Crater lakes and spring water monitoring

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Strategy for searching for eruption precursors

❑ the main driving force of eruptions is the fluid phase!

❑ fluids are much more mobile than melts:

➢ even dormant volcanoes can release magmatic fluid components

➢ gases may bring information to the surface well in advance to magma extrusion or even precursory geophysical event

❑ fluids are sensitive to thermodynamic changes and mass balance effects at depth

➢ geochemical variations in surface gas emissions can reflect changes in eruptive potential at depth

➔ fluids are optimal targets to search for eruption precursors

❑ the various kind of fluids :

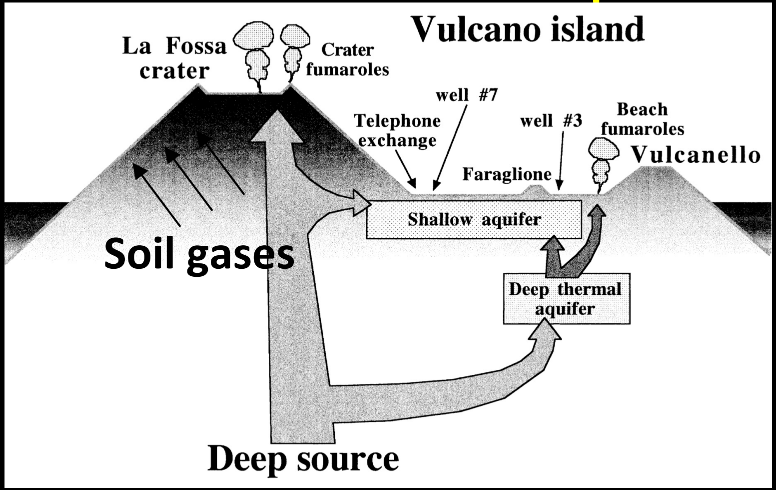
➢ high temperature gases

➢ soil gases

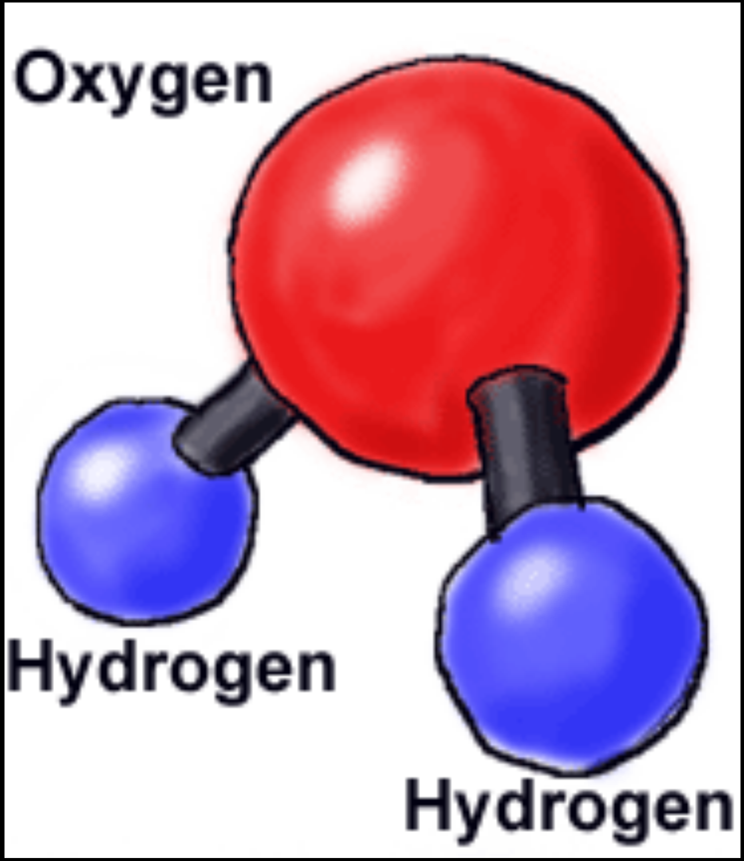
➢ crater lake waters

➢ thermal waters

➢ plume gases



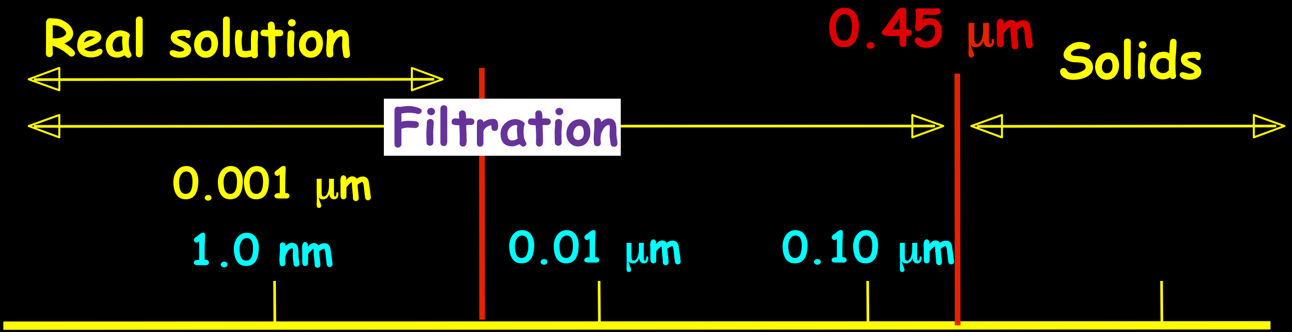
Water



- Dissolved solid load
- Suspended solid load
- Organic and inorganic nutrients
- Pollutants and contaminants
- Colloids and gels
- Organic compounds
- Organo-metallic compounds

Water

A single portion of a certain water body will contain the same chemical and isotopic features and any induced perturbation will be reflected in any part of that portion



Real solution

0.45 µm

Solids

Filtration

0.001 µm

1.0 nm

0.01 µm

0.10 µm

Soluble matter			Colloids		Particles	
Free metallic ions	Ionic pairs Metallic chelates	Organo-metallic compounds	Metallic species on organic molecules	Metallic species on colloids	Metallic species on organic matter	Inorganic solids, adsorbed precipitates

Main components (ions)

Cations

Ca^{2+}

Mg^{2+}

Na^{+}

K^{+}

Anions

CO_3^{2-} + HCO_3^{-}

SO_4^{2-}

Cl^{-}

mg/L o ppm

Minor	Trace	Ultratrace	components
Some fraction of mg/L (ppm)	Tens of μg/L (ppb)	Fractions of ng/L (ppt)	

Volcanic (crater) Lakes

Limnology

Limnology (from several sources)

Also called freshwater science and concerns the study of fresh waters, specifically lakes, and ponds (both natural and manmade), including their biological, physical and chemical aspects. F.A. Forel (1841-1912) established the field with his studies of Lake Geneva. Limnology traditionally is closely related to hydrobiology, and concerns with the application of the principles and methods of physics, chemistry, geology and geography to ecological problems. Limnology studies: i) the spatial distribution of the lakes, ii) their dimensions and morphology, iii) their chemical composition and iv) the energy (thermal from the Sun and mechanical from the wind) that these water bodies receives and v) the living organism that are present in these ecosystems.

and from degassing magmas whose matter
and/or energy reaches the surface

- CAVW ➔ 16% of the 714 volcanoes younger than 10 ka contain a lake
- higher percentages for subduction-related volcanoes
- many lakes contain hot waters
- they are fed by meteoric water (precipitation, runoff, and so forth)
- they have a deep component interacting with shallow waters
- some are mixtures of HCl and H_2SO_4 ➔ pH down to 0 or even less
- they can store large amounts of lethal gases (CO_2)


Kawa-Ijen

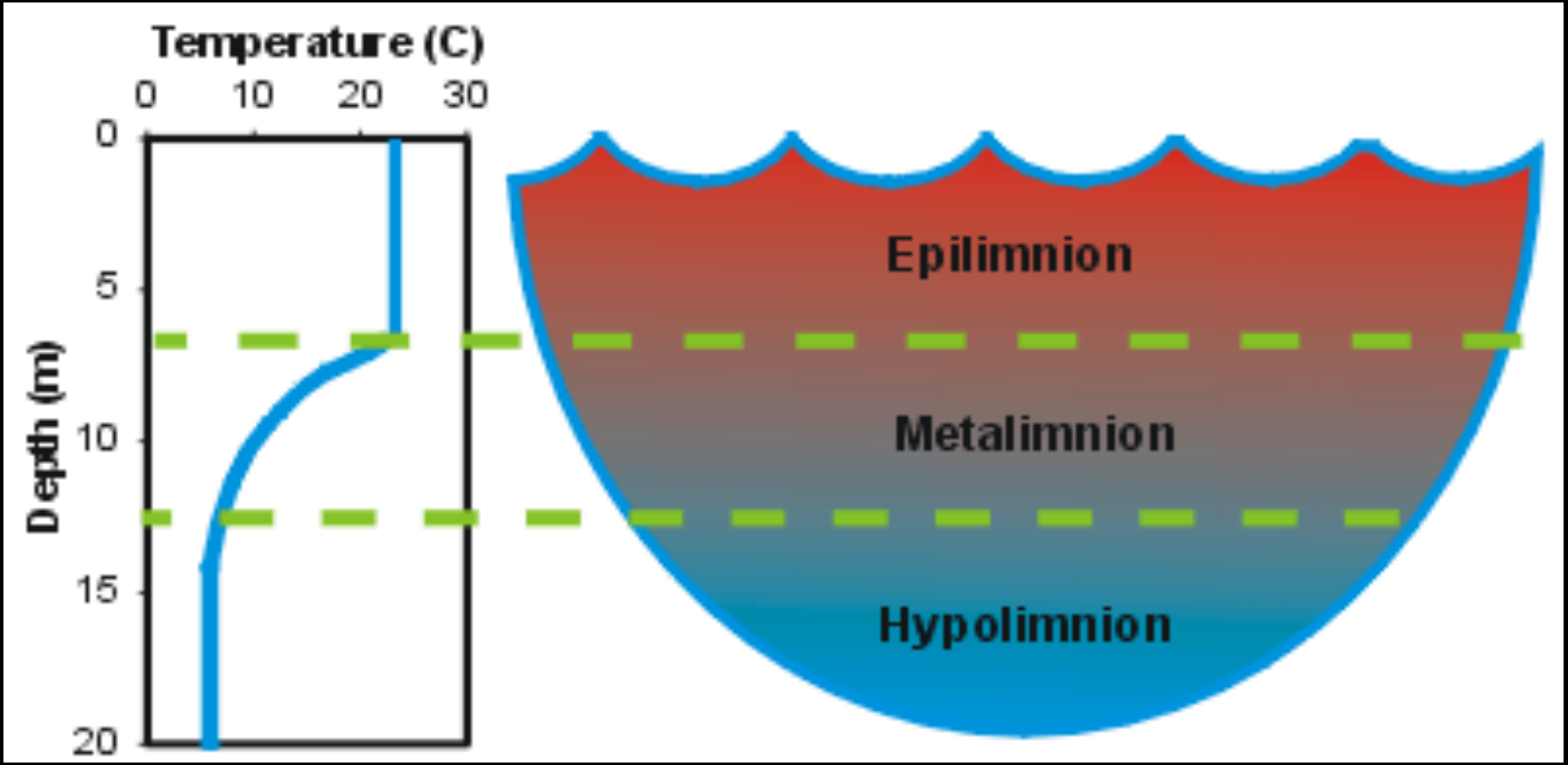

Irazu


Poas

Is a lake stratified?

Epilimnion: is the most surficial layer and is affected by the solar radiation allowing the surface temperature being higher than that of the underlying layers

Metalimnion is that layer where a rapid decrease in temperature occurs



If a lake is relatively deep **Hypolimnion** can be formed whose temperature is around 4 °C:.

Consider a 20 m deep lake in an Alpine environment.
Density max H_2O: 4 °C

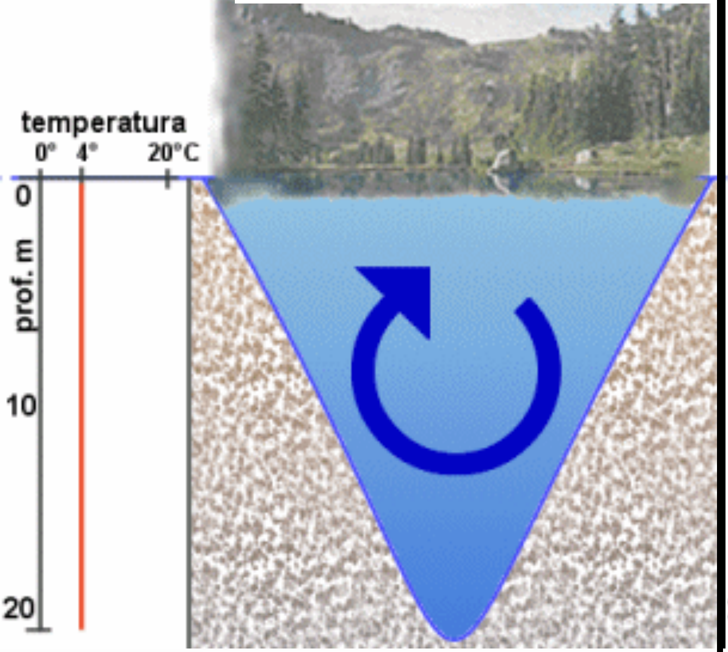
Winter ends: T= ca. 4 °C.

Solar radiation increases and surface temperature increases

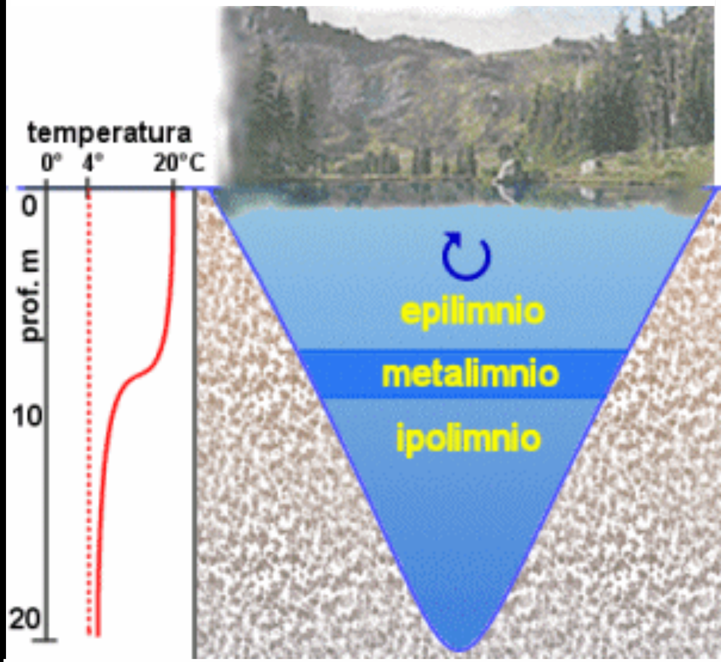
Surface water cools down and sinks

When ice is formed an inverse stratification occurs and it stabilizes an inverse thermal stratification.

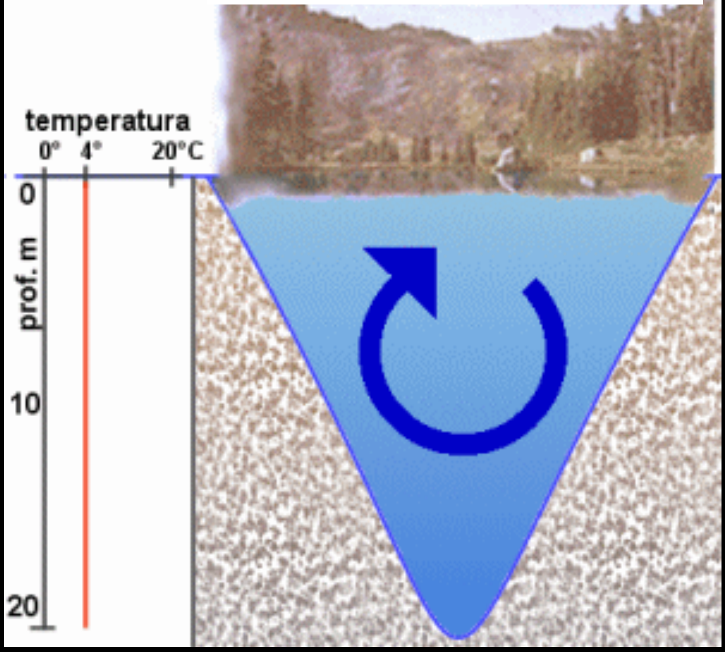
Spring circulation



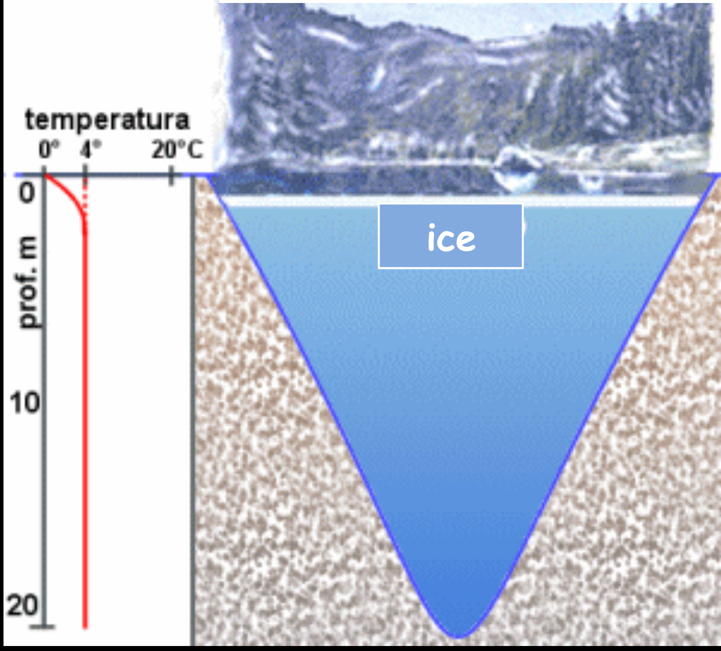
Summer stratification



Autumn circulation



Winter stratification



According to climatic conditions and lake depths, we may have annual cycling of the lake waters. Accordingly, a sort of classification can be done:

Olomictic lakes, at least one full circulation phase;

Dimictic lakes, two phases of full circulation;

Oligomictic lakes, phase of full circulation not each year;

Monomictic lakes, and so forth;

Meromictic lakes, no full circulation phase (perennial stratification due to either thermal reasons or high saline and gas contents or both).

Two other definitions:

A chemical one:

Chemiocline – It is a cline (water layer where the physico-chemical properties rapidly change) caused by a rapid and sharp vertical chemical gradient. It is similar to thermocline (metalimnion) where warmer water meets cooler waters.

…and a general one:

Crater lak [illegible] volcanic lakes hosted in an active volcano (e.g. Poas, [illegible] Chichon, Kawah Ijen).

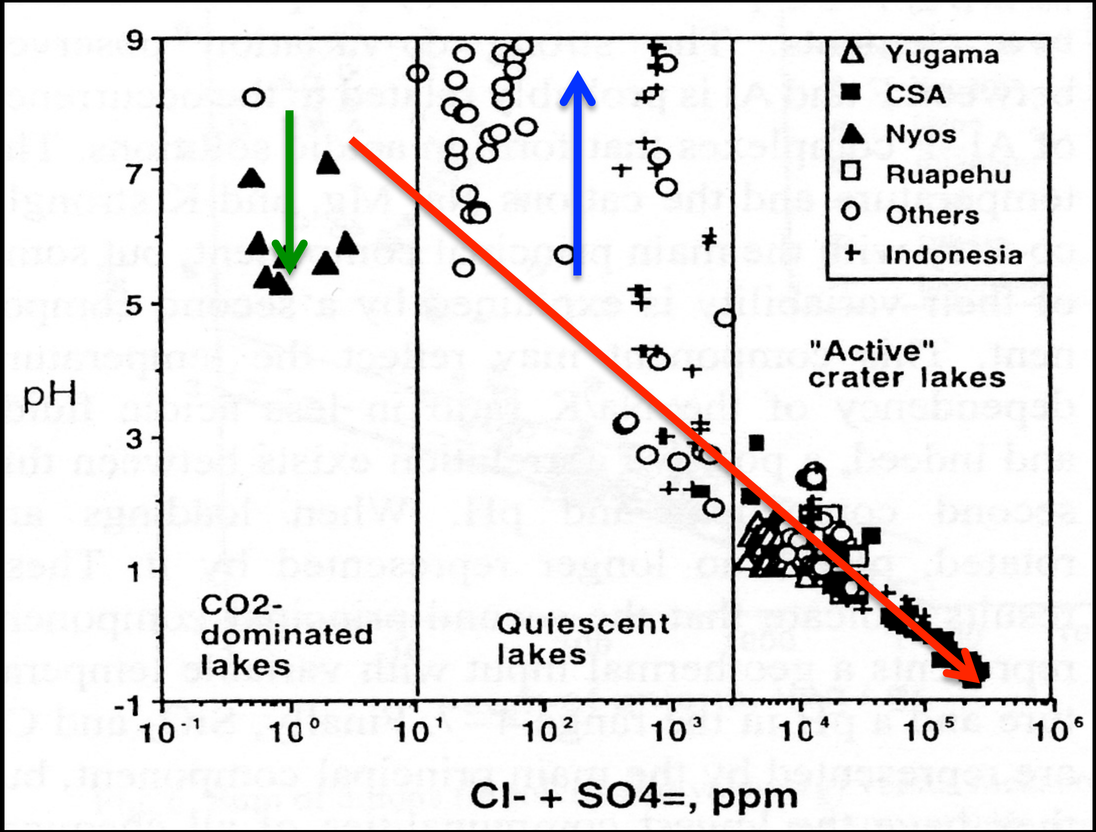
Volcanic lakes are not necess[illegible]ter of an active volcano.
Other lakes: maar lake, caldera lake, etc.

Volcanic lakes

Volcanic lakes: chemical classification

chemistry: large diversity of lakes

- Neutral pH (~7), diluted (TDS < 100 mg/L), ex : Crater Lake, USA
- Lakes with intermediate acidity (pH~2-6) and mineralization (TDS<2000 mg/L)
- Highly acidic (pH<1) strongly mineralized (TDS > 100,000 mg/L), ex: Kawa-Ijen, Indonesia
- various chemical facies : high Na-Cl (Kelut, Indonesia), high $Cl-SO_4$ (Oyunuma), high HCO_3 (Nyos)



pH vs. $Cl+SO_4$ classification

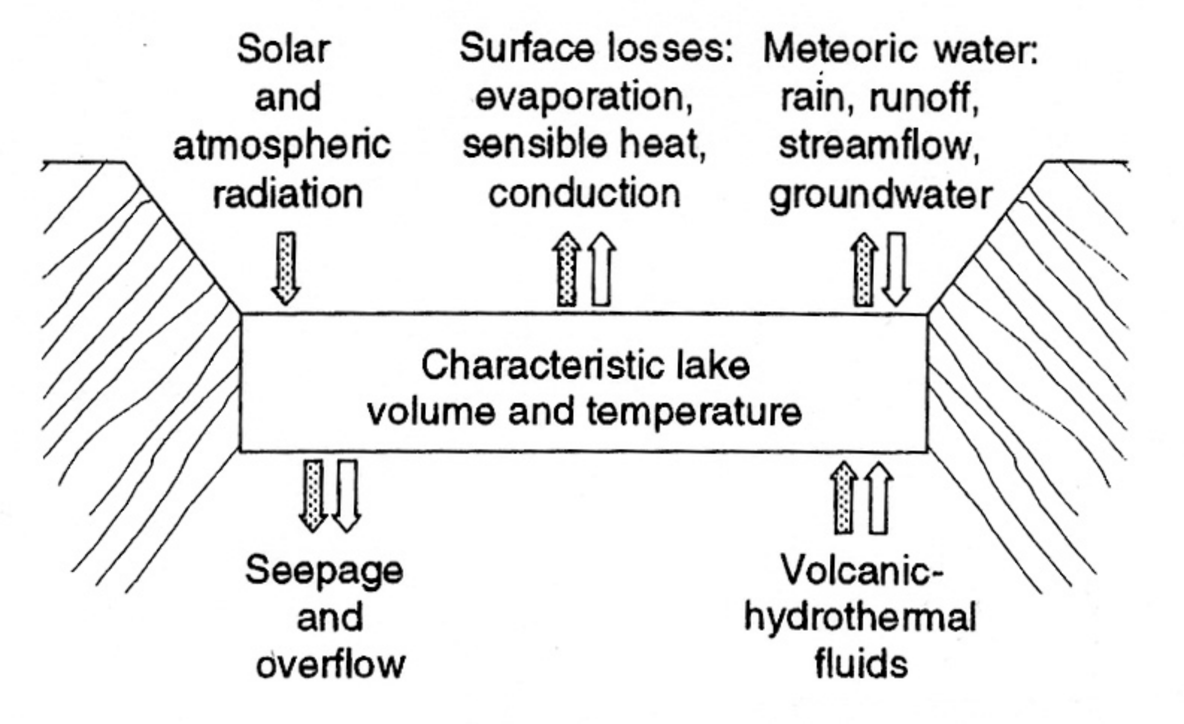
- main discriminating parameters: pH and components derived from acid gases dissolution (Cl^-, SO_4^{2})
- 3 main groups of lakes :
  - CO_2-lakes : neutral pH (~5-7) + low $Cl+SO_4$ (< 5 ppm) + CO_2-dominated
  - geothermal quiescent lakes: large-range pH (2-9), moderate Cl $+SO_4$ (< 2000 ppm)
  - active crater lakes: acidic pH (2 to -1), high $Cl+SO_4$ (> 2000 ppm)

Necessary physical constraints to maintain a volcanic lake

- Sufficient input of meteoric water
- Sufficiently impermeable lake bottom/ basin
- Input of heat and vapor… but not too much

- So: very delicate equilibrium to make a lake sustain in time

Volcanic lakes as condensors & calorimeters



Total mass and heat budget of volcanic lakes

❑ **Persistent volcanic lakes**. Hydrothermal systems feed heat, water & matter from a cooling, degassing magma body;

❑ **Global budget of mass**:

➢ inputs are: volcanic & hydrothermal fluids + meteoric water (rainfall, runoff, stream flow);

➢ outputs are: evaporation, lake water seepage, overflow, ground infiltration;

❑ **global budget of heat**:

➢ input is derived from enthalpy of the entering fluid + solar & atmospheric radiation;

➢ outputs are: evaporative & radiative fluxes from lake surface, seepage and overflow and cooling effects by rainfall and runoff in lake.

