Miocene to Recent migration of arc volcanism in NW Sumatra: the consequence of ridge subduction?

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Department of Geosciences,
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2015.03.03 NCU

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MS (NTNU)- Experimental petrology
PhD (NTU)- Volcanology and Petrology
Postdoc (NTU)- Geochemistry
→ Sumatra
→ Northern Luzon Arc
→ NTVZ

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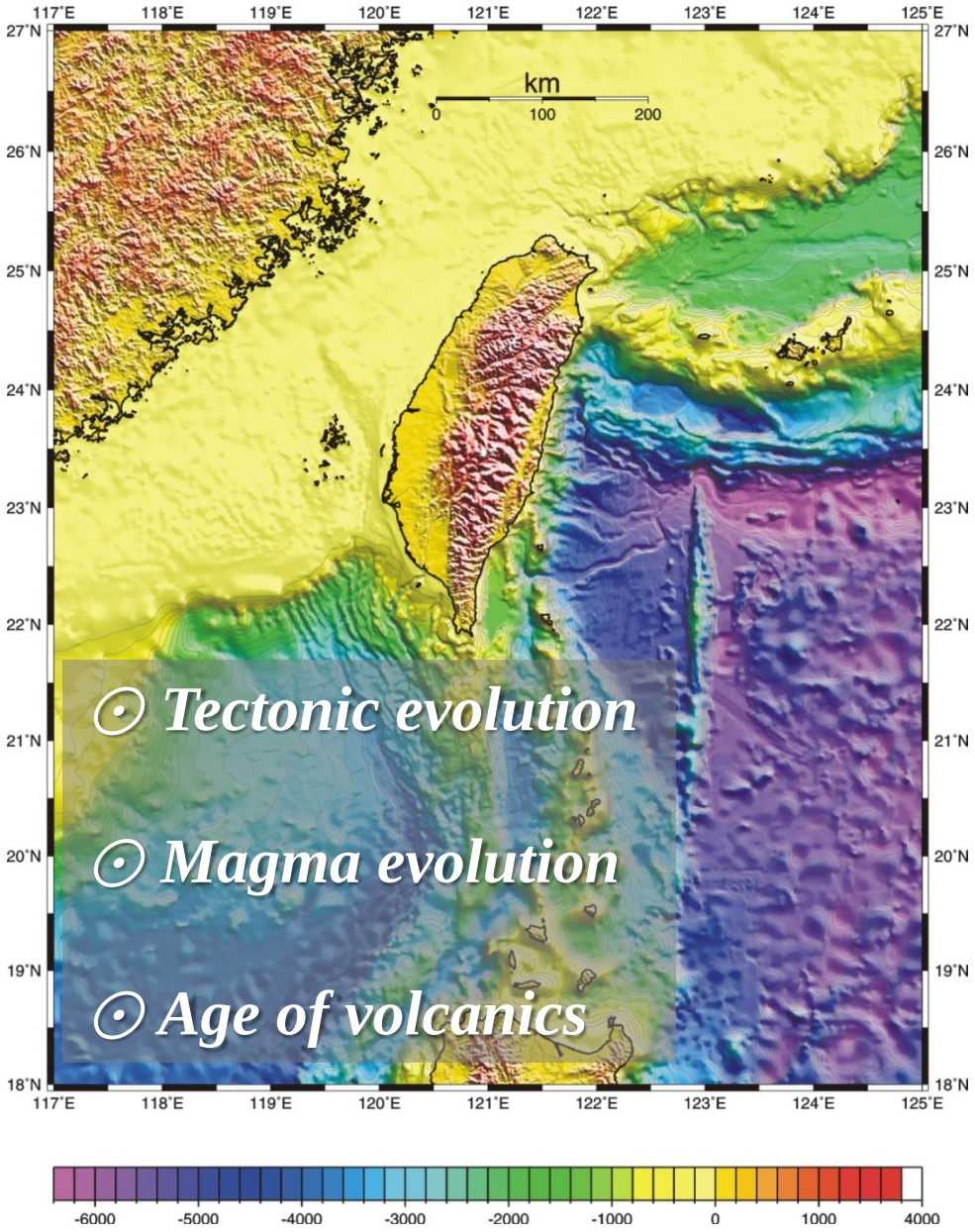
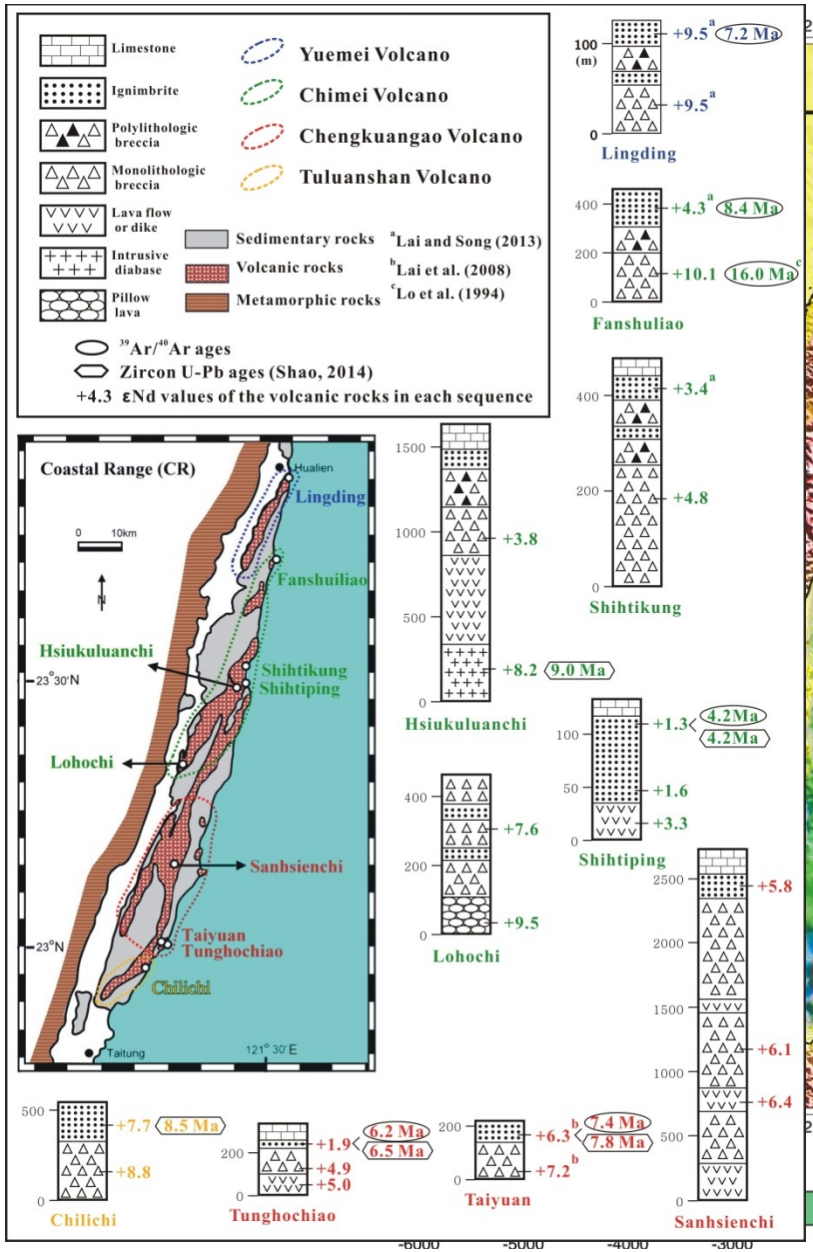
Outline

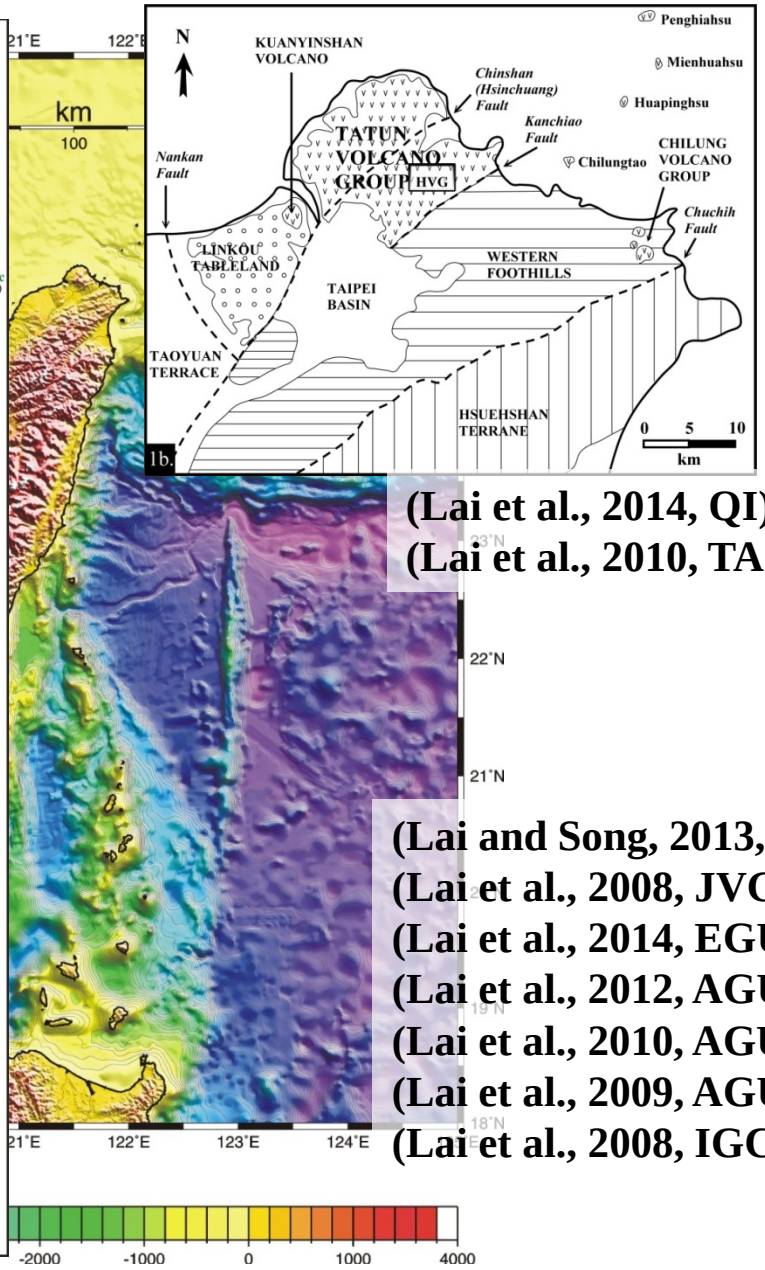
- ⊙ **Why we went so far away to study Sumatra?**
- ⊙ **Structural, tectonic evolution and volcanism in Sumatra.**
- ⊙ **Geochronology and geochemistry works in NW Sumatra.**
- ⊙ **Migration of volcanism with time in NW Sumatra.**
- ⊙ **Present and future works.**

In the beginning…



In the beginning…



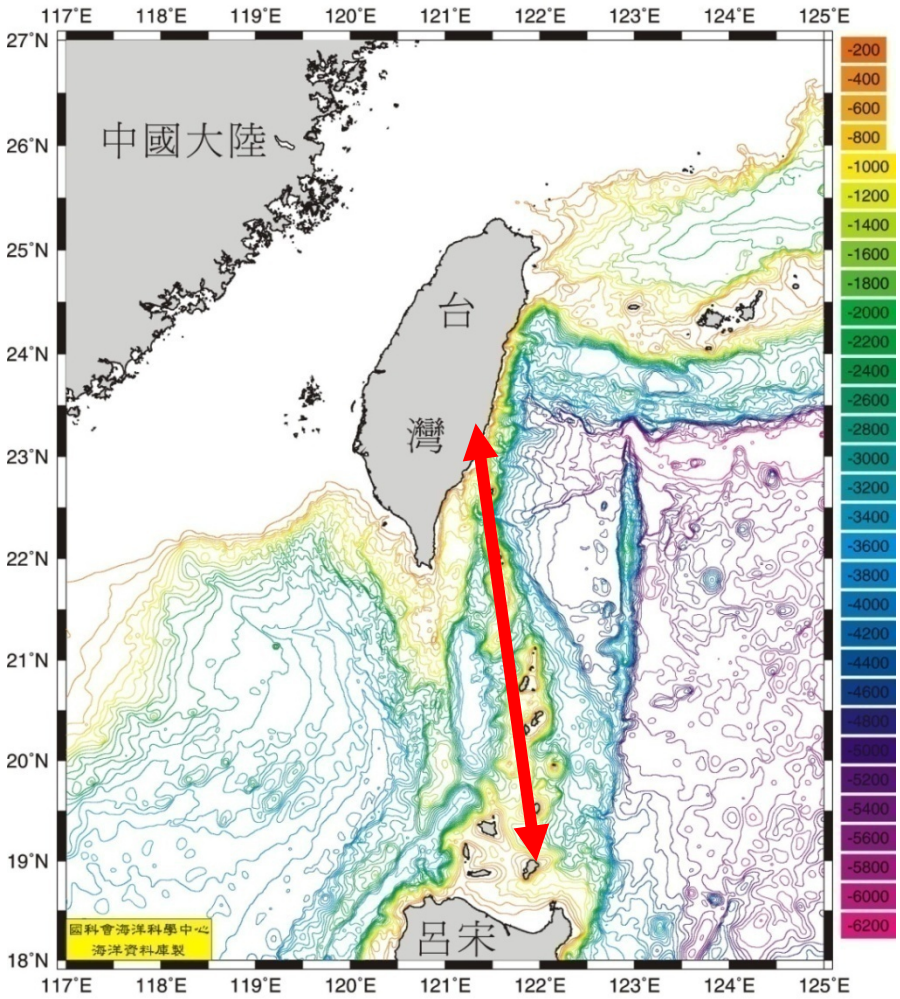


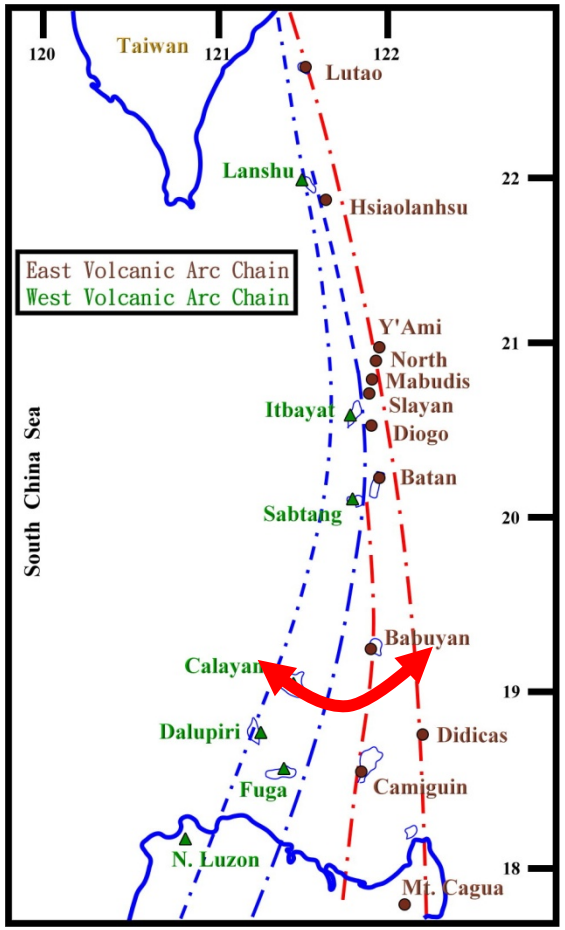
(Lai et al., 2014, QI)
(Lai et al., 2010, TAO)

(Lai and Song, 2013, JAES)
(Lai et al., 2008, JVGR)
(Lai et al., 2014, EGU)
(Lai et al., 2012, AGU)
(Lai et al., 2010, AGU; WPGM)
(Lai et al., 2009, AGU)
(Lai et al., 2008, IGCP-524)

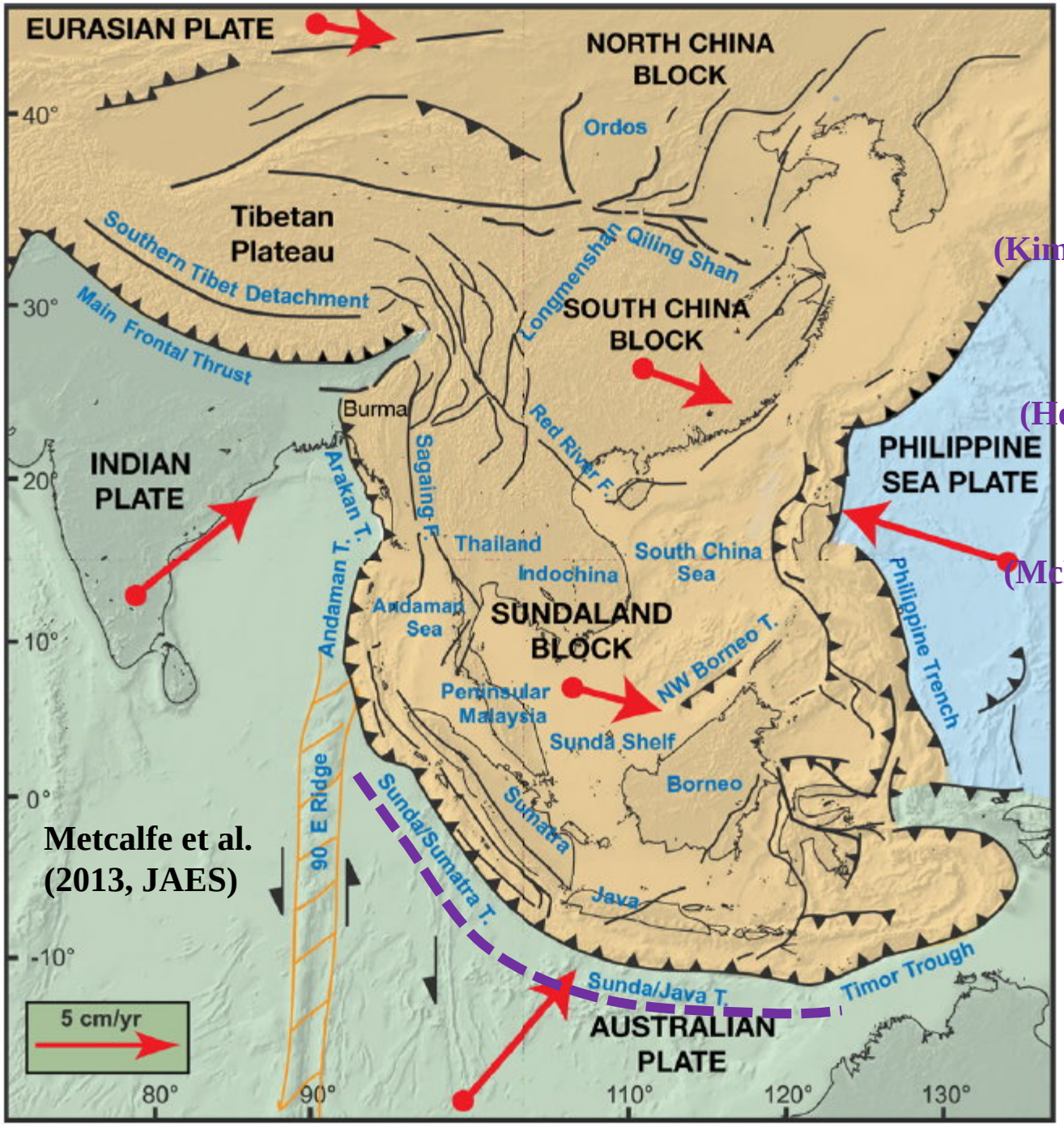
Geochemical variations along-/across- arc

Along-arc geochemical variations can be found in the Northern Luzon Arc.
(Chen et al., 1990, GCA; Song, 1990)





Across-arc geochemical variations are observed between two arc chains.
(Yang et al., 1996, Tectonophysics)



Metcalfe et al. (2013, JAES)

Other examples

NE Japan Arc
(Kimura and Yoshida, 2006, JP)

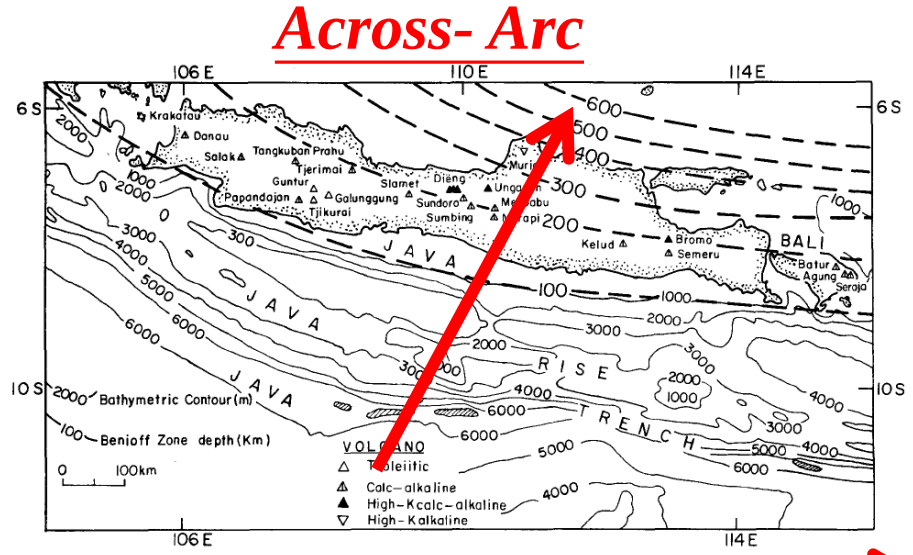
Izu-Bonin Arc
(Hochstaedter et al., 2001, G^3)

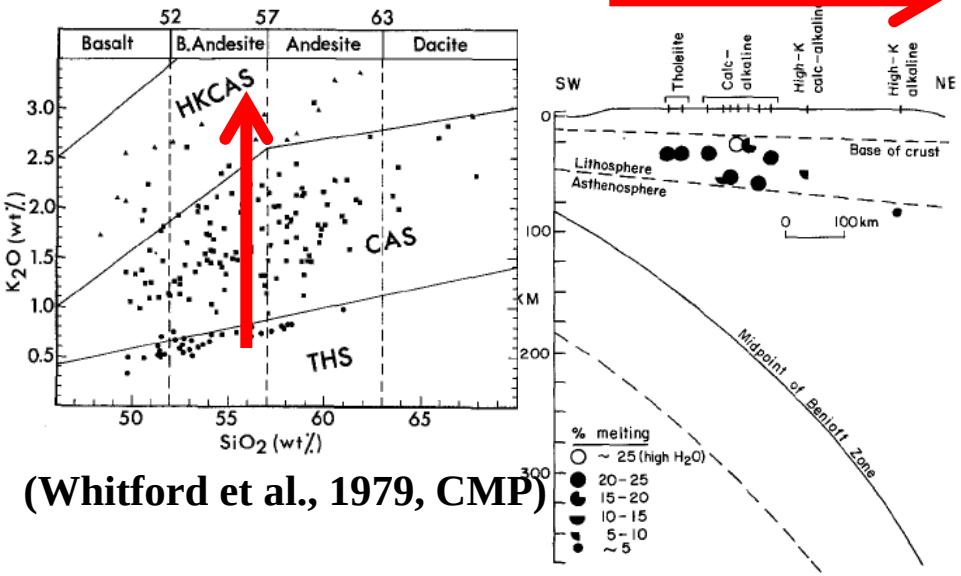
Northern Luzon Arc
(McDermott et al., 1993, CMP; Fourcade et al., 1994, CG)

Southern Luzon Arc
(de Boer et al., 1980, Tectonophysics)

Banda Arc
(Vroon et al., 1993, JGR; 2001, GCA)

Sunda Arc: Java





(Whitford et al., 1979, CMP)

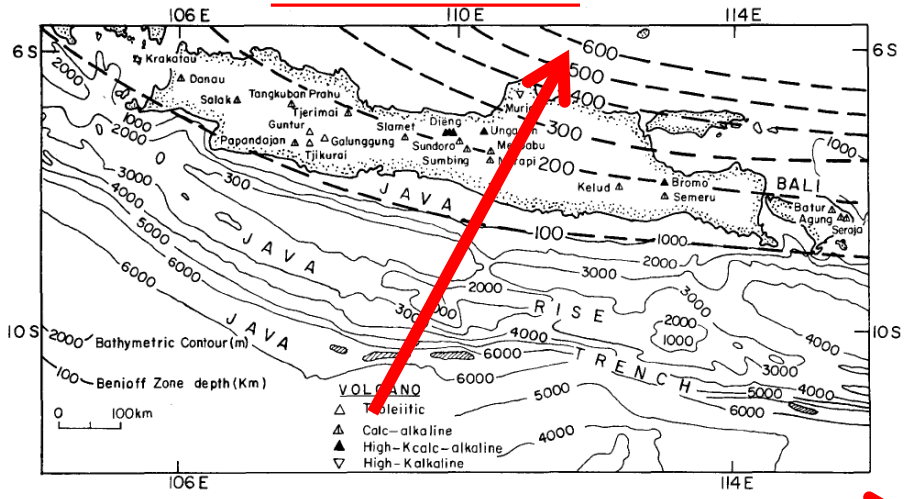
Low degrees of partial melting

→ enriched in incompatible elements (K, Ba, Sr, U, Th, LREEs)

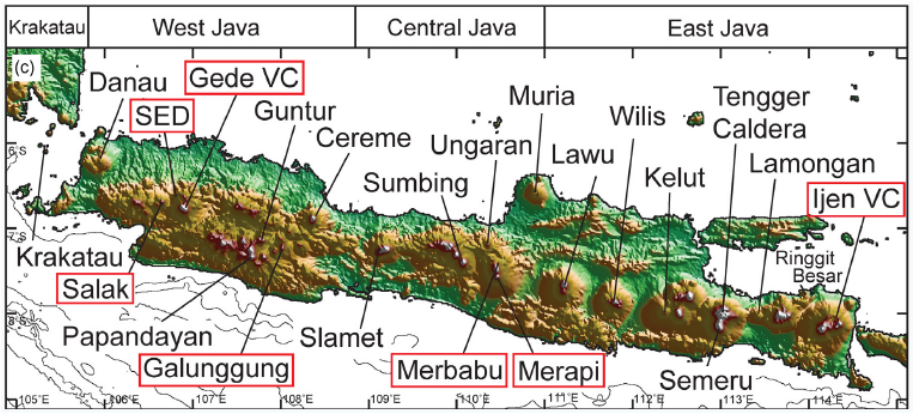
不相(共)容元素 = 親岩漿元素

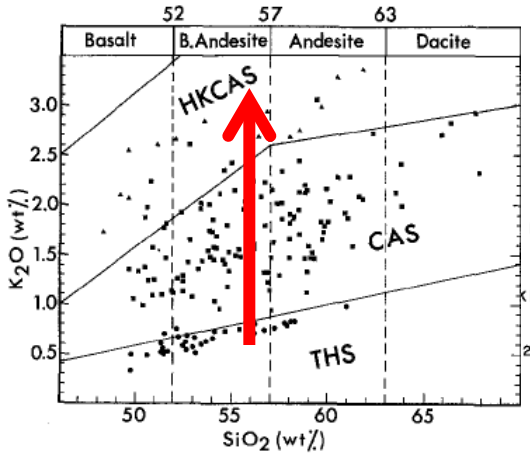
Sunda Arc: Java

Across- Arc

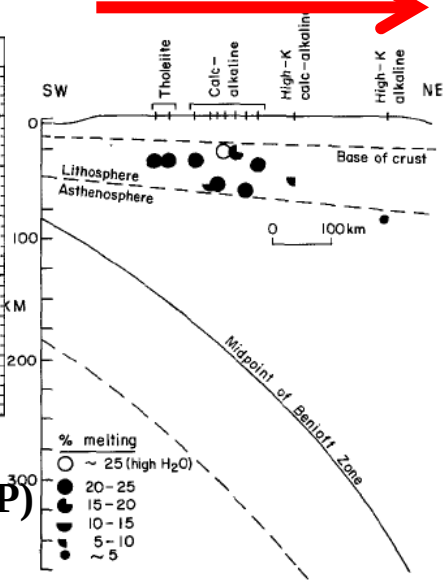


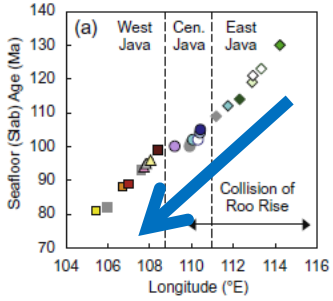
Along- Arc



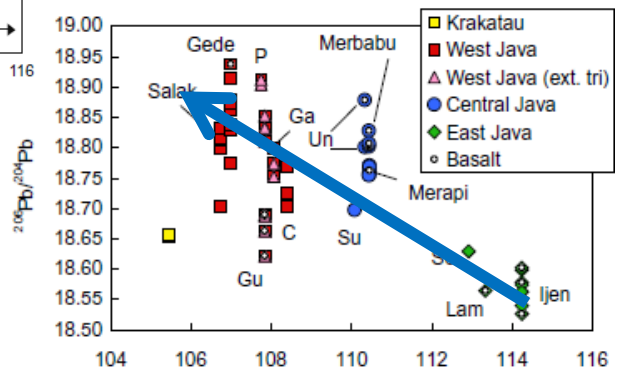


(Whitford et al., 1979, CMP)



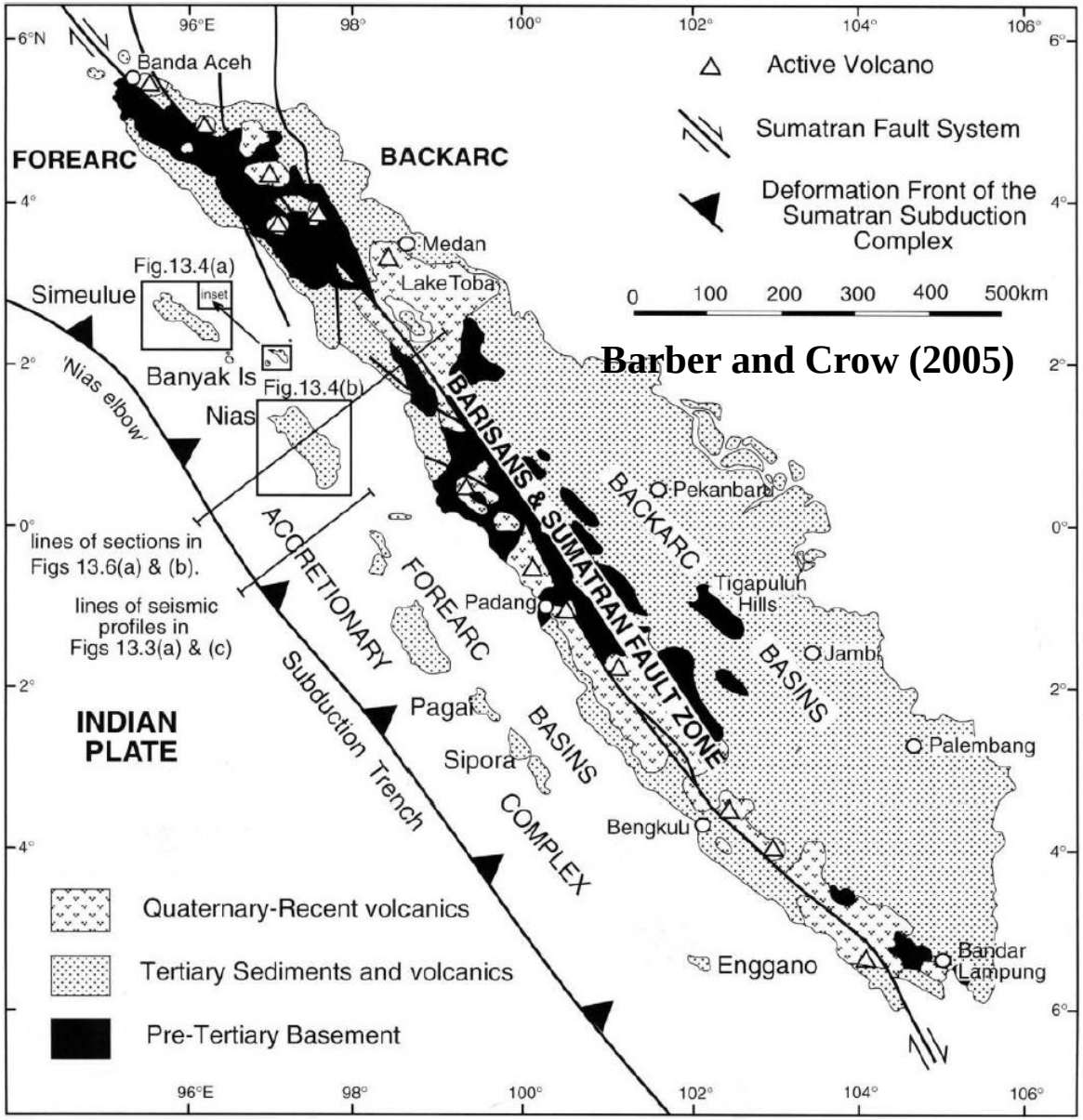


↓ crustal material contamination



(Handley et al., 2014, GCA)

