Bandung Train The Trainers 16th -28th May 2016

Introduction to geothermal systems and basics of volcanology

Train The Trainers workshop , WP 1.04 WP leader Peter Fokker TNO

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Module on hydrothermal systems

Hydrothermal system module

- Main components of hydrothermal systems (geology)
- Tectonic setting: intra-plate, passive margin, heat transport

Break ☺

- Volcanoes: **geology of geothermal systems in Indonesia**
- Eruptive products in the **field - reservoir rocks**
- Petrography and geochemistry of magmas: **reservoir rock properties**

Break ☺

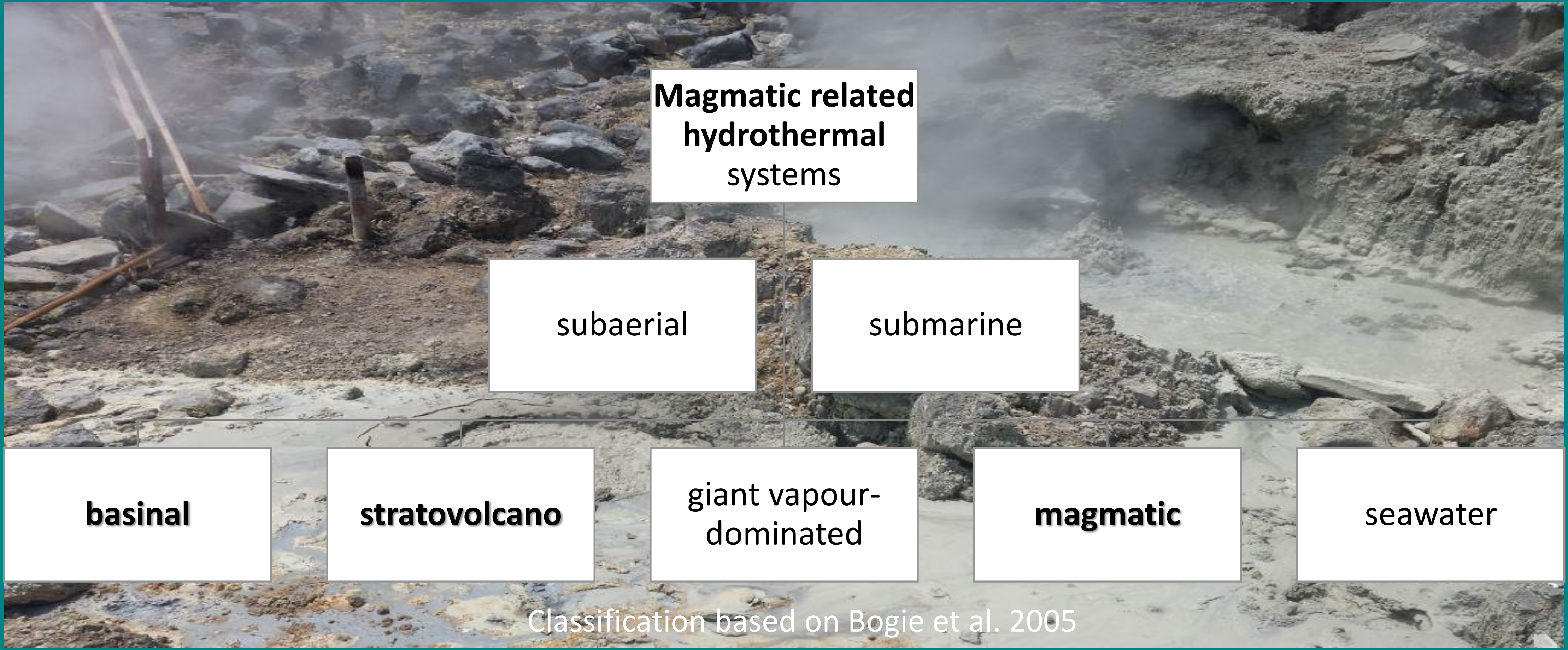
- Geophysics: examples from resistivity studies
- Geothermal systems: conceptual model example from East Java

Afternoon practice excercise

- Rock observation and description
- Microscope observation of thin sections

- Exercise
- Reservoir rock evaluation:
- may a rock act as reservoir?

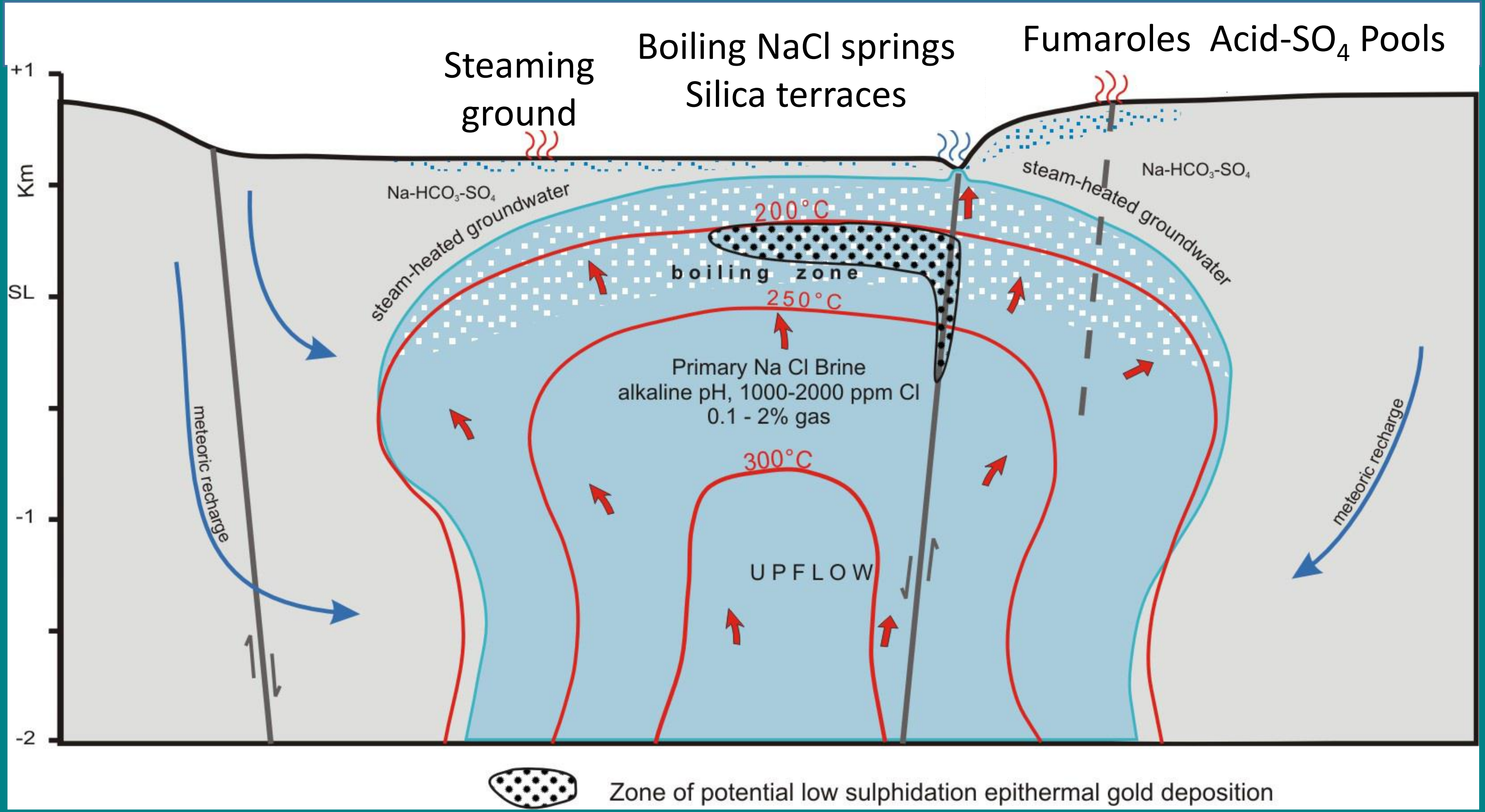
Classification of magmatic related hydrothermal systems



Classification based on Bogie et al. 2005

Basinal type hydrothermal system

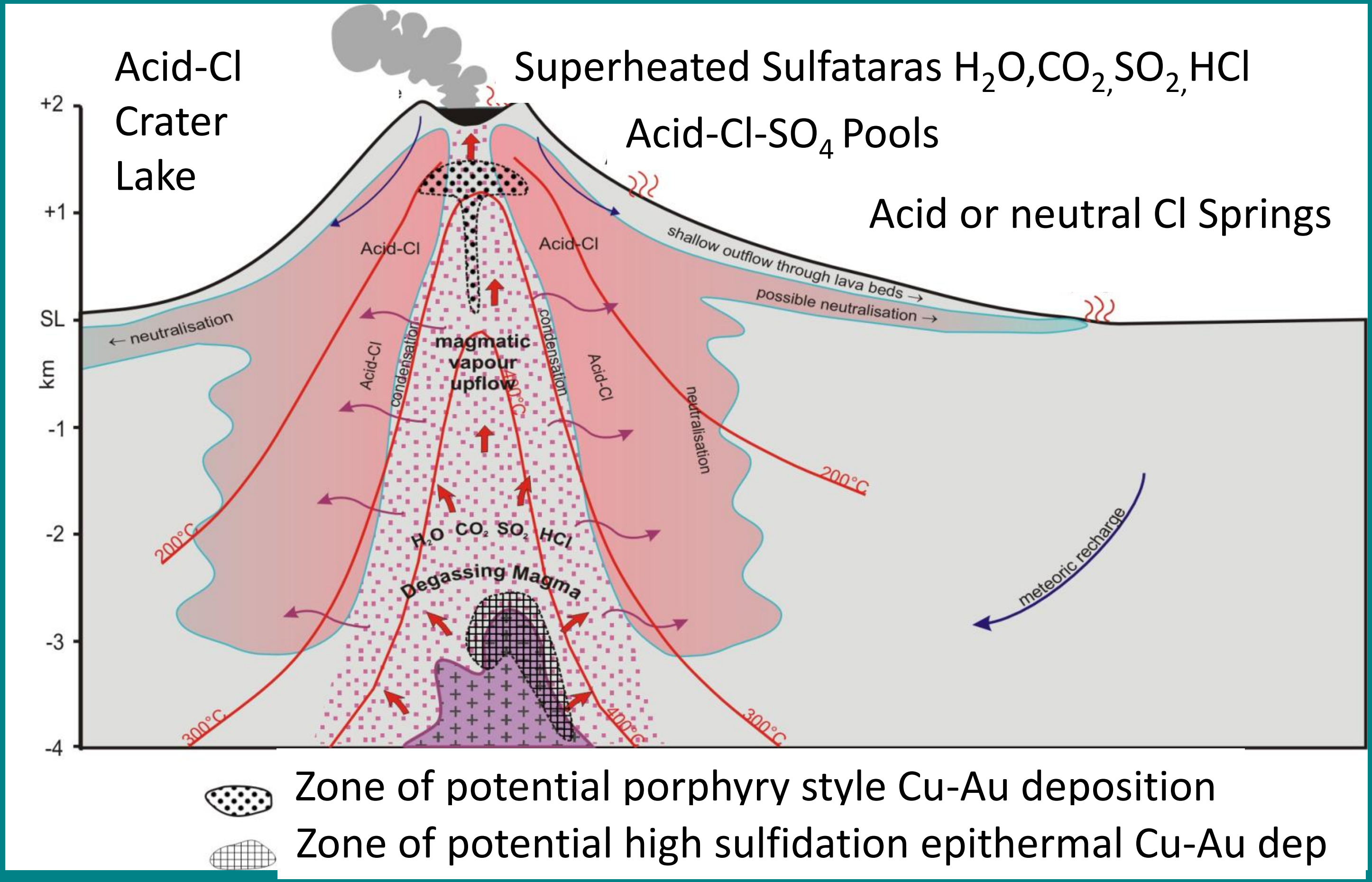
Setting: **pull apart basin**
Suoh, Sumatra, Indonesia
Wairakei New Zealand
Boiling area shallow
Deep convective hydrothermal waters reach the surface
Gold deposits may occur



Bogie et al. (2005)

Stratovolcanic type hydrothermal system

Andesitic stratovolcano often with caldera
Travertine deposits occur in the springs area
Neutral Cl springs can be developed

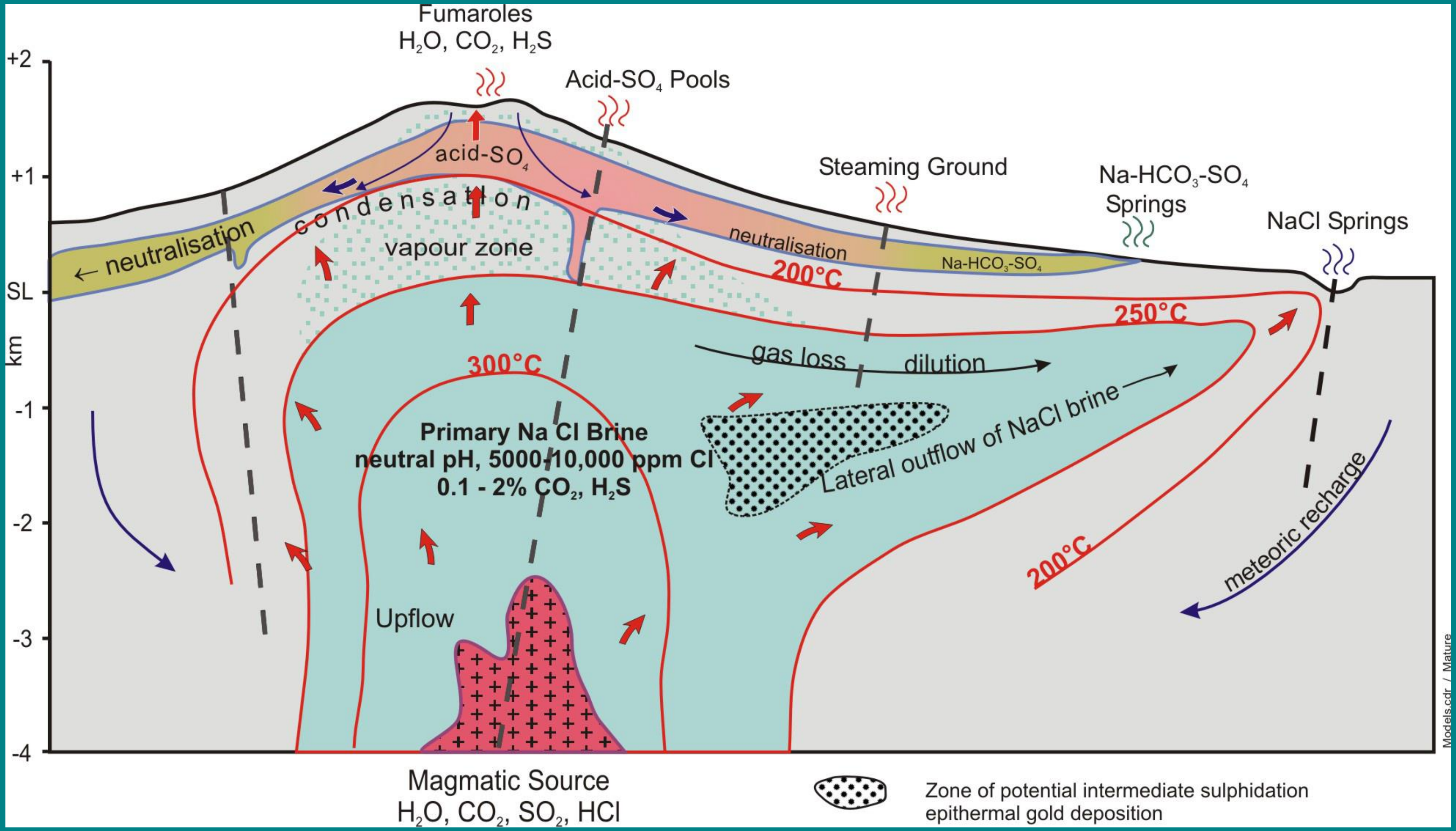


immature

Bogie et al. (2005)

Stratovolcano type hydrothermal system

Darajat/Kamojang, West Java, Indonesia
Example of the latest stage of a strato Volcano
Reservoir temperature approx. **240ºC**
Cl rich springs also at high elevations

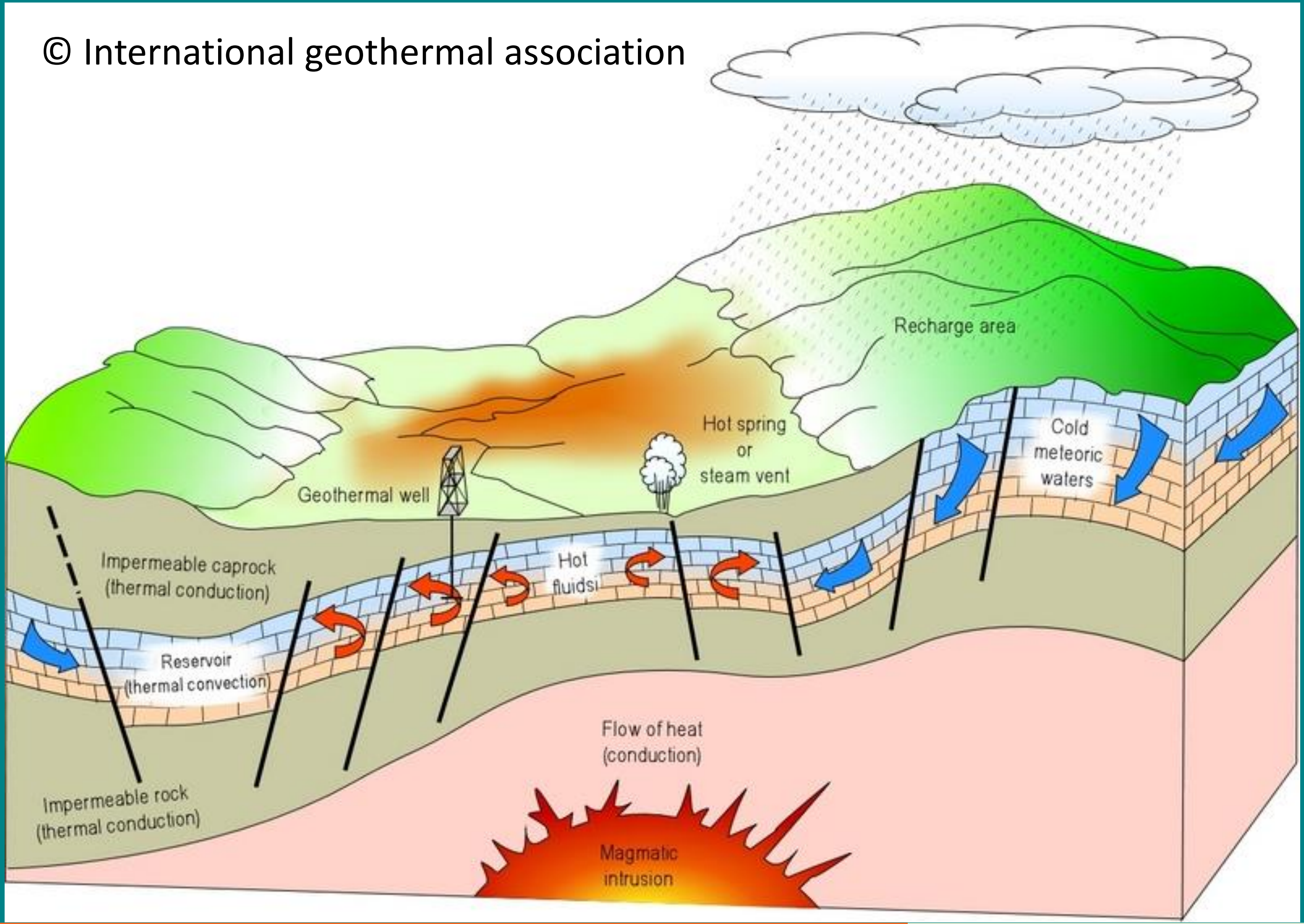


mature

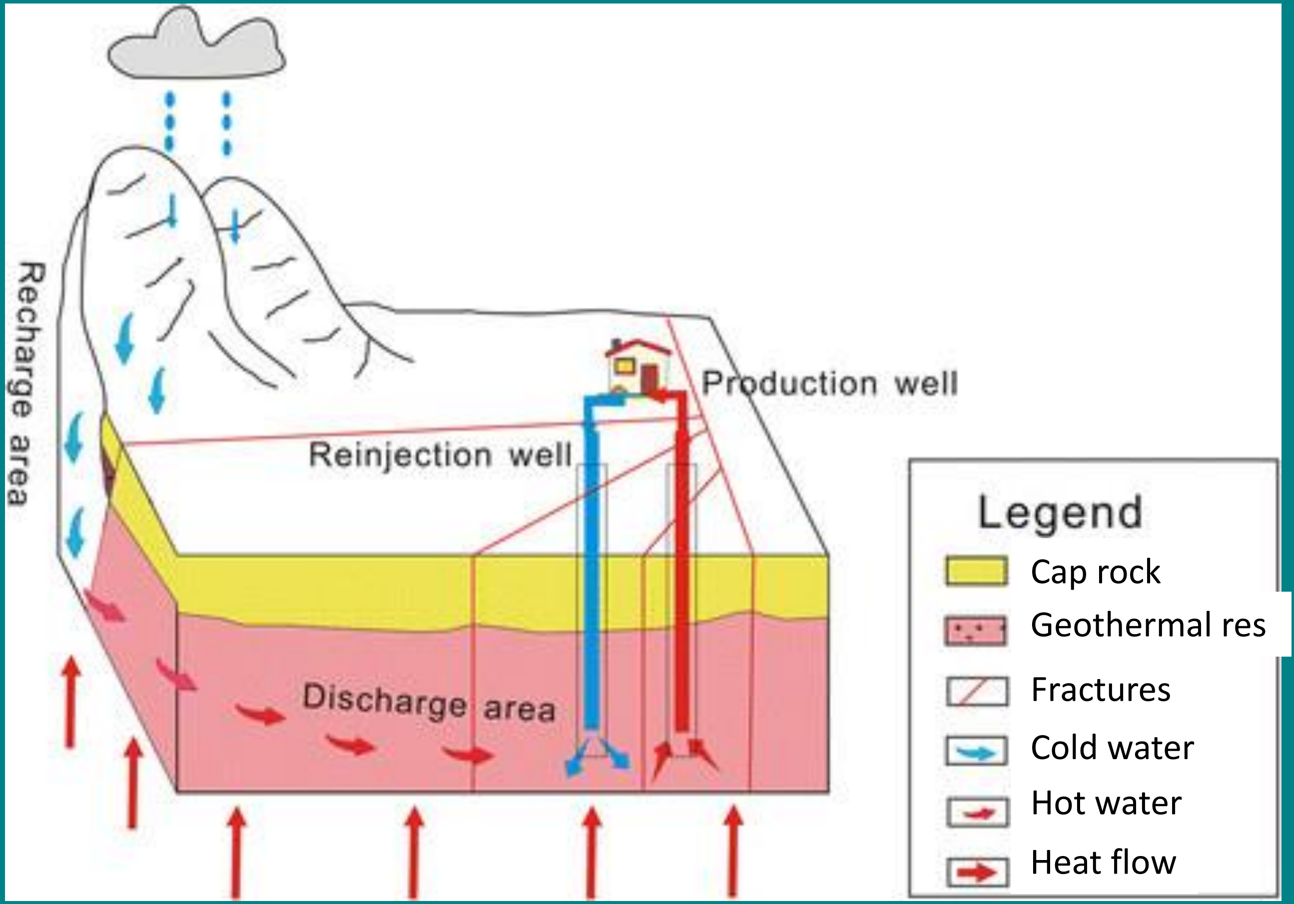
Bogie et al. (2005)