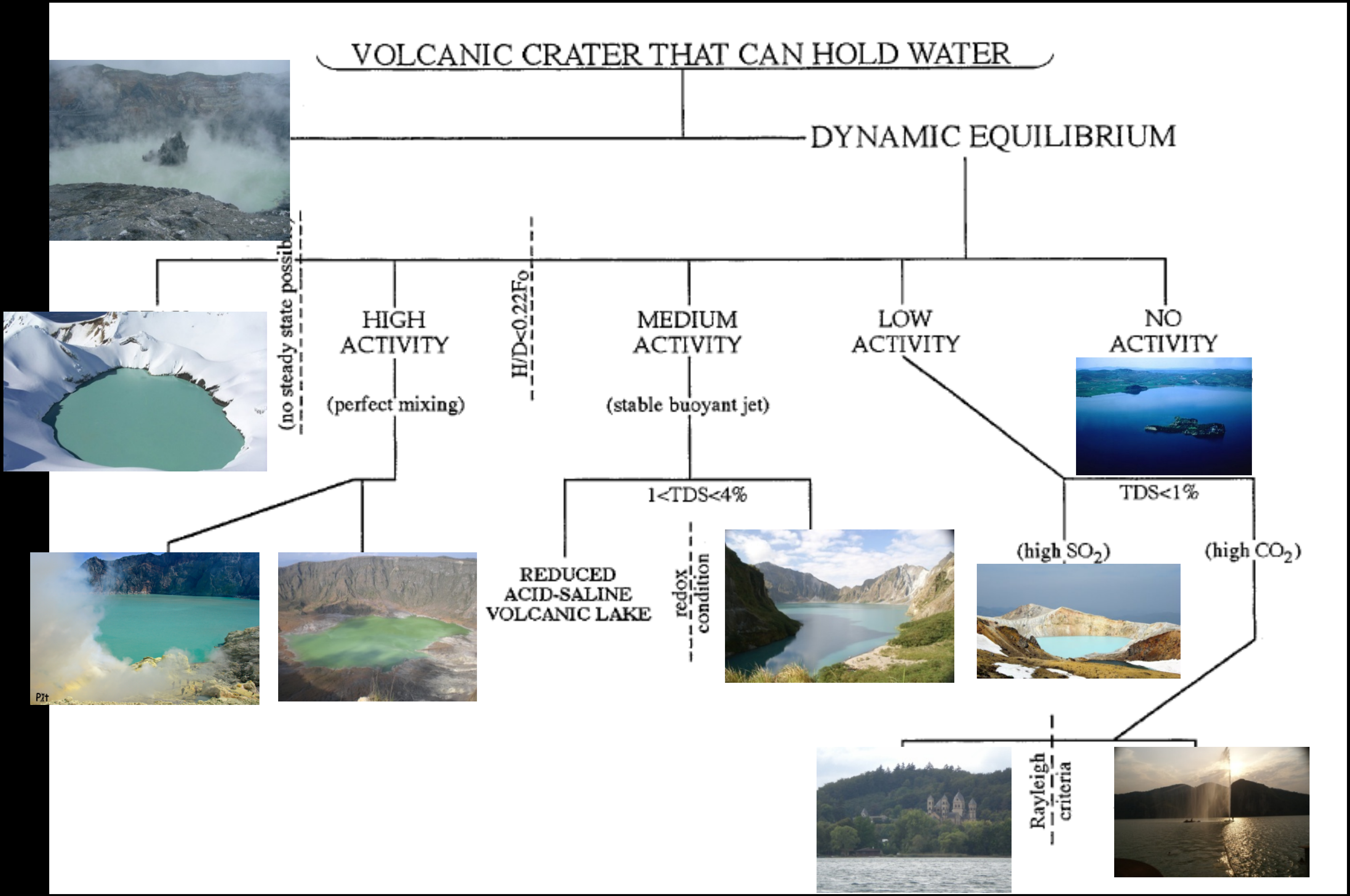
Dynamic processes in lakes

❑ ratio heat input/heat dissipation determines the persistence and the temperature of the water

❑ most heat dissipation occurs at lake surface ➔ small lakes have small capacity for heat dissipation and their T rises quickly with small inputs from depth

❑ *great lakes are better buffered against variations in heat inputs*

Pasternack & Varekamp (1997)



VOLCANIC CRATER THAT CAN HOLD WATER

DYNAMIC EQUILIBRIUM

(no steady state possib

HIGH ACTIVITY

(perfect mixing)

$H/D<0.22Fo$

MEDIUM ACTIVITY

(stable buoyant jet)

LOW ACTIVITY

NO ACTIVITY

$1<TDS<4\%$

REDUCED ACID-SALINE VOLCANIC LAKE

redox condition

$TDS<1\%$

(high SO_2)

(high CO_2)

Rayleigh criteria

Volcanic Risk

ELSEVIER

Journal of volcanology and geothermal research

Journal of Volcanology and Geothermal Research 97 (2000) 195–214

www.elsevier.nl/locate/volgeores

The hazards of eruptions through lakes and seawater

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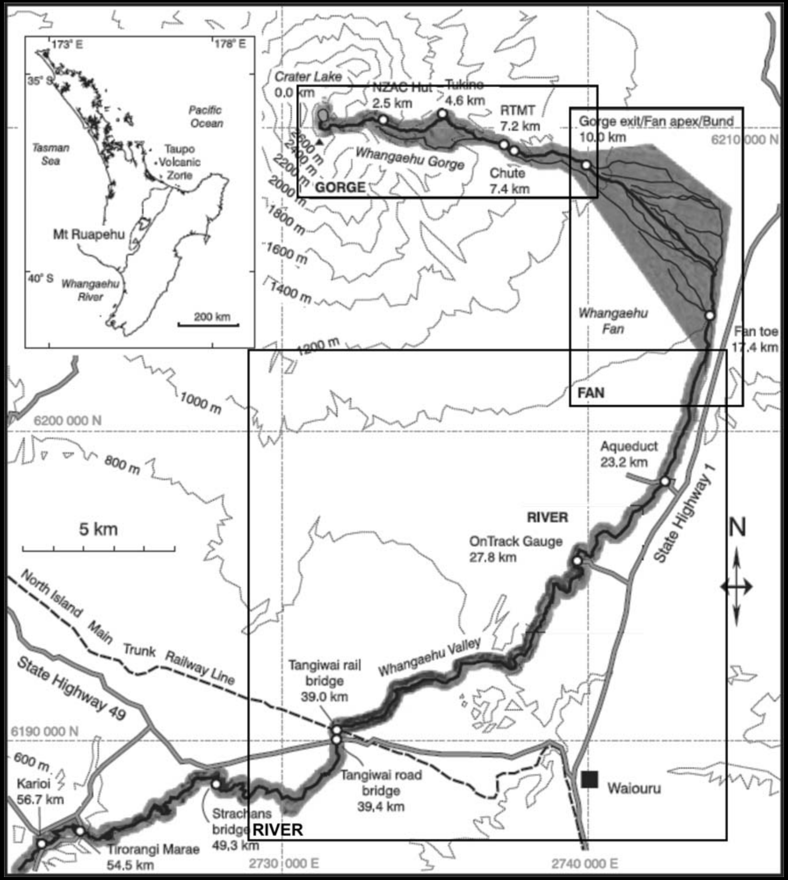
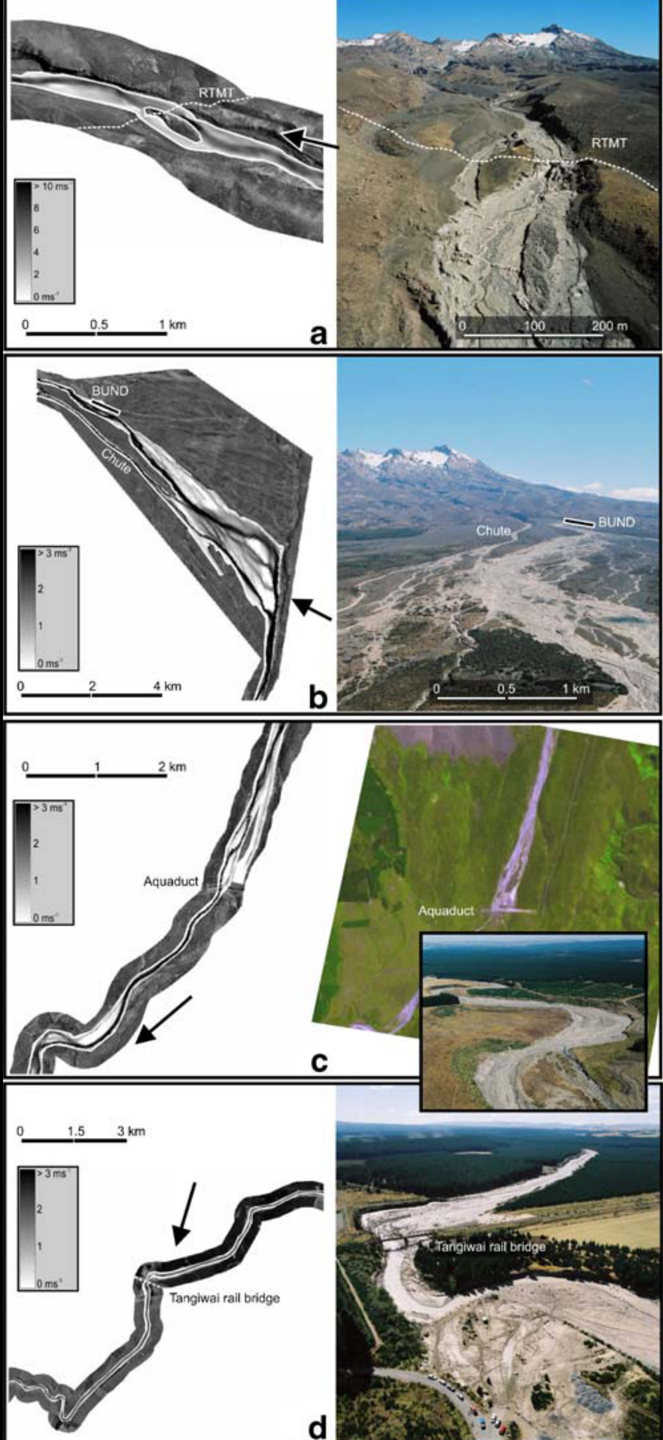
Abstract

Eruptions through crater lakes or shallow seawater, referred to here as subaqueous eruptions, present hazards from hydromagmatic explosions, such as base surges, lahars, and tsunamis, which may not exist at volcanoes on dry land. We have systematically compiled information from eruptions through surface water in order to understand the circumstances under which these hazards occur and what disastrous effects they have caused in the past. Subaqueous eruptions represent only 8% of all recorded eruptions but have produced about 20% of all fatalities associated with volcanic activity in historical time. Excluding eruptions that have resulted in about a hundred deaths or less, lahars have killed people in the largest number of historical subaqueous eruptions (8), followed by pyroclastic flows (excluding base surges; 5) tsunamis (4), and base surges (2). Subaqueous eruptions have produced lahars primarily on high (>1000 m), steep-sided volcanoes containing small (<1 km diameter) crater lakes. Tsunamis and other water waves have caused death or destroyed man-made structures only at submarine volcanoes and at Lake Taal in the Philippines. In spite of evidence that magma–water mixing makes eruptions more explosive

Direct Volcanic Risk (DVR)

Lahars, e.g. Ruapehu, NZ





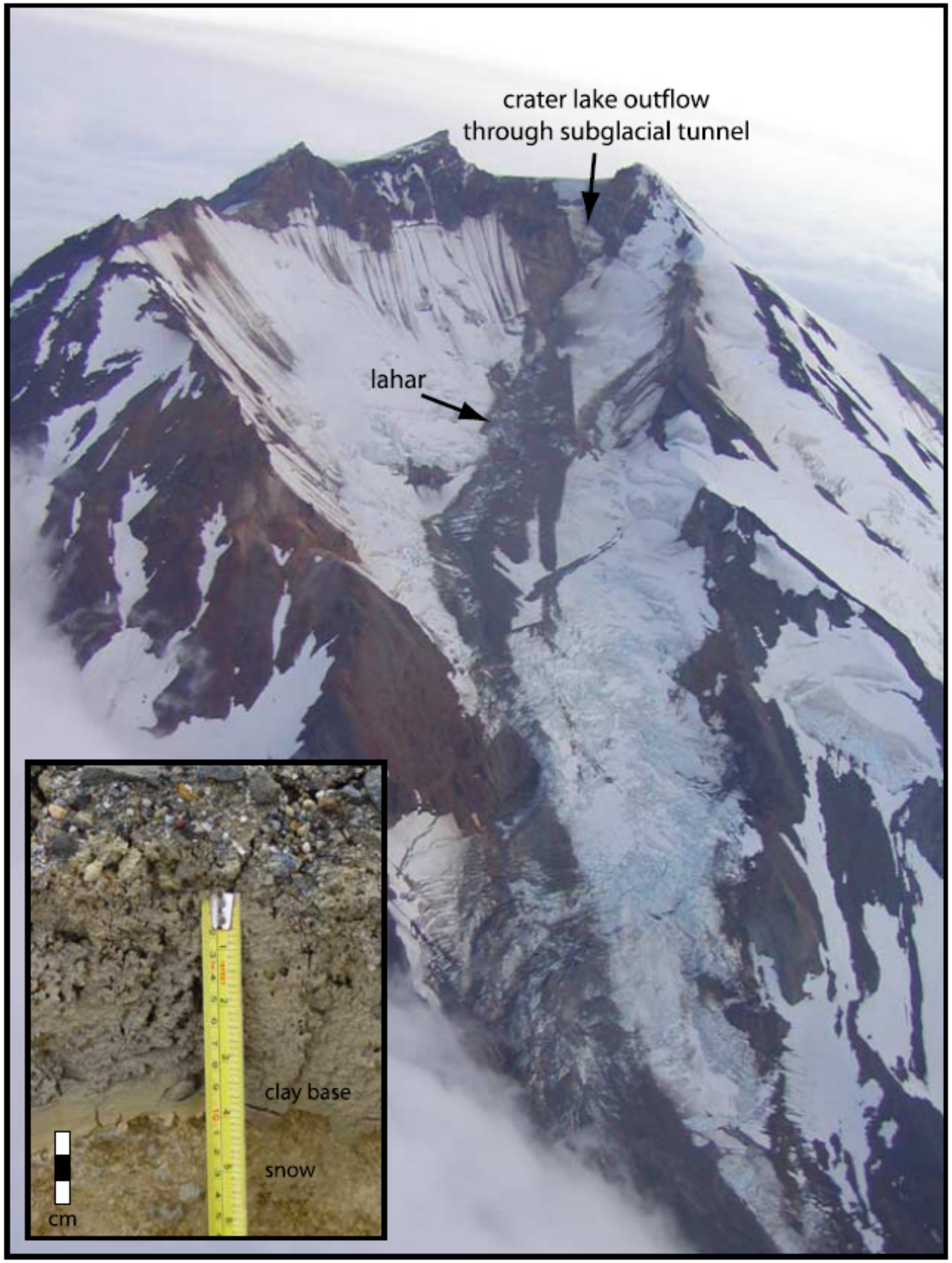
Carrivick et al. 2009

Direct Volcanic Risk

Chiginagak, Alaska, 2005

Schaefer et al. (2008)

DVR



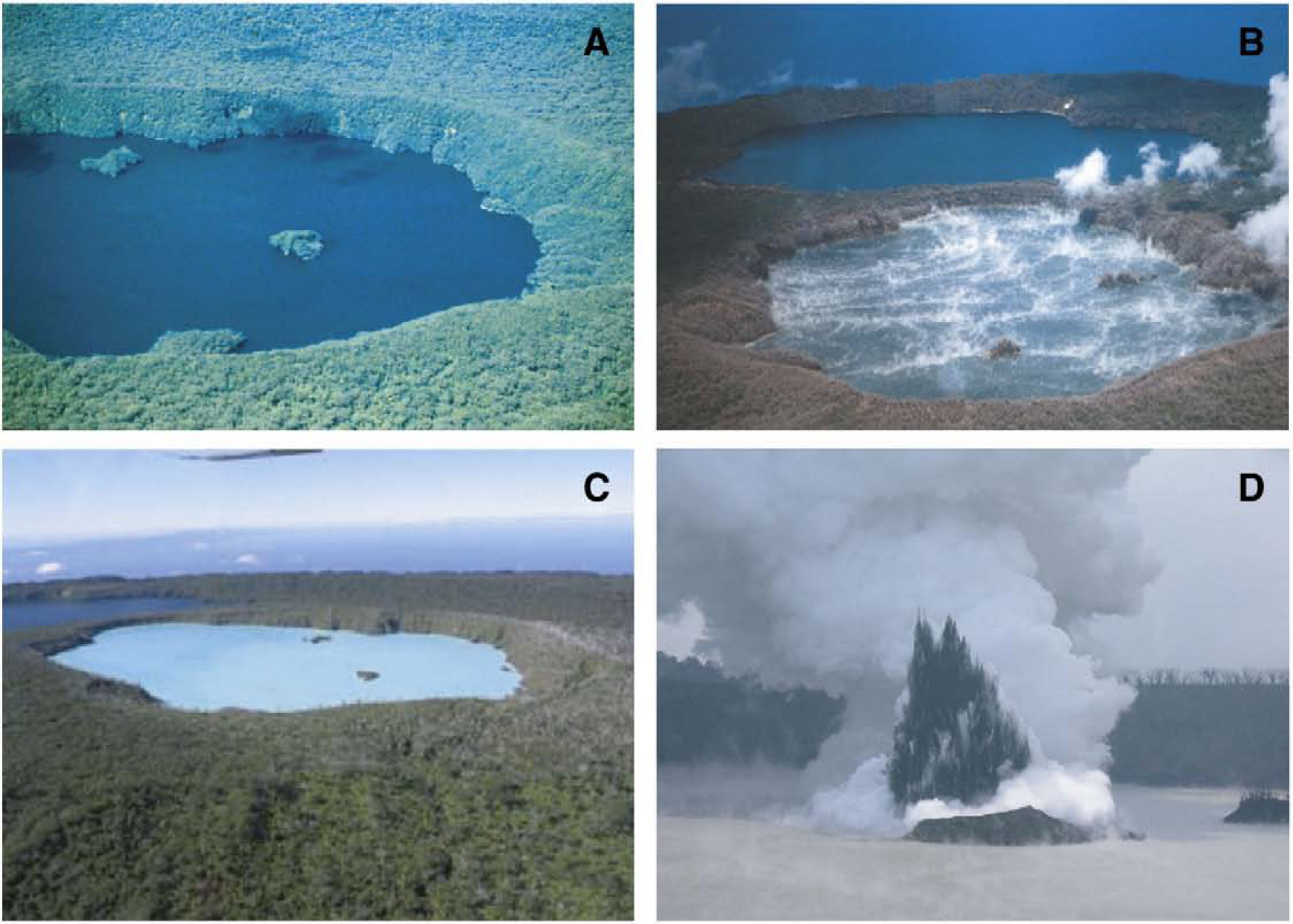
Chiginagak,
Alaska, 2005

Schaefer et al. (2008)

DVR

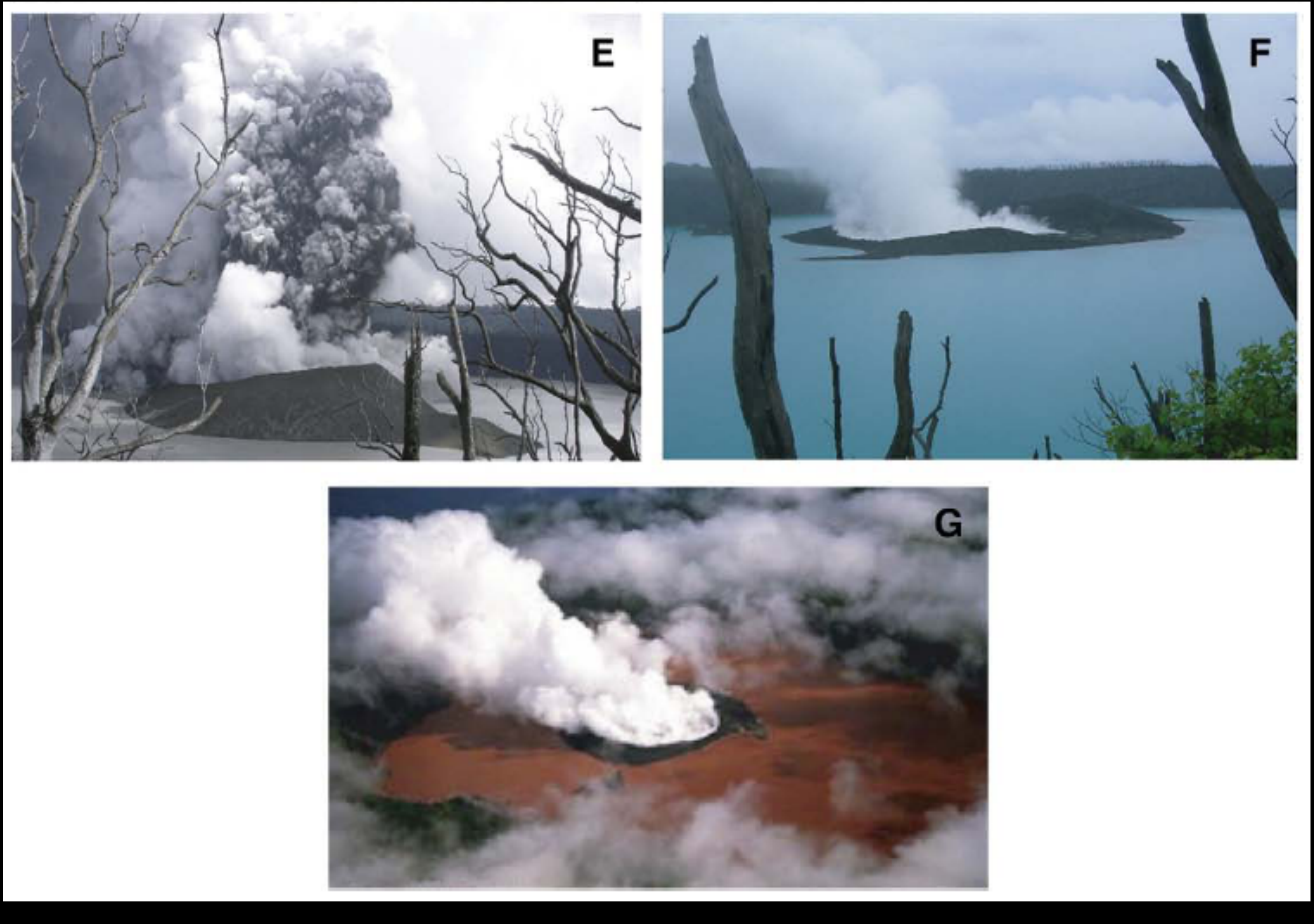
Poas, Phreatic eruptions

Phreatomagmatic eruptions, Voui, Vanuatu, 2005-2006 *Bani et al. (2009)*



Voui, Vanuatu, 2005-2006

Bani et al. (2009)

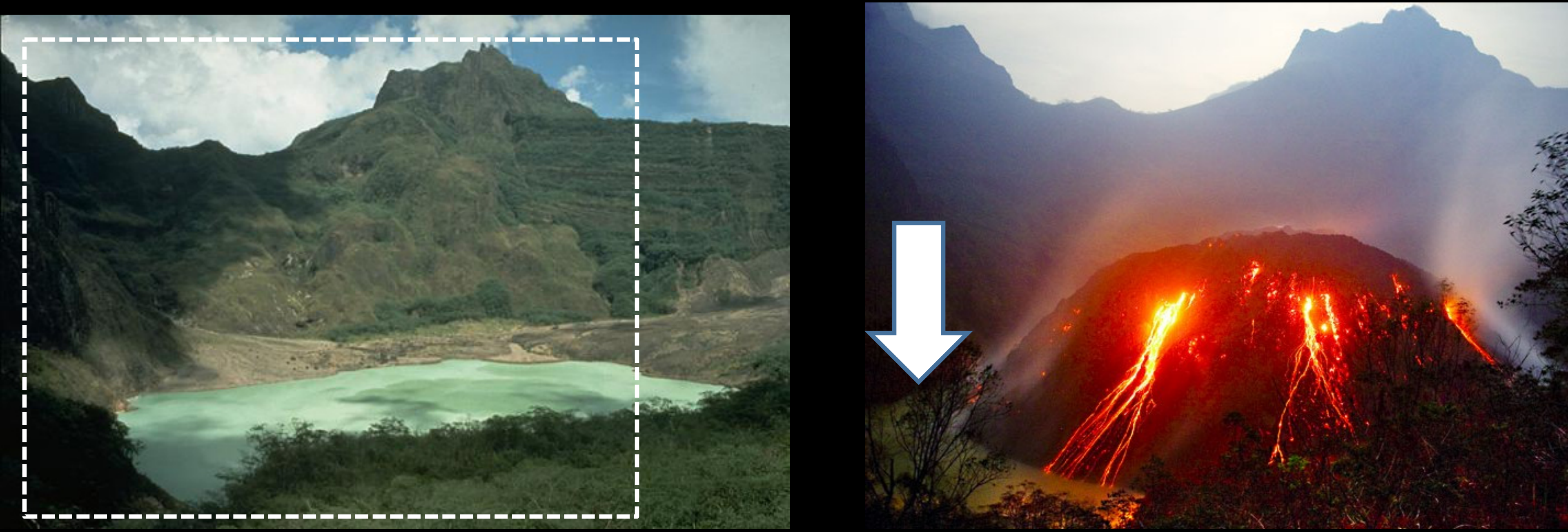


Magmatic activity:
Santa Ana, El Salvador,
Octobre 2005

Scolamacchia et al. (2010)

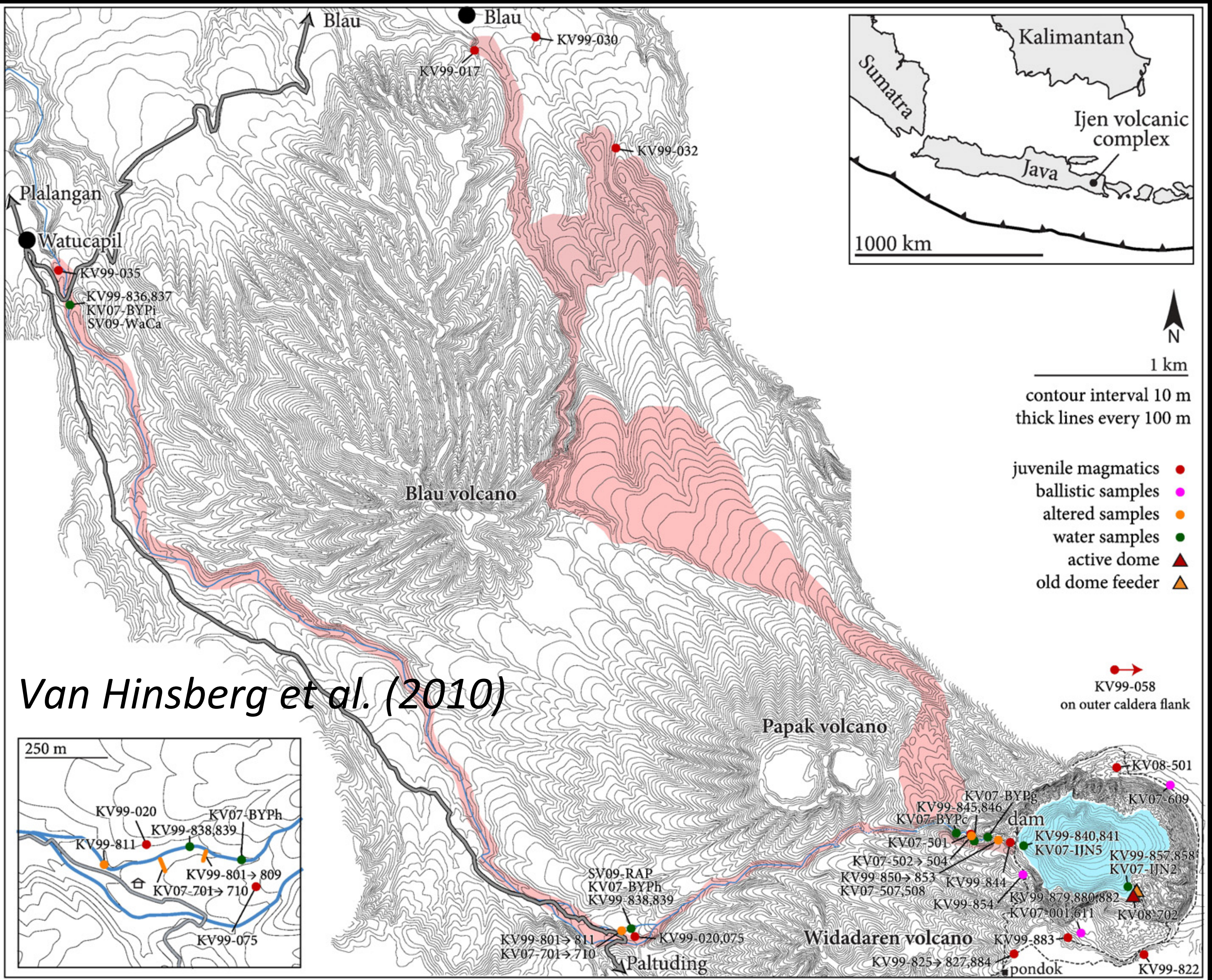
Dome intrusion

Kelut, Indonesia, 2007



DVR

Indirect Volcanic Risk (IVR) dispersion brine in the environment



Van Hinsberg et al. (2010)

IVR: “Nyos-type” limnic gas bursts

IVR: Dispersion in the volcanic edifice + corrosion, mechanical stability

Irazú, Costa Rica

IVR: Dispersion in the volcanic edifice + corrosion, mechanical stability

How can we study volcanic lakes?

