I laghi vulcanici: rischio e sorveglianza geochimica

Lake (limnic) ecosystems

- Origins and classifications
- Lakes as open systems
- Light and temperature
- Lake chemistry
- Primary productivity
- Secondary productivity
- Lake evolution
- Perturbations

Lake classification: geological origin

Lakes result from impoundment of water by:

- tectonic downwarping (e.g. Lake Victoria)
- tectonic faulting (e.g. Dead Sea)
- volcanic eruption (e.g. Crater Lake)
- landslide dams
- ice dams
- biotic dams (e.g. Beaver lake)
- glacial erosion (e.g. Lake Peyto)
- glacial deposition (e.g. Moraine Lake)
- river channel abandonment (e.g. Hatzic Lake)
- deflation

Types

- Open
  - has outflow of water
  - Ppt + inflow = Evap + outflow
    - clastic sedimentation common
- Closed
  - no major outflow
  - inflow > Evap
  - chemical sedimentation may dominate due to concentration of ions
- Perennial
  - inflow from at least 1 perennial stream
  - rarely dry up
- Ephemeral
  - salt-pan basins
  - dry up seasonally; fed by springs, runoff, groundwater
  - Salts important ephemeral deposits
    - salts are bedded

Volcanic (crater) Lakes

Limnologia

- 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 shallow water
- 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)

Un lago vulcanico è una specie di tappo di acqua meteorica sopra ad un cratere vulcanico.

Solamente il 16% dei 714 vulcani con età <10,000 anni listati nel Catalogue of Active Volcanoes of the World hanno un lago.

La peculiarità dei laghi vulcanici è che la loro esistenza richiede uno speciale bilancio fra il flusso di calore vulcanico e il raffreddamento atmosferico e fra le precipitazioni e l'evaporazione.

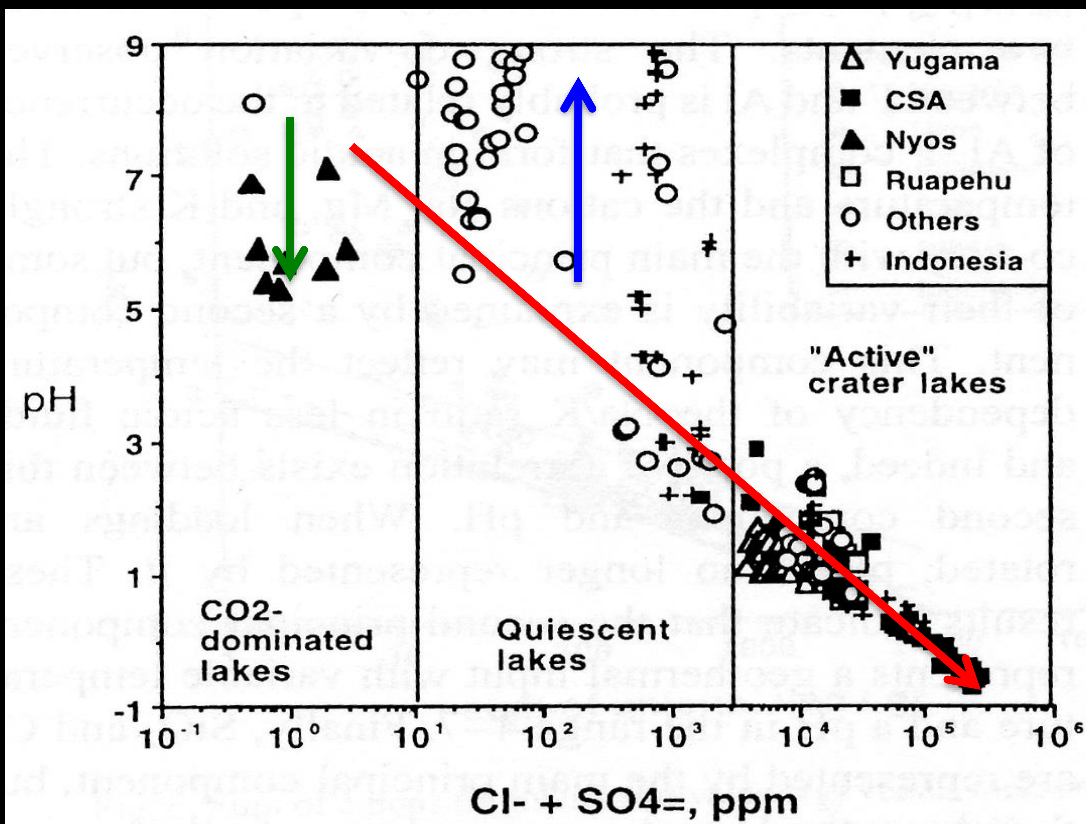
La struttura vulcanica (e.g. permeabilità del substrato e forma del cratere) è importante ma sono le forze endogene e quelle esogene che condizionano la chimica di un lago che a sua volta è indicativa dell'attività vulcanica e dei processi idrogeochimici.

- I vulcani che contengono un lago craterico si ritrovano prevalentemente in aree di vulcanismo di subduzione;
- Sono tipici di aree con piovosità relativamente elevata;
- Molti sono caratterizzati da acqua calda
- Possono accumulare grandi quantità di gas
- Spesso presentano una alta acidità delle acque (con pH fino a 0)

Chimica dei laghi vulcanici

pH neutro, diluito (TDS < 100 mg/L) es: Crater Lake, USA
pH intermedio (pH ~ 2-6) e relativamente mineralizzato (TDS<2000 mg/L)
pH acido (pH<2), fortemente mineralizzato (TDS>100,000 mg/L), es: Kawa-Ijen

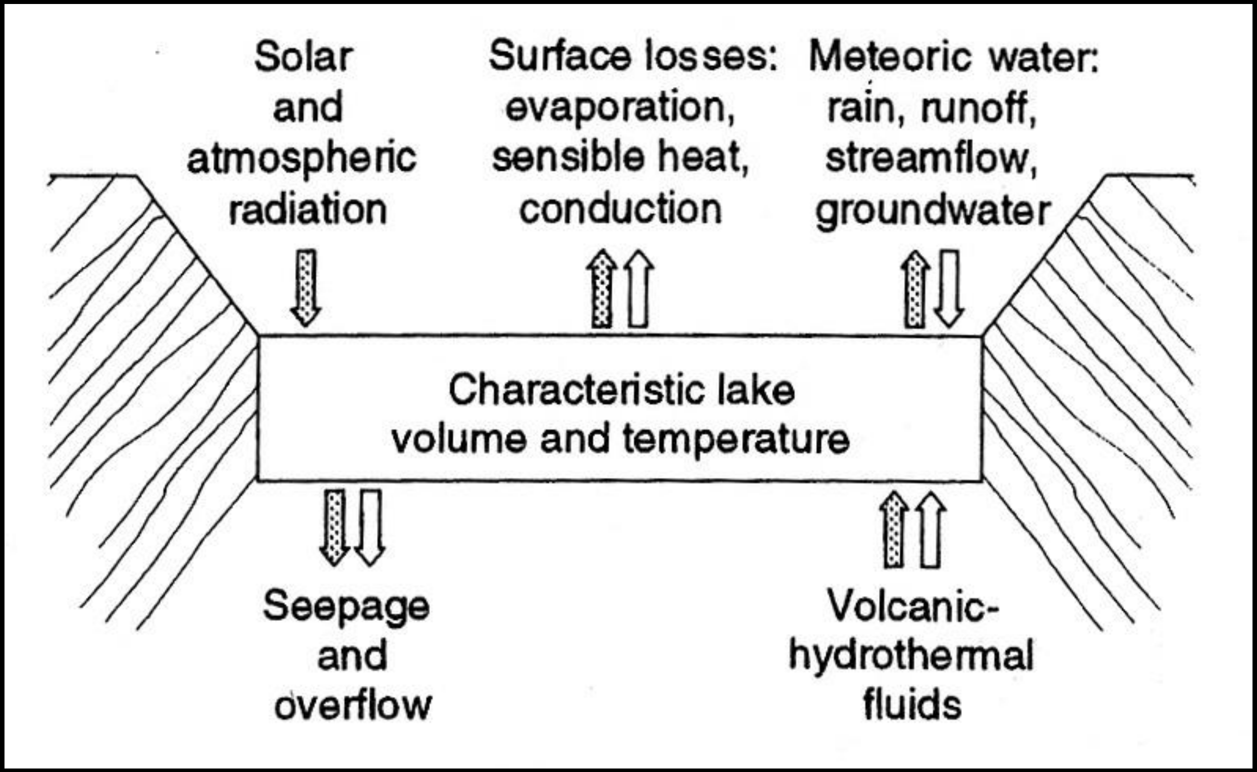
Varie facies geochimiche: alto Na-Cl (Kelut) e $Cl-SO_4$ (Oyunuma), alto HCO_3 (Nyos)



Classificazione pH-$Cl+SO_4$

- ❑ Principali parametri discriminanti: pH e componenti derivati dalla dissoluzione di gas acidi (Cl^-, SO_4^{2})
- ❑ 3 principali gruppi di laghi:
  - ➢ laghi a CO_2: neutri pH (~5-7) + basso $Cl+SO_4$ (< 5 ppm) + dominati da CO_2
  - ➢ laghi geotermali quiescenti: pH variabile (2-9), moderato $Cl+SO_4$ (<2000 ppm)
  - ➢ laghi craterici attivi: pH acido pH (2 - -1), alto $Cl+SO_4$ (>2000 ppm)

I laghi vulcanici agiscono da condensatori e calorimetri



Processi dinamici nei laghi

- ❑ Il rapporto fra calore di input e calore dissipato determina la persistenza e la temperatura dell'acqua;
- ❑ La maggior parte del calore dissipato è alla superficie del lago ➔ laghi piccoli hanno piccola capacità di dissipazione e la loro T aumenta rapidamente con piccoli input;
- ❑ Grandi laghi sono meglio tamponati rispetto alle variazioni dovute agli input di calore

❑ laghi vulcanici persistenti risultano da sistemi idrotermali che trasportano calore, acqua e materia da magmi in degassamento e raffreddamento;

❑ **Budget globale di massa:**

➢ Input: vulcanico & fluidi idrotermali (gas, vapore, brine) + acqua meteorica (precipitazione, runoff)

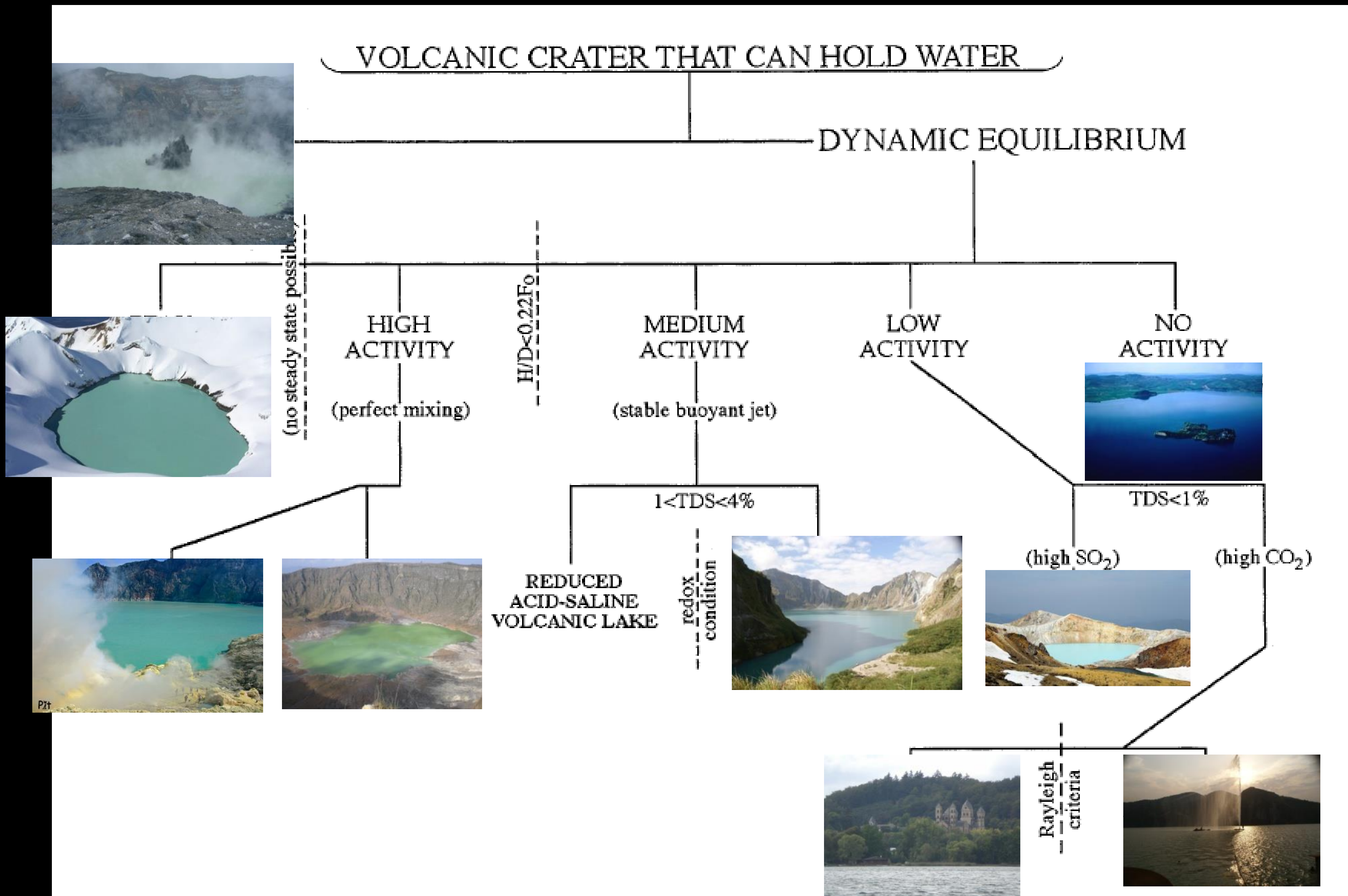
➢ Output: evaporazione, infiltrazione di acqua del lago, overflow,

❑ **Budget globale di calore:**

➢ Input derivato dall'entalpia del fluido in ingresso + radiazione solare e atmosferica;

➢ Output derivato da flussi evaporativi e radiativi dalla superficie del lago, infiltrazione e overflow e effetto di raffreddamento per precipitazioni e runoff nel lago.

Pasternack & Varekamp (1997)



Volcanic Risk

ELSEVIER

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

Journal of volcanology and geothermal research

www.elsevier.nl/locate/volgeores

The hazards of eruptions through lakes and seawater

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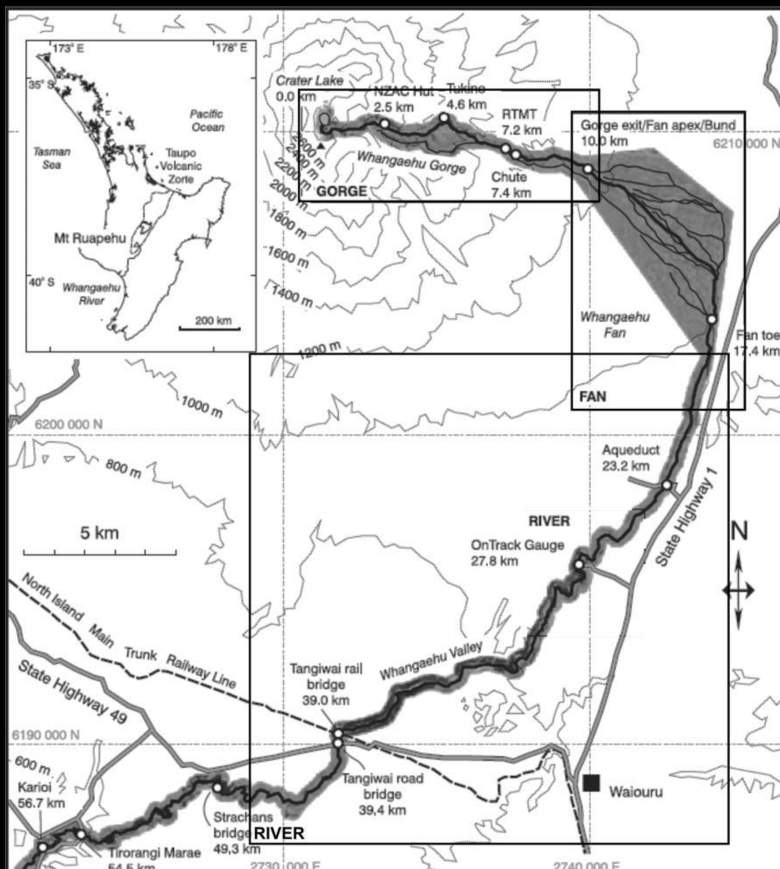
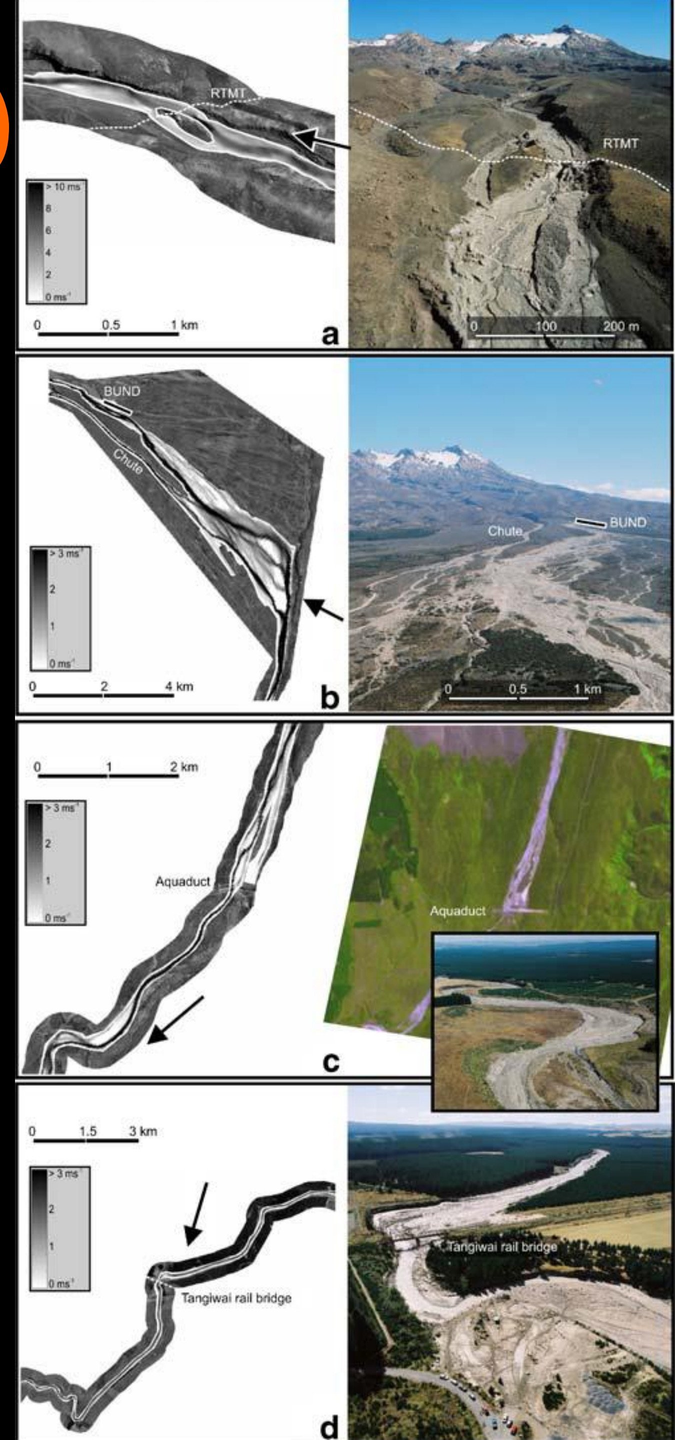
Abstract

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

Direct Volcanic Risk (DVR)

Lahars, e.g. Ruapehu, NZ



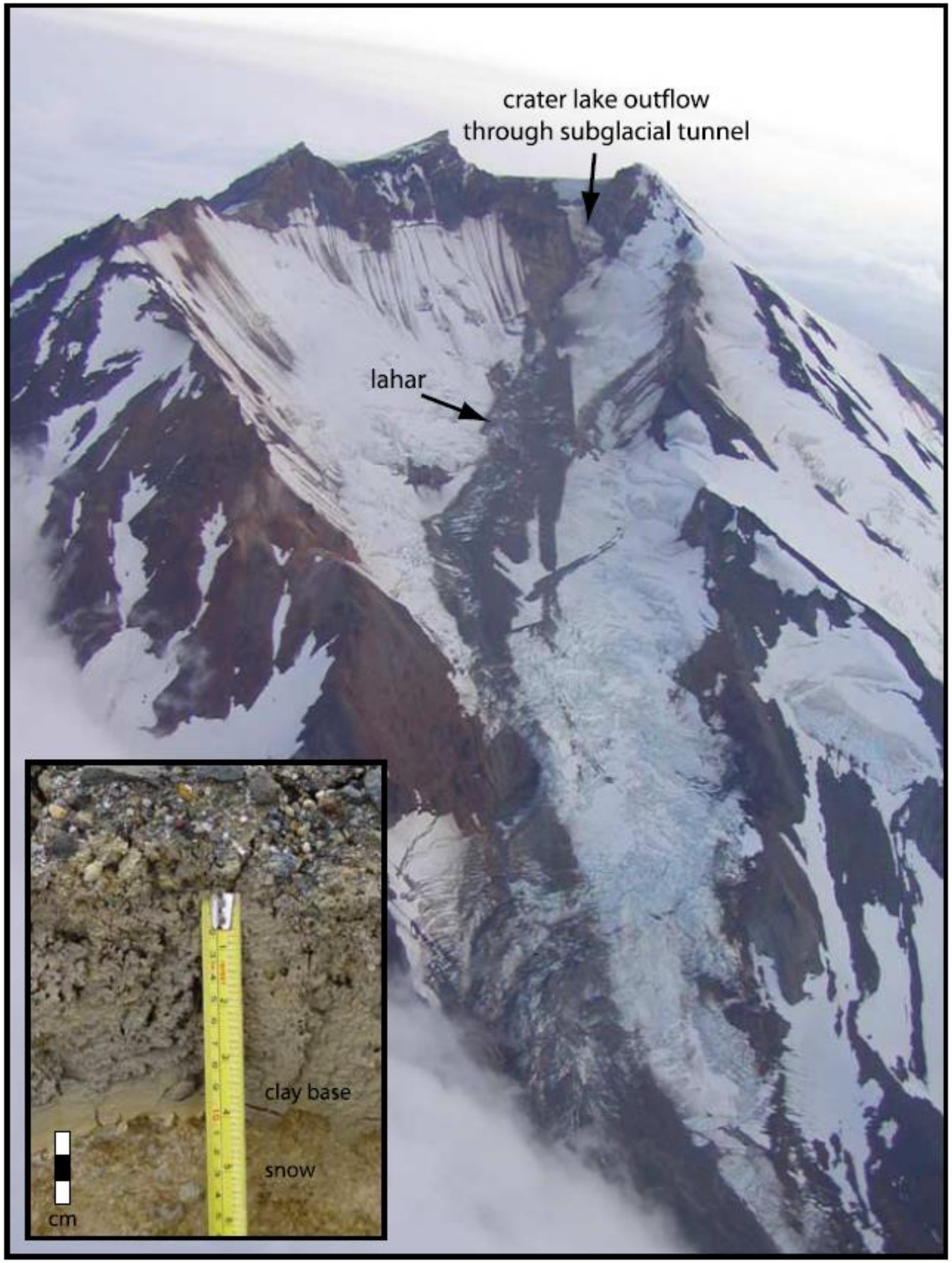


Carrivick et al. 2009

Direct Volcanic Risk

Chiginagak, Alaska, 2005

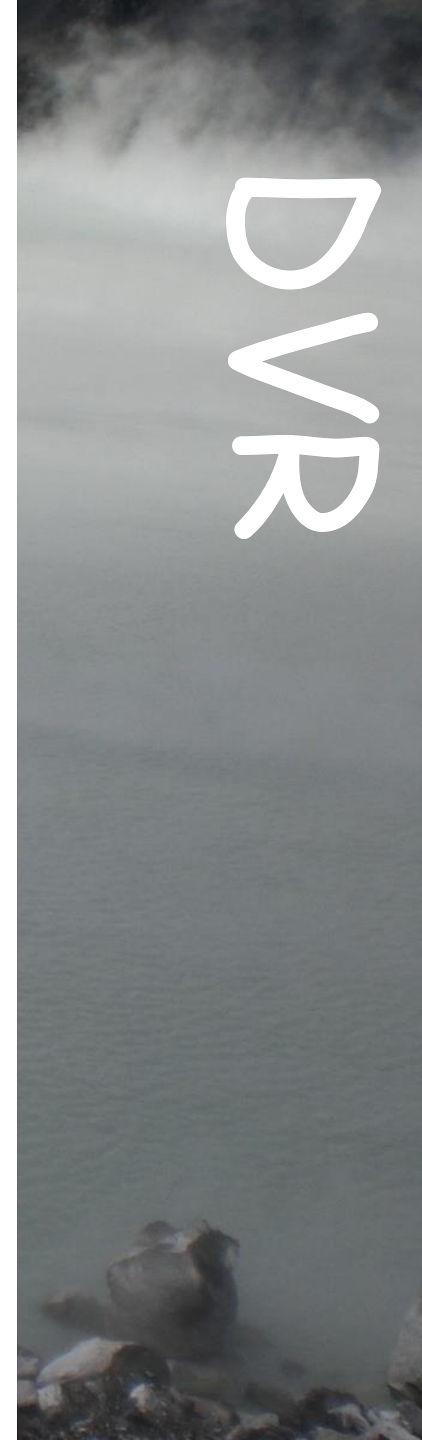
Schaefer et al. (2008)



DVR

Chiginagak,
Alaska, 2005

Schaefer et al. (2008)