Structural map of Sumatra



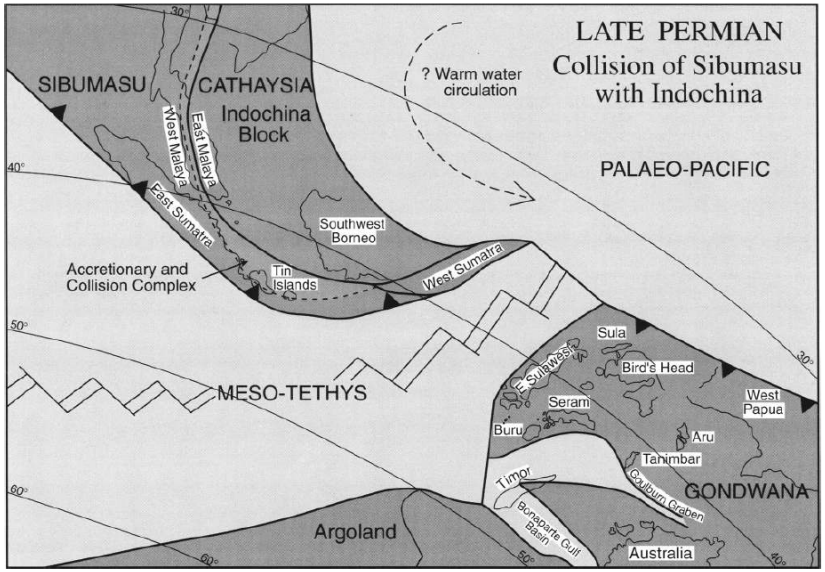
→ **Arc-trench system**

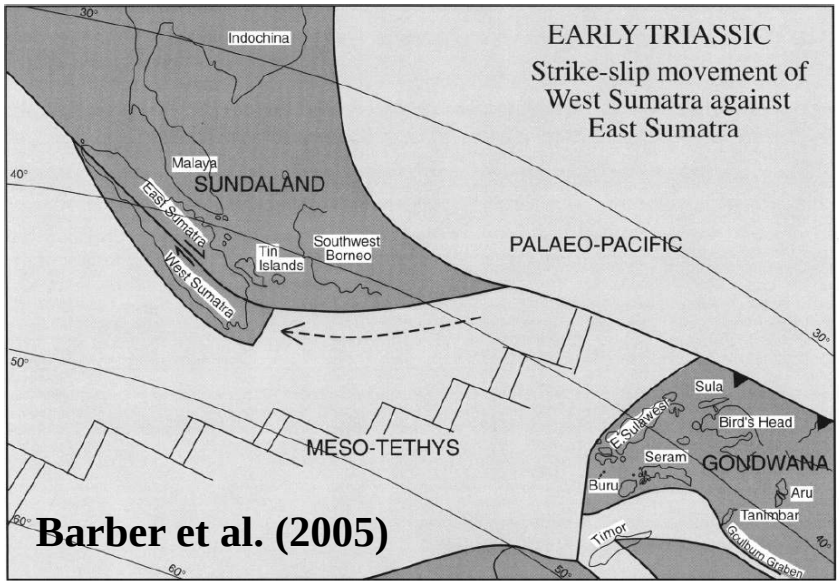
→ **Sumatra fault zone**

→ **Volcanism**

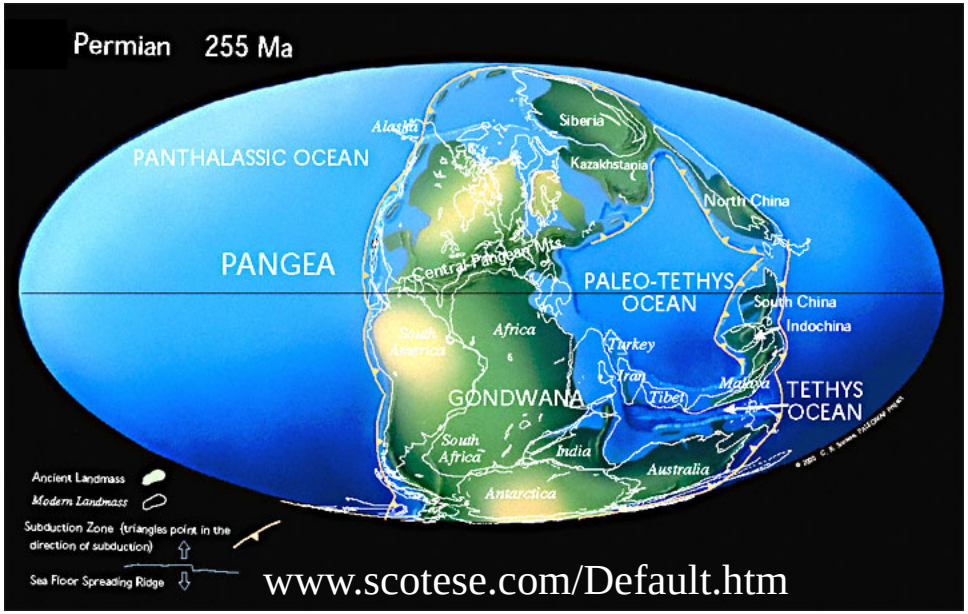
→ **Toba volcano**

Tectonic evolution in Sumatra





Barber et al. (2005)



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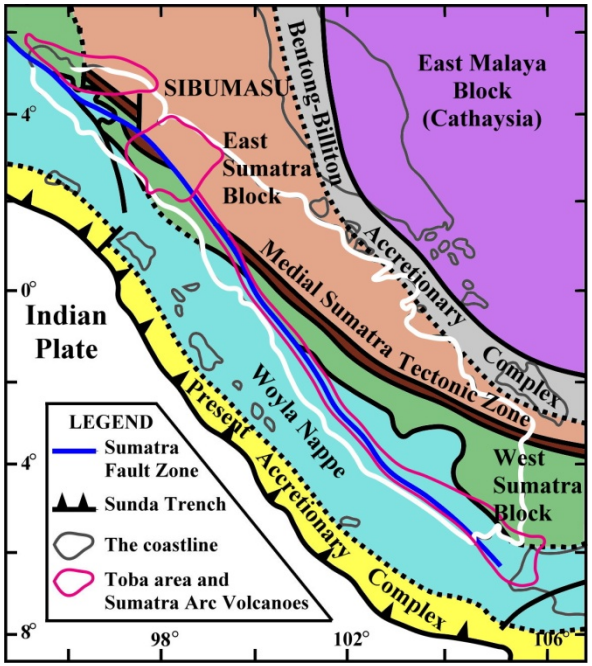
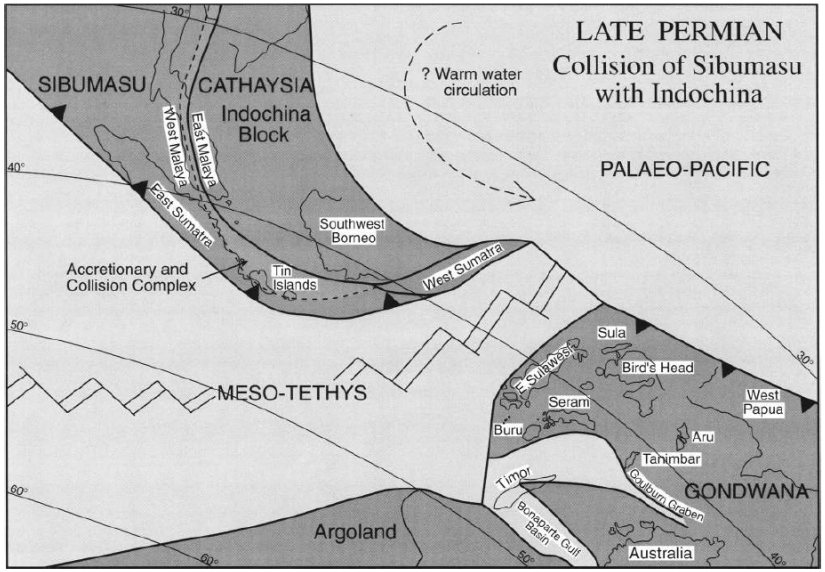
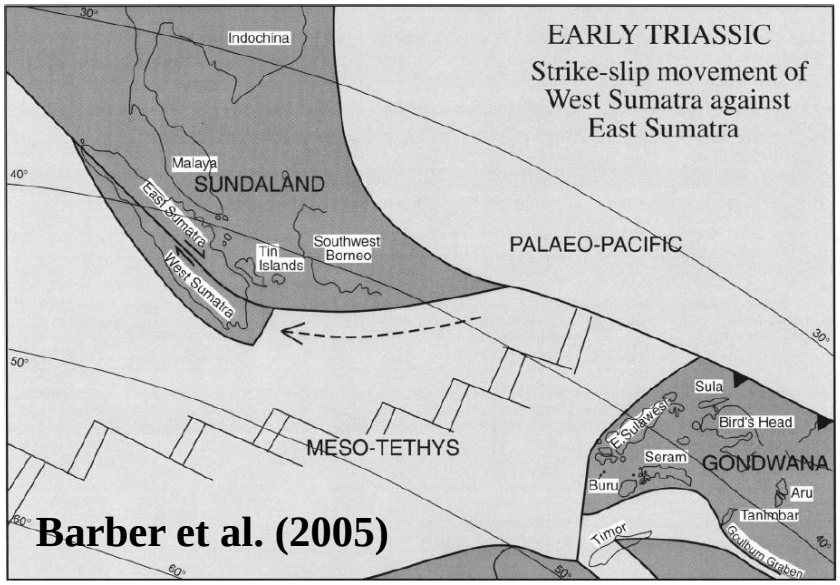
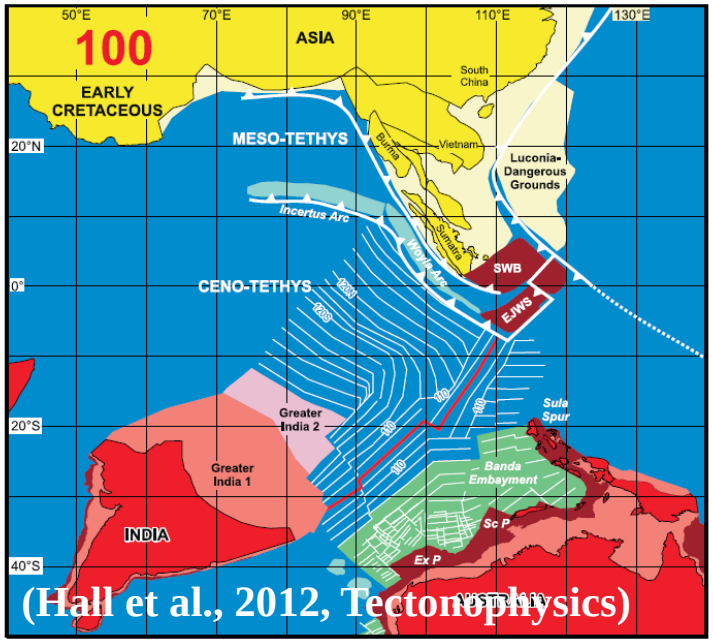


Tectonic evolution in Sumatra





Barber et al. (2005)



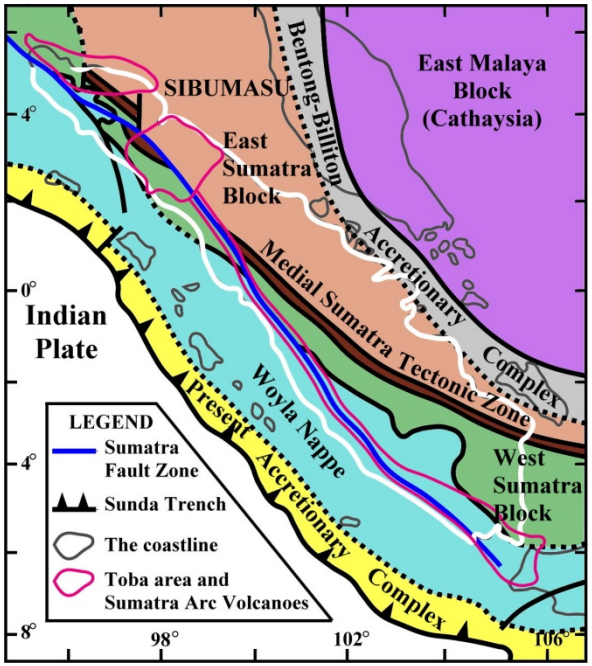
(Hall et al., 2012, Tectonophysics)

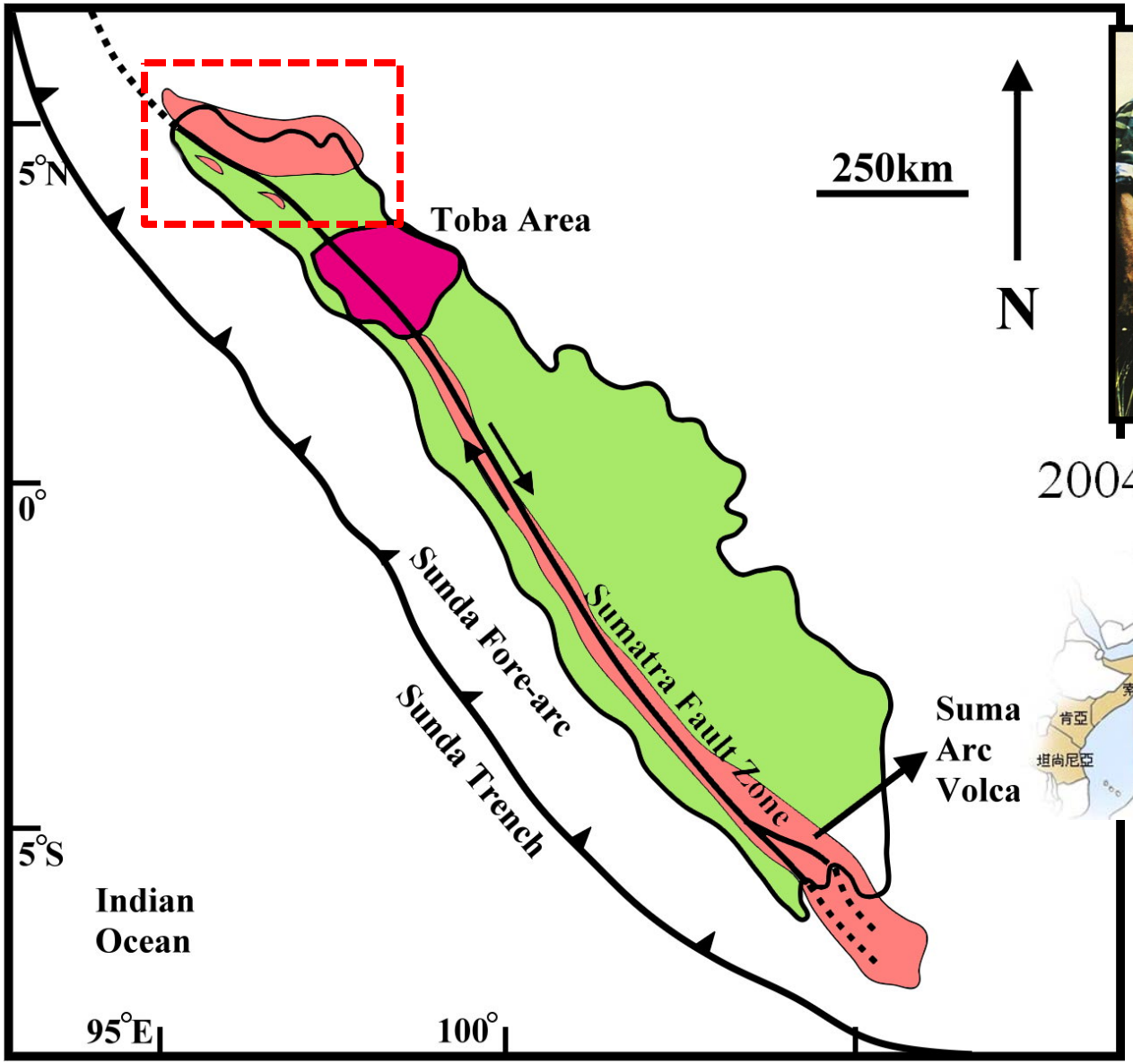
Three tectonic blocks in the Sumatra Island:

East Sumatra

West Sumatra

Woyla





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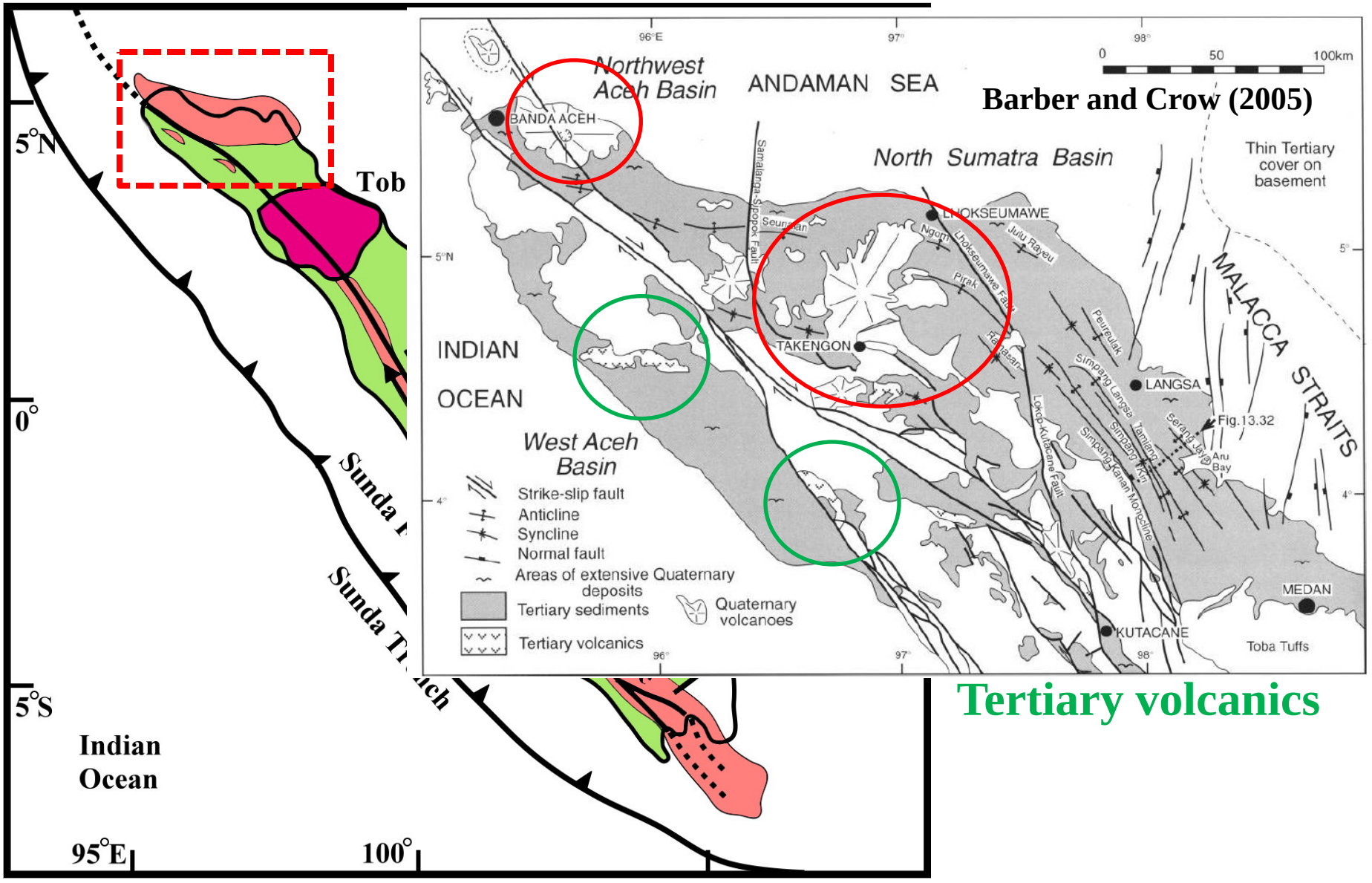
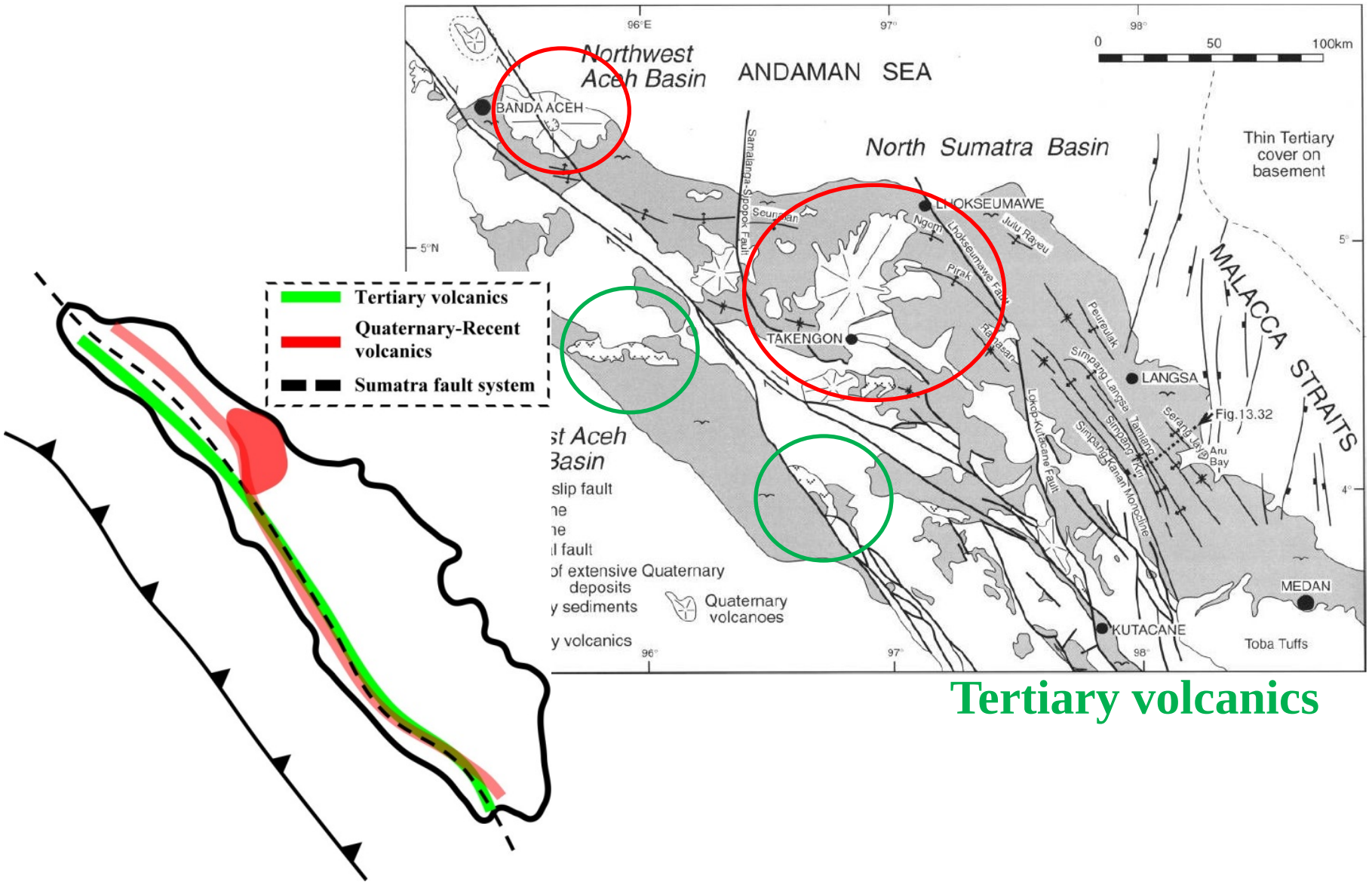
Quaternary volcanoes

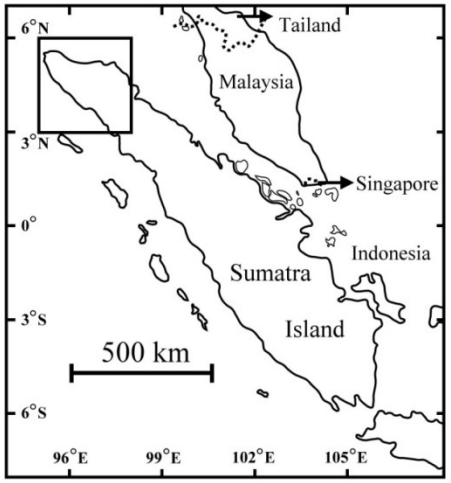


Tertiary volcanics

Quaternary volcanoes



Tertiary volcanics

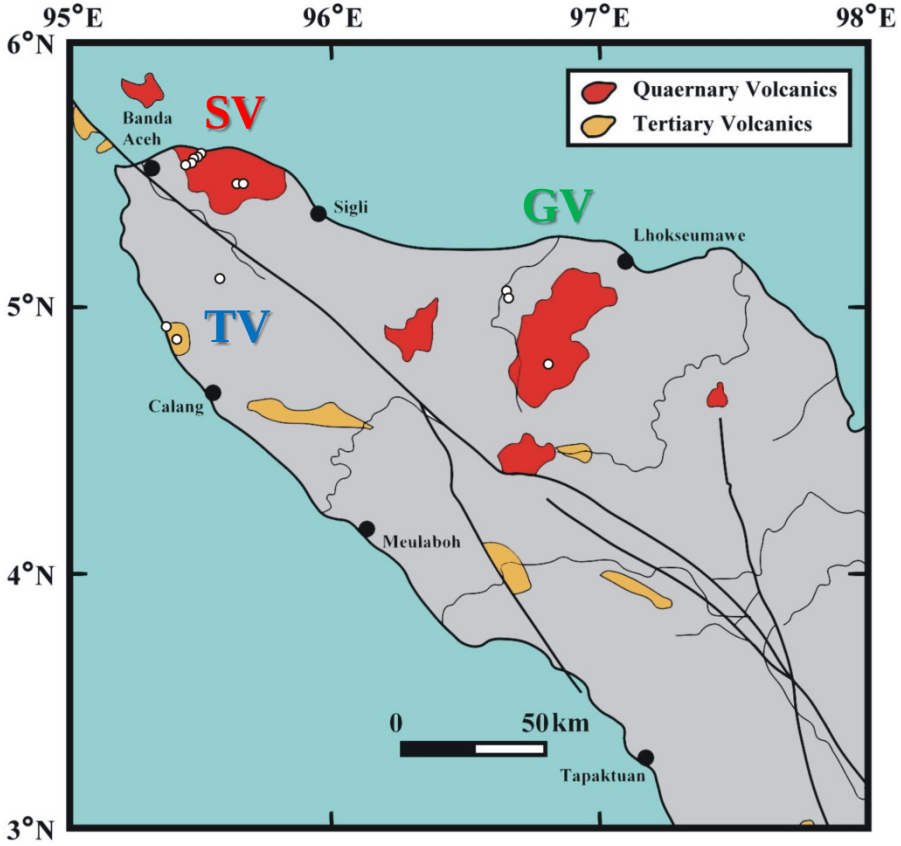


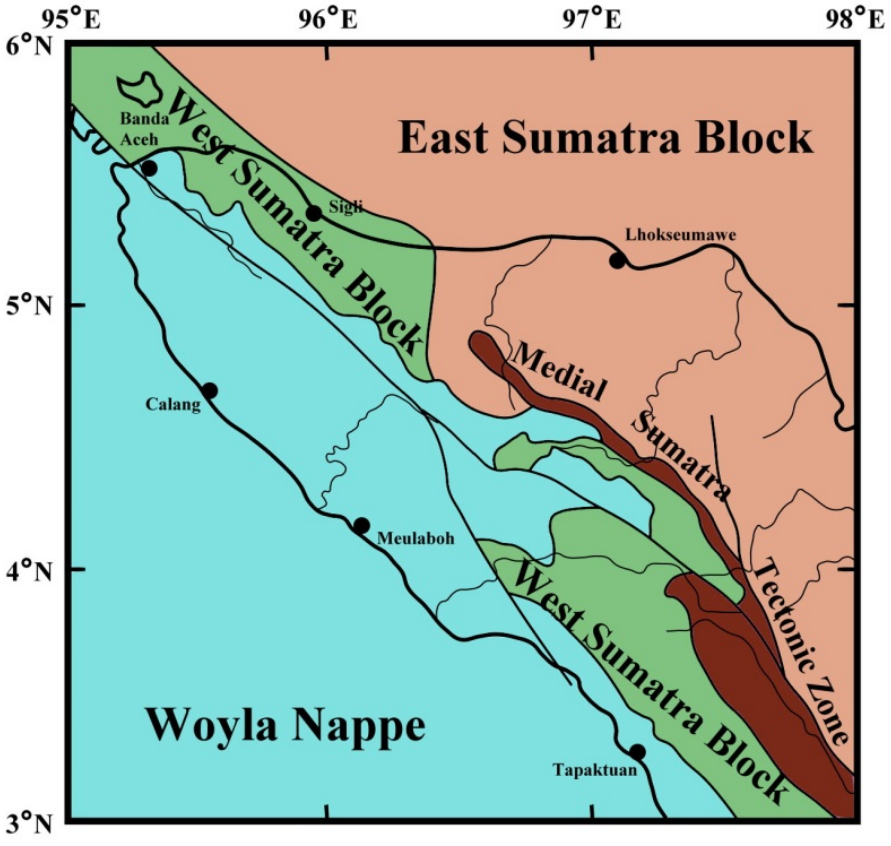
Sample collection

Geureudong volcano (GV) → East Sumatra Block

Seulawah volcano (SV) → West Sumatra Block

Tertiary volcanic rocks (TV) → Woyla Nappe





Zircon U-Pb geochronology

The U-Pb system

$^{238}U \longrightarrow ^{234}U \longrightarrow ^{230}Th \longrightarrow ^{226}Ra \longrightarrow \ldots ^{210}Pb \longrightarrow ^{206}Pb$

4.5×10^9 yrs 2.5×10^5 yrs 7.6×10^4 yrs 1.6×10^3 yrs 22 yrs

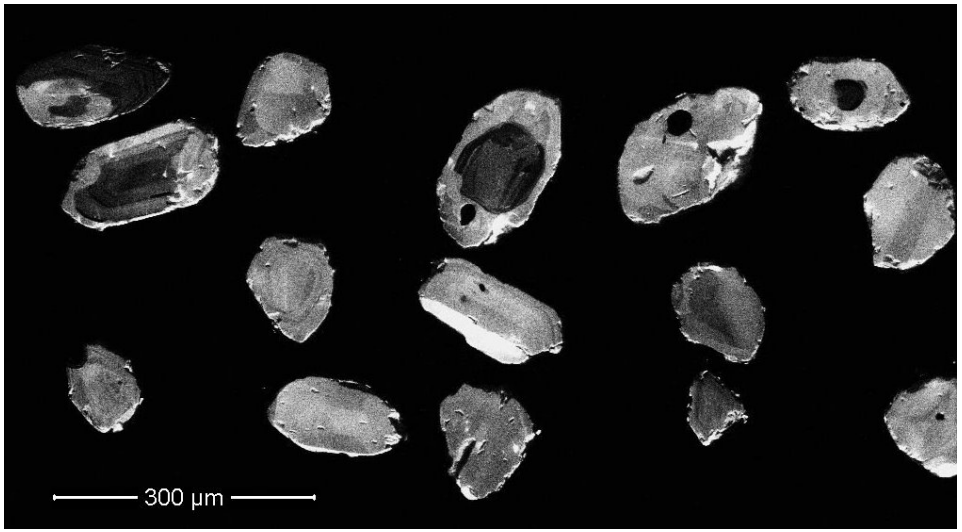
$^{235}U \longrightarrow ^{231}Pa \longrightarrow ^{227}Ac \longrightarrow \ldots ^{207}Pb$

0.7×10^9 yrs 3.4×10^3 yrs 22 yrs

Why zircon?

widespread
robust
emplacement temperature
low common Pb
high U, Th contents
.....