- Direct observations
- In situ measurements
- Geophysics
- Fluid geochemistry

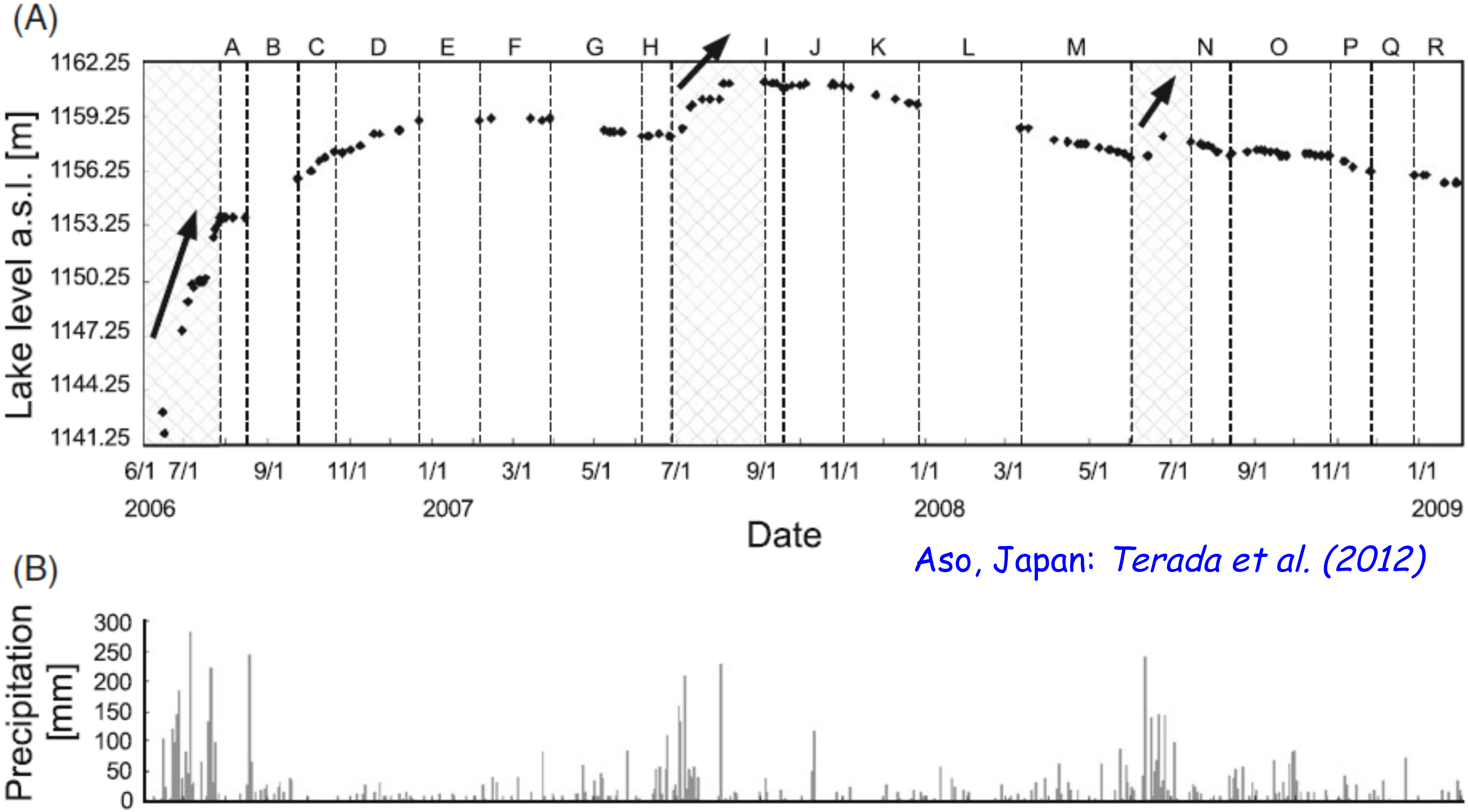
- Identify physico-chemical changes…
- Conceptual models
- Volcanic monitoring

Direct observations

Dimension/level: fixed camera

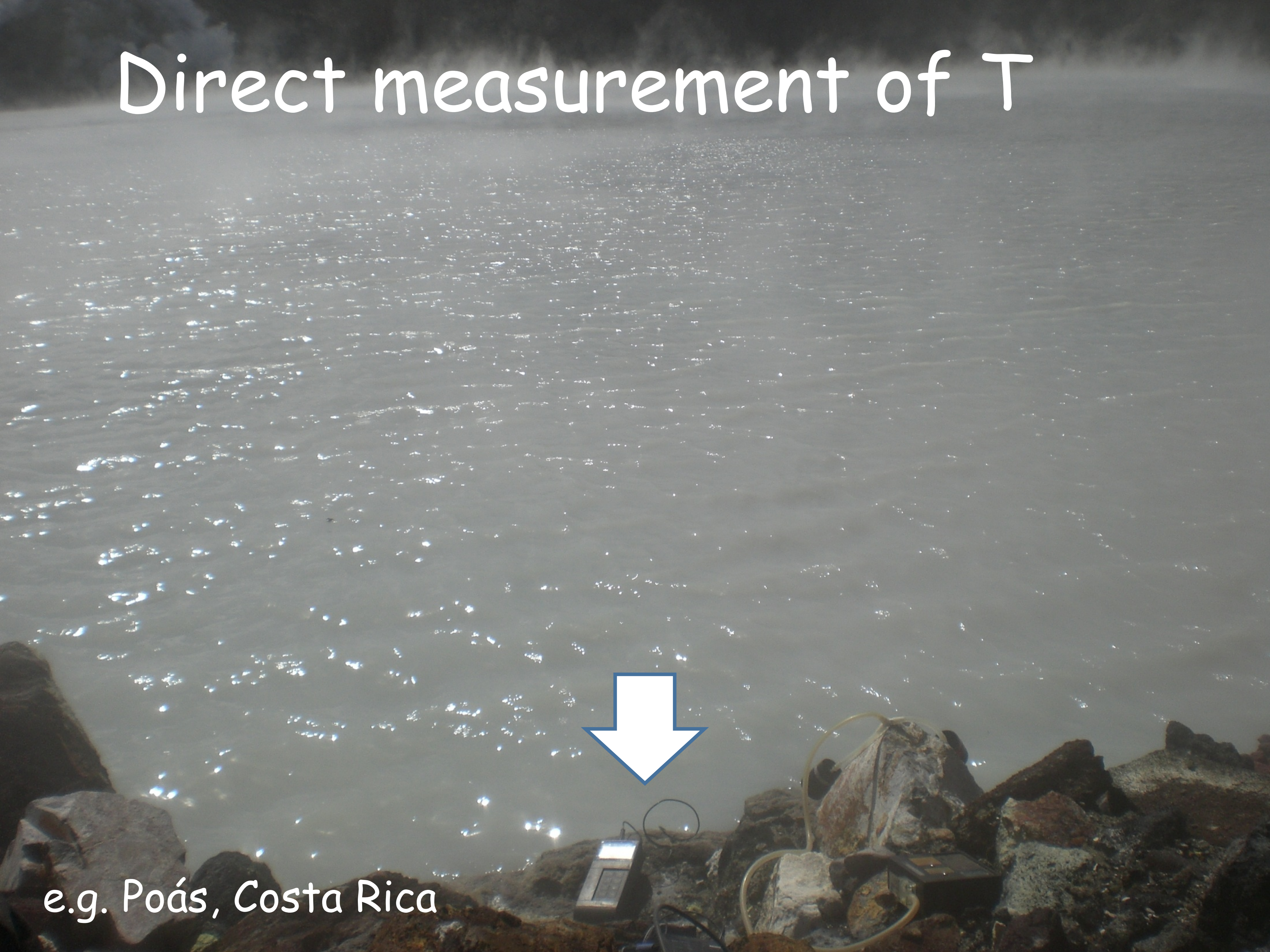
Aso, Giappone: *Terada et al. (2012)*

Direct observations



Aso, Japan: *Terada et al. (2012)*

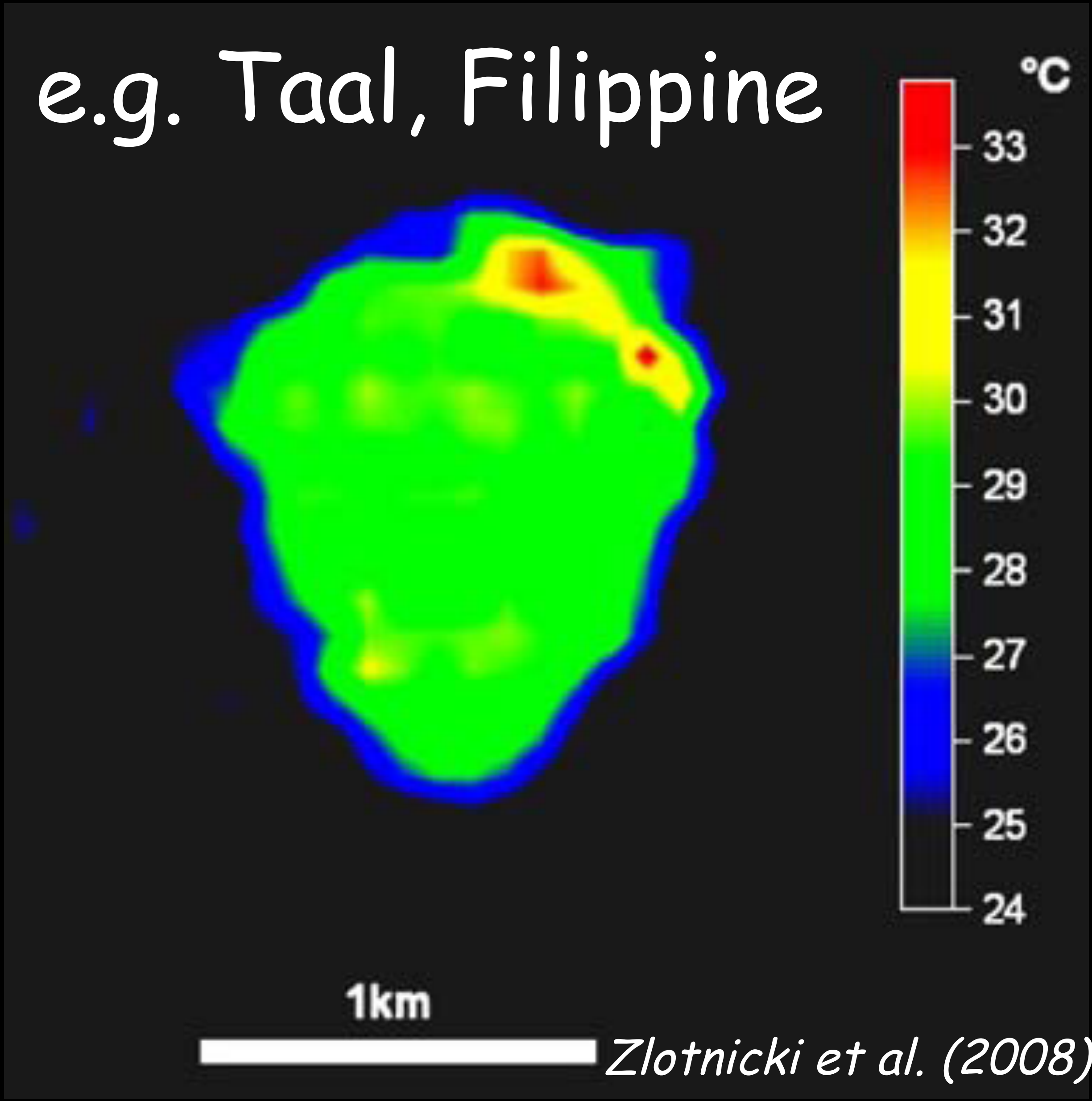
Direct measurement of T



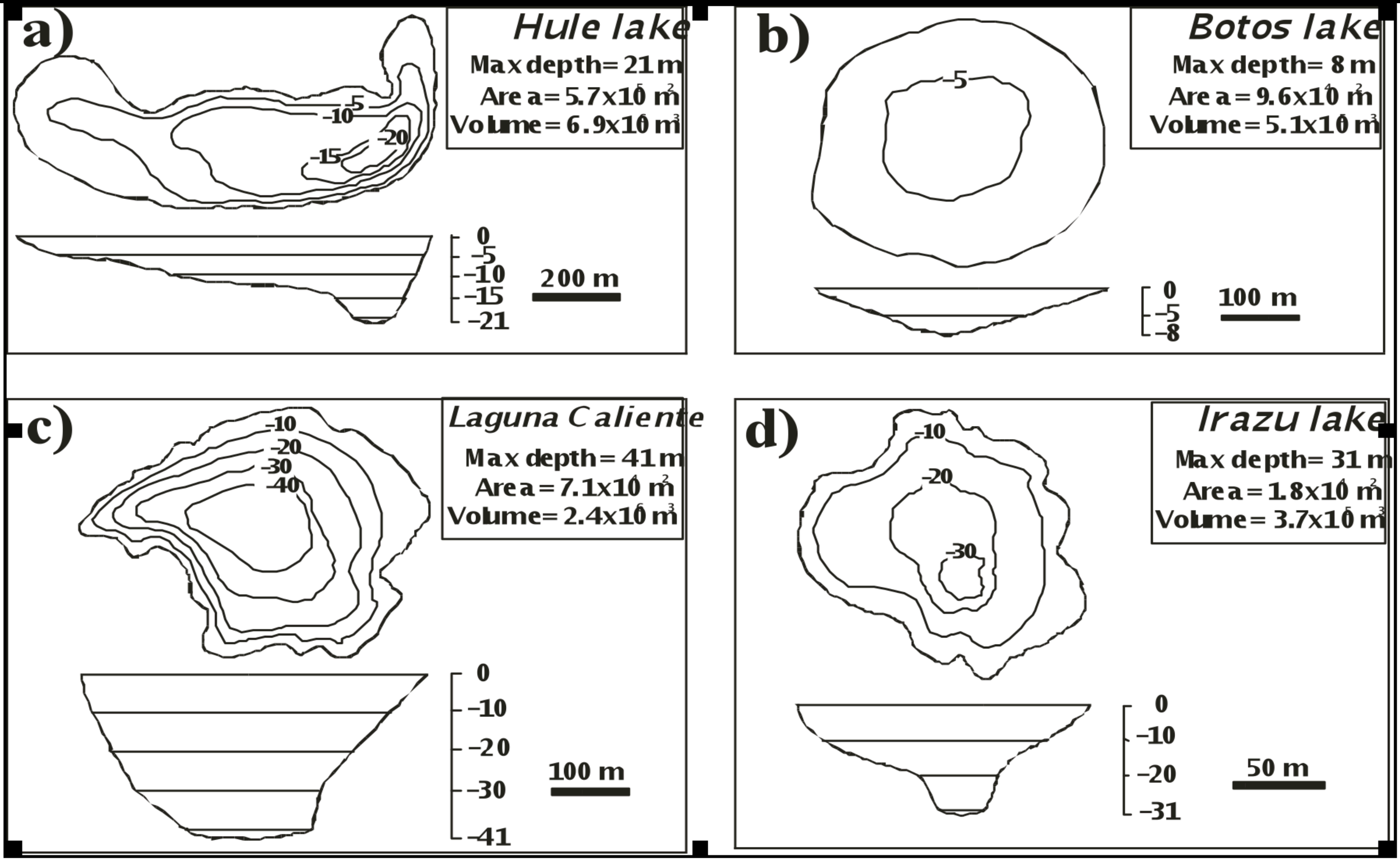
e.g. Poás, Costa Rica

Temperature

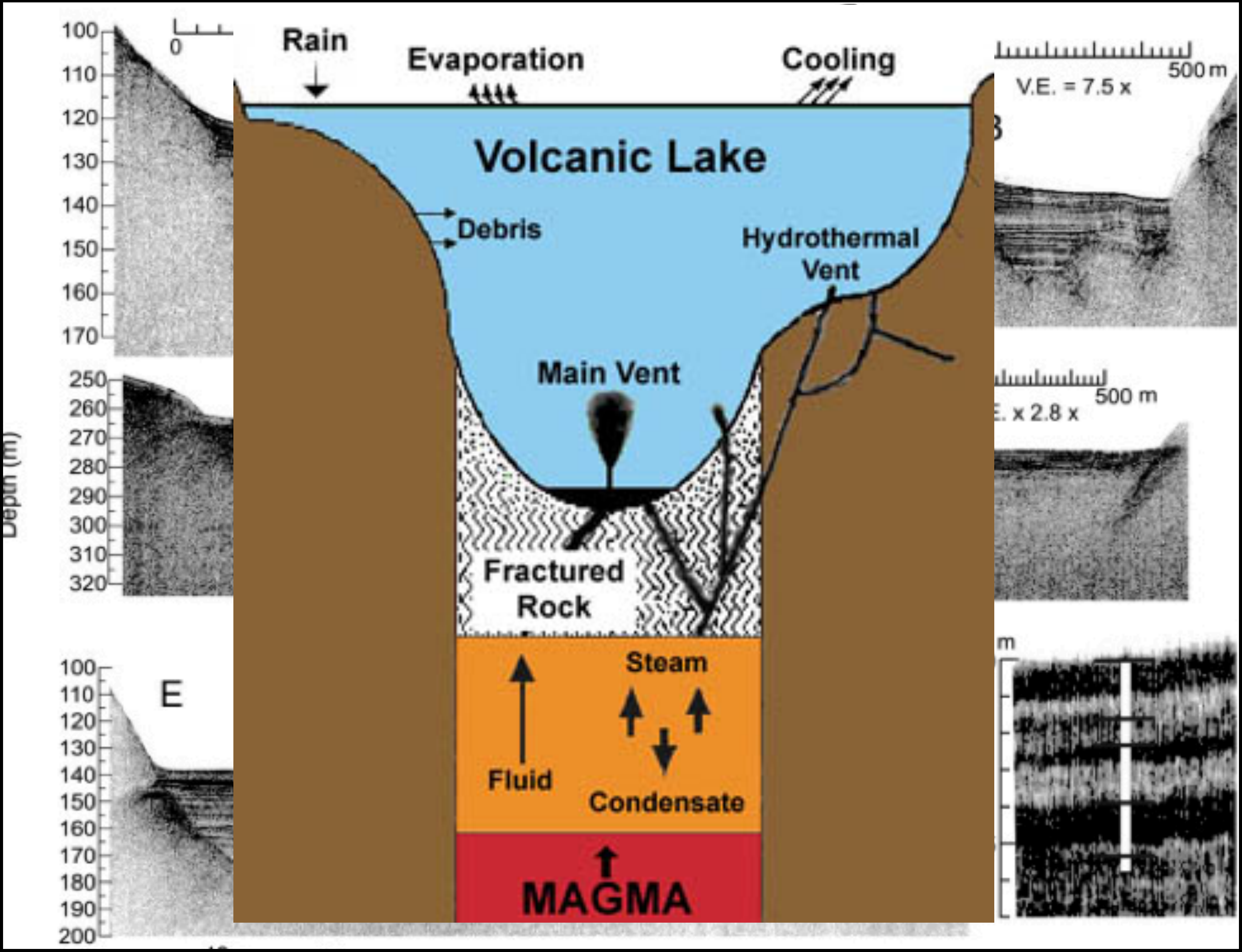
e.g. Taal, Filippine



Zlotnicki et al. (2008)

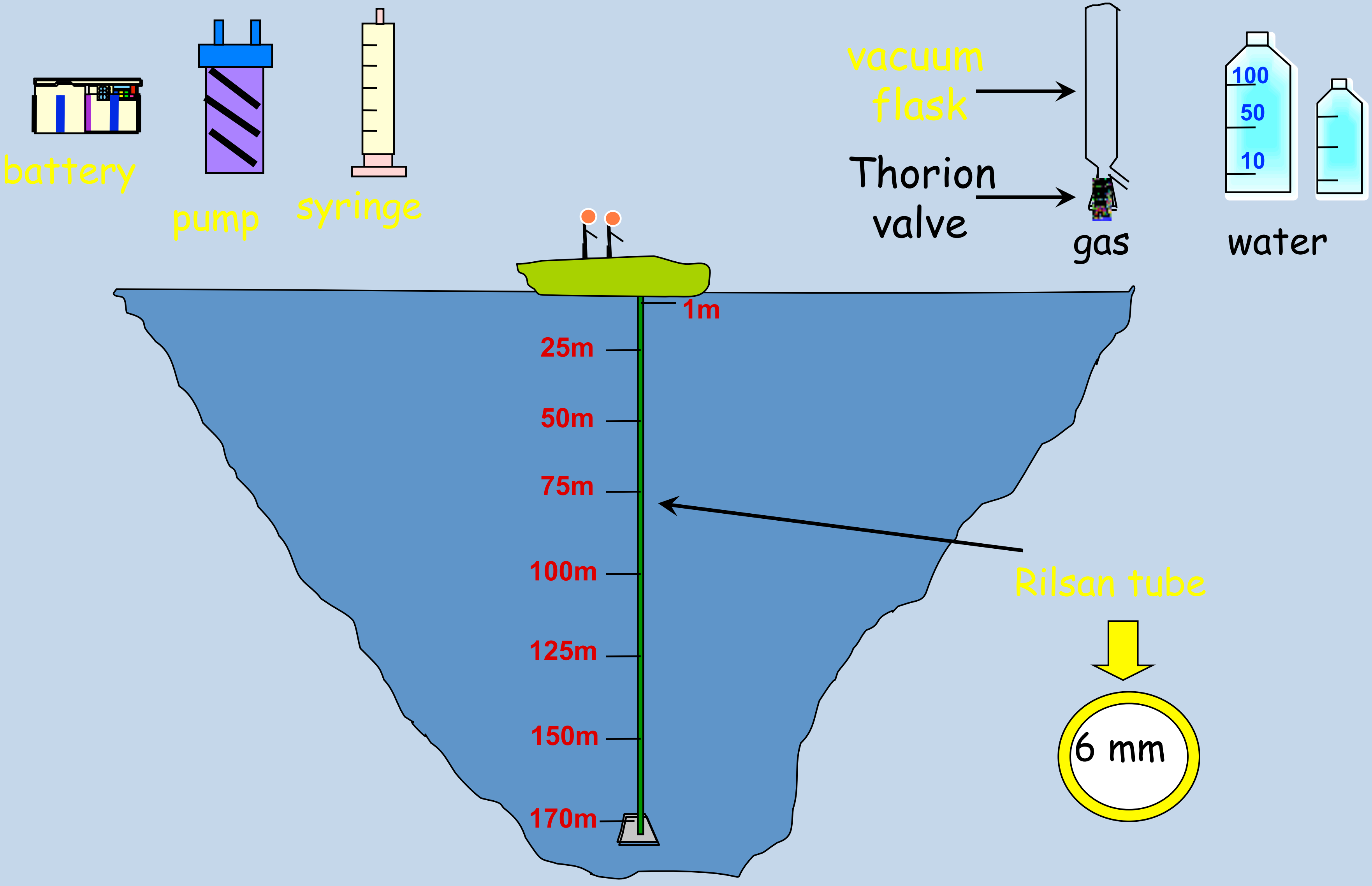


Depth-ratio: ratio between the mean and maximum depth.