A-type: 2-50 m

B-type: 51-250 m

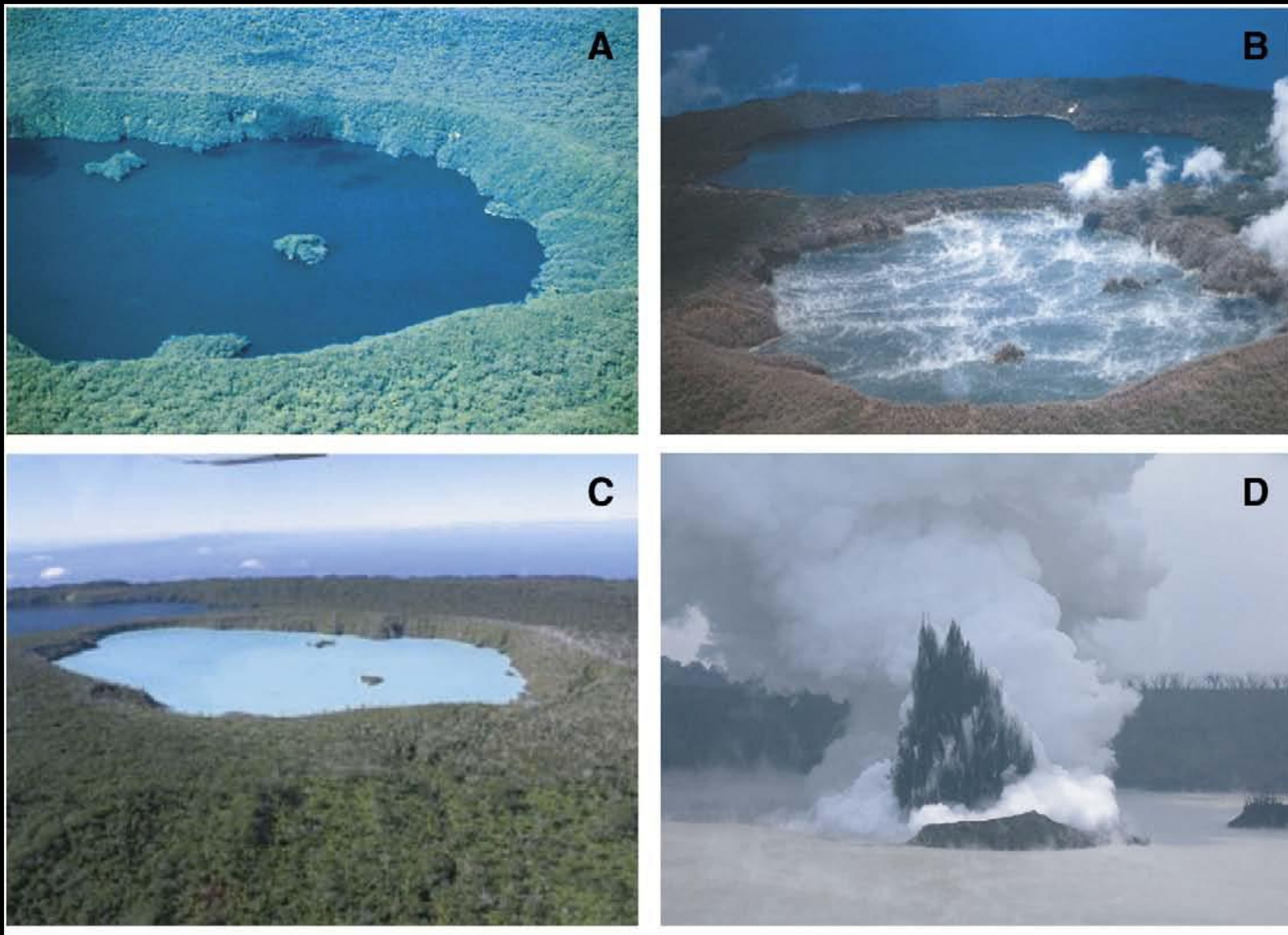
C-type: >250 m

Dome intrusion

Kelut, Indonesia, 2007

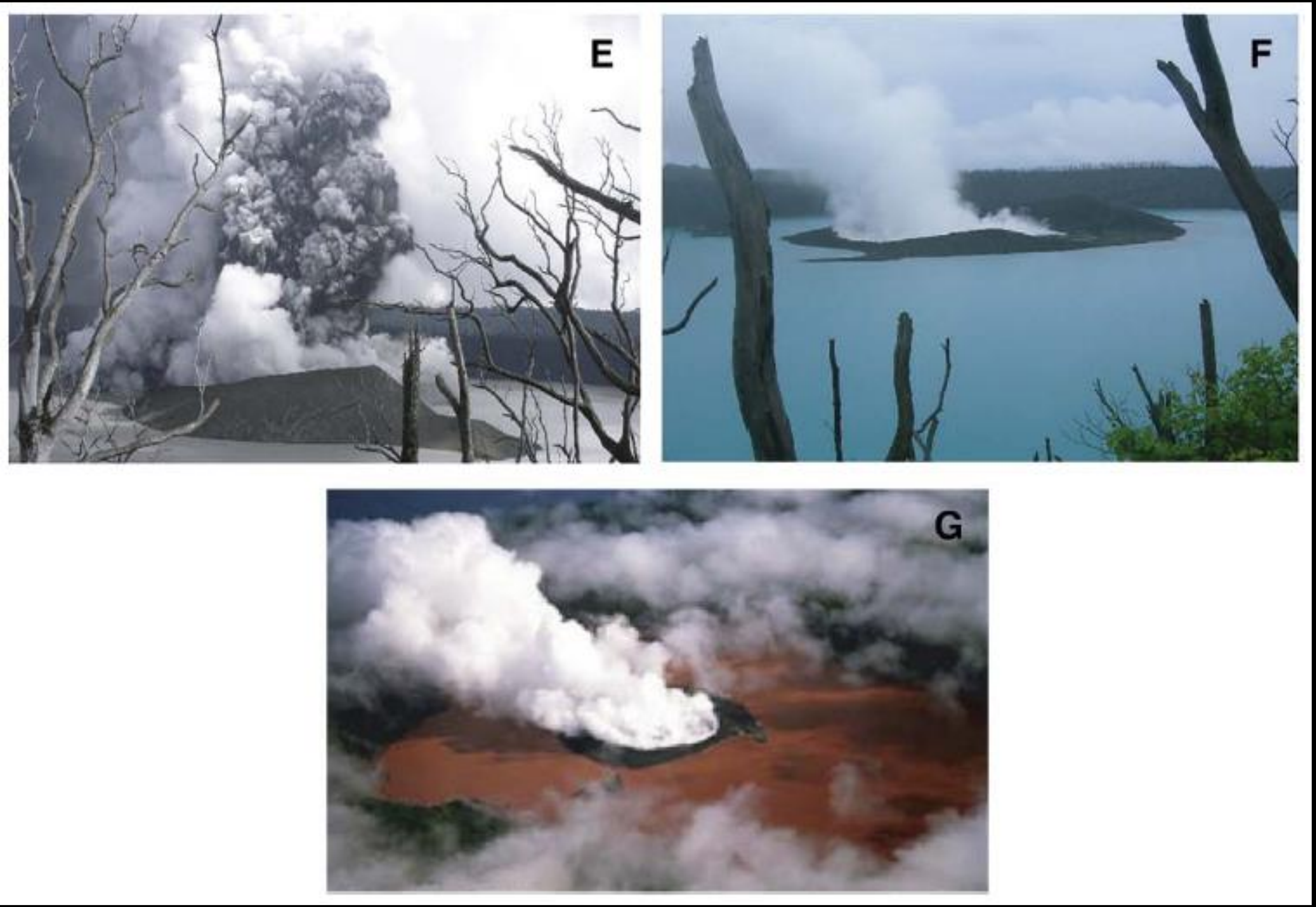
DVR

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



Voui, Vanuatu, 2005-2006

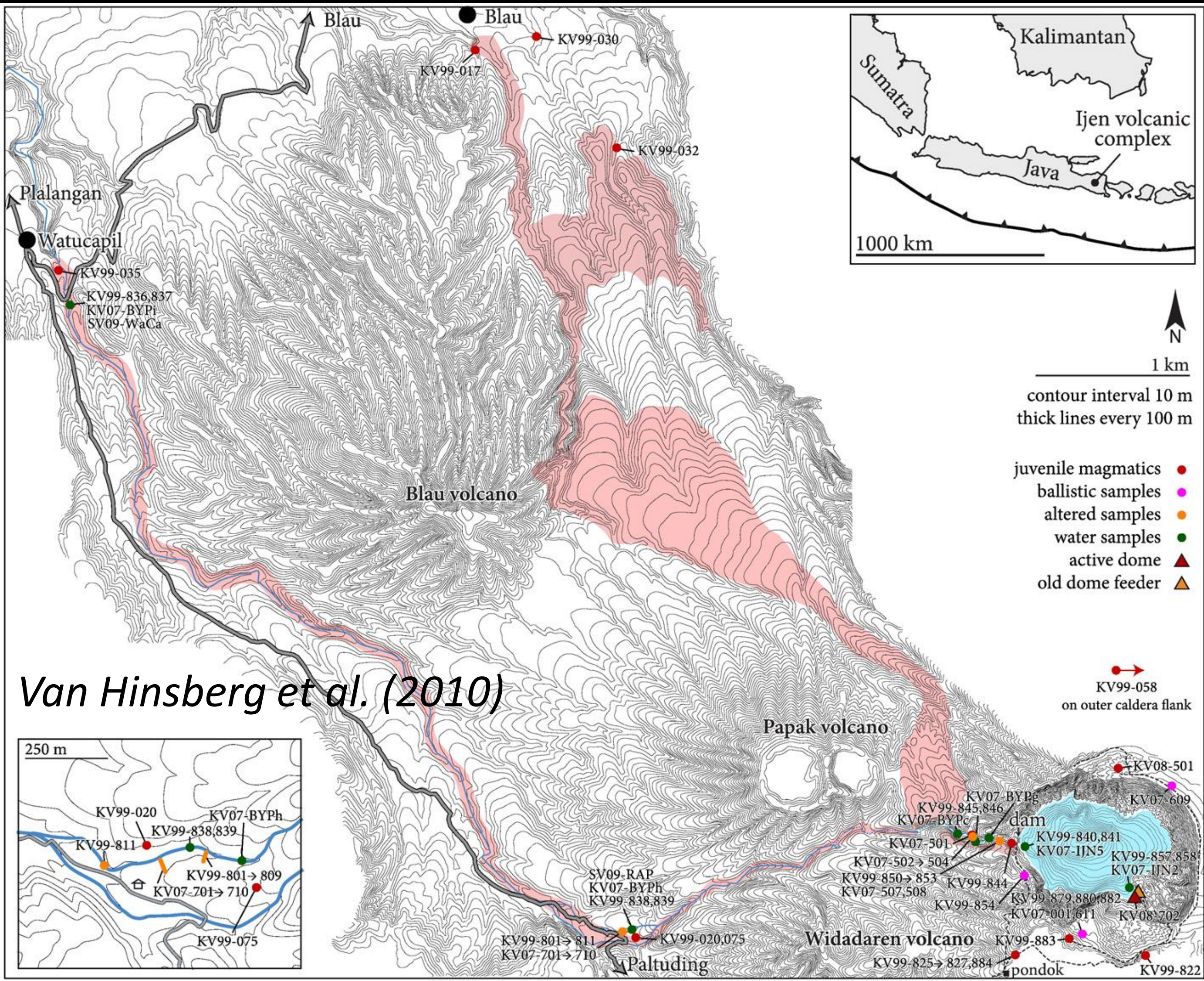
Bani et al. (2009)



Magmatic activity: Santa Ana, El Salvador, Octobre 2005

Scolamacchia et al. (2010)

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

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

How do we study volcanic lakes?

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

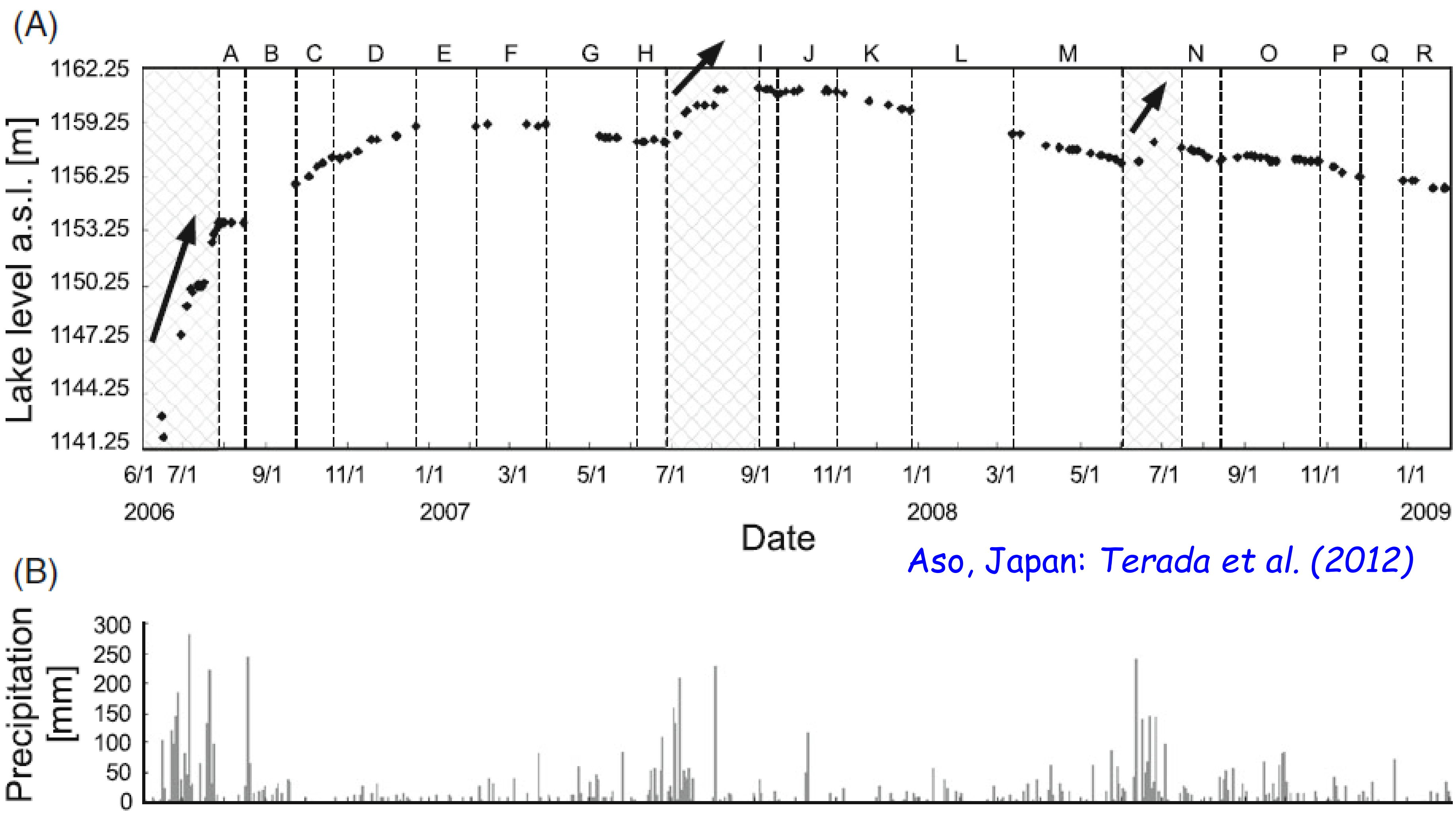
- Identify physico-chemical changes…
- Conceptual models
- Volcanic monitoring

Direct observations

Dimension/level: fixed camera

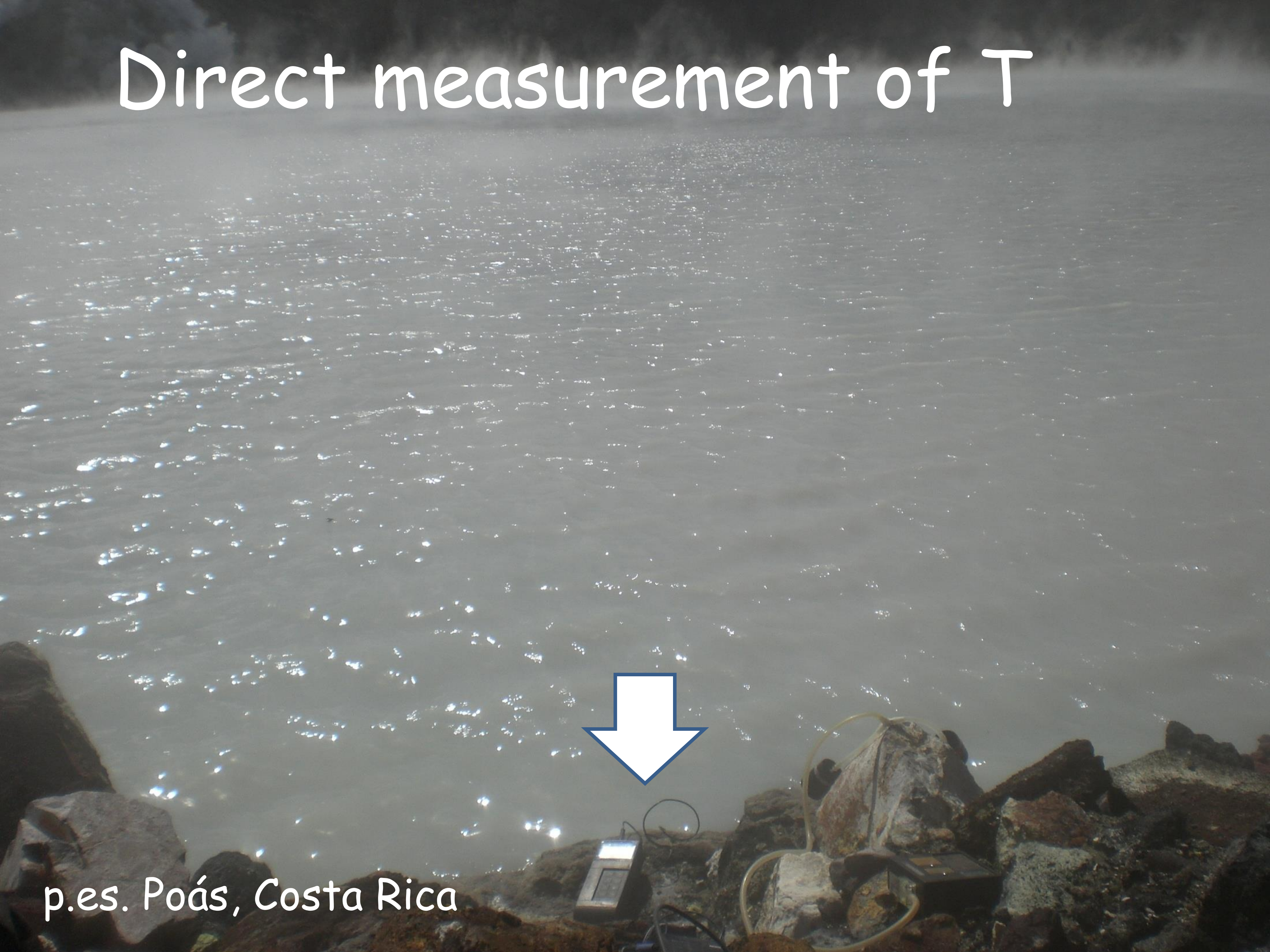
Aso, Giappone: *Terada et al. (2012)*

Direct observations



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

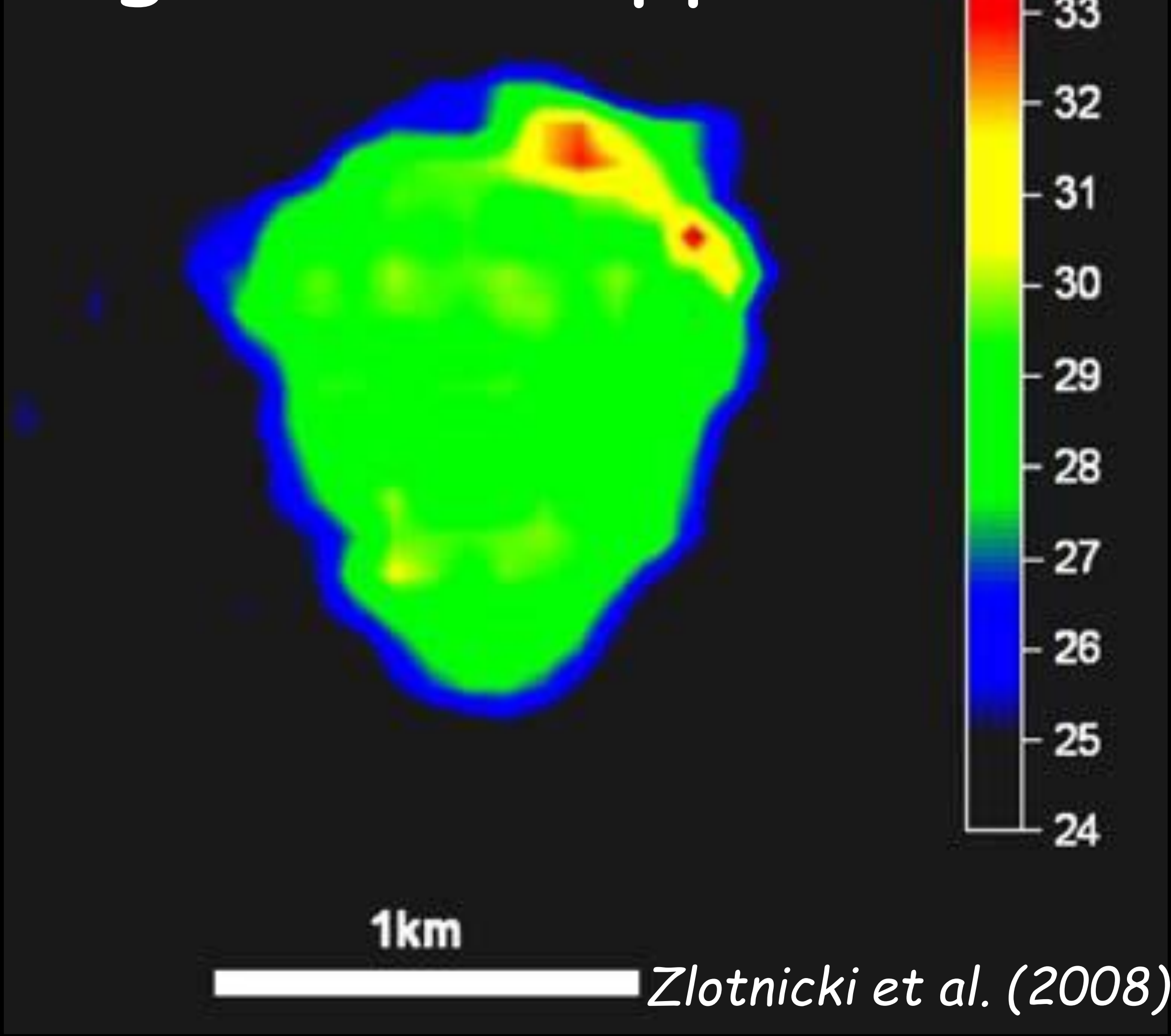
Direct measurement of T



p.es. Poás, Costa Rica

Temperature

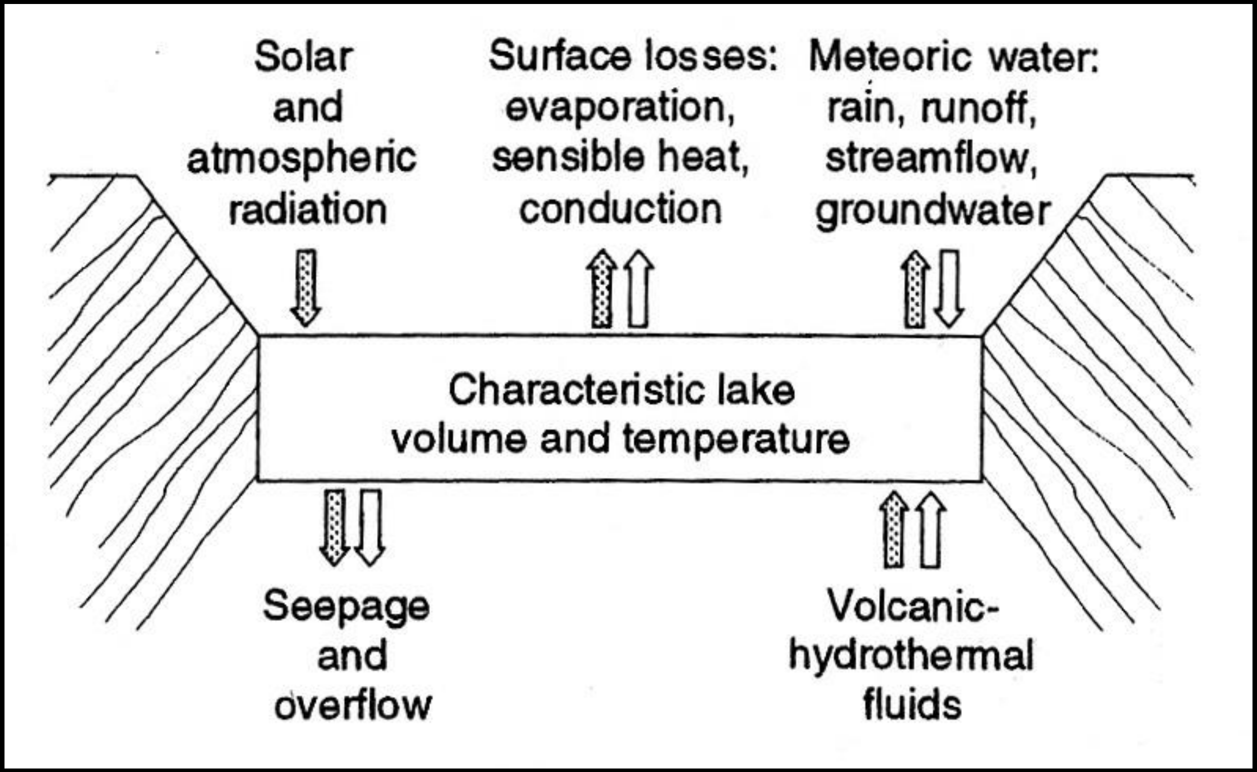
e.g. Taal, filippine



Zlotnicki et al. (2008)


Active Crater lakes

Active Crater lakes: condensers & calorimeters



Persistent volcanic lakes result from hydrothermal systems which transport heat, water & chemicals from a cooling & degassing magma body

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

great lakes are better buffered against variations in heat inputs

Fluid balance

Inputs: volcanic & hydrothermal fluids (gas, steam, brines) + meteoric water (precipitation, runoff, streamflow)

outputs: evaporation, lake water seepage, overflow, ground infiltration

Heat balance

Input: enthalpy of the entering fluid + solar & atmospheric radiation

Outputs: evaporative & radiative fluxes from lake surface, seepage and overflow and cooling effect of precipitation and runoff in lake

Active Crater lakes and volcanic hazard

Heat-water interaction…phreatic and phreato-magmatic eruptions

Ash (volcanics)-water interaction…lahars

How to study (and monitor) active crater lakes ?

