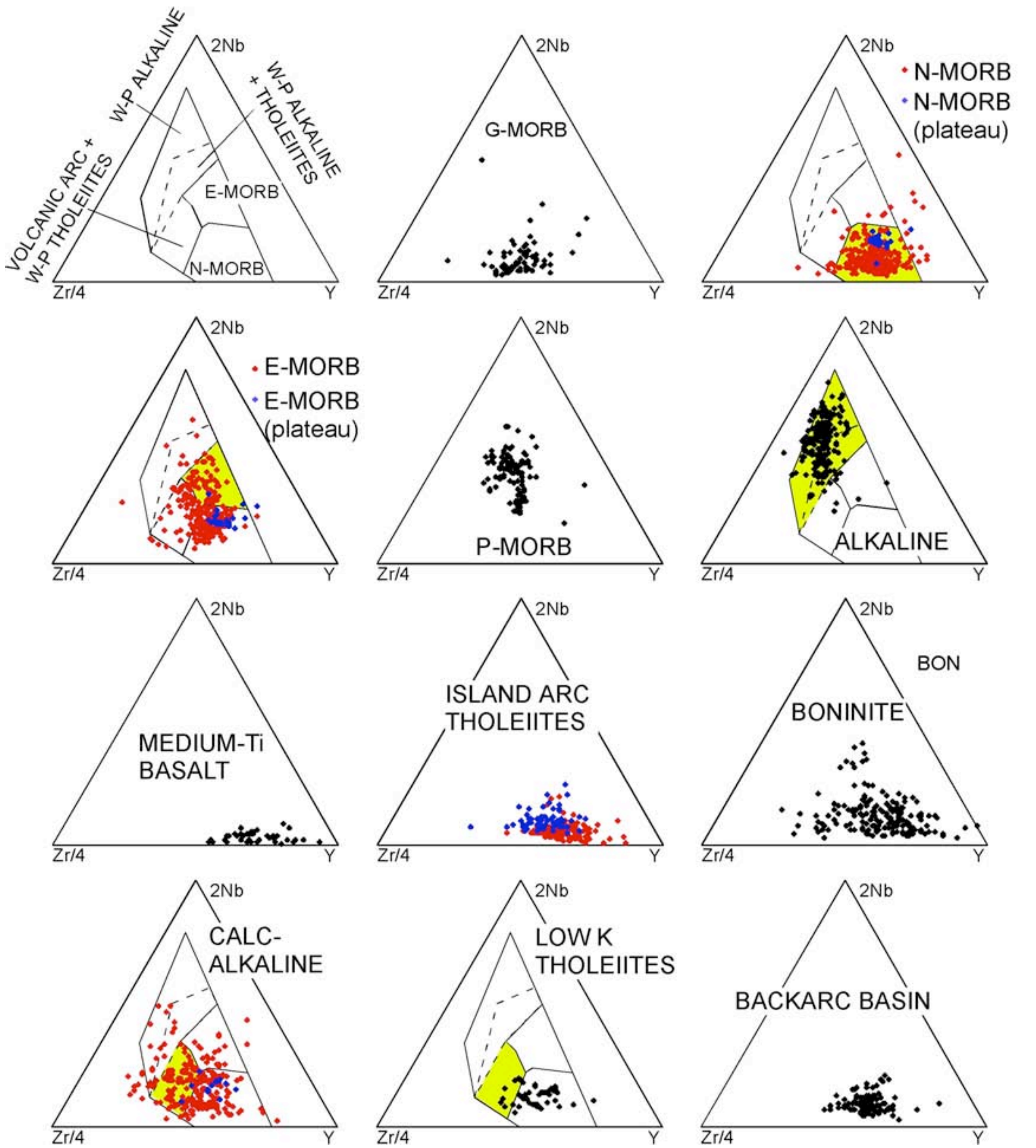
Yellow: proper fields for each rock-type

No fields: rock-type not considered in this discrimination

Just some examples:

Meschede (1986)
Chem. Geol., 56: 207-218

n > 2000 samples



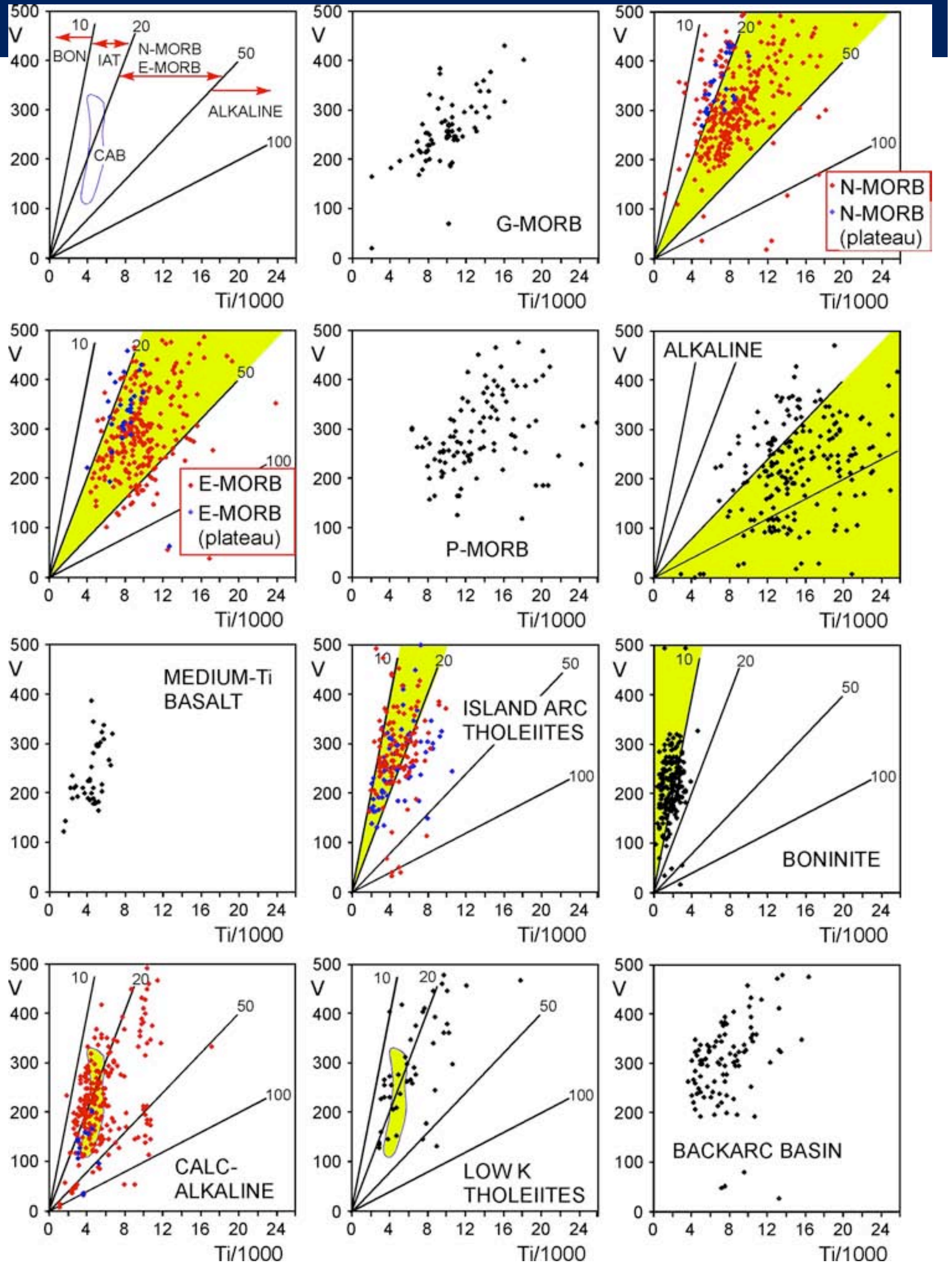
Yellow: proper fields for each rock-type