Rain
Evaporation
Cooling
Volcanic Lake
Debris
Hydrothermal Vent
Main Vent
Fractured Rock
Steam
Fluid
Condensate
MAGMA
Depth (m)
100
110
120
130
140
150
160
170
250
260
270
280
290
300
310
320
E
100
110
120
130
140
150
160
170
180
190
200
0
500 m
V.E. = 7.5 x
B
500 m
E. x 2.8 x
m

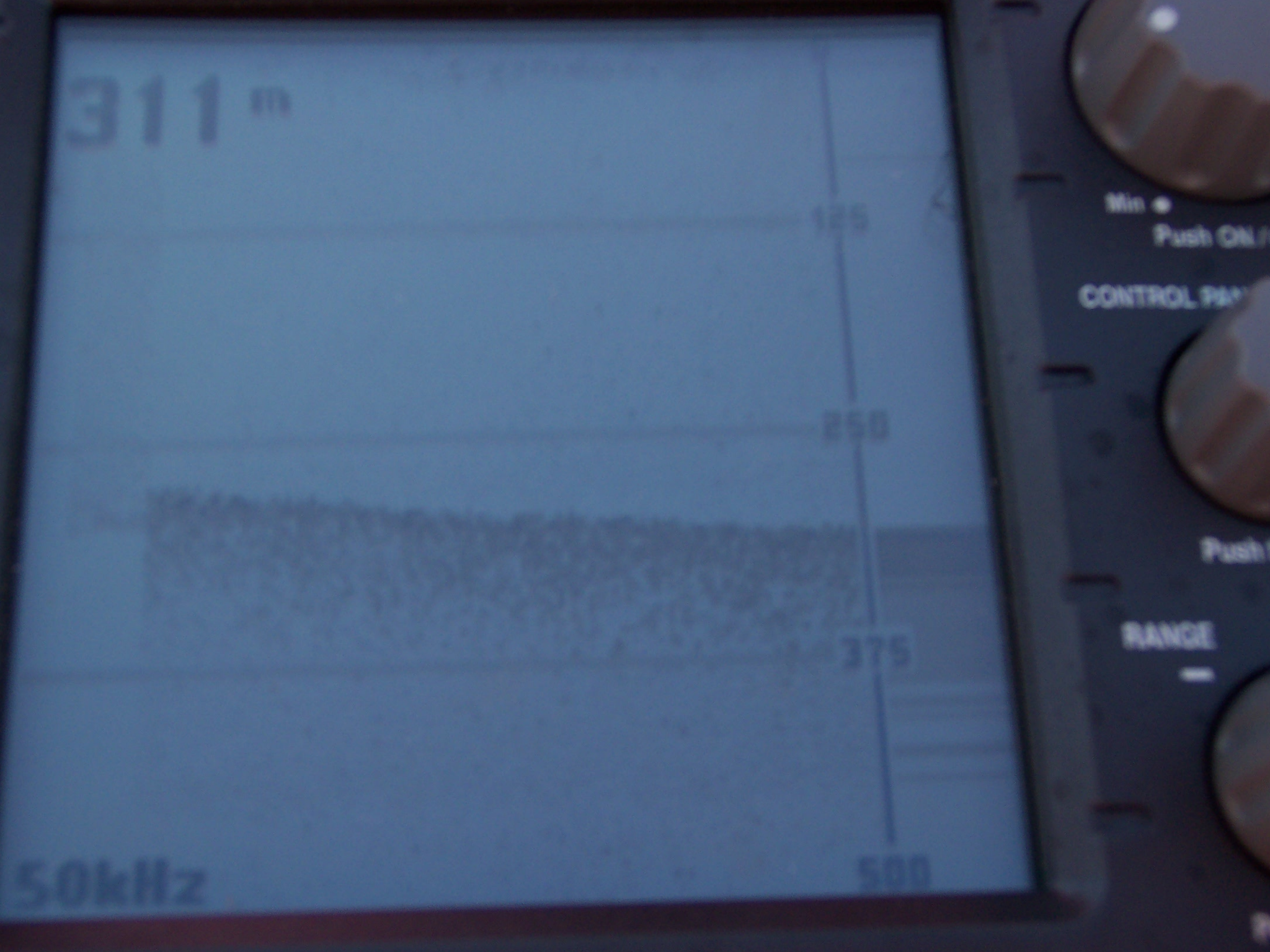
sampling equipment

sampling vials




INCOE

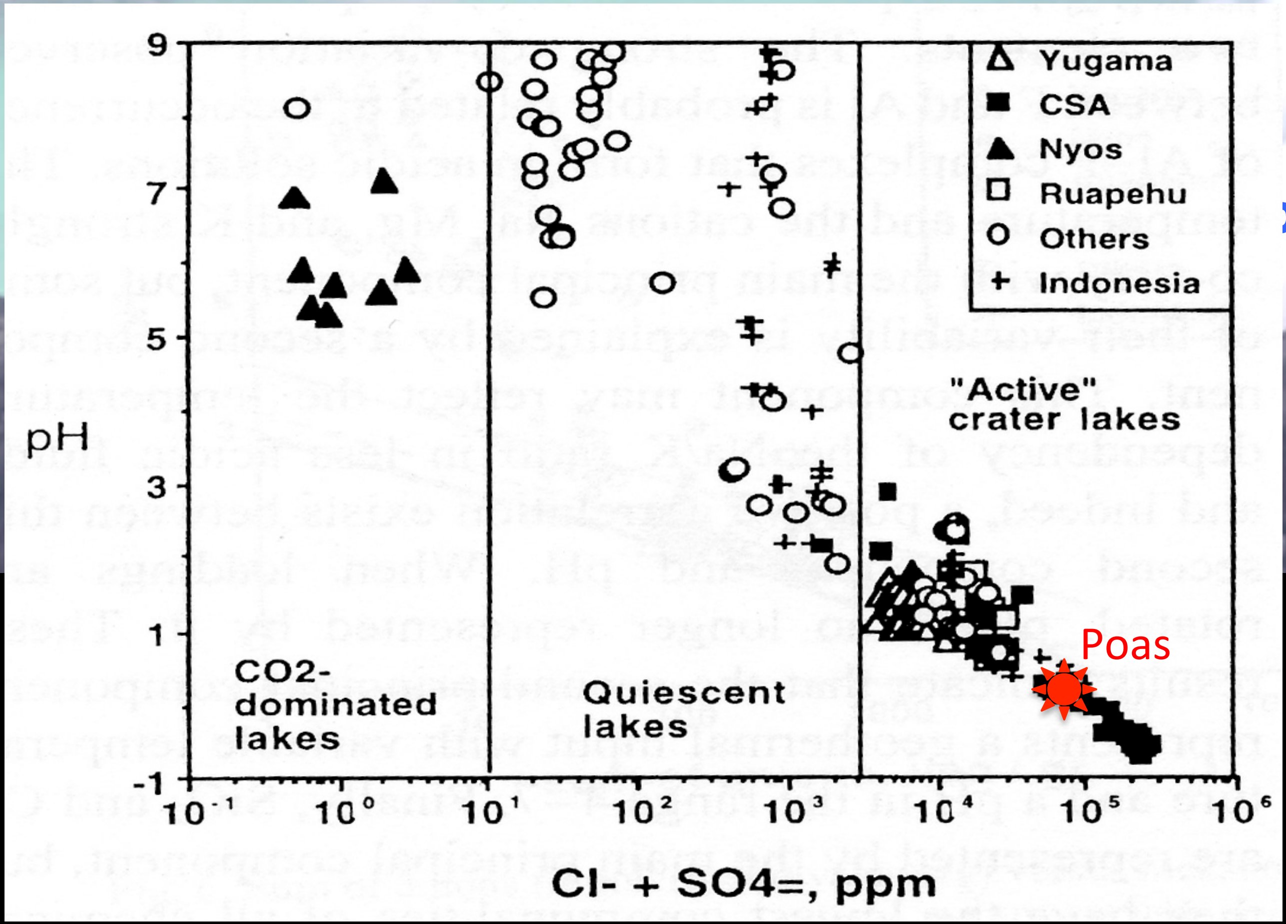

YAMAHA
Enduro


311 m
125
250
375
500
50kHz
Min
Push ON
CONTROL PAN
Push
RANGE


MARCO

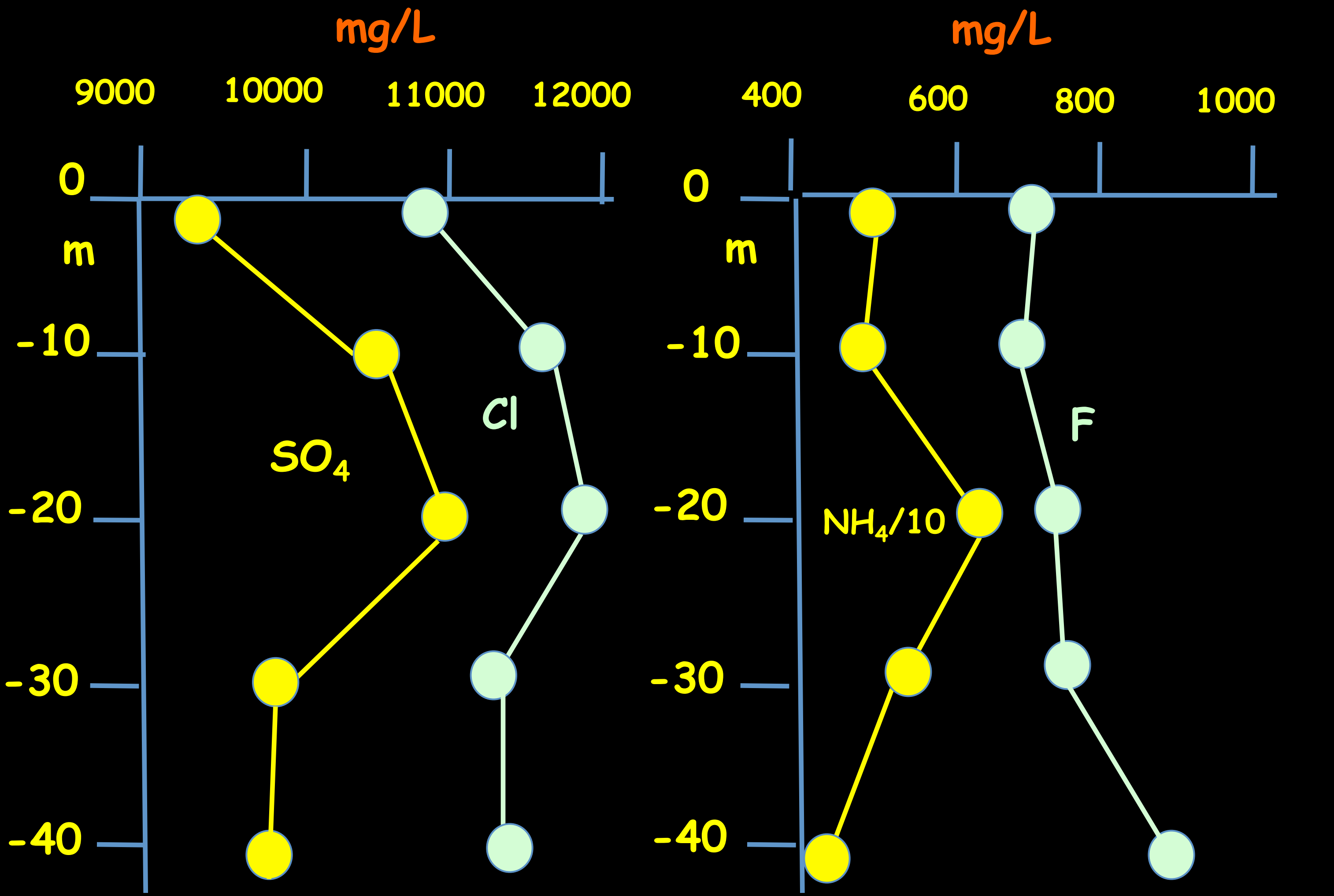
The basaltic-to-dacitic active volcano of Poas (2708 m a.s.l.) is characterized by three roughly N-S oriented craters: Von Frantius, Botos (hosting a cold lake) and Laguna Caliente

Laguna Caliente

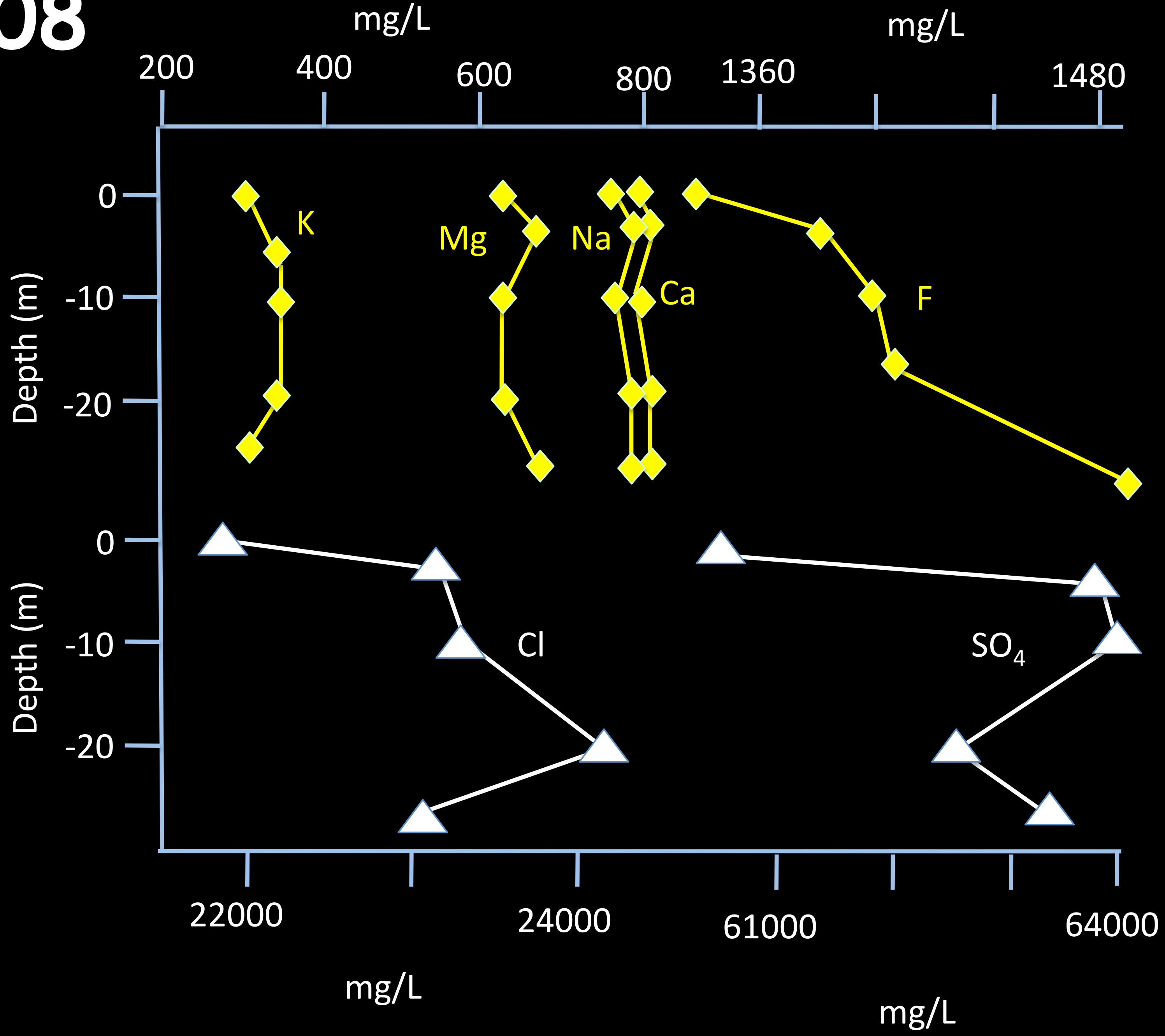


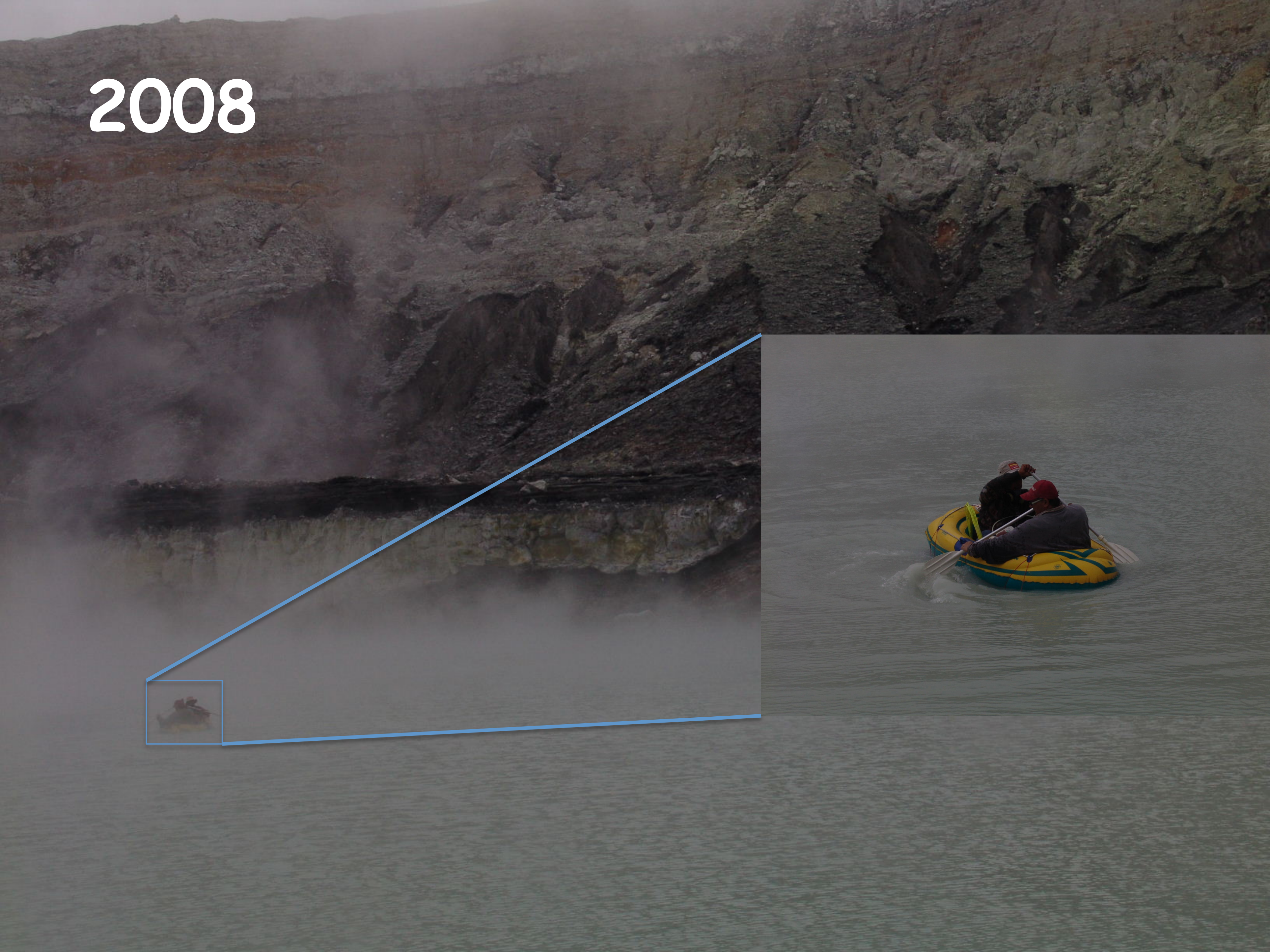
oint

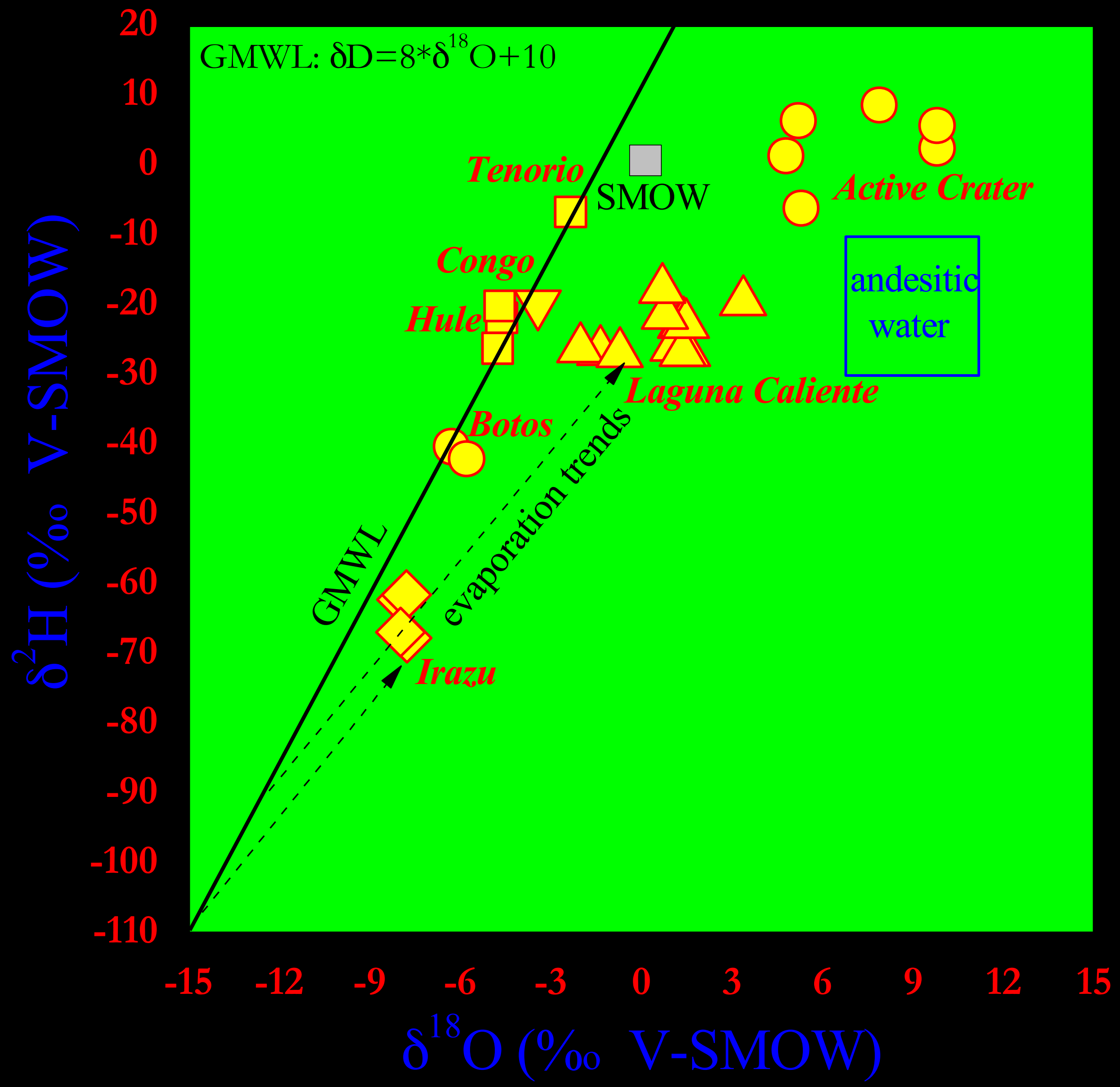
2001 - 2.4x10^6 m^3



2008


mg/L
200
400
600
800
1360
mg/L
1480
0
-10
-20
Depth (m)
K
Mg
Na
Ca
F
0
-10
-20
Depth (m)
Cl
SO_4
22000
24000
61000
64000
mg/L
mg/L


2008


GMWL: δD=8*δ18O+10
Tenorio
SMOW
Active Crater
Congo
Hule
andesitic water
Laguna Caliente
Botos
GMWL
evaporation trends
Irazu
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-15
-12
-9
-6
-3
0
3
6
9
12
15
δ2H (‰ V-SMOW)
δ18O (‰ V-SMOW)

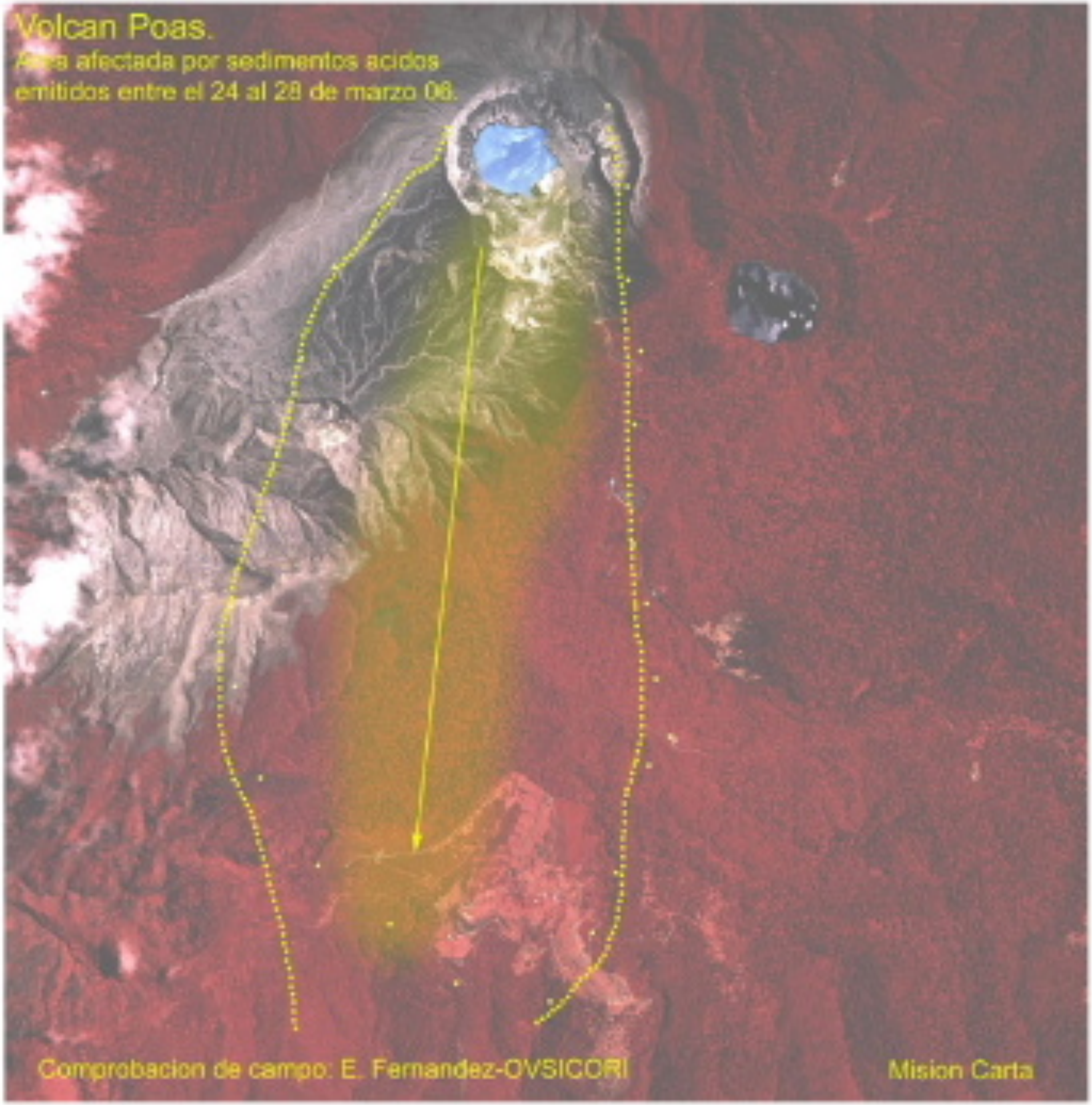

03.26.2006 18:43


03.26.2006 18:43


03.26.2006 18:44


03.26.2006 18:43


03.26.2006 18:43



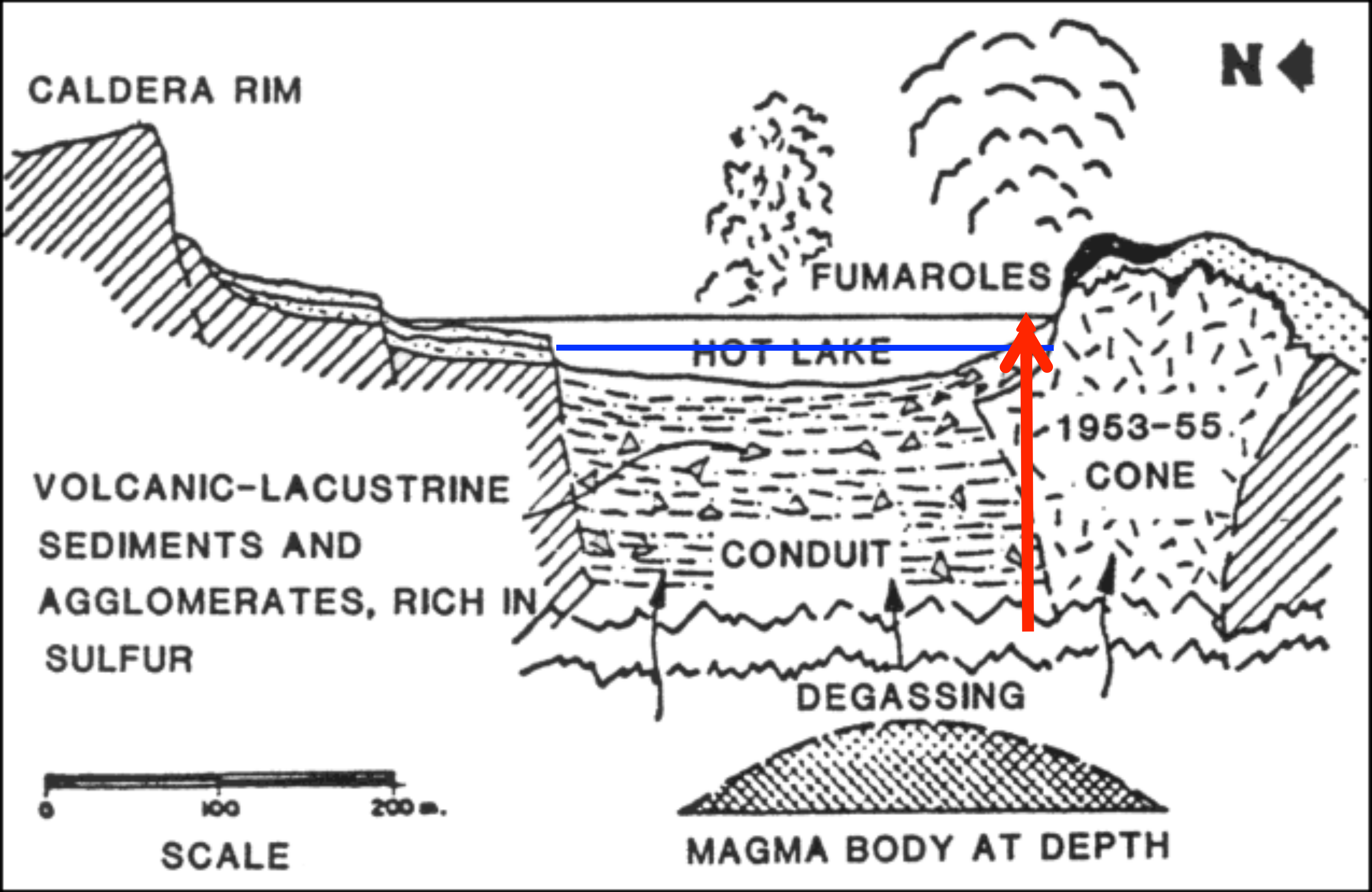
Volcan Poas.