- The box model approach

Mass balance: sum of the in- and output fluxes of water mass

water mass budget of the lake can be expressed in a differential form:

$$V_L - V_{L0} = Q_f\,Dt + Q_m\,Dt + Q_{sp}\,Dt - Q_e\,Dt - Q_s\,Dt - Q_o\,Dt$$

$V_L - V_{L0}$ is the change in volume of crater lake water during the period of observation

Q_f is the input flux of "volcanic" fluid from beneath the lake (kg/s)

Q_m is the input flux of meteoric water (kg/s)

Q_{sp} is the input flux of water from springs located outside the lake (kg/s)

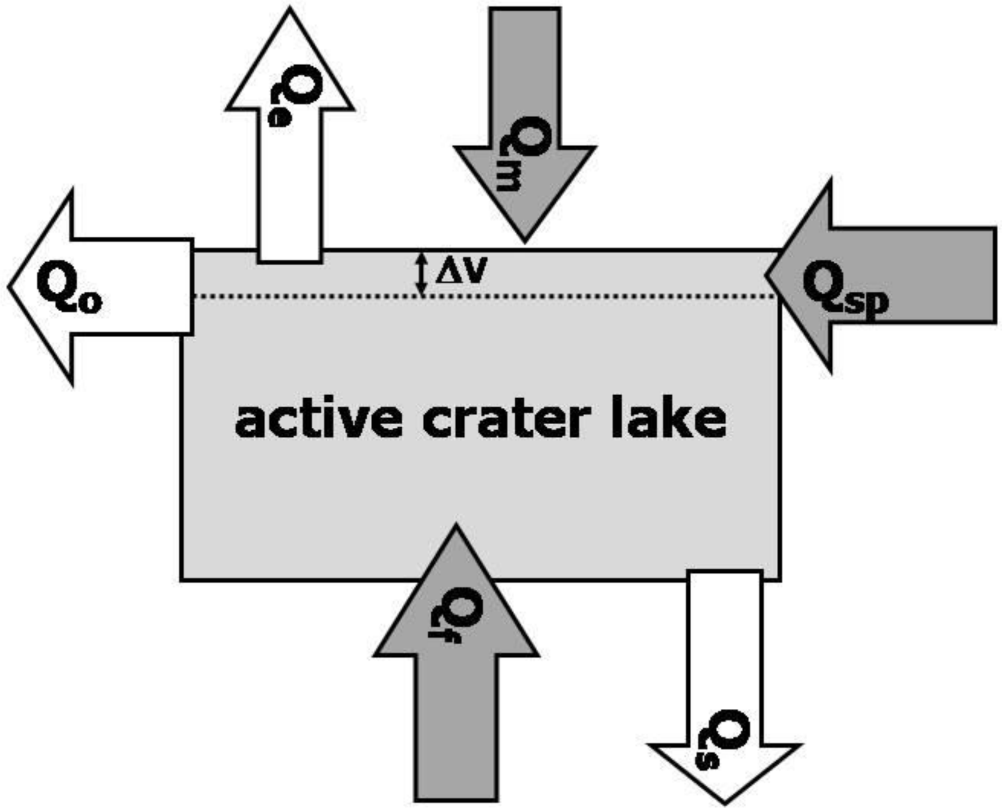
Q_e is the evaporative flux of water from the lake surface (kg/s)

Q_s is the seepage flux of water at the lake bottom (kg/s)

Q_o is the overflow flux of water out of the lake basin (kg/s)

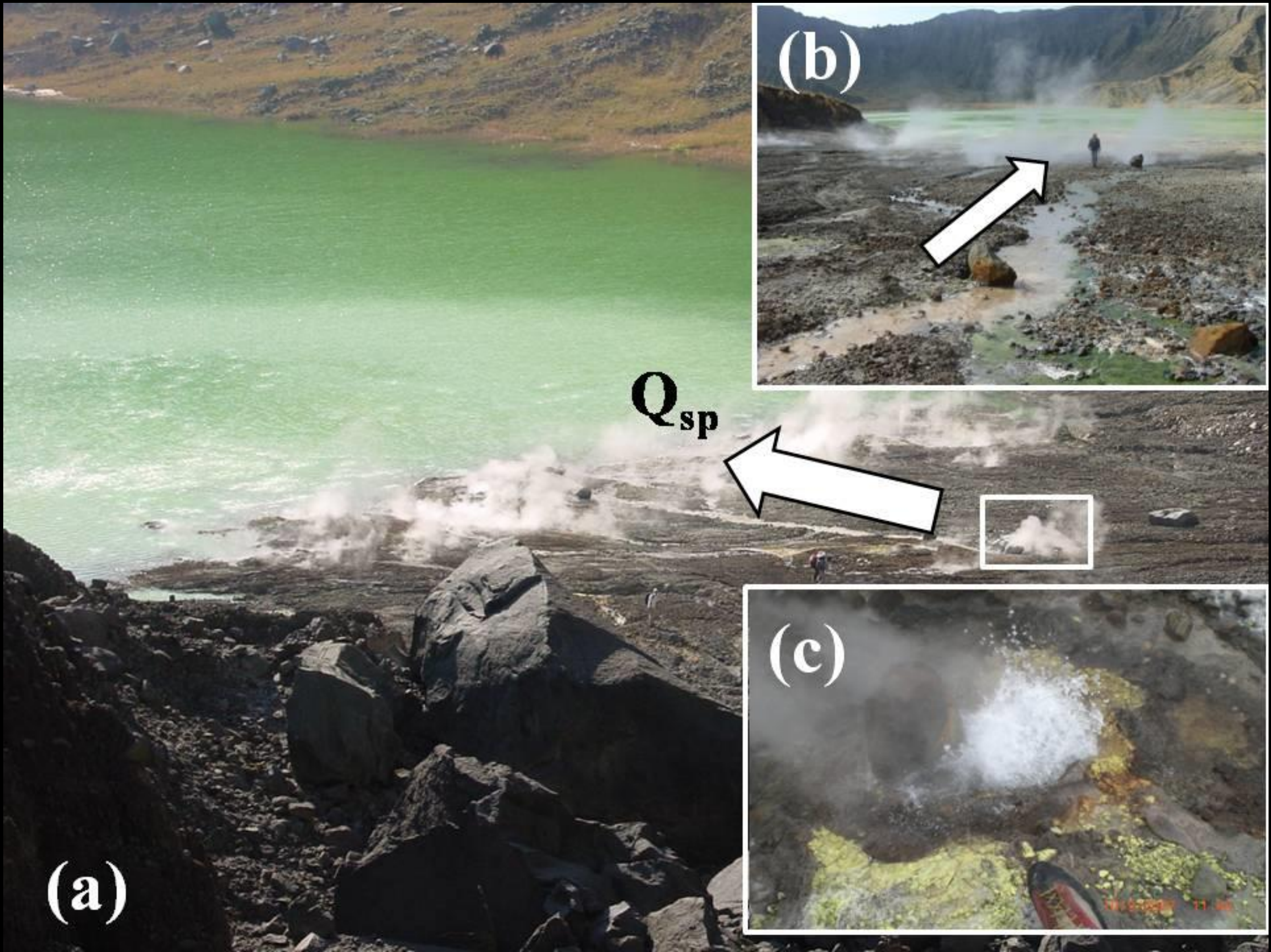
Dt is the period (s) between two times of observation of the crater lake (≈ sampling frequency).

Mass input and output



some example…

Input from springs (out of the lake)



Evaporative flux

What can be measured ?

- the variation in lake volume (V_L - V_{L0}). In general, the lake volume is deduced empirically and independently for each crater lake
- The input flux of meteoric water (Q_m) depends on the precipitation rate that can be measured installing a rain gauge as near as possible to the lake.
- The input flux of springs (Q_{sp}) and the overflow output flux (Q_o) located outside the lake in the catchment area can be directly measured in the field, by means of a flow meter device.
- The evaporative output (Q_e) can be calculated from latent heat of vaporization of water on the basis of wind speed, air humidity and temperature, atmospheric pressure and water lake temperature.

What cannot be measured ?

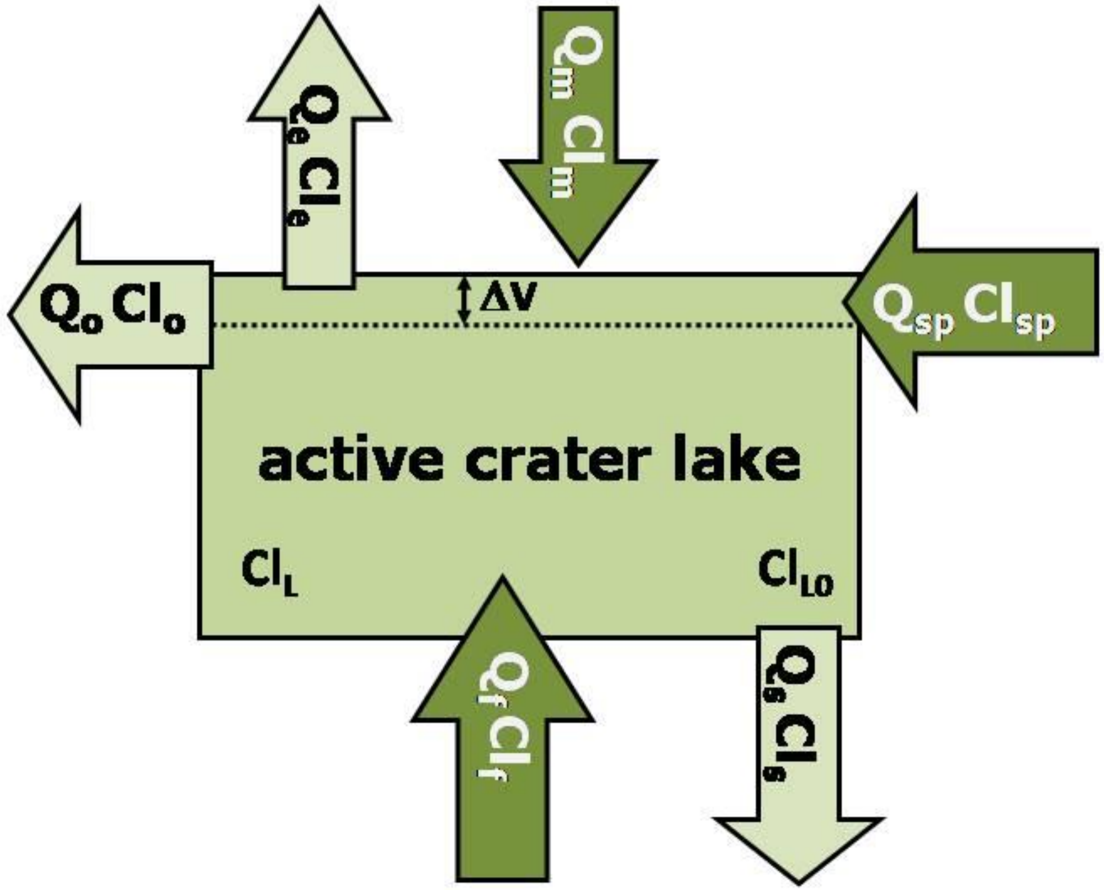
- The seepage loss (Q_s) through the crater lake floor may (to solve the equation, must) be only estimated semi-quantitatively on the basis of hydrogeochemical models

Chemical badget

- Multiplying each term in the mass budget with the corresponding concentrations of a conservative chemical species (Cl), we obtain the chemical budget equation:

$V_L\ Cl_L – V_{L0}\ Cl_{L0} = Q_f\ Cl_f\ Dt + Q_m\ Cl_m\ Dt + Q_{sp}\ Cl_{sp}\ Dt – Q_e\ Cl_e\ Dt – Q_s\ Cl_s\ Dt – Q_o\ Cl_o\ Dt$

Chemical budget

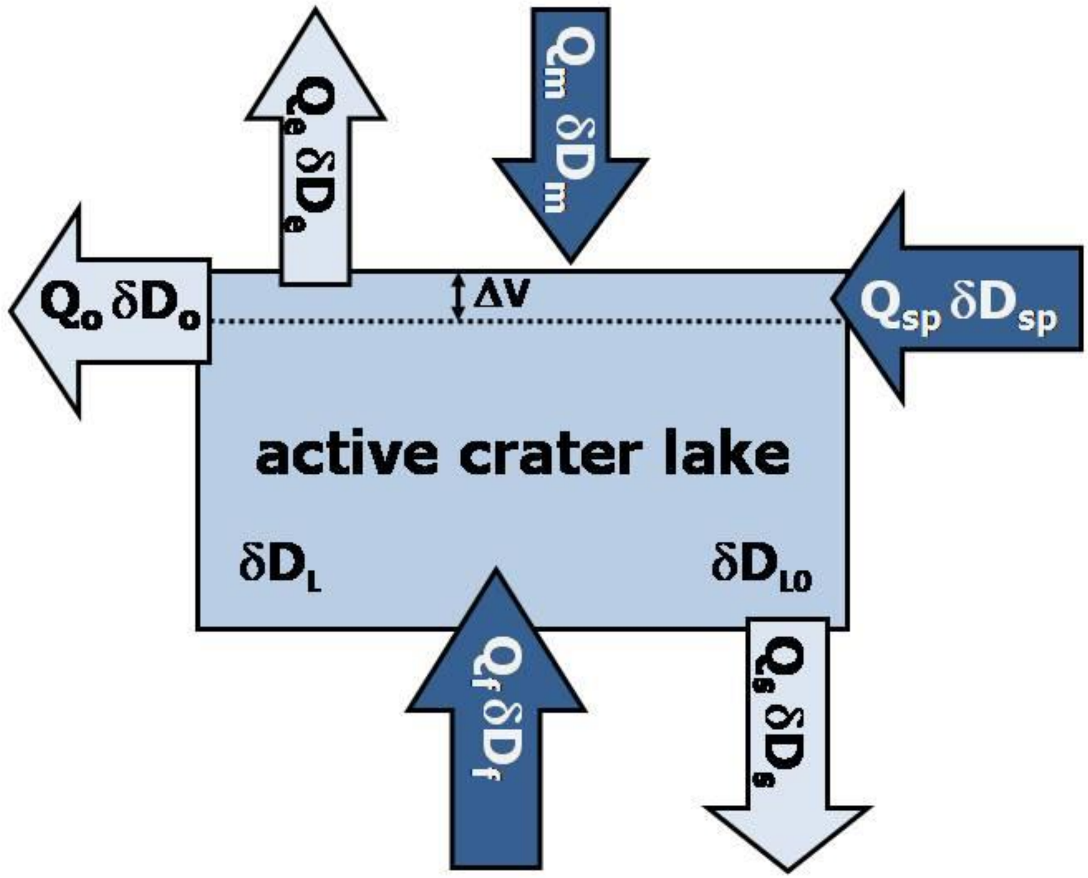


Isotope badget

- Multiplying each term in the mass budget with the corresponding values of the water isotopic composition (δD or $\delta^{18}O$), we obtain the isotope budget equation:

$$V_L\,\delta D_L - V_{L0}\,\delta D_{L0} = Q_f\,\delta D_f\,Dt + Q_m\,\delta D_m\,Dt + Q_{sp}\,\delta D_{sp}\,Dt - Q_e\,\delta D_e\,Dt - Q_s\,\delta D_s\,Dt - Q_o\,\delta D_o\,Dt$$

Isotope budget

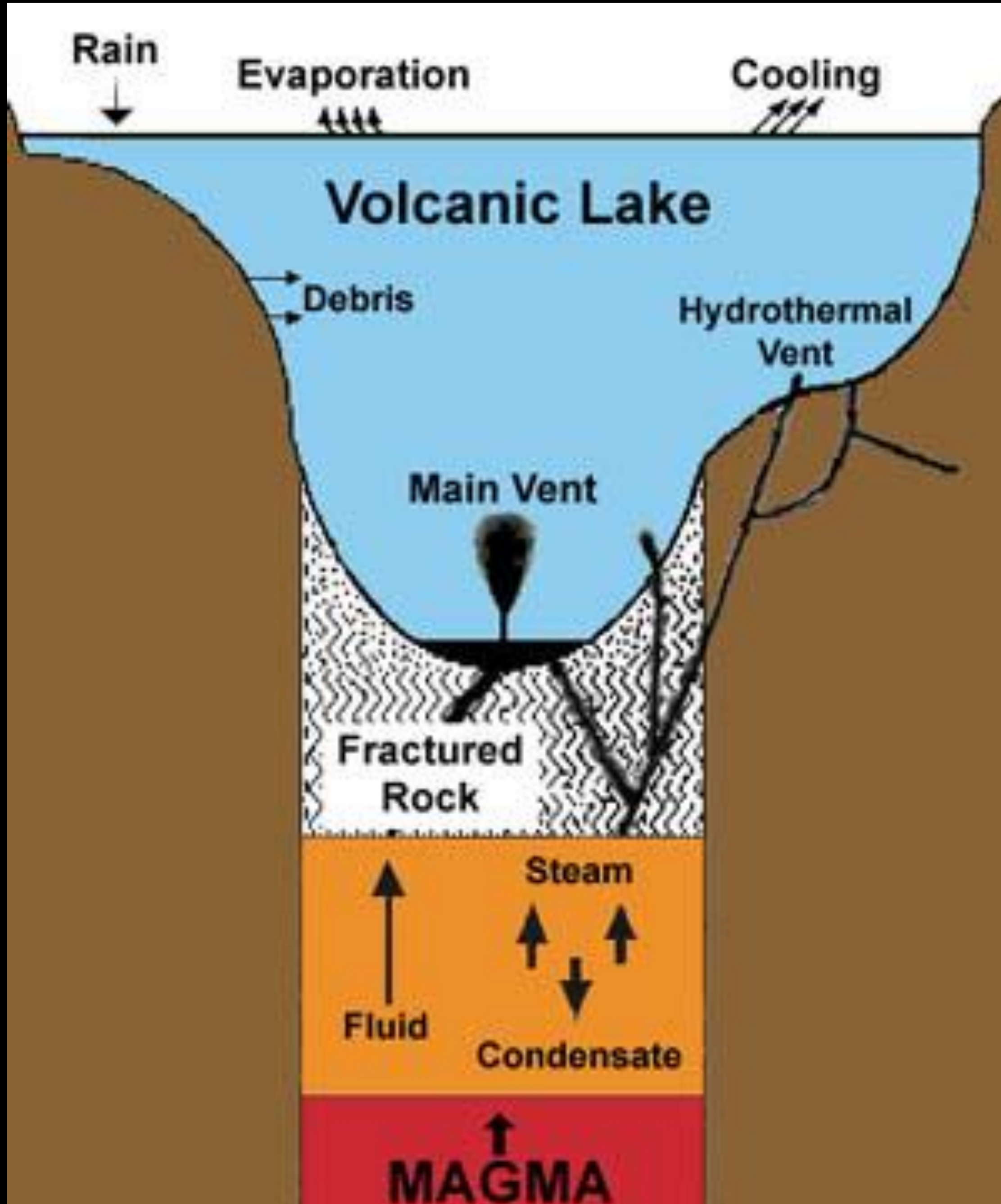


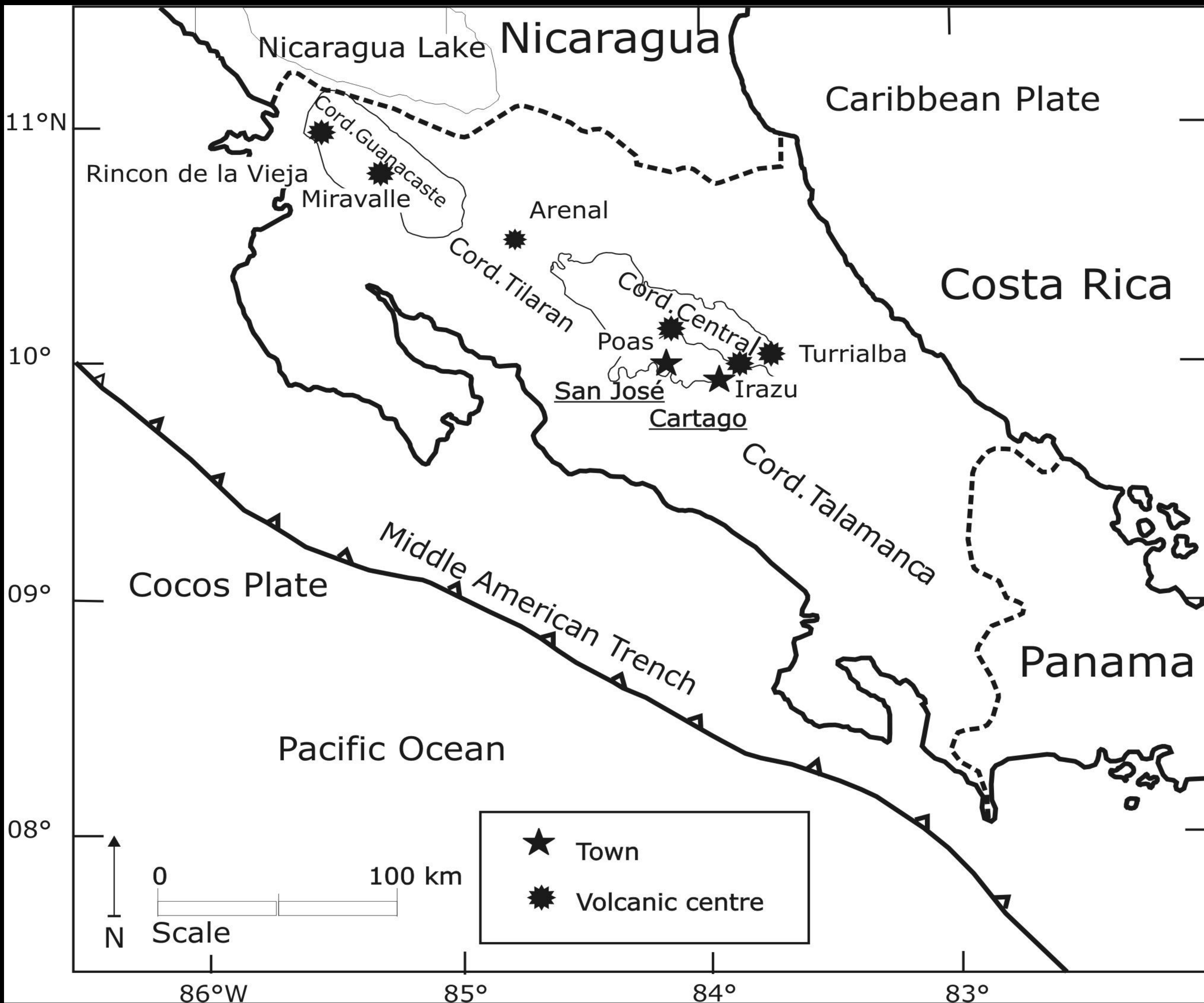
Aims ?

By quantification of the non-volcanic factors affecting the physical-chemical state of the active crater lake, the box model allows to calculate the volcanic input flux (Q_f), which cannot be directly measured.

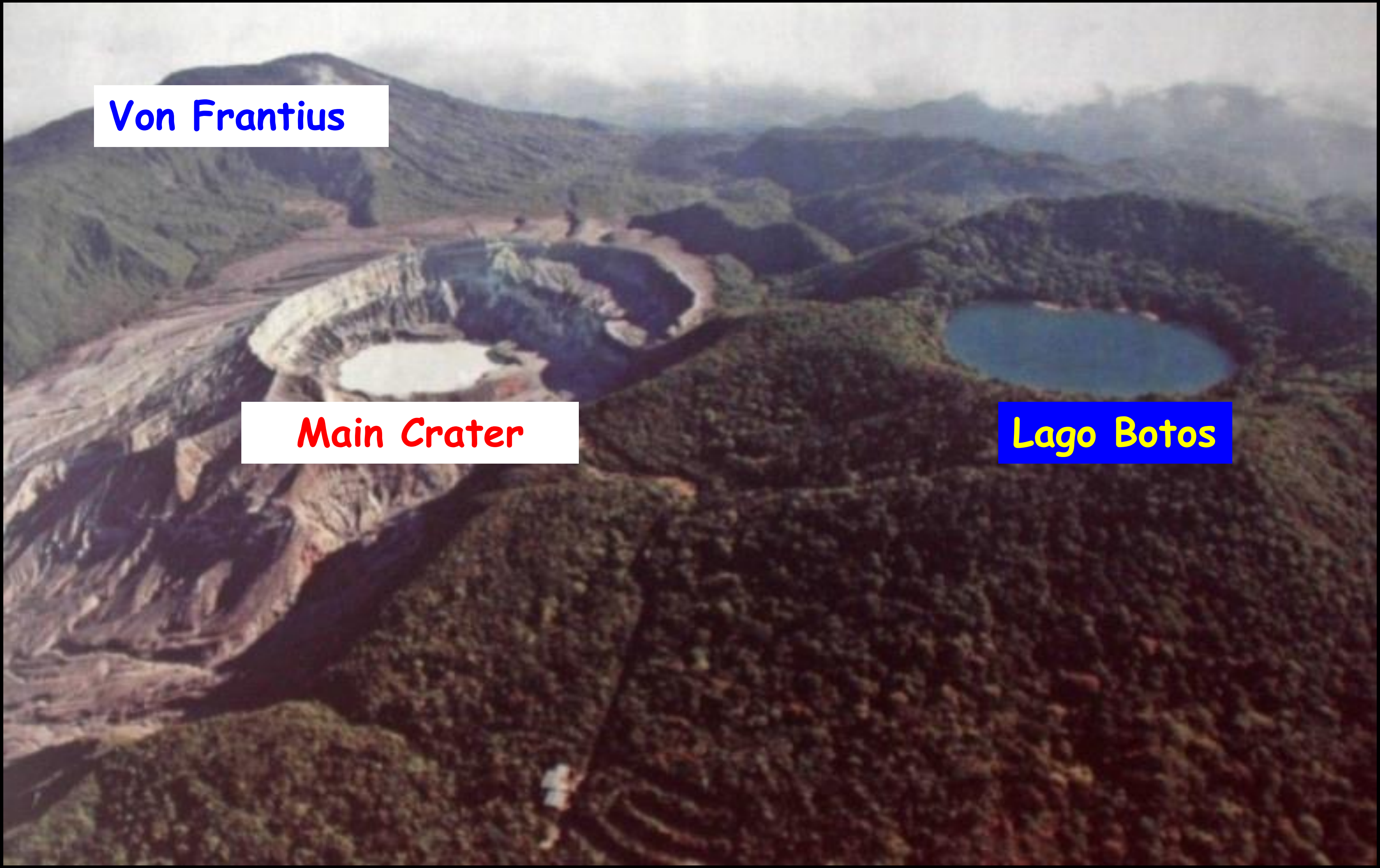
Variation in volcanic fluid inputs may be related to changes of….volcanic activity.