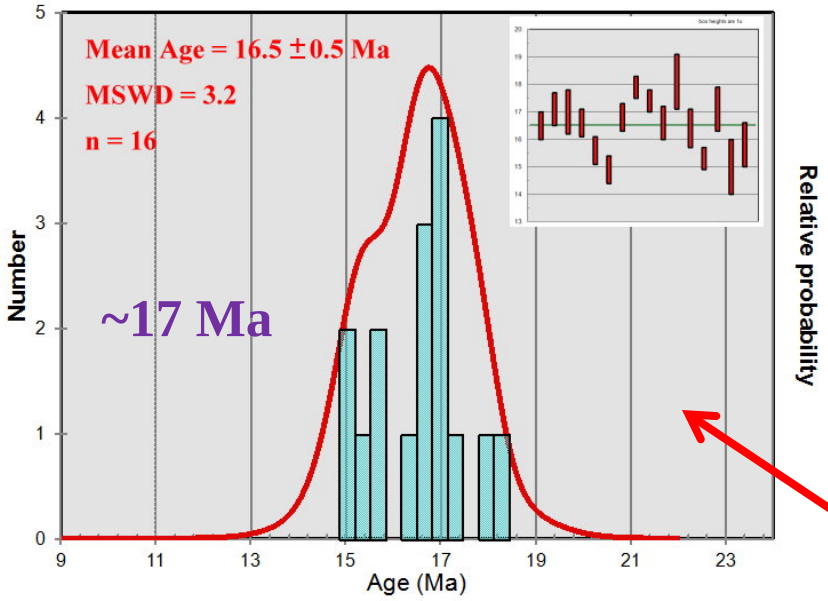
(Cherniak and Watson, 2003)

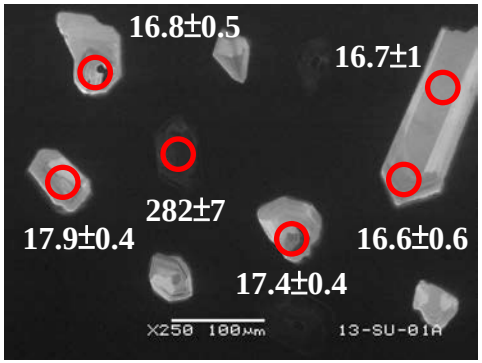


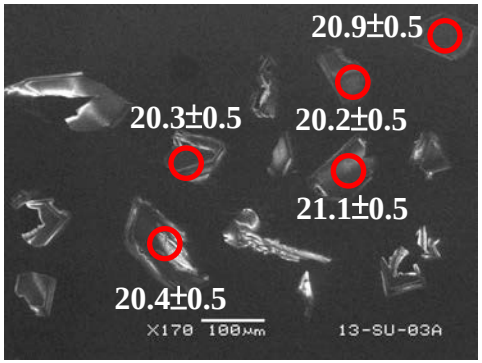
Cathodoluminescence image (CL image)

Age + structure = history (Corfu et al., 2003)

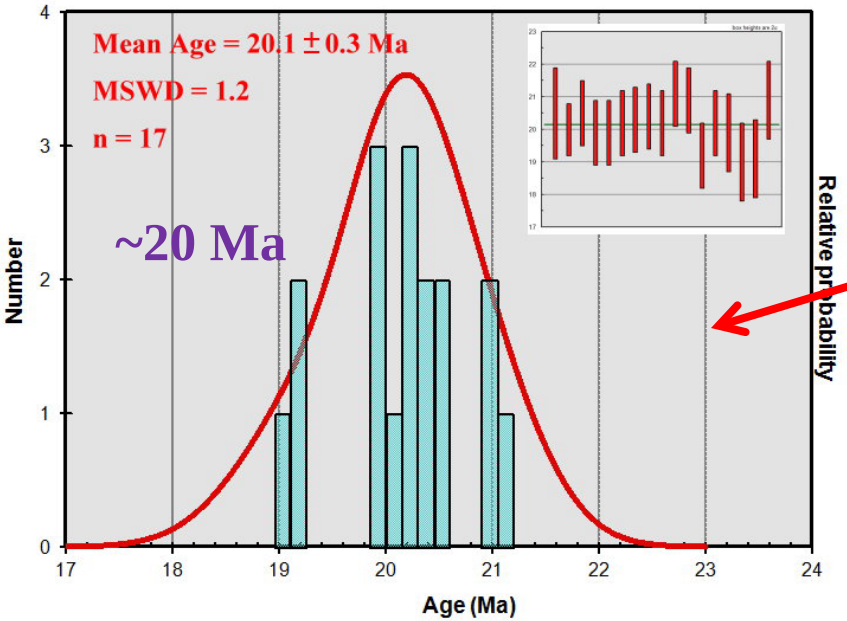
Results: Zircon U-Pb dating (Tertiary volcanic rocks)

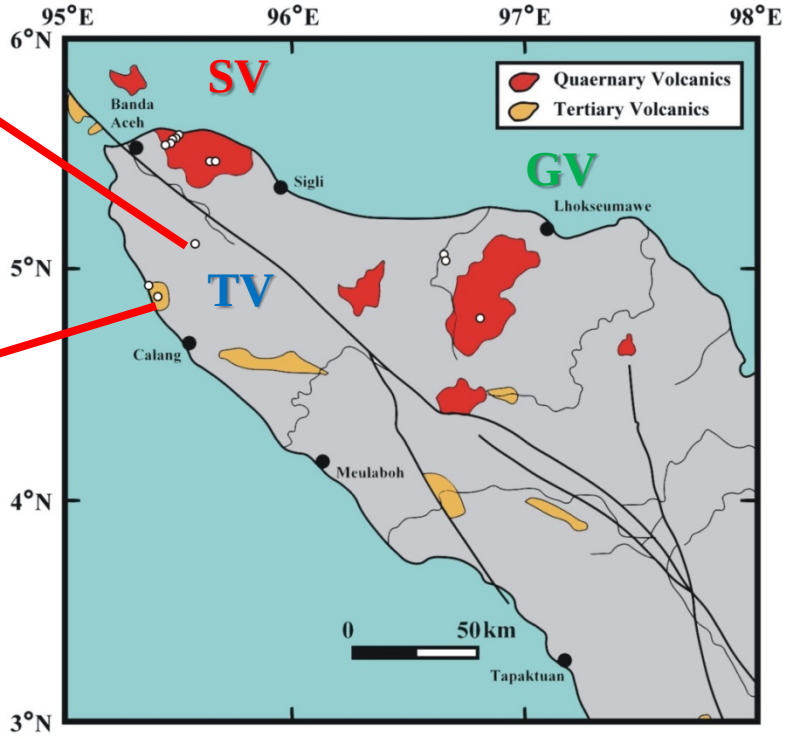






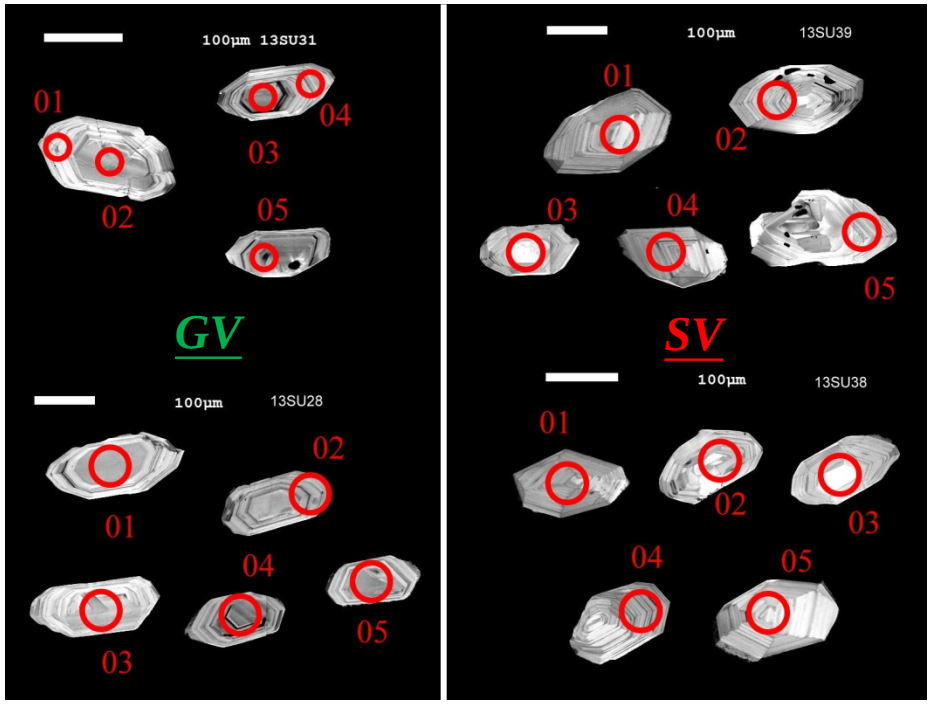
CL images of zircons



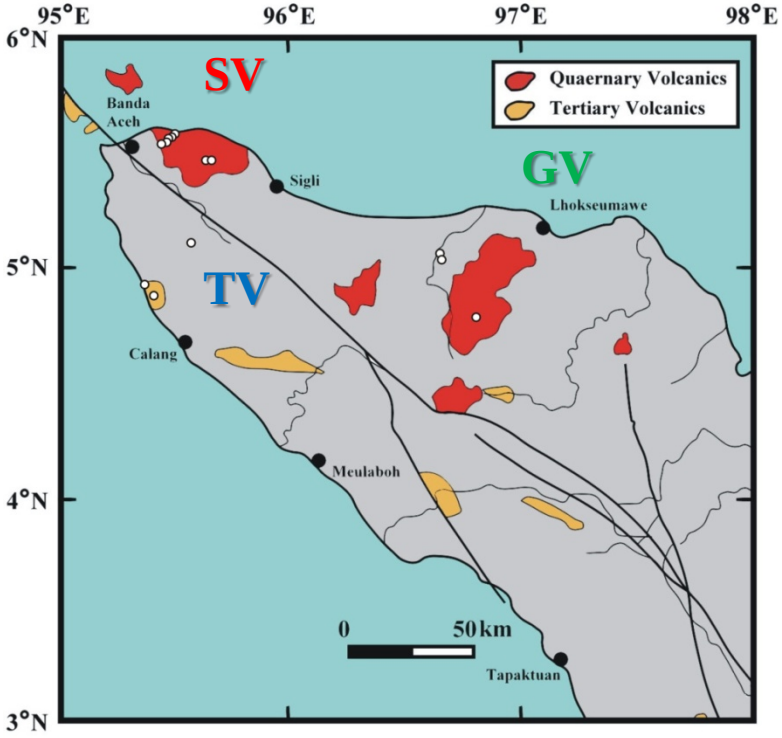


Results: Zircon U-Pb dating (Quaternary volcanoes)

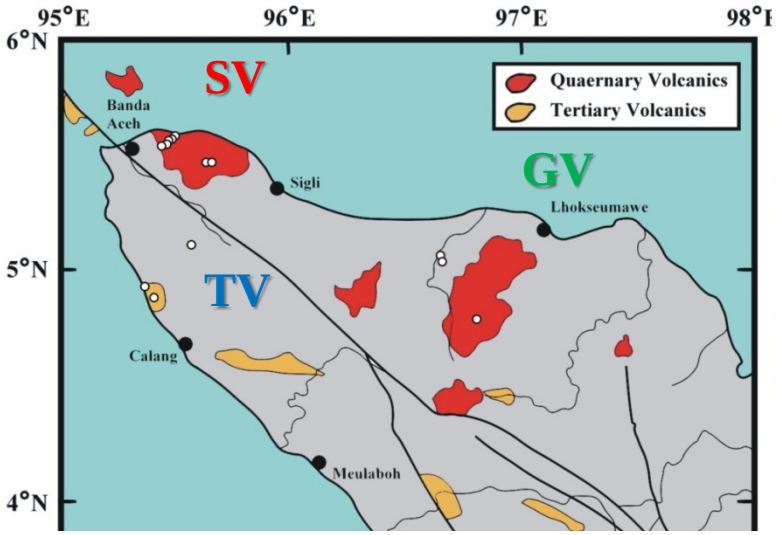
0.03 to 0.24 Ma
(magmatic zircons dating in Beijing)

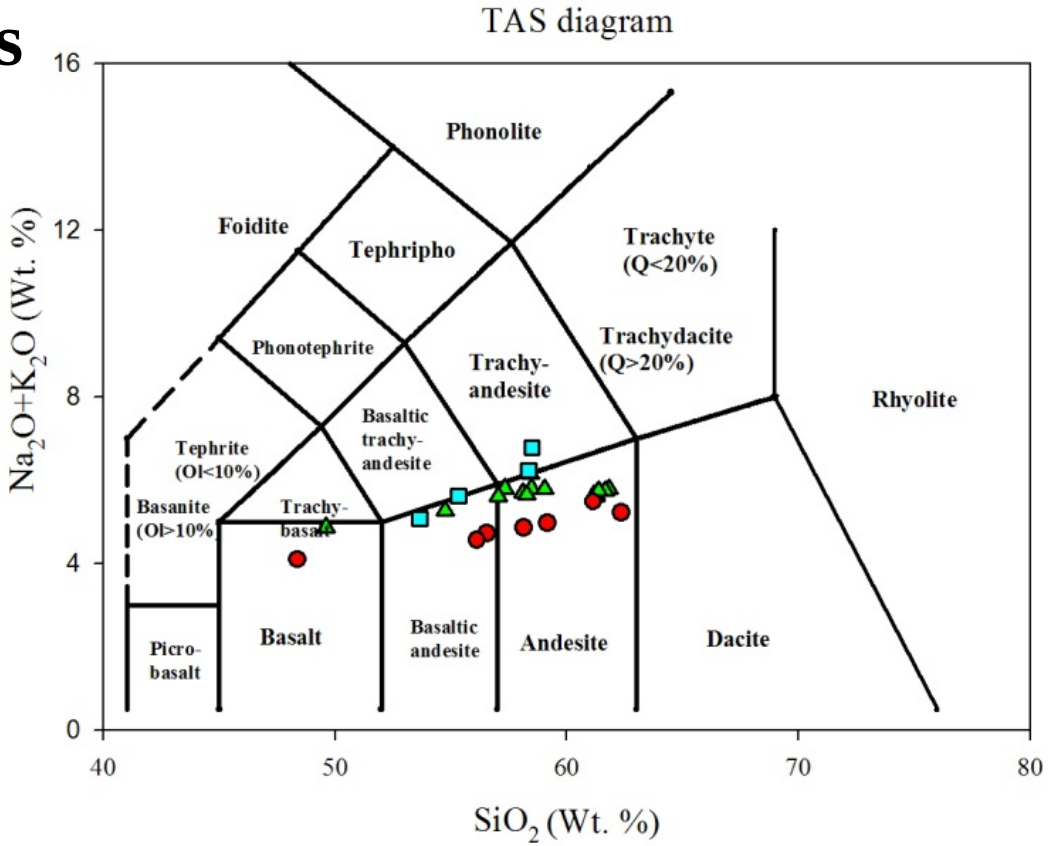


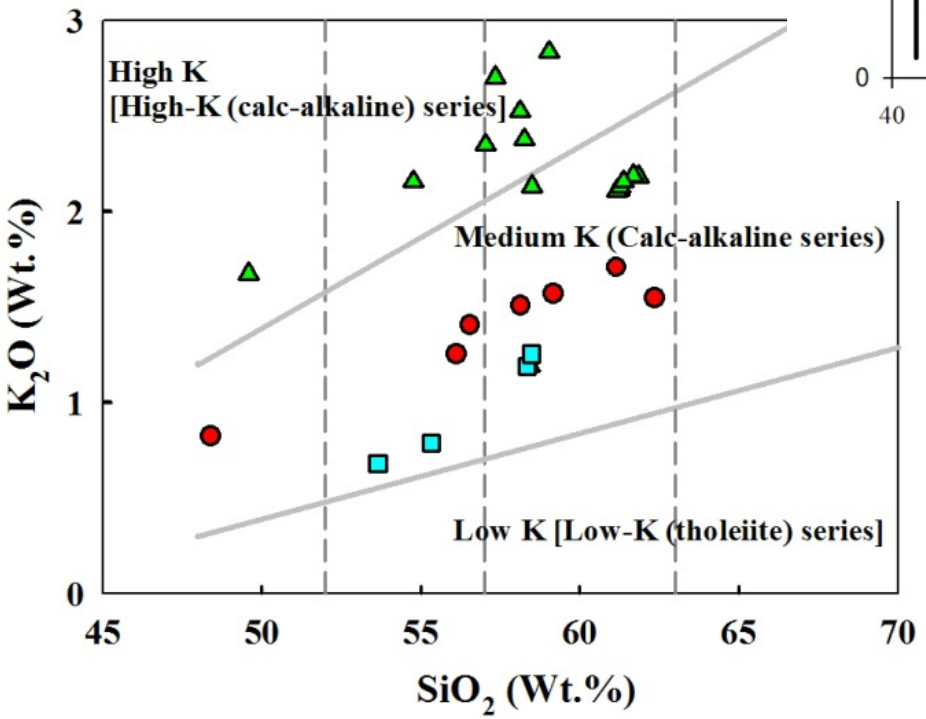
CL images of zircons



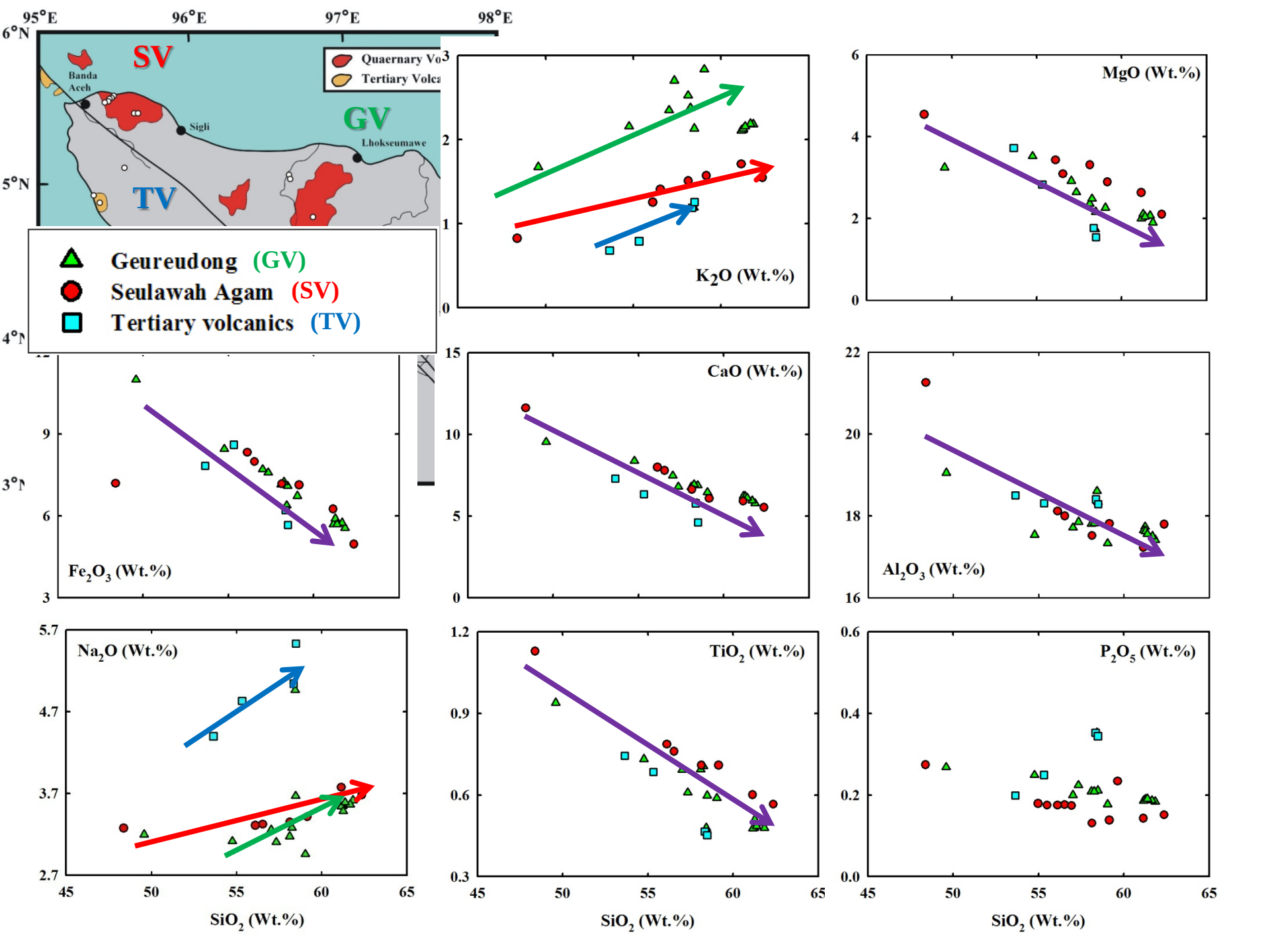
Results: Major elements



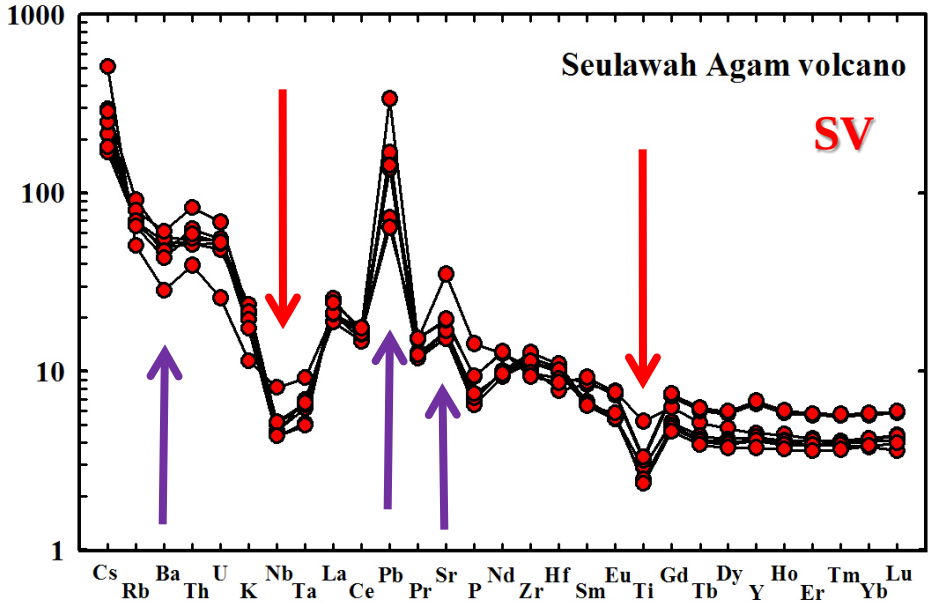


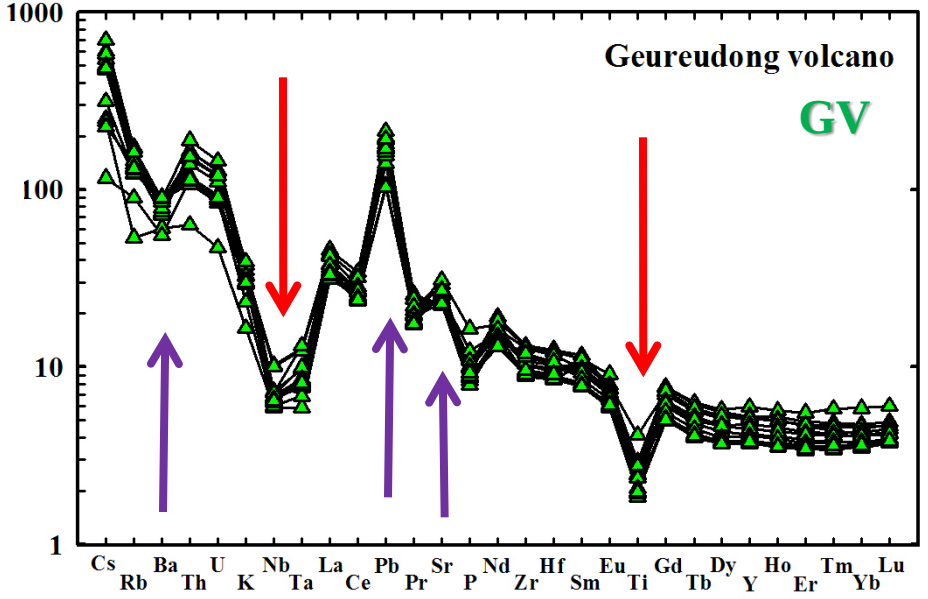


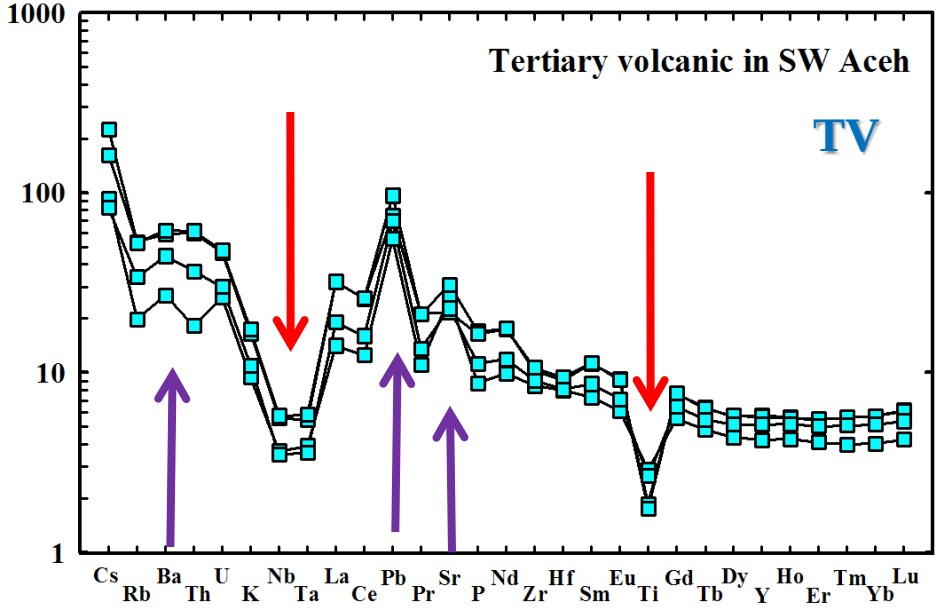
Geureudong (GV)
Seulawah Agam (SV)
Tertiary volcanics (TV)

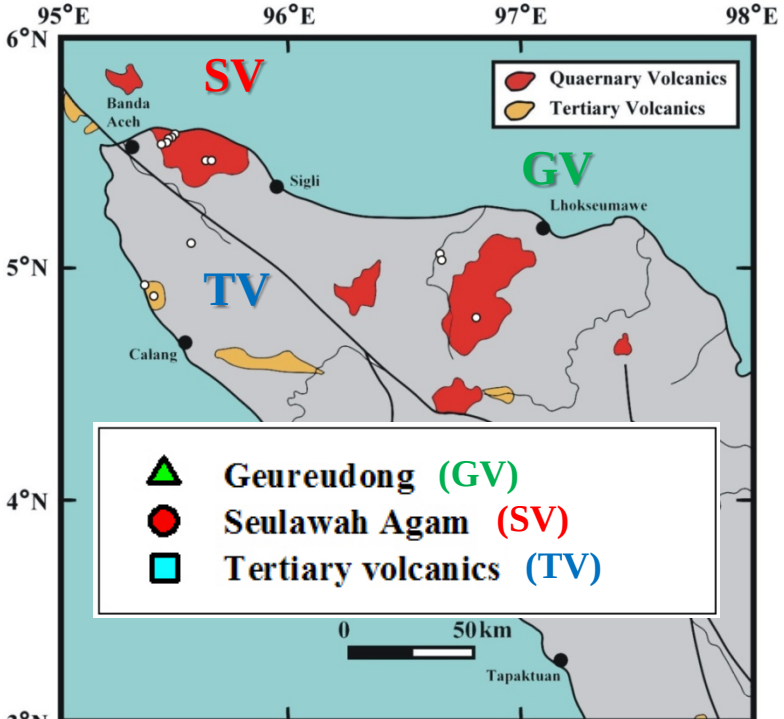

95°E
96°E
97°E
98°E
6°N
5°N
4°N
3°N
SV
GV
TV
Banda Aceh
Sigli
Lhokseumawe
Quaernary Vo
Tertiary Volca
Geureudong (GV)
Seulawah Agam (SV)
Tertiary volcanics (TV)
K2O (Wt.%)
MgO (Wt.%)
Fe2O3 (Wt.%)
CaO (Wt.%)
Al2O3 (Wt.%)
Na2O (Wt.%)
TiO2 (Wt.%)
P2O5 (Wt.%)
SiO2 (Wt.%)
SiO2 (Wt.%)
SiO2 (Wt.%)