No fields: rock-type not considered in this discrimination

Just some examples:

Shervais (1982)
Earth Plan. Sci. Lett., 59: 101-118

n > 2200 samples



Yellow: proper fields for each rock-type

No fields: rock-type not considered in this discrimination

Why do these diagrams fail in so many instances?

from Vermeesch, 2006, *G3*:
(1) use of the arithmetic means of multiple samples (no physical meaning);
(2) samples not statistically representative (either limited number of samples or limited number of places);
(3) data not original (calculated using concentrations of other elements);
(4) only a limited number of the various basaltic types that can be found in ophiolites;
(5) propagation of analytical errors when using element ratios or triangular diagrams is hard to evaluate;
(6) implications of the constant-sum constraint of geochemical data were ignored

However (what puzzled me):

- diagrams are not only made on a statistical base, but also on a petrological base, which should be reliable independently from the number of samples used (or, at least, it should mitigate the influence of a poor statistics).
- the discrimination diagram that is by far the most reliable is that of Shervais (1982) based on the simple correlation Ti - V
- All other diagrams (those less reliable) are based on element ratios

Hence:

- Beside the previous reasons, I felt there should be some mathematical reasons associated with using element ratios

Beware of Spurious Correlations

Thanks to Gerti Xhixha and Manjola Shyti
(PhD students in Physics from my Department)

Spurious correlations (Pearson, 1896, *Proc. R. Soc. London*)

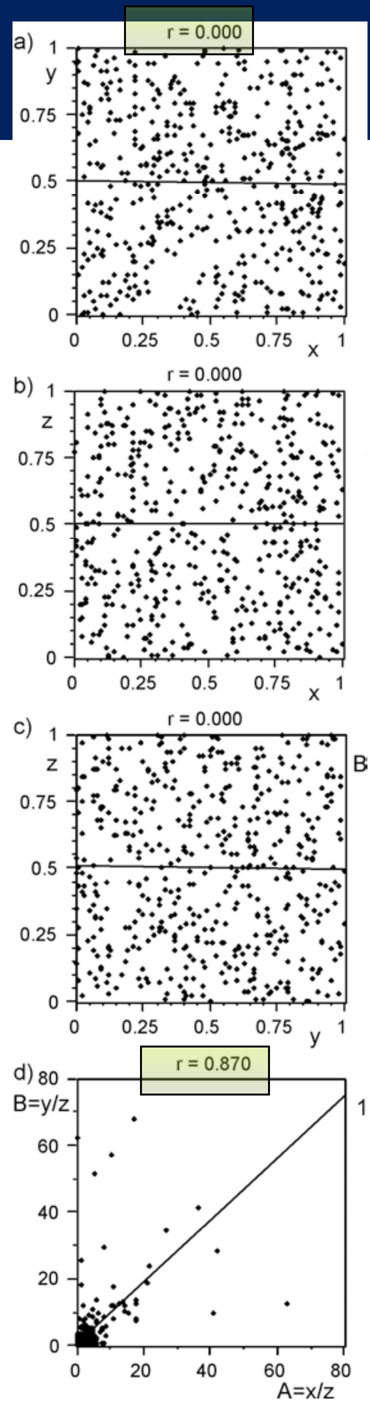
Spurious correlation refers to the correlation between indices that have a common component. He used this term to describe the correlation between ratios that exists even if all the component variables of the ratios are uncorrelated.

i.e. (x/z vs y/z); (x+z vs y+z); (x vs y/x); x vs x/y); etc.

Spurious self-correlations

(Kenney, 1982, *Water Resource Research*)

Spurious self-correlation refers to the correlation between indices that have a common denominator.
i.e. (x/z vs y/z)



Spurious self-correlations

Chayes (1949) *J. Geol., 57, 239-254*: The correlation coefficient (r) is a remarkably useful index of the relation between two variables

General Formula for:
$x=X_1/X_2$ and $y=X_3/X_4$

$$r_{xy} = \frac{r_{13}C_1C_3 - r_{14}C_1C_4 - r_{23}C_2C_3 + r_{24}C_2C_4}{(C_1^2 + C_2^2 - 2r_{12}C_1C_2)^{1/2}(C_3^2 + C_4^2 - 2r_{34}C_3C_4)^{1/2}}$$

where: C = coefficient of variation

$$C = \frac{S_k}{\overline{X}_k} \qquad S_k = \left(\frac{1}{n-1}\sum_{i=1}^{k} X_{ki}^2\right)^{1/2} \qquad \overline{X}_k = \frac{1}{n}\sum_{i=1}^{n} X_{ki}$$

for common denominator ➟ $X_2=X_4$, that is: $x=X_1/X_2$ and $y=X_3/X_2$
then: $C_4=C_2$, $r_{24}=1$, $r_{12}=r_{14}$ and $r_{23}=r_{34}$
the General Formula is reduced to

$$r_{xy} = \frac{r_{13}C_1C_3 - r_{12}C_1C_2 - r_{23}C_2C_3 + C_2^2}{(C_1^2 + C_2^2 - 2r_{12}C_1C_2)^{1/2}(C_3^2 + C_2^2 - 2r_{23}C_3C_2)^{1/2}}$$