Area afectada por sedimentos acidos emitidos entre el 24 al 28 de marzo 06.

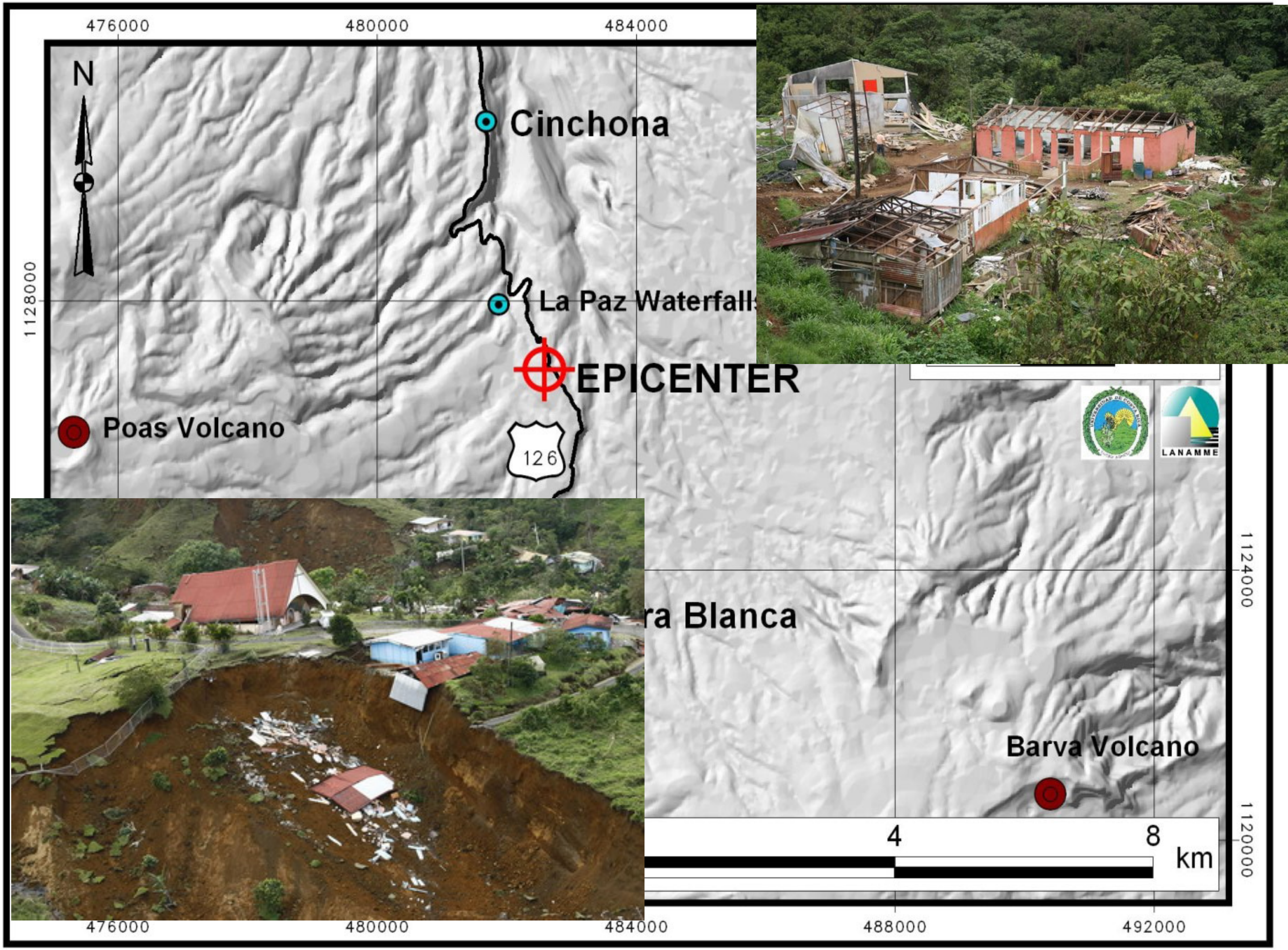
Comprobacion de campo: E. Fernandez-OVSICORI

Mision Carta

Pre-March 2006 lake rim


CALDERA RIM
N
FUMAROLES
HOT LAKE
1953-55
CONE
VOLCANIC-LACUSTRINE
SEDIMENTS AND
AGGLOMERATES, RICH IN
SULFUR
CONDUIT
DEGASSING
0
100
200 m.
SCALE
MAGMA BODY AT DEPTH


25/12/2009 09:53


476000
480000
484000
N
Cinchona
La Paz Waterfalls
EPICENTER
Poas Volcano
126
1128000
1124000
1120000
ra Blanca
Barva Volcano
LANAMME
4
8
km
476000
480000
484000
488000
492000

ERUPTION PHASES I, II, III and IV

PHASE I: vent clearing
Jan '05-Mar '06

- ✓ Lake level rise
- ✓ Lake heating
- ✓ Spectacular S flow (May 2005)
- ✓ Appearance of S spherules (December 2005)

PHASE II: phreatic eruption vs enhanced evaporation
Mar '06-Dec '08

- ✓ High initial Mg/Cl
- ✓ Relative Mg/Cl peaks ~ eruptions
- ✓ Evaporation (high T °C, SO_4, Cl) ~ no eruptions
- ✓ Less evaporation: inefficient heat and mass dissipation… eruptions

Phreatic eruptions, Poás, 2006-present

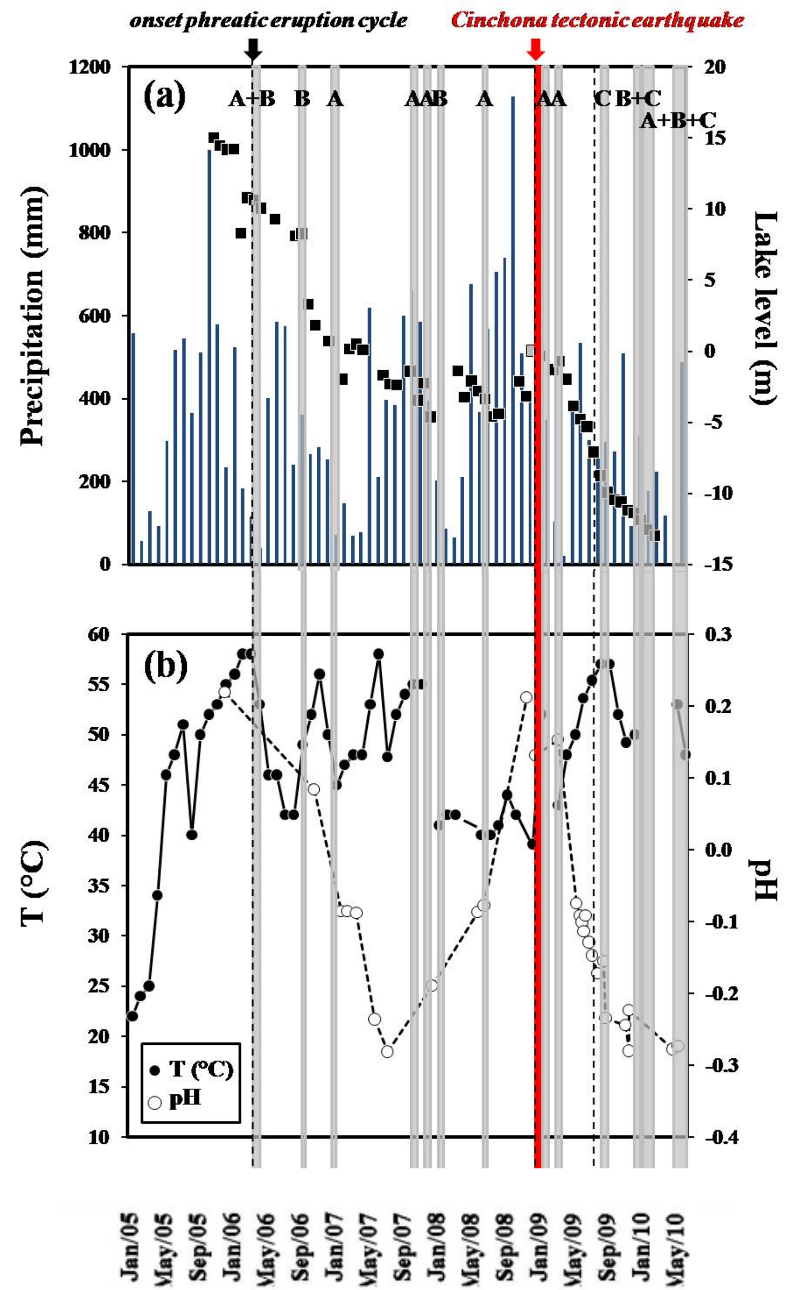
A-type: 2-50 m

B-type: 51-250 m

C-type: >250 m

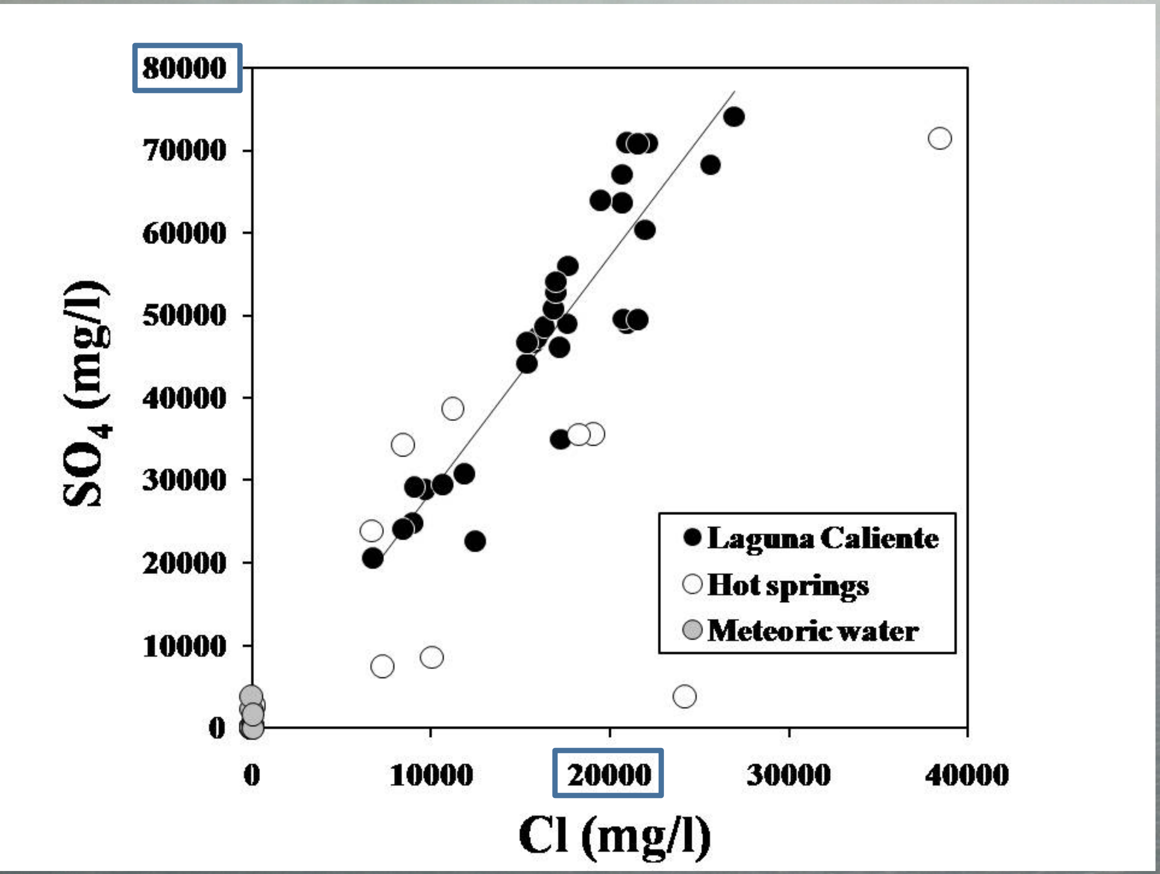
VOLCANO MONITORING = Δ vs time

(1) Physical parameters



- ✓ Steady lake level drop, no correlation with rainfall or eruptions
- ✓ 15-month pre-eruption lake water T increase (22 to 56°C)
- ✓ Heating episodes, not always correlated with eruptions
- ✓ pH "cycles"

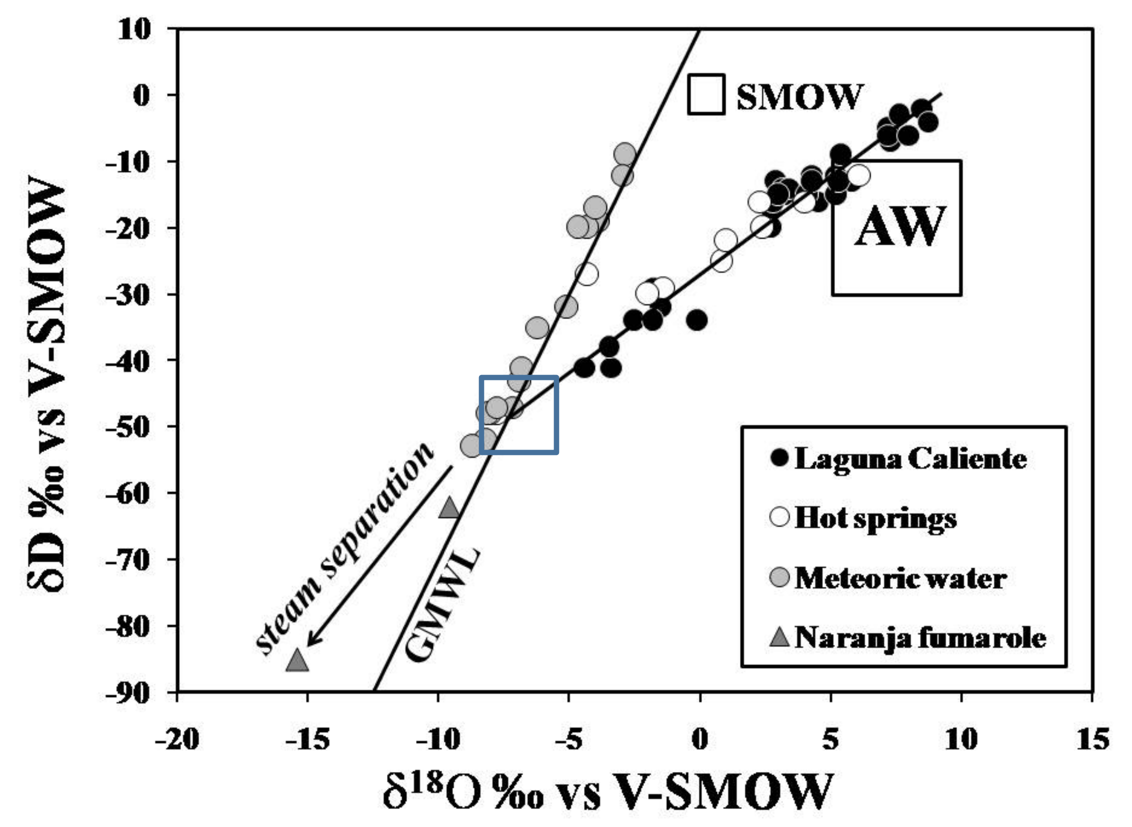
WATER CHEMISTRY



pH = -0.3 to 0.3
TDS = 30 to 111 g/l
(>90% = SO_4 + Cl + F)
% residual acidity: 55 to 74%

Lake water sampling

STABLE ISOTOPES: δD and $\delta^{18}O$



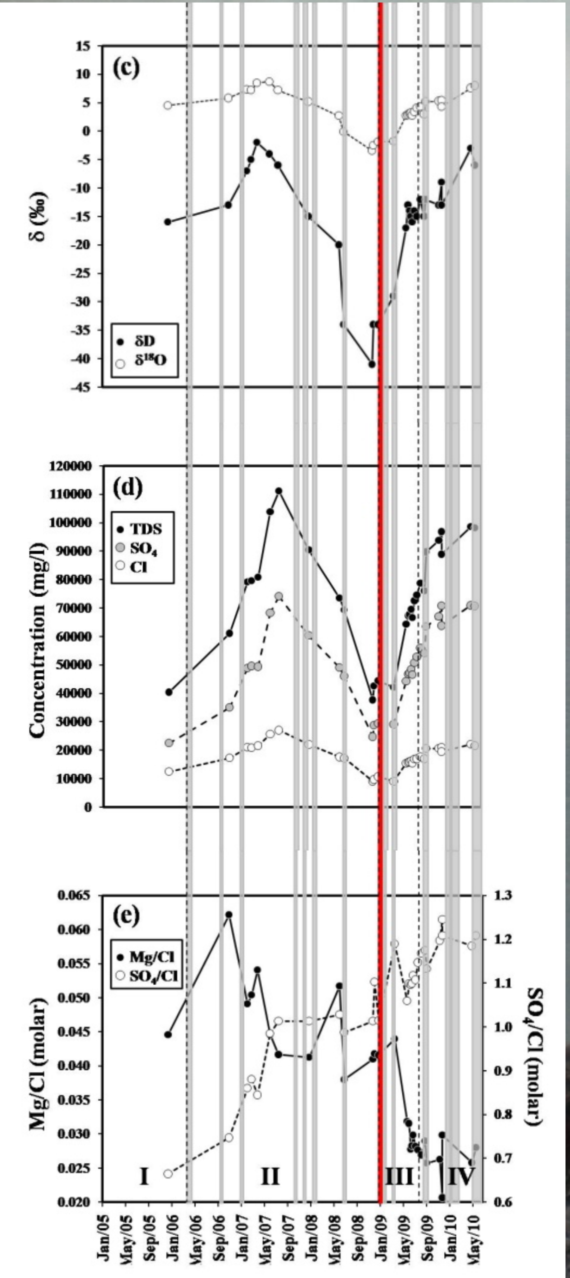
- ✓ Evaporation vs Mixing?
- ✓ AW = "andesitic water"

(Taran et al. 1989; Giggenbach 1992)

Lake water sampling

GEOCHEMICAL MONITORING = Δ vs time

(2) Chemical, intensive parameters



- ✓ High δ → evaporation?
- ✓ Low δ → more meteoric? Or steam input?

- ✓ High TDS, SO_4, Cl → evaporation or "volcanic" input?

- ✓ SO_4/Cl ↑ → Cl loss by evaporation
- ✓ Mg/Cl ↓ → water-magma interaction

CONCLU TORING?

- ✓ T gau
- ✓ Remo
- ✓ Plum
- ✓ Plum d δD-$\delta^{18}O$?

Last cou
Poás is
Magmat
Or just

Acidic to hyperacidic lakes are generally well mixed (no vertical or partial stratification) due to the rapid ascent of the hdyrothermal fluids. They are thus dangerous because they are intimately associated with the volcanic activity

A different dangerous (and sneaky) hazard is from those lakes that tend to accumulate CO_2 at depth. They are potentially able to produce gas emissions (CO_2-clouds) that can overflow from the lake banks and move in topographic lows

Apparently only three lakes in the world have a high gas (CO_2-rich) concentration at depth!

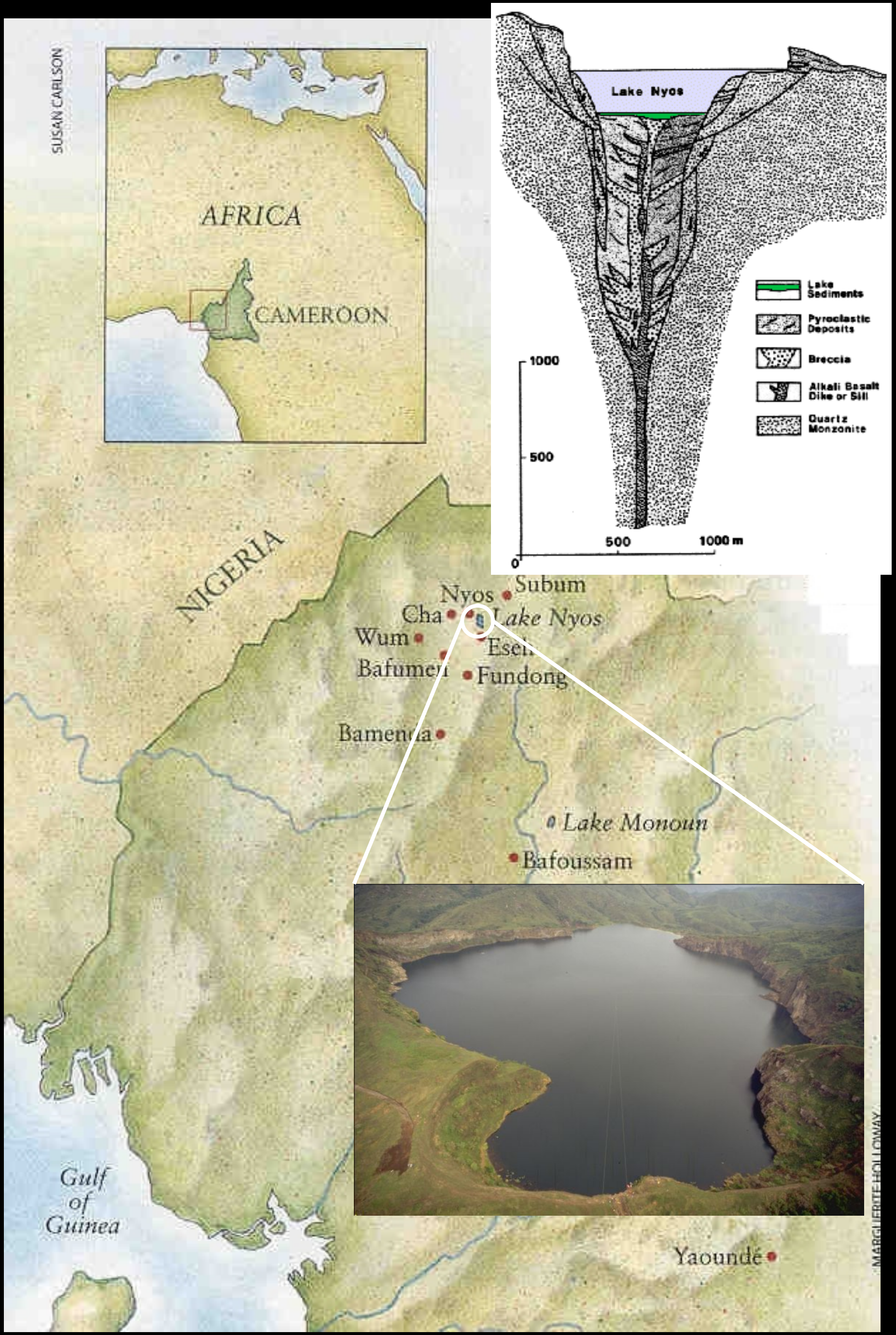
Courtesy of NASA-Goddard

Lakes **Nyos** e **Monoun** in Cameroon

Lake **Kivu** in East Africa

General infos on Lake Nyos

- Volcanic/Maar Crater Lake
- Age: ~400 ka
- Surface = 1.58 km^2
- Max depth. = 210 m
- Chemiocline ≈50 m
- Volume = 179,400,000 m^3
- Rainfall = 2.5 m/yr
- Inflow
  - 0-50 m: rainfall & streams
  - 50-210 m: CO_2-rich soda springs
- Outflow
  - Natural spilling

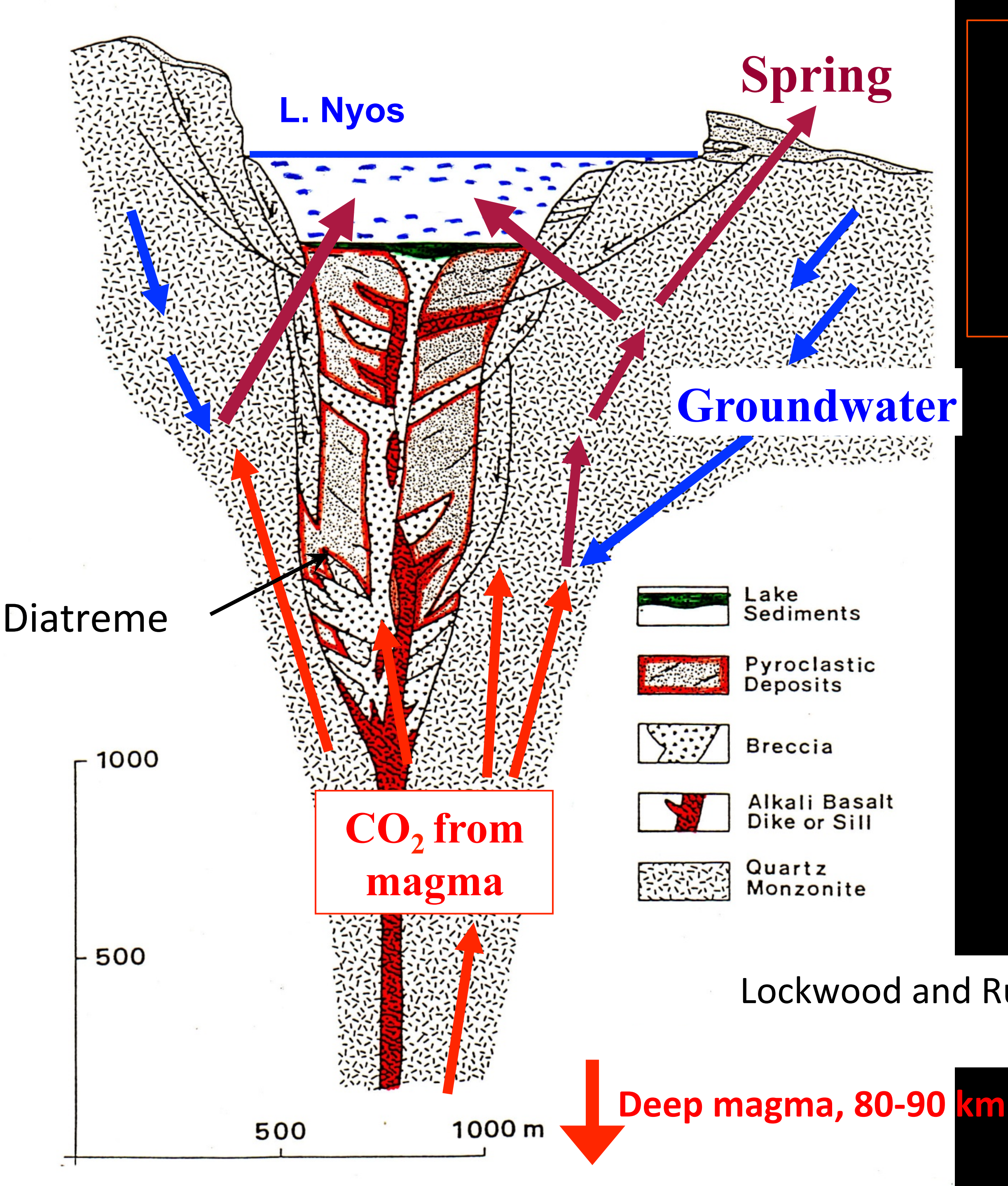


Lake Nyos (Cameroon)