Hydrothermal systems: main components

- **Water**
- **Heat**
- **Fractures – pathways**
- **Heat conduction**

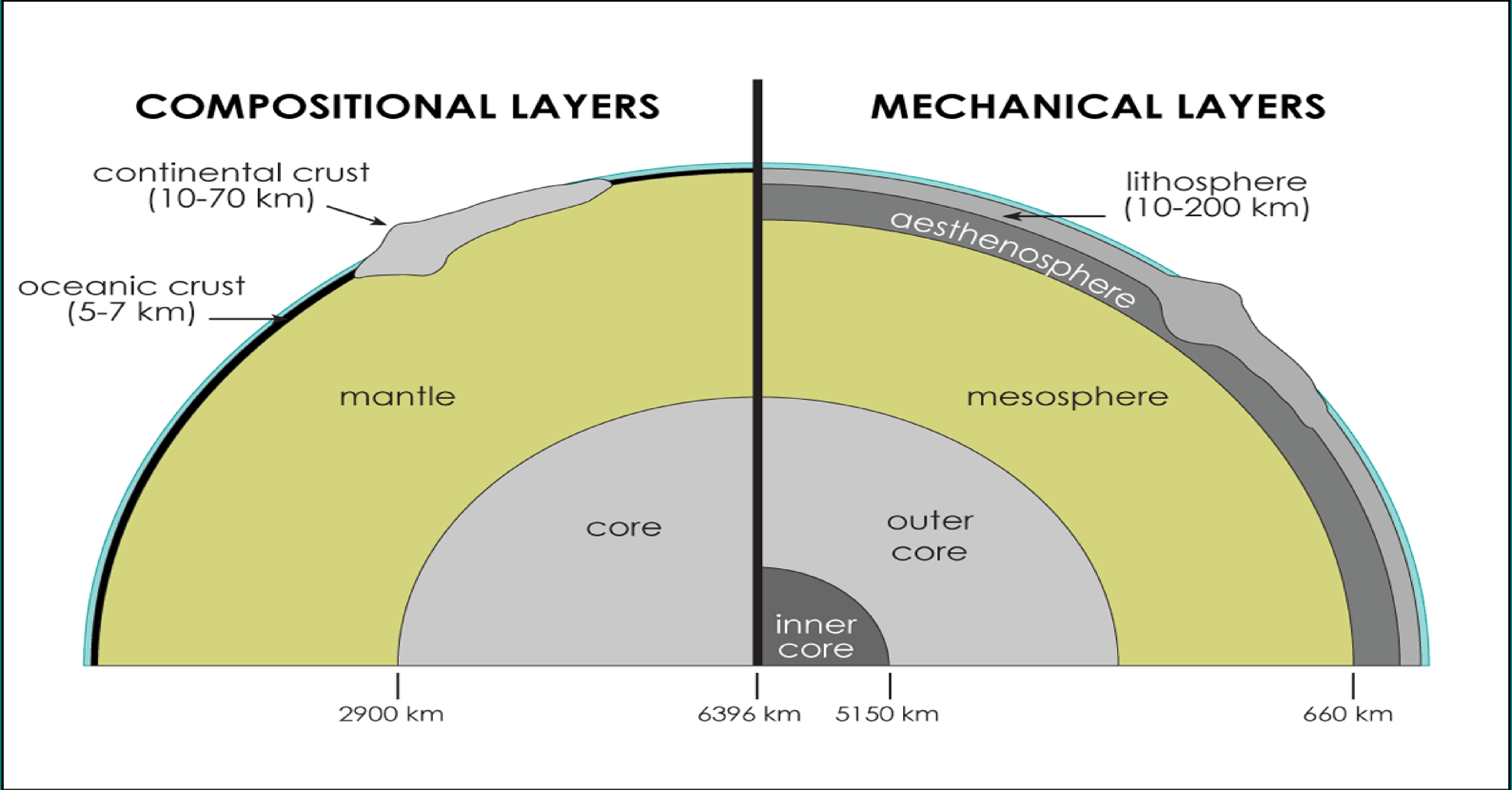


Hydrothermal system components

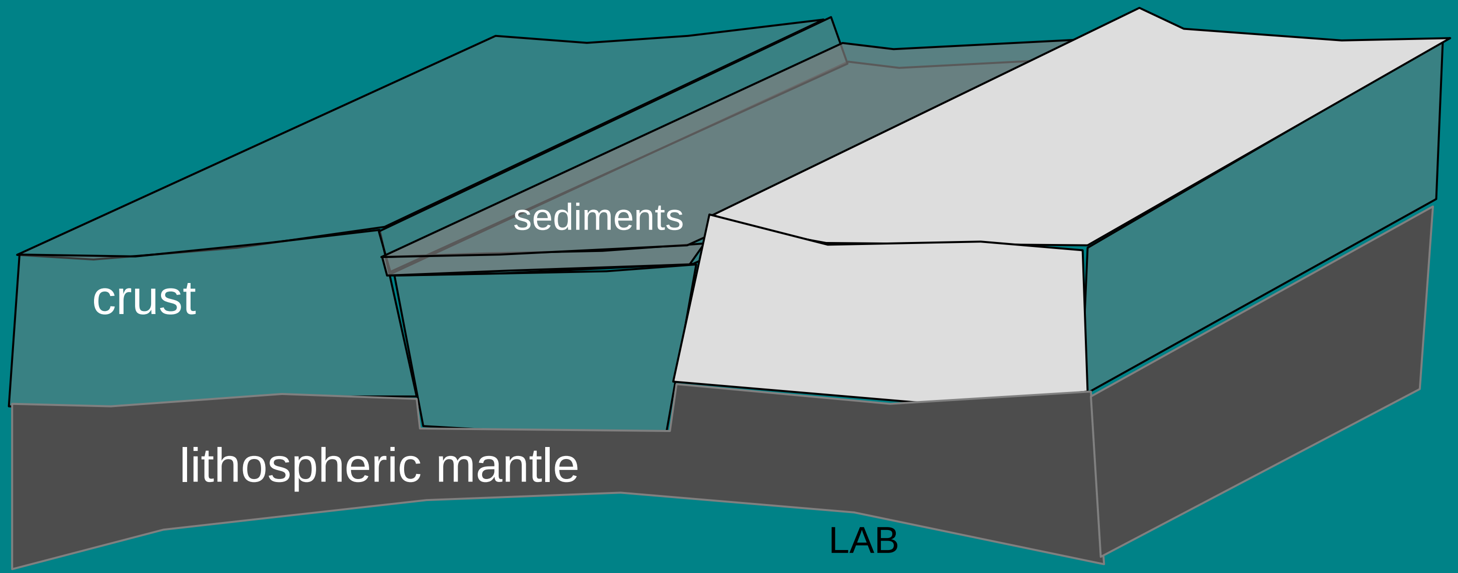


Recharge area: water is stored
Discharge area: hot water
Upflow area: area close to the reservoir
Outflow area: distal region of the geothermal systems

Kong et al. 2014


COMPOSITIONAL LAYERS
MECHANICAL LAYERS
continental crust
(10-70 km)
oceanic crust
(5-7 km)
mantle
core
lithosphere
(10-200 km)
aesthenosphere
mesosphere
outer
core
inner
core
2900 km
6396 km
5150 km
660 km

heat in reservoirs…



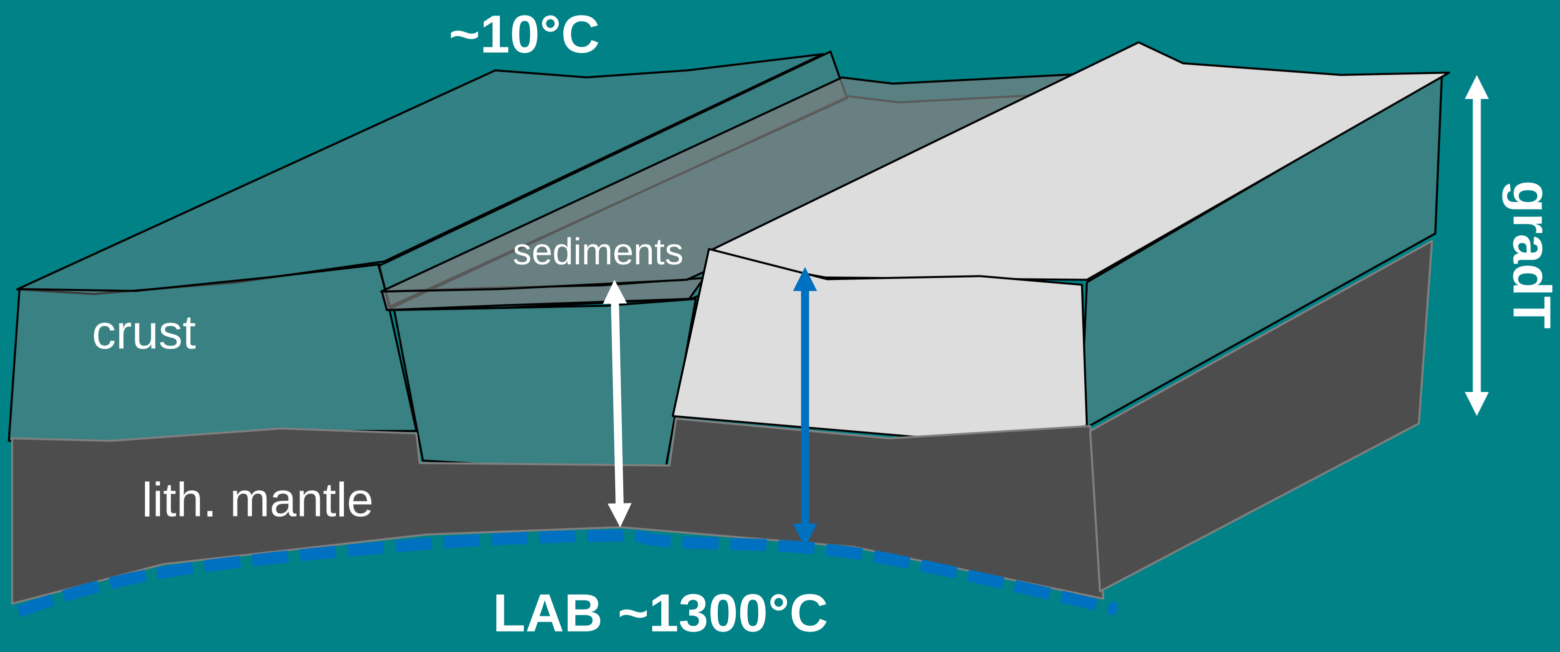
controlled by

heat sources

heat transport mechanisms

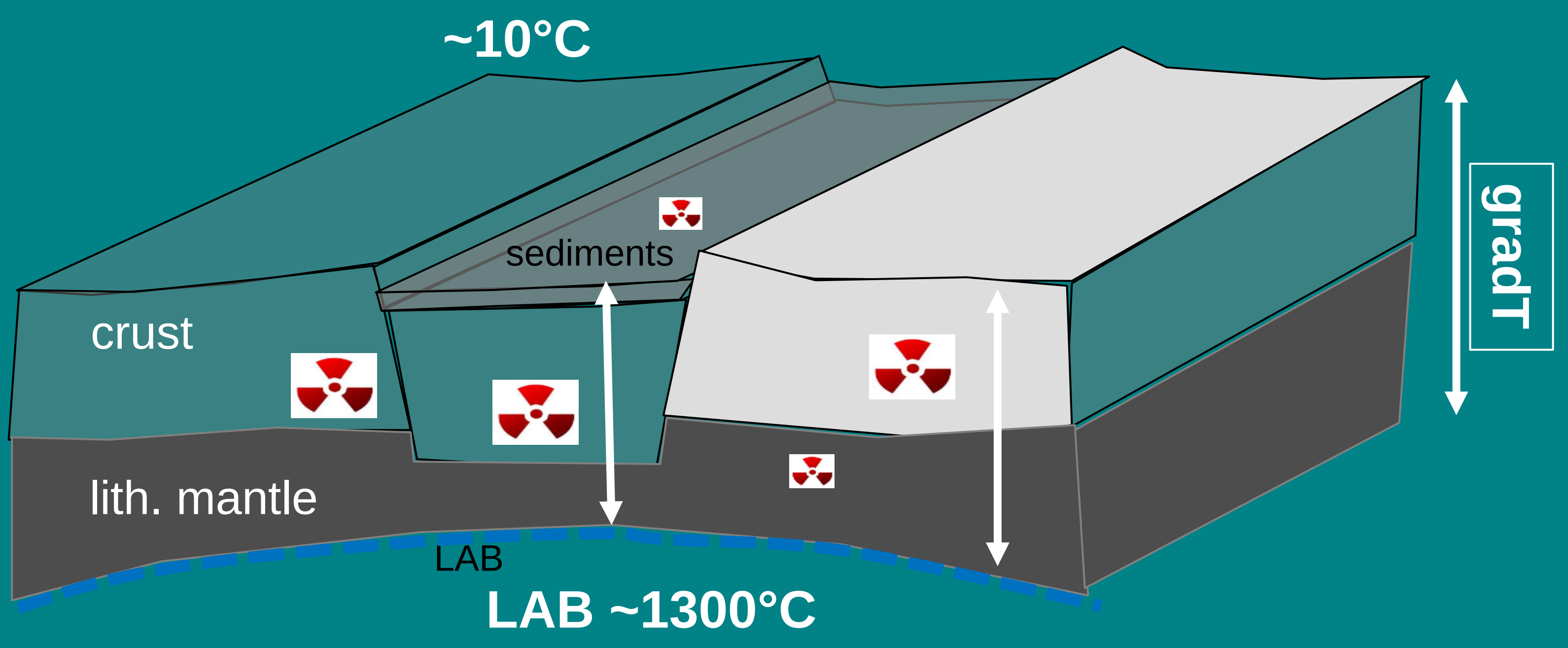
heat sources

- heat input from asthenosphere



heat sources

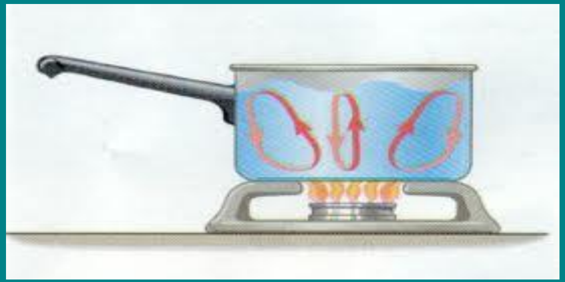
- heat input from asthenosphere
- radiogenic heat produced in the lithosphere



heat transport mechanism?

conduction

advection



convection

⇨by diffusion

⇨pressure driven

⇨bouyancy-driven

which relevant at which scale?

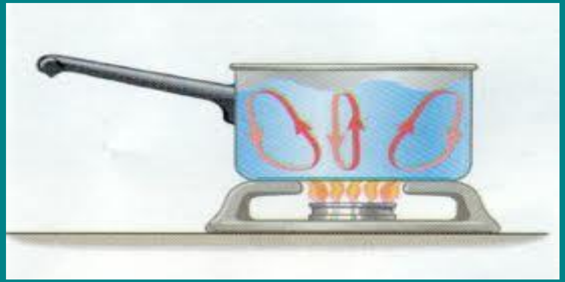
mechanisms of heat transport

conduction

advection

sediment fill

along faults



convection

relevance

⇨**dominant process**

lithosphere-scale

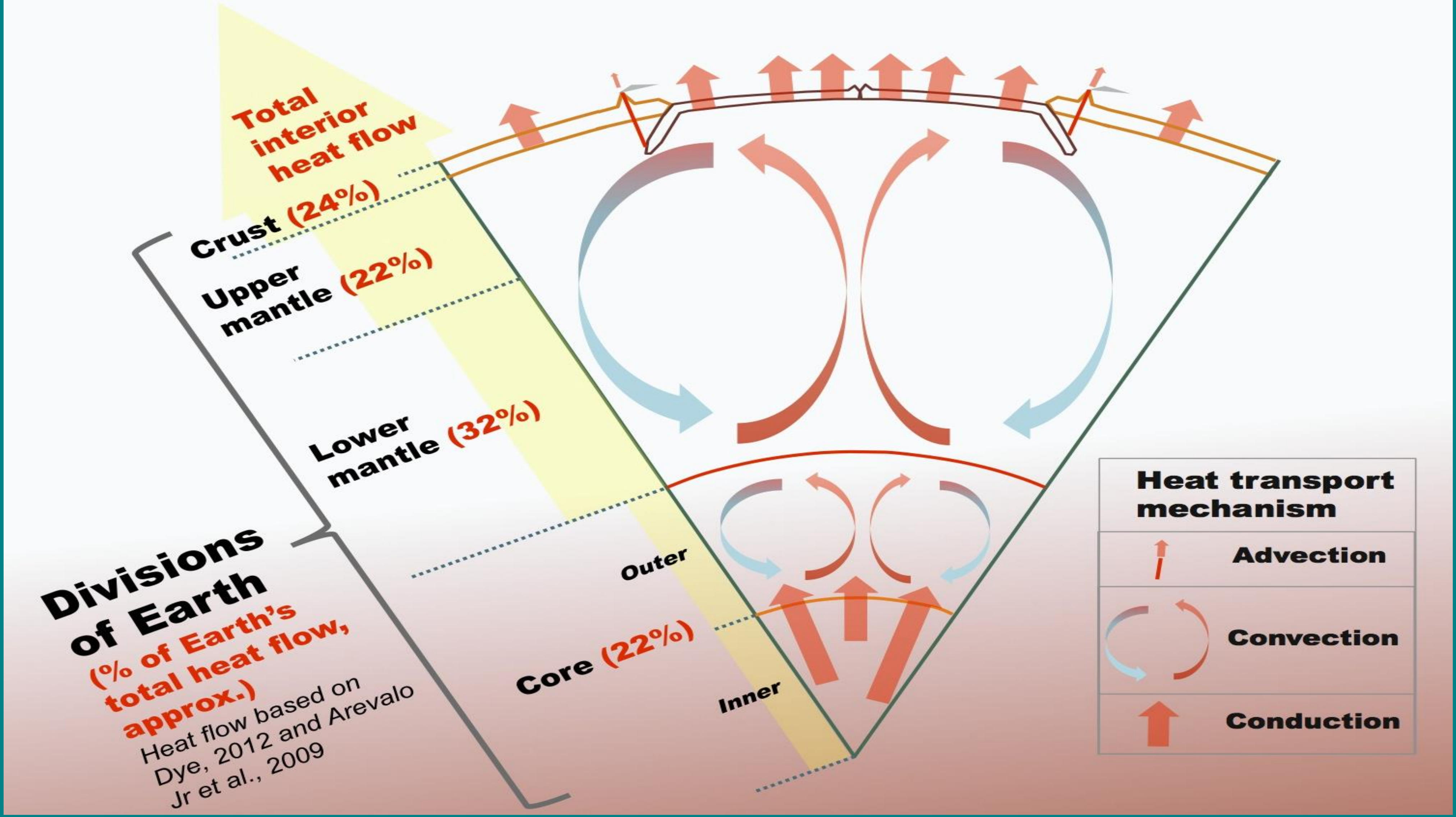
⇨**advective cooling** regional (basin-scale) importance