Results: Trace elements

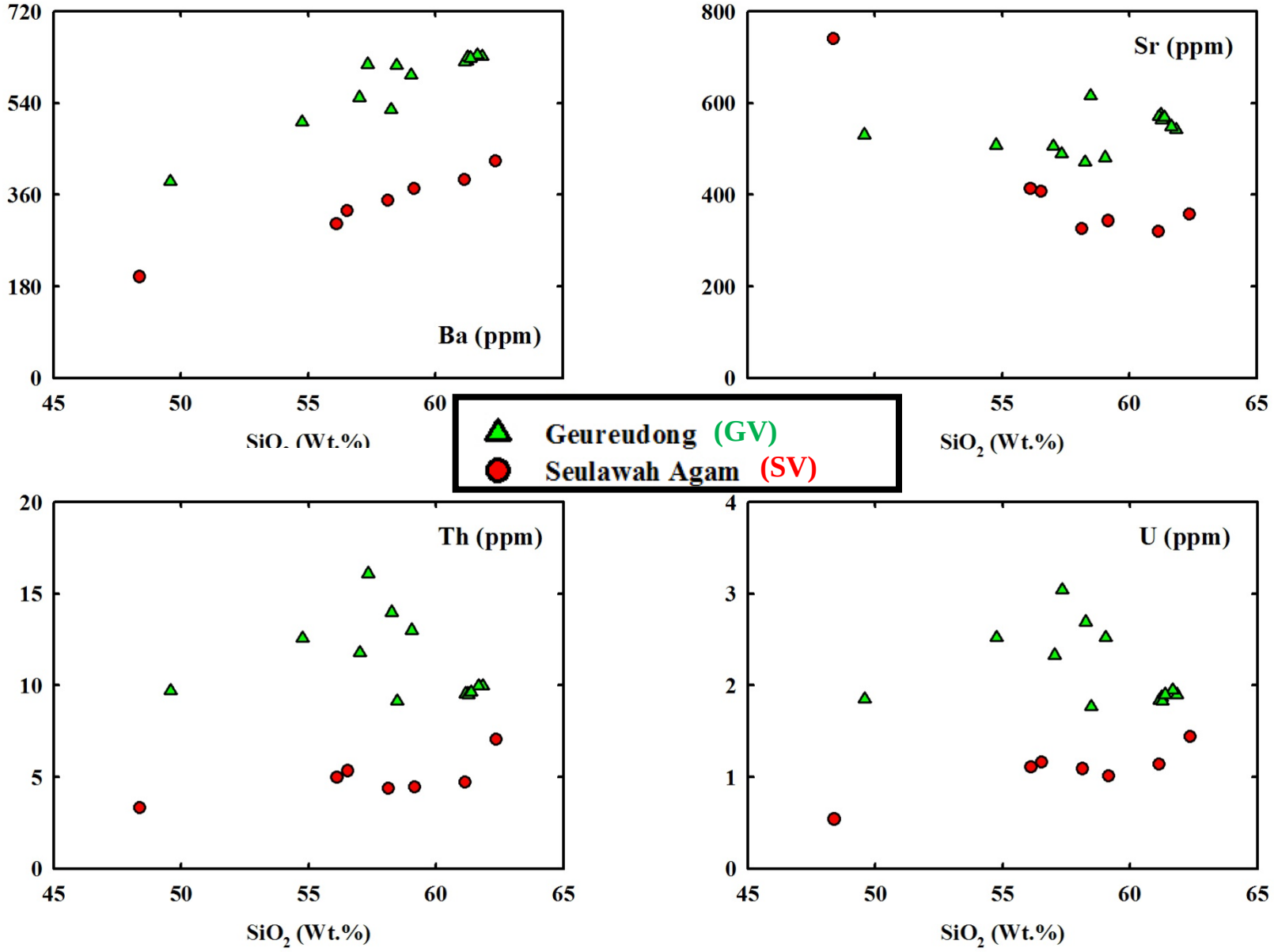




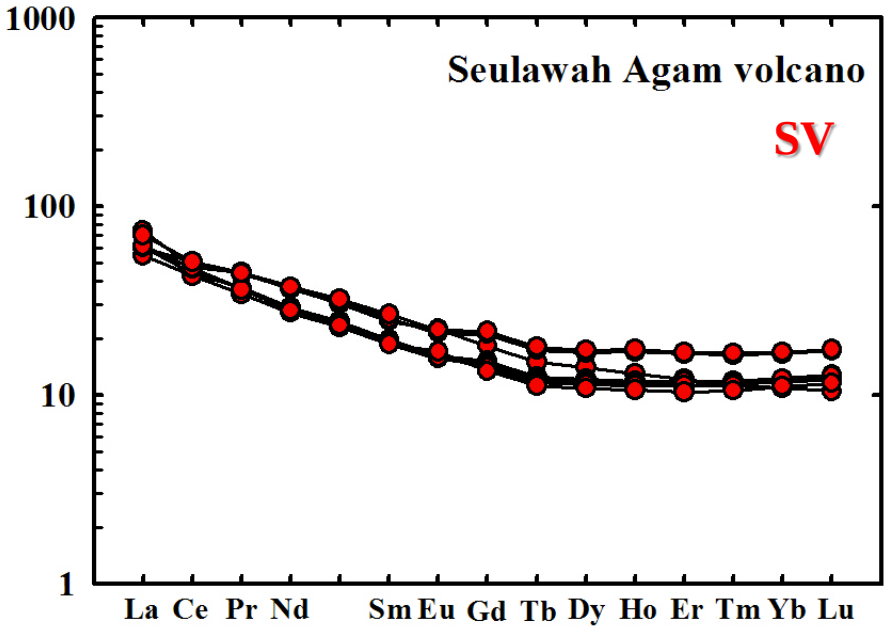


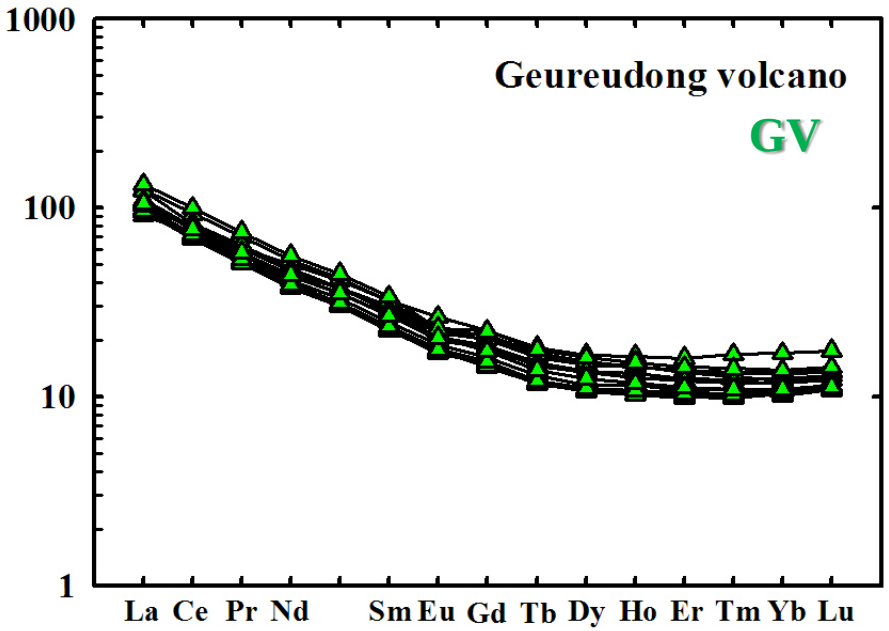


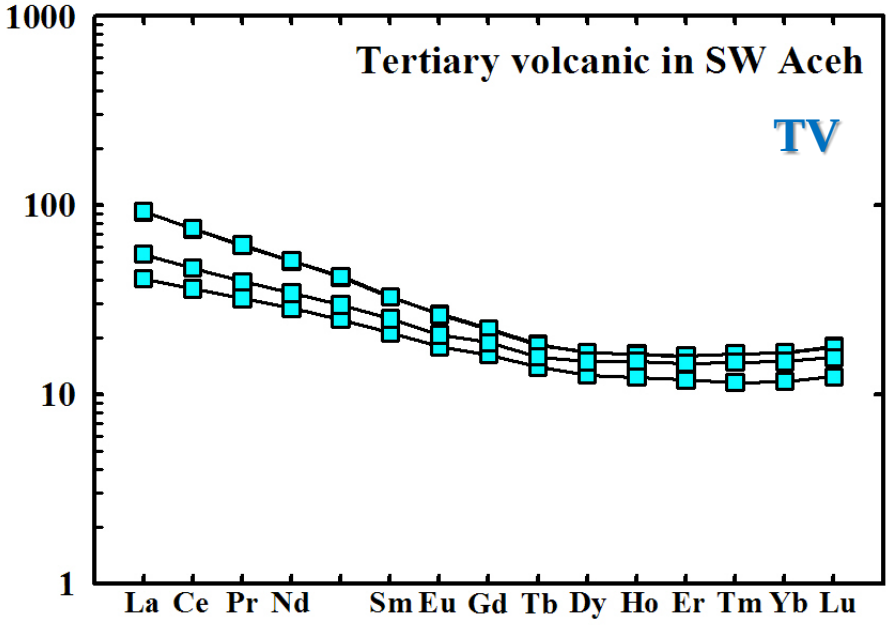
Results: Trace elements

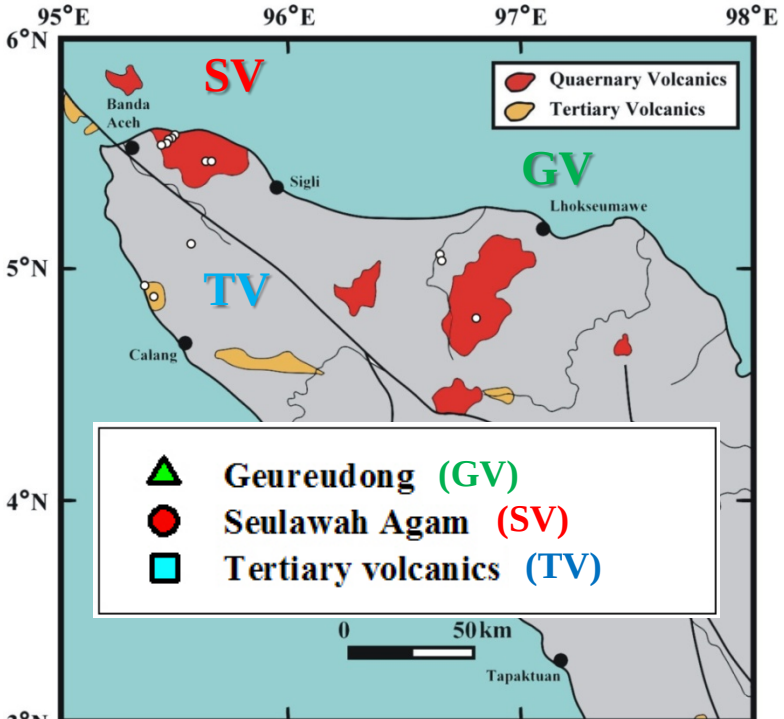


Results: Trace elements

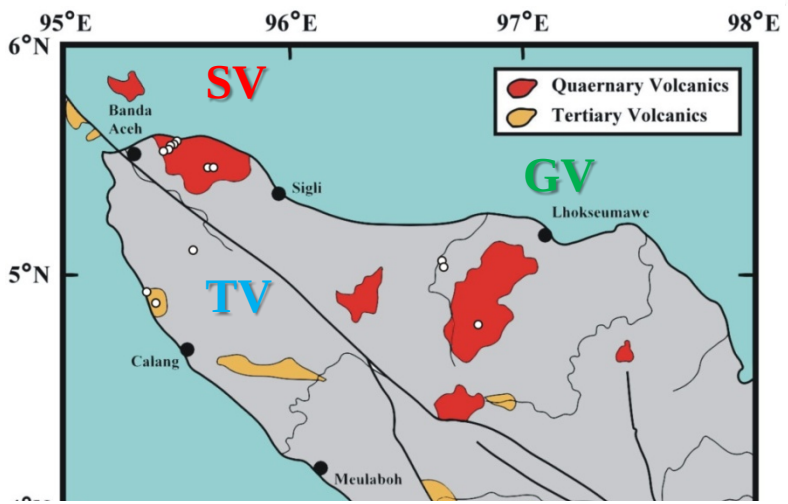


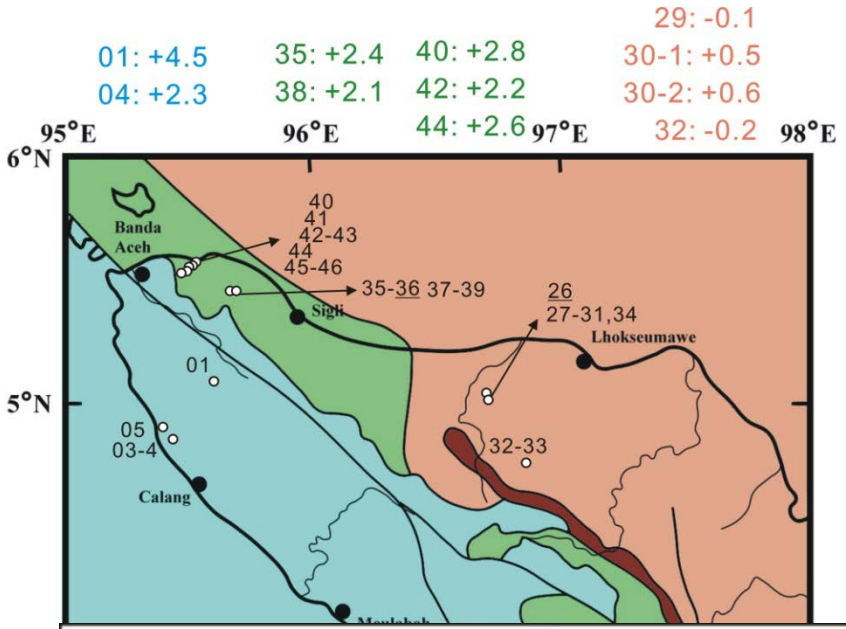


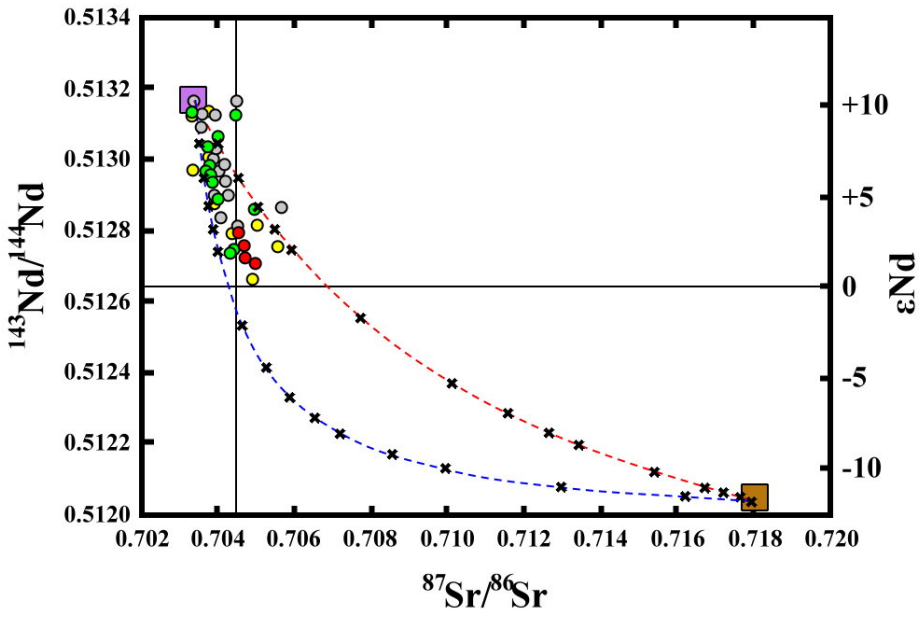


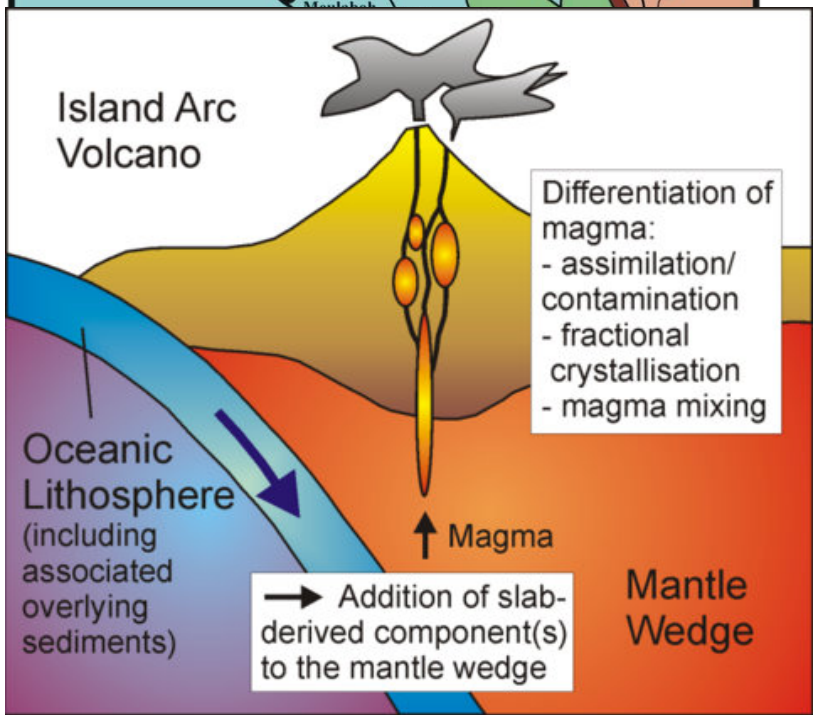


Results: Nd isotopes

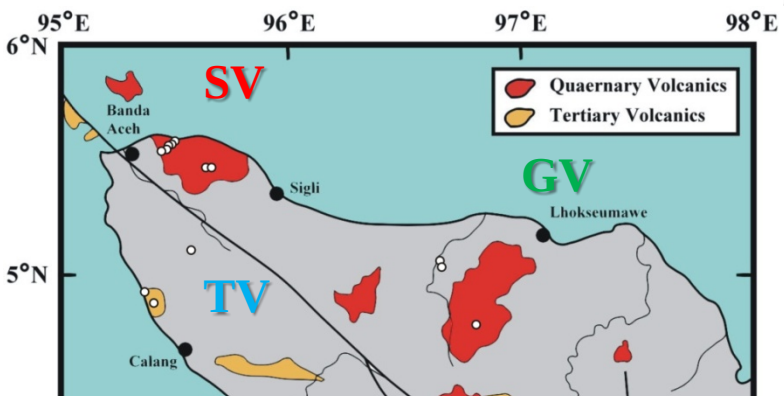


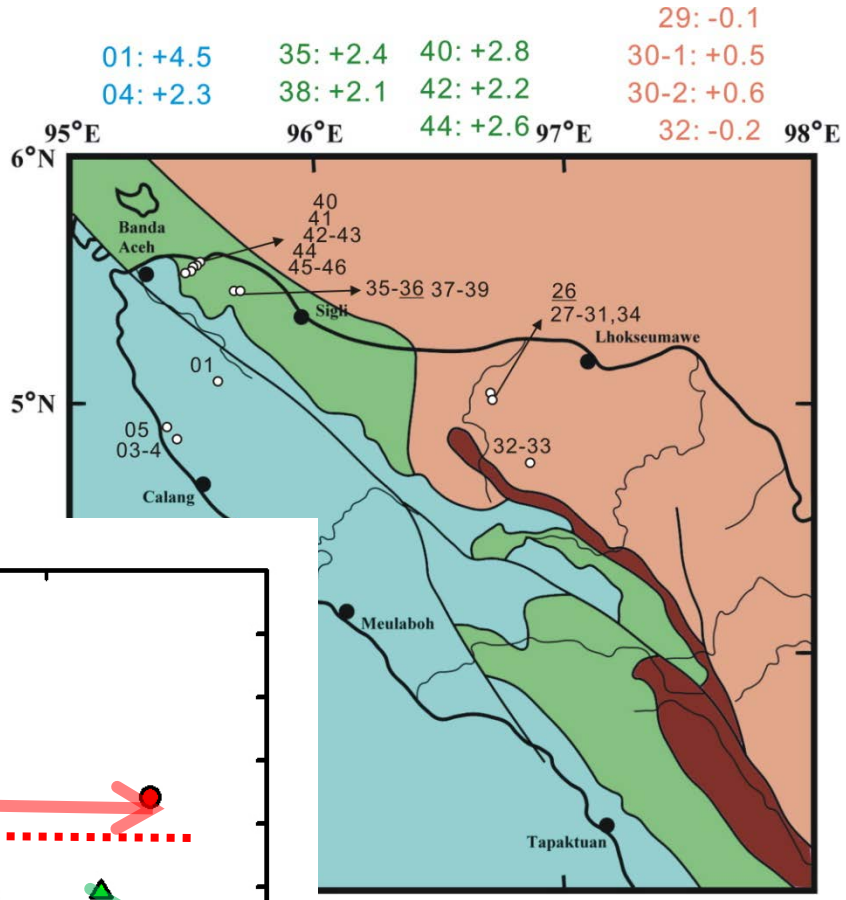


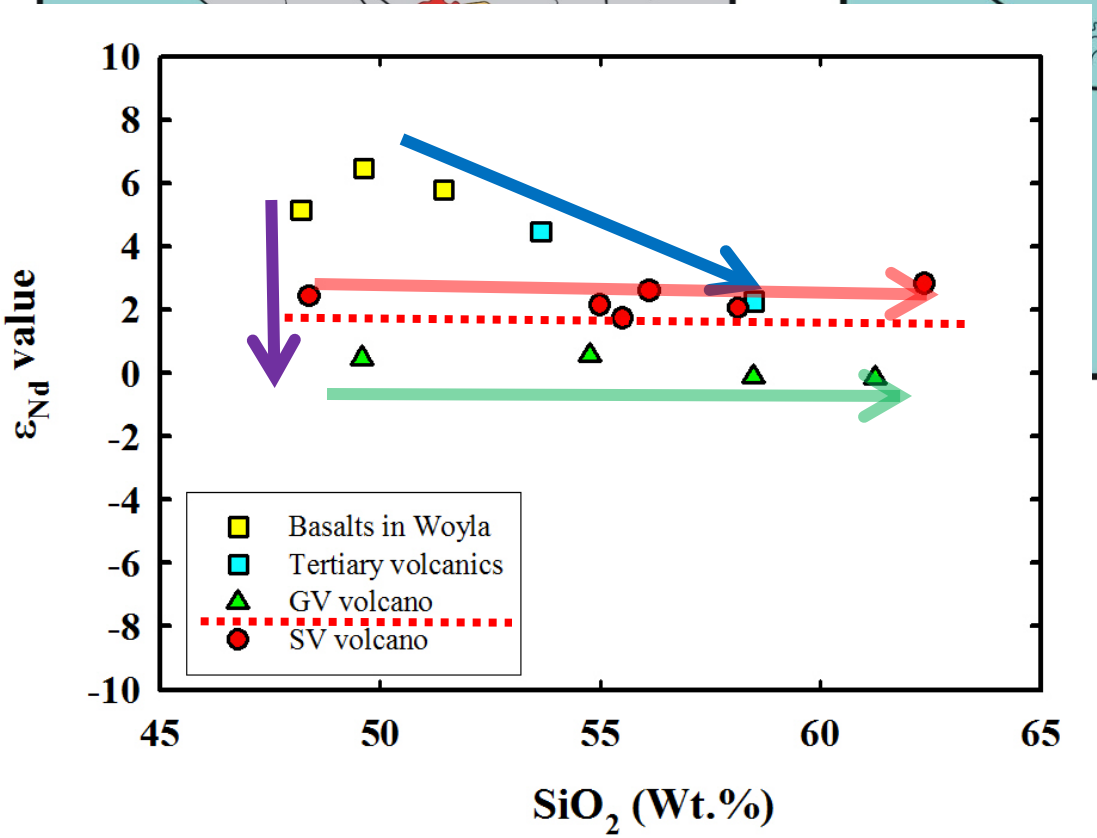




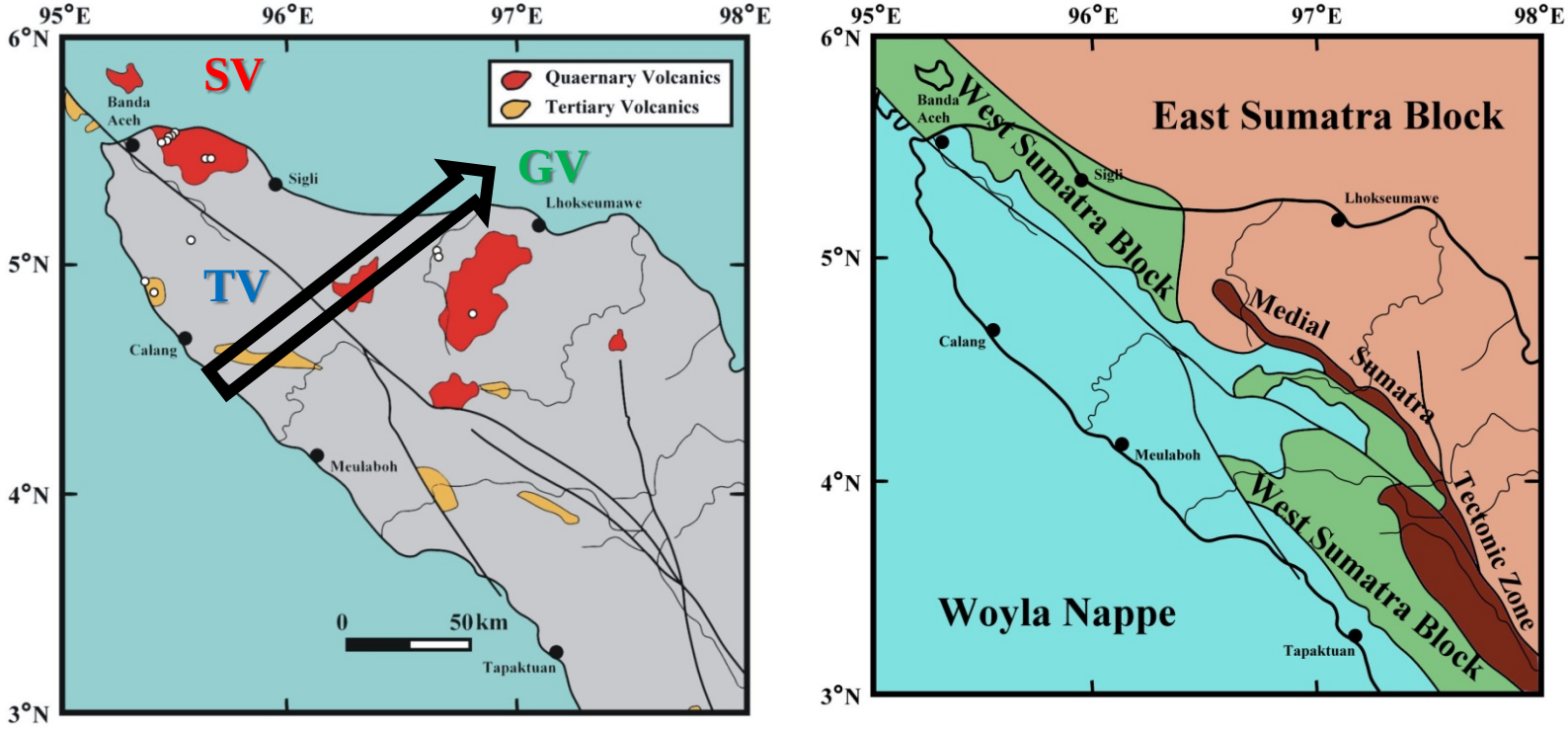
Results: Nd isotopes







A quick summary

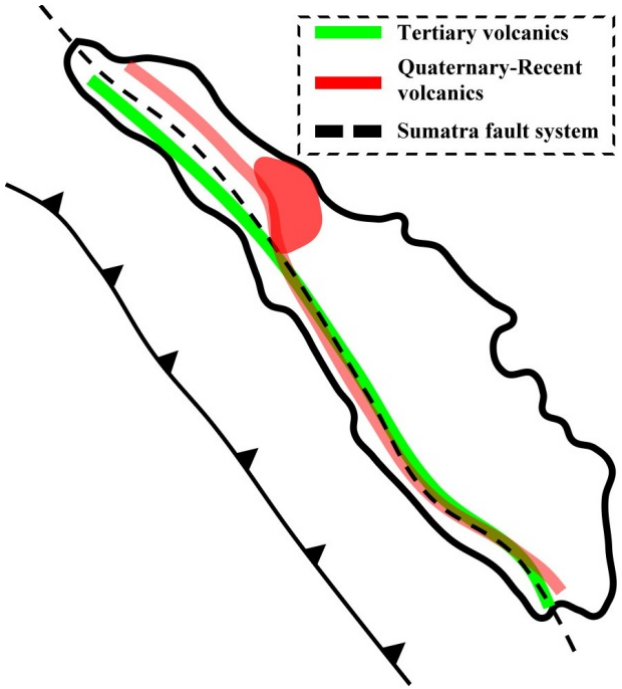


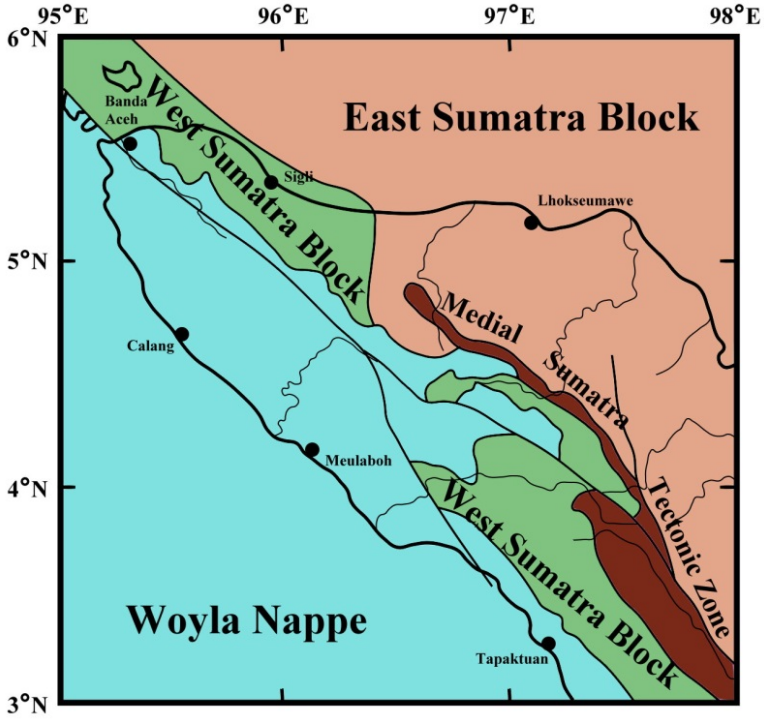
☆ Volcanoes located on three different terranes, i.e., Woyla, West Sumatra and East Sumatra from SW to NE. They are island-arc volcanic rocks belong to basalts to andesites.