ACIDIC LAKES


Rain
Evaporation
Cooling
Volcanic Lake
Debris
Hydrothermal Vent
Main Vent
Fractured Rock
Steam
Fluid
Condensate
MAGMA

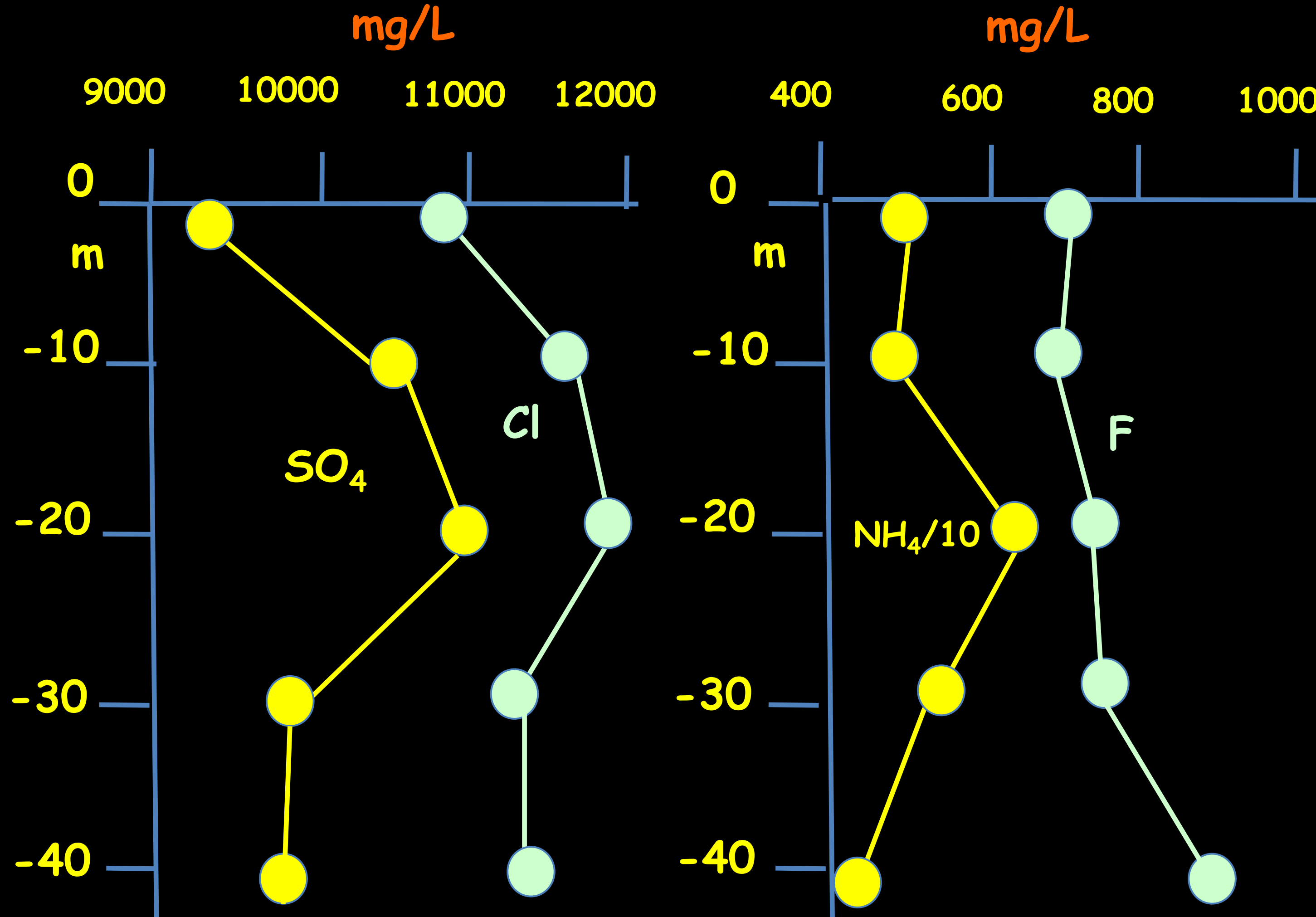


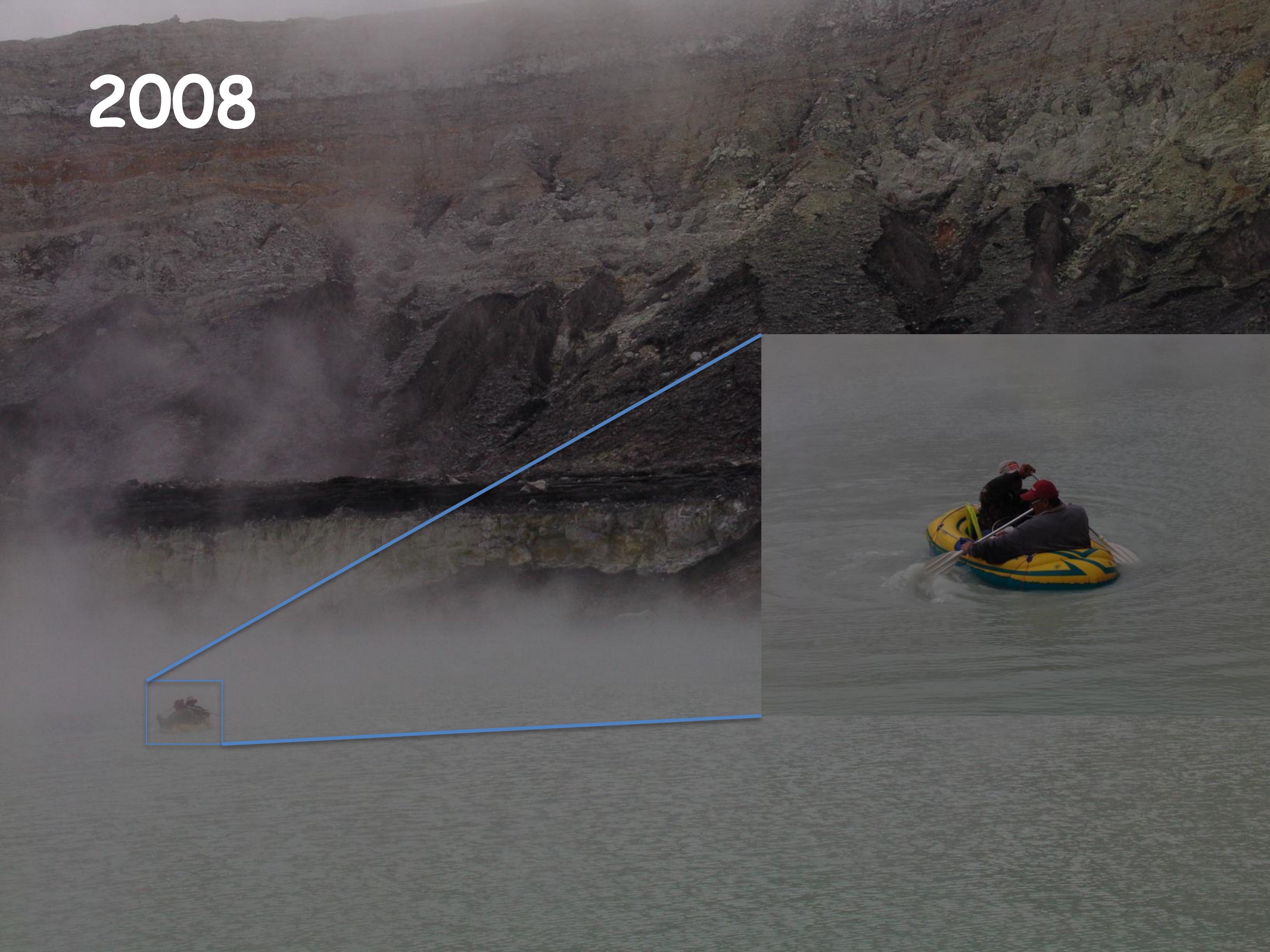
Nicaragua
Nicaragua Lake
Caribbean Plate
11°N
Cord.Guanacaste
Rincon de la Vieja
Miravalle
Arenal
Cord.Tilaran
Costa Rica
Cord.Central
Poas
Turrialba
10°
San José
Irazu
Cartago
Cord.Talamanca
Middle American Trench
09°
Cocos Plate
Panama
Pacific Ocean
08°
0
100 km
N
Scale
Town
Volcanic centre
86°W
85°
84°
83°



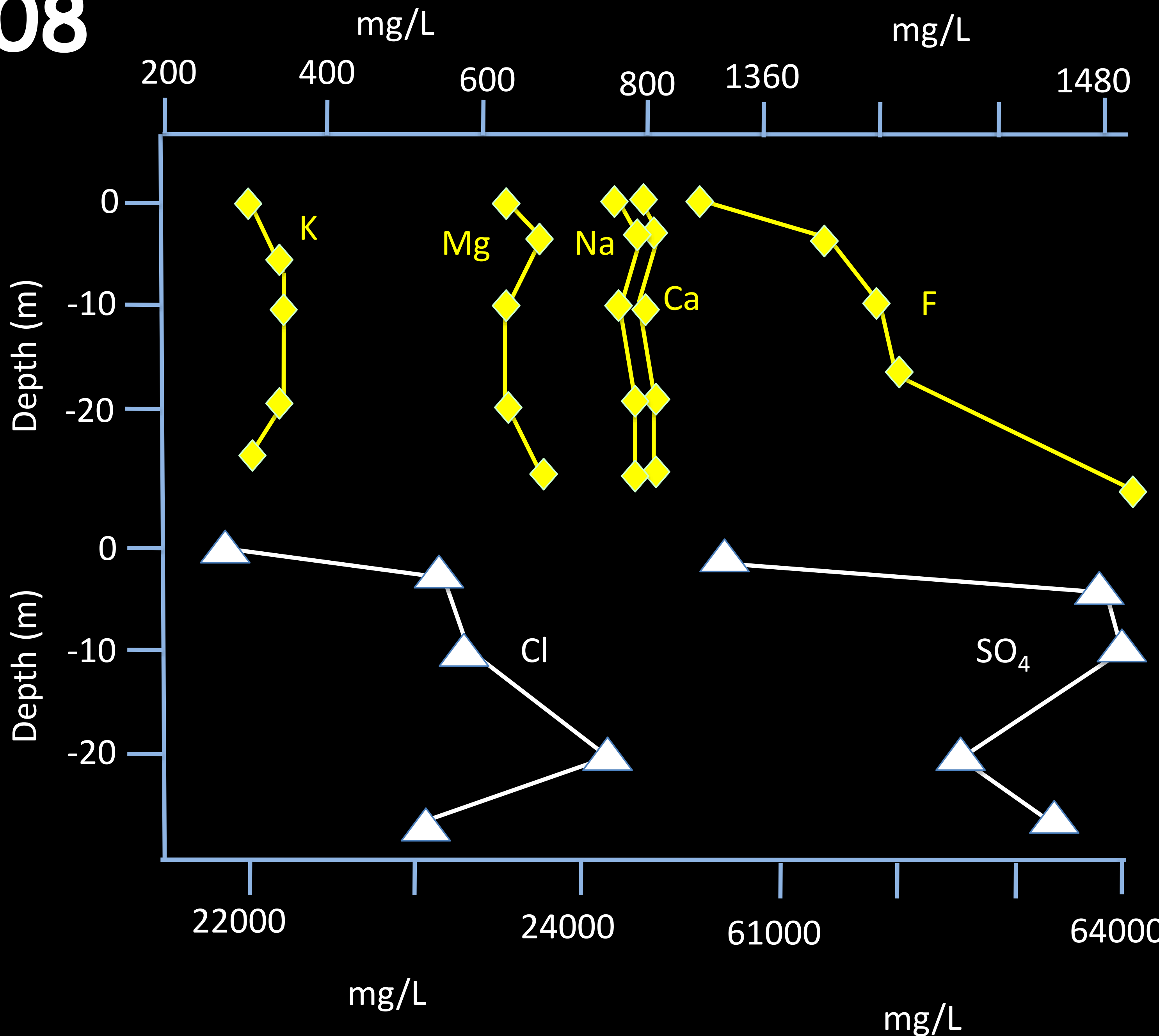
The basaltic-to-dacitic active volcano of Poas (2708 m a.s.l.) is characterized by three roughly N-S oriented craters: Von Frantius, Botos (hosting a cold lake) and Laguna Caliente

2001 - 2.4x10^6 m^3

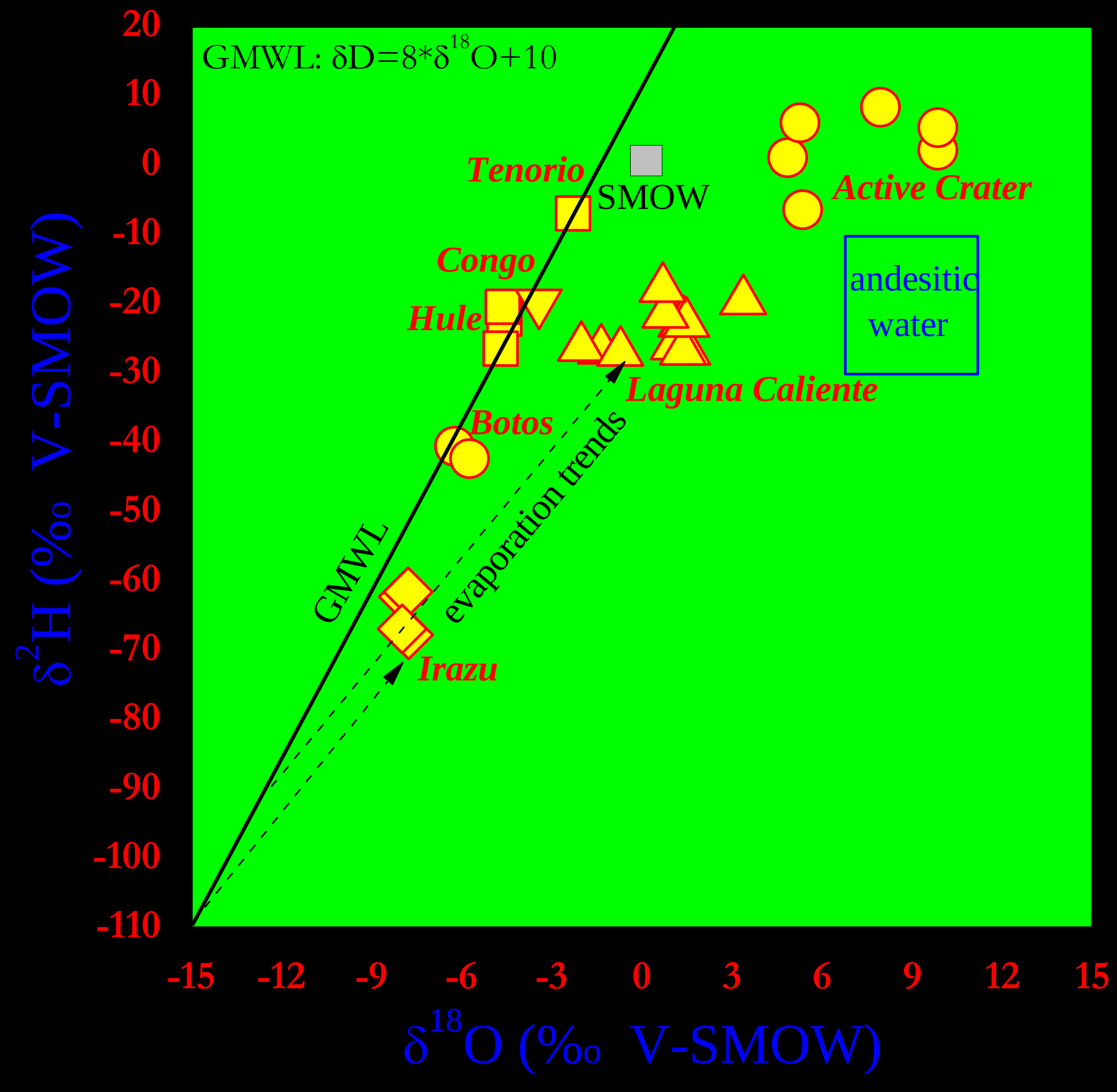



2008

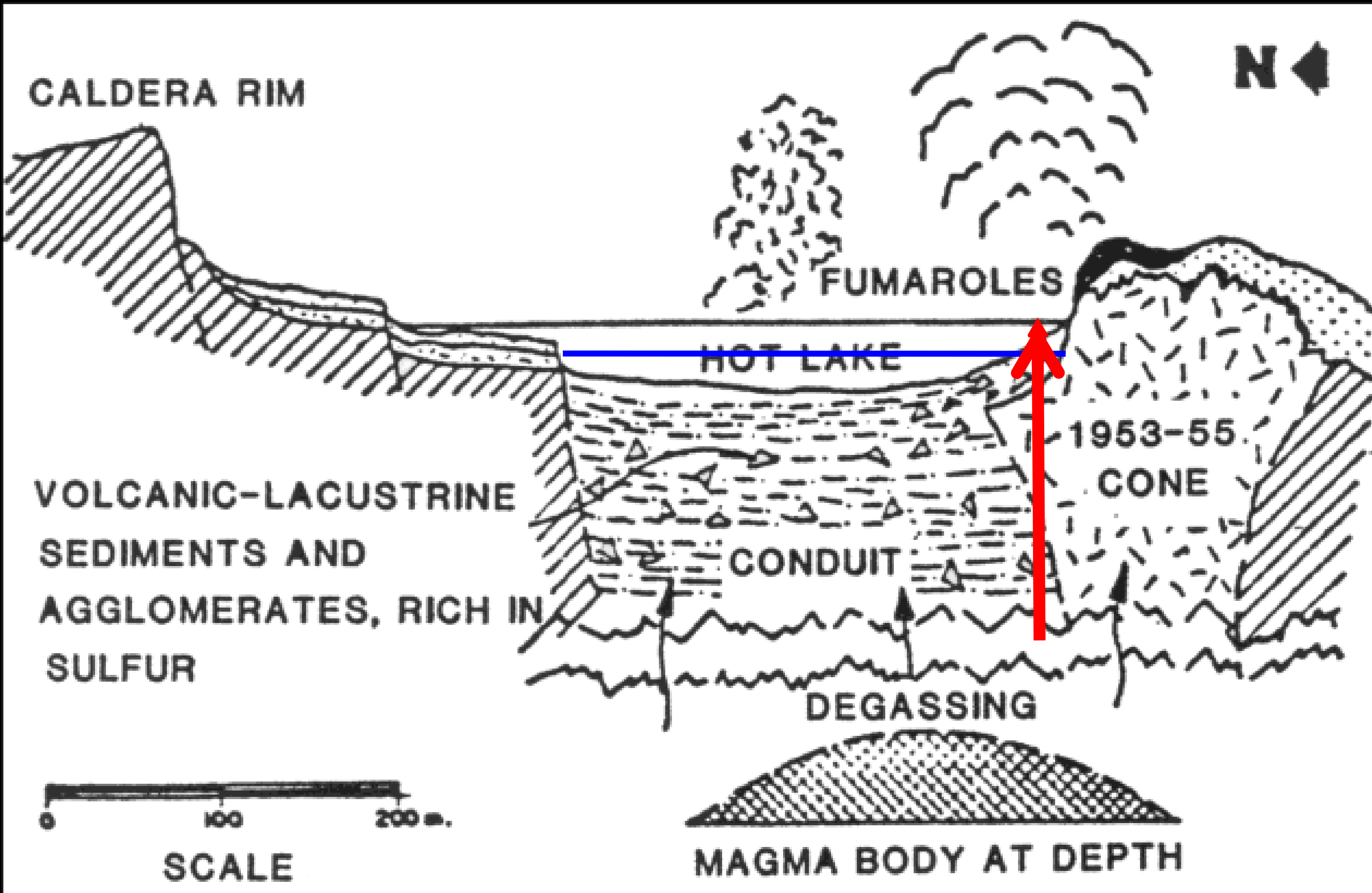
2008



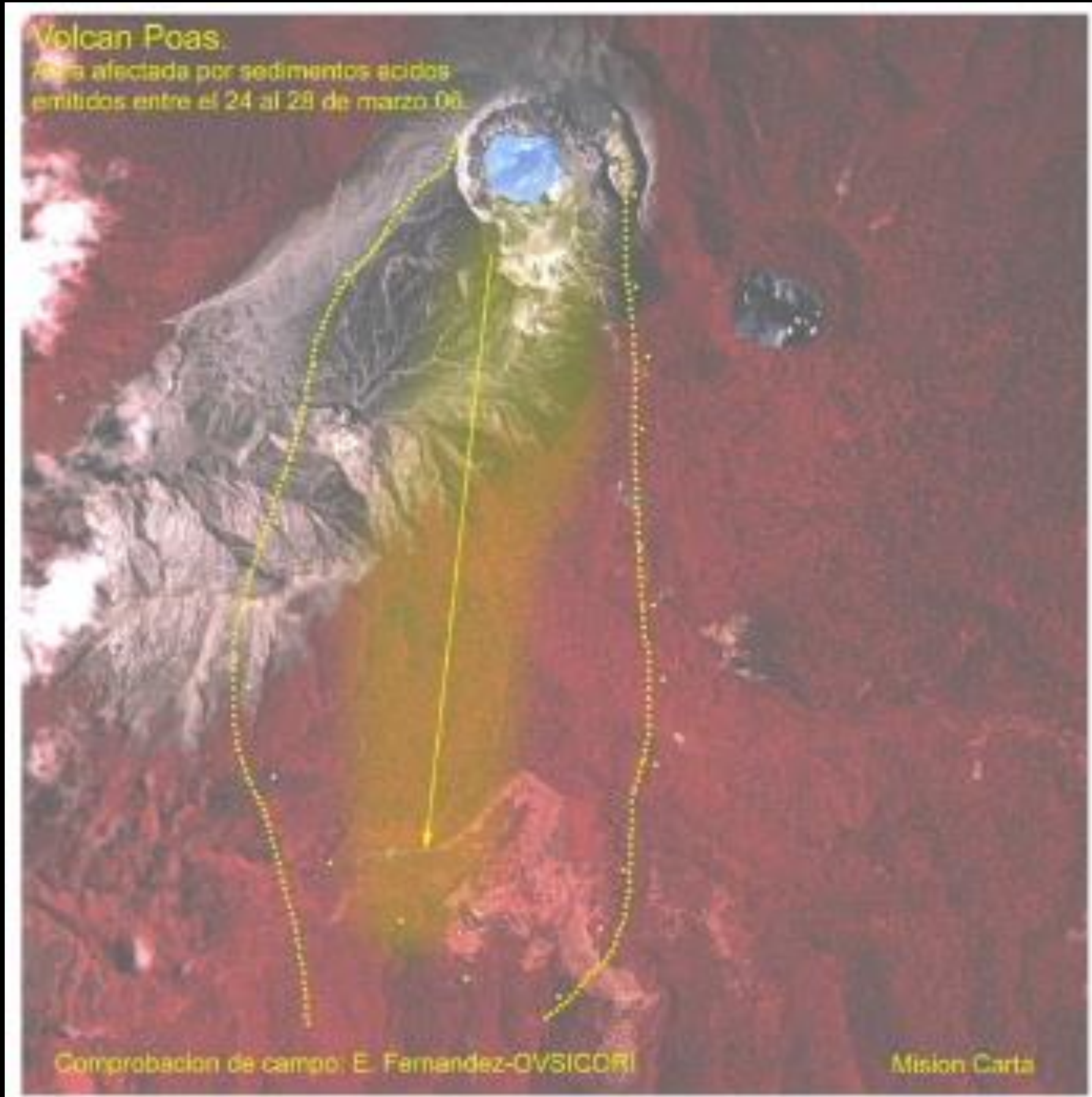
mg/L
200
400
600
800
1360
mg/L
1480
0
-10
-20
Depth (m)
K
Mg
Na
Ca
F
0
-10
-20
Depth (m)
Cl
SO4
22000
24000
61000
64000
mg/L
mg/L



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)

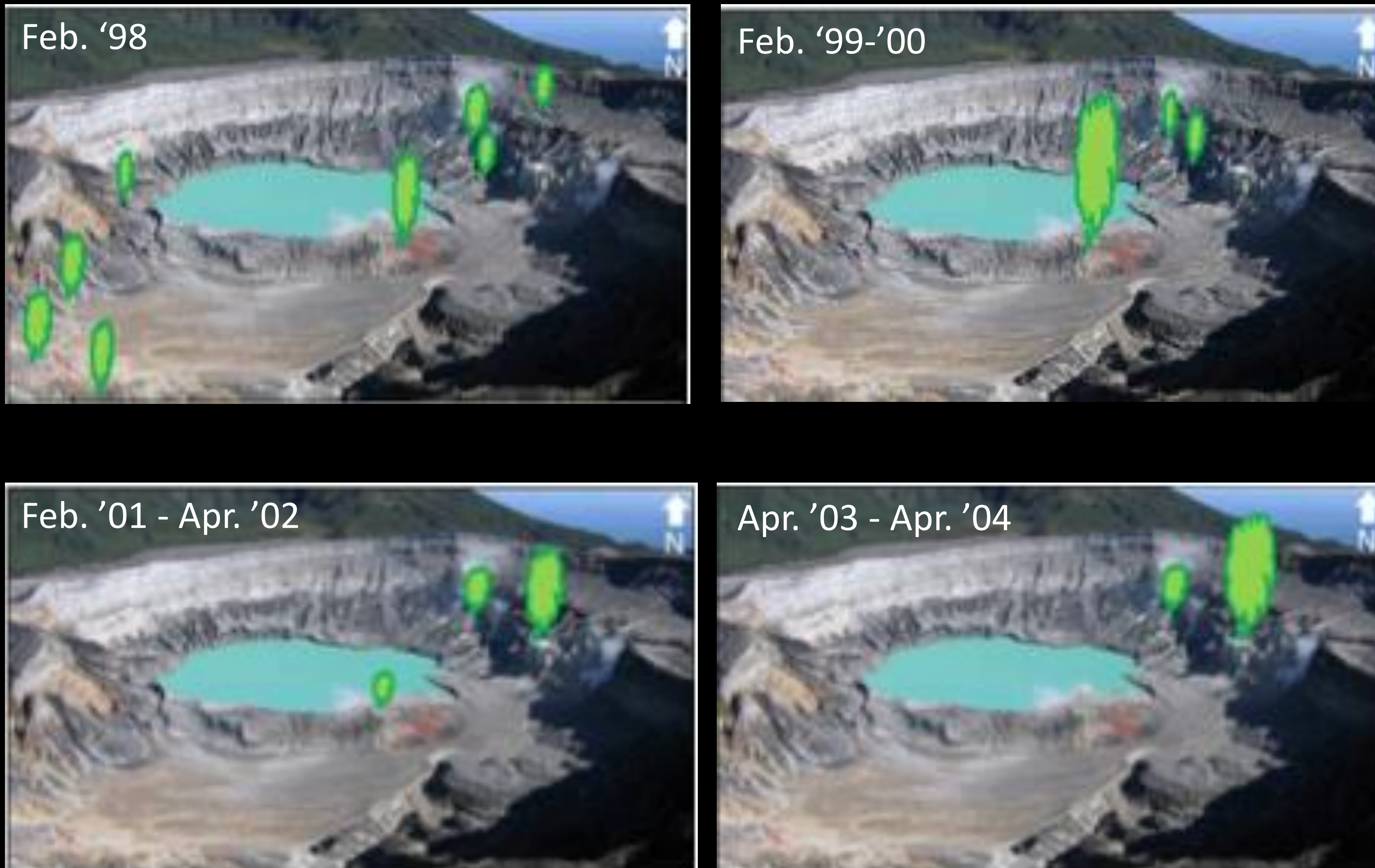


CALDERA RIM
N
FUMAROLES
HOT LAKE
1953-55
CONE
VOLCANIC-LACUSTRINE
SEDIMENTS AND
AGGLOMERATES, RICH IN
SULFUR
CONDUIT
DEGASSING
0
100
200 m.
SCALE
MAGMA BODY AT DEPTH