⇨**free convection**: **local** (low gradient in hydraulic head + sufficiently thick permeable layer)

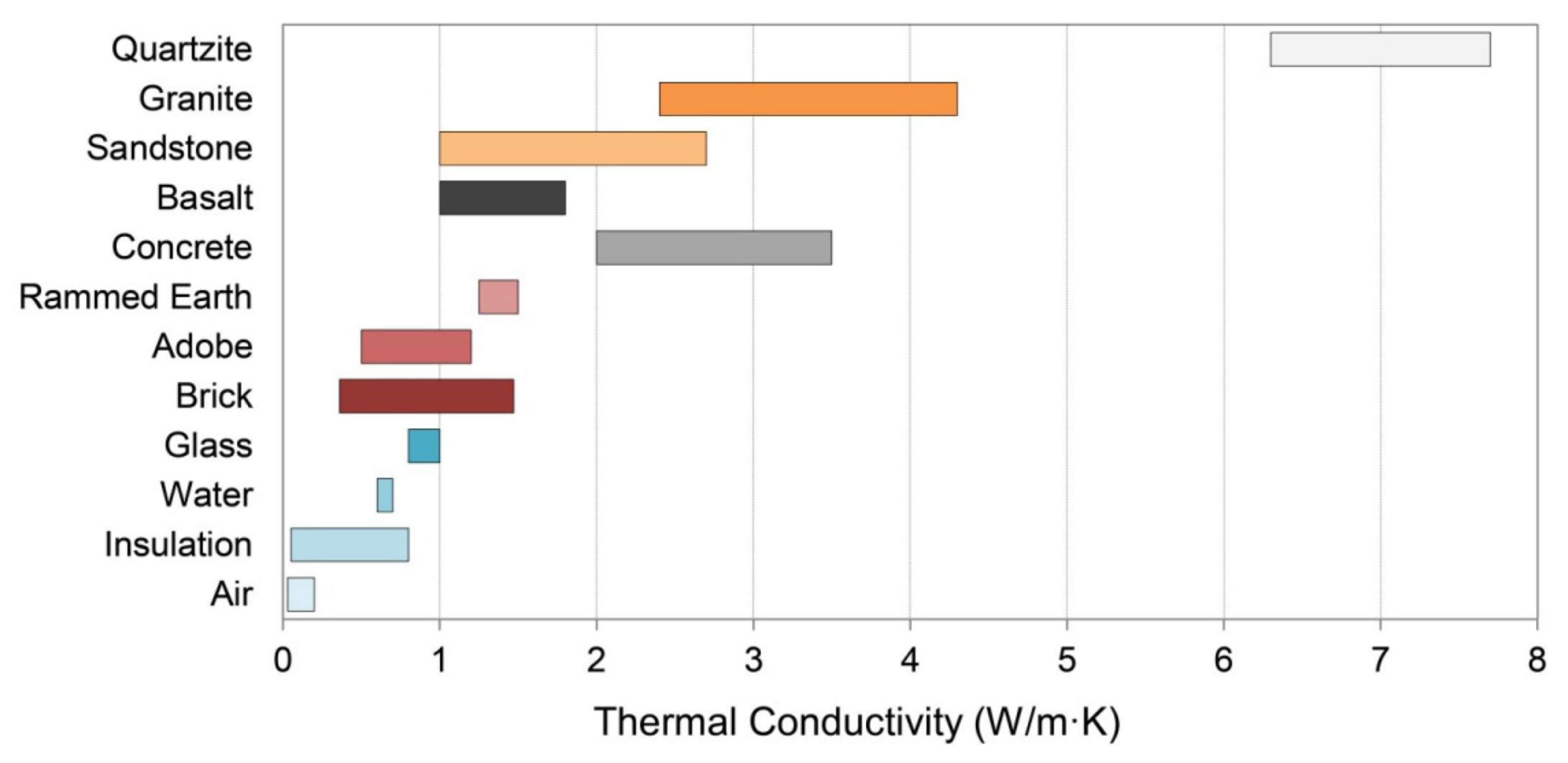
⇨ full thermohaline convection extremely difficult to achieve:

GEO CAP

Heat transport mechanisms within the Earth

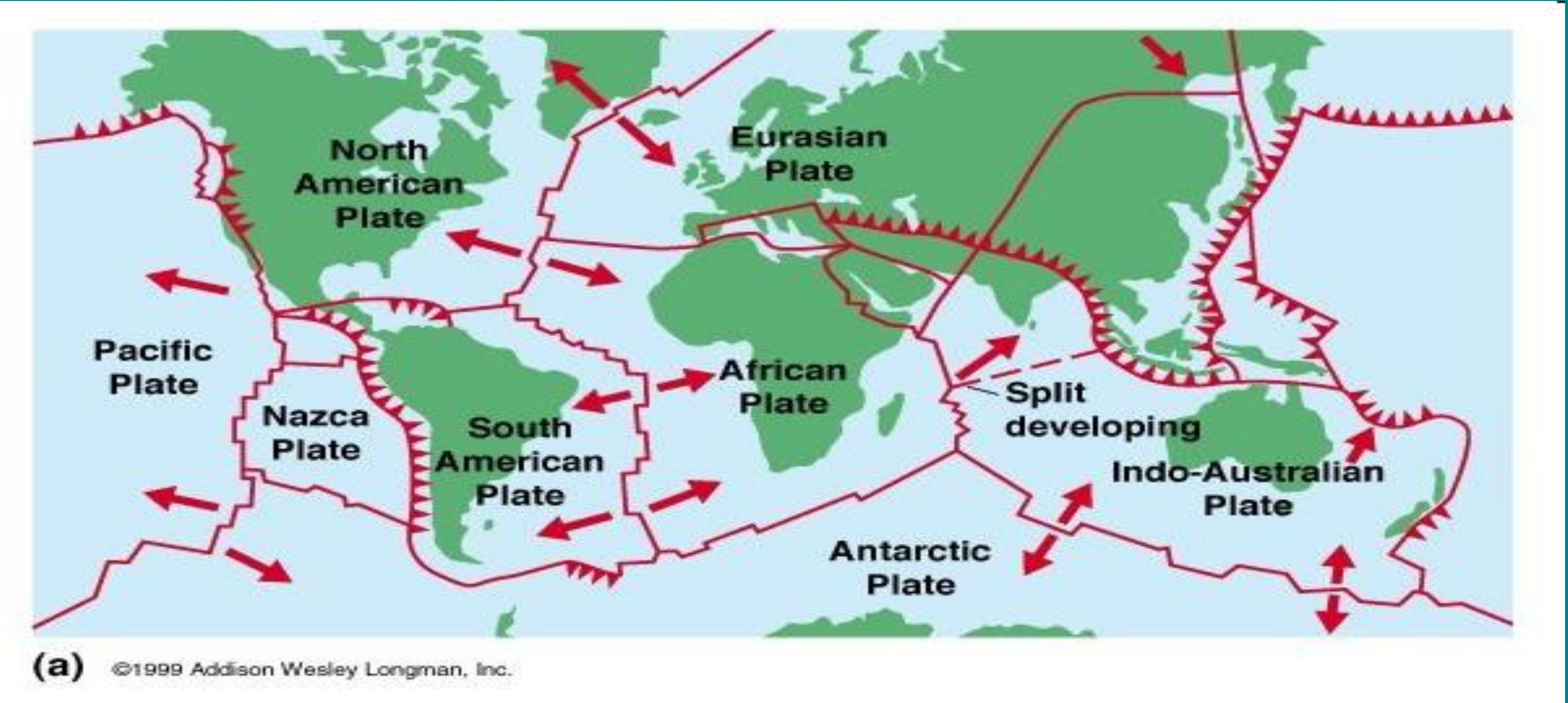


Thermal conductvity of rocks, water and common materials



http://www.mdpi.com/2076-3263/3/1/63/htm

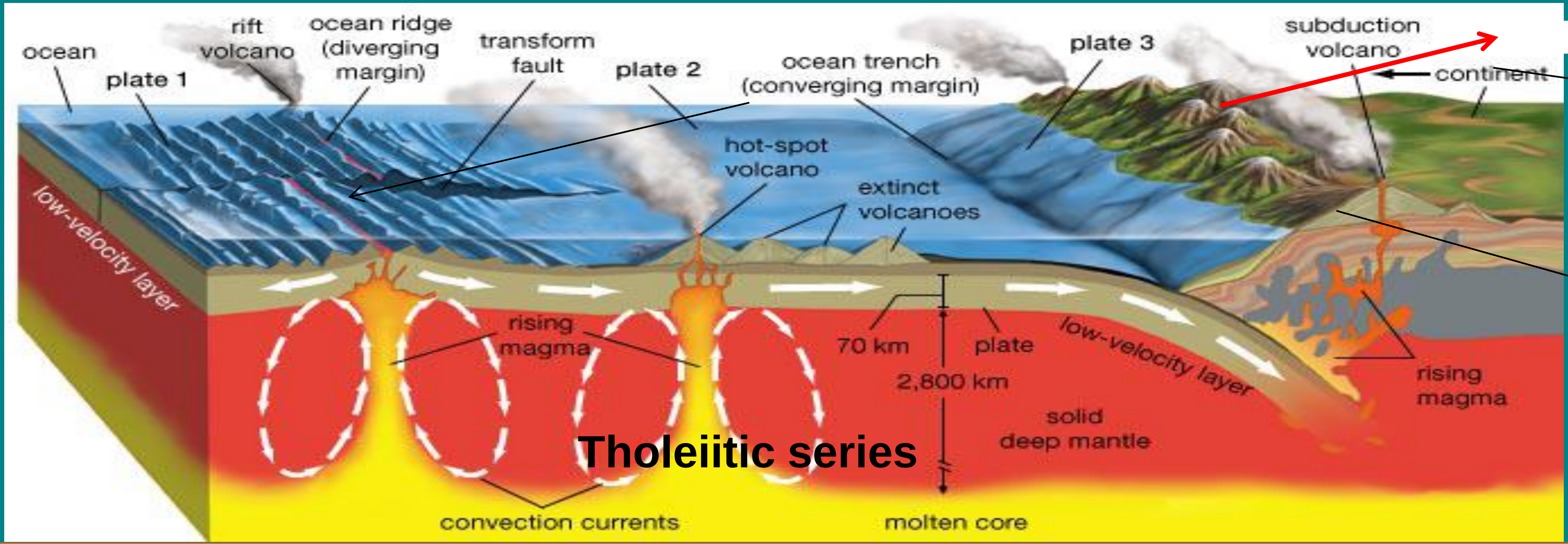
Plate tectonics



Tectonic settings

- **Lithosphere with oceanic crust**: Located on the ocean floors along the ridges. Every single lava flow expands the ridge´s flanks –new Earth crust production. As in Iceland
- **Lithosphere with continental crust:** the continental plate splits- leading to two separate continental plate. Volcanic activity caused by lithosphere thinning -stretching and pressure drop

Wilson cycle: thinning and opening of lithosphere with compression and subduction



series

-Tholeiitic
-alkaline,
-peralkaline

Calc-alkaline
tholeitic

Active margin volcanoes -convergence

- Subductive margin type b: subduction slab consists of lithosphere from oceanic crust - volcano rises due to the collision between two plates
- Andes type: subduction of oceanic crust lithosphere and oceanic crust ($\rho_{\text{oceanic lithosphere}} > \rho_{\text{continental lithosphere}}$)

Intra-plate volcano

- Continental plate: volcanoes occur due the thinning of the lithosphere

Magma chamber: the "fuel"

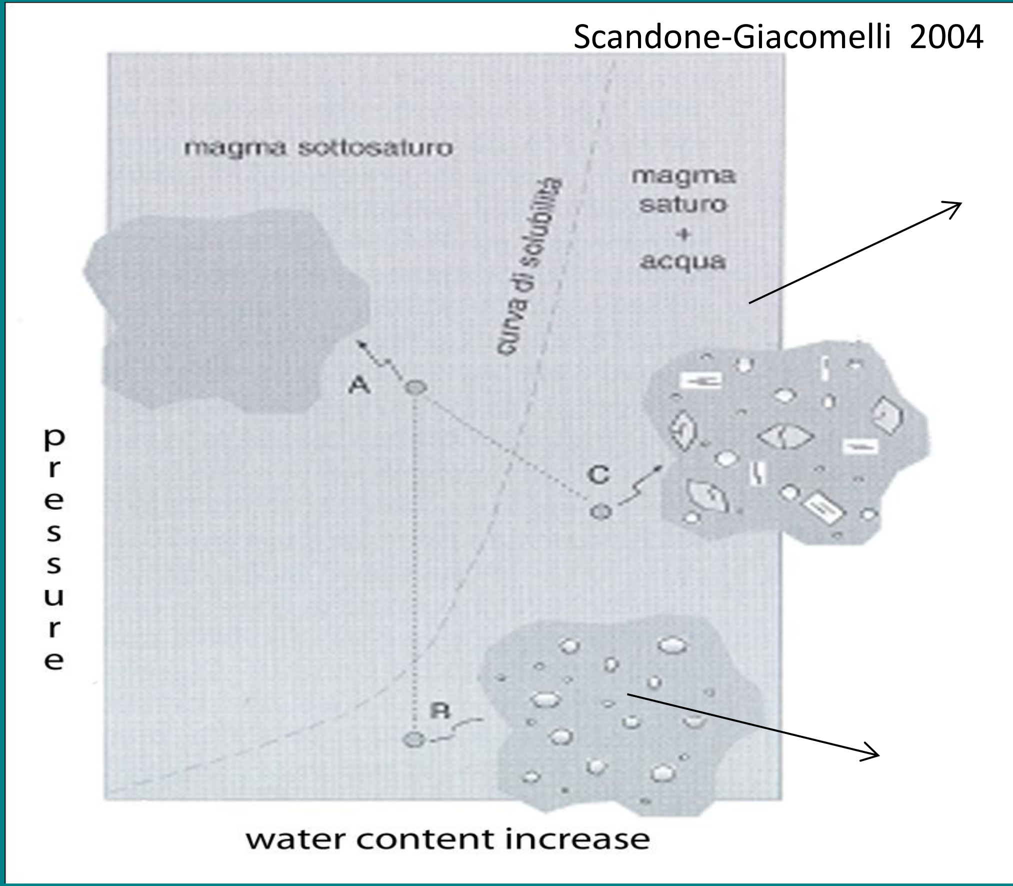
- Major magma source - as long as filled with magma the volcano is active
- Magma chamber not necessary the trap → deeper origin magma, i.e. magma transits in the magma chamber
- Place where crystallization starts to occur. Most important factors are P and T, water and gases
- Magma cools down- looses heat and "stops" in the magma chamber
- Magma reaches surface more easily with low viscosity

How to locate the magma chamber:

1) Density contrast - gravity anomaly in plutons and dykes
   density magma ≤ density host rocks
2) Analysis of seismic waves velocities: Vp and Vs

15 minutes break….

Formation of magma - what happens in the magma chamber?



Magma from melting of peridotite

Magma+gas+crystals

Different melt composition - not all minerals turn into liquid

Gases and volatiles remain in the melt as long
As the saturation point is reached
Gas exolves – **"juvenile gas"**
Vesciculation bubbbles build in the melt

Magma+gas

Fluids are always Si rich - except carbonatitic magma

Volcano: structure

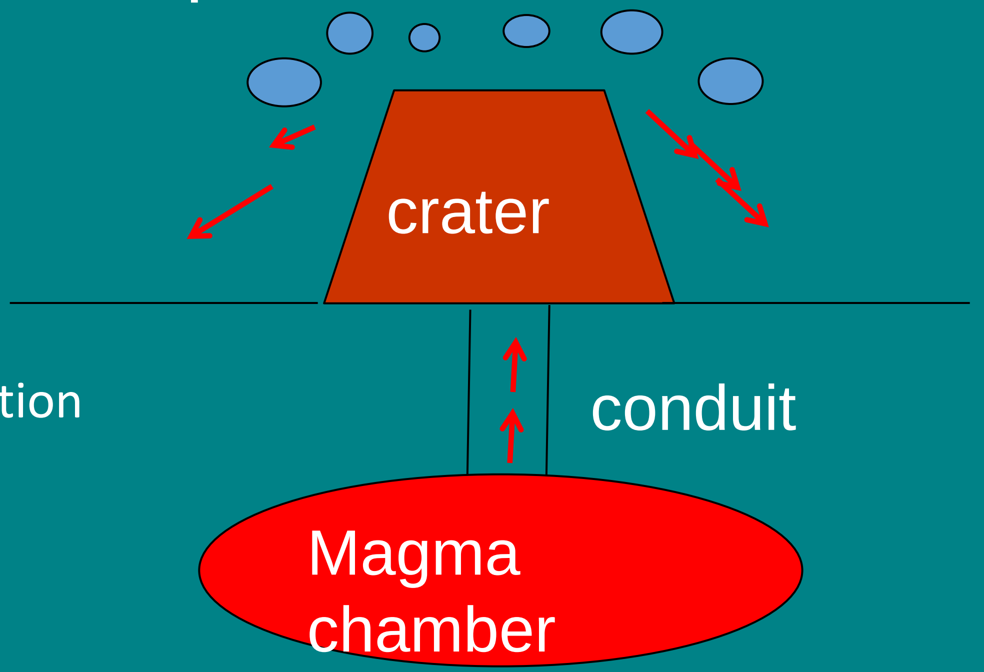
Volcano: open superficial rupture or fracture in the earth crust allowing **magma**, **ashes** and **gas** to escape the surface

Lava, ashes, gases, lapilli, bombs,
Tuffs (in the field as outcrop), pyroclastites….

Interaction magma-ground water

Magma fragmentation

Magma chamber: crystallization
Mixing-mingling phenomena
Petrology of magma and eruption type
are determined here



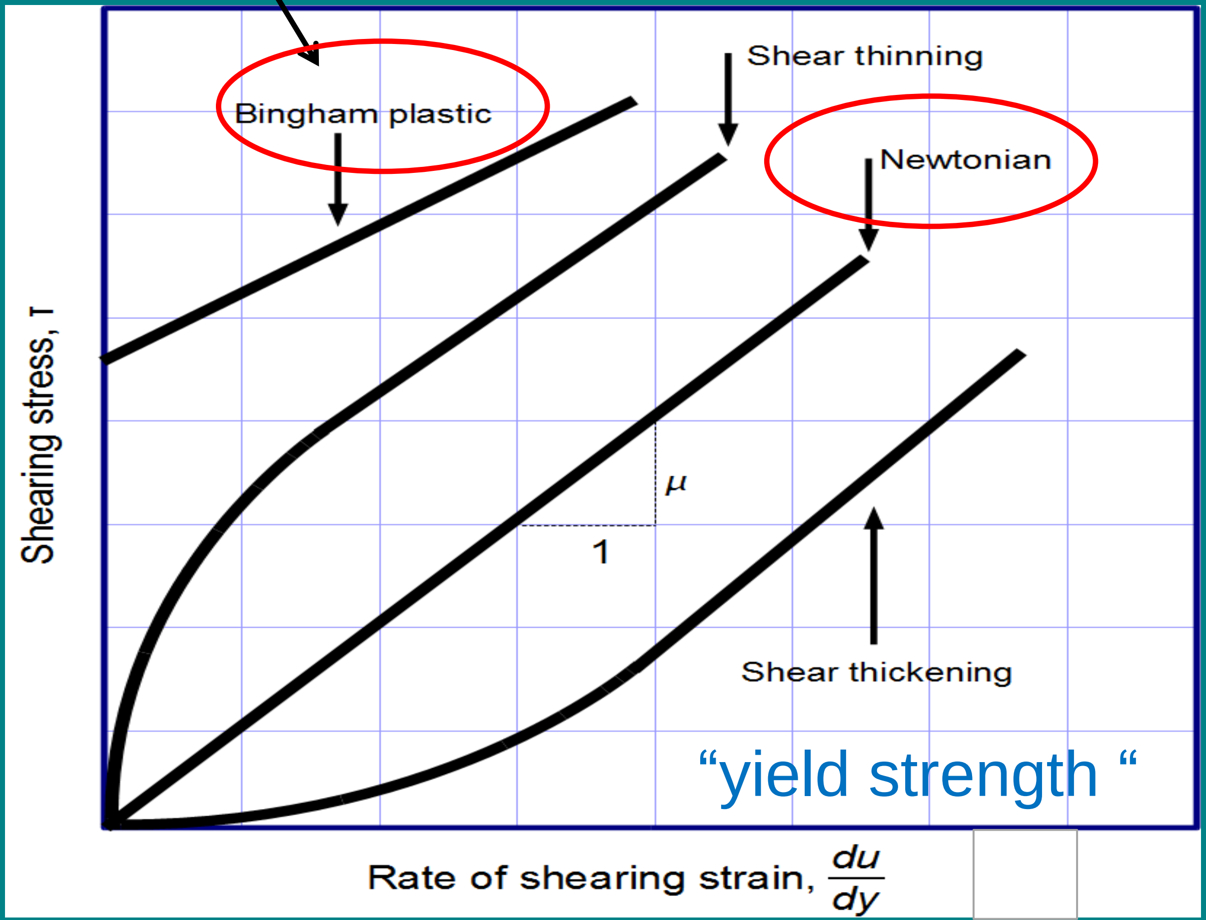
Maars-cindered cones: examples from East Java



In this area a great amount of maars and cindered cones occur
Some of them filled with water, some of them dry—hot springs?