If $r_{12} = r_{13} = r_{23} = 0$, then the formula for a common denominator is reduced to:

$$r_{xy} = \frac{C_2^2}{(C_1^2 + C_2^2)^{1/2}(C_3^2 + C_2^2)^{1/2}}$$

The importance of the order of magnitude of the variables x, y, z
If $C_1 = C_2 = C_3$, then $r_{xy}=0.5$
If $C_2 > C_1 = C_3$, then $r_{xy}>0.5$
If $C_1 = C_3 = C_2/2$ then $r_{xy}>0.67$
If $C_1 = C_3 = C_2/10$ then $r_{xy}>0.99$

Spurious self-correlations

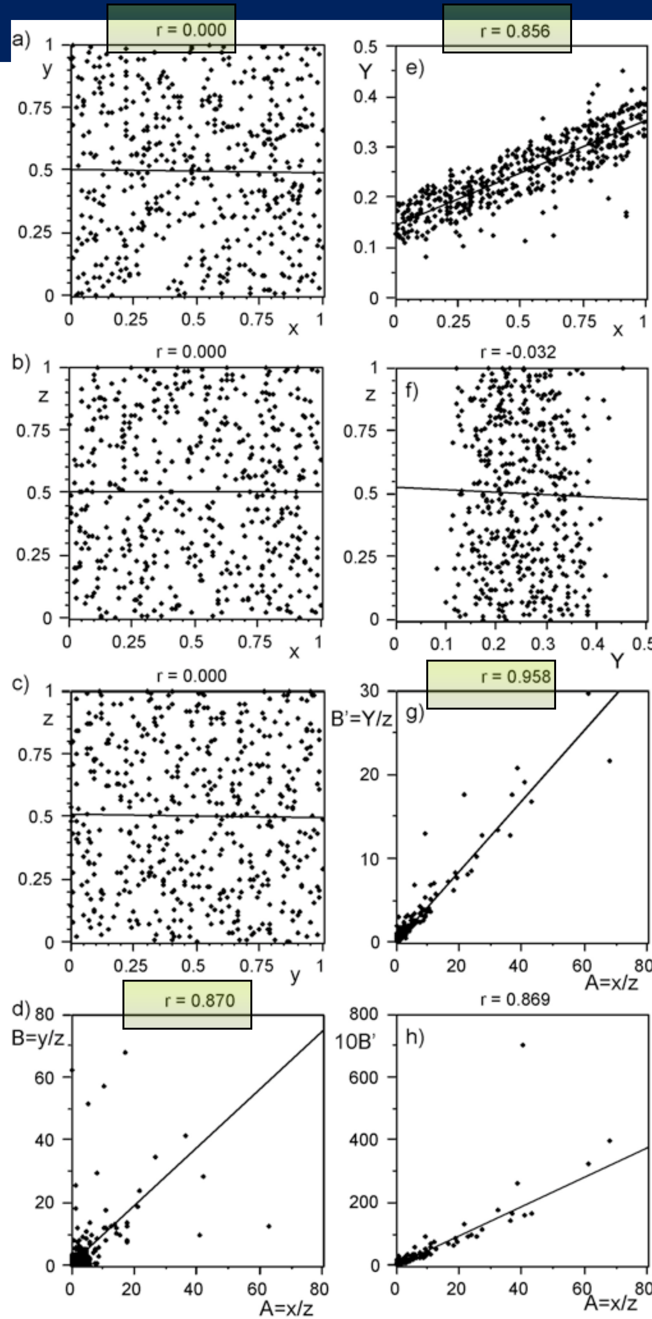
From the equations in Chayes (1949) it can be demonstrated that:

- The lesser are $r_{(x,y)}$ $r_{(x,z)}$ $r_{(x,z)}$ the greater is $r_{(x/z,\ y/z)}$

-If $r_{(x,y)} >> r_{(x,z)} = r_{(x,z)}$ the influence of spurious self correlation is reduced (or even negligible)

- When $r_{(x,y)} \neq r_{(x,z)} \neq r_{(y,z)}$, the resulting $r_{(x/z,\ y/z)}$ are variable and unpredictable

- $r_{(x/z,\ y/z)}$ is strictly depending on the order of magnitude of the variables x, y, z



Chayes (1949) concluded that:

-using element ratios with a common variable should be avoided;

- the formation of ratios should be confined to those cases in which hypotheses being tested (*a priori*) deal with ratios;

- deducing a meaning from ratios (as often observed in literature) is in many cases ambiguous and in a few cases definitely misleading;

- The passage from ratio correlation (e.g., x/z vs y/z) to inference about relations between absolute measures (i.e., x vs. y) - as often observed in literature - is ambiguous at best and often misleading;

- Absolute measures are always preferable when large numbers of observations must be recorded;

- mixing in one x/z vs. y/z graph different magmatic series having different (x, y, z) correlation coefficients and comparing them to each other is mathematically inconsistent (if not absurd)