☆ They erupted at different ages from Tertiary (TV), Quaternary to Recent (SV and GV).

☆ The concentrations of K_2O, incompatible elements and LREEs increasing while εNd values decreasing from TV, SV to GV.

A quick summary





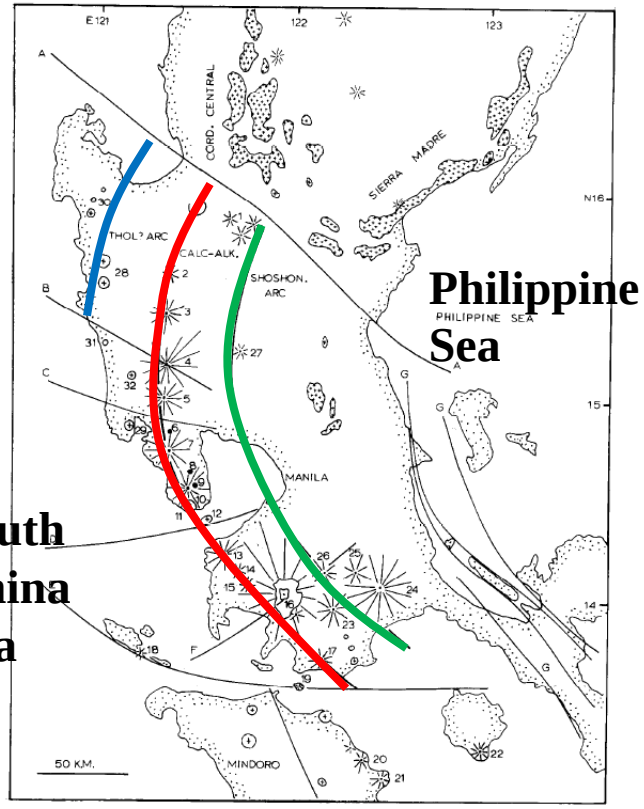
☆ **Crustal contamination occurred before magma erupted on the Woyla terrane.**

☆ **Source contamination changed the source compositions and formed different magmas to erupt on the West and East Sumatra Block.**

☆ **Volcanic chains overlapped with the Sumatra Fault Zone in central and SE Sumatra, but separated at northern of Toba with different ages.**

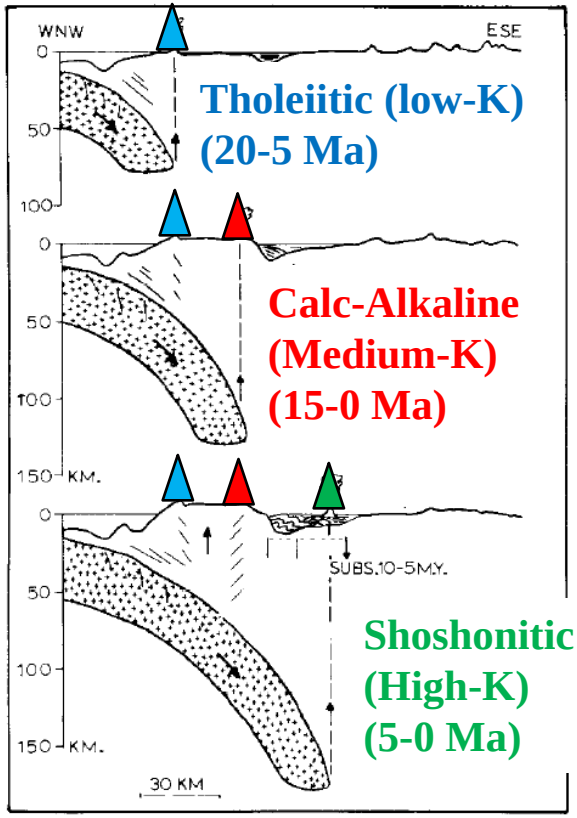
Across-arc geochemical variations in other arc systems

Example 1. The Southern Luzon Arc



Philippine Sea

South China Sea



Tholeiitic (low-K) (20-5 Ma)

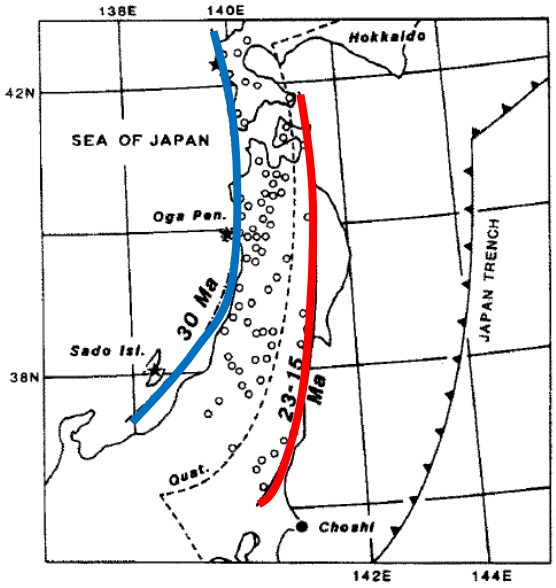
Calc-Alkaline (Medium-K) (15-0 Ma)

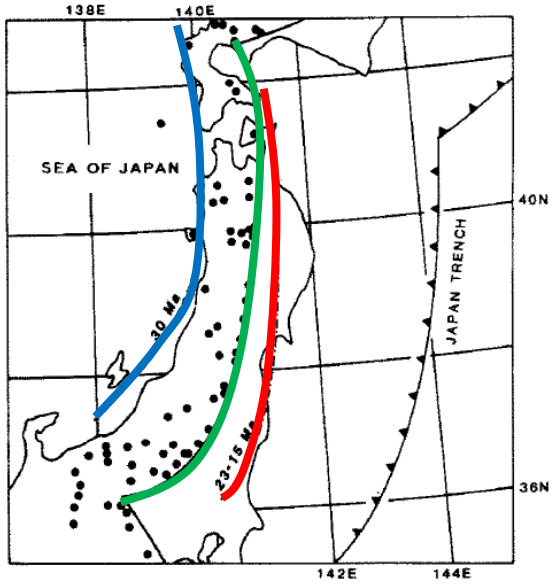
Shoshonitic (High-K) (5-0 Ma)

(de Boer et al., 1980, Tectonophysics)

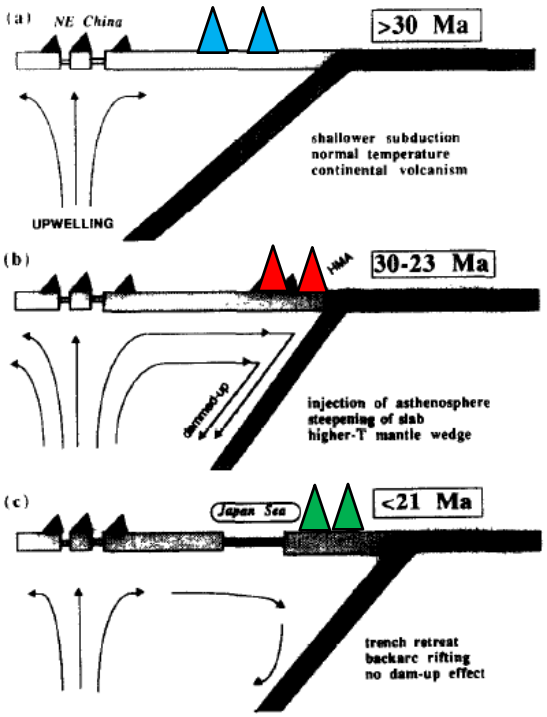
Across-arc geochemical variations in other arc systems

Example 2. NE Japan Arc





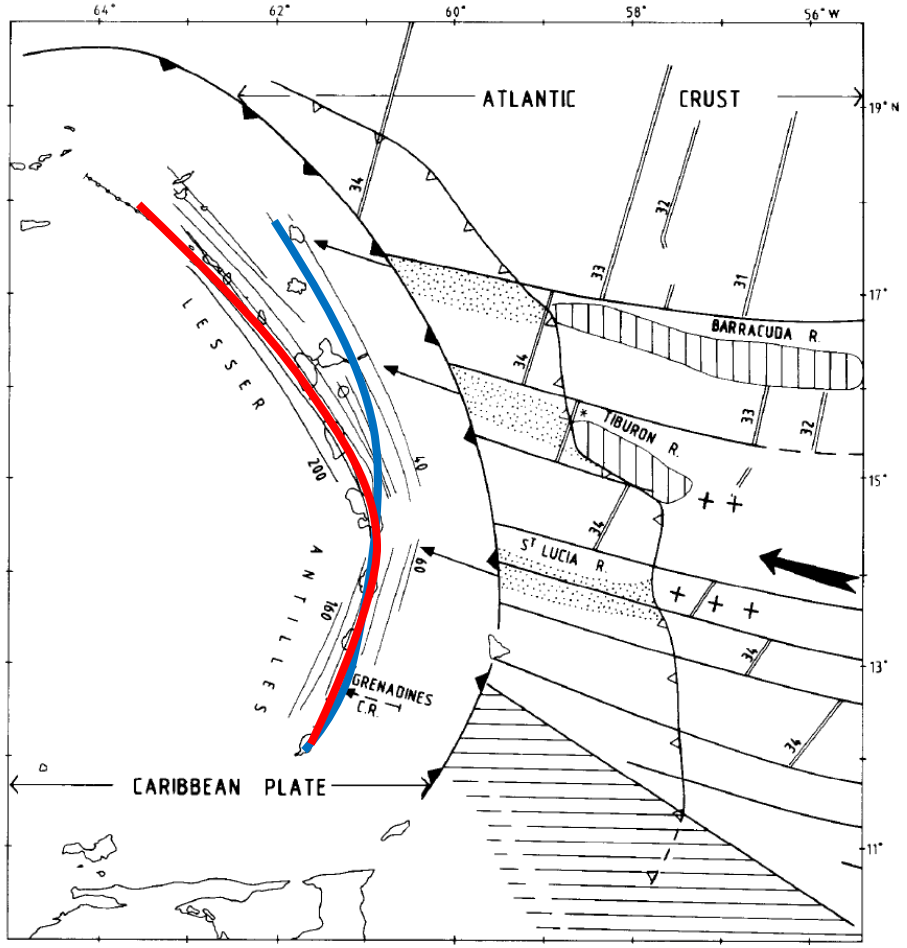
Tatsumi et al.
(1989, Tectonophysics)

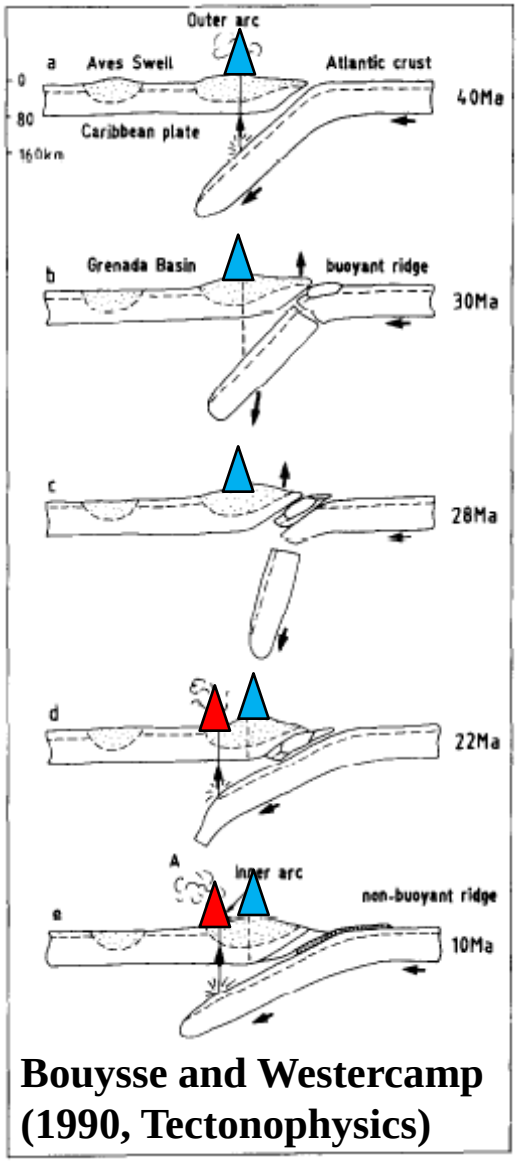


Tatsumi and Kimura
(1991, Tectonophysics)

Across-arc geochemical variations in other arc systems

Example 3. Lesser Antilles Arc

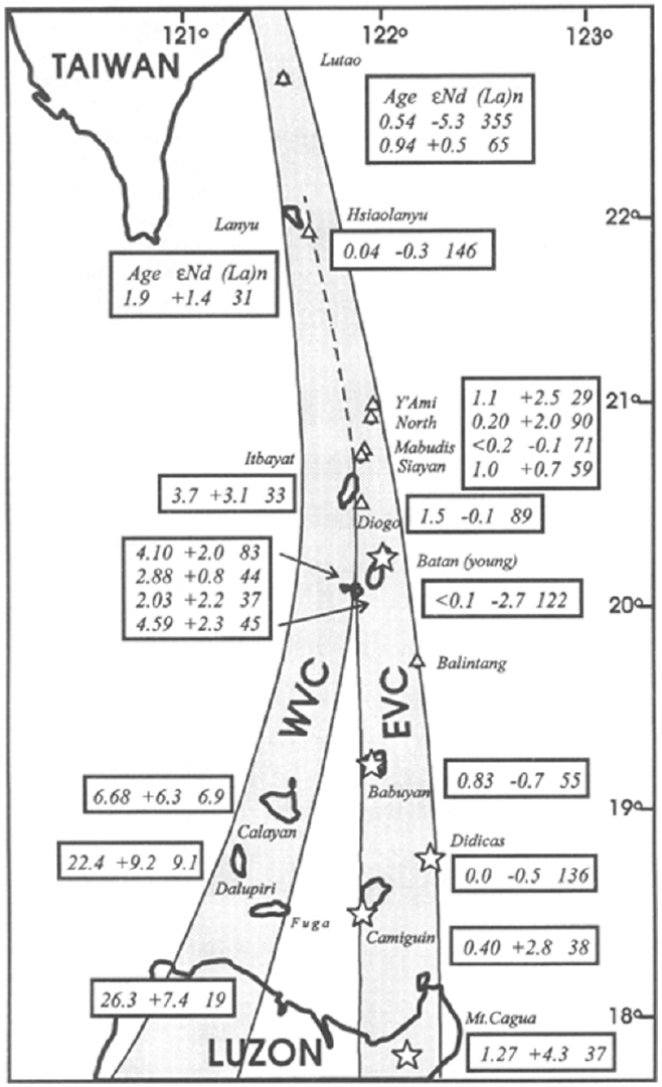


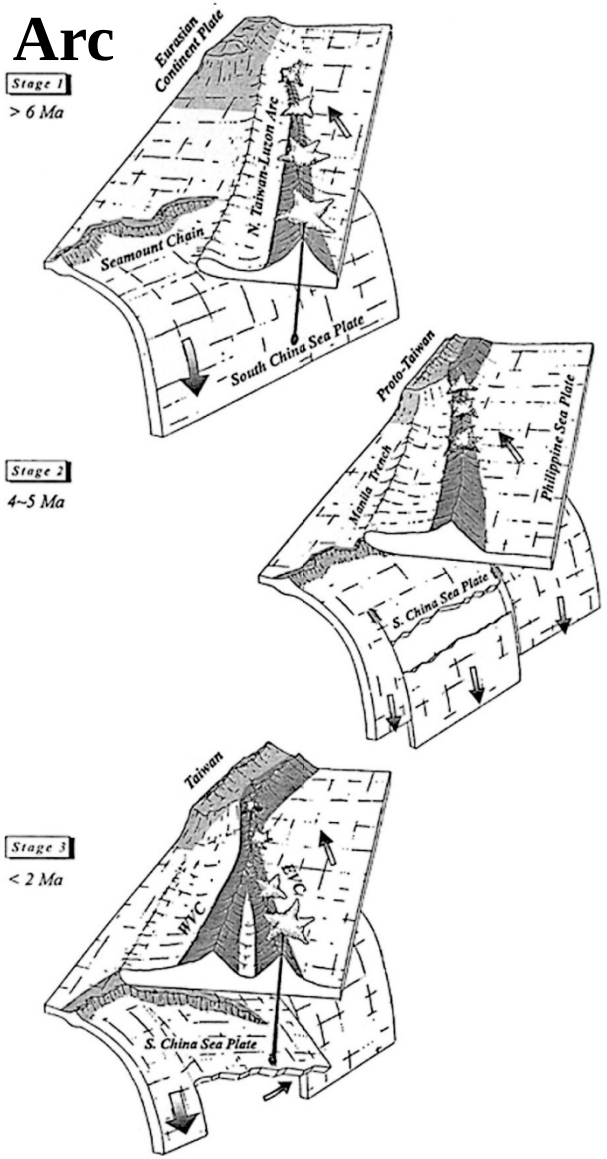


Bouysse and Westercamp (1990, Tectonophysics)

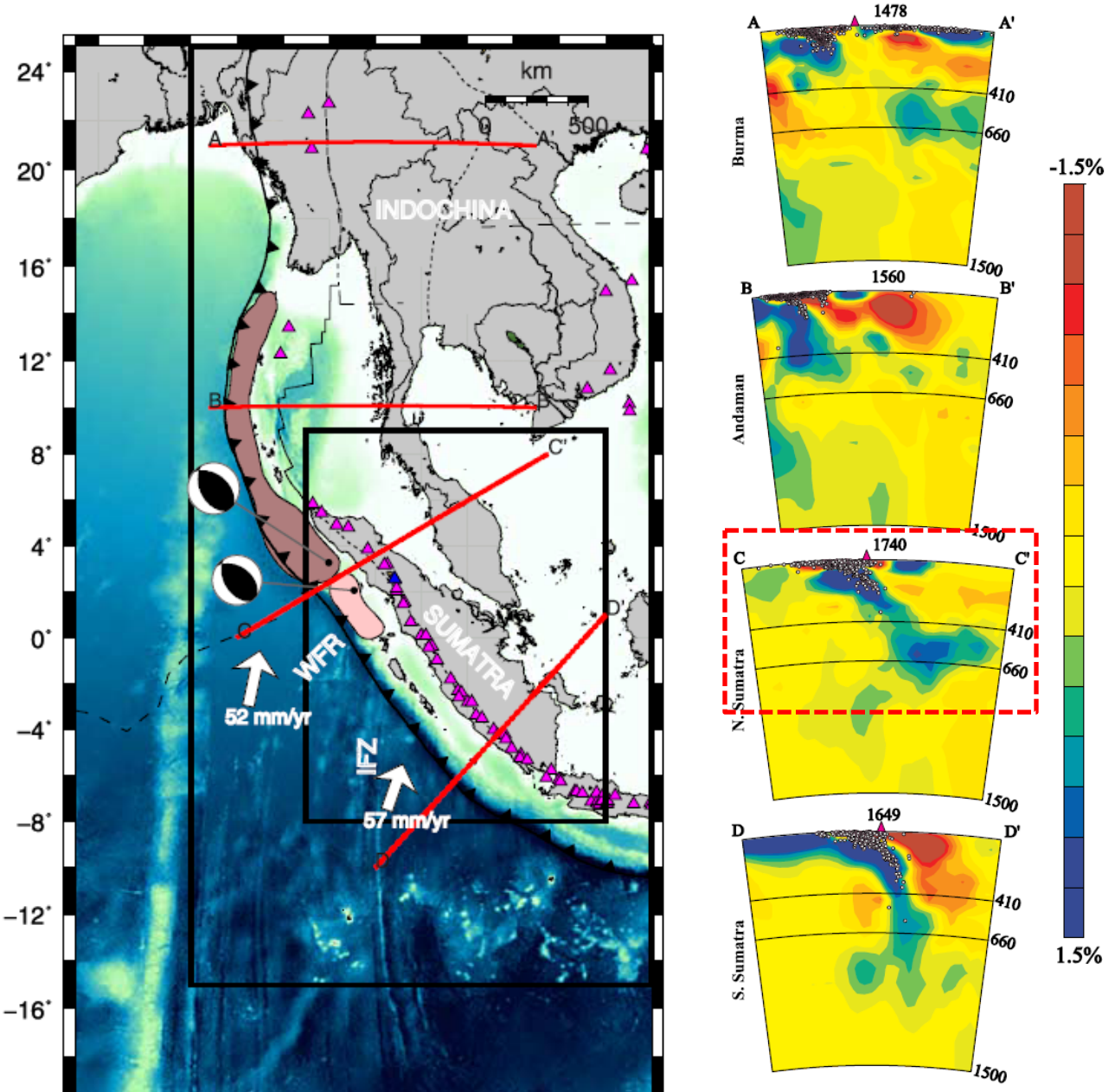
Geochemical variations in double arc system

Example 4. The Northern Luzon Arc

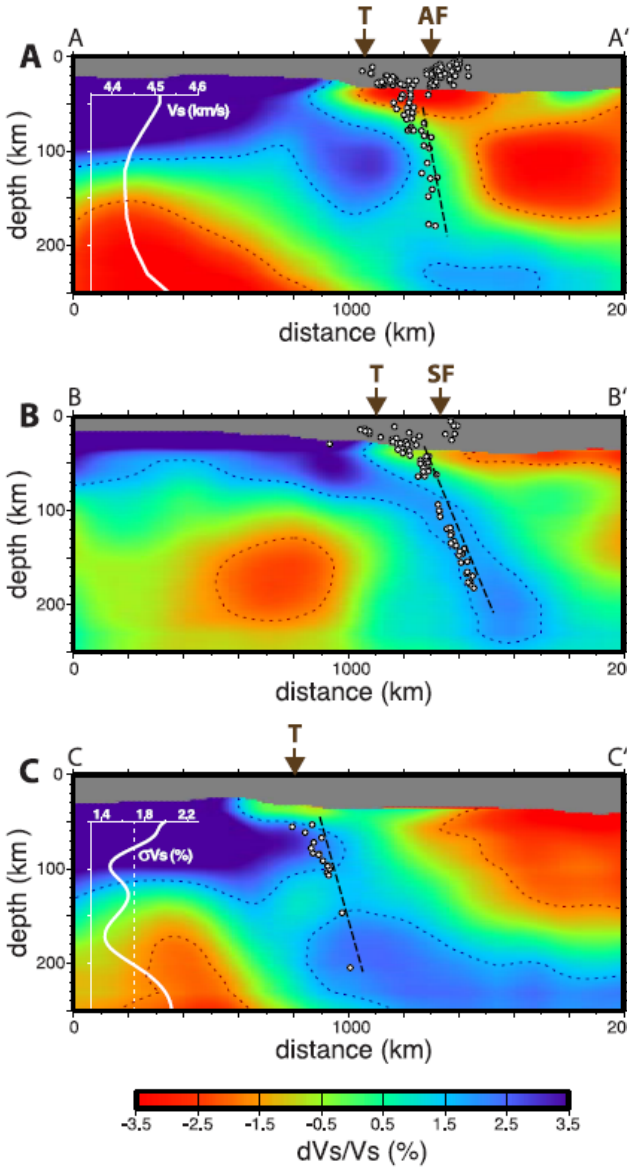




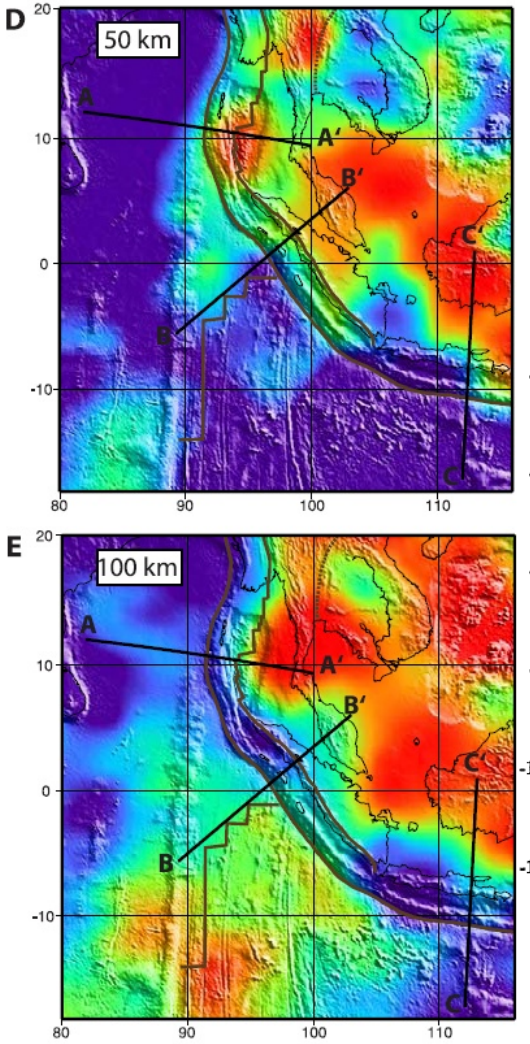
(Yang et al., 1996, Tectonophysics)

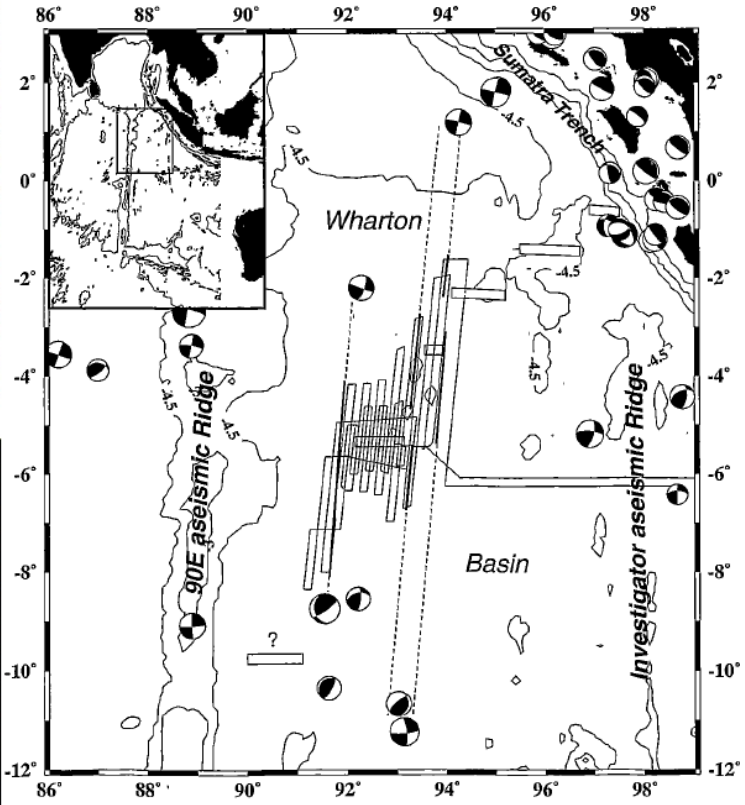


(Pesicek et al., 2008, GRL)

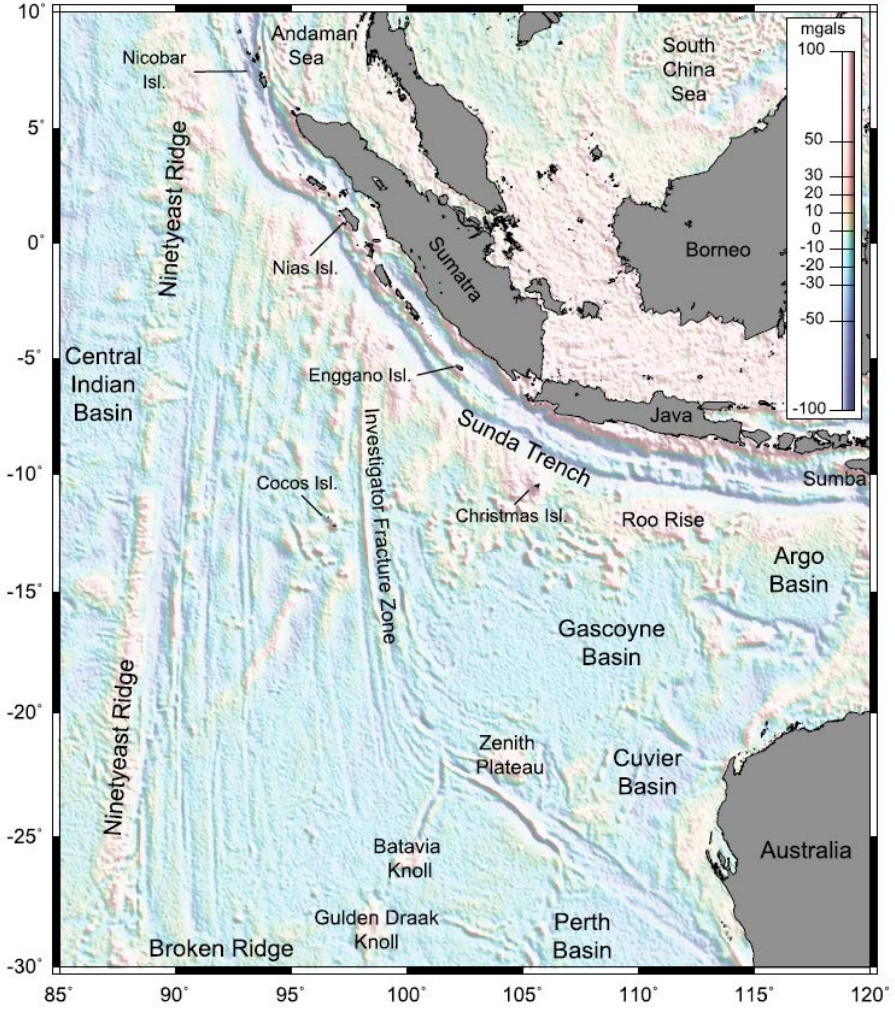


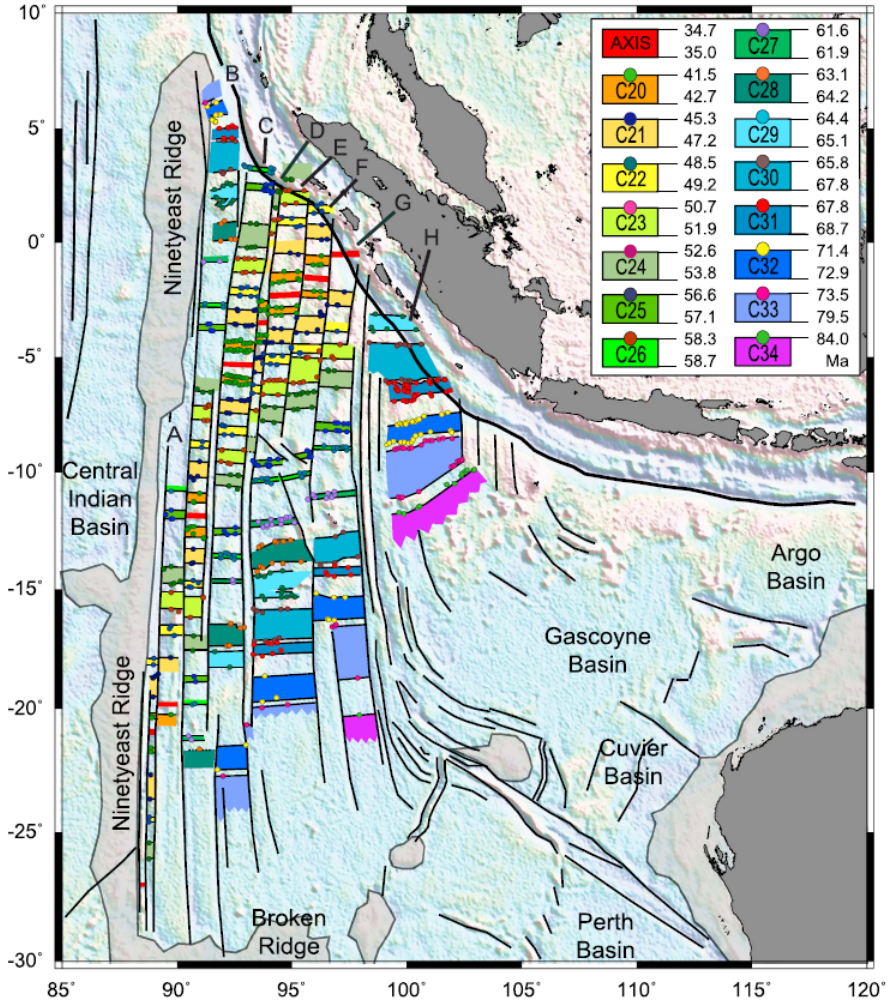
(Shapiro et al., 2008, GRL)