The 1986 event

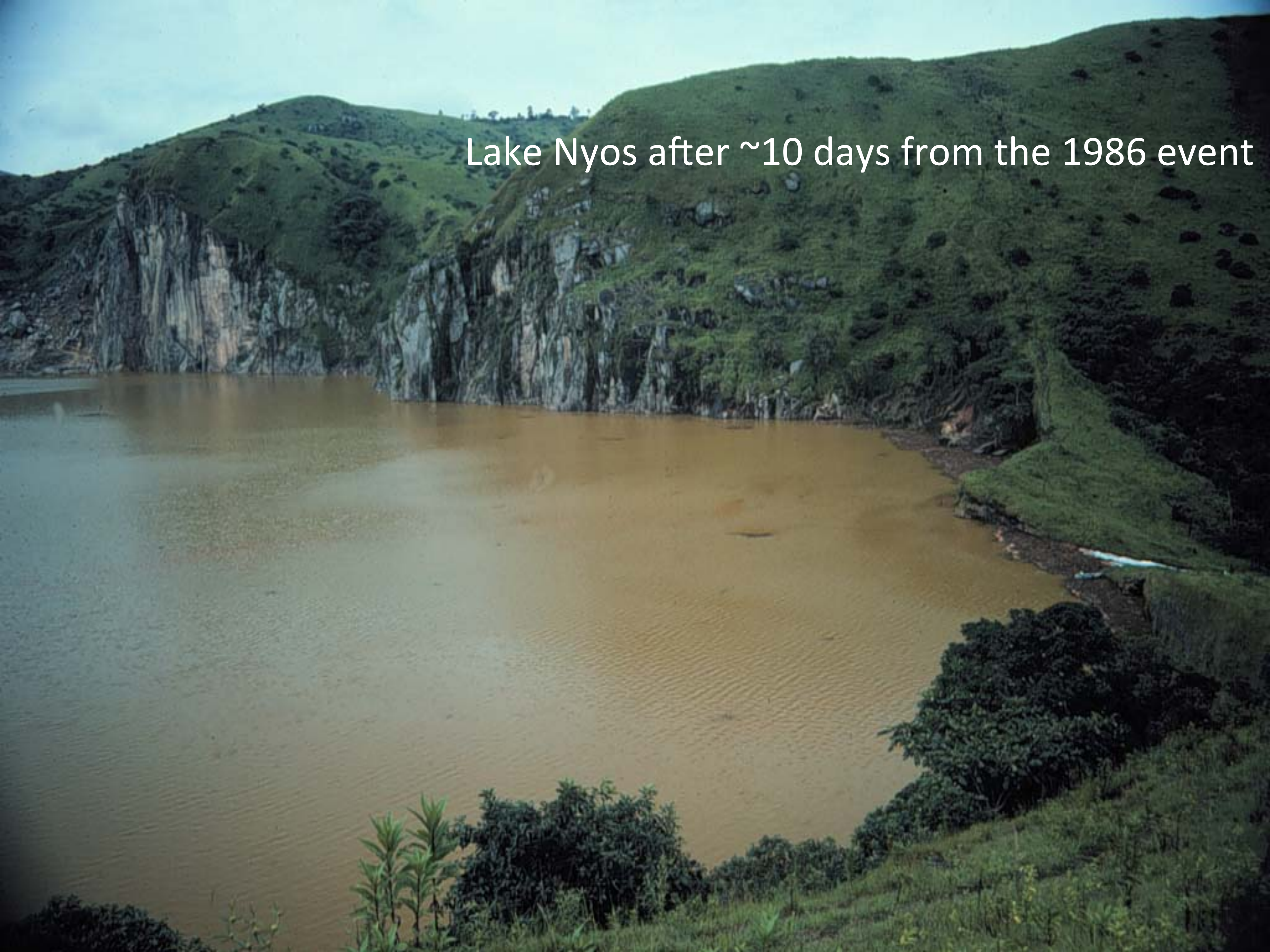
- ~1 km^3 of CO_2 is emitted
- ~1800 people died along with thousands of cattle.
- Causes: rapid overturn of the deep-seated layers of the lake
    - Volcanic or limnic?

CO_2-rich soda-spring



Lockwood and Rubin, 1989

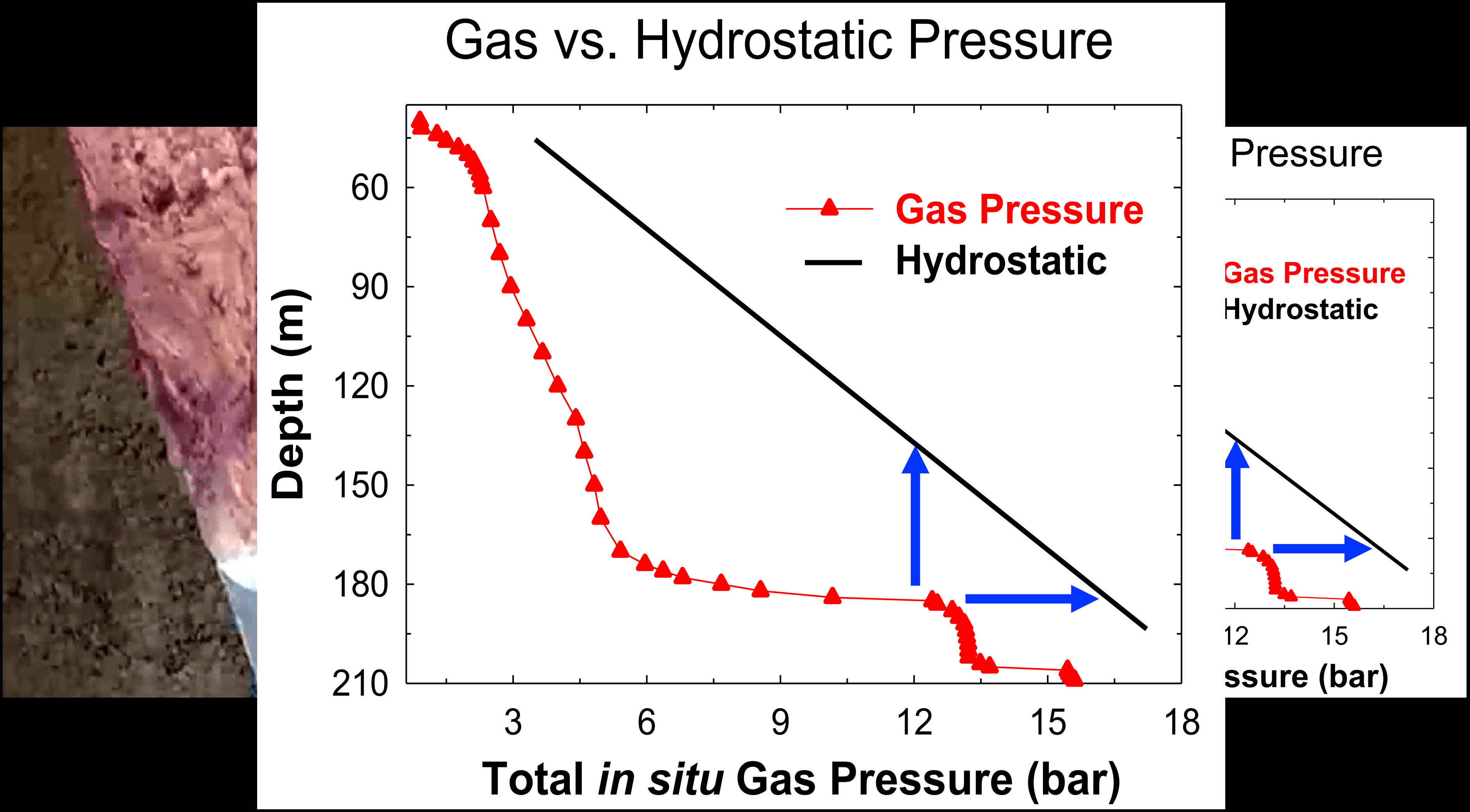
The CO_2-rich gas cloud provoked casualties up to the distance of 26 km from the lake!



Lake Nyos after ~10 days from the 1986 event

The lake waters turned to a red-brown color due to the presence of Fe-oxy-hydroxides.

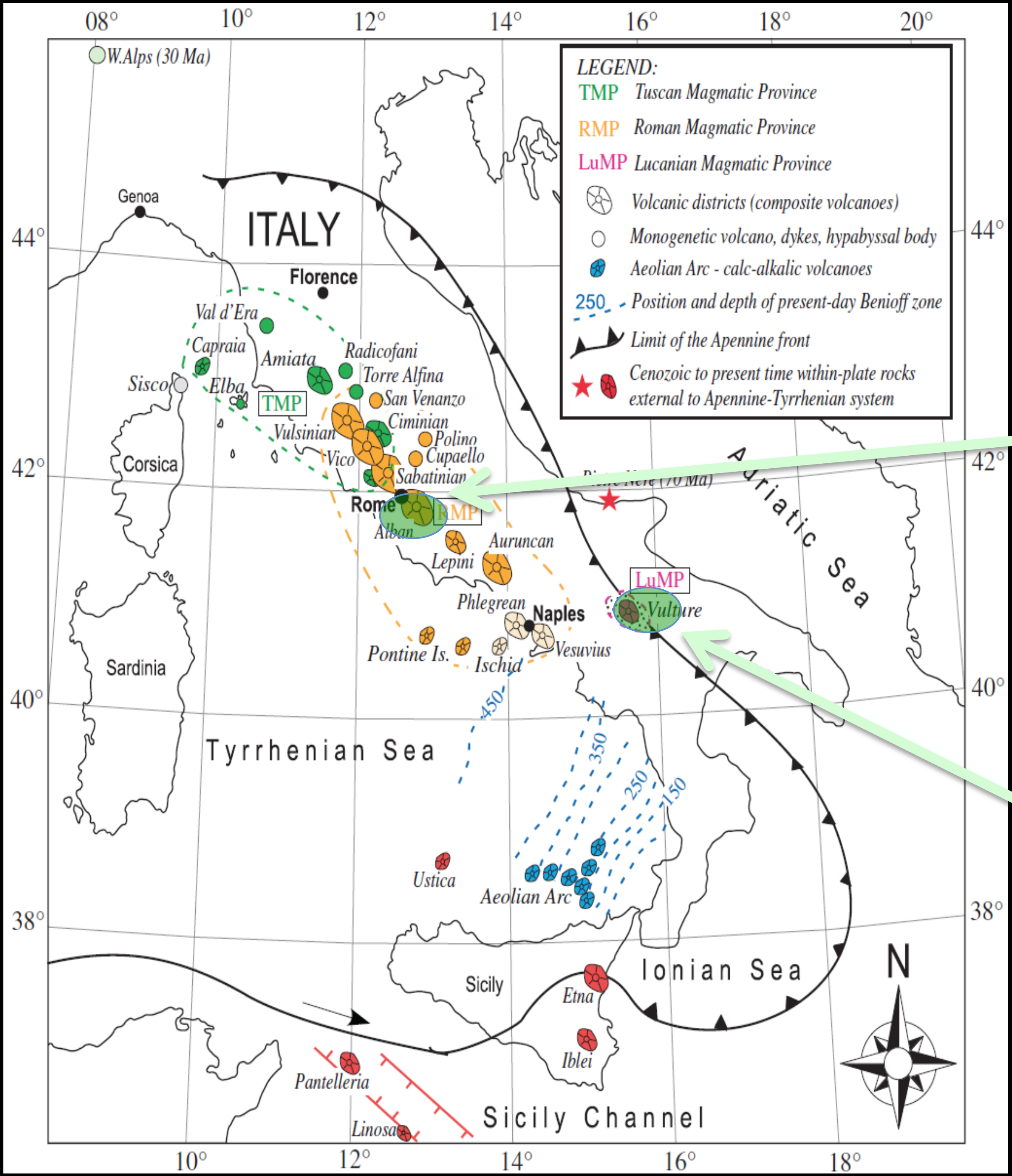
What caused the gas burst?



Apparently, the CO_2-rich cloud was released from intermediate depths and covered the whole lake, suggesting a strong and efficient horizontal and turbulent mixing.

To mitigate or even prevent the hazard associated with new limnic eruptions: degassing

- 2001: a degassing column was successfully installed:
  - Continuously degassing
  - 50 m of CO_2 fountaning
    - Spray = 90% CO_2 and 10% water.
    - 50.000 m^3/day



Lake Albano

Lakes of Monticchio

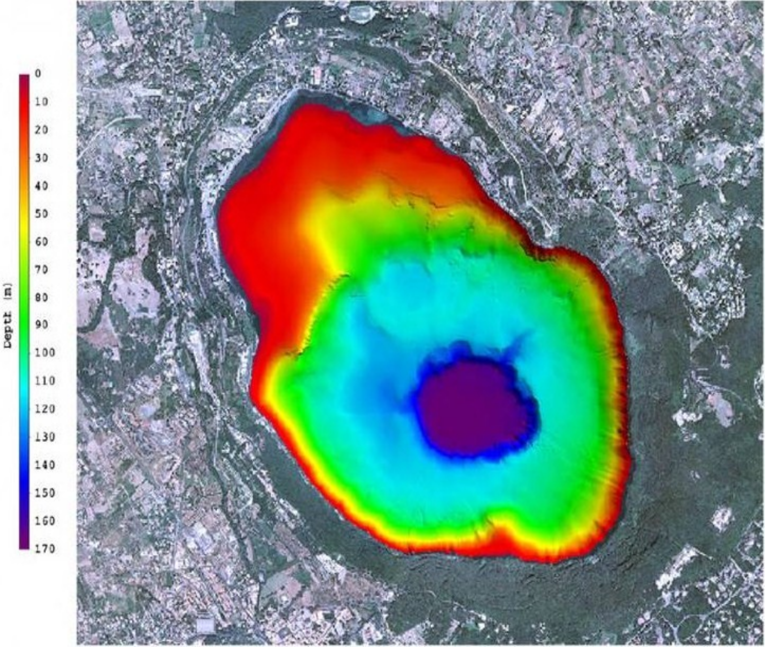
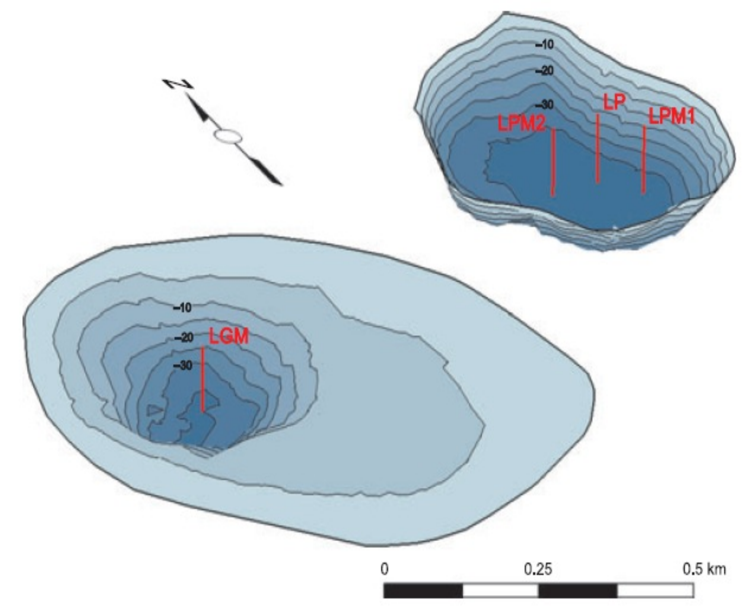
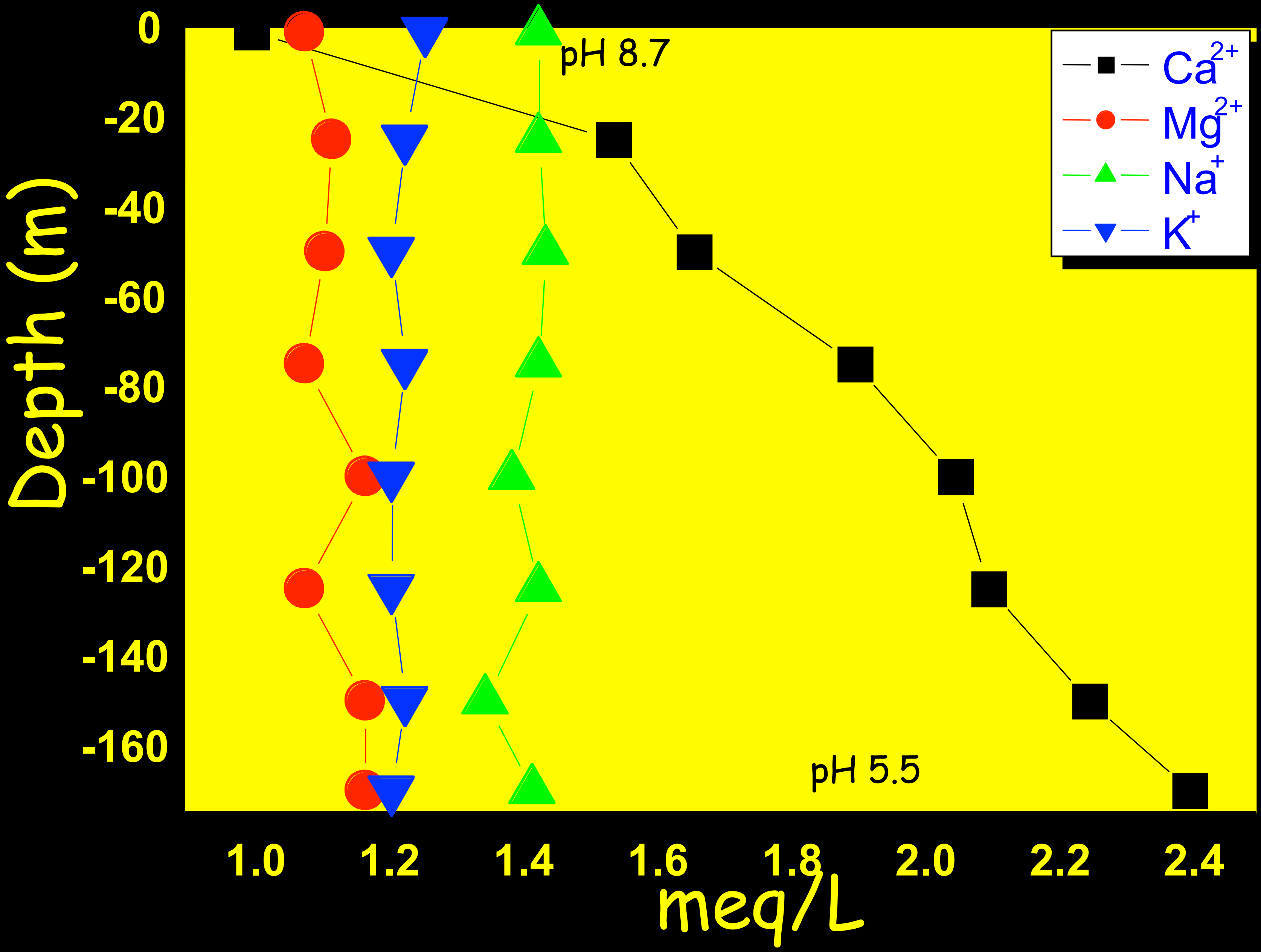