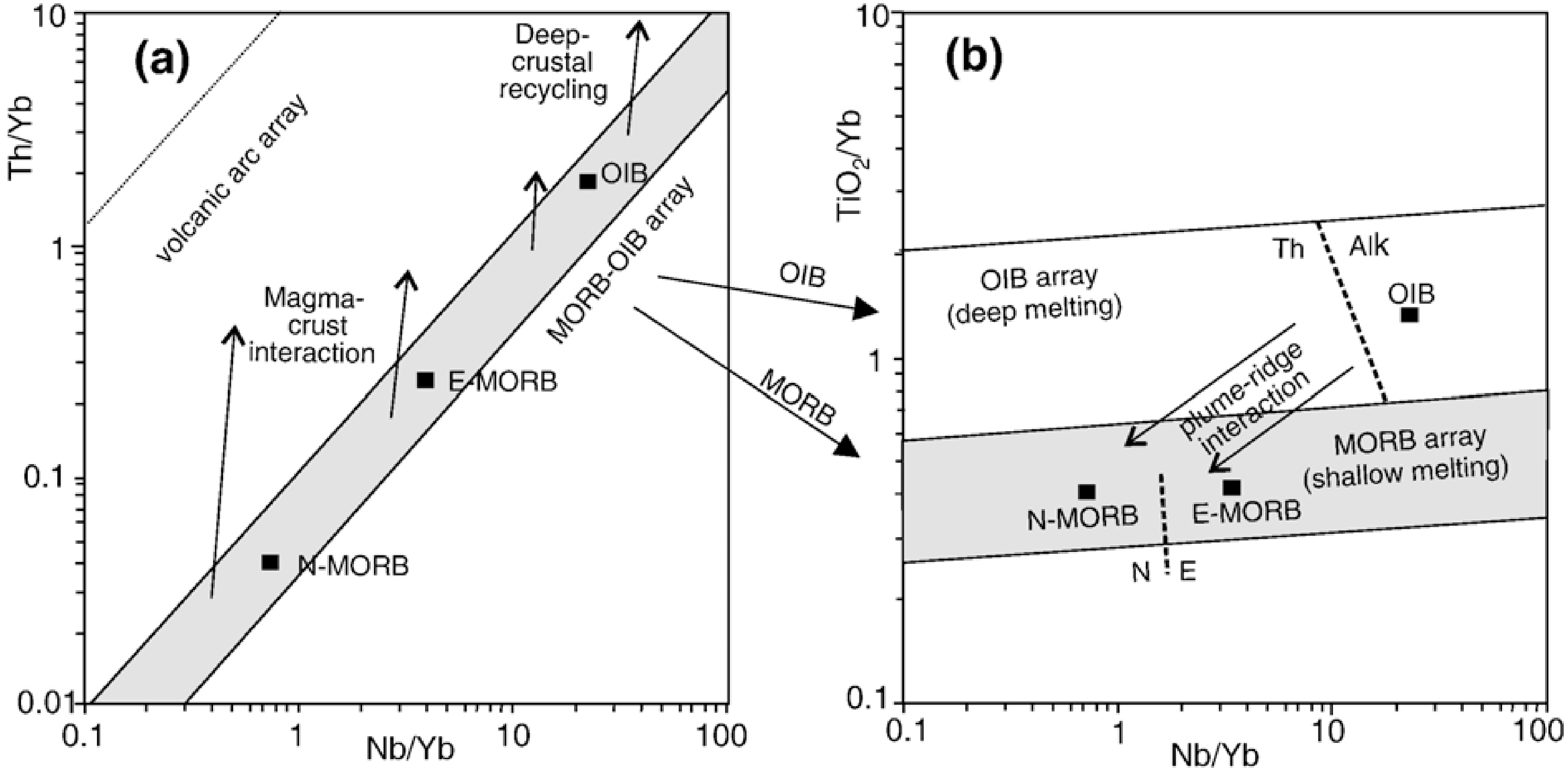
Chayes (1949) concluded that:

Finally:

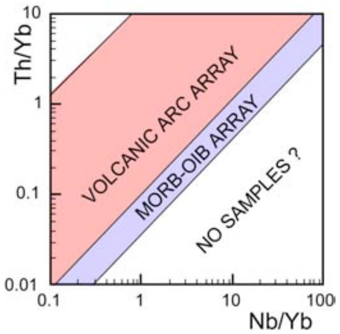
- The effects induced by self correlations are well known since the 40s-50s in zoology, botanic, economics, agronomy, anthropology, etc, but totally overlooked in geology. Chayes in 1949 wrote: "*perhaps the definition of spurious correlation is too old to be known and properly taken into account*".

An example of binary plot using ratios with a common element: The Th-Nb proxy (Pearce, 2008, *Lithos*)

Pearce (2008) has demonstrated the importance of the Th–Nb proxy for highlighting crustal input and hence distinguishing oceanic, non-subduction setting from subduction-related settings.

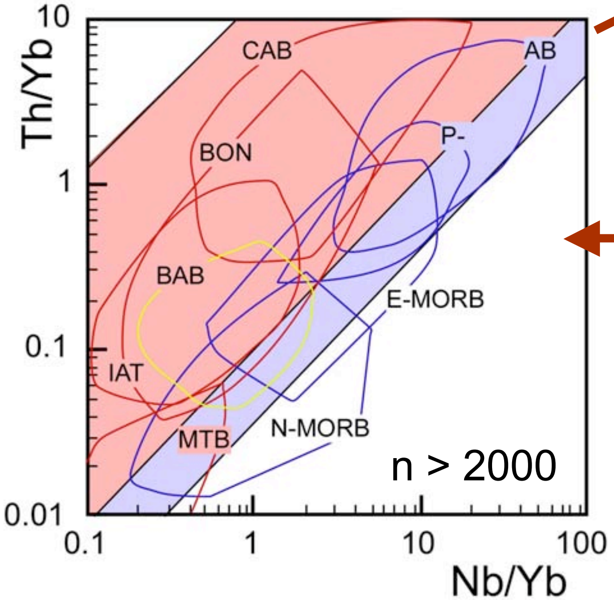


The Th-Nb proxy (Pearce, 2008, *Lithos*)

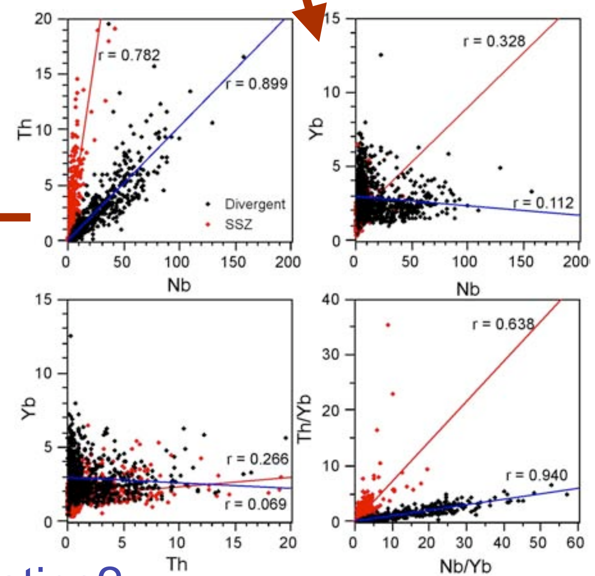


However, though increasingly popular, this diagram is far to be accurate

From Chayes (1949): plotting in one x/z vs. y/z graph different magmatic series having different (x, y, z) correlation coefficients and comparing them to each other is mathematically inconsistent.



Spurious correlations affect the results to variable and unpredictable extents



A couple of reflections:

- Do we really need using Nb e Th within “unpredictable” ratios?
- Can these elements be used as absolute measures for discriminating different tectonic settings?