Volcan Poas.
afectada por sedimentos acidos
emitidos entre el 24 al 28 de marzo 06.
Comprobacion de campo: E. Fernandez-OVSICORI
Mision Carta


Poas volcano, Costa Rica
General view of east crater wall
destroyed by phreatic activity.
Pre-March 2006 lake rim


N
1
2
3
4
5
6


Feb. ‘98
N
Feb. ‘99-’00
N
Feb. ’01 - Apr. ’02
N
Apr. ’03 - Apr. ’04
N

Cinchona earthquake (Jan 2009)


25/12/2009 09:53

Nyos type lakes

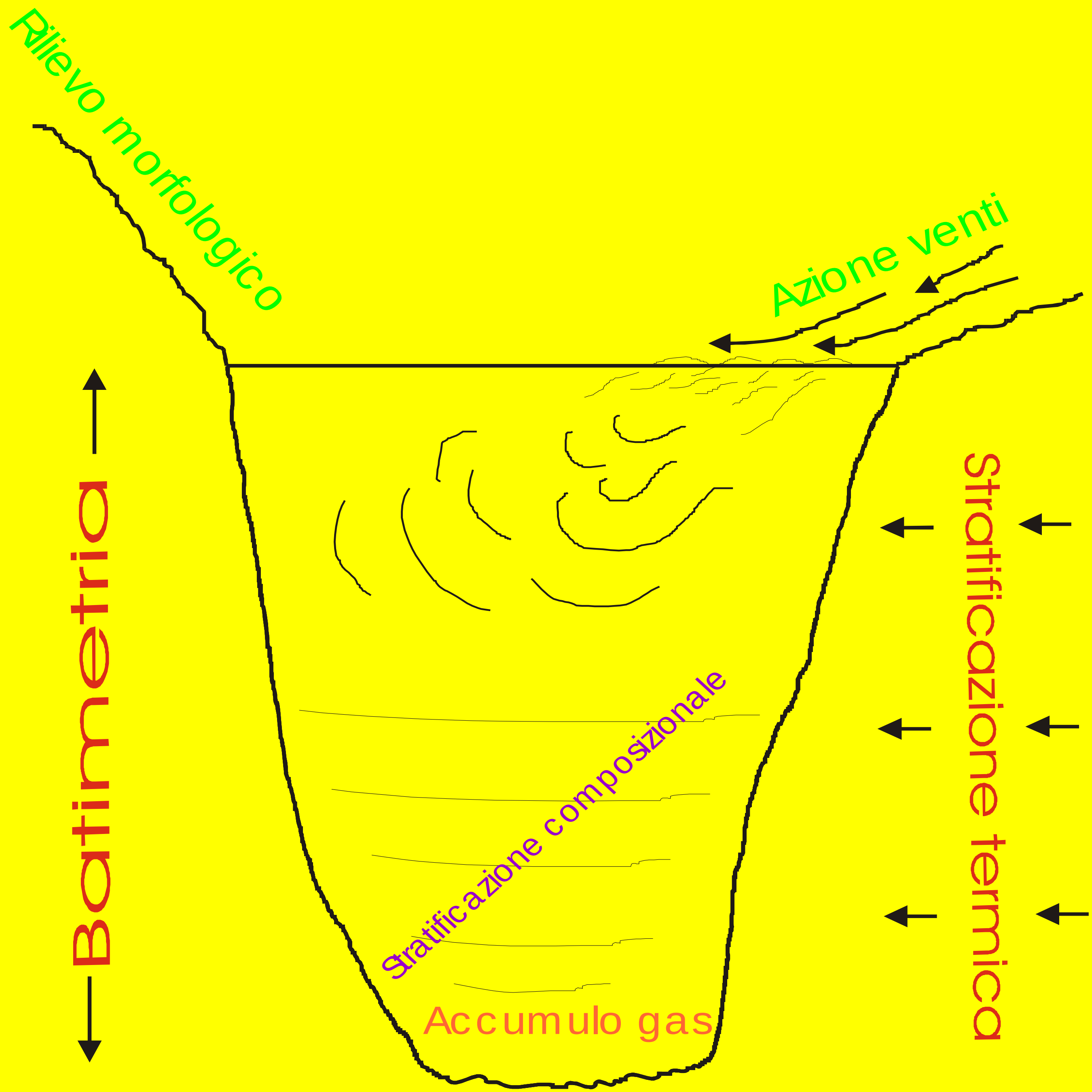
“Gas burst”

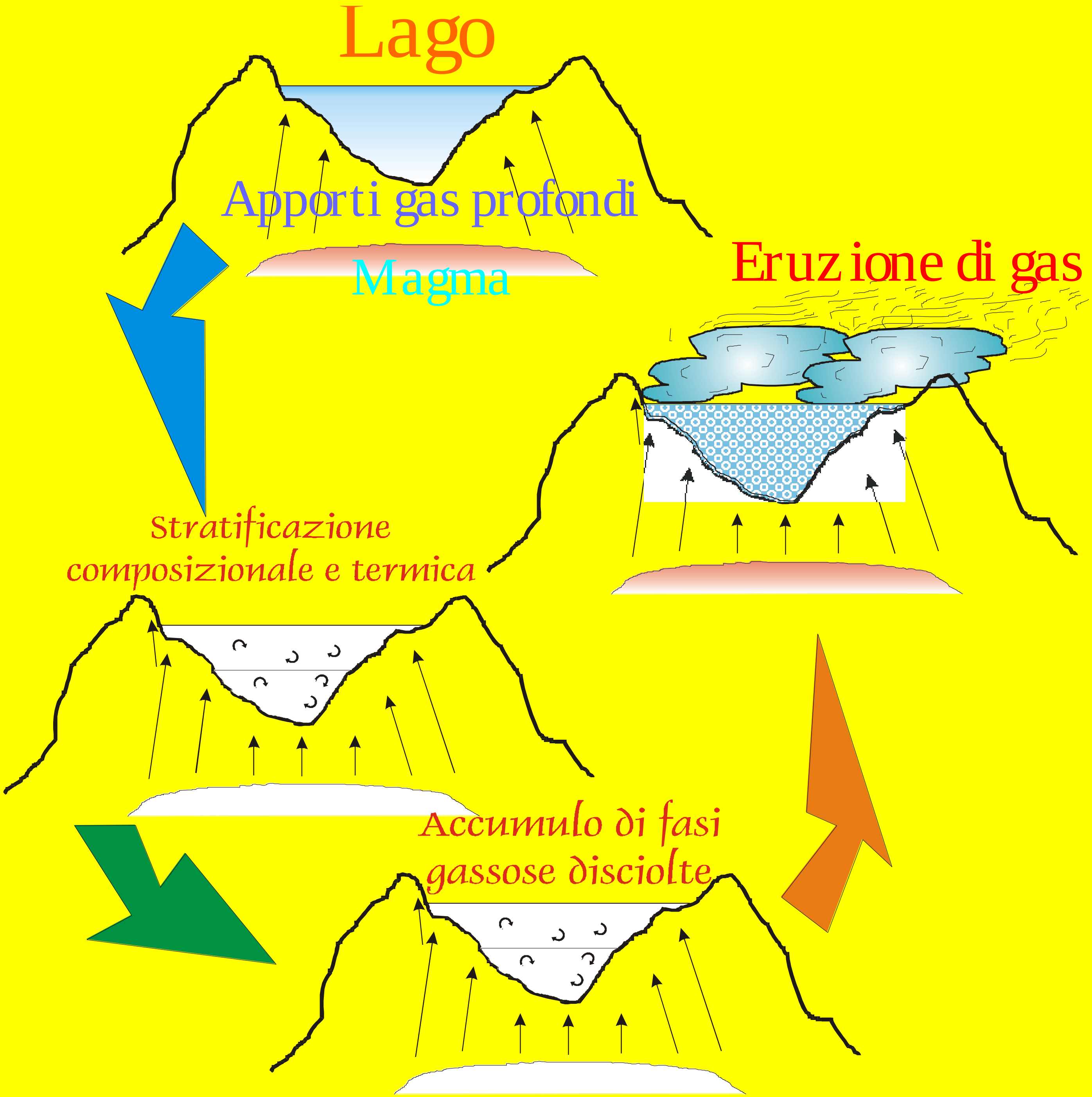
A phenomenon regulated by the balance between gas input and gas loss. A gas bursts may occur when recharge surpasses loss. Alternatively, the gas excess may be released through a controlled degassing, where the cycle of recharge-release is short-circuited.

Lethal CO_2-rich gas mass released from crater lake in volcanoes at hydrothermal stage

“CO_2 clouds” can run along several km without significantly mixing with air

The Nyos lethal wave


Rilievo morfologico
Azione venti
Batimetria
Stratificazione termica
Stratificazione composizionale
Accumulo gas


Lago
Apporti gas profondi
Magma
Eruzione di gas
Stratificazione composizionale e termica
Accumulo di fasi gassose disciolte

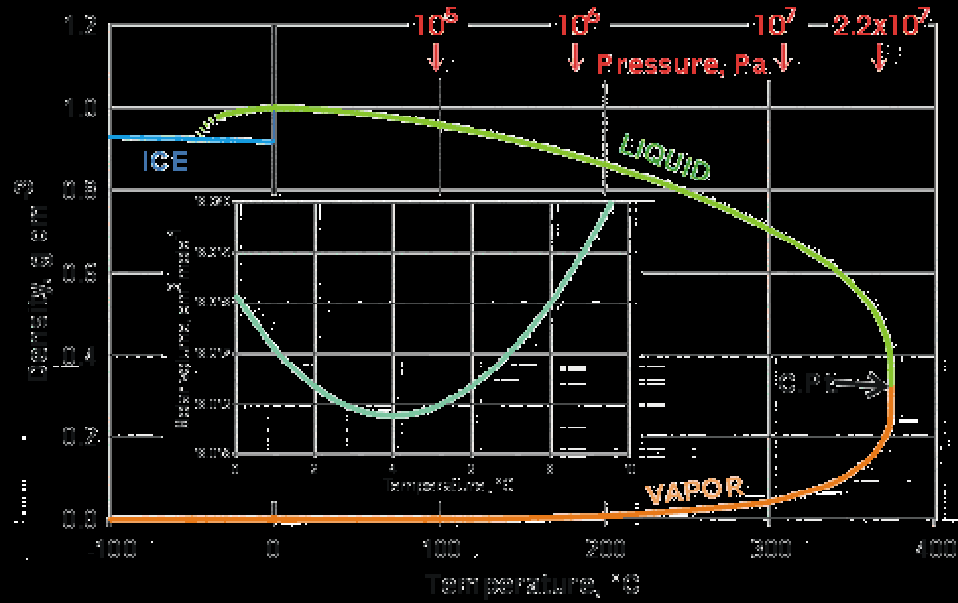
How to study (and monitor) Nyos-type lakes ?

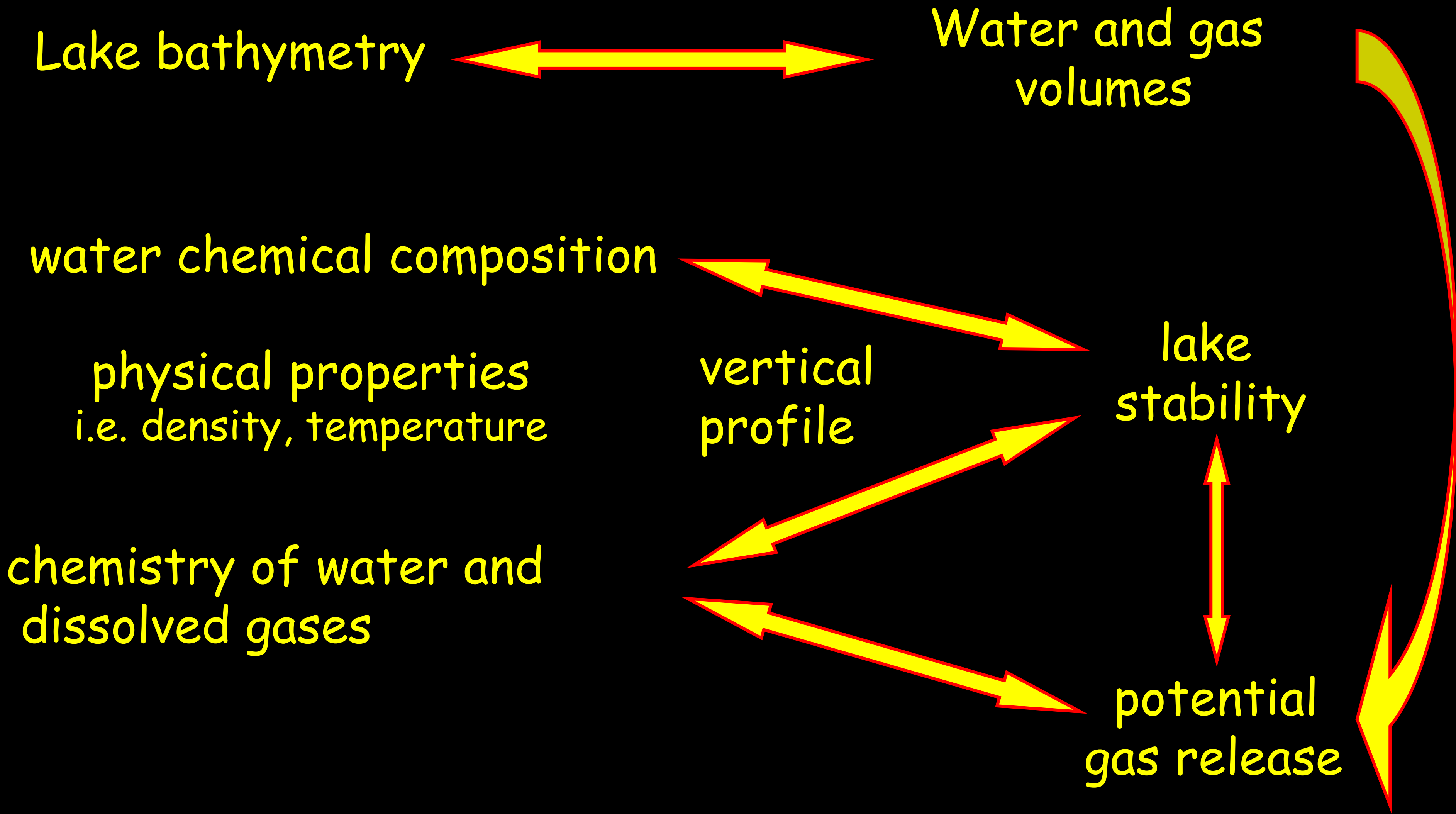
- Assessment of thermal and chemical stratification: the density gradient

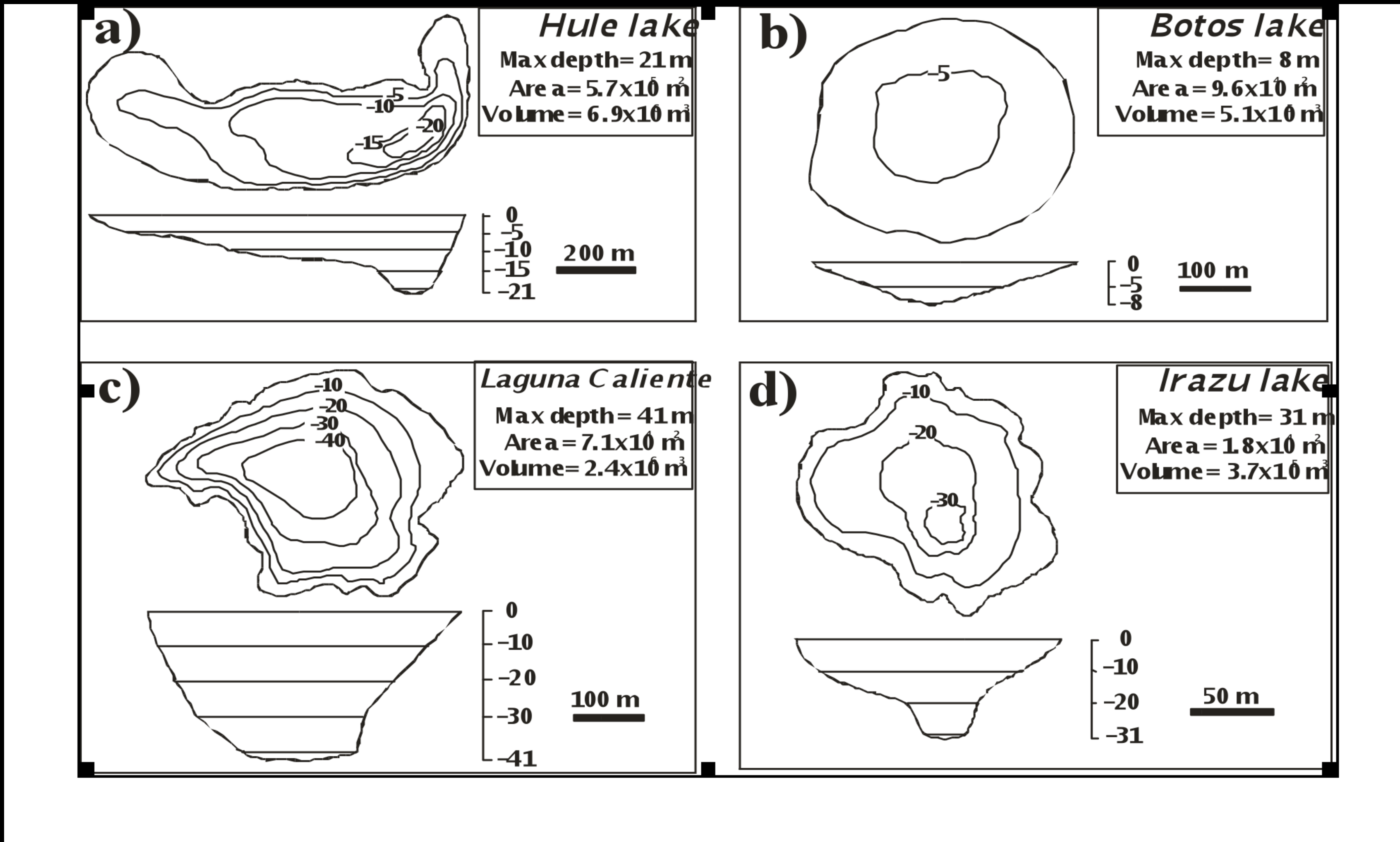
The density gradient is the main parameter controllin lake stability. It depends on temperature and composition vertical profiles, as well as the distribution of dissolved gases

Temperature-Density

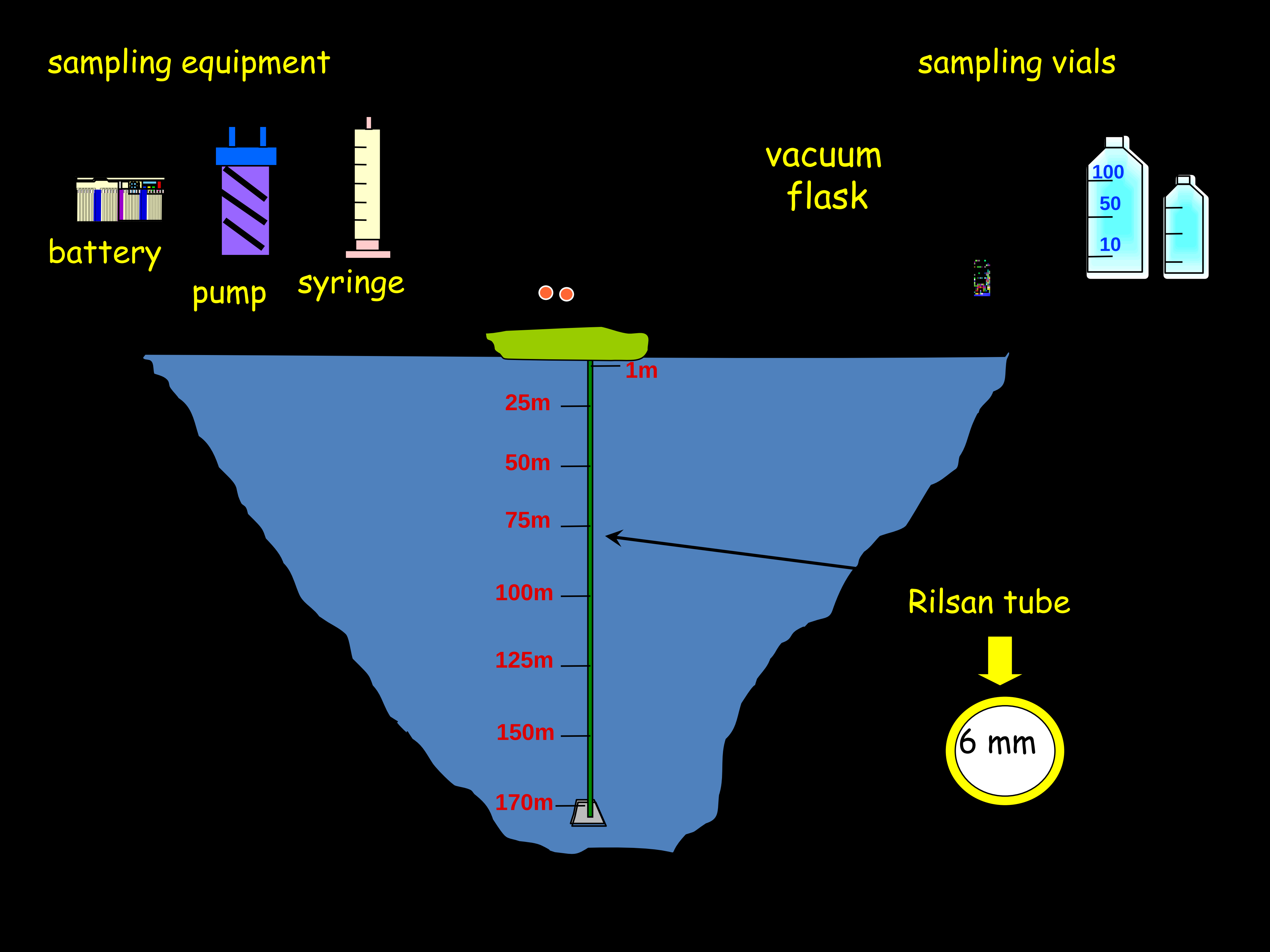
- Non-linear
- Maximum density at 4°C
- Lower density at higher and lower temperatures
- Hydrogen bonding and molecular movement




Lake bathymetry
Water and gas volumes
water chemical composition
physical properties
i.e. density, temperature
vertical profile
lake stability
chemistry of water and dissolved gases
potential gas release

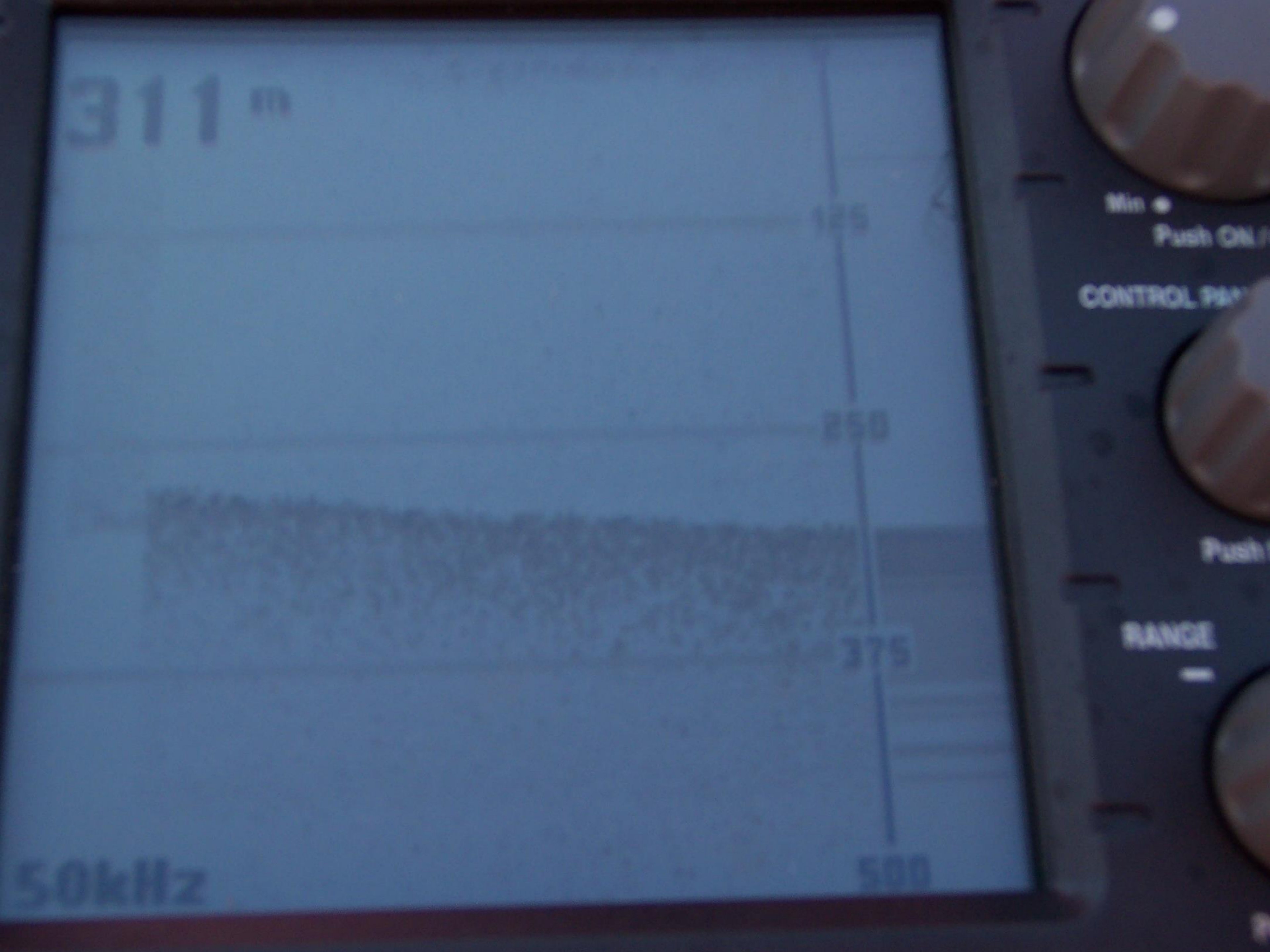


Depth-ratio: rapporto fra la profondità media e quella massima.


sampling equipment
sampling vials
battery
pump
syringe
vacuum
flask
100
50
10
1m
25m
50m
75m
100m
125m
150m
170m
Rilsan tube
6 mm


INCOE


YAMAHA
Enduro


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


MARCO

I laghi acidi o iperacidi sono generalmente ben mescolati a causa dei fluidi che risalgono dal profondo e non presentano stratificazioni chimiche significative. Generalmente, la loro pericolosità è associata all'attività vulcanica più che al lago stesso.