Depth (m)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170


Image © 2010 DigitalGlobe
Google
Albano

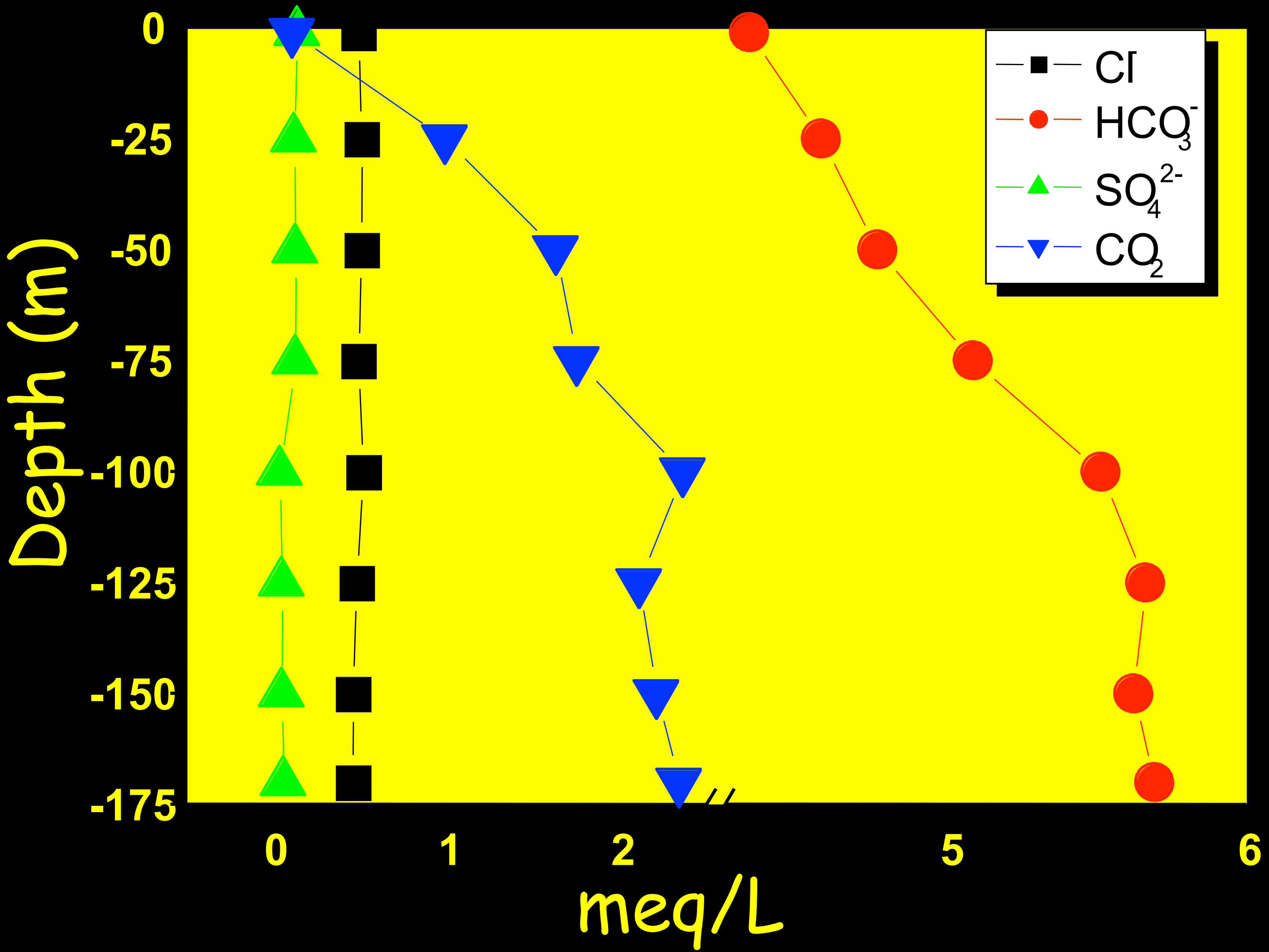

N
-10
-20
-30
LPM2
LP
LPM1
-10
-20
LGM
-30
0
0.25
0.5 km


Monticchio
Grande
Monticchio
Piccolo

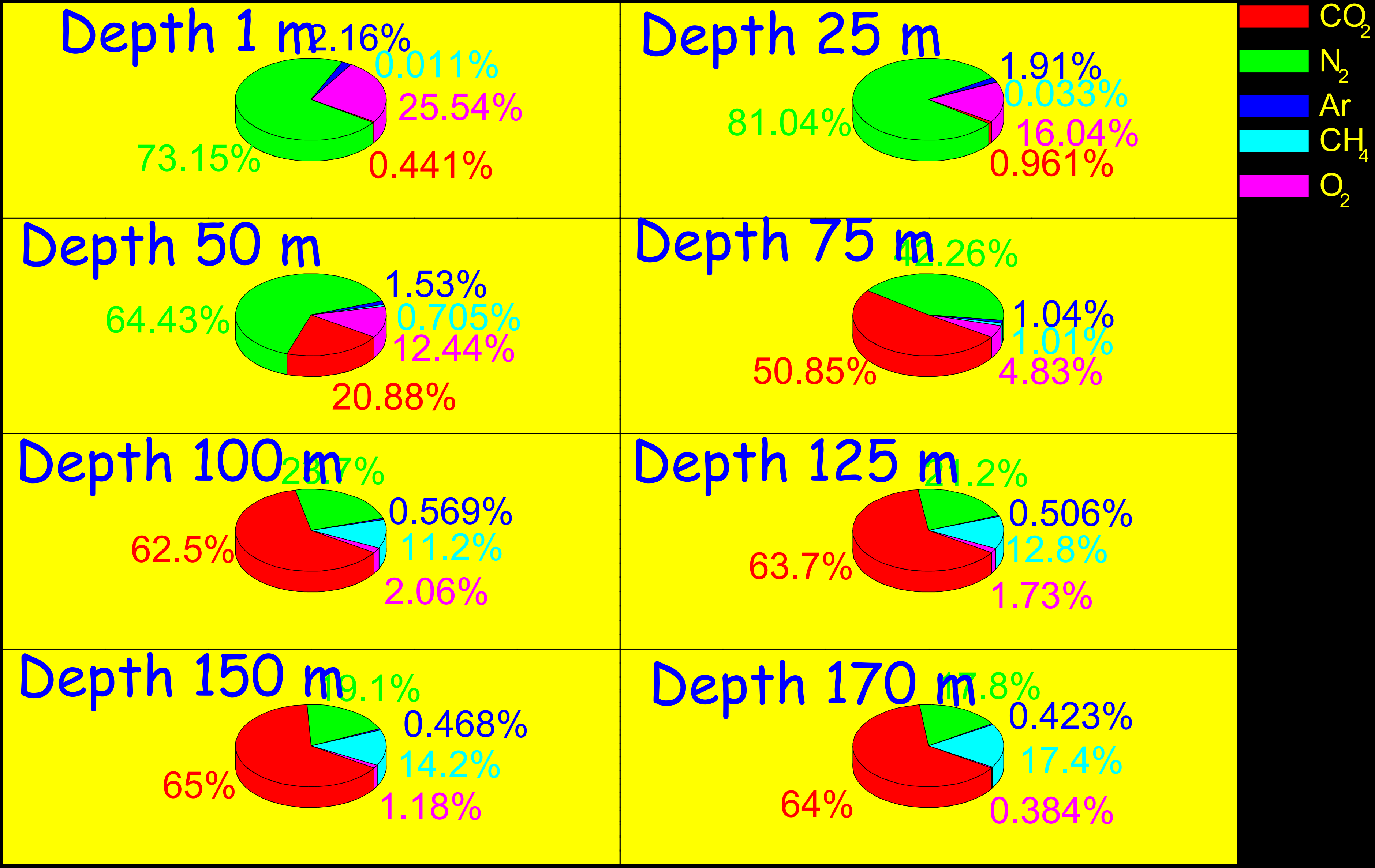
Cations: Lake Albano

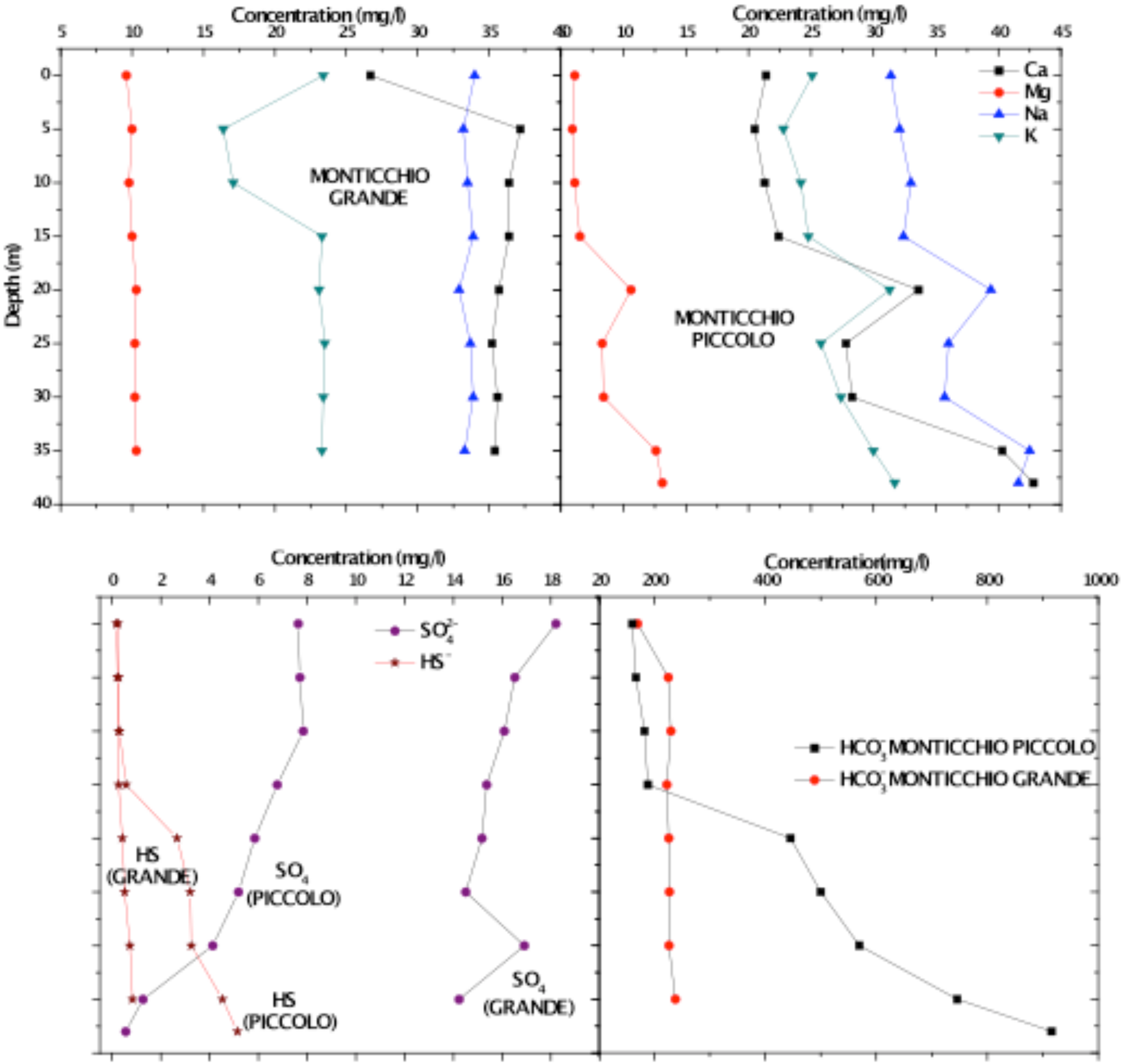


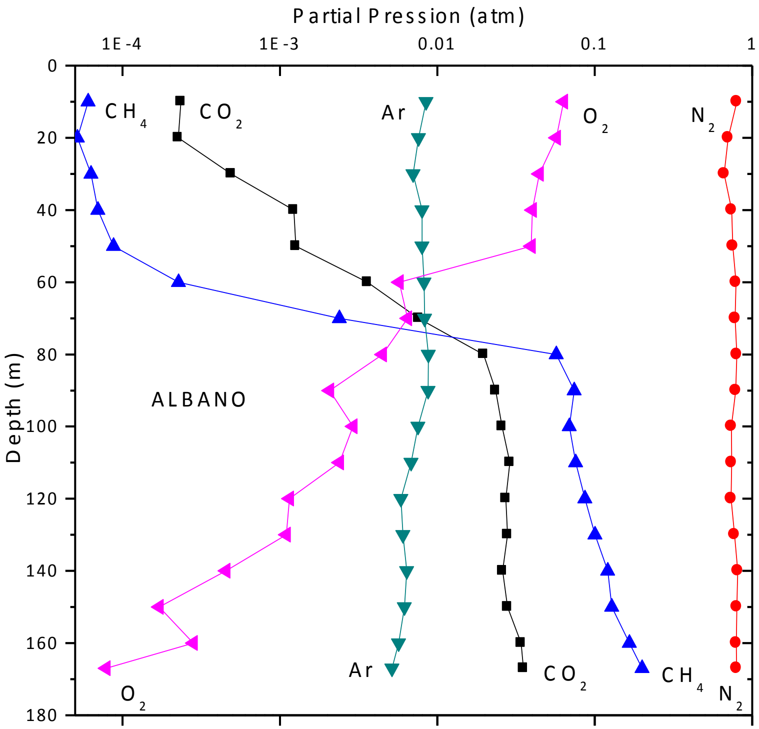
Anions: LakeAlbano

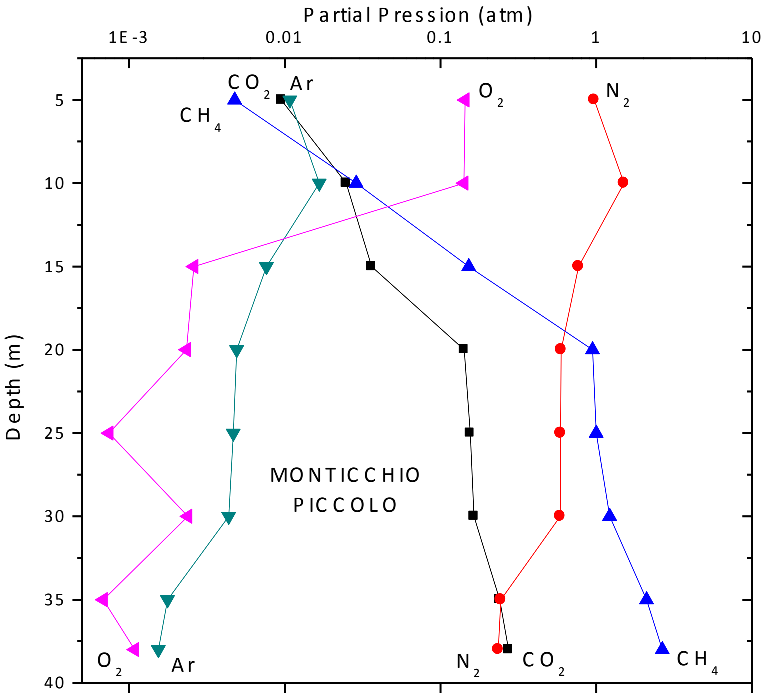


Composizione dei gas disciolti




Concentration (mg/l)
5
10
15
20
25
30
35
40
45
Depth (m)
0
5
10
15
20
25
30
35
40
MONTICCHIO GRANDE
MONTICCHIO PICCOLO
Ca
Mg
Na
K
Concentration (mg/l)
0
2
4
6
8
10
12
14
16
18
20
SO_4^{2-}
HS^-
HS (GRANDE)
SO_4 (PICCOLO)
HS (PICCOLO)
SO_4 (GRANDE)
Concentration(mg/l)
200
400
600
800
1000
HCO_3^- MONTICCHIO PICCOLO
HCO_3^- MONTICCHIO GRANDE


Partial Pression (atm)
1E-4
1E-3
0.01
0.1
1
0
20
40
60
80
100
120
140
160
180
Depth (m)
ALBANO
CH4
CO2
Ar
O2
N2
Ar
CO2
CH4
N2
O2


Partial Pression (atm)
1E-3
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25
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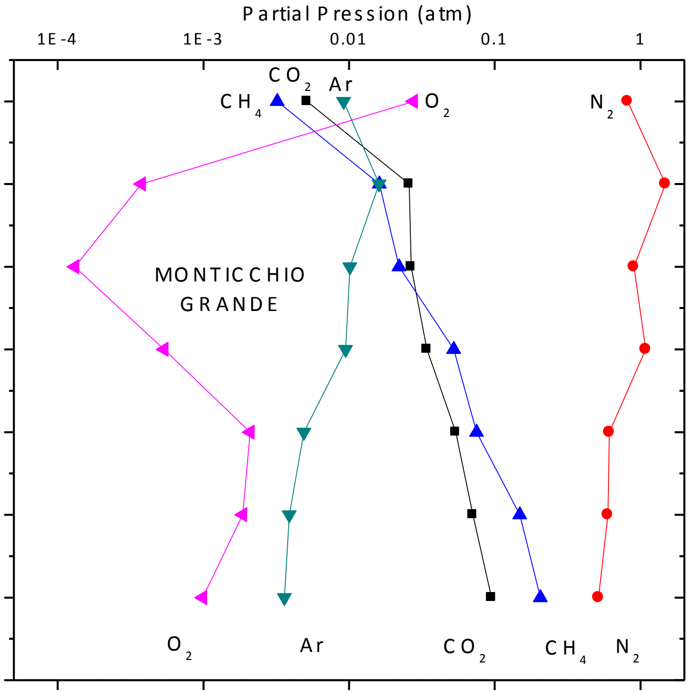
35
40
Depth (m)
CO2
Ar
CH4
O2
N2
MONTICCHIO
PICCOLO
O2
Ar
N2
CO2
CH4


Partial Pression (atm)
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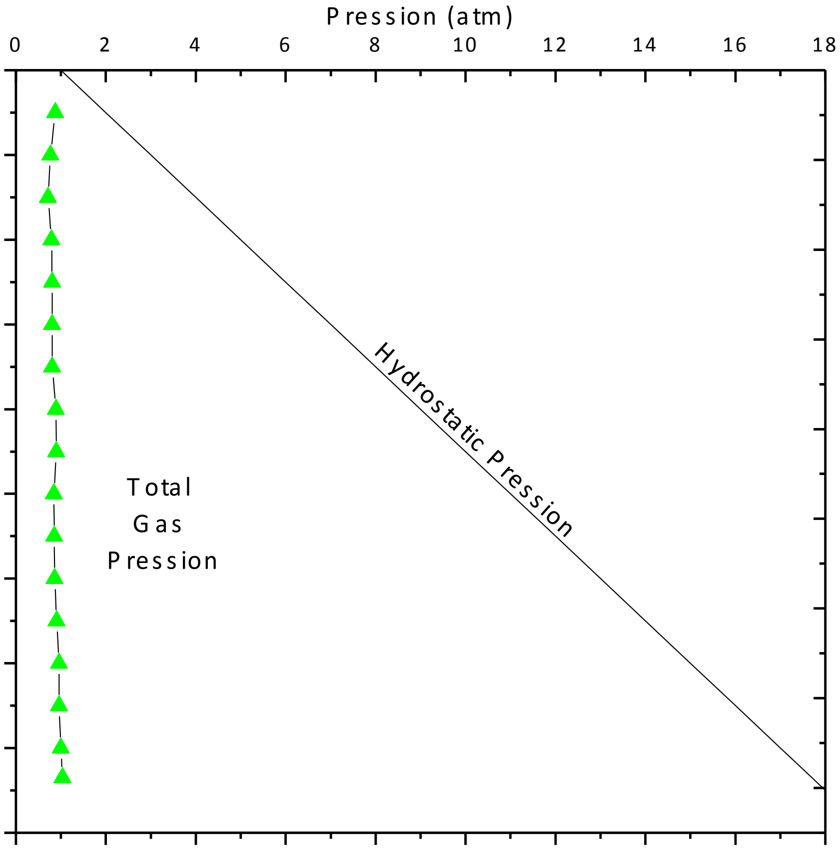
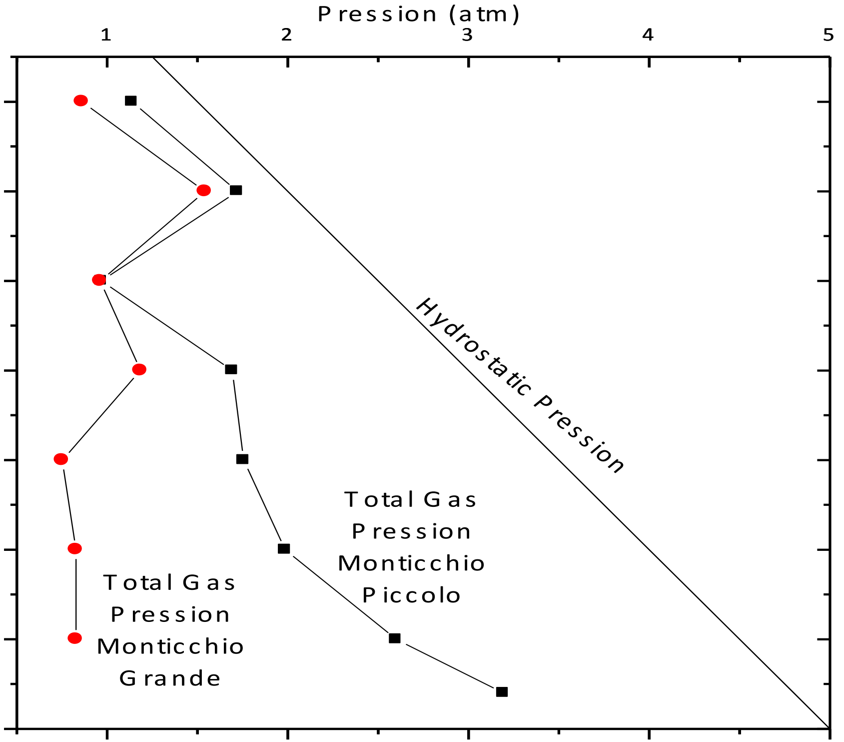
1E-3
0.01
0.1
1
CO2
Ar
CH4
O2
N2
MONTICCHIO
GRANDE
O2
Ar
CO2
CH4
N2



Albano

Laghi di Monticchio



Volcanic lakes

IAVCEI (www.iavcei.org) has a proper scientific commission (CVL) devoted to the study of volcanic lakes, testifying the importance that these peculiar water bodies have in volcanology.

http://www.ulb.ac.be/sciences/cvl/index.html

It is just recently that geologists and limnologists are collaborating each other. In the past they were almost two separated worlds. Thanks to CVL these communities are discussing to better comprehend limnic dynamics.

THE FIRST BOOK ON…

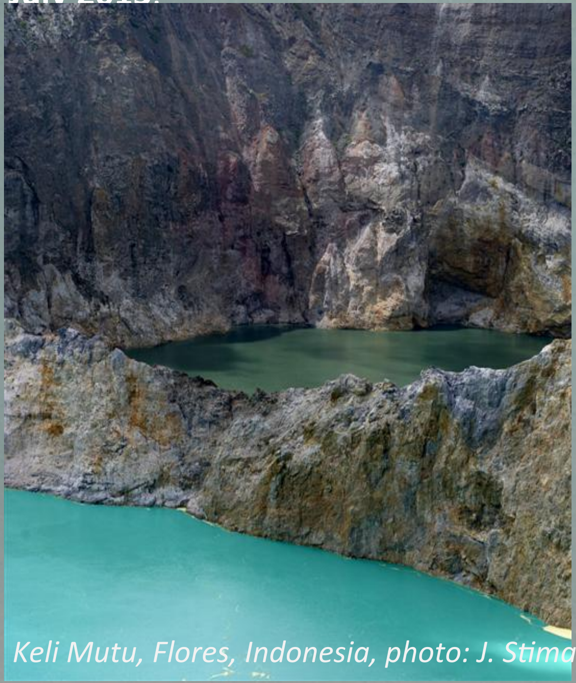
VOLCANIC LAKES

(Editor: Springer-Heidelberg)

Guest-editors: Dmitri Rouwet, Bruce Christenson, Franco Tassi, Jean Vandemeulebrouck

To be released in 2013

✓The Guest-editors are delighted to announce a work-in-progress, the first book on: **"Volcanic Lakes"**. The book is planned to be promoted during the next IAVCEI General Assembly, and following Workshop of the Commission on Volcanic Lakes (IAVCEI-CVL8), Kagoshima, Japan, **July 2013**.



Keli Mutu, Flores, Indonesia, photo: J. Stimac

✓This **book aims** to give an overview on the present state of volcanic lake research, covering topics such as volcano monitoring, the chemistry, dynamics and degassing of acidic crater lakes, mass-energy-chemical-isotopic balance approaches, limnology and degassing of Nyos-type lakes, the impact on the human and natural environment, the eruption products and the impact of crater lake breaching eruptions, numerical modeling of gas clouds and lake eruptions, thermo-hydro-mechanical and deformation modeling, CO_2 fluxes from lakes, volcanic lakes observed from space, biological activity, continuous monitoring techniques, and some aspects more. We hope to offer an updated manual on volcanic lake research, providing classic research methods, and point towards a more high-tech approach of future volcanic lake research and continuous monitoring. The book will contain 30-35 chapters, authored by the experts in the various fields of interest.

✓The **target audience** of the book is strictly scientific, composed of volcanologists, limnologists, geochemists, geophysicists, and

Ruapehu, New Zealand, photo: B. Christenson

Turrialba, Costa Rica, photo: D. Rouwet

Thermal waters

a recall about volcanic thermal waters

why are there thermal waters ?

☐ active volcanoes display high structural contrasts → high level of permeability heterogeneities

☐ development of groundwater systems with different sources (meteoric water, sea water)

☐ the spatial distribution of groundwater systems is highly heterogeneous

→ interaction of rising volatiles from depth with groundwater systems

classification of waters: 4 main types

☐ **bicarbonate peripheral waters** (HCO_3 character, high or low TDS, high or low T)

☐ **volcanic waters** (SO_4-Cl character, high TDS and high T)

☐ **steam-heated waters** (SO_4 character, high T, medium TDS)

☐ **chloride-rich waters** (high TDS)

Rincon de la Vieja, Costa-Rica

Solutes: main anions

Chloride

~50 to ~20,000 mg/kg

(to ~200,000 mg/kg in hypersaline brines)

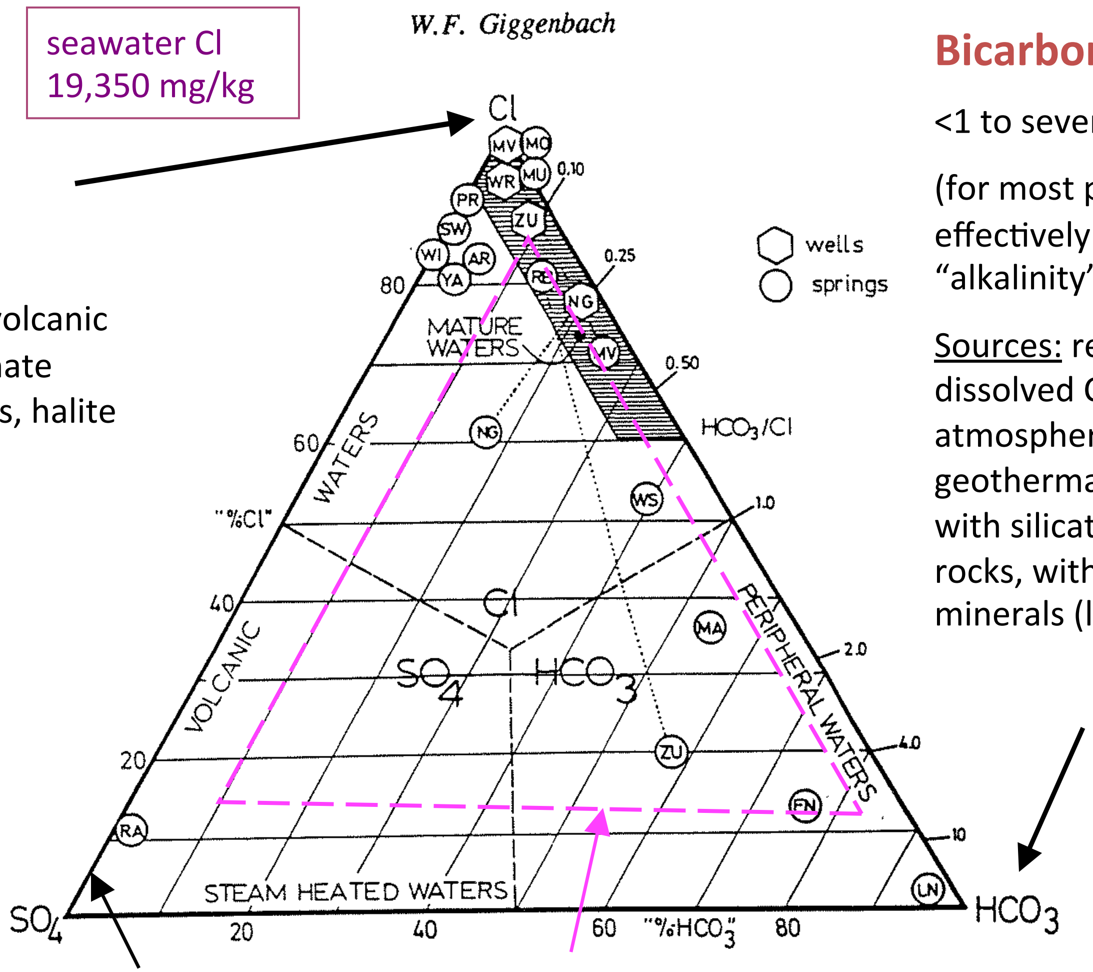
<u>Sources:</u> traces of Na-K-Cl in volcanic rocks (seawater origins), connate seawater in sedimentary rocks, halite deposits

Sulfate

~10 to ~1500 mg/kg

(to ~100,000 mg/kg in acid volcanic steam condensates

<u>Sources:</u> oxidized sulfide minerals and H_2S, sulfate mineral deposits (gypsum, anhydrite)



seawater Cl
19,350 mg/kg

W.F. Giggenbach

Bicarbonate

<1 to several 1000 mg/kg

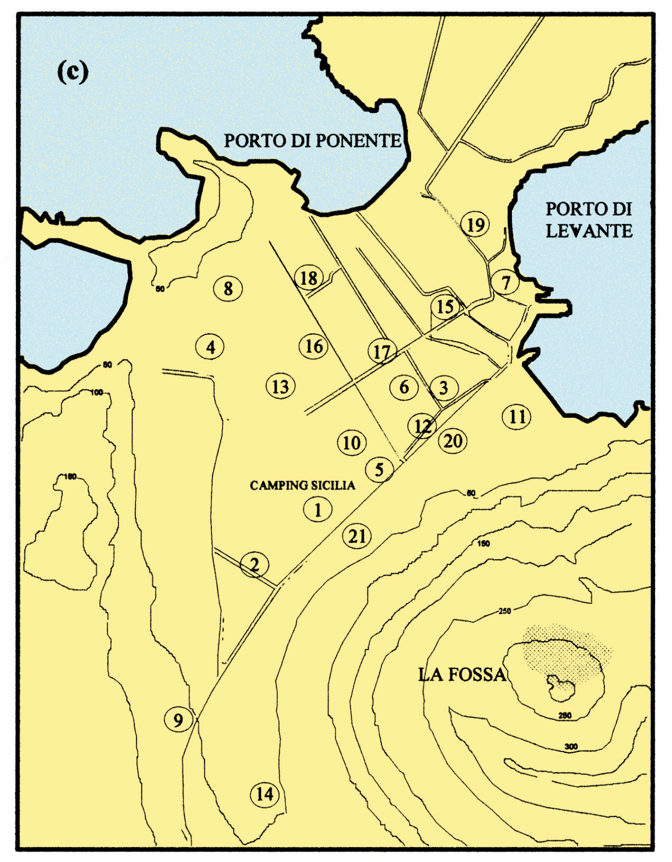
(for most purposes, effectively the same as “alkalinity”)

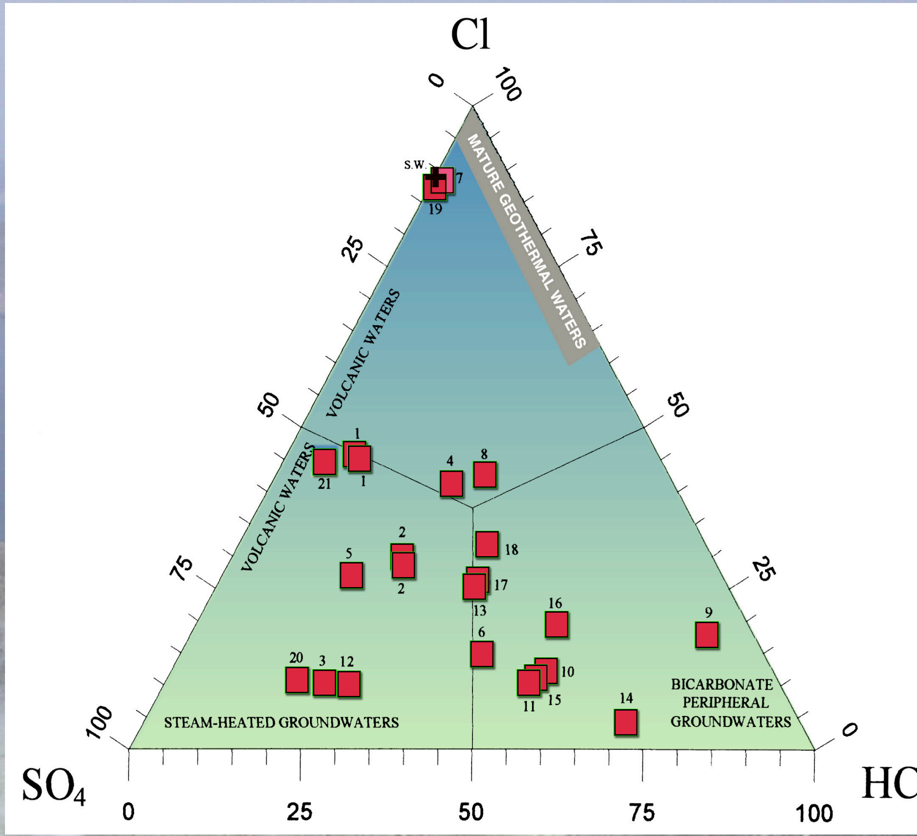
<u>Sources:</u> reactions of dissolved CO_2 from atmosphere and/or in geothermal/volcanic steam, with silicate minerals in rocks, with carbonate minerals (limestone)