Part 3

-The dataset and a review of the different types of ophiolitic basalts

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-The new proposal

Th-Nb Diagram

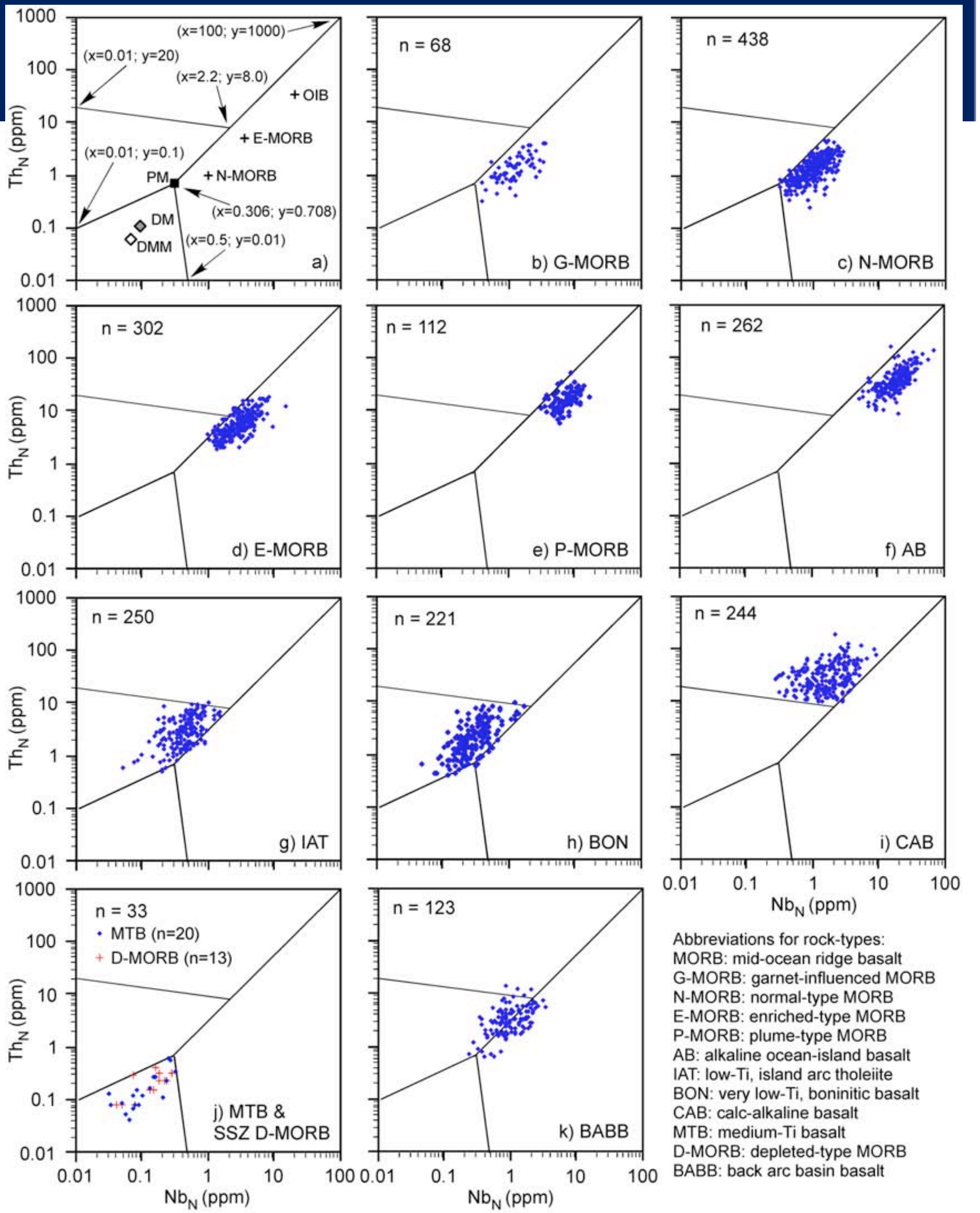
(preliminarily published by Saccani et al., 2011, *Lithos* and already used by other authors).

Nb & Th normalised to the N-MORB composition (Sun & McDonough, 1989).

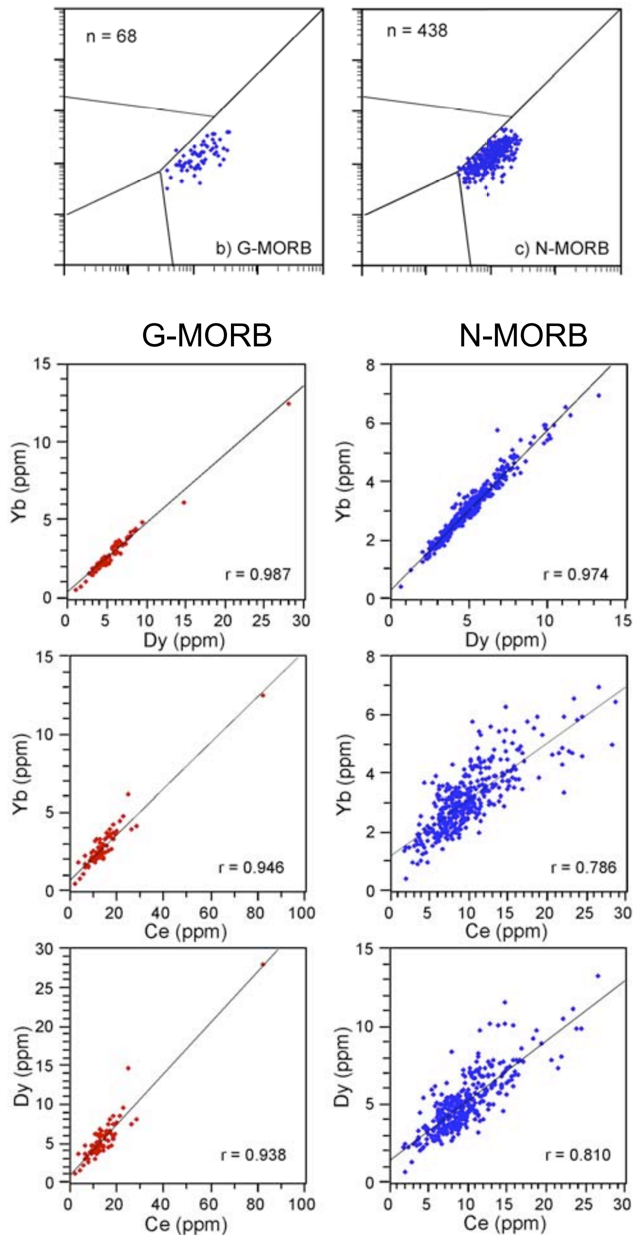
Why using normalised elements?