Viscosity: behavior of a fluid

Magma



Magma belongs to the category of Bingham or Newtonian

A fluid must overcome the Yield strength in order to flow

Magma classification

- Ultra-basic: wt.% SiO_2 <45%
- Basic: wt.% SiO_2:45-52 wt. %
- Intermediate: wt.% SiO_2:52-66 wt. %
- Acid: wt.% SiO_2: 66 wt. %

The process yielding to the evolution if a magma is called:

<u>Magmatic fractionation</u>

Crystallization process leading to the evolution of magma with different compositions

Enrichment on residual melt

Melt with 55% SiO_2

Olivine

Residual Melt with 60% SiO_2

crystallization of olivine Mg_2SiO_4

Effusive activity: outcrop example in East Java-Tiris

Lava flow

Andesite aphiriric:
70 wt% labradorite
30 wt% olivine

Radial structures

Radial structures:
Rapid degassing
Rapid cooling
Contact with H_2O

Effusive products-major classification

Pahoe-hoe

Usgs.gov

Agu.org

Outcrop detail - Lamongan-Tiris

AA

Usgs.gov

Lamongan West flank

Pillow lavas

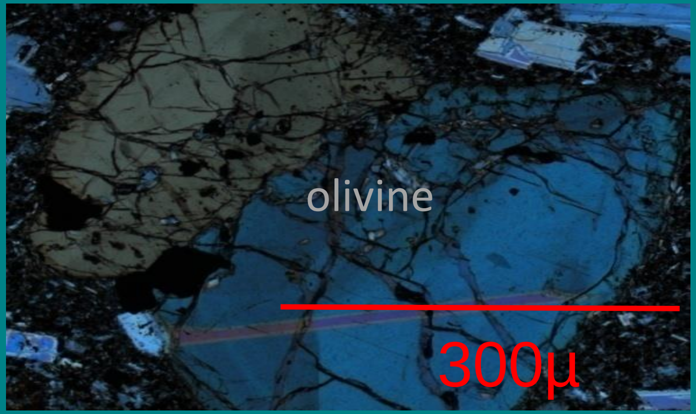
See floor eruption-lava outcome from ridges or underwater volcanoes

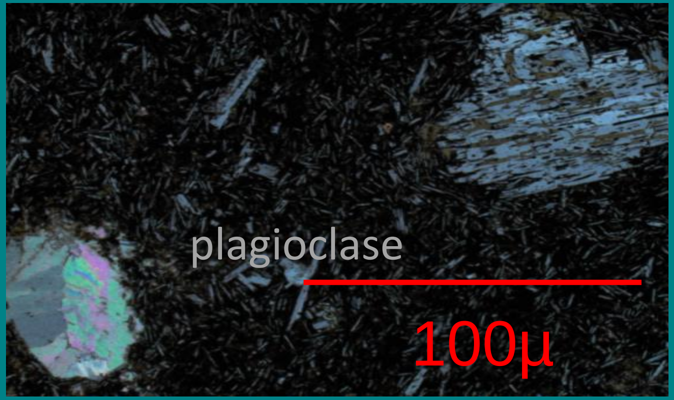
Volcano.oregonstate.edu

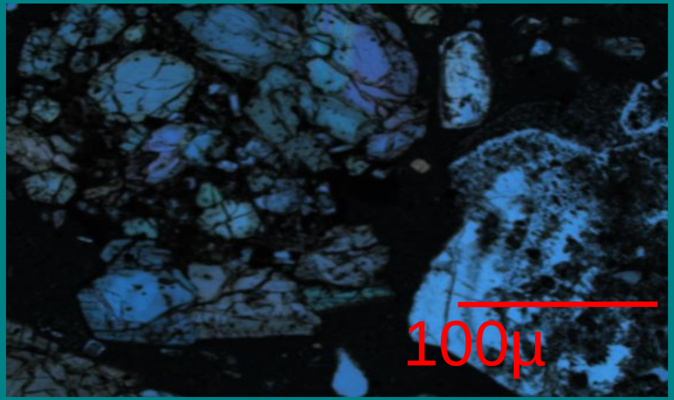
Wikipedia

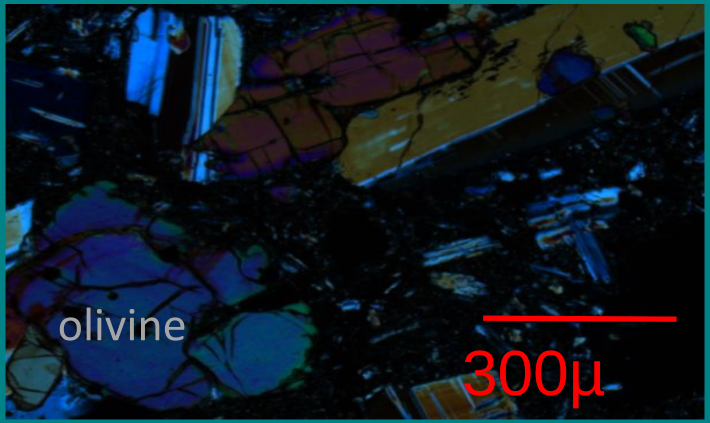
Pillow lava cross section New Zealand

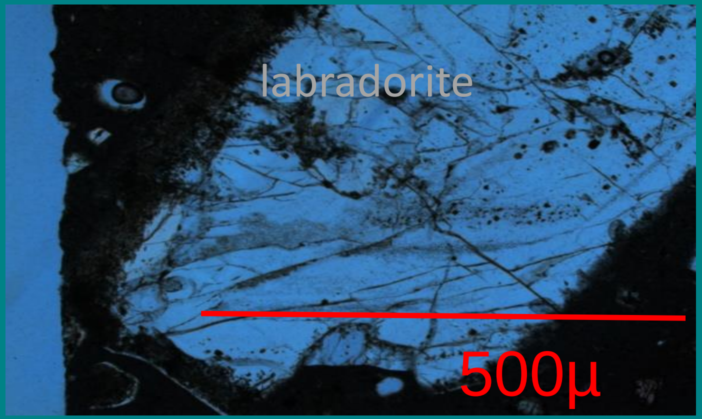
Effusive activity-products under the microscope











East Java-Tiris

Lava Toba-Sumatra

Explosive products - major classification

1) Juvenile: bearing glass, pumices, scoria

Bombs: released as liquid > 64mm

Blocks: released as solid > 64 mm

Fine ash: <62 µm

Coarse ash: 2mm-62 µm

Picture by Agung-UGM Yogya

Explosive activity-outcrops

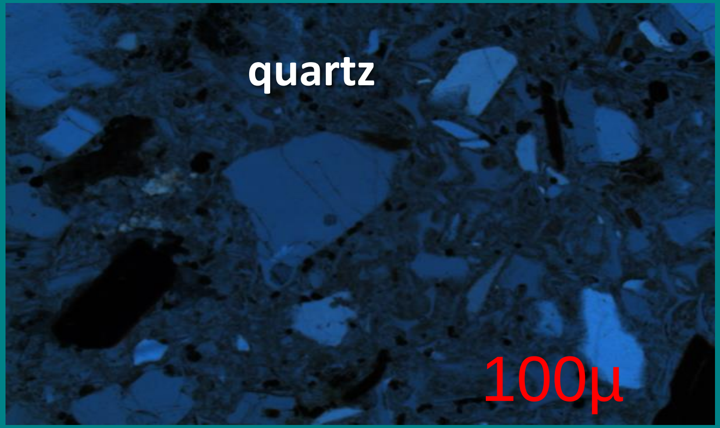
Sumatra

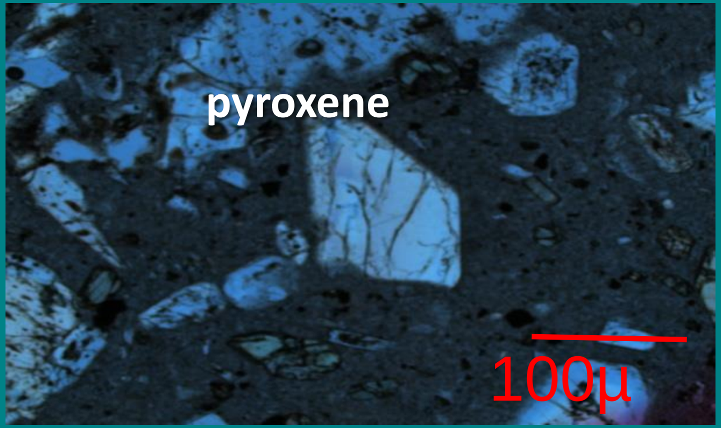
Pictures: Inga Moeck

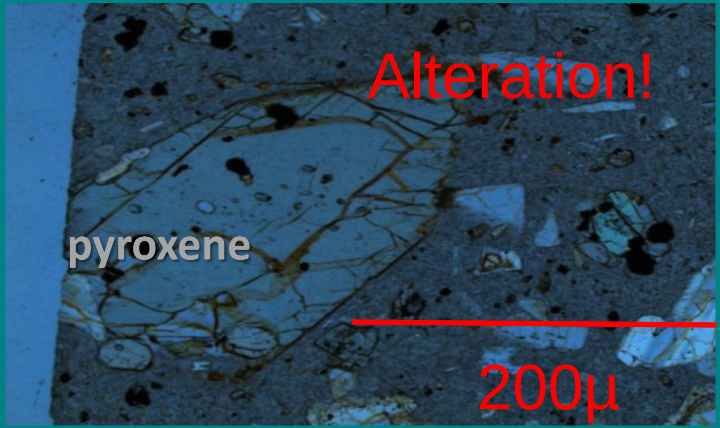
Tiris, East Java

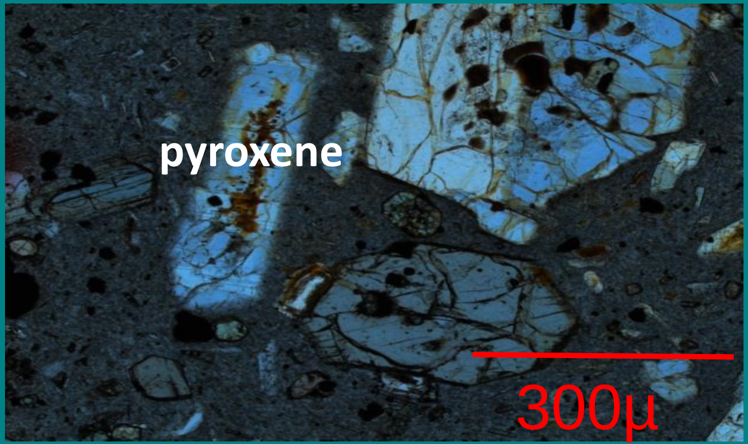
Turbulent pyroclastic flow

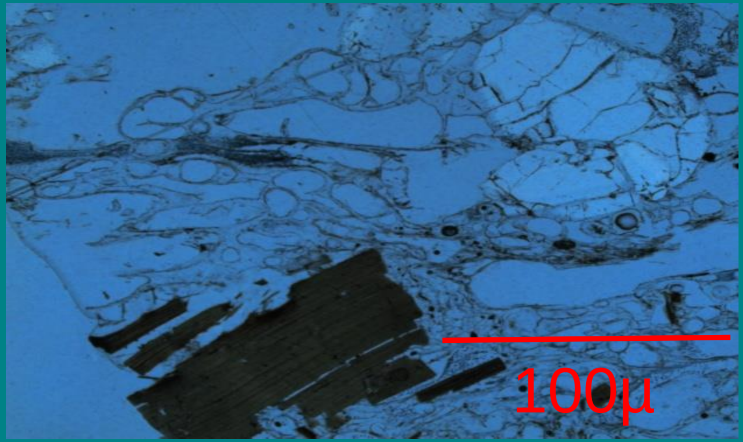
Explosive activity products: thin sections







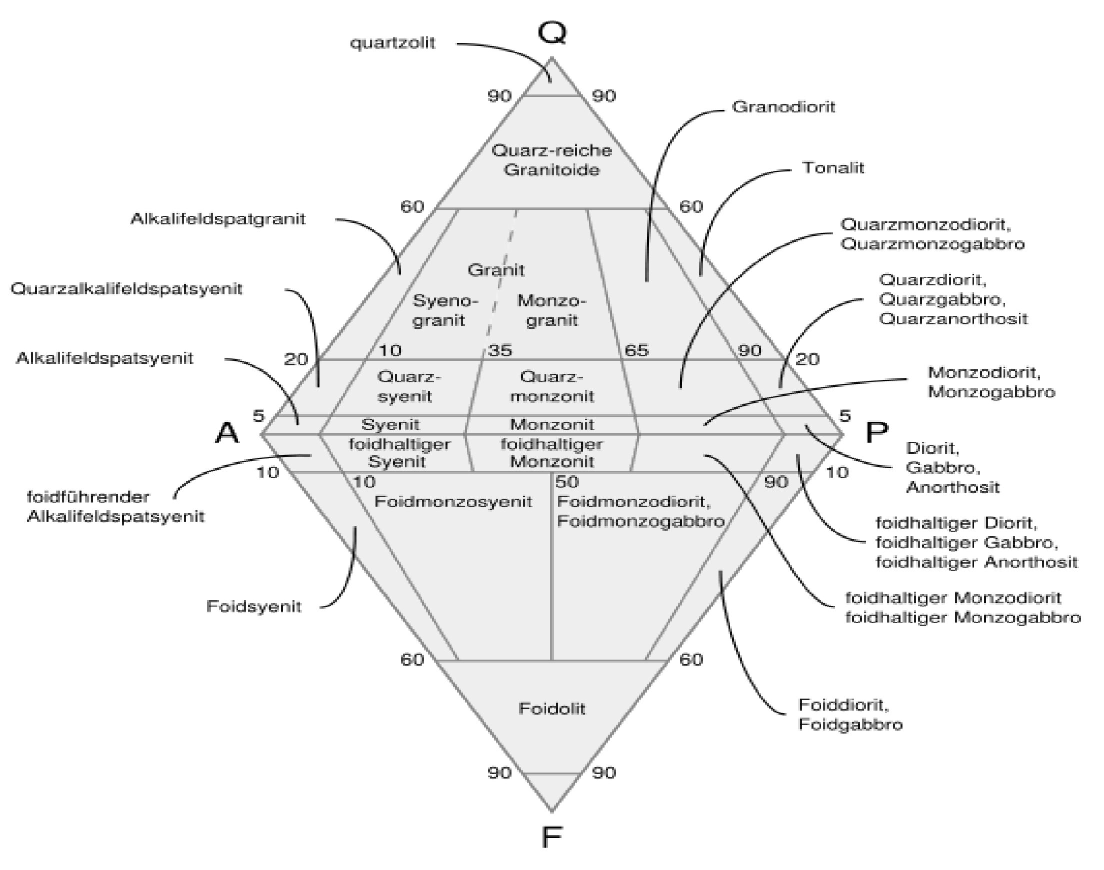




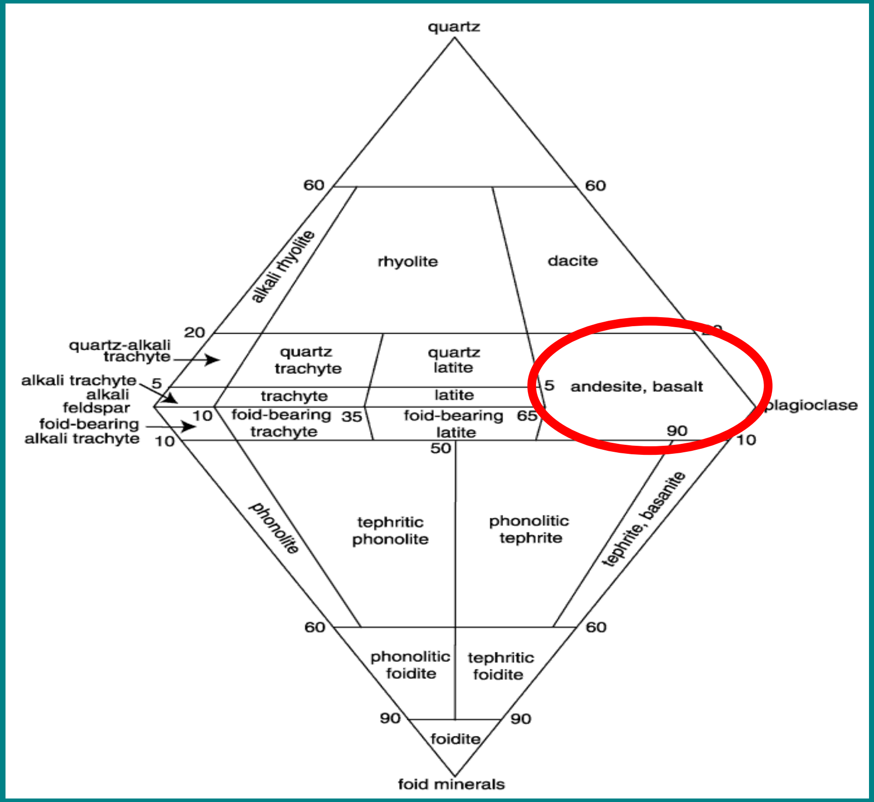
Thin sections from Toba Tuff:
With typical prismatic habit
And SiO_2 welding

Petrography: magmatic-volcanic rock classification (Streckeisen diagram)