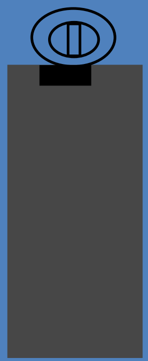
Di ben altra natura sono quei laghi che tendono ad accumulare CO_2 in profondità. Essi sono potenzialmente in grado di produrre delle emissioni gassose (CO_2-clouds) che possono "straripare" dagli argini (bordi craterici) e diffondersi nei bassi topografici!

PERCHE'?

Metano

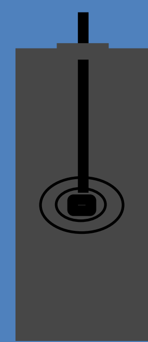
(+ leggero dell'aria)

Sensori ubicati in ambienti chiusi in funzione della densità del gas



Monossido di carbonio

(come l'aria)



H_2S e CO_2

(+ pesante dell'aria)

Densità dei gas g/mL

Idrogeno	0.000089
Elio	0.000180
Aria	0.001280
CO_2	**0.001977**
CO	0.001250
H_2S	0.001450
H_2O	1.00

I fenomeni di "Gas burst"

L'evoluzione chimica dei laghi con acque ricche in CO_2 può incrementare la loro natura letale. Essa è regolata dal bilancio fra l'input e l'output di gas. Un'emissione gassosa può avvenire quando la ricarica sorpassa la perdita. Alternativamente, l'eccesso di gas può essere emesso attraverso un degassamento controllato, dove il ciclo carica/rilascio è cortocircuitato.

Masse gassose ricche in CO_2 rilasciate da laghi craterici in vulcani allo stadio idrotermale

"CO_2 clouds" possono muoversi per vari km senza mescolarsi significativamente con l'aria

When does a limnic eruption occur?

Pre-requisite: Presence of a gas reservoir

"external" destabilizing phenomenon

and/or

Gas tot pressure (Σpressure igas) > hydrostatic pressure

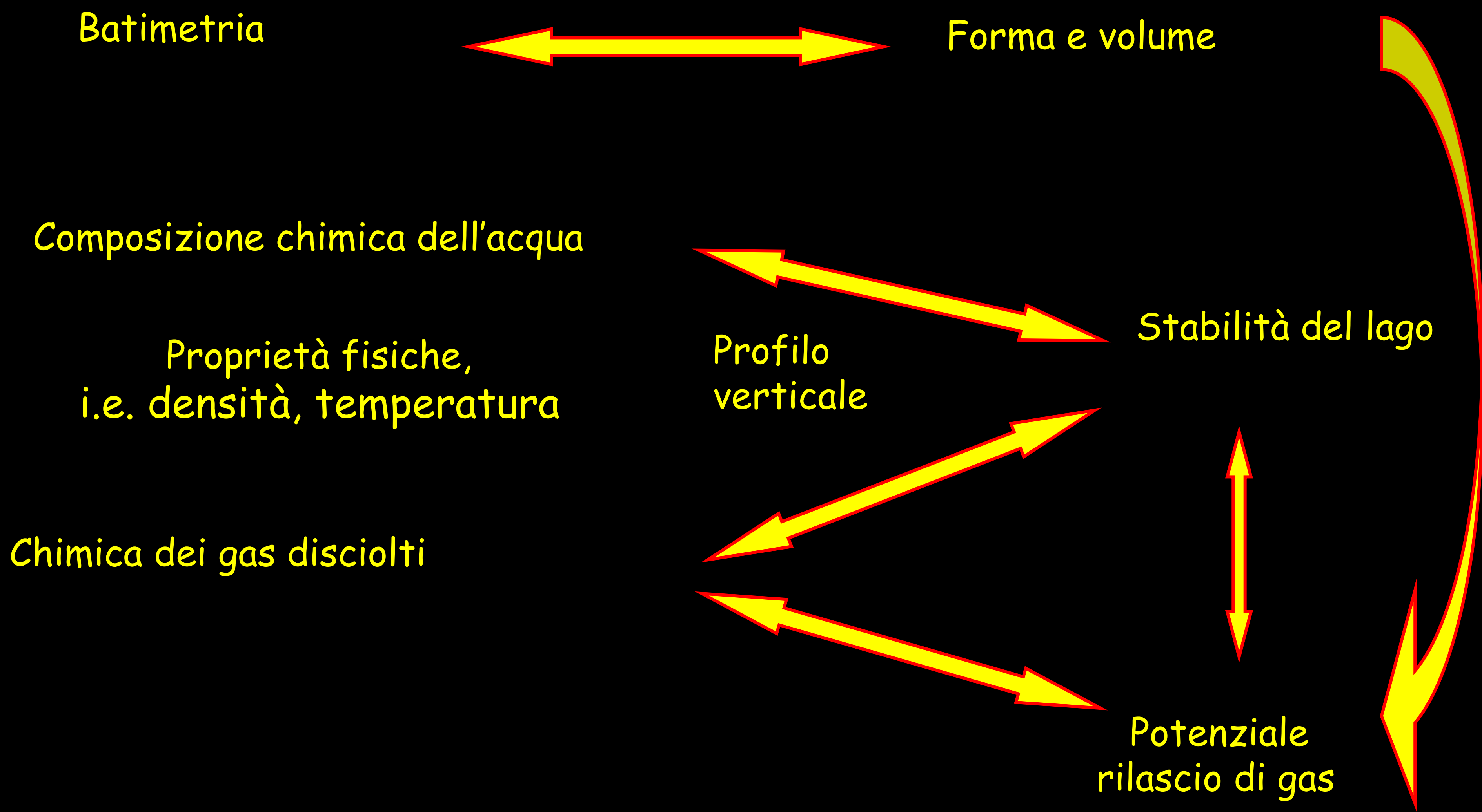
Gas exolution from deep (?) lake strata

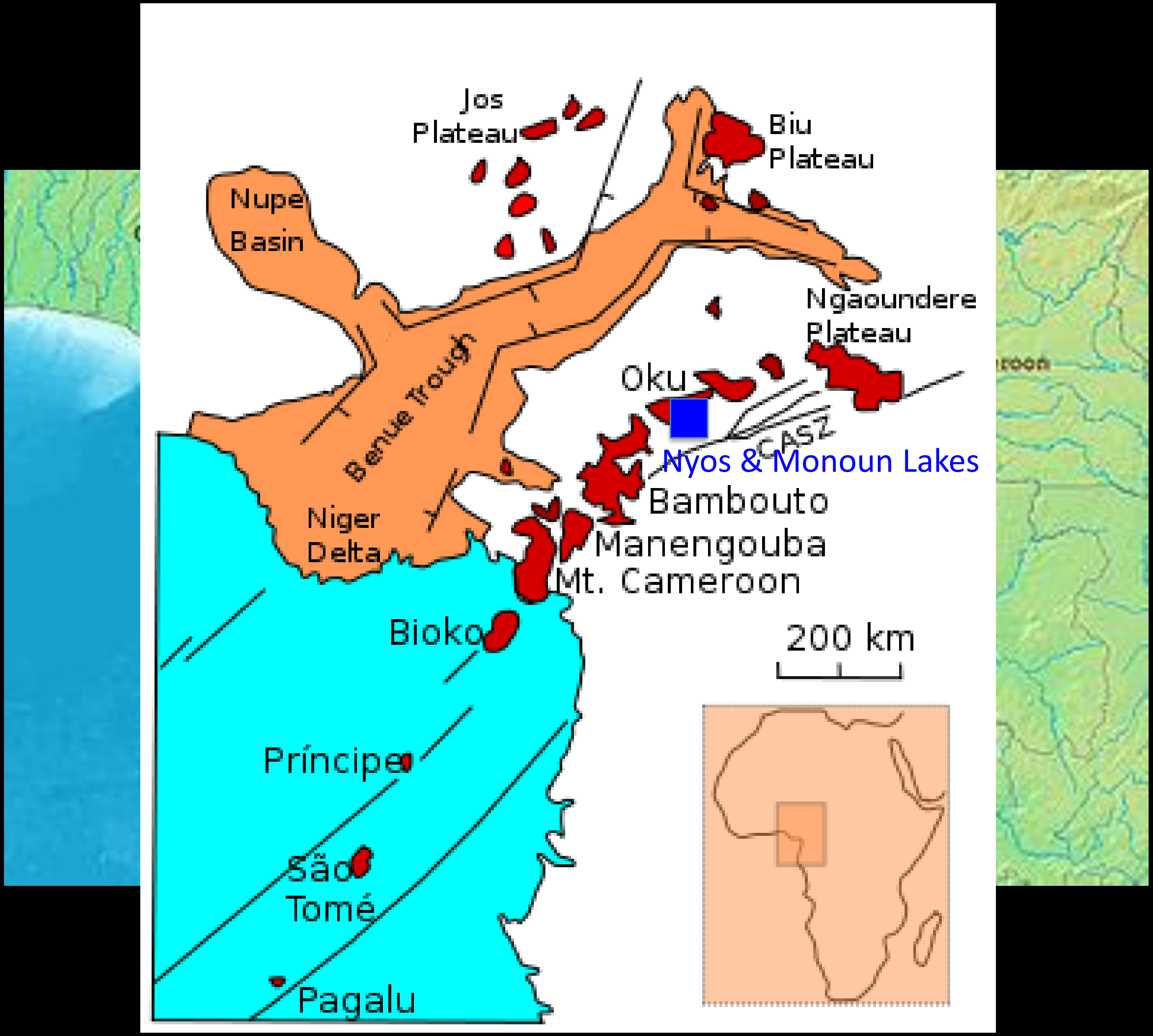
Lake stability mainly depends on the distribution of the density gradient along the vertical profile controlling the resistance to turbulent mixing.

Water density mainly depends on:

- Water temperature
- Water salinity
- Dissolved gases

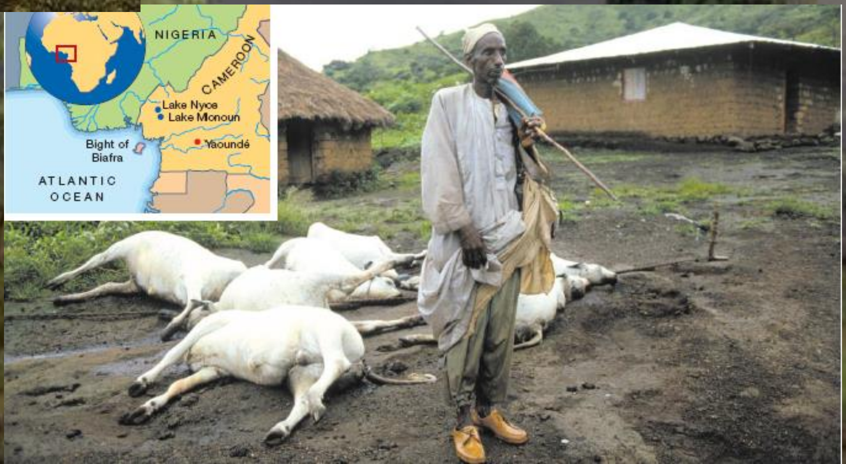
Per valutare il rischio da emissione gassosa




Jos
Plateau
Biu
Plateau
Nupe
Basin
Benue Trough
Ngaoundere
Plateau
Oku
CASZ
Nyos & Monoun Lakes
Bambouto
Manengouba
Mt. Cameroon
Niger
Delta
Bioko
200 km
Príncipe
São
Tomé
Pagalu

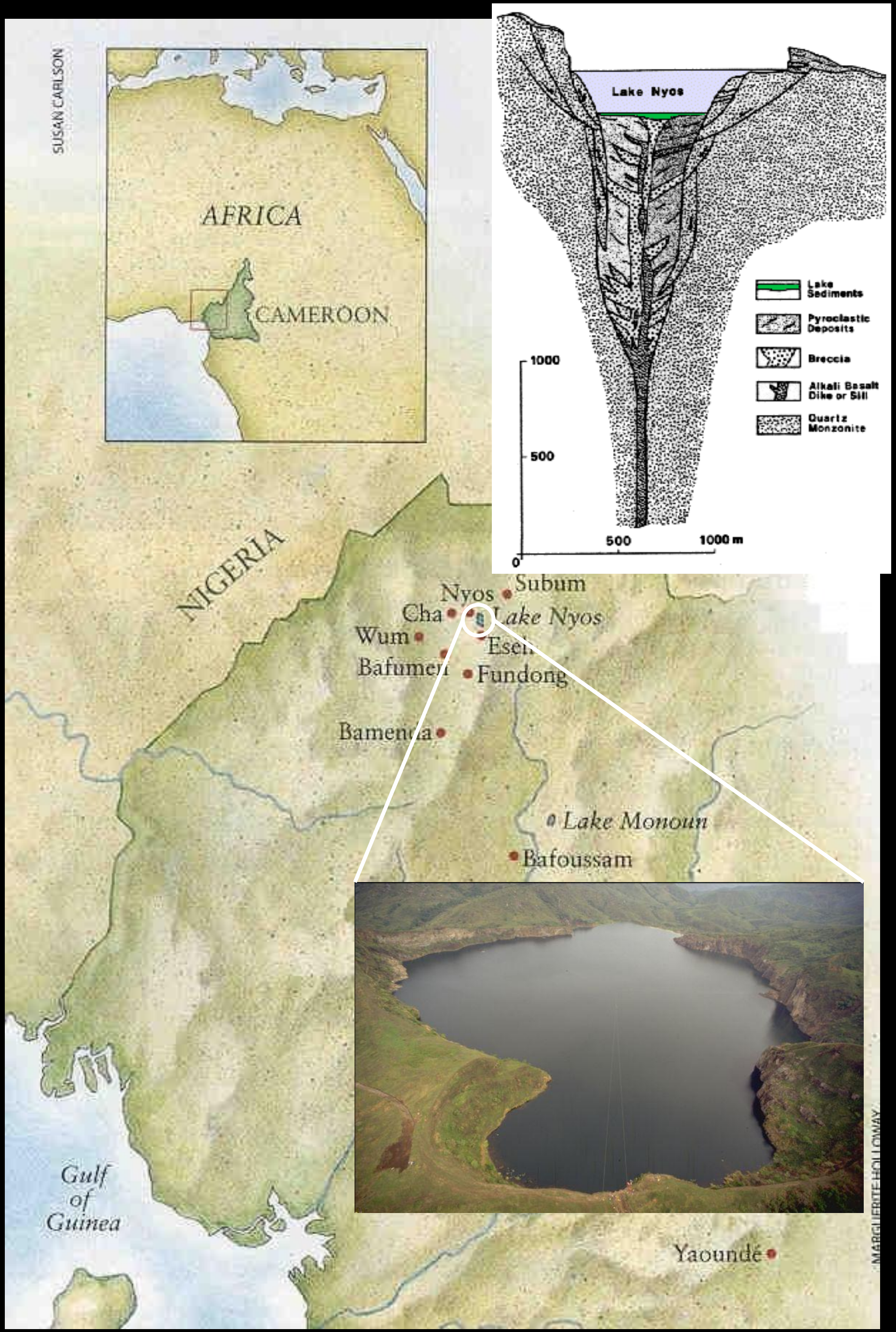
Lake Nyos (Camerun)
Il disastro del 1986

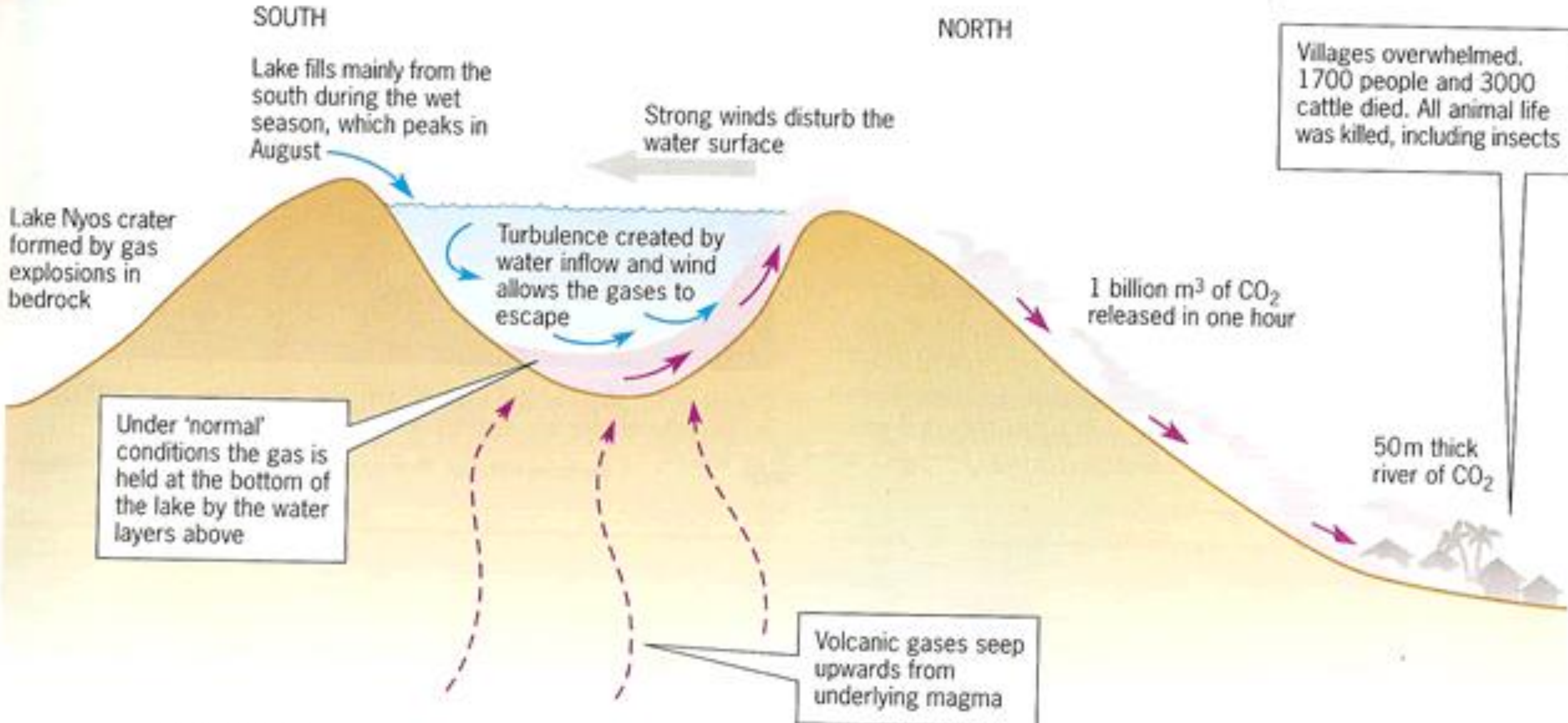
- ~1 km^3 di CO_2
- ~1800 morti assieme a migliaia di capi di bestiame.
- Cause = rapido ribaltamento degli strati profondi dell'acqua del lago
  - **Vulcanica o limnica?**



Info generali

- **Volcanic/Maar Crater Lake**
- **Formato ~400 ka**
- **Area lago = 1.58 km^2**
- **Max prof. = 210 m**
- **Chemioclino ≈50 m**
- **Volume = 179,400,000 m^3**
- **Piovosità = 2.5 m/yr**
- **Inflow**
  - **0-50 m: pioggia & torrenti**
  - **50-210 m: soda spring**
    - **Acque ricche in CO_2**
- **Outflow**
  - **Spillaggio naturale (troppo pieno)**

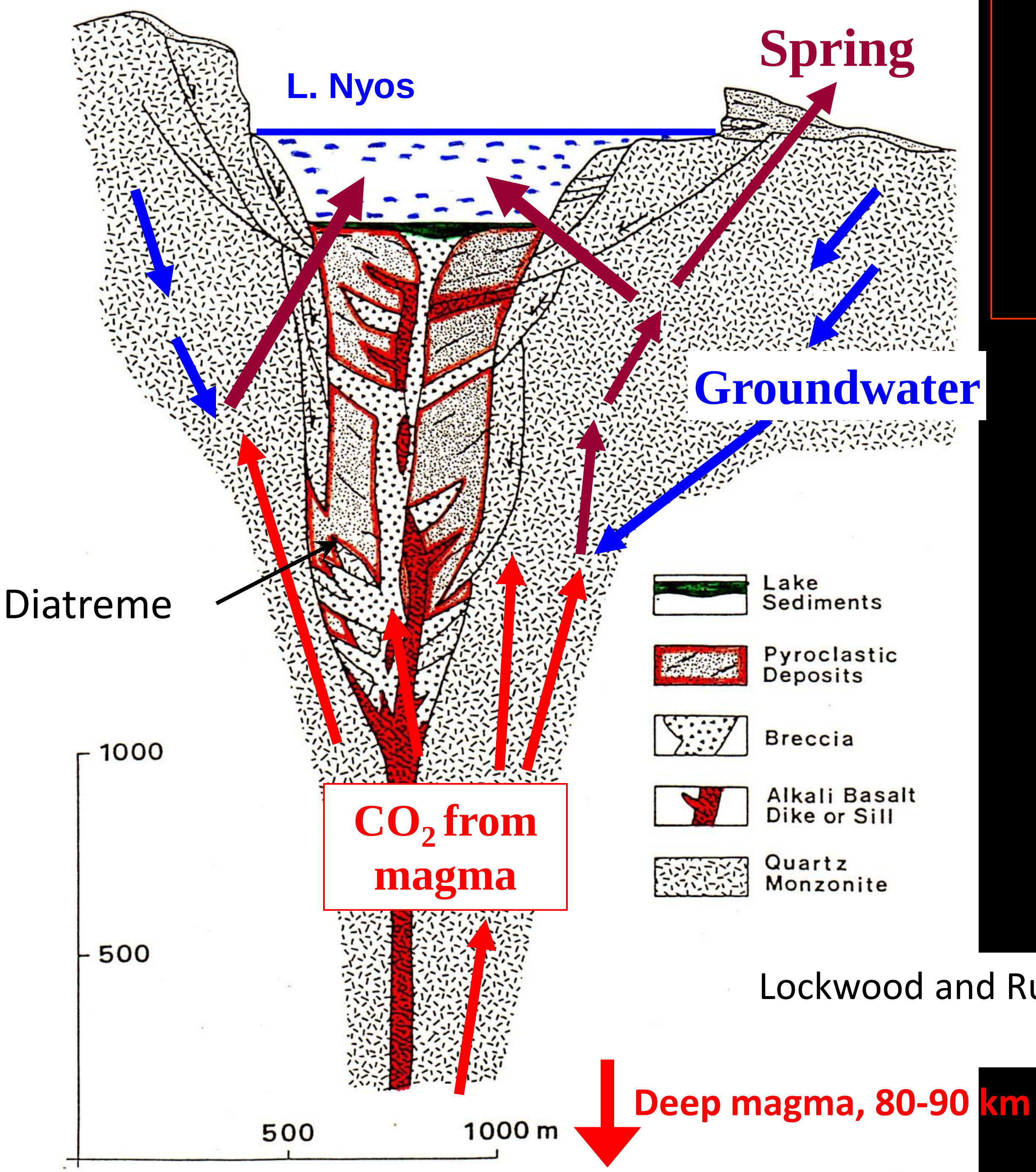




The Lake Nyos, Cameroon, disaster of 21 August 1986. The lake lies in an area of ancient volcanic activity associated with continental plate spreading in the past. This event could be repeated.


gas cloud path
Fungom
Fang
Subum
Lower Nyos
Cha
gas cloud path
Kam
Tsote
Upper Nyos
Lake Njupi
Lake Nyos
Kumbi
Bwabwa
La nube di gas
ha ucciso sino persone ed
animali sino a 26 km dal lago

Formazione di soda-spring ricche in CO_2



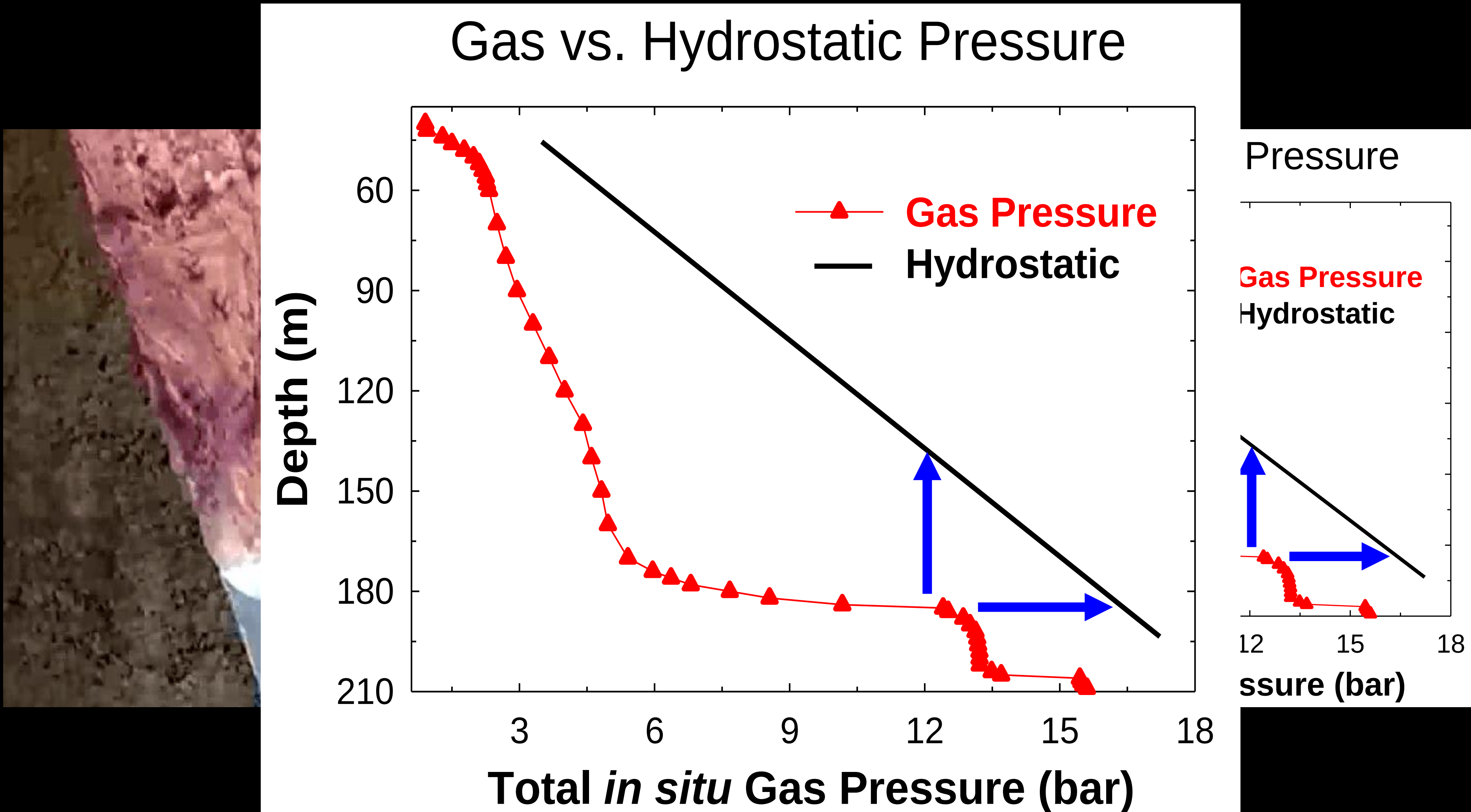
Lockwood and Rubin, 1989


Lake Nyos dopo circa ~10 giorni dal disastro dell’Agosto 1986

The Nyos lethal wave

Il colore rossastro indotto da ossi-idrossidi di Fe

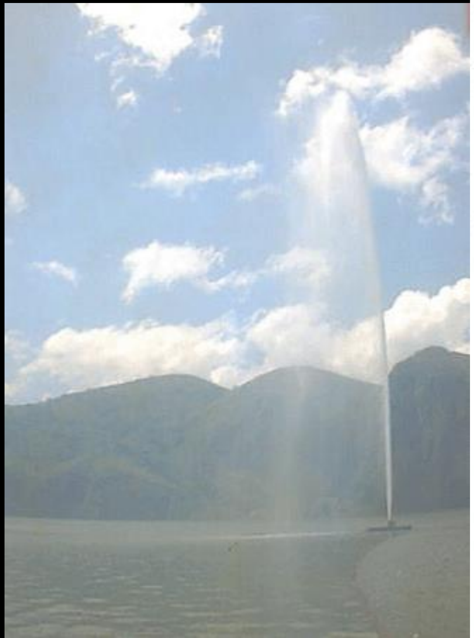
Che cosa ha innescato il gas burst?