Pros:
-prompt identification of the degree of enrichment
-working with comparable numbers (as much as possible)
Cons:
-none

Misclassification rate <1% for every rock-type



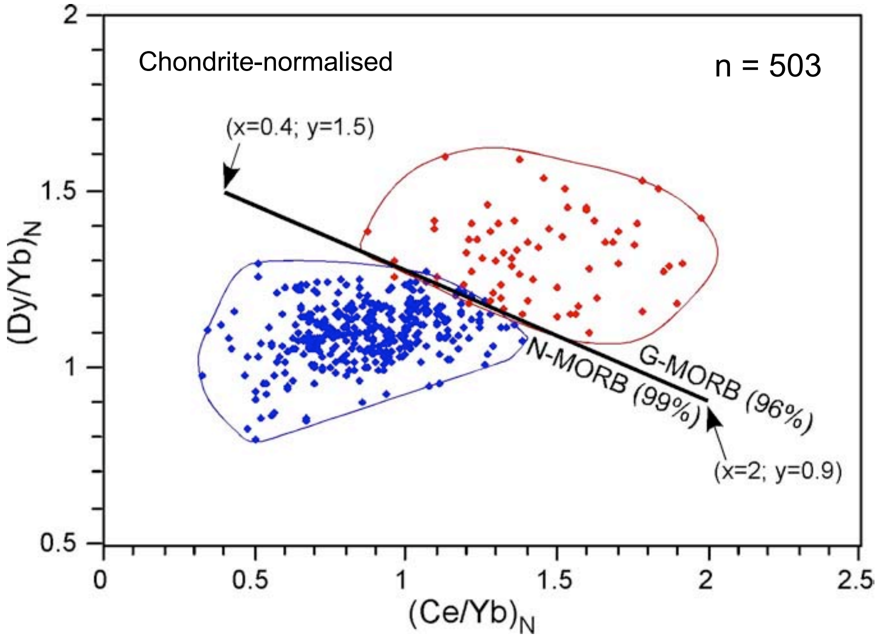
Discriminating G-MORB & N-MORB



LREE/HREE vs. MREE/HREE indicative of garnet signature

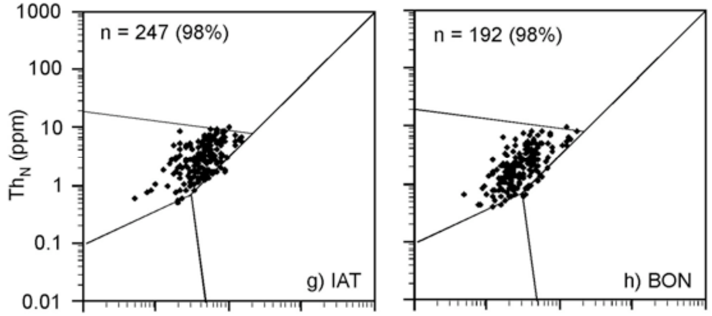
Element ratios are not influenced by spurious self-correlations

--> We CAN use element ratios



Misclassification rate: 1% for N-MORB
4% for G-MORB

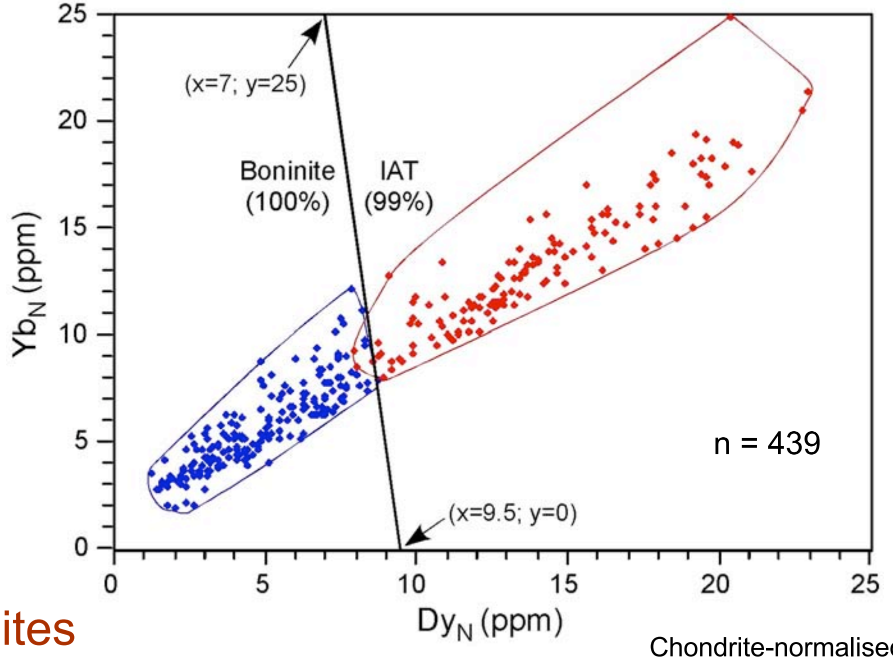
Discriminating IATs & Boninites



Any element ratio results in spurious self-correlations (not shown)