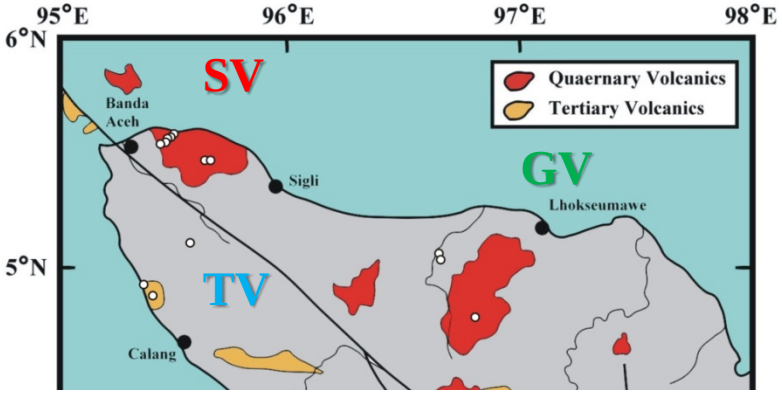


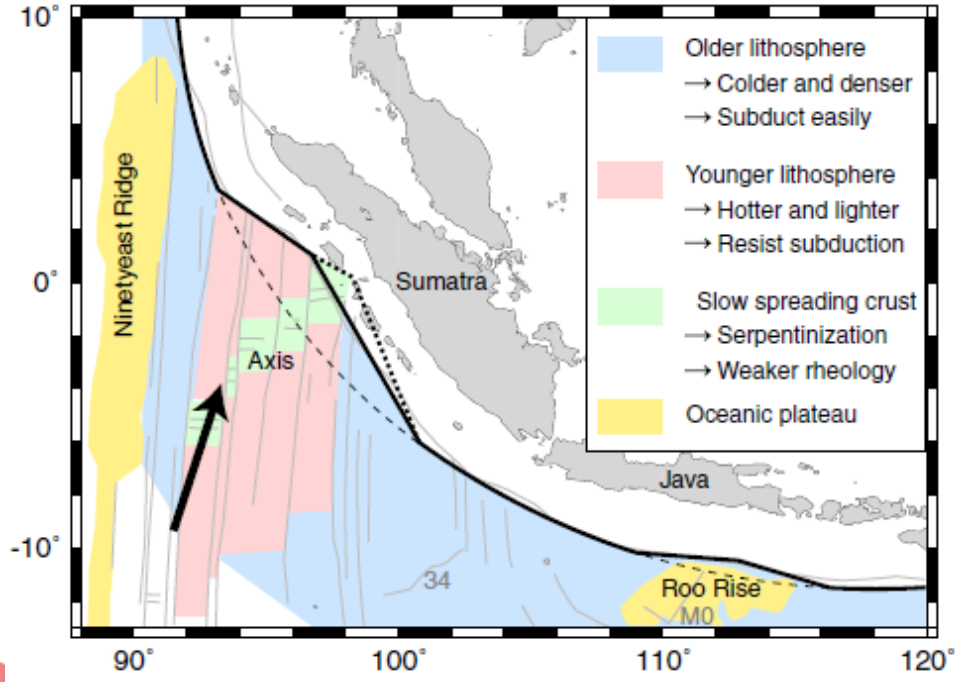
(Deplus et al., 1998, Geology)

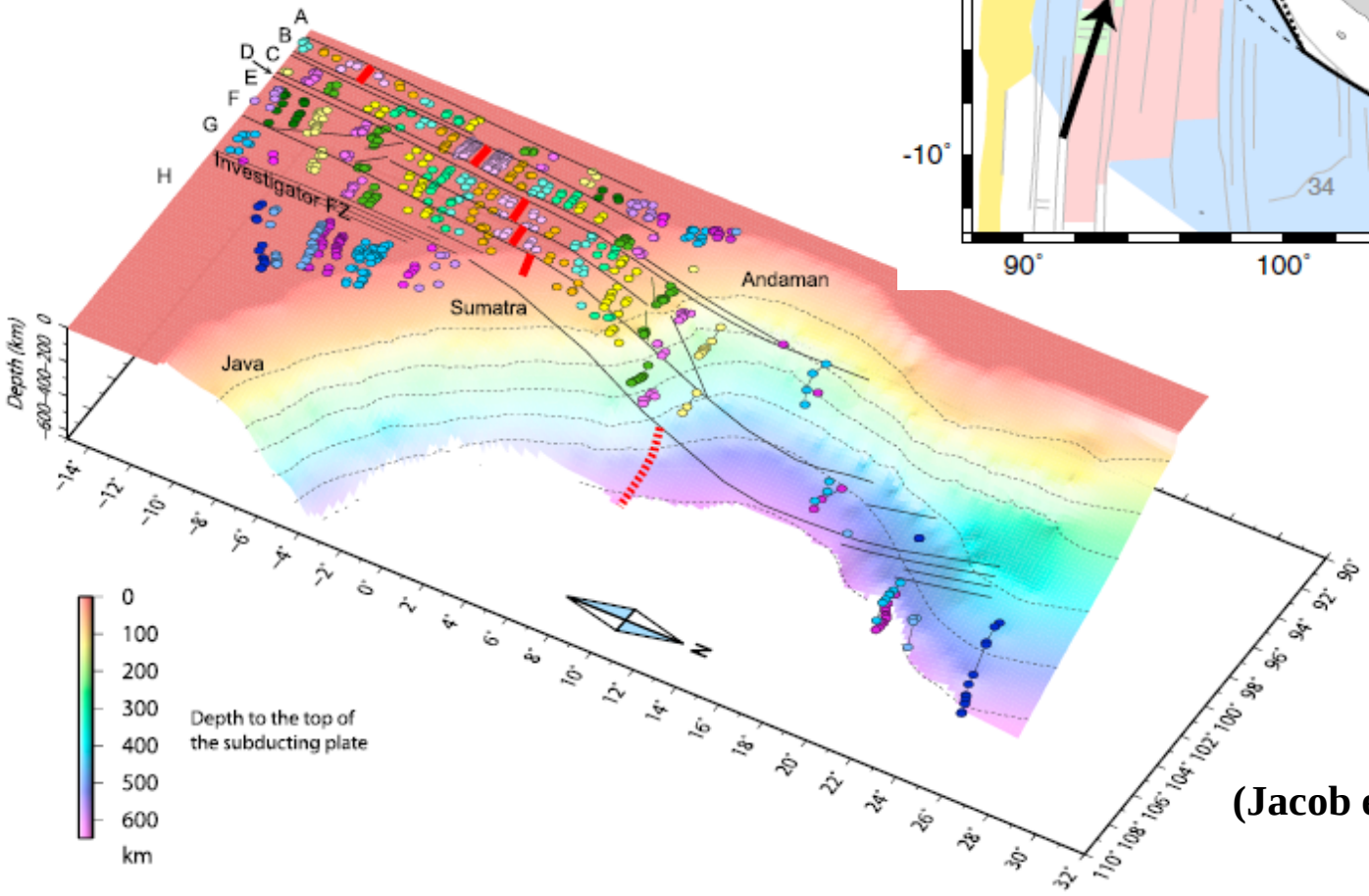




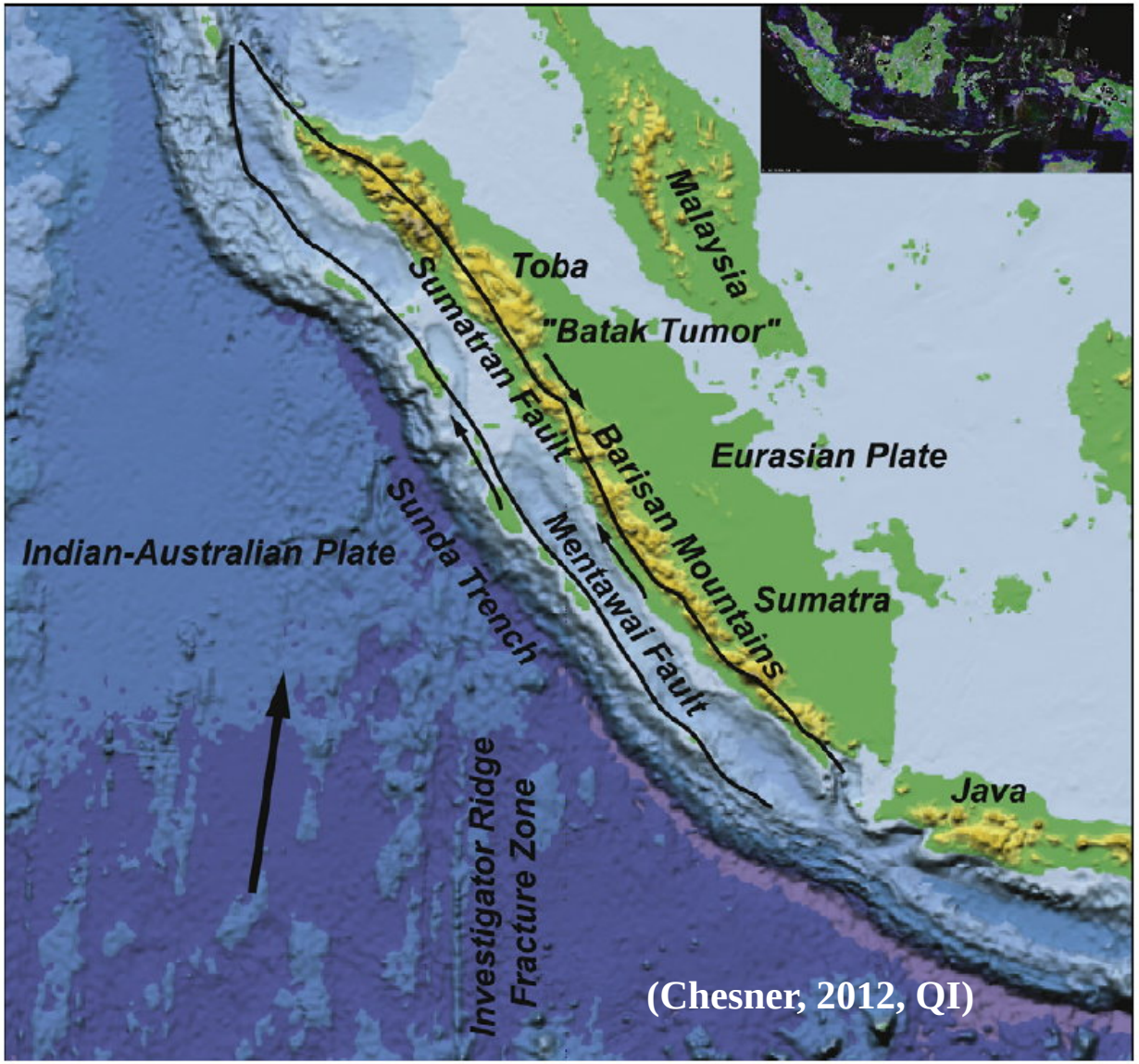
(Jacob et al., 2014, JGR)





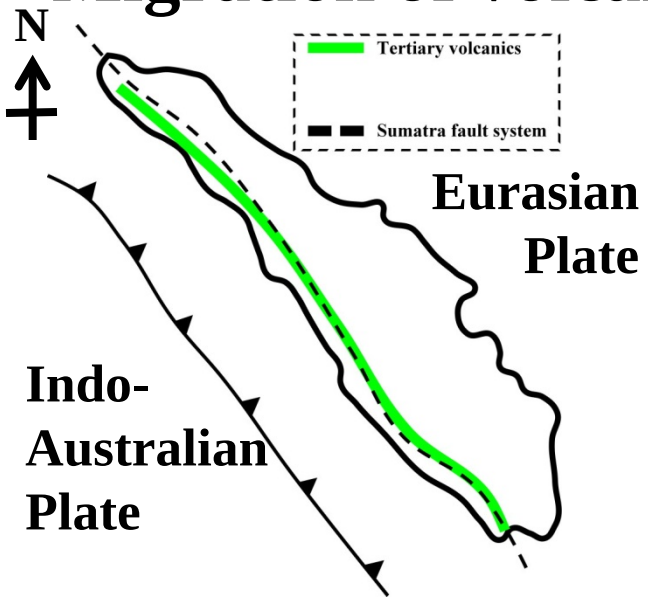


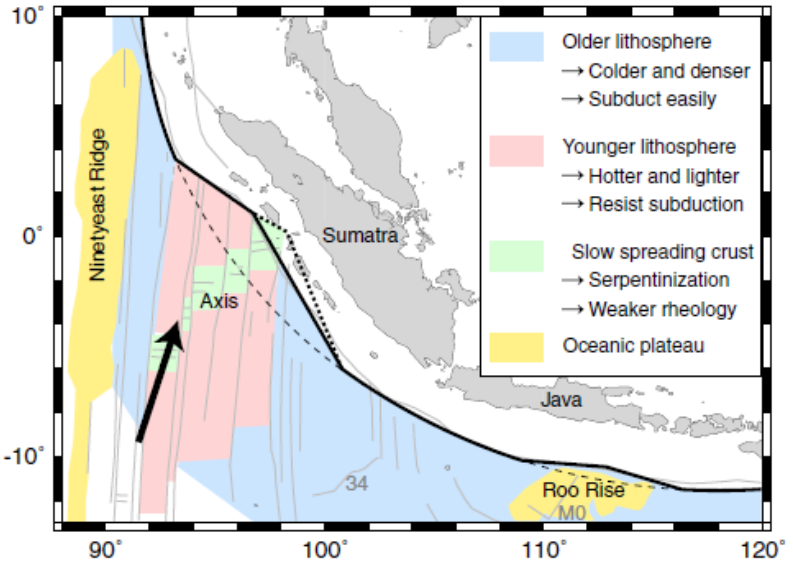
(Jacob et al., 2014, JGR)

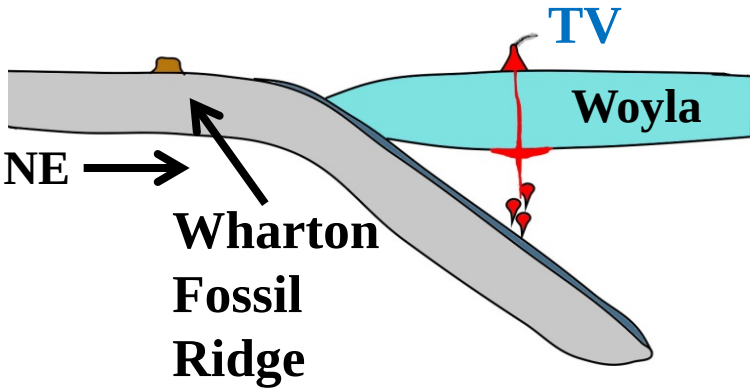


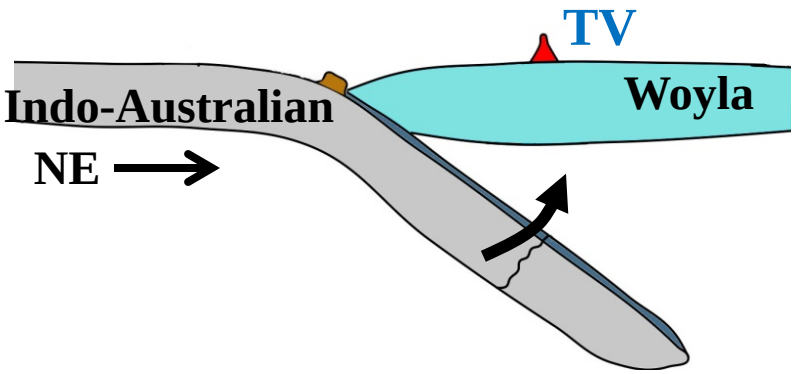
(Chesner, 2012, QI)

Migration of volcanism with time in NW Sumatra









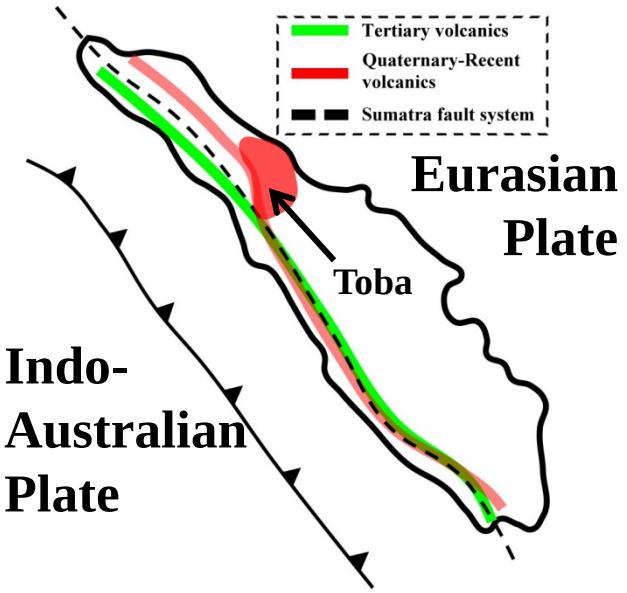
→ Tertiary vlocanics (TV)

→ Concentrations of K_2O, LILEs and LREEs are low.

→ εNd values of these volcanic rocks are between +4.5 to +2.3.

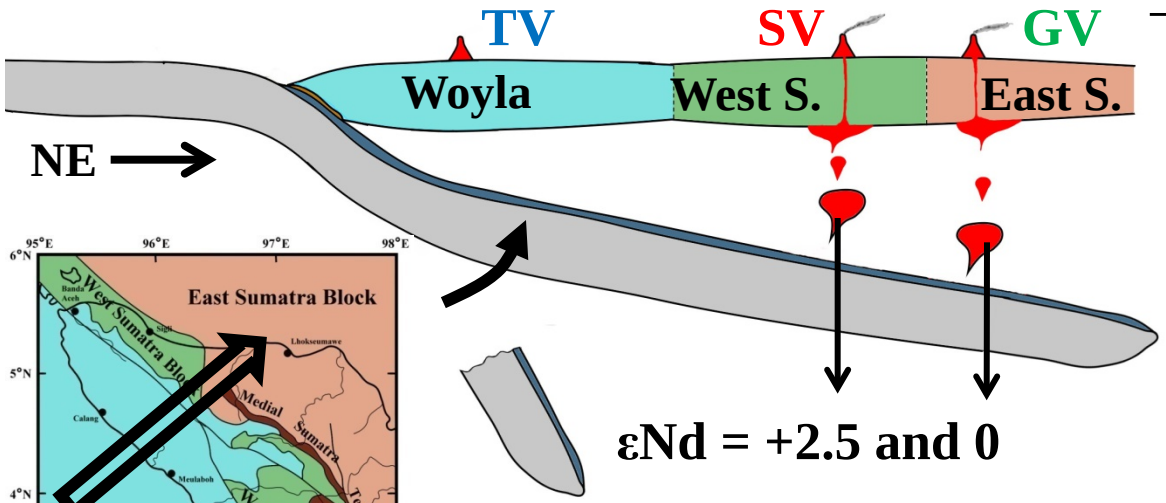
→ Crustal contamination occurred in magmas before they erupted.

Migration of volcanism with time in NW Sumatra



→ Source contamination changed the εNd values to +2.5 (SV) and 0 (GV).

→ The different concentrations of K_2O, incompatible elements and LREEs due to different degrees of partial melting at different depths.



→ Magmas of these Quaternary volcanoes stayed in different magma chambers and went through individual fractional crystallization before their eruption.

Conclusions

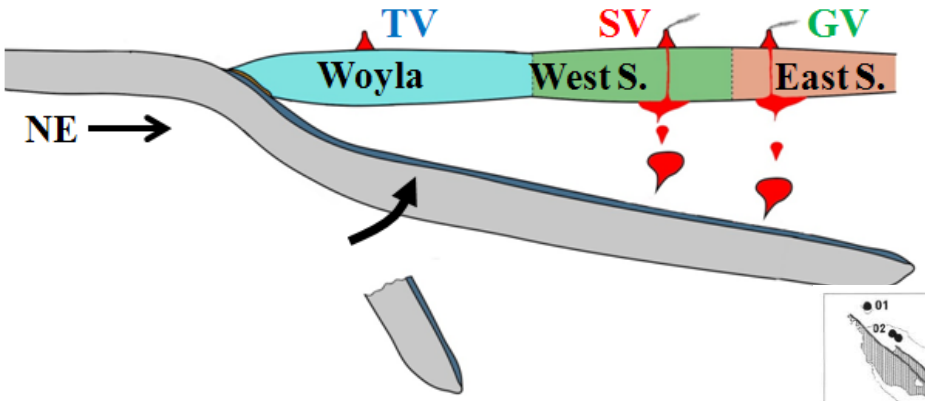
1. Migration of volcanism with time in NW Sumatra may be as a result of changes in the subduction angle which caused by ridge subduction.
2. Volcanic rocks in NW Sumatra located on three different terranes, i.e., Woyla, West Sumatra and East Sumatra from SW to NE. According to the geochemical analyses, they belong to basalts to andesites and mid- to high- K calc-alkaline series.
3. The ages of volcanics on the Woyla terrane were Tertiary and changed to Quaternary to Recent on the West and East Sumatra terrane.
4. Crustal contamination occurred before magma erupted on the Woyla terrane.

Conclusions

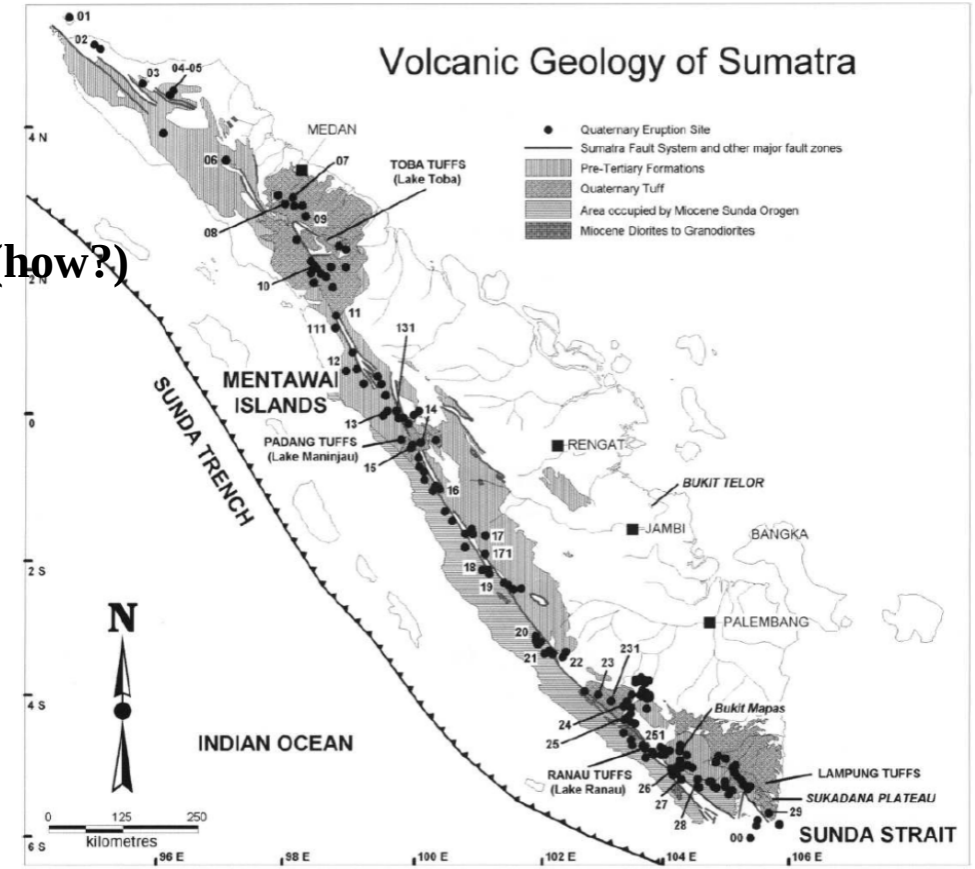
5. Magma formed with higher concentrations of potassium, incompatible elements and LREEs at the deeper depths by lower degrees of partial melting than another shallower one, and then erupted on the East and West Sumatra terrane, respectively.

6. The tectonic evolution in NW Sumatra could be inferred. The Indo-Australian plate subducted before Tertiary and produced volcanoes on the Woyla terrane, then the Wharton fossil ridge resisted to subduction and caused the subducted slab angle became gently and formed the Quaternary volcanoes on the West and East Sumatra terranes.

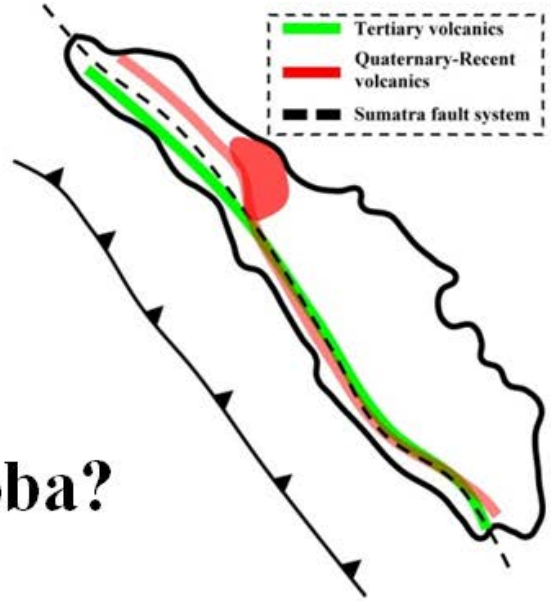
Present and future works



- ⊙ Partial melting (where?)
- ⊙ Crustal and source contamination (how?)
- ⊙ Fractional crystallization (what?)
- ⊙ Ages (when?)
- ⊙ Toba (why?)



Why Toba?

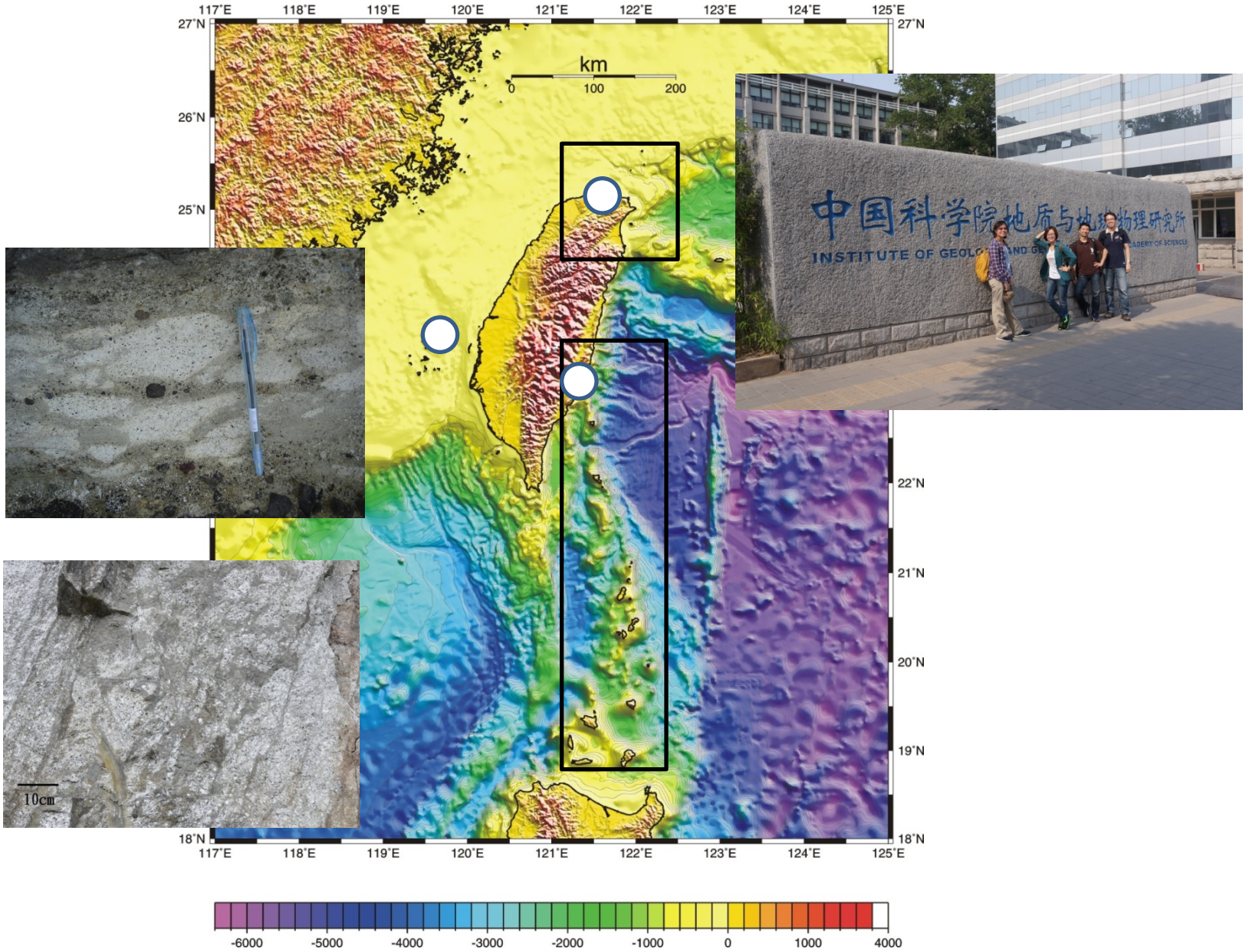

Tertiary volcanics
Quaternary-Recent volcanics
Sumatra fault system


Lake Toba with Samosir island
MEDAN
Binjai
Lubukpakan
Baungan(Perbaungan)
Sungaibamban
Bangunpurba
TEBINGTINGGI
Brastagi
Kabanjahe
Labuhanruku
Teluknibung
Kisaran
PEMATANGSIANTAR
Tanjungbalai
Lake
Sidikalang
Parapat
Labuhanbilik
Toba
Balige
Siborongborong
Singkilbaru (Singki)
Barus
Tarutung
Rantauprapat
Kotapinang
Sibolga
Langgapayung
Sumatera Utara
Gunungtua
Binanga
Padangsidempuan
Gunungsitoli
Daludalu
Pulau Nias


Toba lake
12 10 2014


Sinabung
12 10 2014


12 10 2014


117°E
118°E
119°E
120°E
121°E
122°E
123°E
124°E
125°E
27°N
26°N
25°N
22°N
21°N
20°N
19°N
18°N
km
0
100
200
10cm
-6000
-5000
-4000
-3000
-2000
-1000
0
1000
4000

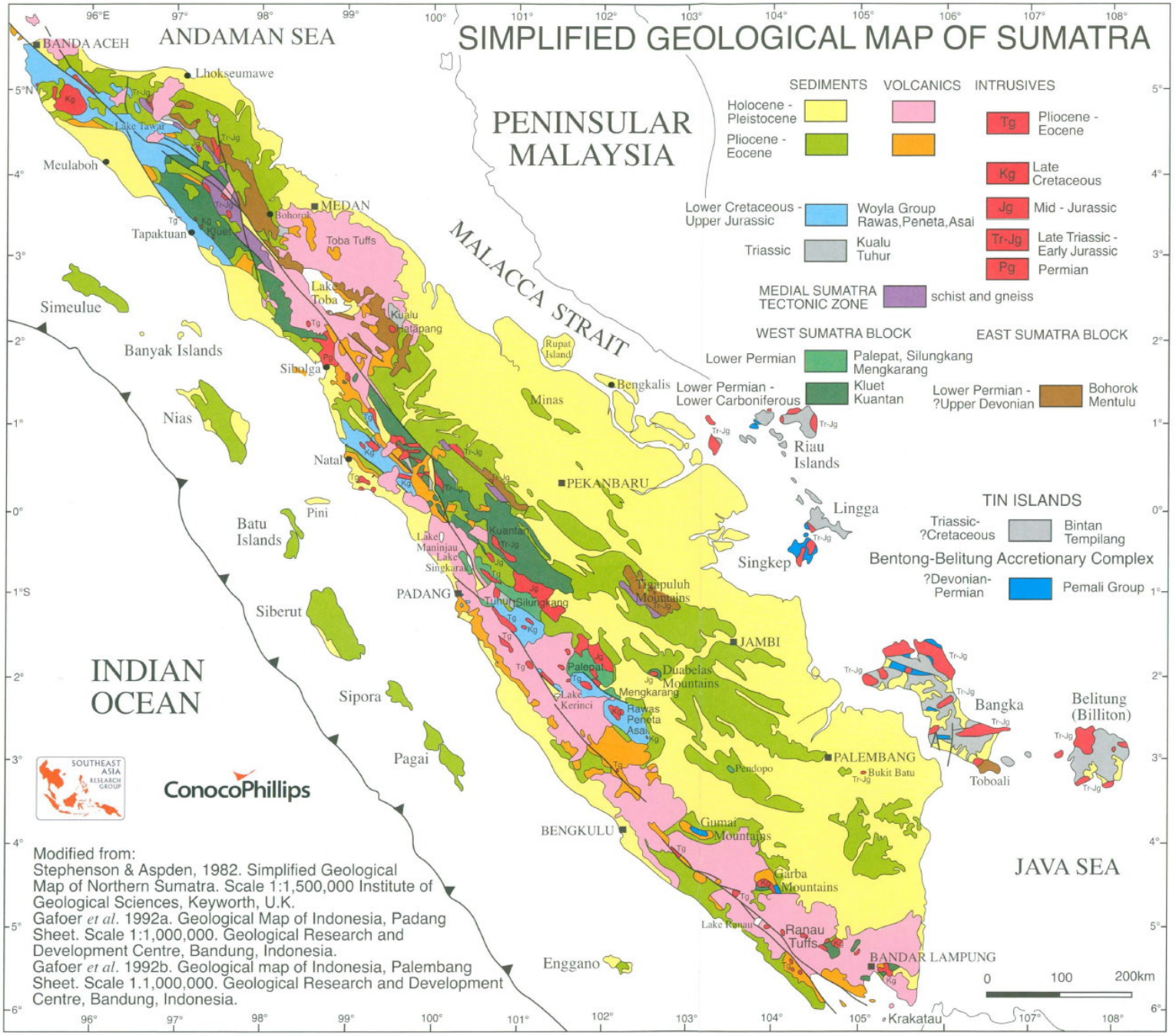

NOW EVERYONE CAN FLY


6
Tanduk Benua
Pulau
Silalahi
Simanindo
Tomok
P. Pardepur
12 06 2014


12 10 2014

Silra


Thank you for your attention!