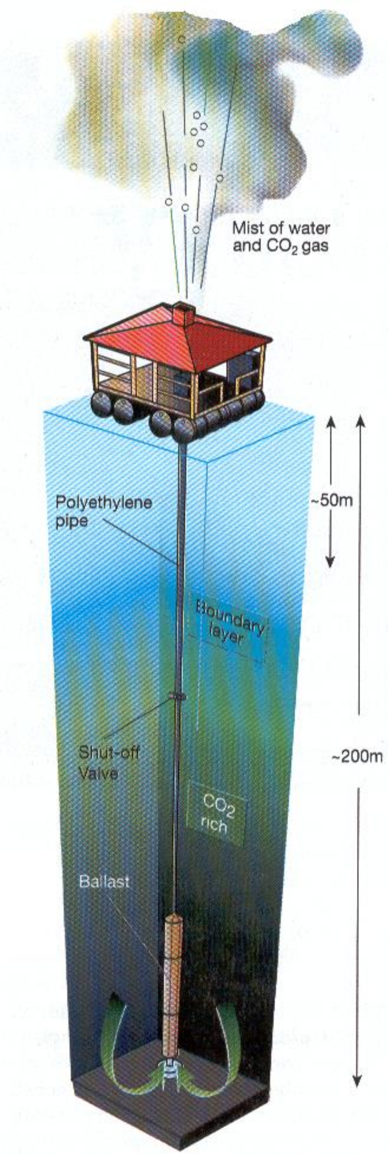


Il gas venne liberato da profondità intermedie e si estese per tutto il lago, indicando un forte mixing orizzontale e turbolento.

Prevenire il rischio di nuove emissioni di CO_2: il processo di degassamento

- 2001: una colonna di degassamento installata con successo ed innescata.
  - In continuo
  - 50 m di fontana di CO_2
    - Spray = 90% CO_2 e 10% acqua.
    - 50.000 m^3/giorno





Degassing Lake Nyos

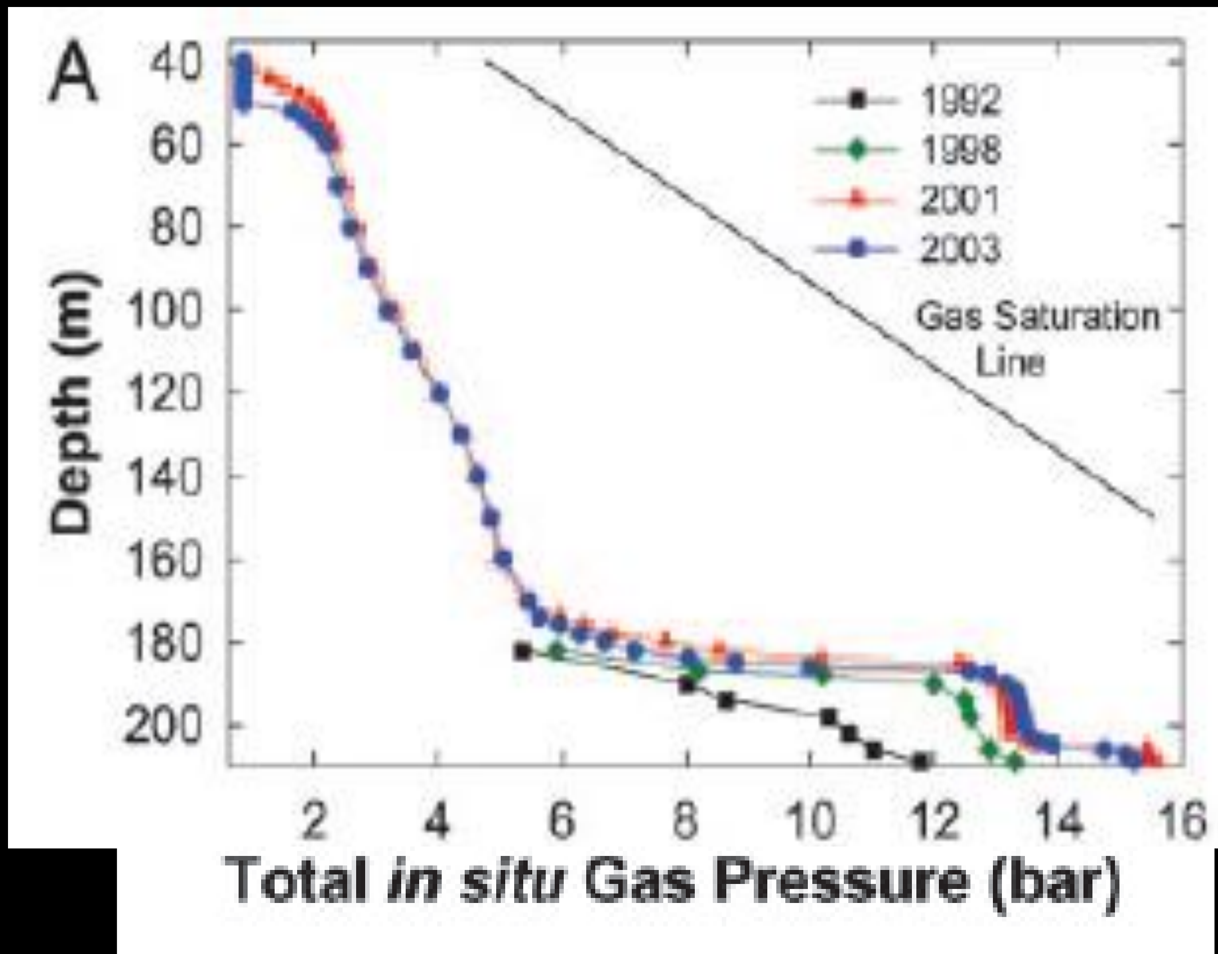
Degassing Lake Nyos

- 2001: full fledge degassing column was successfully assembled, installed and primed.
  - continuous
  - 50 m fountain
    - Spray = 90% CO_2 and 10% water.
    - 50,000 STP m^3/day

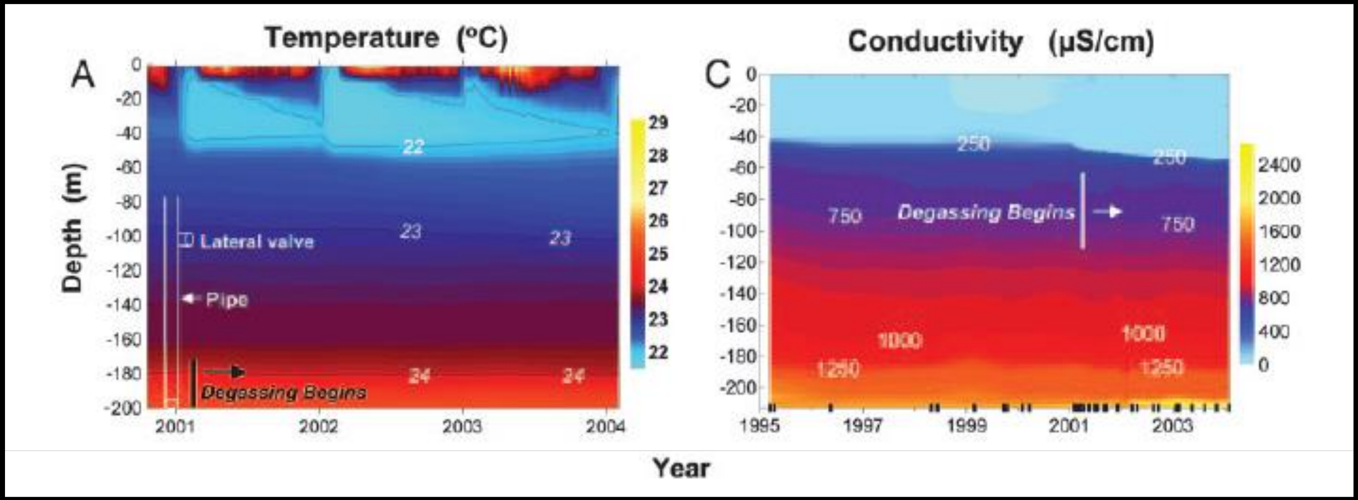
Gas Pressure

Table	
Date	205.8 m
April 1	1,591
May 1	2,520
Nov. 1	2,084
Jan. 2	1,748
Oct. 2	*2,344*
Jan. 2	*2,516*
Jan. 2	*2,418*
April 1	317,133
May 1	349,000
Nov. 1	338,300
Jan. 2	300,500
Oct. 2	*351,400*
Jan. 2	*354,800*
Jan. 2	*363,800*

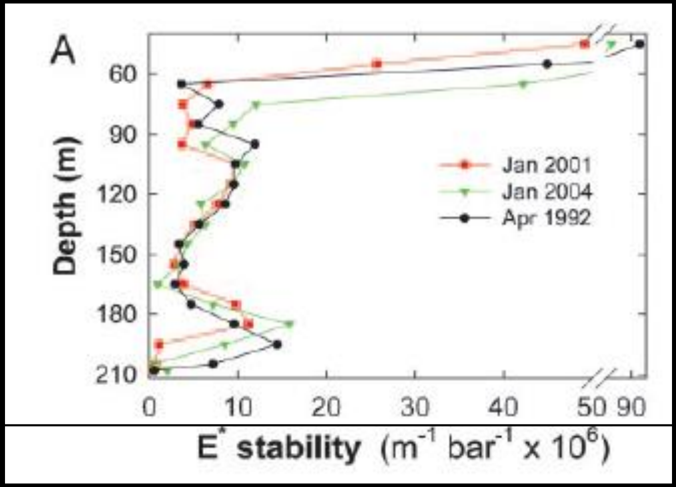
All s



Stability



Relatively consistent over time



- Slight lowering of chemocline
- 1992-2001 decrease due to buildup of gas pressure.
- Since degassing, stability has on average increased.
- Degassing has a relatively minor impact on stability.

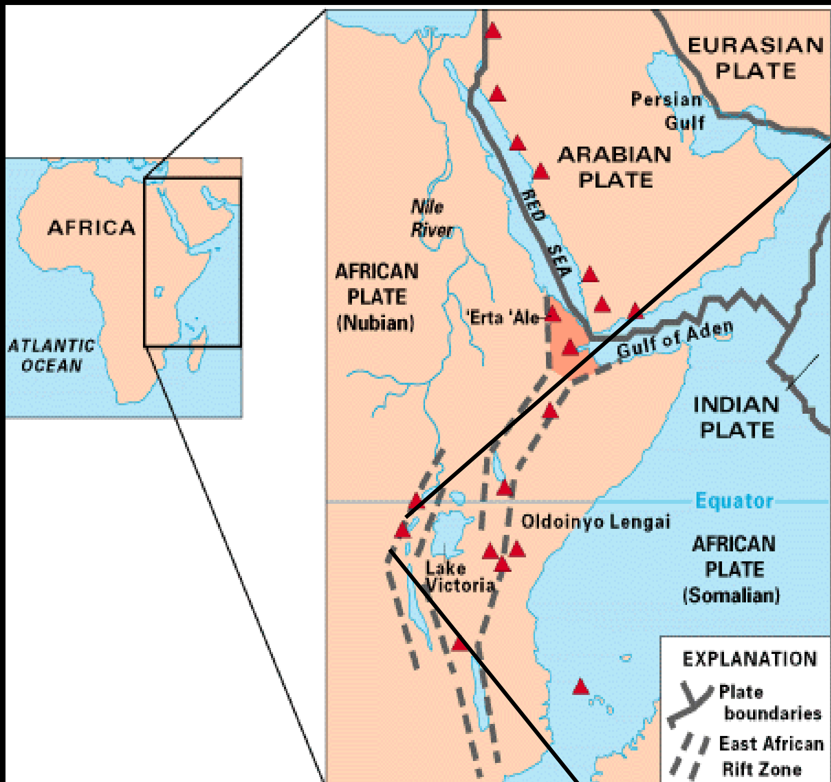
- Lake Nyos has a rapid gas recharge rate
- Draw down to safe levels could take decades.
- During this time, gas concentrations in lake are sufficient to result in another disaster.

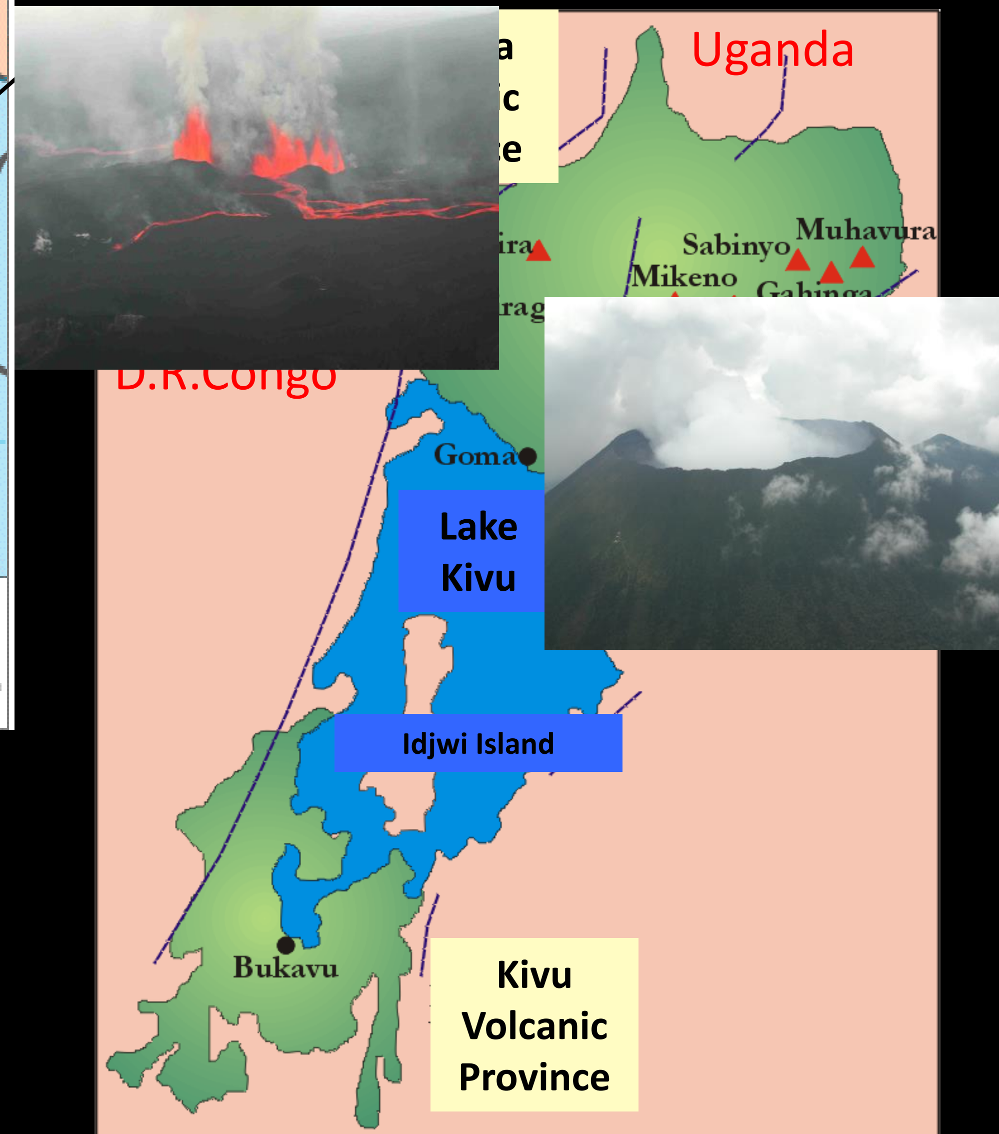
- The addition of 4 degassing pipes would result in safe levels of CO_2 by 2010.
- If these are successfully completed, the ~12,000 refugees could return to the Nyos valley after over 20 years.

A Natural Disaster Crisis is often an endless crisis: people might be at risks for many years, decades or even centuries. There is always a permanent need for Surveillance (monitoring), Awareness and Prepardness in order to locally increase RESILIENCE.

Resilienza: capacità di auto-riparazione

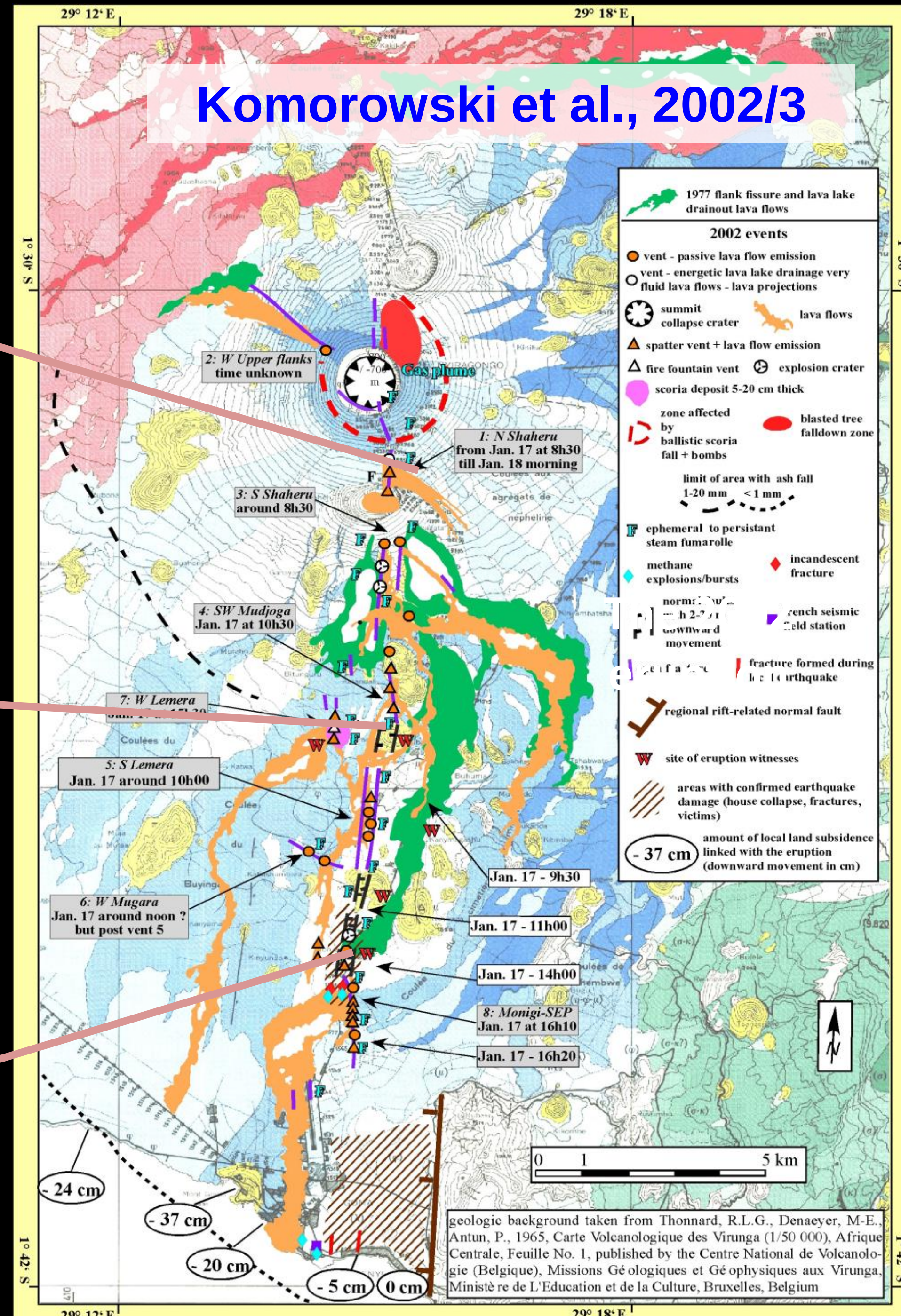
The geodynamical setting

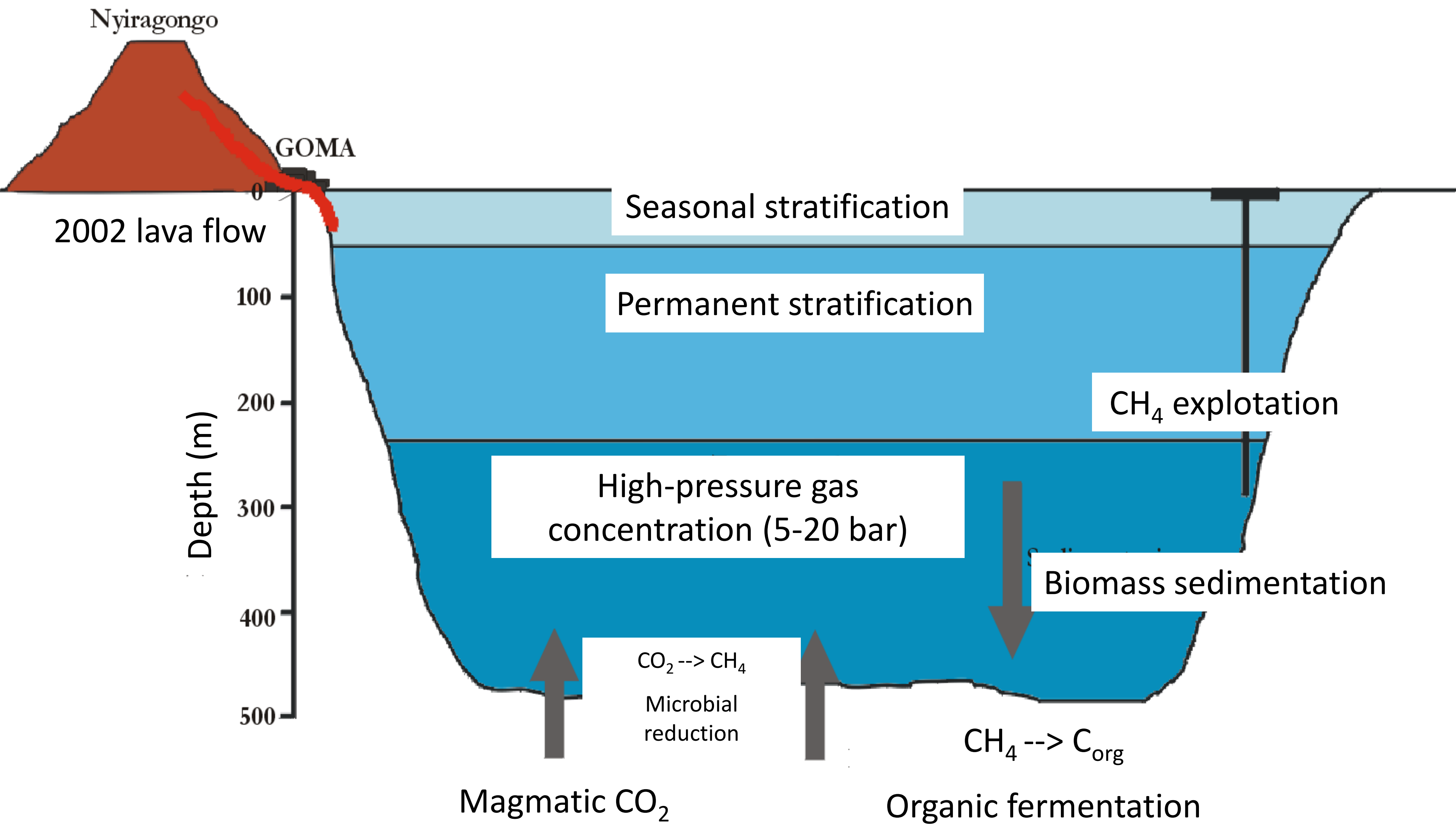




Western Branch of the EARS (East African Rift System)