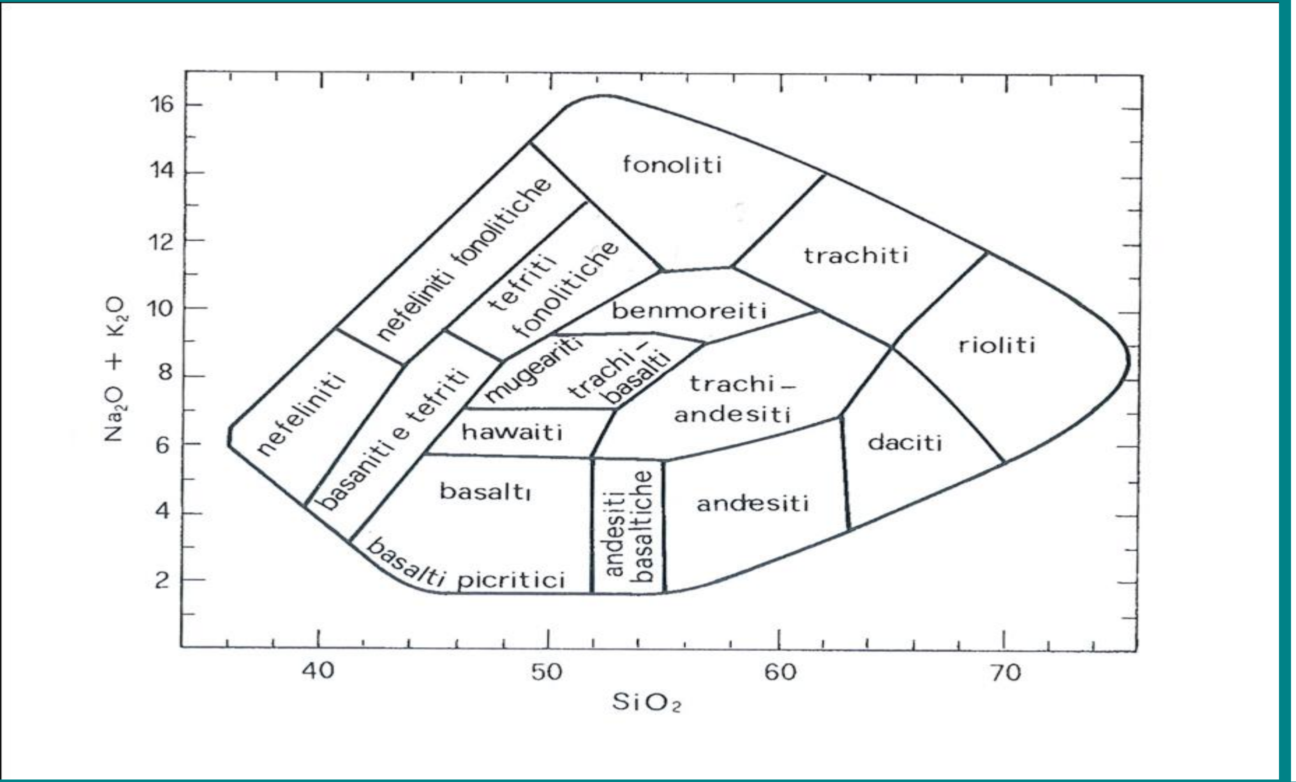
Plutonic rocks

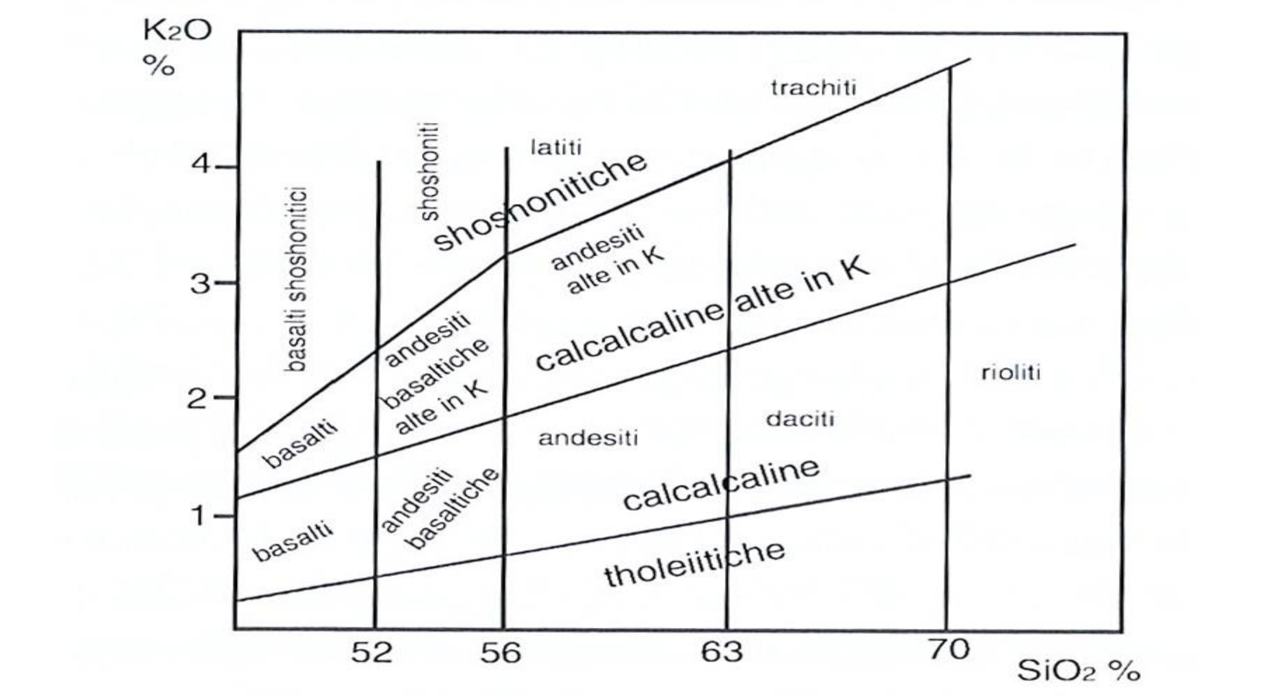


Volcanic rocks



Petrology and geochemistry





Le Bas et al. (1976) from Scandone and Gicacomelli 2004

The geodynamic setting strongly influences the resulting magma composition.
Information on single oxide weight fraction can be obtained with
Electron microprobe and with X-ray diffraction…..

Highlights about trace elements:

1) The mantle source of most of the MORB (Mid Ocaean Ridge Basalts) is chemically depleted and quite homogenous

2) The mantle source of OIB (Ocean Island Basalts) and most of the subduction basalts is more enriched and heterogenous than MORB

3) The basalts of the ocean basin (MORB and OIB) show positive Nb-Ta and Negative Pb-anomalies

4) Subduction basalts show the opposite phenomenon

Important consequences for the global mantle dynamic

Geochemical characteristics

- K distributions in the lava and K/Na ratio
- Isotopic ratio..$^{87}Sr/^{86}Sr$: important information about the magma origin:

  0.703-0.705: upper mantle

  > 0.708: crustal influences

  0.705-0.708: both influences

Other isotopes provide age information on magmatic rocks:

Lava are often hard to be distinguished due to their similarity and age determination makes easier the volcanologist task.

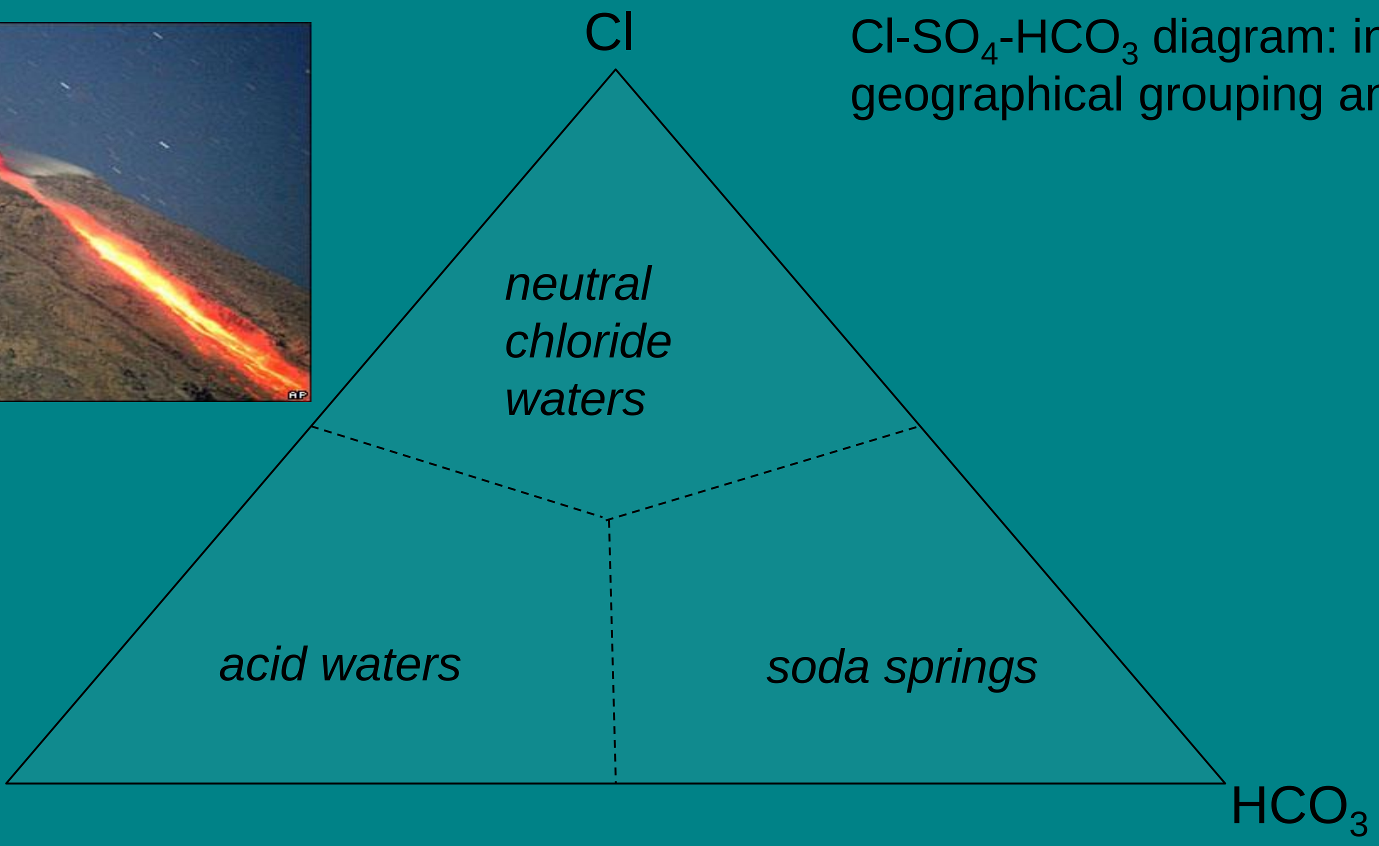
Geochemistry - fluid

In the exploratory phase the task of geochemistry is mainly to

- Estimate subsurface temperatures by using chemical and isotope geothermometers as well as mixing models
- Identify the origin of the geothermal fluid, mainly with isotopic techniques
- Define chemical properties of the fluid with respect to environmental issues, scaling ....
- Provide data to a conceptional model of the geothermal system

Sampling fluids in North Sumatra, Indonesia

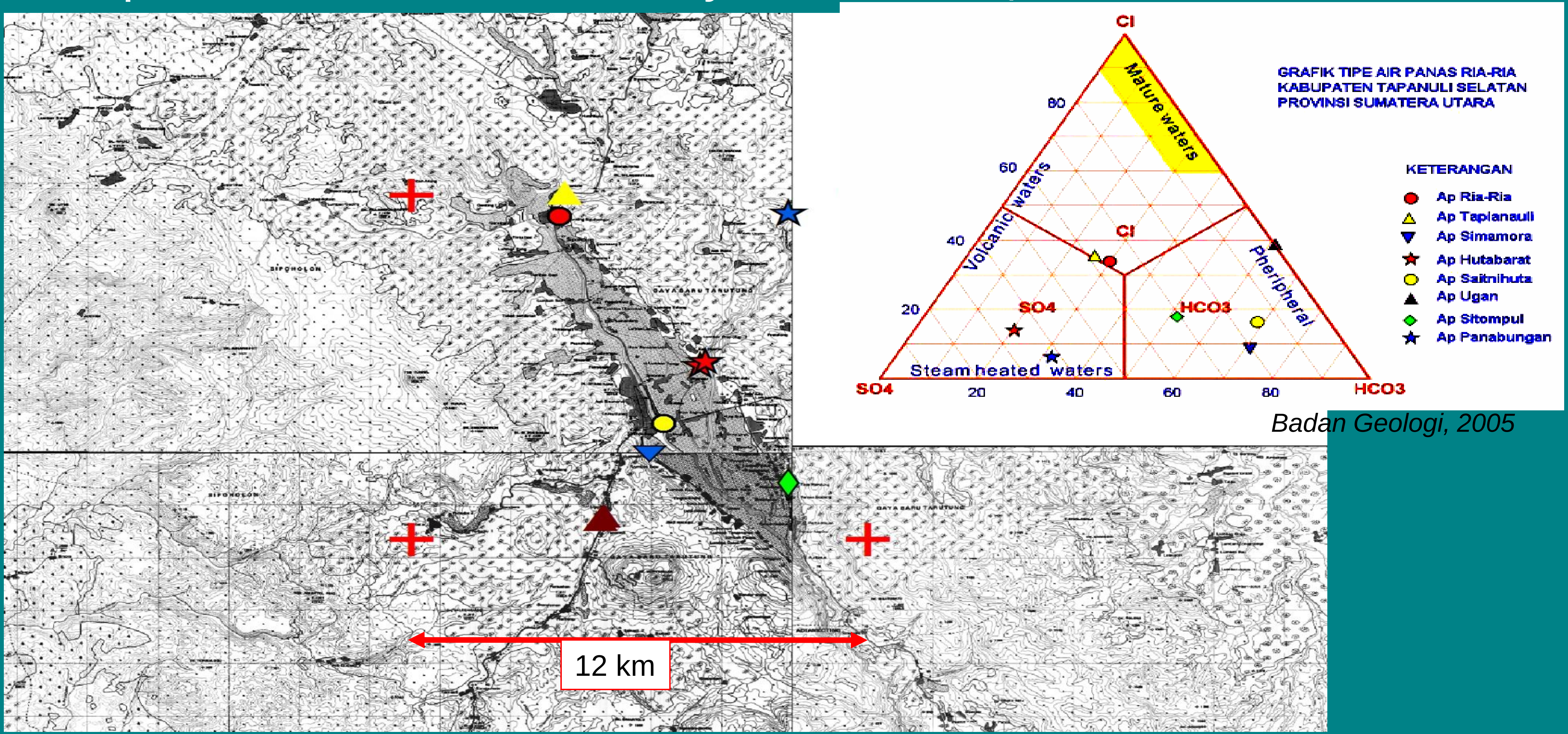
Indonesia: Fluid classification in high enthalpy geothermal systems



Cl-SO_4-HCO_3 diagram: indication on geographical grouping and mixing

Giggenbach, 1988

Example for Fluid Geochemistry Distribution, North Sumatra



Badan Geologi, 2005

Geophysics: Constraining the Earth's sub-surface with observations at the surface

Geophysical techniques measure physical phenomena:

- Gravity
- Magnetism
- Elastic waves
- Electricity
- Electromagnetic waves

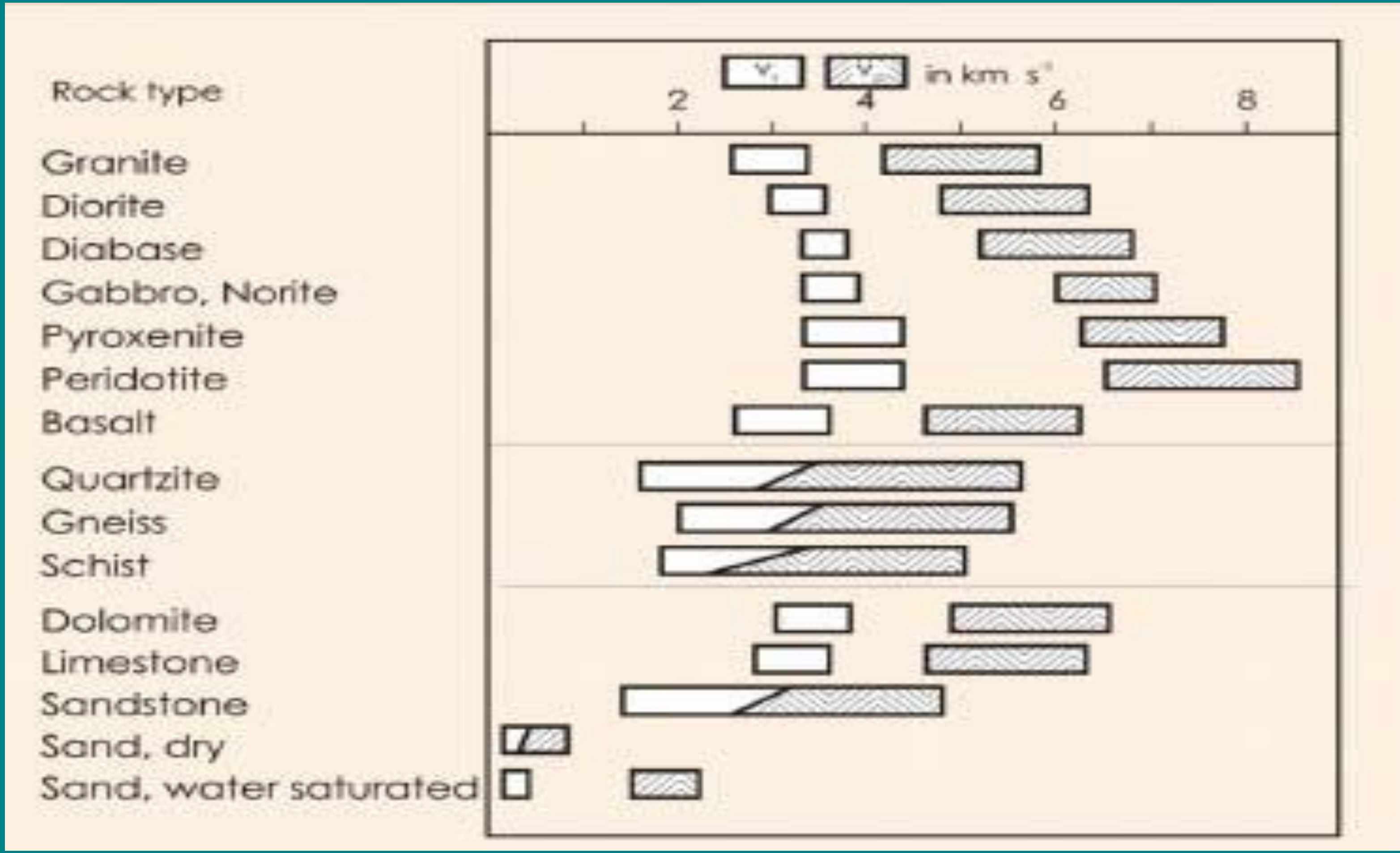
Which are sensitive to sub-surface physical properties:

- Density
- Magnetic susceptibility
- Seismic wave velocity and density
- Resistivity (conductance/inductance/permitivity)