SIMPLIFIED GEOLOGICAL MAP OF SUMATRA
ANDAMAN SEA
PENINSULAR MALAYSIA
MALACCA STRAIT
INDIAN OCEAN
JAVA SEA
BANDA ACEH
Lhokseumawe
Lake Tawar
Meulaboh
MEDAN
Bohorok
Toba Tuffs
Tapaktuan
Lake Toba
Kualu
Tatapang
Simeulue
Banyak Islands
Sibolga
Rupat Island
Bengkalis
Minas
Nias
Natal
PEKANBARU
Riau Islands
Lingga
Singkep
Batu Islands
Pini
Lake Maninjau
Lake Singkarak
PADANG
Tuhur
Silungkang
Kuantan
Tigapuluh Mountains
Siberut
JAMBI
Palepat
Duabelas Mountains
Mengkarang
Lake Kerinci
Rawas
Peneta
Asai
Sipora
Pagai
Bangka
Belitung (Billiton)
Toboali
PALEMBANG
Pendopo
Bukit Batu
BENGKULU
Gumai Mountains
Garba Mountains
Lake Ranau
Ranau Tuffs
BANDAR LAMPUNG
Enggano
Krakatau
SEDIMENTS
VOLCANICS
INTRUSIVES
Holocene - Pleistocene
Pliocene - Eocene
Tg Pliocene - Eocene
Kg Late Cretaceous
Jg Mid - Jurassic
Tr-Jg Late Triassic - Early Jurassic
Pg Permian
Lower Cretaceous - Upper Jurassic
Woyla Group Rawas,Peneta,Asai
Triassic
Kualu Tuhur
MEDIAL SUMATRA TECTONIC ZONE
schist and gneiss
WEST SUMATRA BLOCK
EAST SUMATRA BLOCK
Lower Permian
Palepat, Silungkang Mengkarang
Lower Permian - Lower Carboniferous
Kluet Kuantan
Lower Permian - ?Upper Devonian
Bohorok Mentulu
TIN ISLANDS
Triassic-?Cretaceous
Bintan Tempilang
Bentong-Belitung Accretionary Complex
?Devonian-Permian
Pemali Group
0 100 200km
SOUTHEAST ASIA RESEARCH GROUP
ConocoPhillips
Modified from:
Stephenson & Aspden, 1982. Simplified Geological Map of Northern Sumatra. Scale 1:1,500,000 Institute of Geological Sciences, Keyworth, U.K.
Gafoer et al. 1992a. Geological Map of Indonesia, Padang Sheet. Scale 1:1,000,000. Geological Research and Development Centre, Bandung, Indonesia.
Gafoer et al. 1992b. Geological map of Indonesia, Palembang Sheet. Scale 1.1,000,000. Geological Research and Development Centre, Bandung, Indonesia.

Tectonic setting

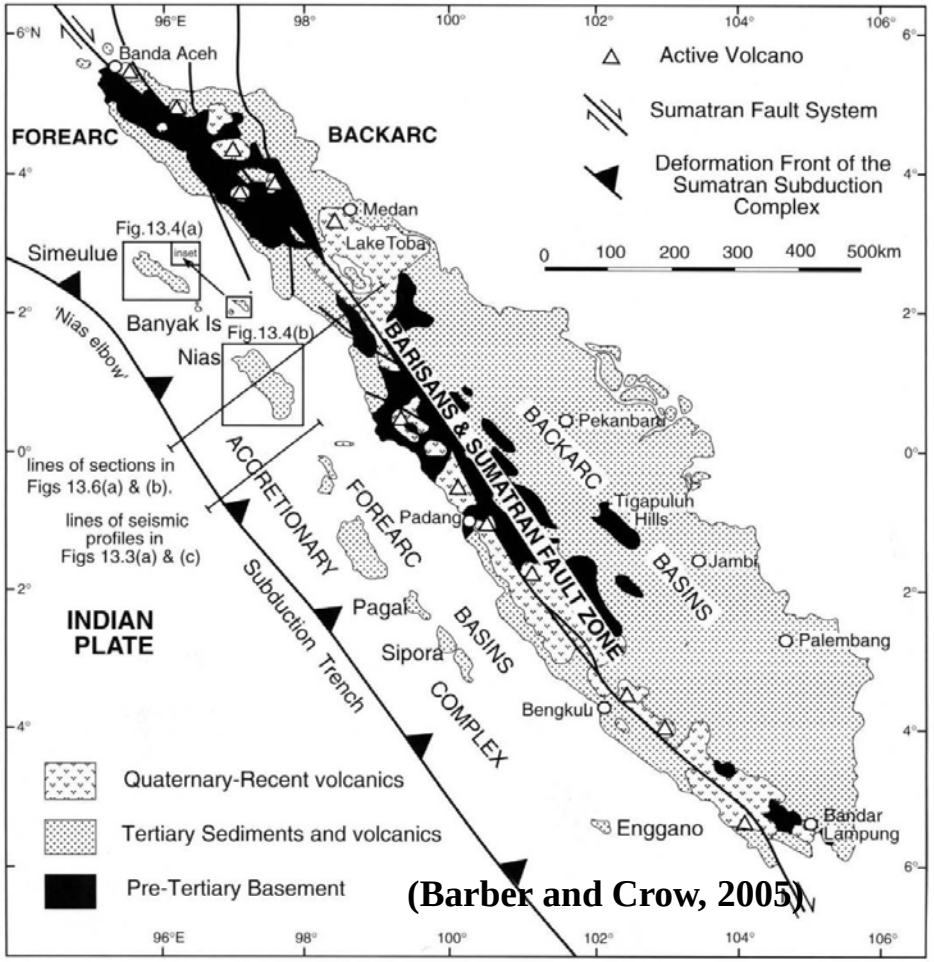
van Bemmelen (1949)

Plate tectonics

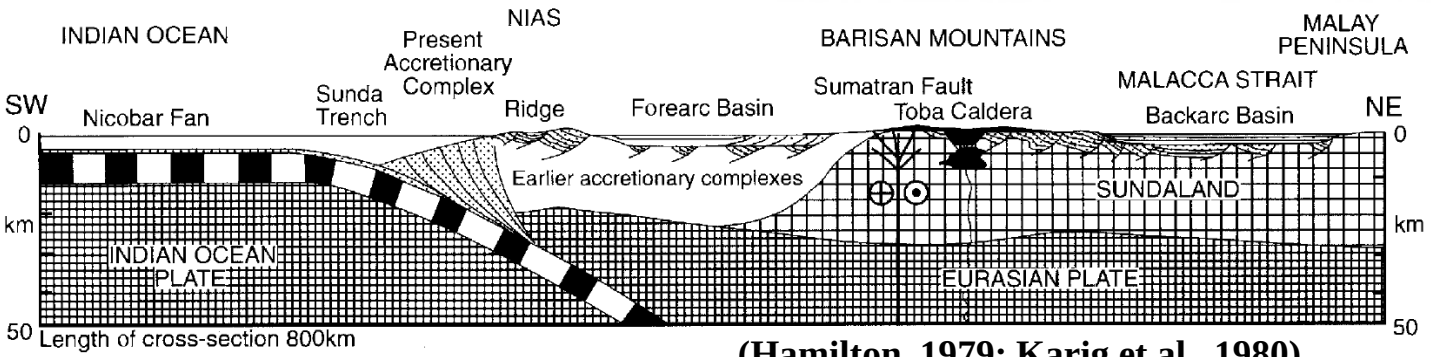
Hamilton (1979)

Three major units:

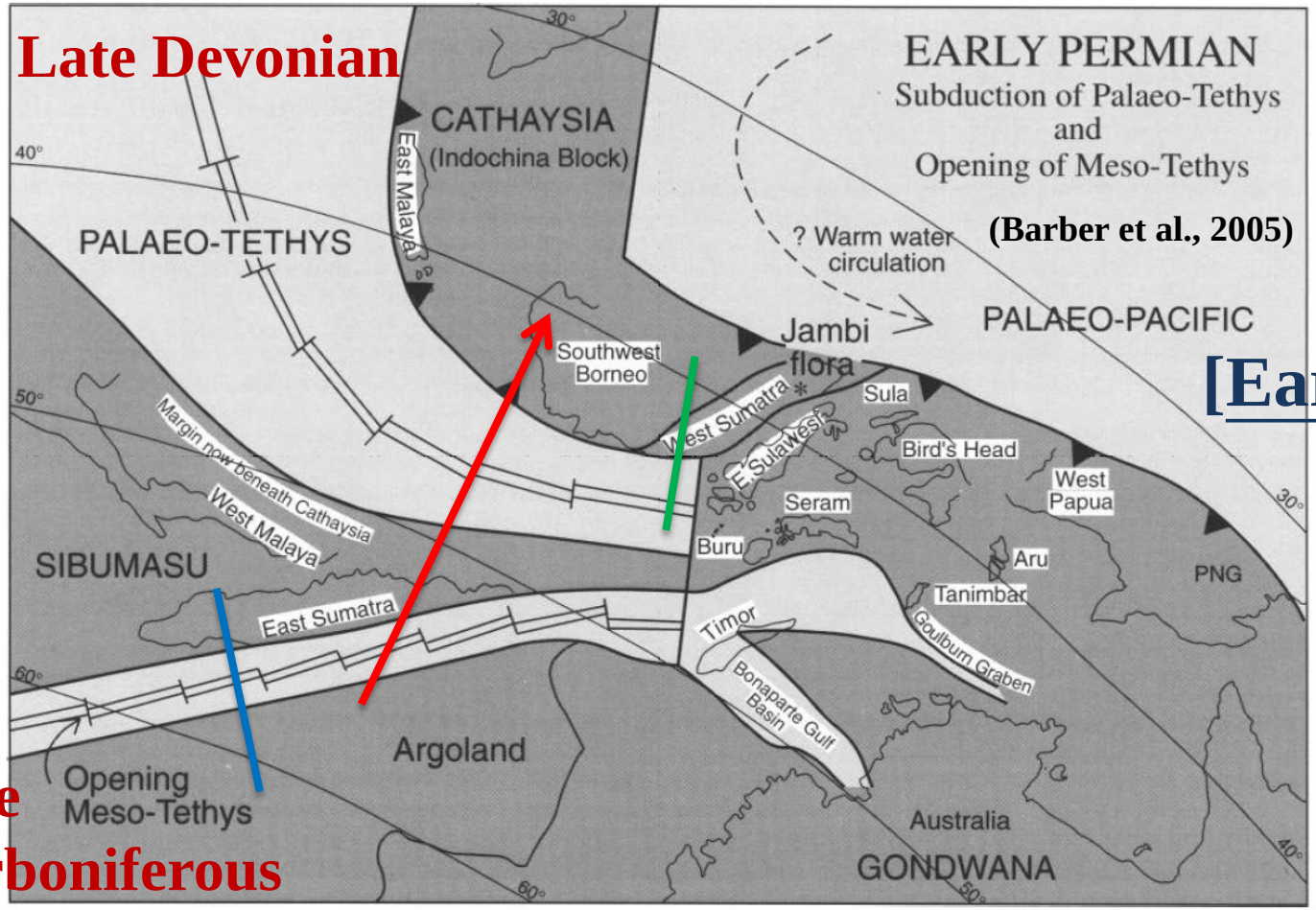
- **Forearc region**
- **Barisan Mountains**
- **Backarc region**



(Barber and Crow, 2005)

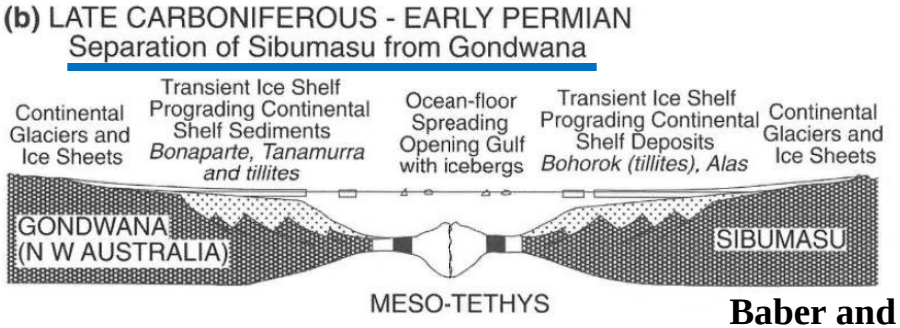


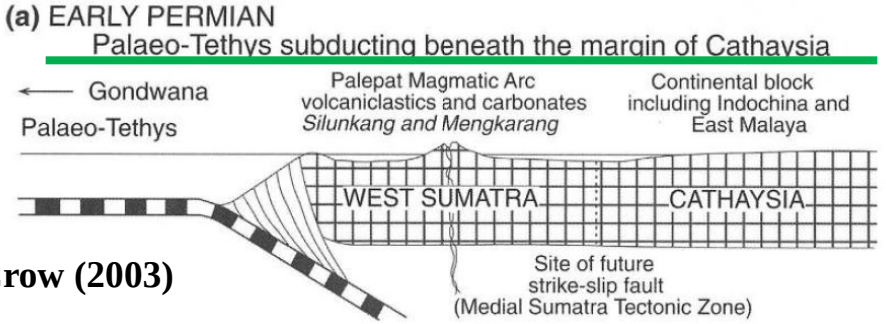
(Hamilton, 1979; Karig et al., 1980)



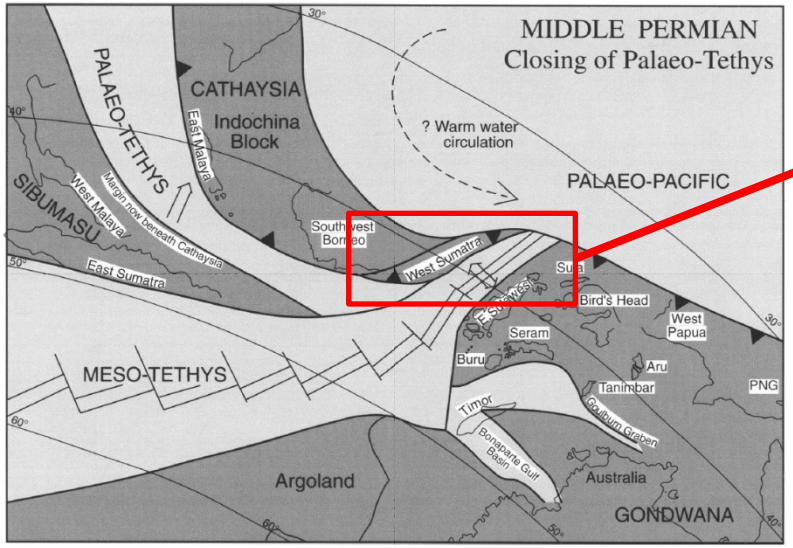
[Early Permian]

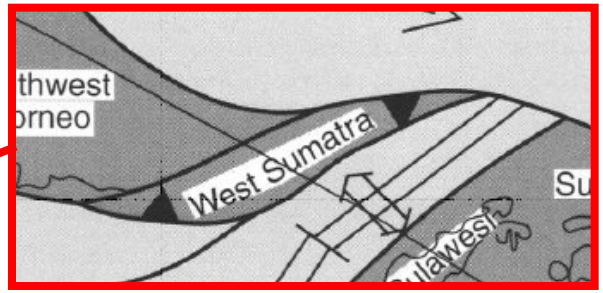
Late Carboniferous





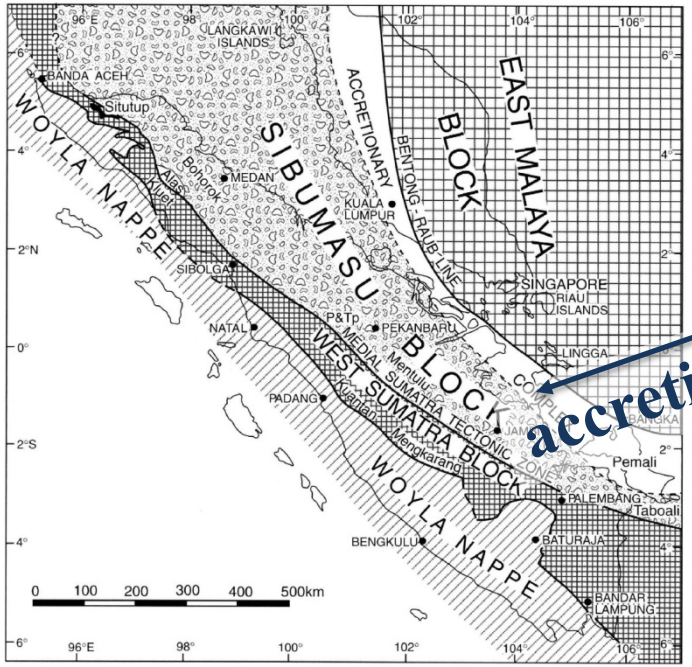
Baber and Crow (2003)





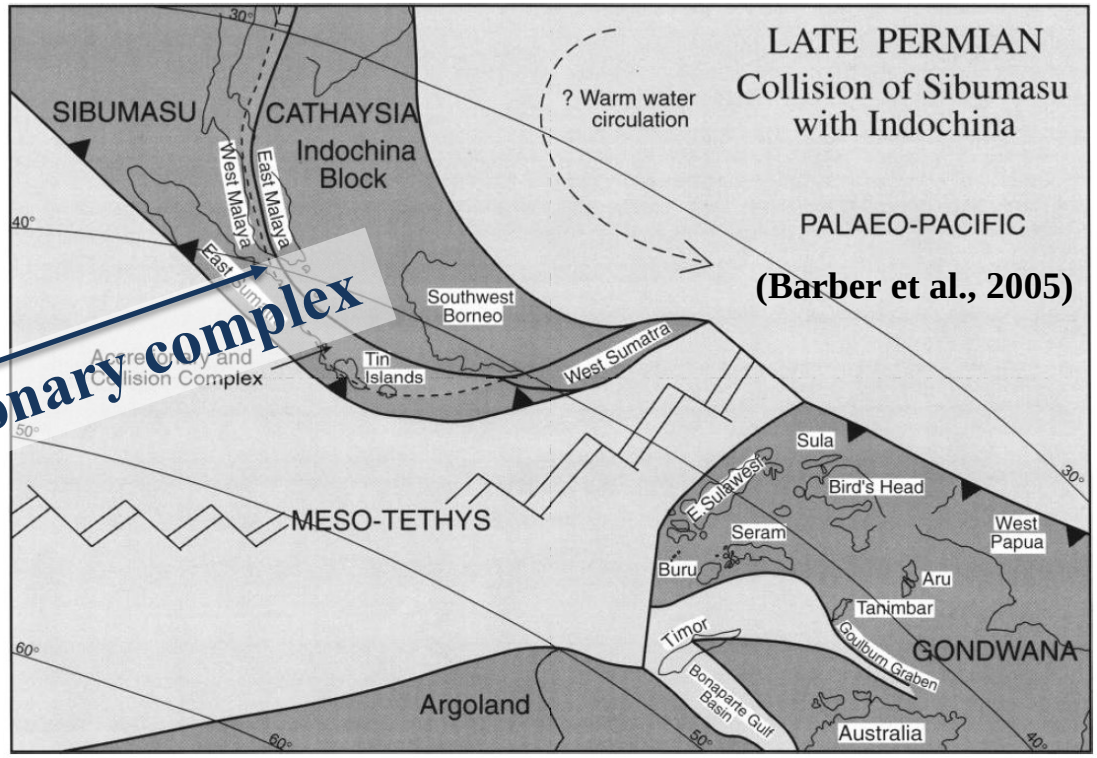
[Middle to Late Permian]

Here is the first arc system: the Permian arc.



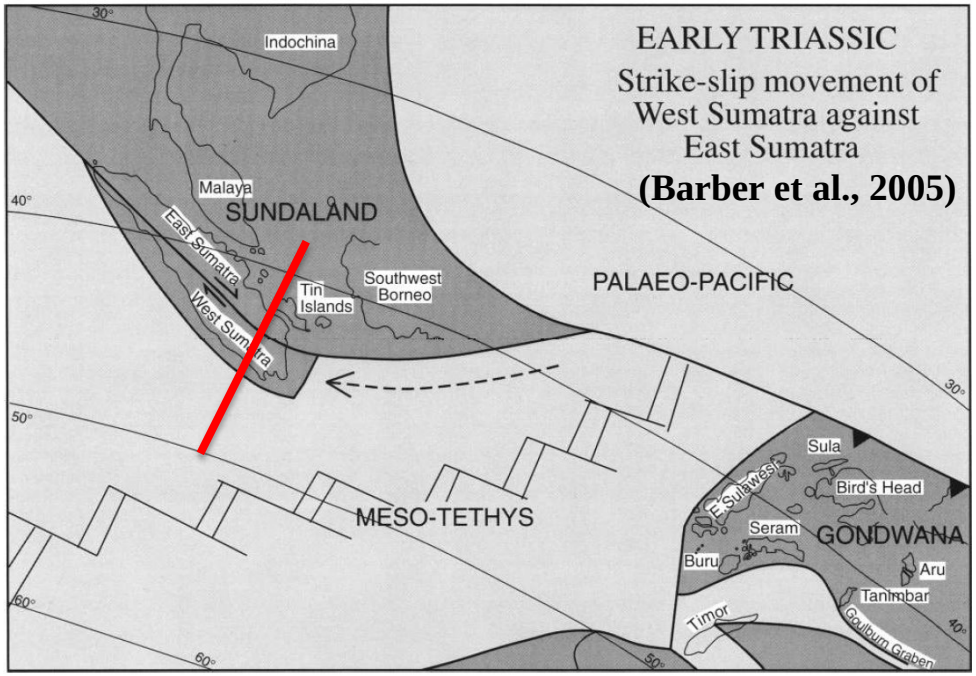
(Hutchison, 1994; Barber and Crow, 2003)

accretionary complex

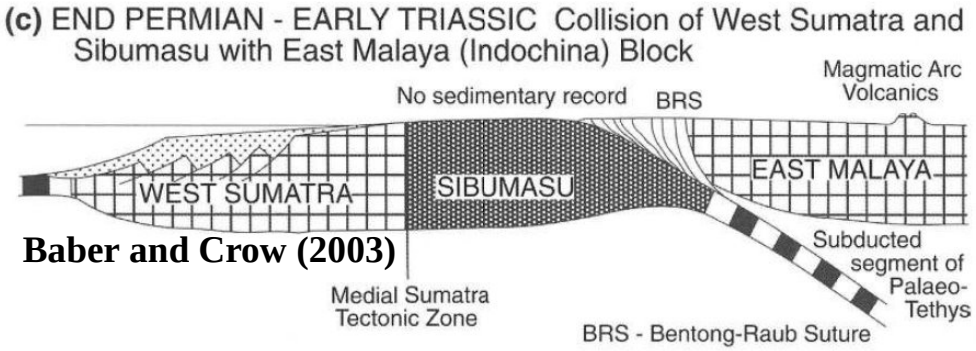


(Barber et al., 2005)

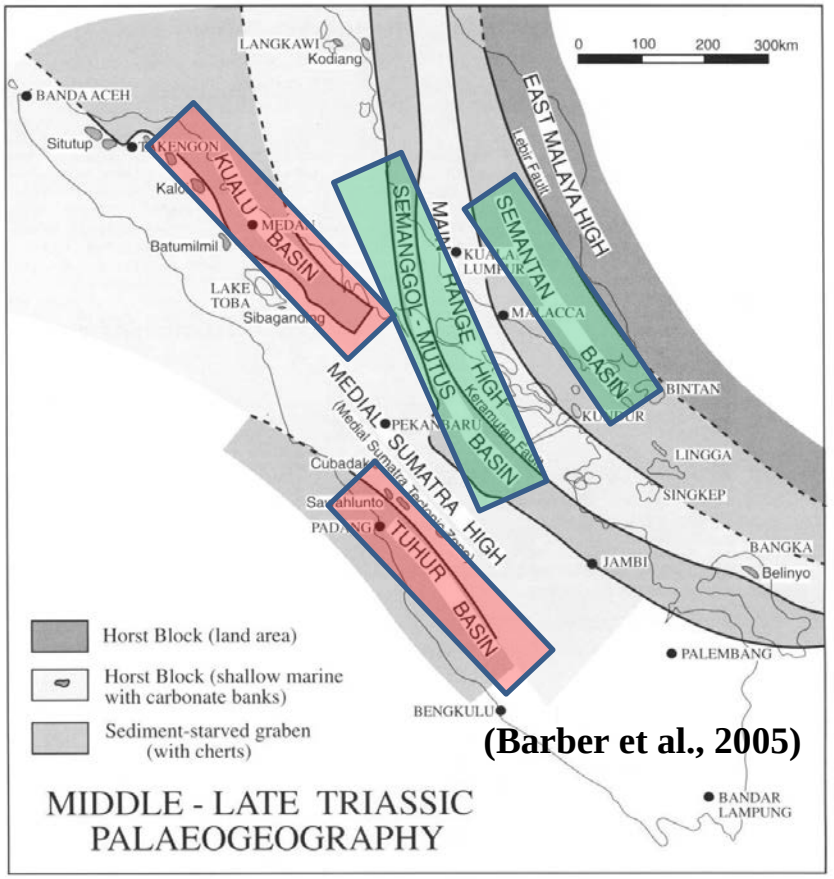
[Early to Late Triassic]



SIBUMASU + Cathaysia = Sundaland

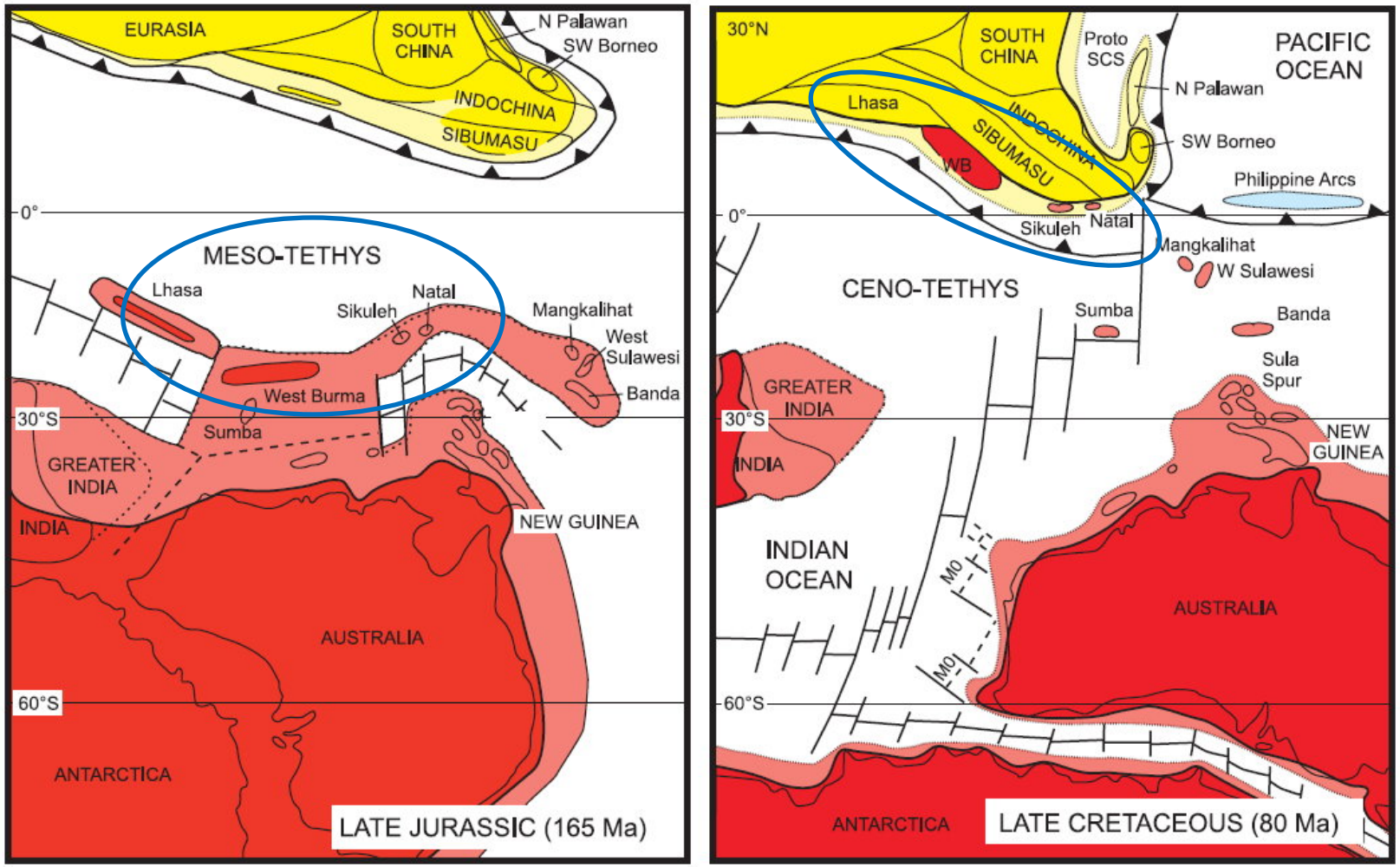


Baber and Crow (2003)