➠ We CANNOT use element ratios

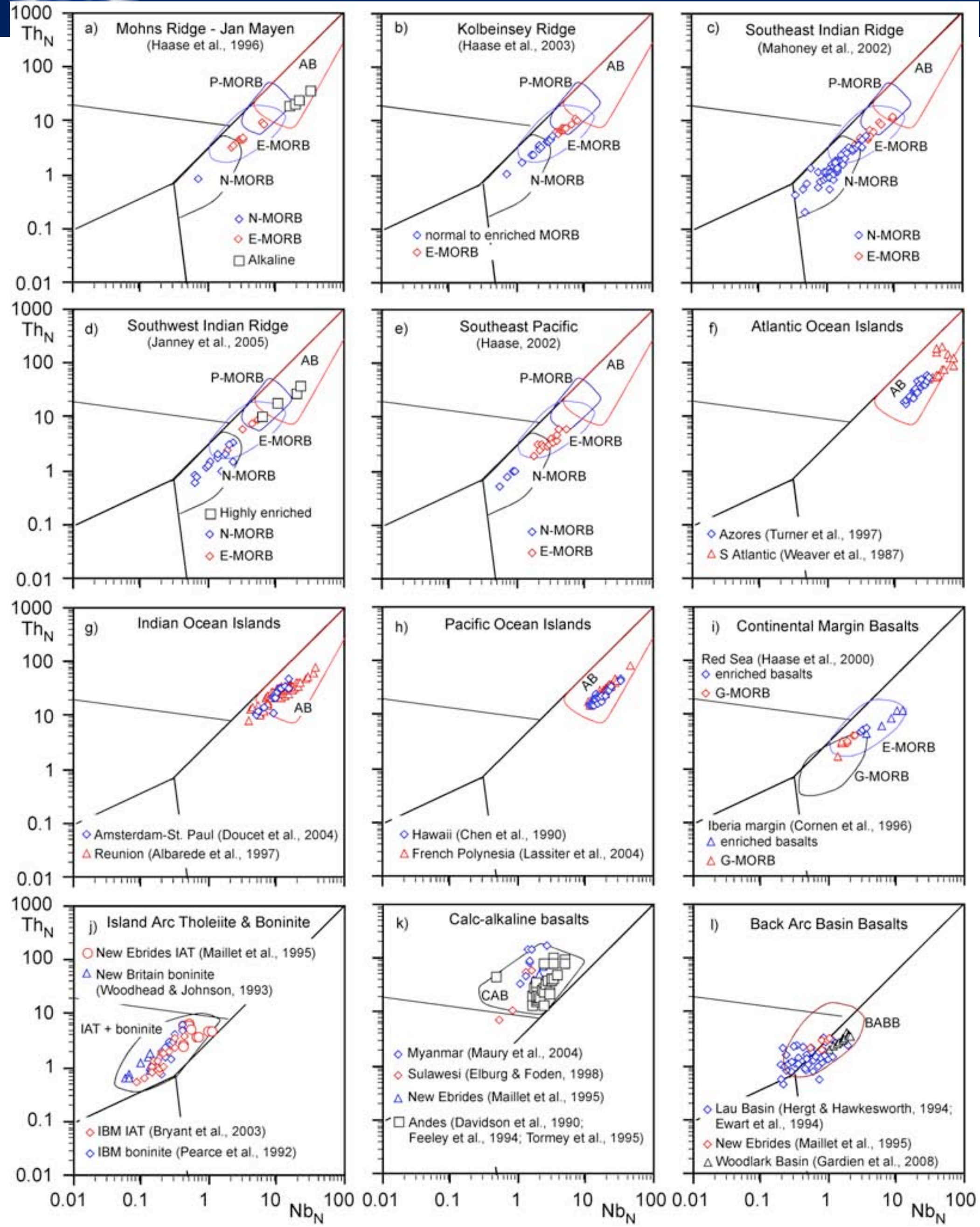
Therefore, simple variables are used.