The Seismic Wave

v = λ * f

seismic velocities in rocks

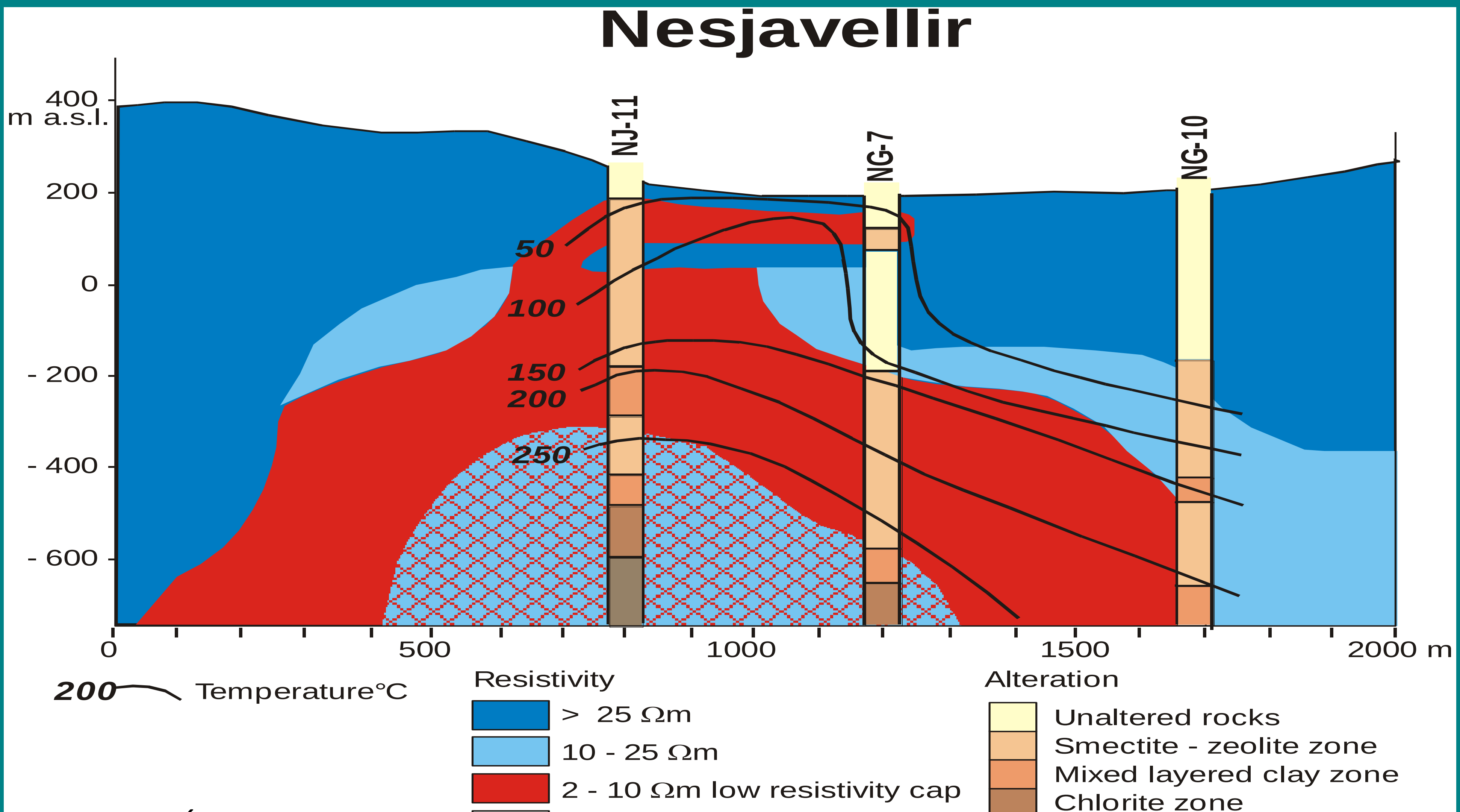


$$v_p = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

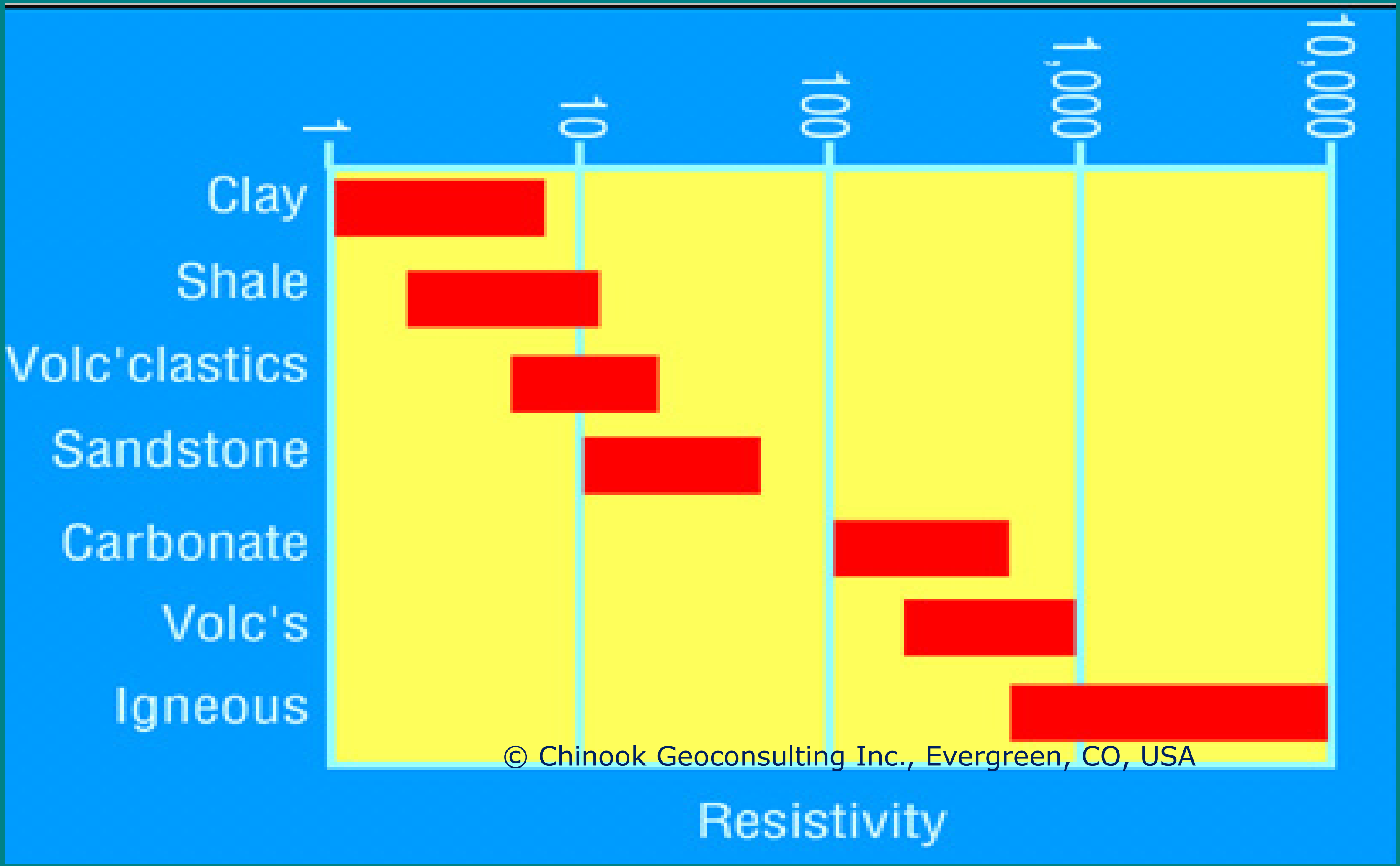
M = linear elastic modulus
K = compression modulus
μ = shear modulus
ρ = density

General resistivity structure

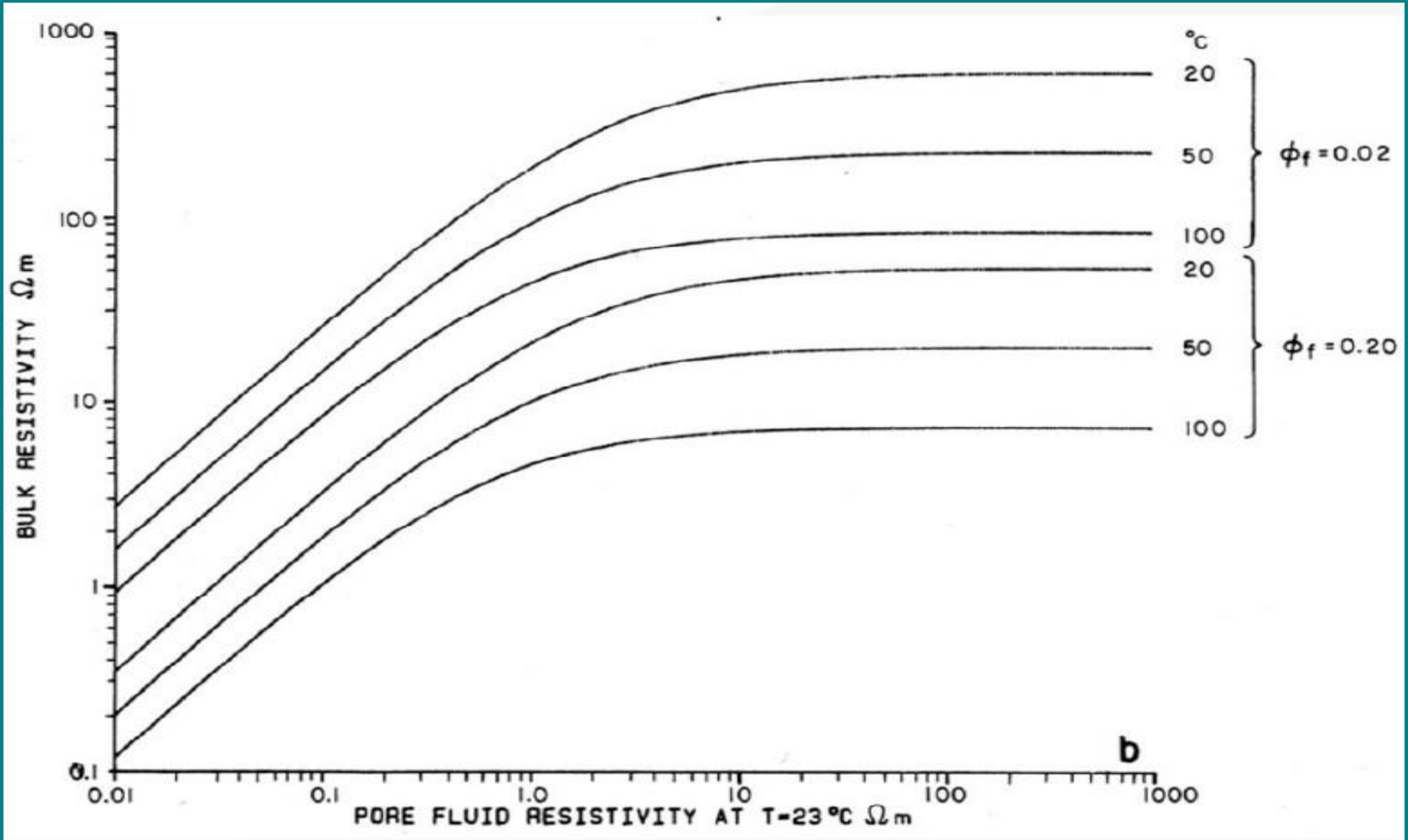


Hersir and Árnason 2014

MT: Resistivity values vary with lithology

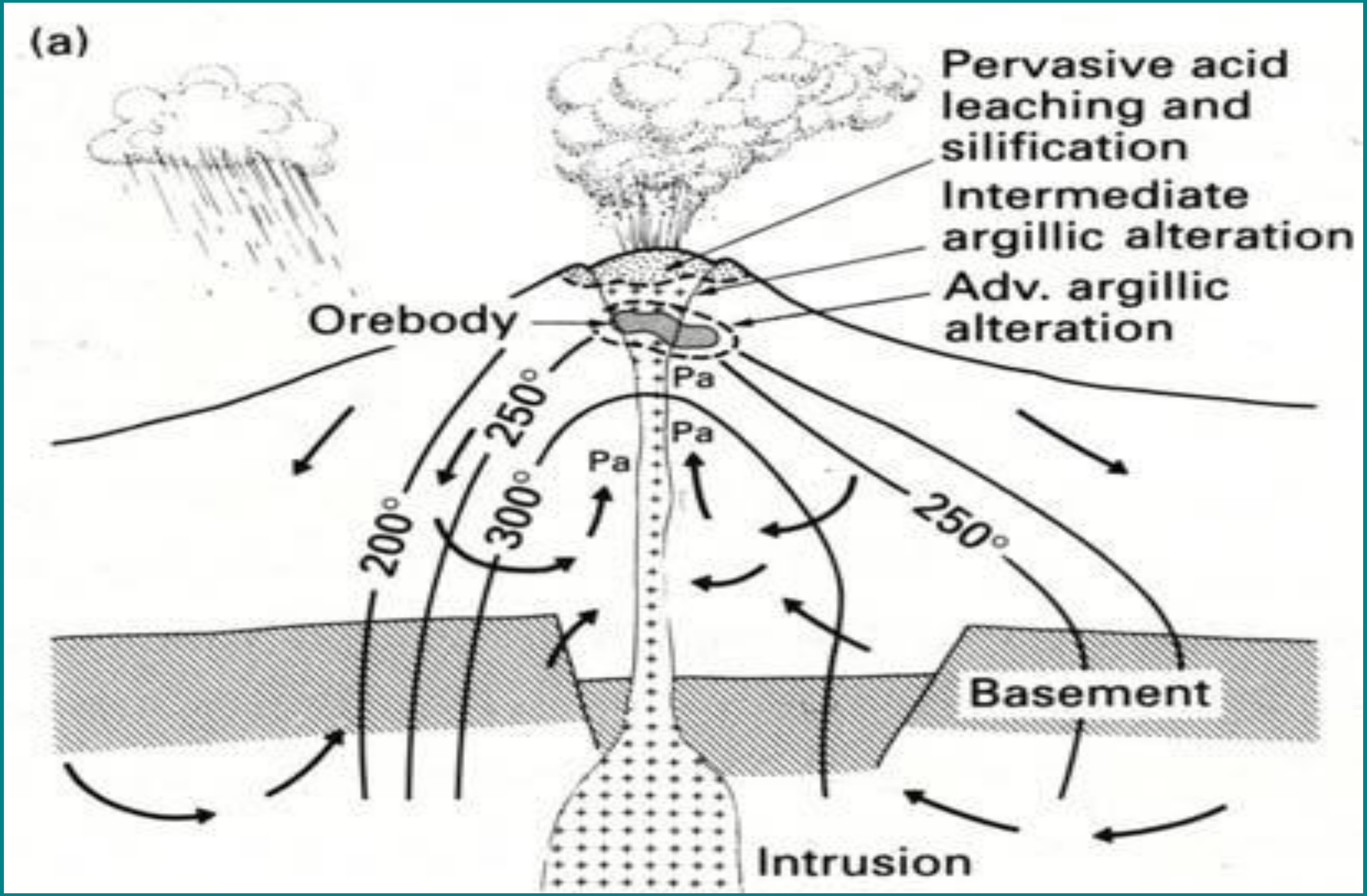


Bulk resistivity as a function of pore fluid resistivity for different temperatures and porosities

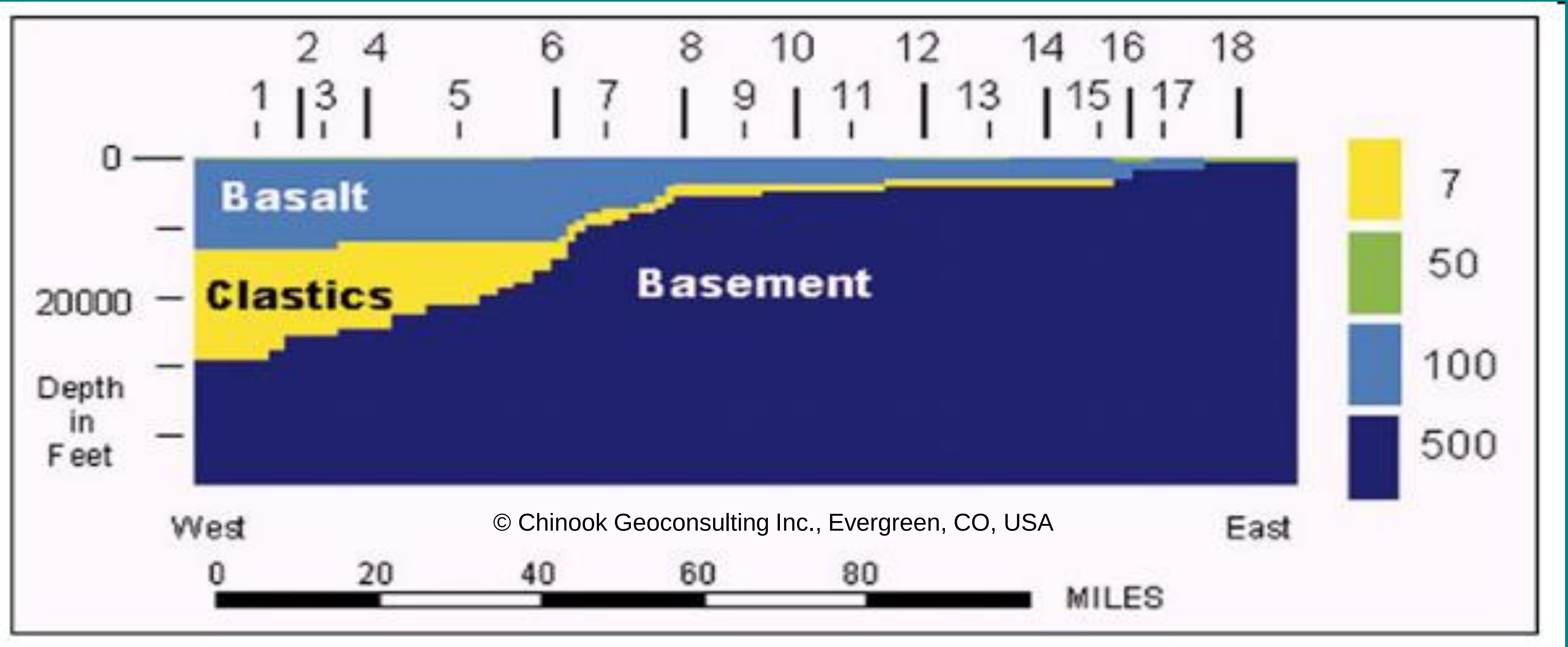


(Flóvenz et al., 1985)

High temperature „conventional“ geothermal system



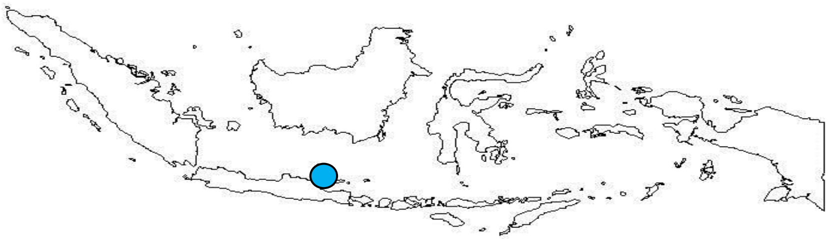
Example of MT resistivity section



How to build and interpret a conceptual model

- Geological setting and exploration strategy
- Rocks analyses and major outcome for a drilling campaign
- Fluid geochemistry
- Hypothetic geological model
- How to be successful in a **water dominated- high temperature system in high terrain**?

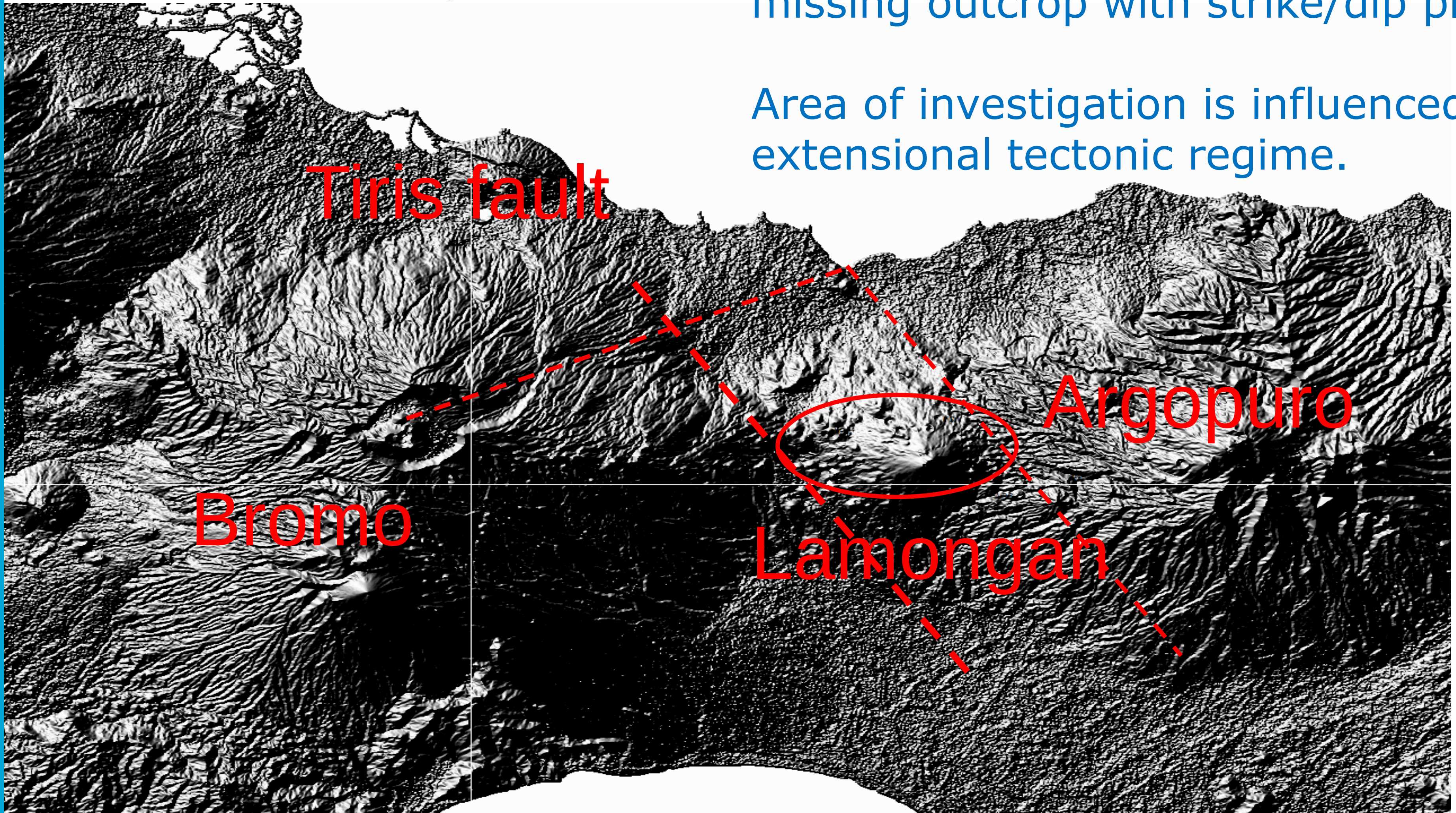
Geological Setting



Lamongan belongs to the Sunda arc as all the active volcanoes on Java;

Fault planes cannot be detected in the field- missing outcrop with strike/dip plane;

Area of investigation is influenced by extensional tectonic regime.