Many sedimentary basins formed during middle to late Triassic

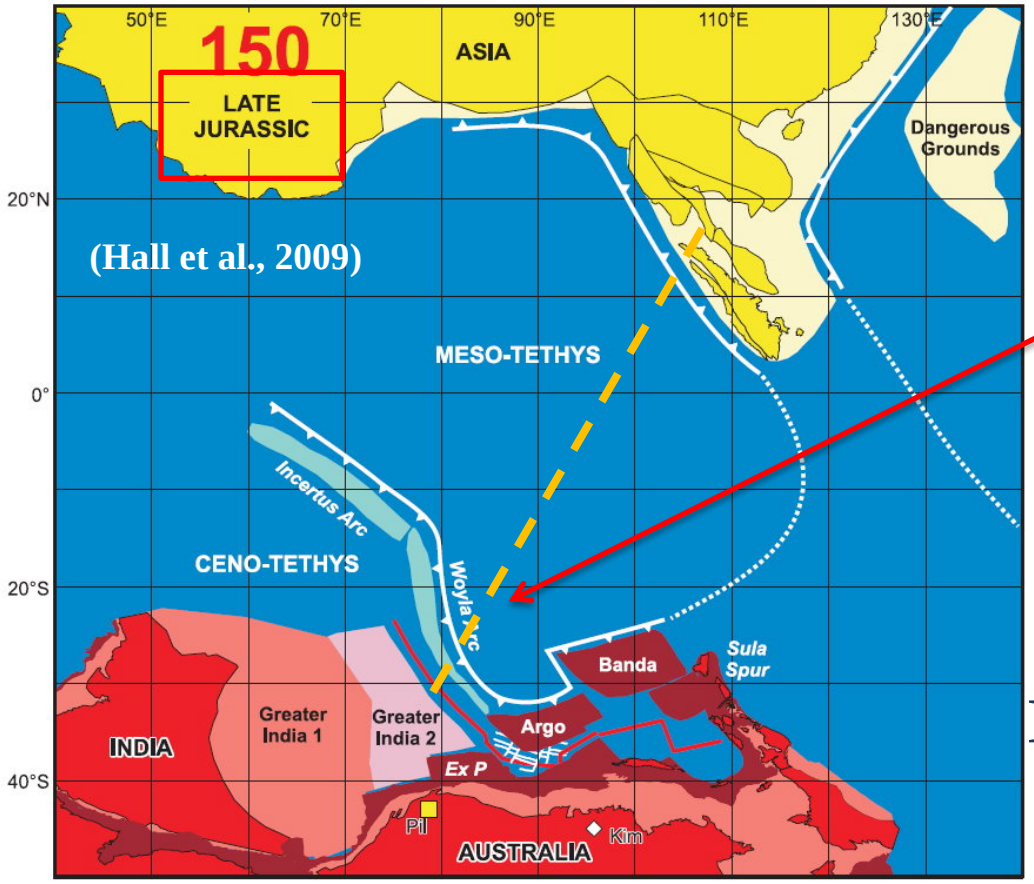
[Late Jurassic to Late Cretaceous]



(Hall et al., 2009)

Late Jurassic → **Late Cretaceous**

[Late Jurassic]

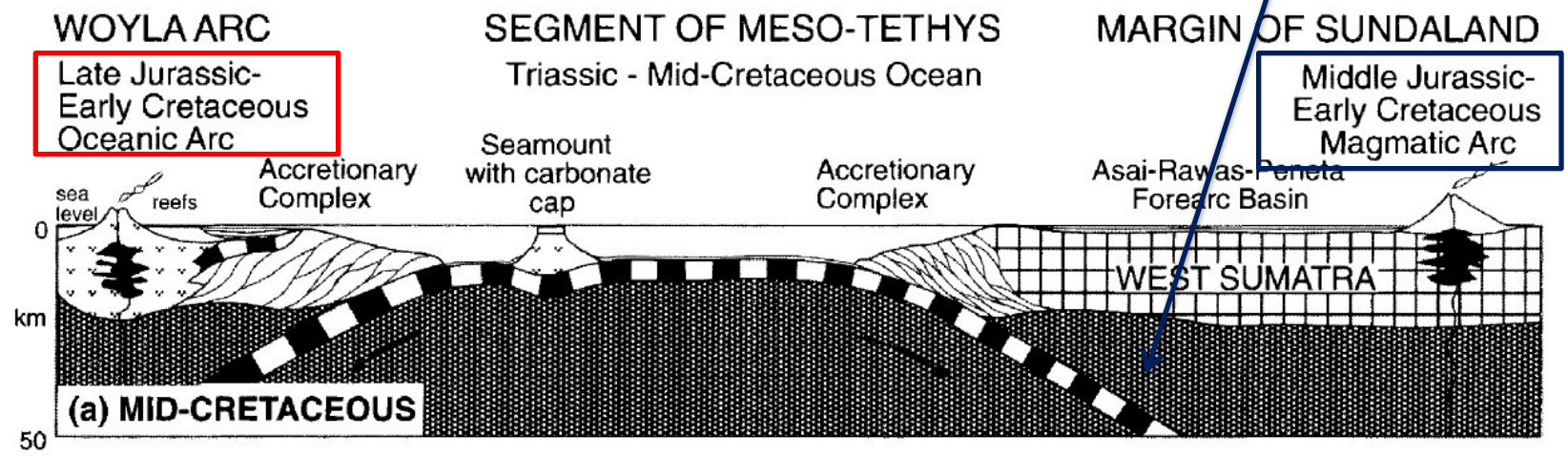


Woyla arc formed at late Jurassic.

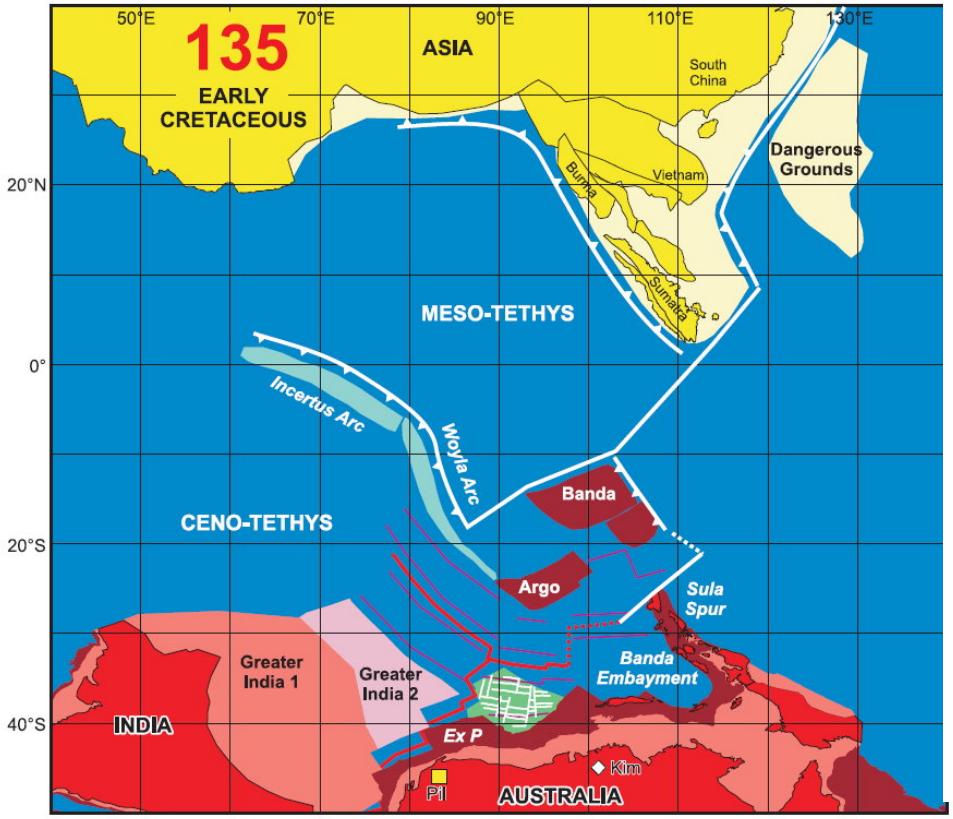
Here is the second arc system:
Mid Jurrasic
to Mid Cretaceous.

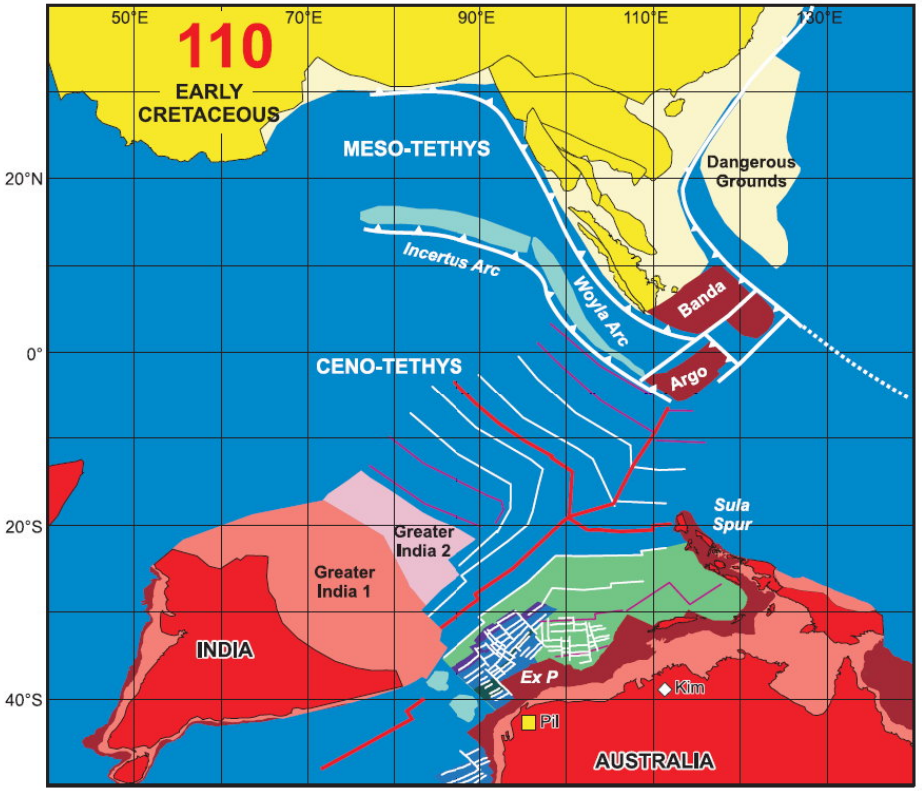
I-type 169Ma Bungo Batholith
203Ma Sulit Air Suite

(McCourt et al., 1996)



[Early Cretaceous]

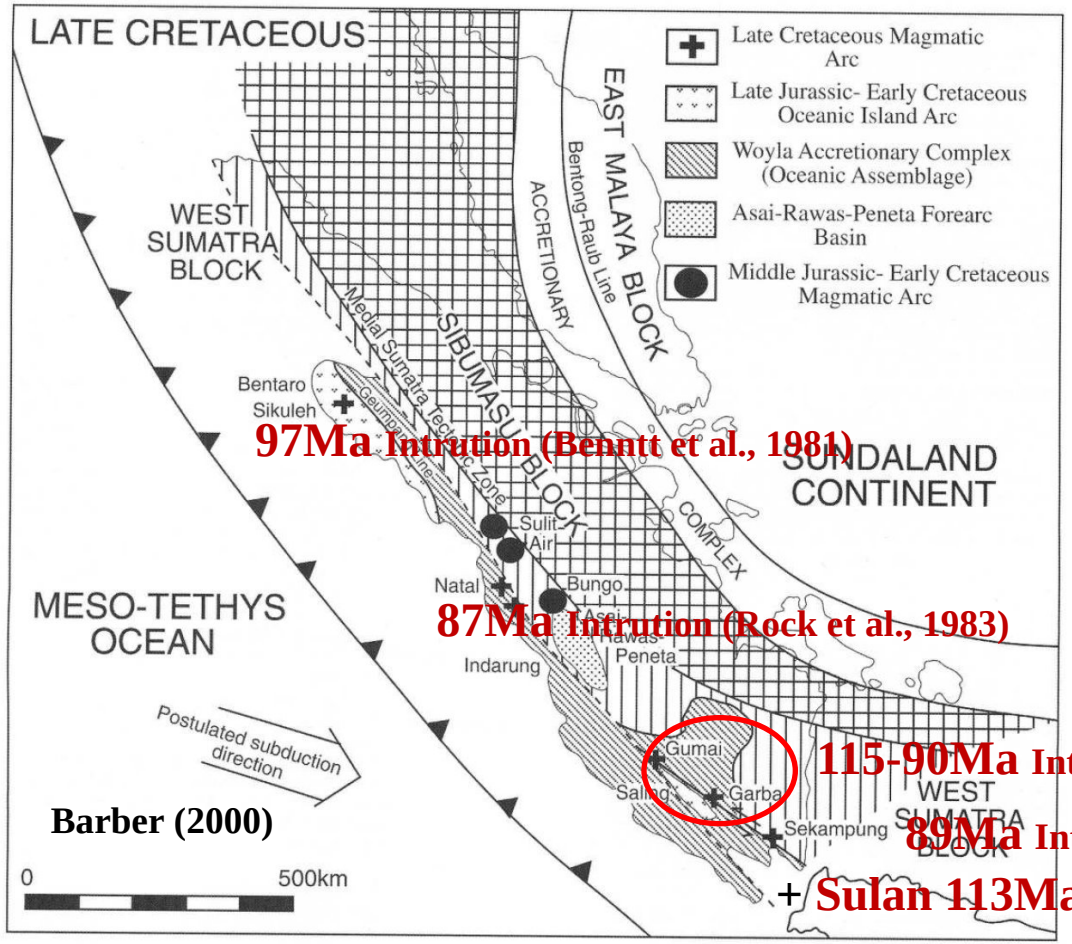




(Hall et al., 2009)

In early Cretaceous:

1. Woyla arc, Argo, Banda moved toward northern.
2. India separated from Antarctica and Australia.
3. The direction of subduction changed at about 110 Ma ago.



Barber (2000)

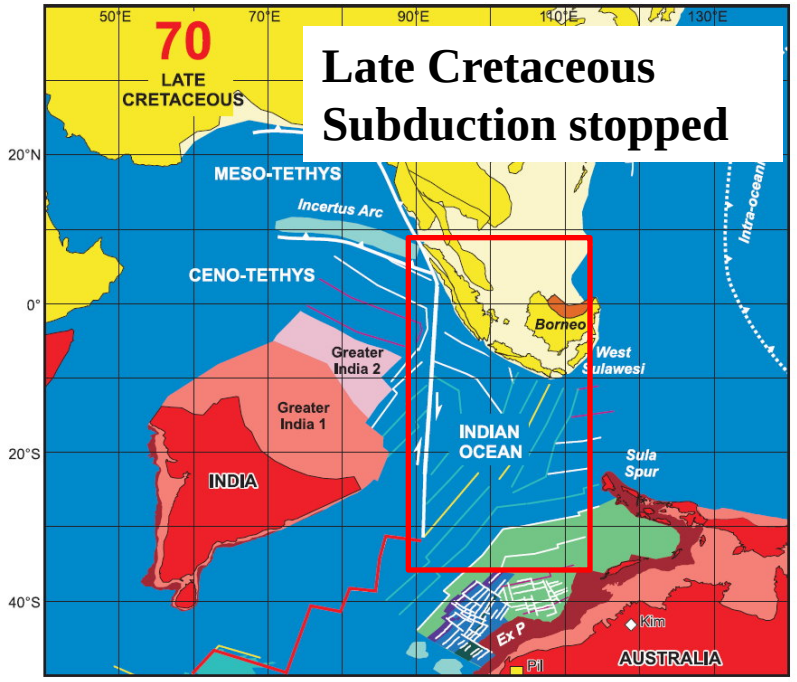
97Ma Intrution (Bennett et al., 1981)

87Ma Intrution (Rock et al., 1983)

115-90Ma Intrution (Gafoer et al., 1994)

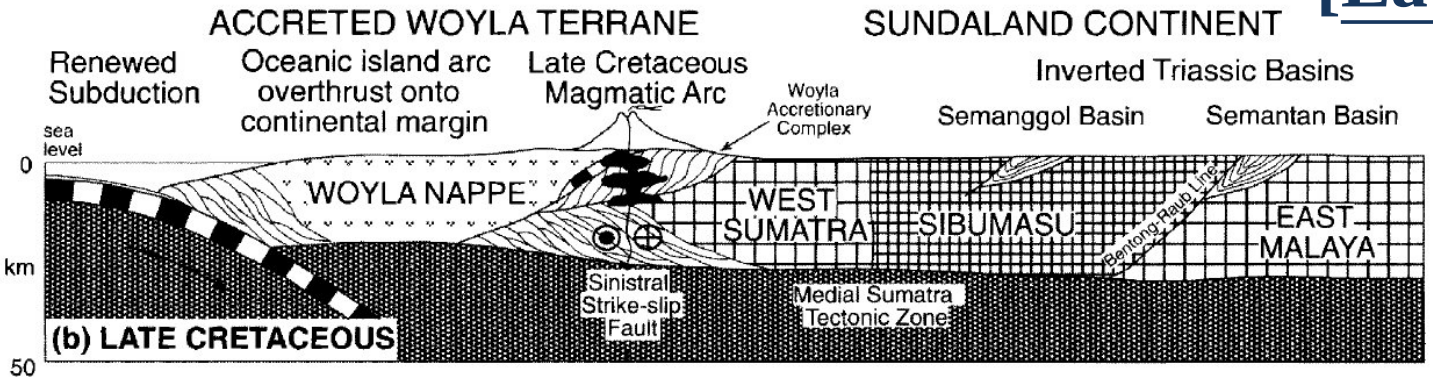
89Ma Intrution (Andi Mangga et al., 1994)

Sulan 113Ma Intrution (Amin et al., 1994)

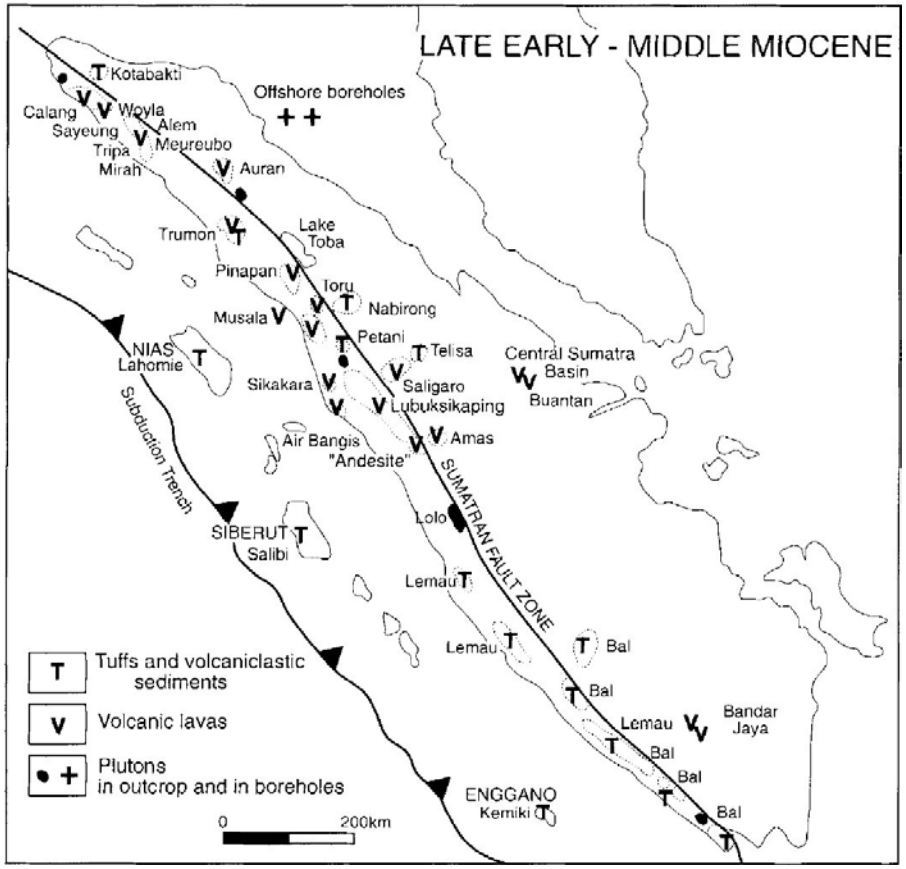


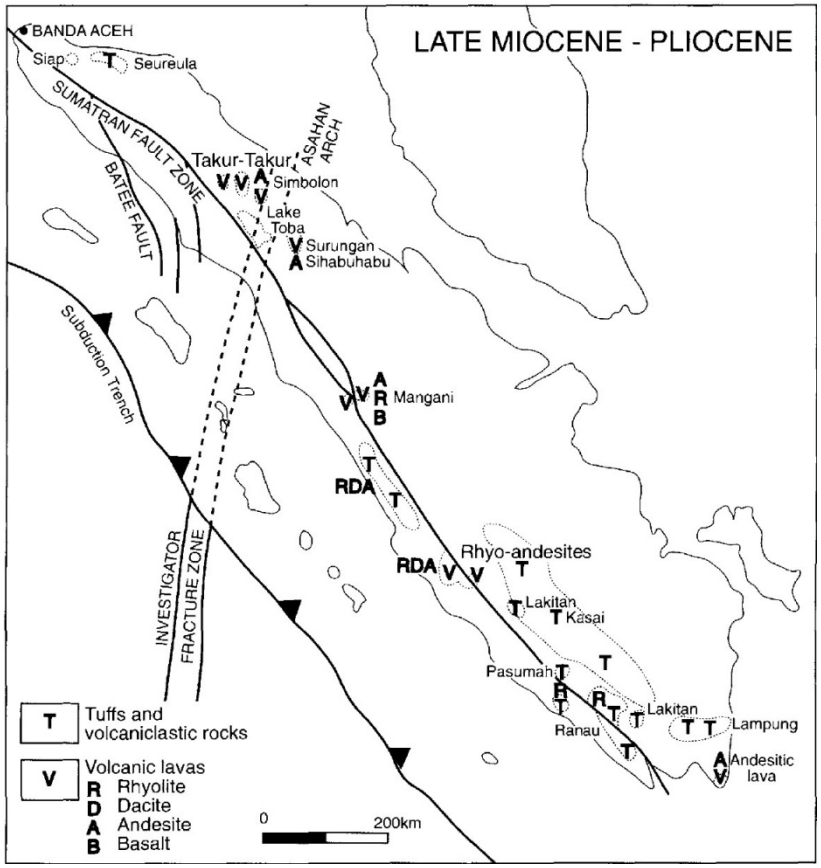
(Hall et al., 2009)

[Late Cretaceous]

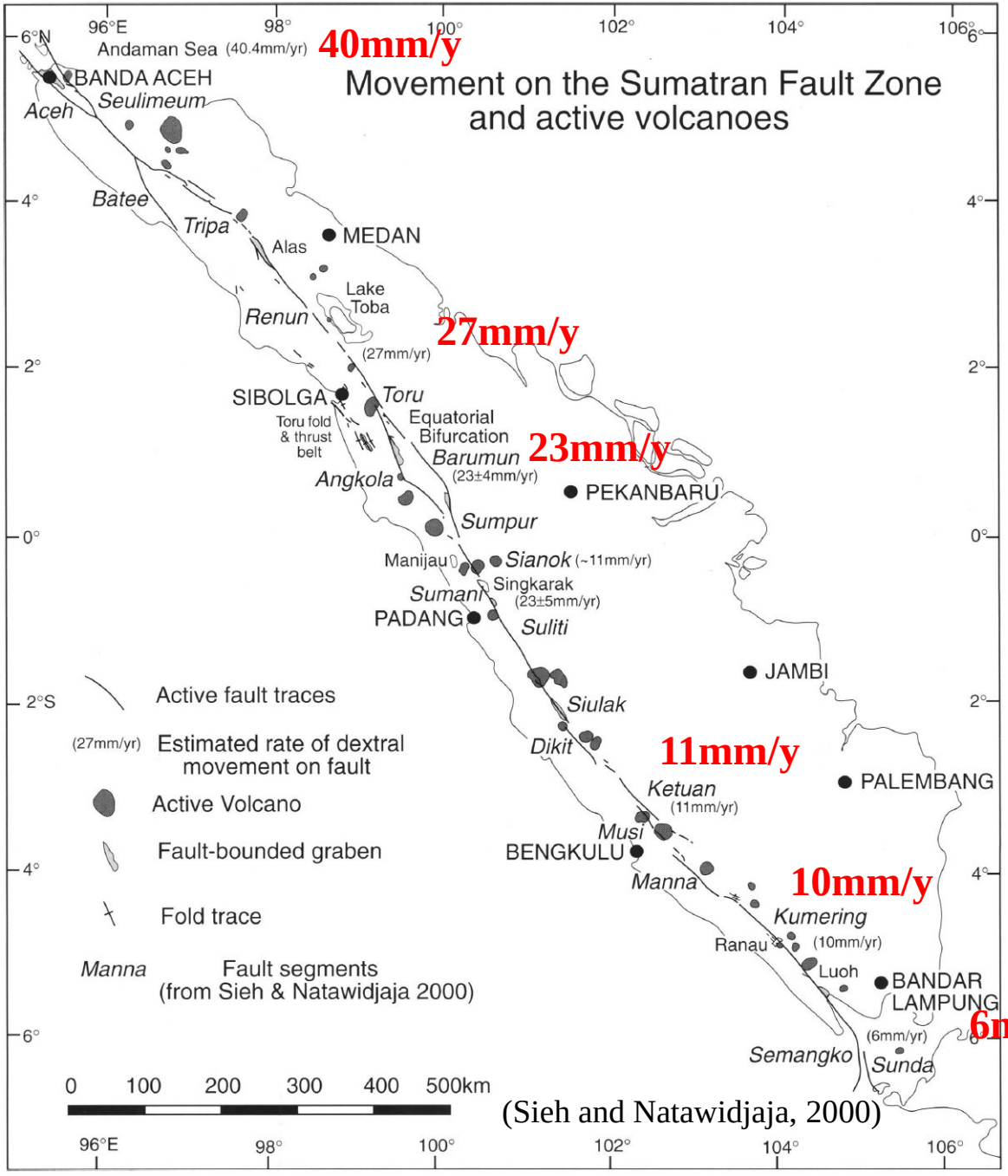


Here is the third arc system: the Late Cretaceous.


LATE EARLY - MIDDLE MIOCENE
Kotabakti
Offshore boreholes
Calang
Woyla
Sayeung
Alem
Meureubo
Tripa
Mirah
Auran
Trumon
Lake Toba
Pinapan
Ioru
Nabirong
Musala
Petani
Telisa
NIAS
Lahomie
Central Sumatra Basin
Sikakara
Saligaro
Lubuksikaping
Buantan
Air Bangis
"Andesite"
Amas
Subduction Trench
SUMATRAN FAULT ZONE
Lolo
SIBERUT
Salibi
Lemau
Bal
Lemau
Bandar Jaya
Bal
Bal
Bal
ENGGANO
Kemiki
Tuffs and volcaniclastic sediments
Volcanic lavas
Plutons in outcrop and in boreholes
0
200km


LATE MIOCENE - PLIOCENE
BANDA ACEH
Siap
Seureula
SUMATRAN FAULT ZONE
BATEE FAULT
ASAHAN ARCH
Takur-Takur
Simbolon
Lake Toba
Surungan
Sihabuhabu
Subduction Trench
Mangani
RDA
Rhyo-andesites
INVESTIGATOR FRACTURE ZONE
Lakitan
Kasai
Pasumah
Ranau
Lakitan
Lampung
Andesitic lava
Tuffs and volcaniclastic rocks
Volcanic lavas
R Rhyolite
D Dacite
A Andesite
B Basalt
0
200km

(Crow, 2005)



(Sieh and Natawidjaja, 2000)

Methods

SIMS (Secondary Ion Mass Spectrometry)

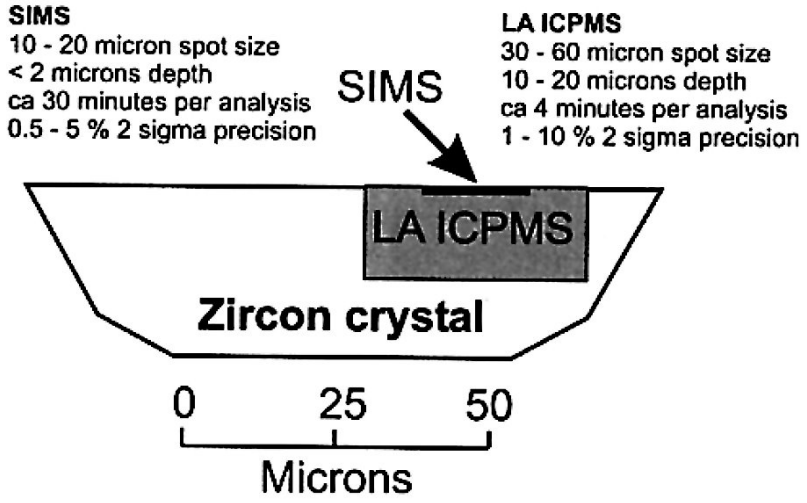
SHRIMP (Sensitive High-Resolution Ion Microprobe)

fist ion: O_2 beam size: 10 to 50 μm (~5 μm)

Cameca NanoSIMS 50

beam size: 1 to 2 μm

high sensitivity, high precision
more expensive, much time



ICP-MS

(Laser Ablation-Inductively Coupled Plasma-Mass Spectrometer)

Laser beam: 40 μm

measure: Pb, U, Th isotopic ratios