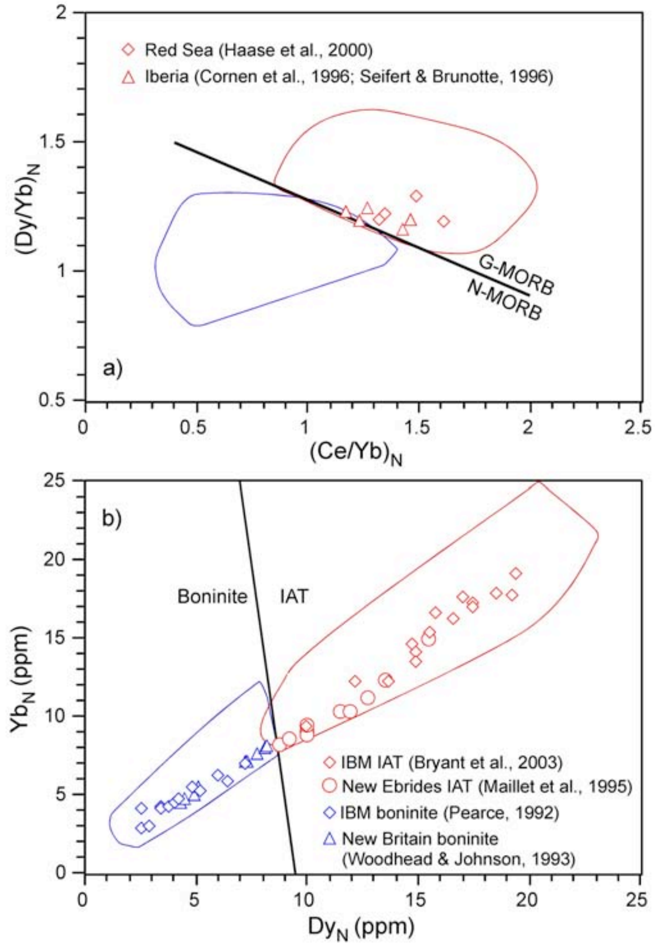
Chondrite-normalised

Misclassification rate: 0% for Boninites
1% for IAT

Testing the method with basalts from modern oceanic settings

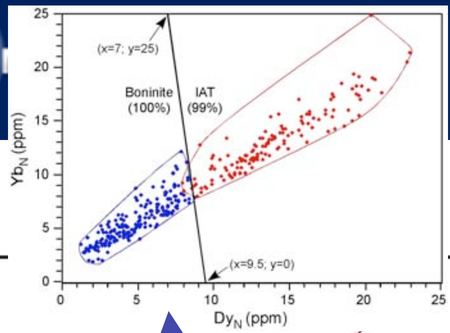


n ~560 basaltic rocks

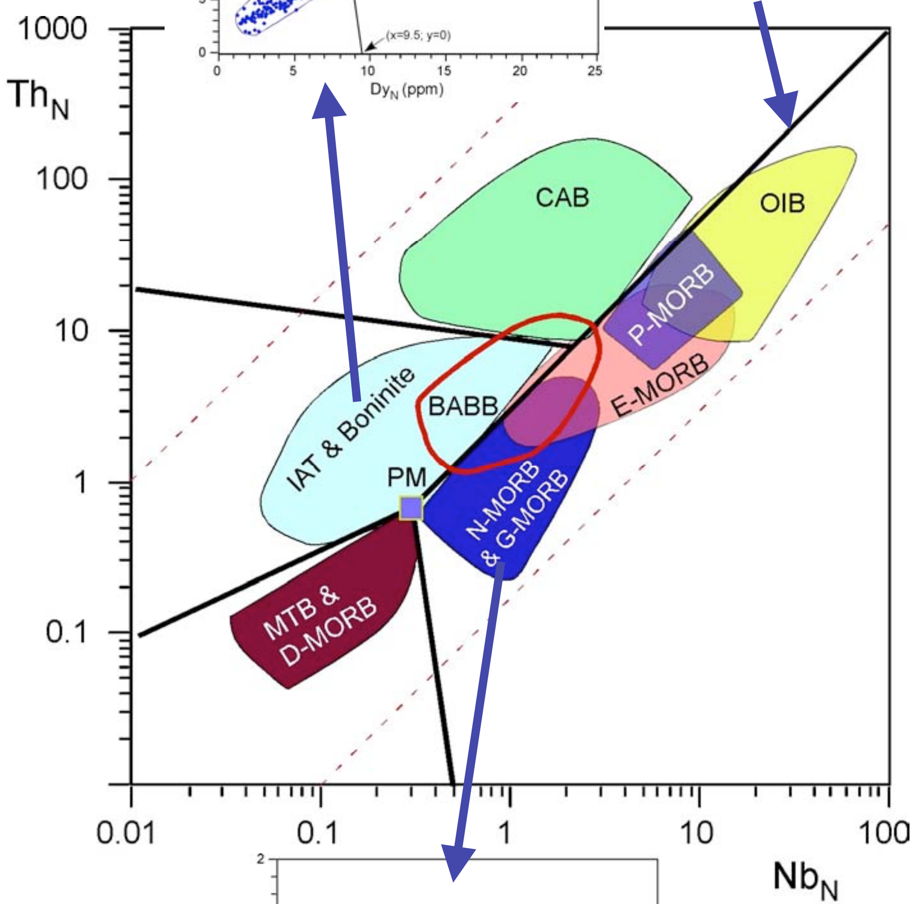


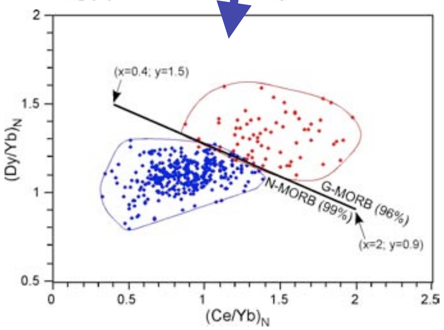
Misclassification rate = 0%
Except CAB (1%) & BABB (5%)

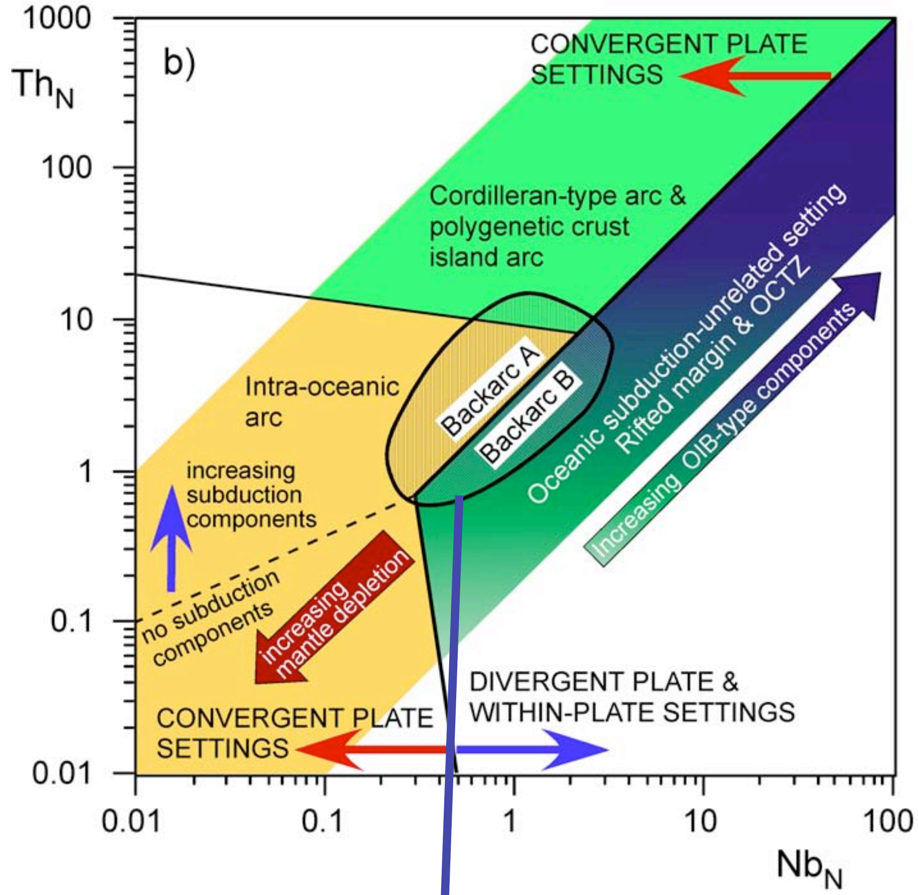
Tectonic Discrimination



Constant $Kd_{(Th)}$ / $Kd_{(Nb)}$ ratio (McKenzie &O'Nions, 1991)







BABB & other basalts not discriminated
However, BAB roughly subdivided into immature (A) and mature (B)

Th-Nb & Ce-Dy-Yb systematic - CONCLUSIONS

PROS:

-The Nb-Th diagram discriminates oceanic basalts (MOR & seamount) from SSZ basalts with <1% misclassification rate (based on ~2600 samples)
➟ 14%-49% in previous discrimination diagrams

-within SSZ basalts, it discriminates between MTB, (IAT+boninite) and CAB. That is: nascent forearc or ridge-subduction interaction, intra-oceanic island arc, cordilleran-type arc with <1% misclassification rate (based on ~850 samples)
➟ 16%-22% IAT & boninite and 4%-61% CAB in previous discrimination diagrams
➟ MTB not included in previous discrimination diagrams

The Dy-Yb diagram discriminates between boninite and IAT basalts with <0.5% misclassification rate (based on ~490 samples)
➟ 20% in previous discrimination diagrams (only Shervais, 1982)

- G-MORB (Alpine-type / Hiberia-type continental rift) can be discriminated from N-MORBs with <2.5% misclassification rate (~570 samples)
➟ G-MORB not included in previous discrimination diagrams

Th-Nb & Ce-Dy-Yb systematic - CONCLUSIONS

LIMITATIONS:

-The Nb-Th diagram does not allow a distinction between basalts generated in the garnet-facies and spinel-facies mantle to be made. Other geochemical indicators must be used in combination for this (e.g., see Pearce, 2008)

-The Nb-Th diagram does not accurately discriminate within the ”oceanic basalt family” (N-, E-, P-MORB e OIB). There are obvious petrological reasons for this. Other geochemical indicators must be used in combination

-The Nb-Th diagram does not discriminate back arc basin basalts (BABB). There are obvious petrological reasons for this. Other geochemical indicators must be used in combination.
Nonetheless, once the BABB nature is recognized, it allow a rough distinction between immature back arc (SSZ components) and mature back arc (relatively primitive mantle source)

Thank you very much for your attention

Emilio Saccani
E-mail: sac@unife.it
Home page: http://docente.unife.it/emilio.saccani

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Where to find the related publication:
http://dx.doi.org/10.1016/j.gsf.2014.03.006
Saccani E. (2014) A new method of discriminating different types of post-Archean ophiolitic basalts and their tectonic significance using Th-Nb and Ce-Dy-Yb systematics. *Geoscience Frontiers*