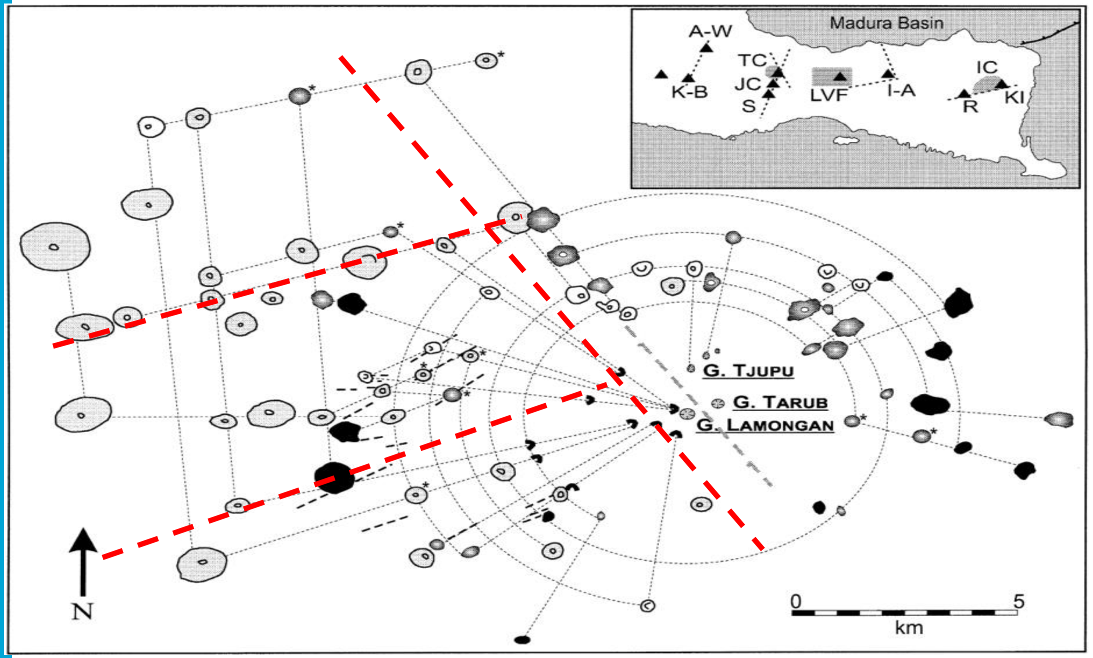


TU Delft

First approach: field recognition and observation

Rock sampling in Domas crater and Lembang

Maars, cindered cones and lineaments



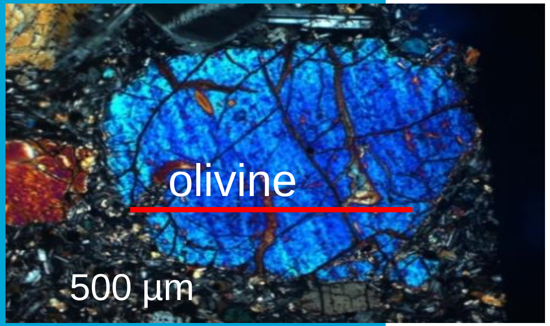
Carn and Pyle 2001

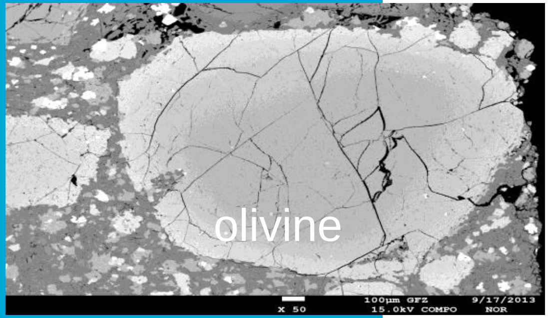
Numerous maars and cindered cones occur in this area.
Some of the maars are aligned along a NW-SE lineament.

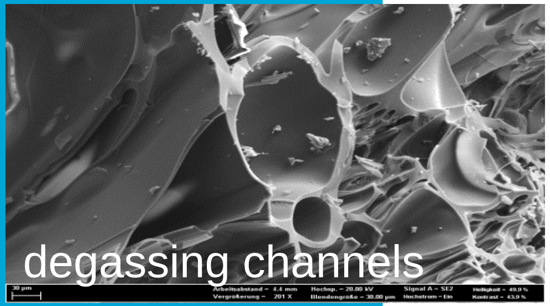
Maars and cindered cones=magma-water interaction
Phreatomagmatic eruption (but no existing records)

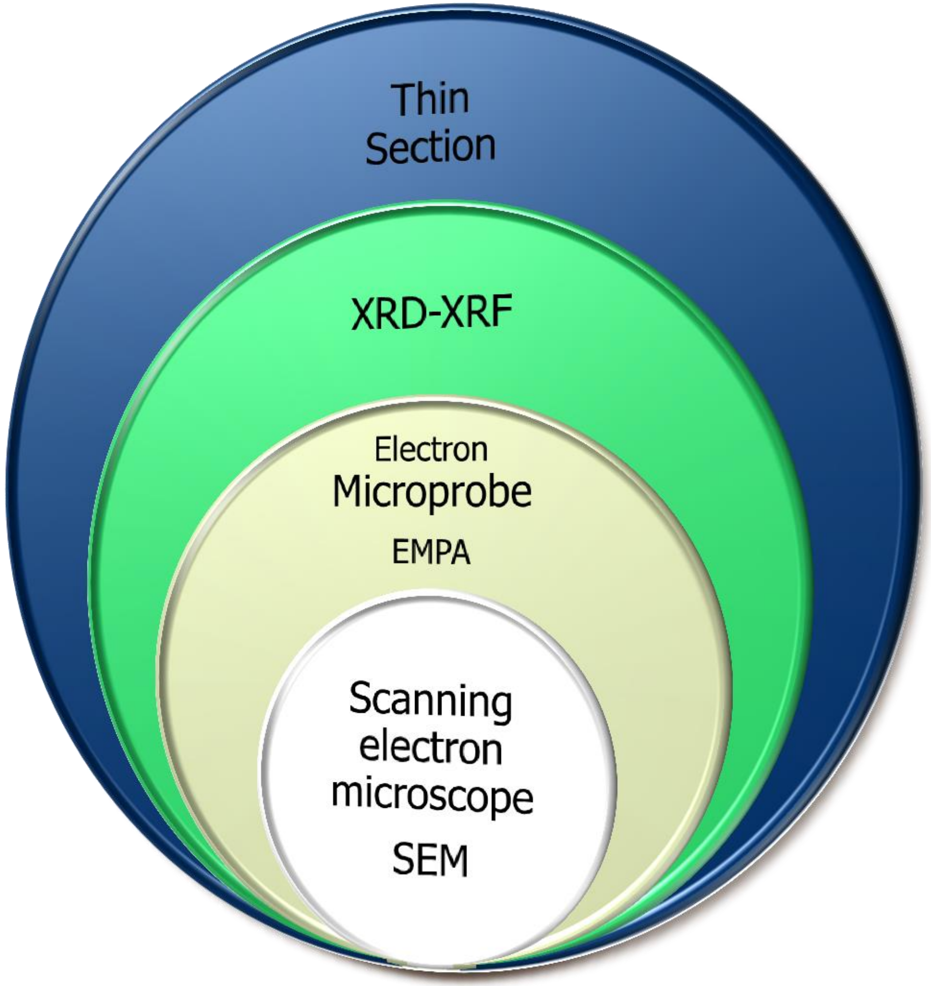
Petrography and petrology of the rocks

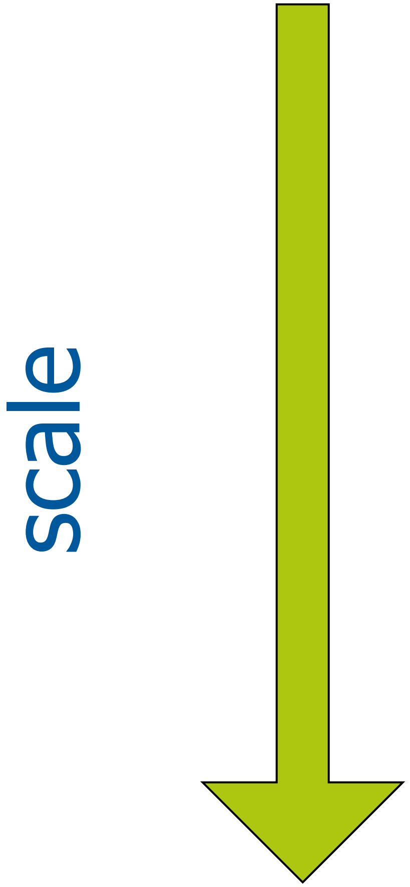
Analytical approach



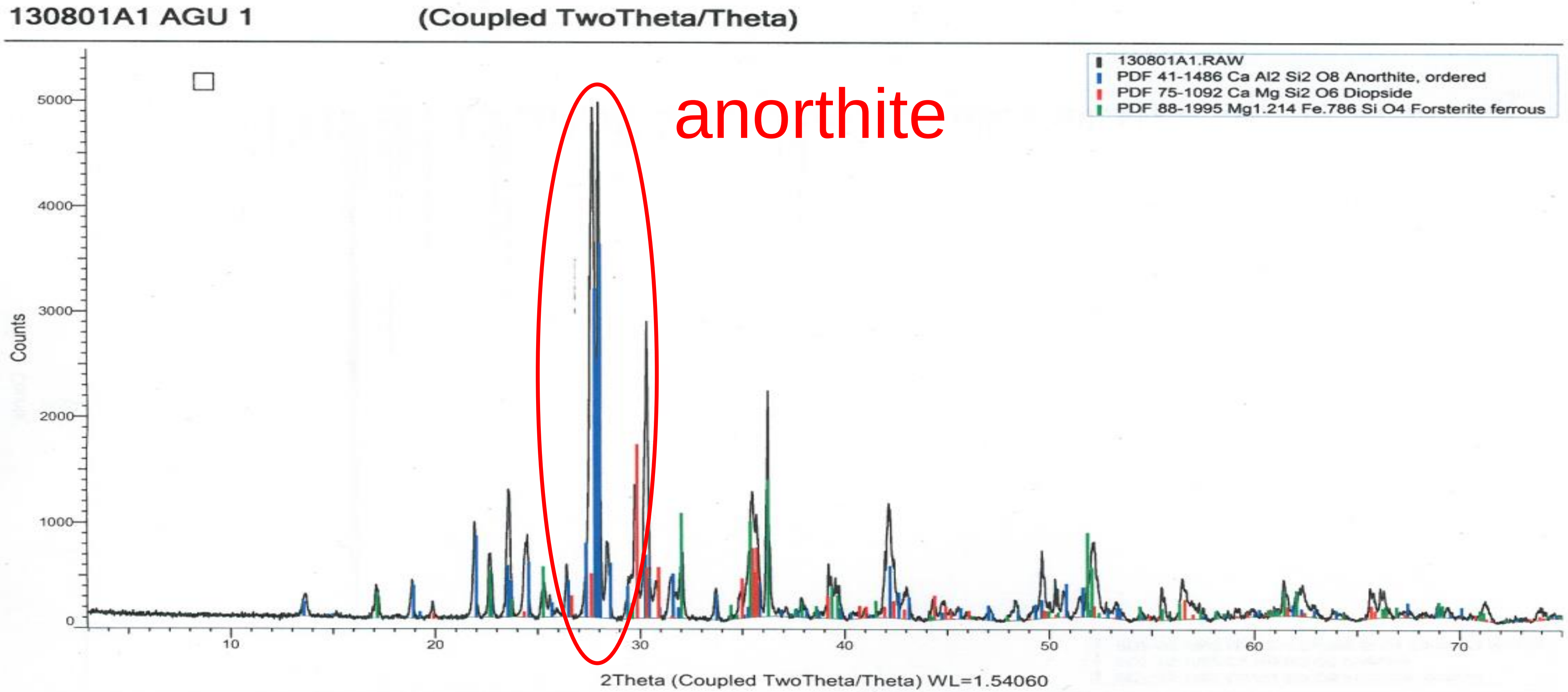






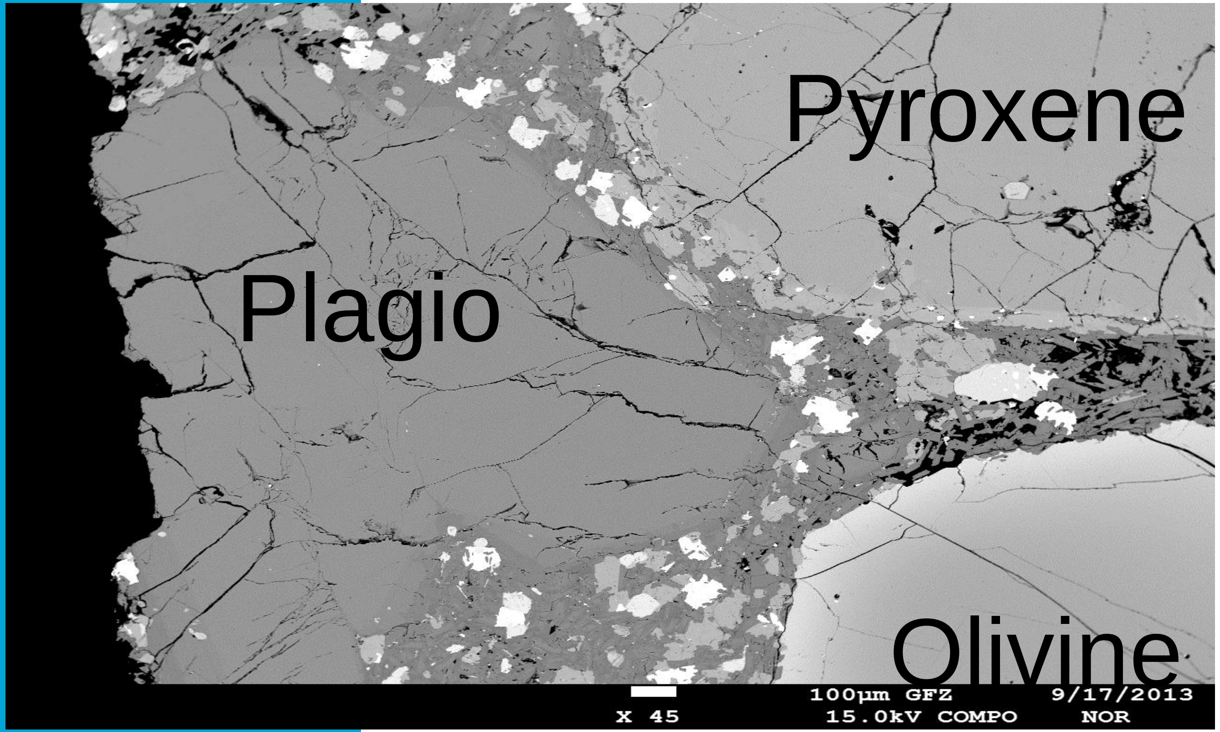


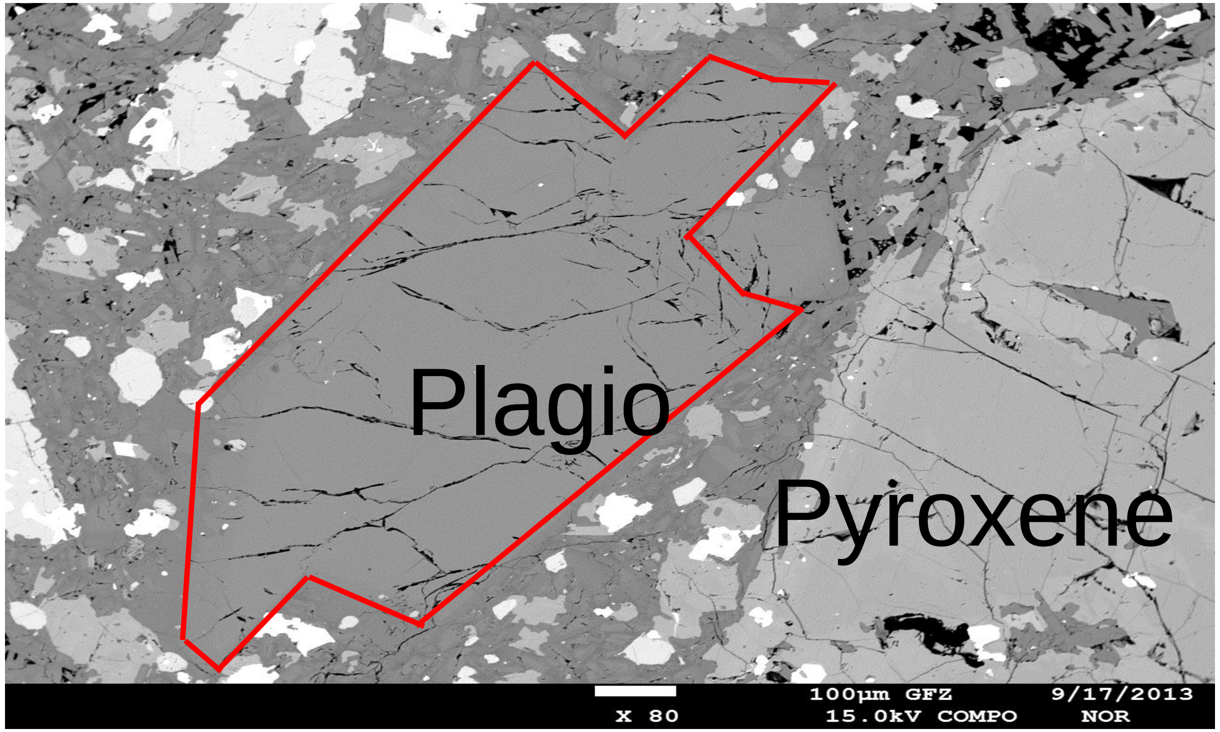
XRD



Qualitative-quantitative analyses of the mineral phases of the rock samples: the more intense the peak the higher is the amount of the mineral in the rock

Microanalytical approach: Electron Microprobe





Detailed point measurements and SE (Secondary Electron) pictures exclude the occurrence of hydrothermal alteration-no altered plagioclase

No clay fraction occurrence detected

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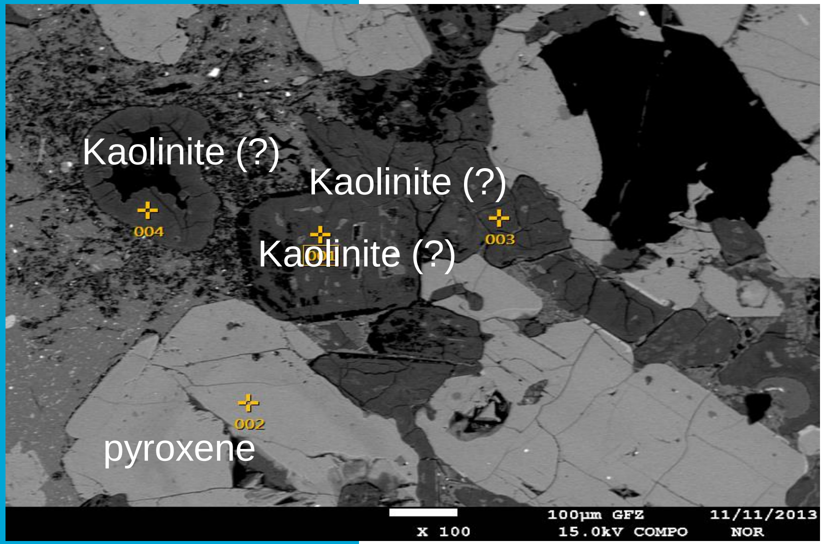
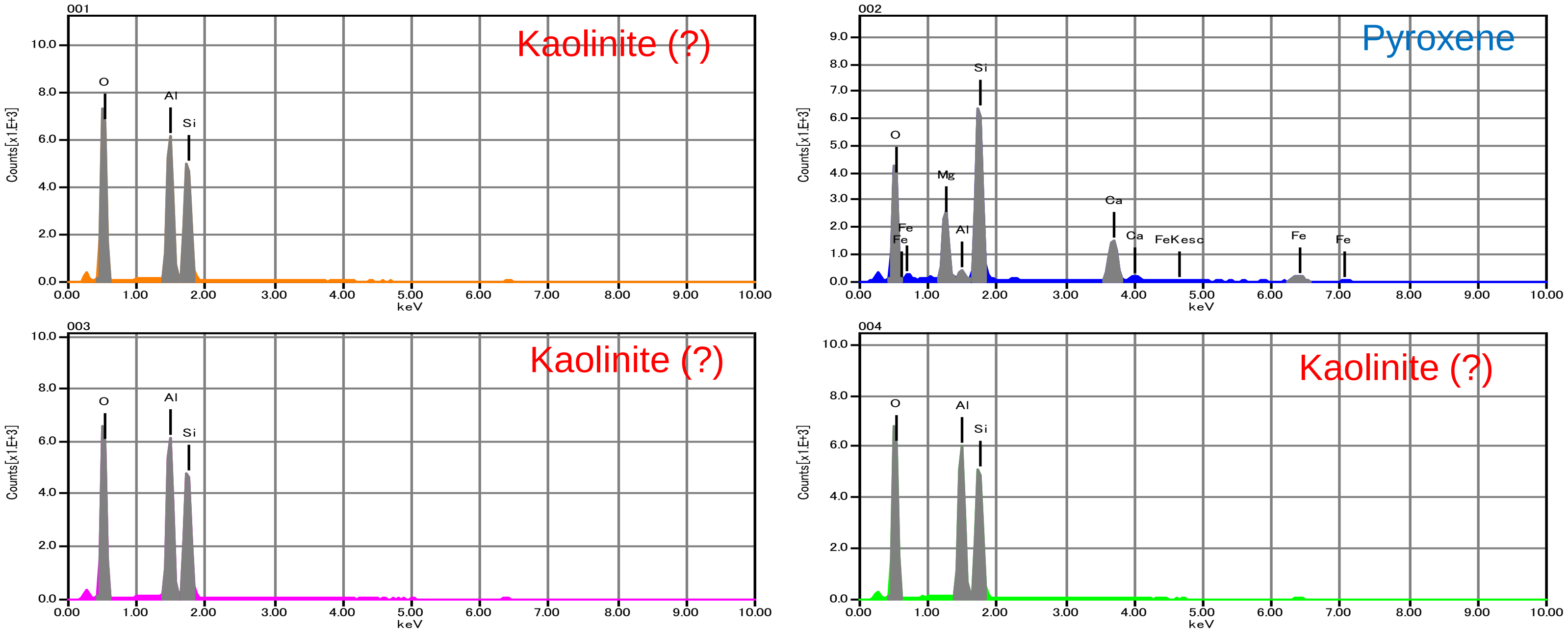
Clay fraction detection (Lake Toba samples)





Clay fraction detected with EDS: a beam hits the surface and detects the cation-anion ratios/peaks.
Clay fraction type (illite-montmorillonite-kaolinite etc) must be detected with XRD prior phase separation.