Extremes of volcanic and steam heated are acidic (no HCO3)

Approximate range among non-volcanic geothermal systems (higher SO_4 exist)

Thermal waters: chemical compositions at Vulcano

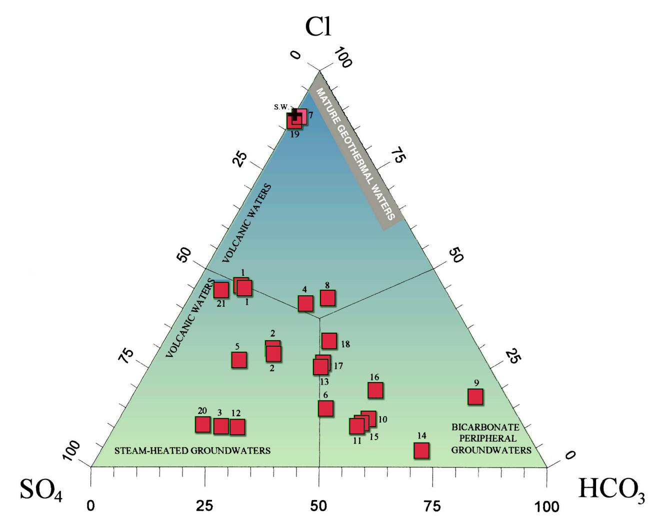




classification of waters : 4 main types

- ❑ bicarbonate peripheral waters (HCO_3 character, high or low TDS, high or low T)
- ❑ volcanic waters (SO_4-Cl character, high TDS and high T)
- ❑ steam-heated waters (SO_4 character, high T, medium TDS)
- ❑ chloride-rich waters (high TDS)

Thermal waters: chemical compositions at Vulcano



recall about chemistry of volcanic gas

- ❑ main components : C, S, H, O, Cl
- ❑ main species : CO_2, SO_2, H_2S, HCl
- ❑ distribution of S species T-dependant
  - ➢ high T ➔ SO_2
  - ➢ low T ➔ H_2S

interpretation of chemical facies

❑ bicarbonate waters

- ➢ low T (25-35 °C) and low TDS (< 1 g/l) ➔ meteoric recharge
- ➢ high T (35-50 °C) and higher (2-3 g/l)➔ dissolution of pure CO_2 in surface waters

❑ volcanic waters (Cl-SO_4 character)

- ➢ high T (40-80 °C) and high TDS (3 - 20 g/l)
- ➢ similar S/Cl ratio to the gas phase ➔ volcanic gasdissolution, low pH, rock dissolution

❑ steam-heated waters (SO_4 character)

- ➢ medium T (25 - 45 °C) and medium TDS (1-3 g/l) ➔ dissolution of hydrothermal H_2S gas in surface waters, oxidation by air : H_2S➔SO_4

❑ Cl-rich waters (Cl character)

- ➢ high T (70-90 °C) and high TDS (➔40 g/l) ➔ gas bubbling in sea water

<u>Conclusion</u>: major composition of thermal waters results from selective gas-water interactions, reflects the gas composition and chemical heterogeneity, and results from groundwater spatial heterogeneities

Thermal waters: chemical compositions at Vulcano: MTE

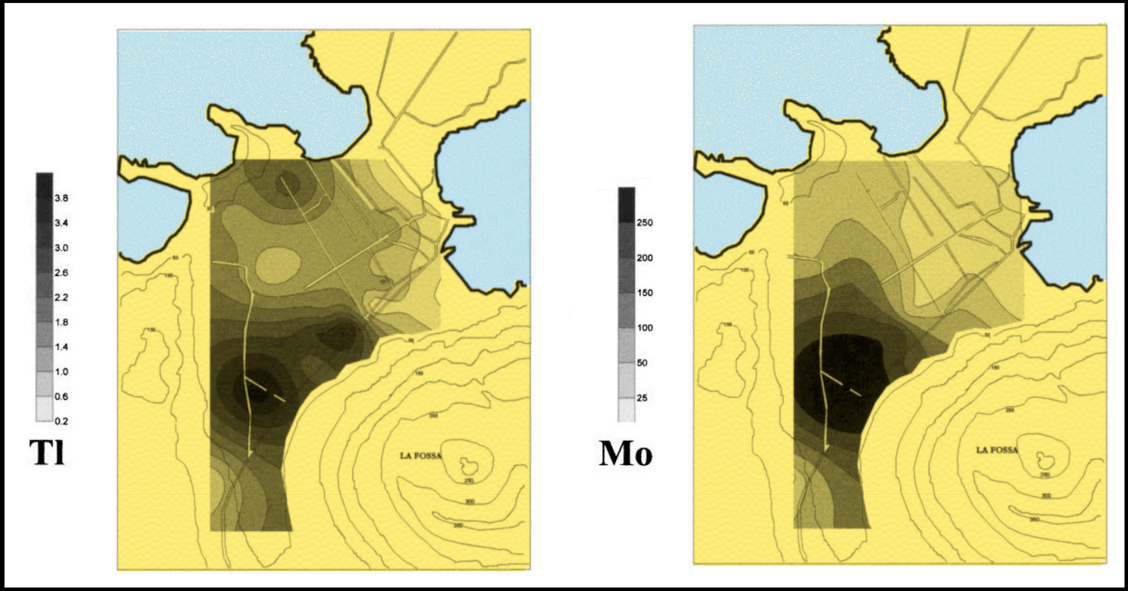
gas-water interactions through metallic trace-elements compositions of thermal waters

gas phase composition in M.T.E. is considered with respect to rock composition:

☐ volatiles elements are strongly enriched (high EF) : Pb, Tl, As, Mo, As, Se, Te, Au …..
☐ refractory elements are poorly enriched (low EF) : Mn, Al, Fe, Ti, Zr, Ni, ….

question : is the MTE pattern of thermal waters controlled by the volcanic gas composition ? are there other processes ?

Spatial distribution of volatile (high EF) MTE

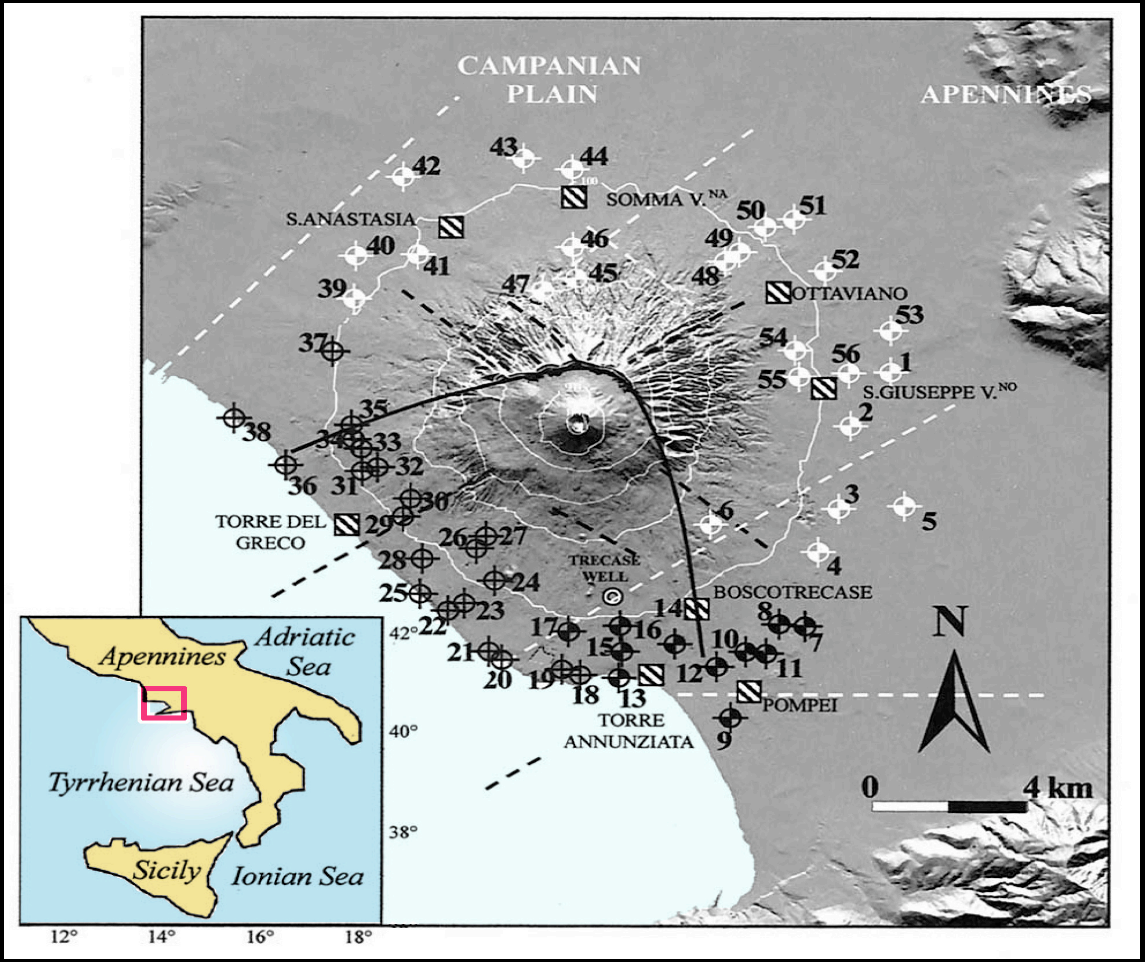


MTE distribution :

☐ volatile MTE are enriched in volcanic waters (Cl-SO_4 character)
☐ highest concentrations are measured at the base of the cone (direct inflow of deep volcanic gas)

conclusion: MTE chemistry reflects volcanic processes (inflow of volcanic gases) but … adsorption processes for many elements

Thermal waters at a dormant volcano: Vesuvius



the site

☐ Vesuvius 1281 m asl,

☐ young volcano (25.000 y)

☐ continental K-rich magmatism (results from subduction of Africa beneath Europe + opening of Thyrenian sea)

☐ historical activity: six magmatic cycles beginning by major plinian events

☐ ex: the AD 79 Pompei plinian eruption

☐ dormant since 1944 (low fumarolic and geophysical activity)

however ....

☐ 1 million people on slopes of Vesuvius

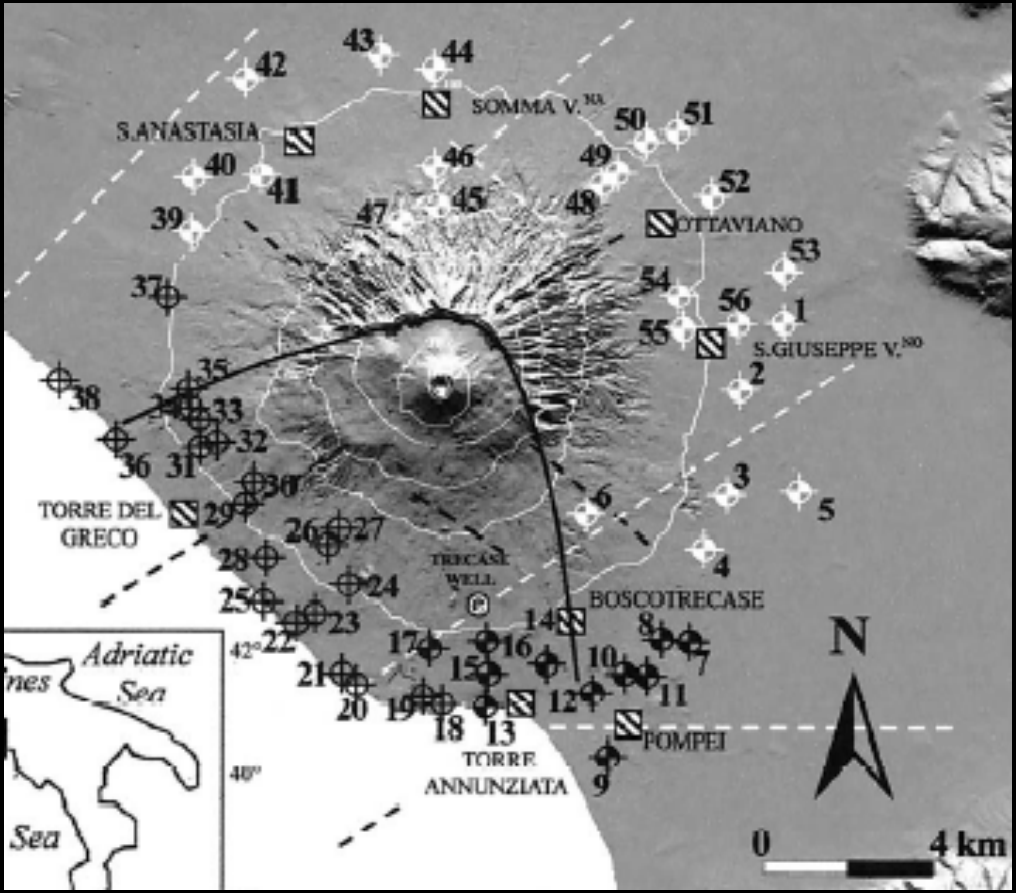
☐ 3 millions in the immediate vicinity

☐ waiting for the future explosive events

➔ a need for indicators of activity

question: are thermal waters potentially good indicators of volcanic activity state and possible unrest at this dormant volcano ?

Thermal waters at a dormant volcano : Vesuvius



the site

the volcano-structural features :

- ❑ caldera rim 400 m high
- ❑ collapse structure (18 ky, results from flank collapse)
- ❑ summit cone
- ❑ tectonic faults
- ❑ hydrothermal fluids in the central crater (fumaroles with T = 80 °C and ^{3}He enrichments with R/Ra = 2.2 – 2.6)

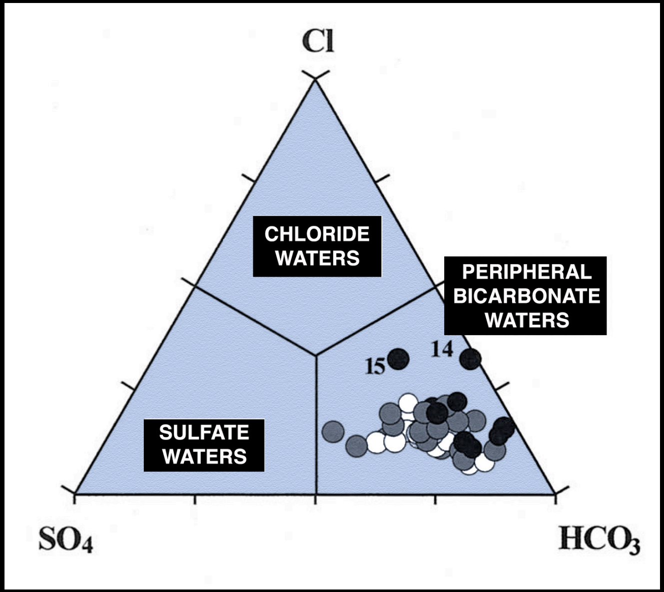
the hydrogeologic features :

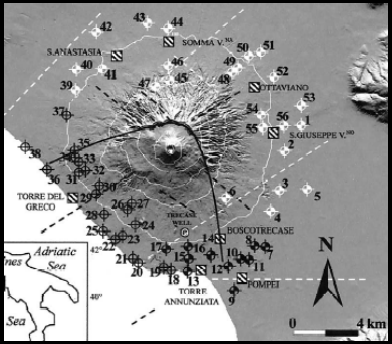
- ❑ water storage & circulation in 2 main structures :
  - ➢ a deep carbonated aquifer
  - ➢ a superficial volcanic aquifer (lavas, pyroclats)

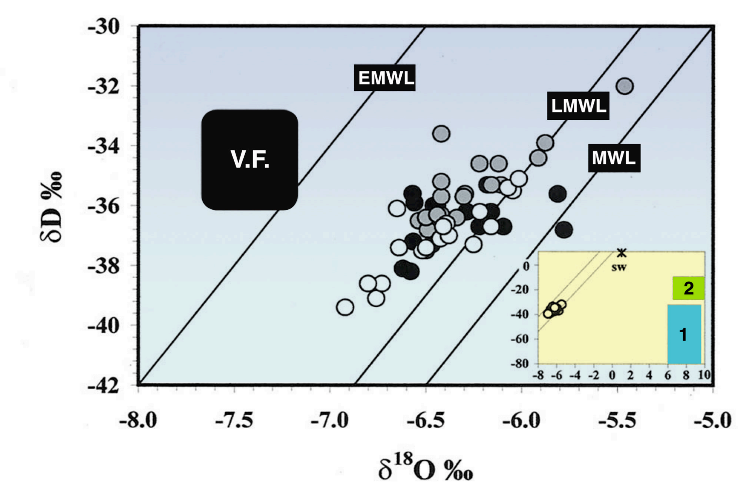
- ❑ 56 thermal & groundwaters (springs, wells, drills): 3 groups
  - ➢ N & E sector waters ⌖5
  - ➢ SW sector waters 37⌖
  - ➢ SE sector waters ⌖9

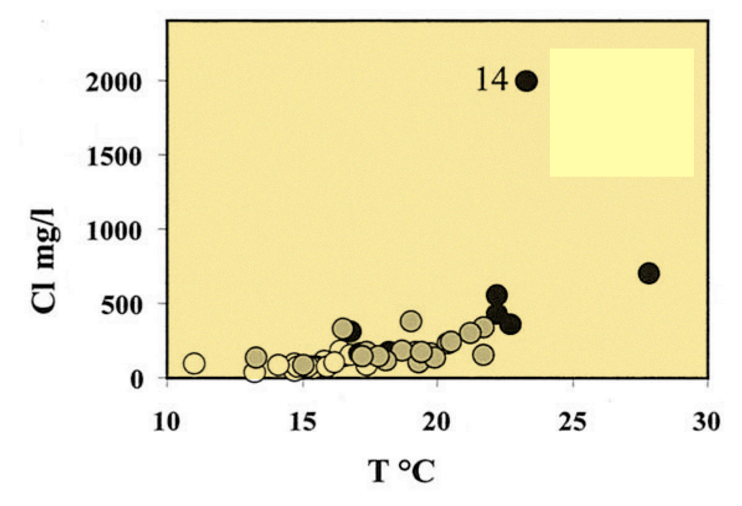
Thermal waters at a dormant volcano : Vesuvius

main hydrochemical features





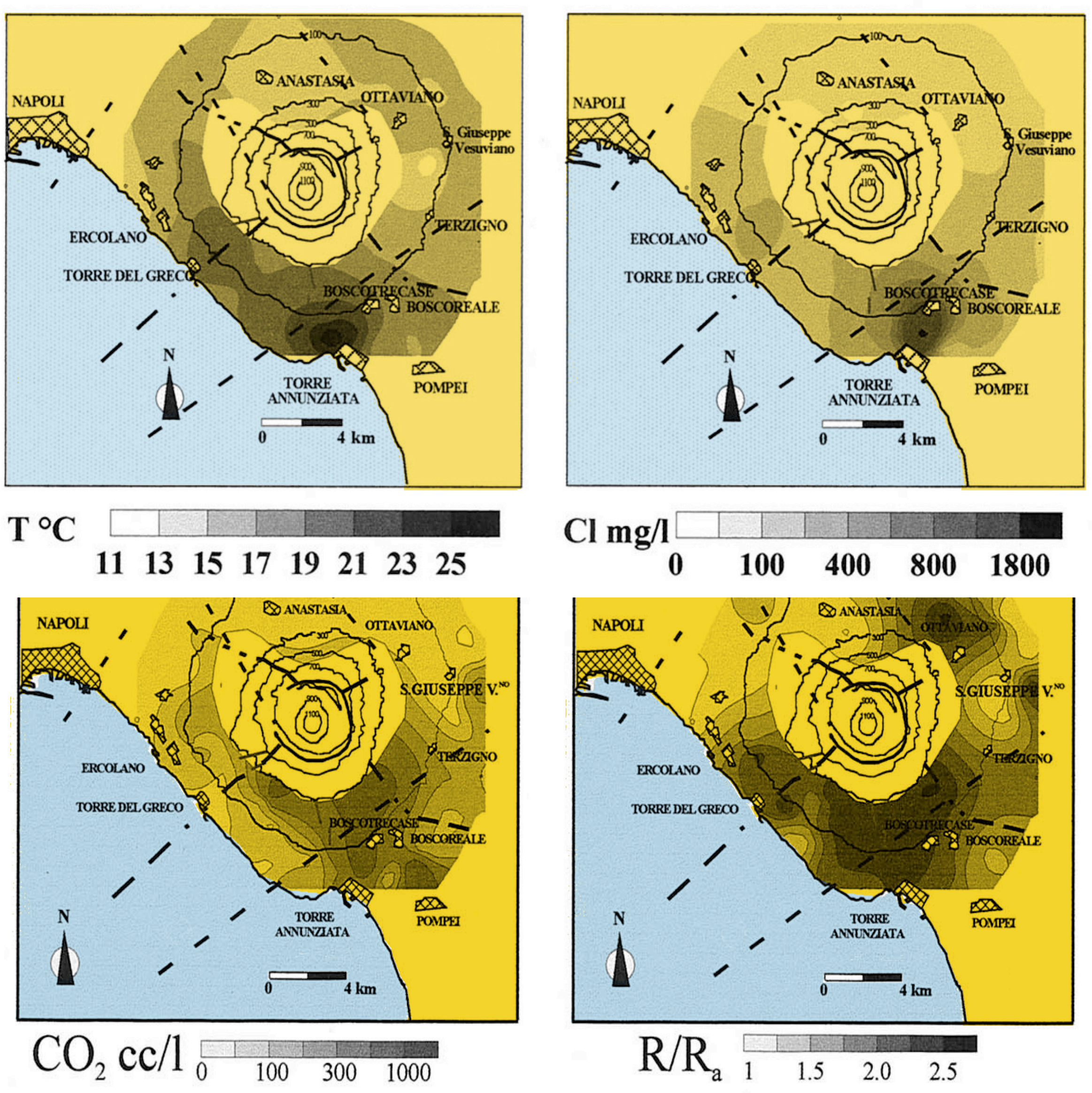




- ❑ all waters have a bicarbonate character with moderate T (11 – 28 °C) and TDS (0.65 – 12.5 g/l)
- ❑ waters are close to the Local Meteoric Water Line (LMWL) ➔ meteoric origin, no high temperature fractionnation processes. The very light discrepancies / LMWL result from low T water-rock interactions
- ❑ SE sector waters have higher Tmean (19.4 °C), [Cl], and TDS than NE sector waters (Tmean : 14.4 °C) ➔ interactions with hydrothermal fluids

Thermal waters at a dormant volcano : Vesuvius

geochemical imaging



❑ T are moderate (11 – 28 °C), with highest values at the SE

❑ Cl concentrations show also the highest values at the SE

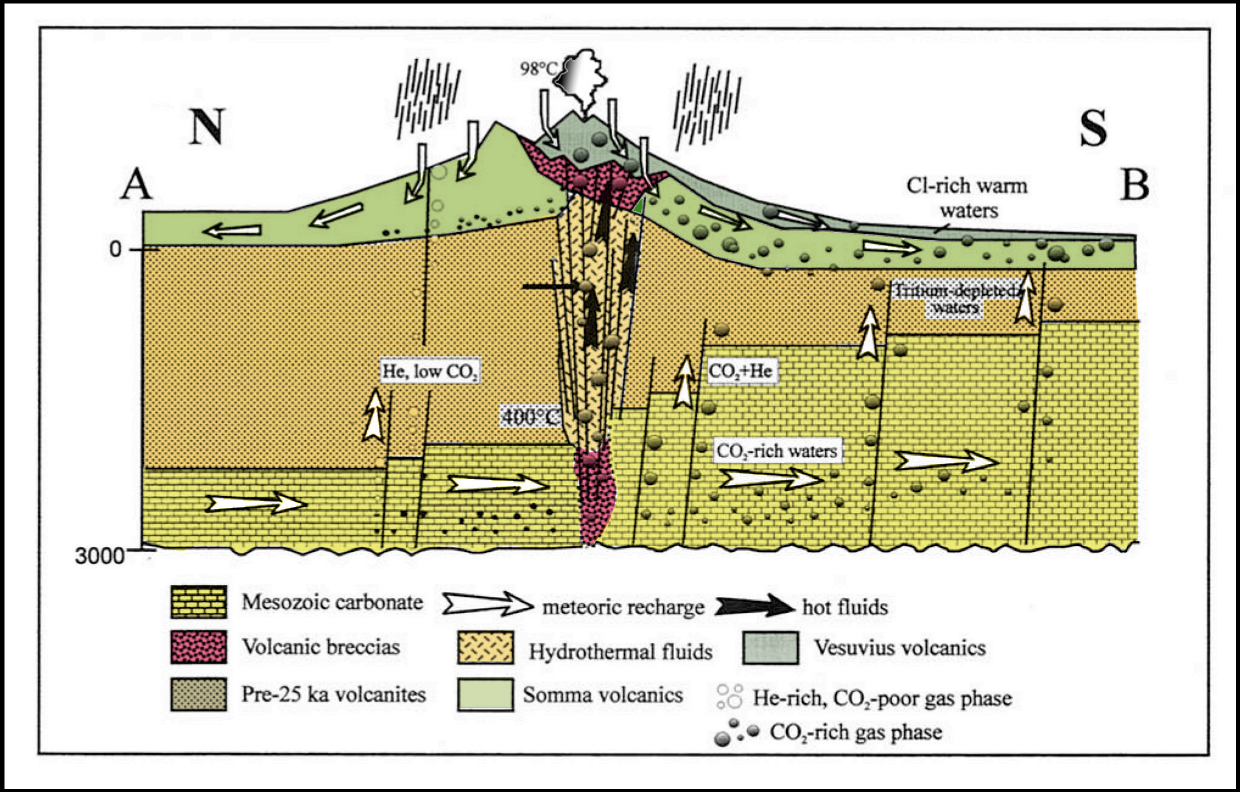
❑ $^3He/^4He$ (R/Ra ratios) are widely distributed, with a mixing between 2 poles : one is atmospheric air (R/Ra = 1) and one is magmatic He (R/Ra = 2.7).

❑ the ^3He-rich magmatic component is enriched in the SE sector and in the N-NE sector

❑ medium to high CO_2 concentrations (50 – 1056 cm^3 STP/l H_2O) in the SE sector

Thermal waters at a dormant volcano : Vesuvius

interpretative geochemical model



synthesis

☐ meteoric origin of waters
☐ low-temperature processes
☐ Cl and TDS increases in the SE sector due to interactions with central hydrothermal fluids
☐ R/Ra of SE waters is similar to fumaroles (~ 2.6)
☐ contribution of magma-derived He in local areas (SE, N) in correlation with main faults
☐ local CO_2 enrichments (SE)
☐the N sector is less affected by deep rising fluids

conclusions :

☐ extensive interactions between rising magmatic volatiles and groundwater
☐ tectonic control on gas ascent (He)
➔ magmatic volatiles circulate through groundwater systems at dormant volcanoes
➔ they have similar character than central crater volatiles
➔ thermal waters at dormant volcanoes constitute good targets for the detection of future unrest

Conclusions

There are several geochemical and isotopic parameters to be used for forecasting volcanic activity

However, the interplay among all the factors that may affect crater lakes as well a spring/well waters does not allow to provide a general rule for mitigating the volcanic risk: each volcano indeed needs to be fully understood and relatively long-term geochemial sequences are necessary

We know fairly well the mechanims that produce a certain water chemical composition. Now, we need instrumentations and time!

Thank you!