> Importance for detection of hydrothermal alteration!

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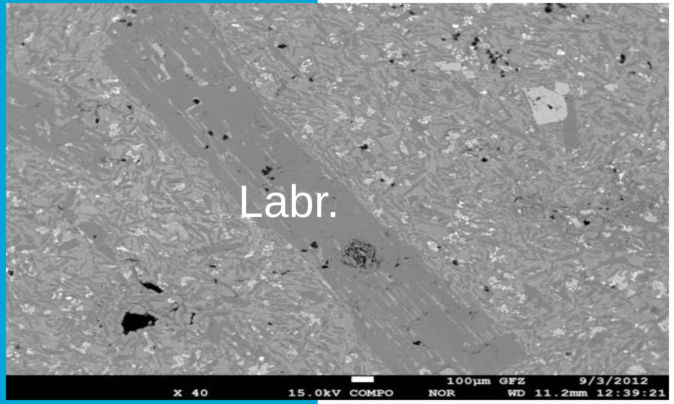
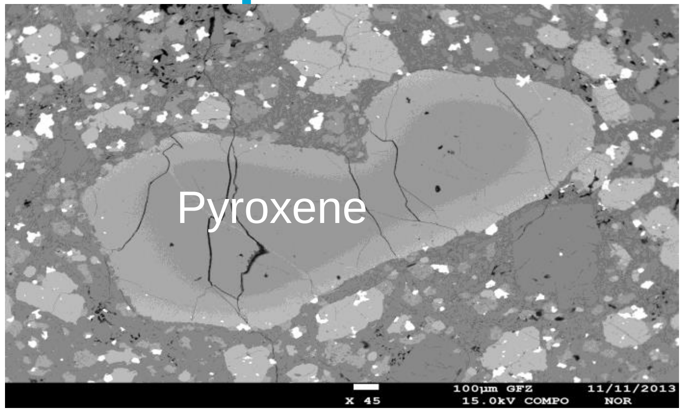
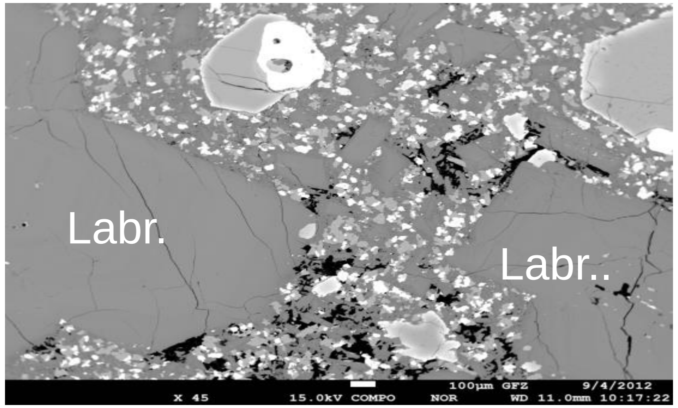
Electron microprobe- SEM images



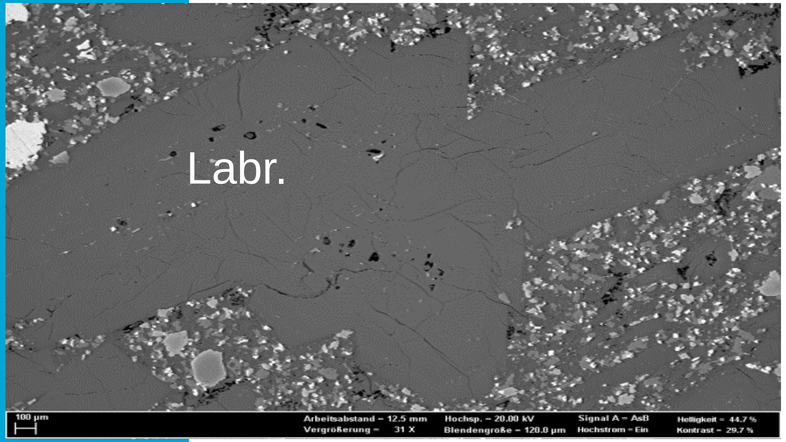
FD8



WP11



FD1



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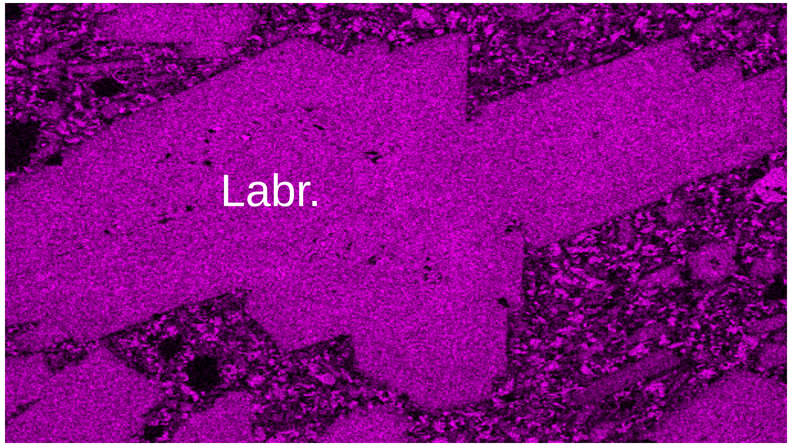

Ca element distribution mapping

Element mapping as helpful tool to find the clay fraction

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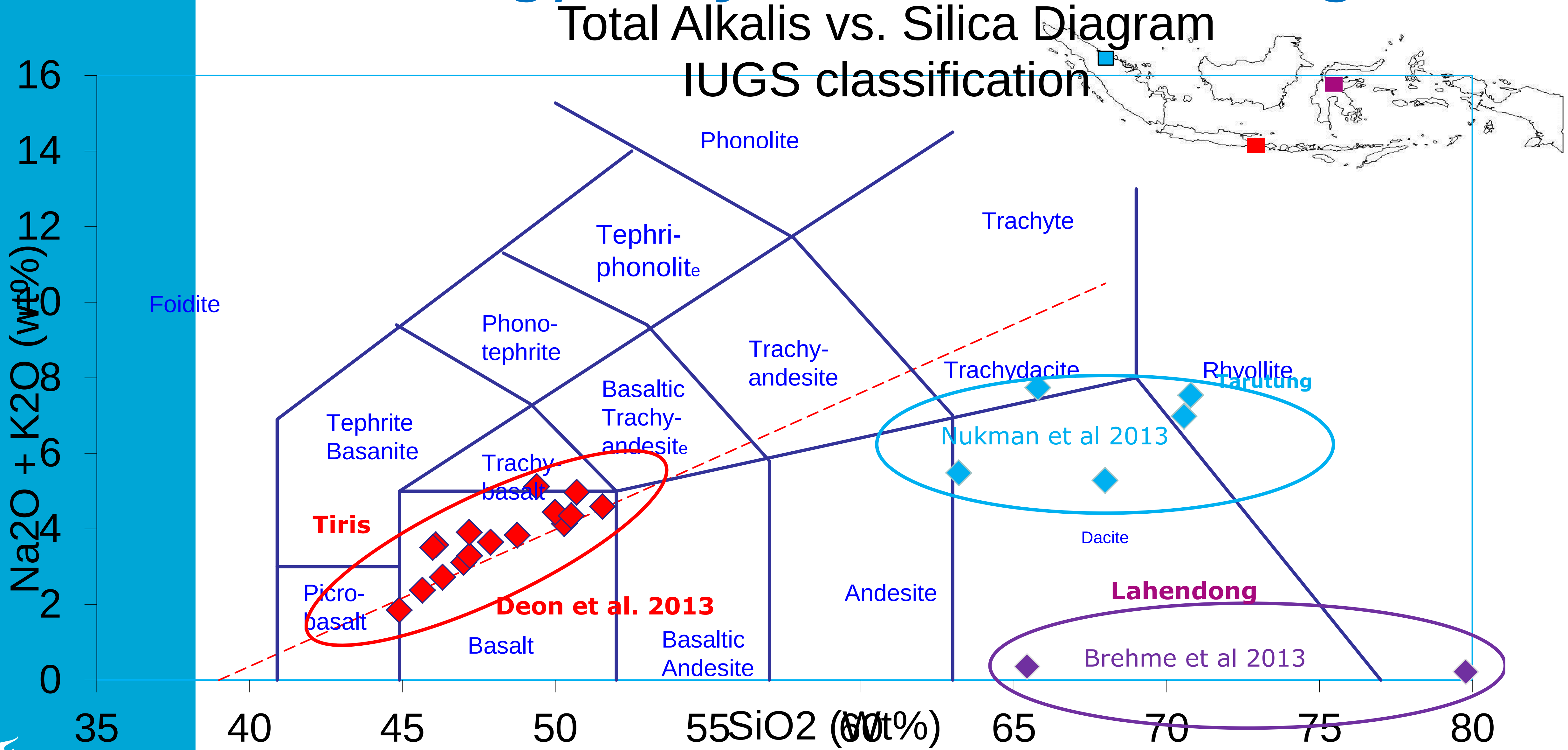
Petrology: major oxides of the magma



Fluid geochemistry

Fluid geochemistry

7 springs (35 – 45 °C).

Springs reveal:

High HCO_3^- content in all springs

Relatively low to moderate Cl^-

Absence of SO_4^{2-}

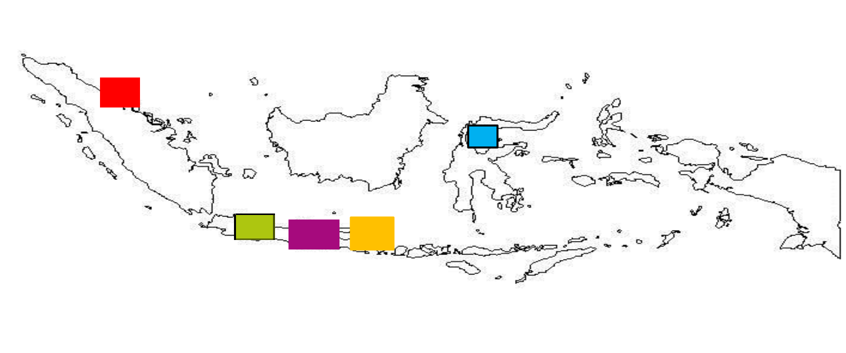
= Lahendong

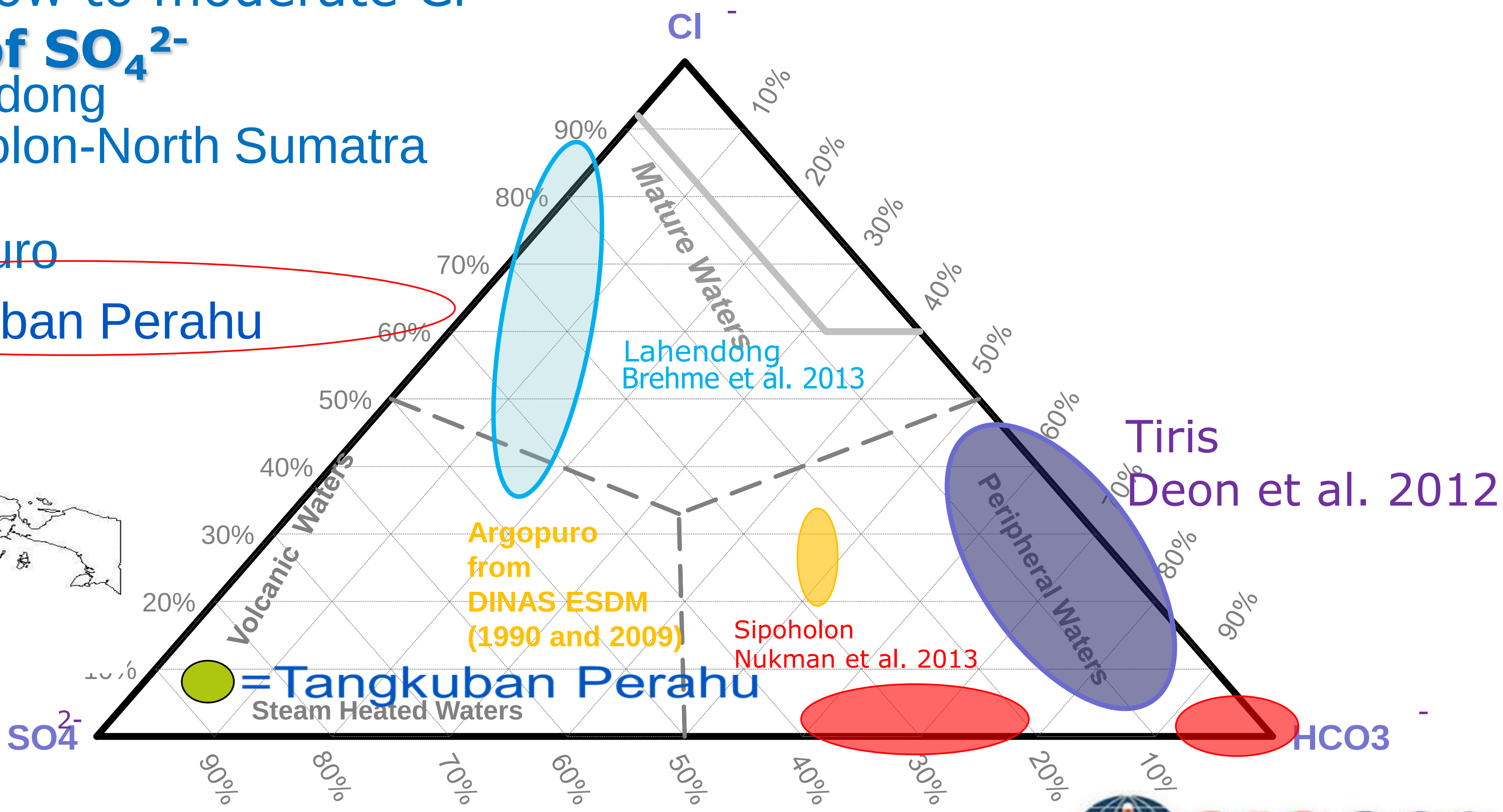
= Sipoholon-North Sumatra

= Tiris

= Argopuro

=Tangkuban Perahu





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Water field sampling: bubbles with NE-SW strike

Deep wells-ground water sampling

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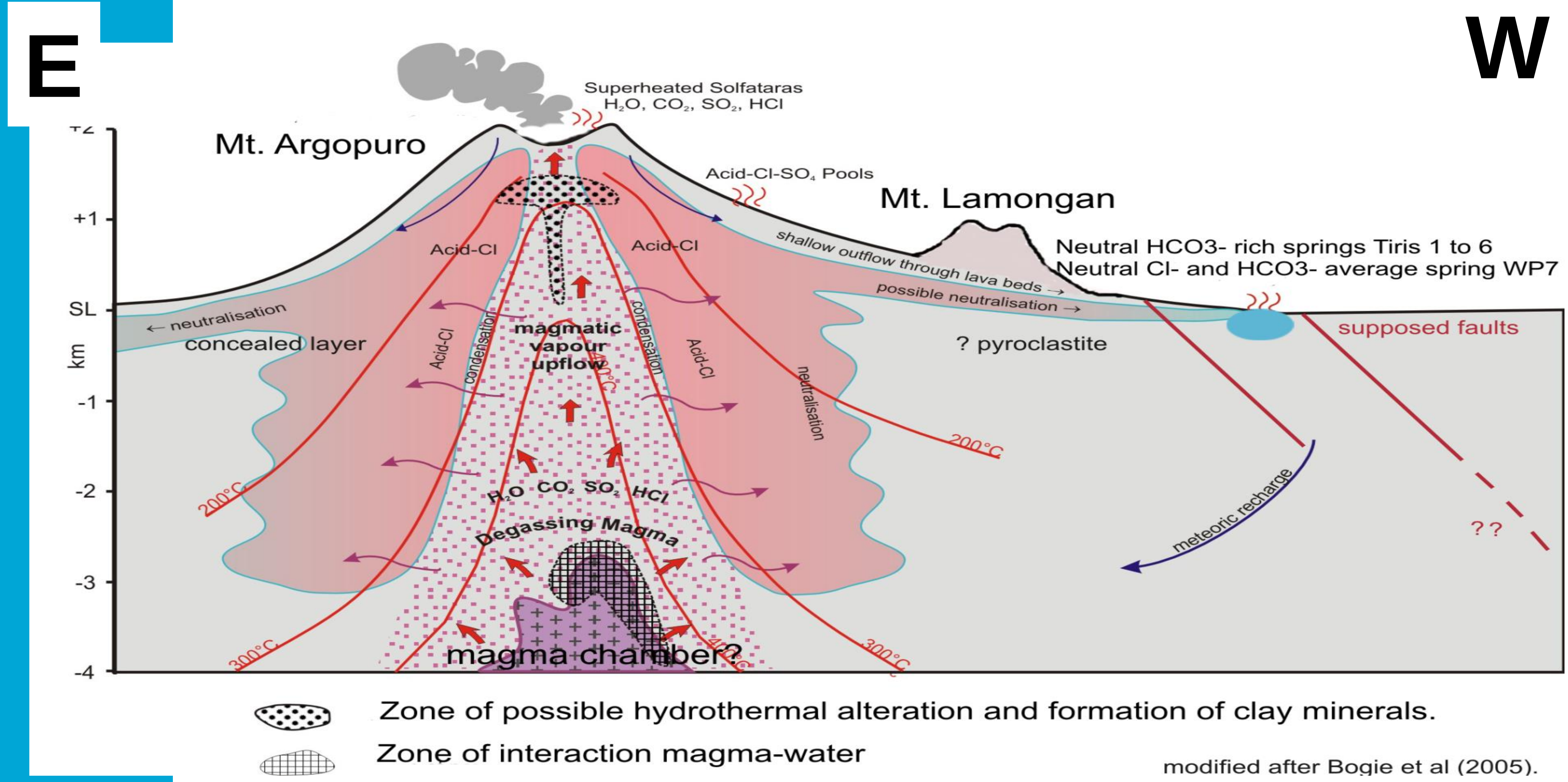
Conceptual model



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GEOCAP Geothermal Capacity Building Program Indonesia - Netherlands

How to proceed in the future….

- A location should be chosen for a first drilling, essential in order to obtain - SUBSURFACE information especially about faults!
- The drilling samples should be analyzed as suggested to detect hydrotherma alteration-SUBSURFACE
- Eventual deep fluid samples would contribute to improve the knowledge of th complex geological-volcanological system of the area as well as rock water interaction

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Geothermal manifestation in magmatic and a-magmatic setting

Hot springs:
Deliver a useful glance of the buried hot water and steams

Sipoholon

Tiris

Geothermal manifestation

wikipedia

Rinehart (1980) pointed that a **geyser** is an hot spring that periodically becomes Hydro-thermodynamically unstable. Superheated water comes to the surface and goes up to 50 meter in the air.

Travertine: water heated around magma bodies reacts
With carbonate and release CO_2-hot water are cooled
And mix with cooler ground water and reach chemical
Equilibrium with the aquifer rocks at 70° C.
Once at the surface CO_2 is released-water becomes $CaCO_3$
Oversaturated and the carbonate precipitation form travertine

Summary

- Main components of hydrothermal systems
- Volcano: structure, definition
- Type of volcanism: intra-plate, passive margin
- Magma: chemical and physical properties
- Type of volcanic activity
- Deposit in the field
- Petrography and geochemistry
- Case study on an Indonesian geothermal field
- Geothermal Manifestation

Thank you for you attention
Terima Kasih atas Perhatian Anda