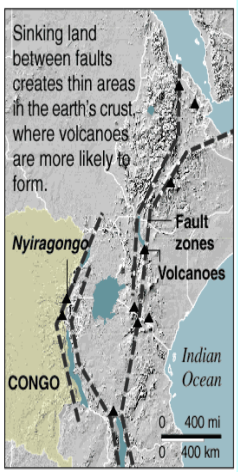
17-18 January, 2002




Nyiragongo
GOMA
2002 lava flow
0
100
200
300
400
500
Depth (m)
Seasonal stratification
Permanent stratification
CH_4 explotation
High-pressure gas concentration (5-20 bar)
Biomass sedimentation
CO_2 --> CH_4
Microbial reduction
CH_4 --> C_{org}
Magmatic CO_2
Organic fermentation

Kivu Lake

Kivu Lake



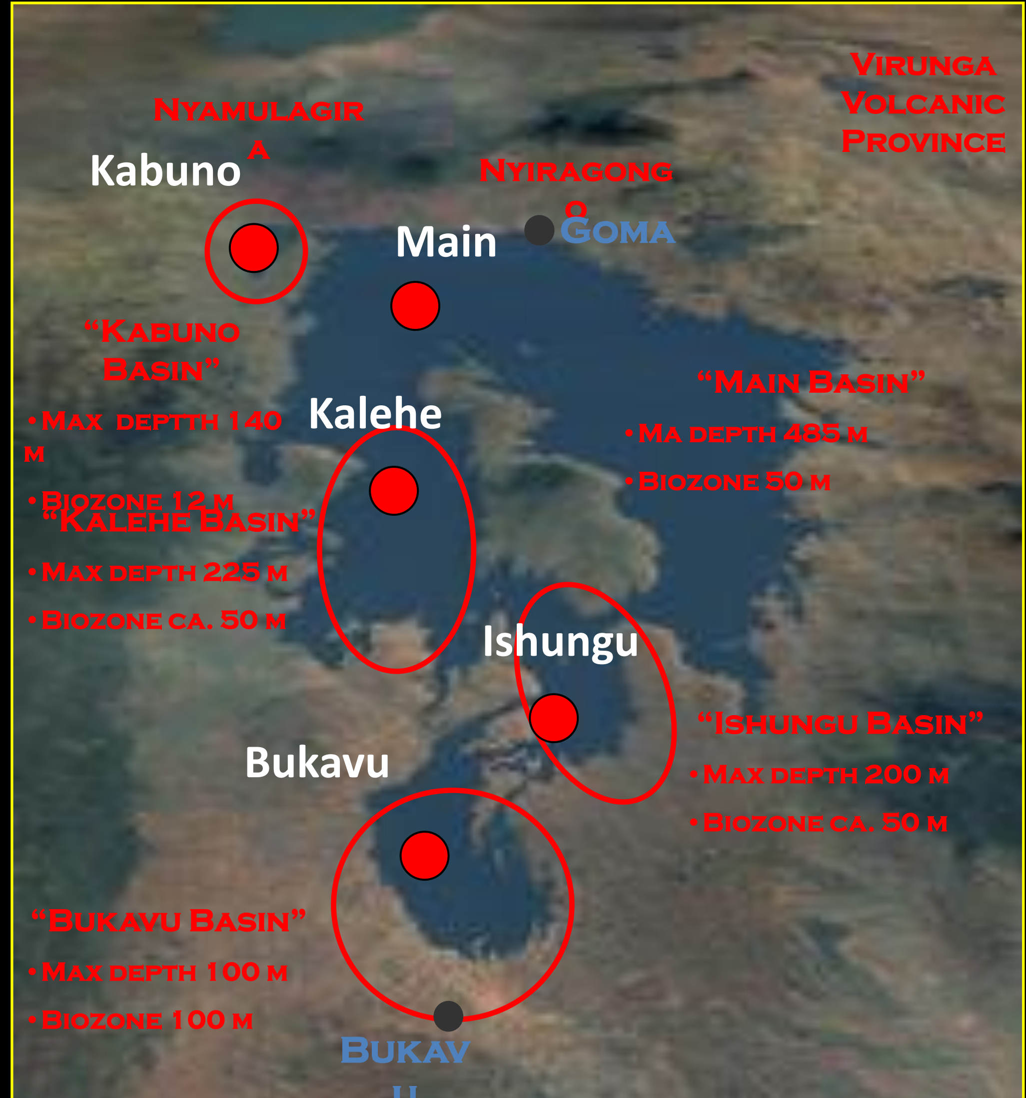
SOURCES: USGS; Associated Press; U.N.; ESRI AP

- High concentrations of dissolved gases such as at Monoum and Nyos (Cameroon)
- Volcanic damming lake, i.e the drainage towards north was cut by lava flows
- Area: 2060 km²
  Mean depth: 240 m
  Drainage area: 7140 km²
  TDS: 1.2 g/L
  -50 m: anoxic layer
  Estimated volume: ≈ 580 km³
- Highly stratified, e.g. pH: 9 at Surface, pH: 6.5 at -478 m
- Gas at -250 m: CO_2, CH_4 & H_2S

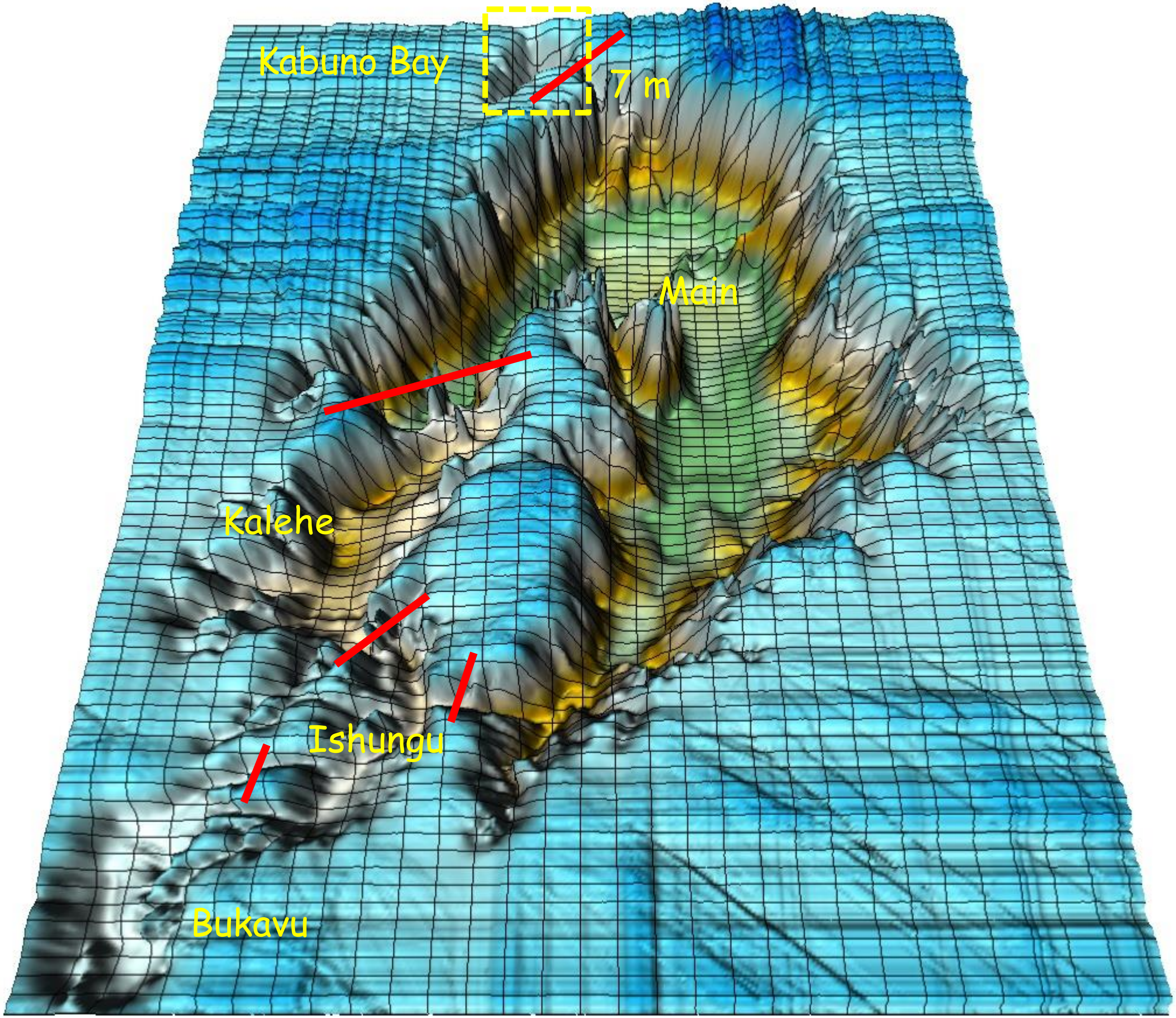
70 % (CO_2)

28.5 % (CH_4)

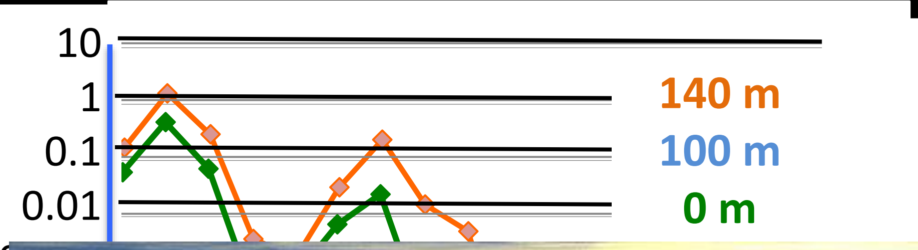
0.17% (H_2S)

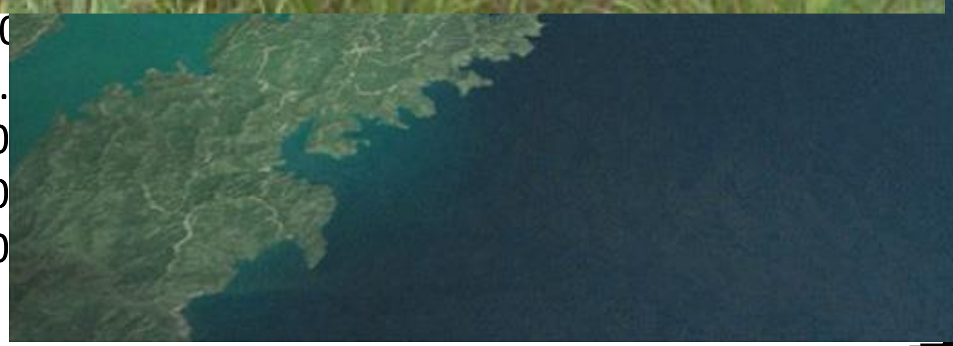


An estimated amount of about 250-300 and 55 km³ of CO_2 and CH_4, respectively



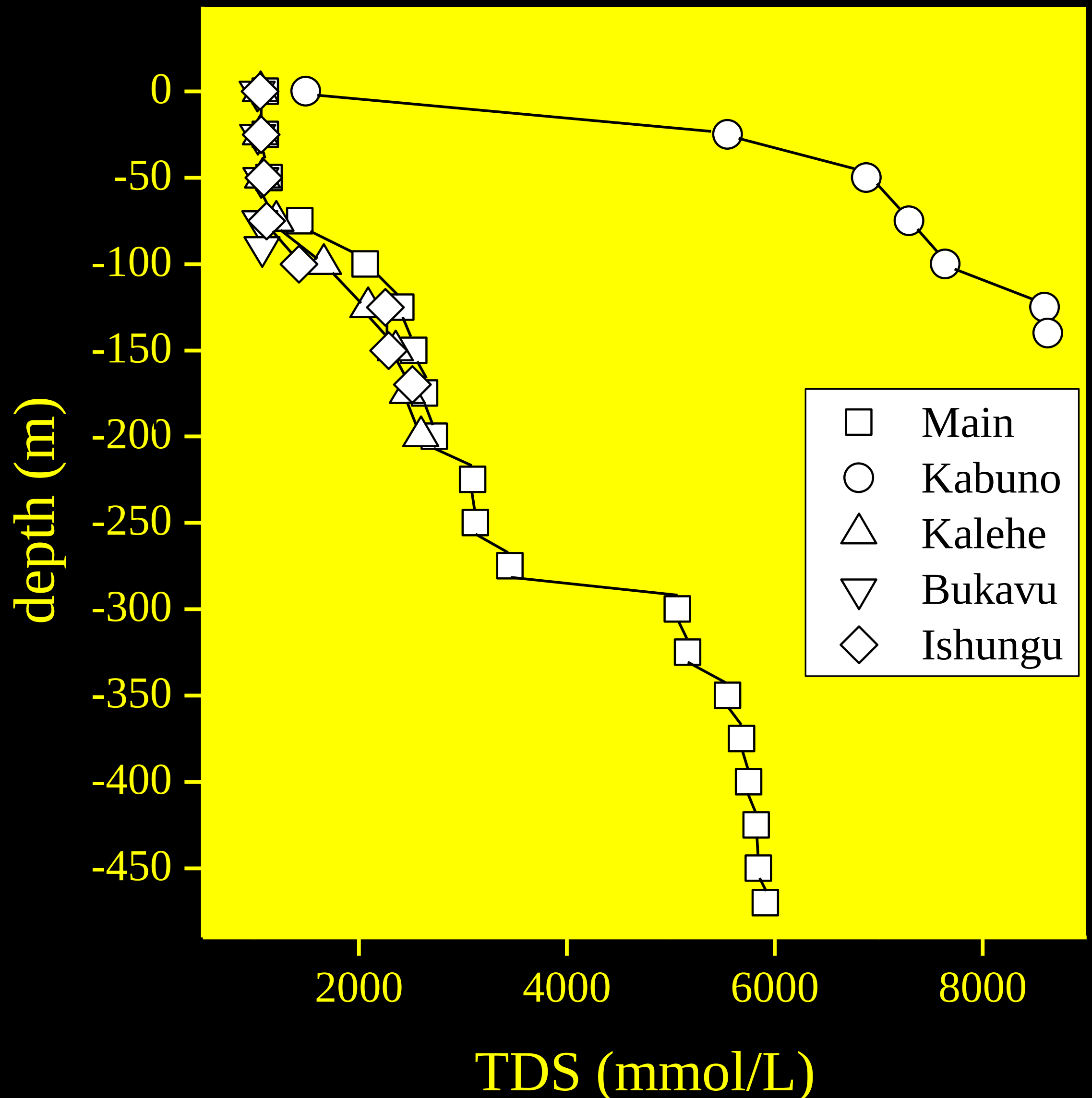
Kabuno Bay
7 m
Main
Kalehe
Ishungu
Bukavu


10
1
0.1
0.01
140 m
100 m
0 m
0.
0.0
0.00
0.000

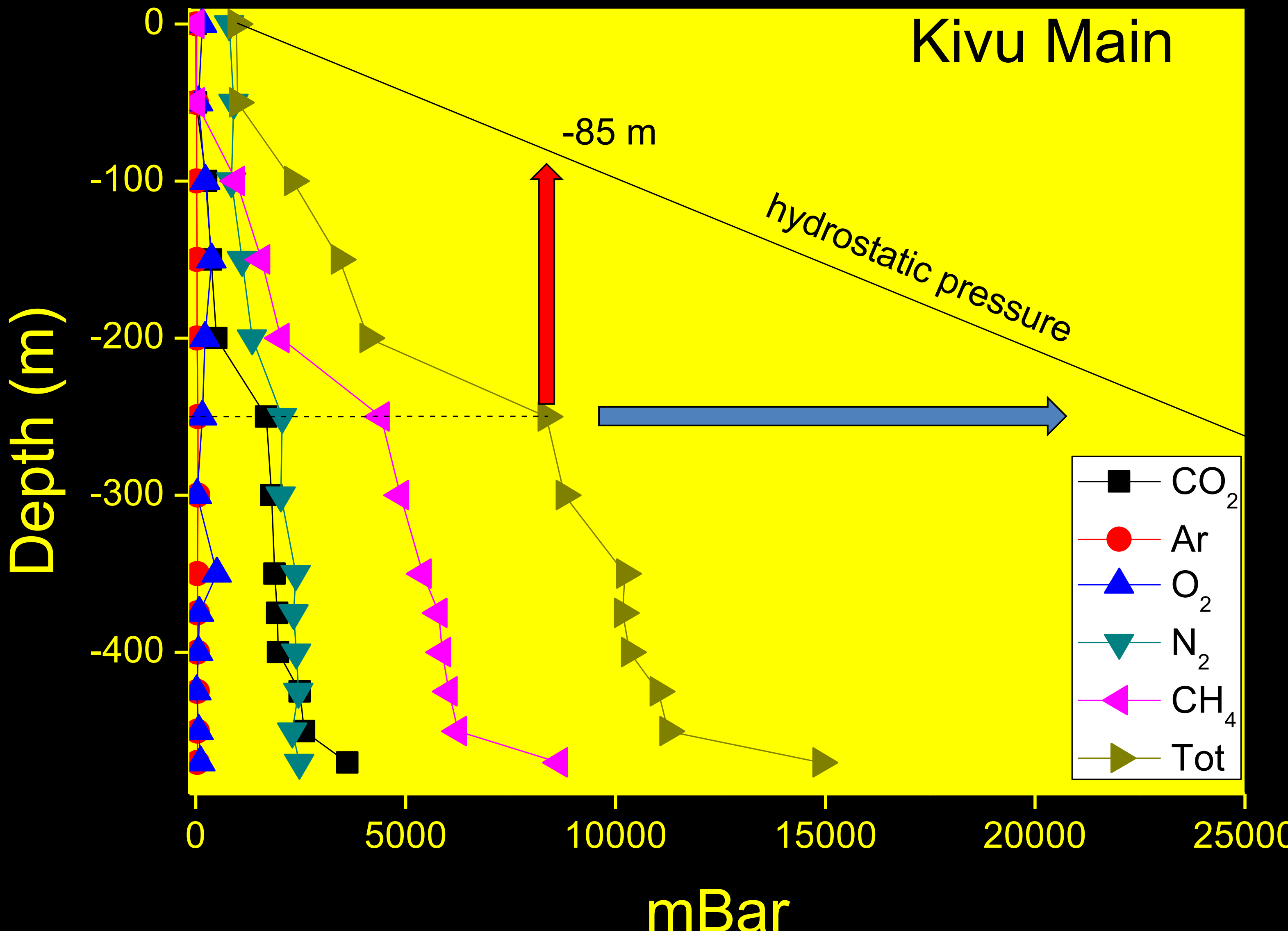



CO_2-rich dry vents:
CO_2 up 96 %

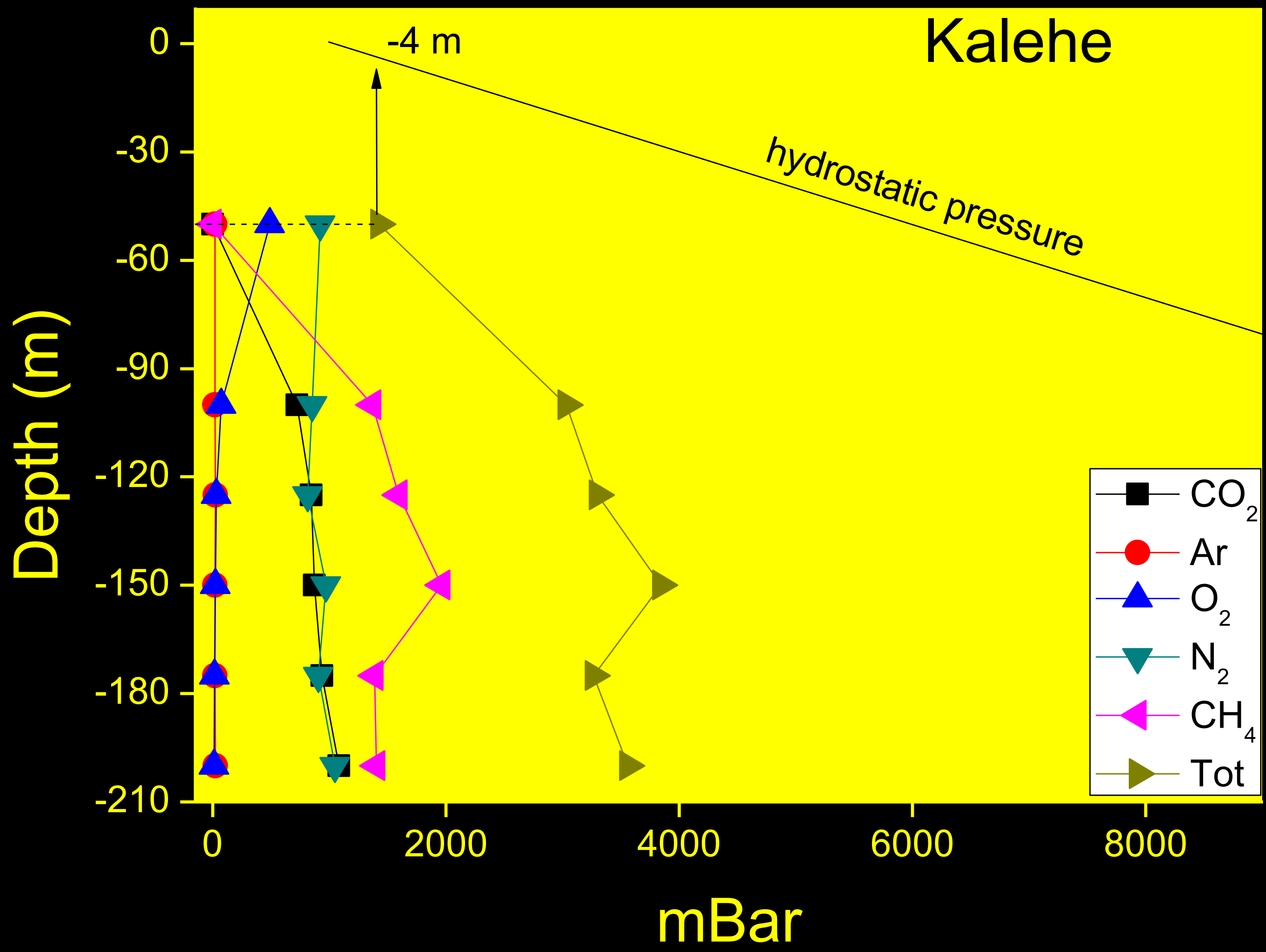
Parameters controlling lake stability: vertical distribution of total dissolved solids (TDS)



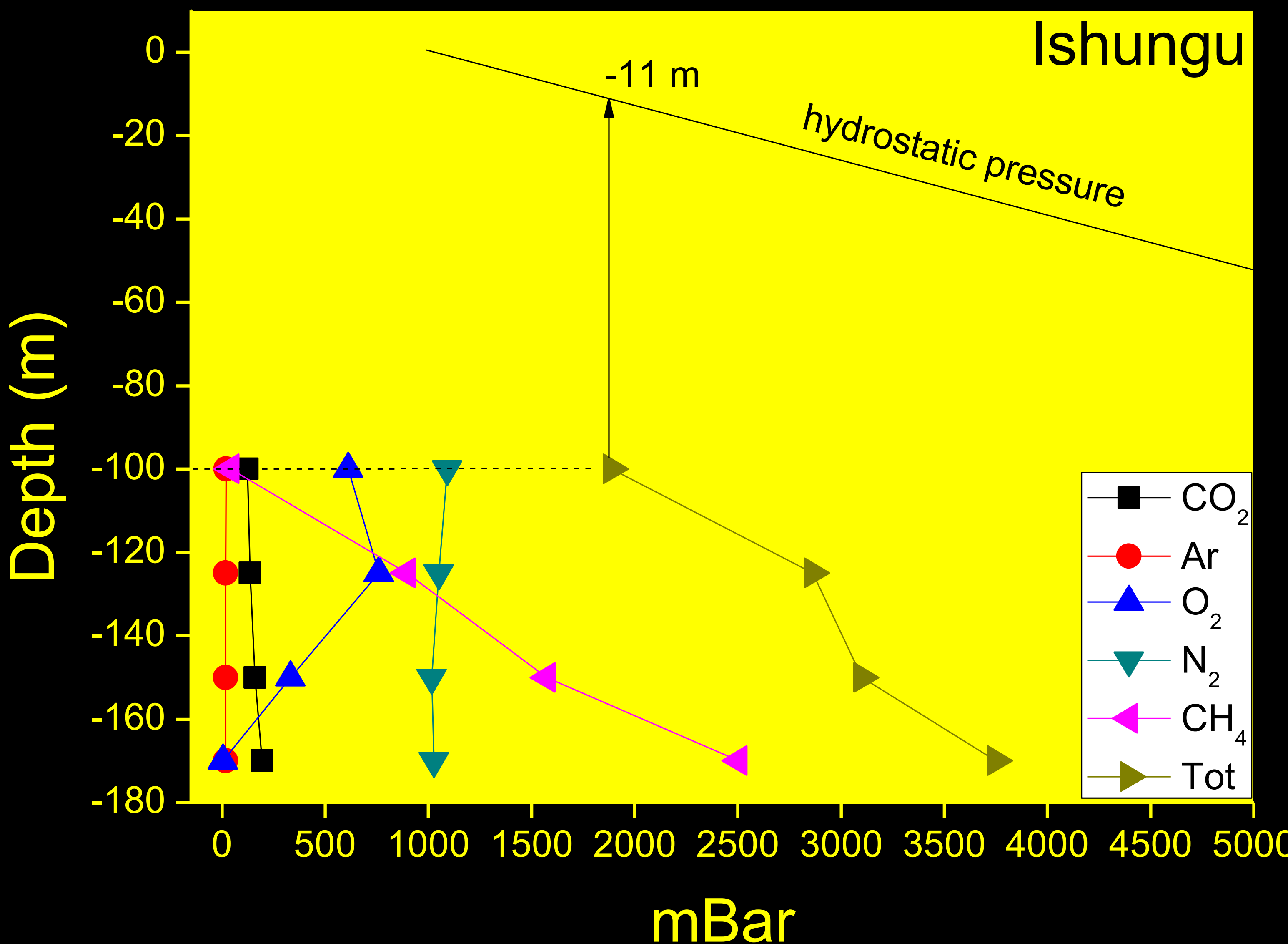
Parameters controlling lake stability: vertical distribution of the main dissolved gases (Main basin)



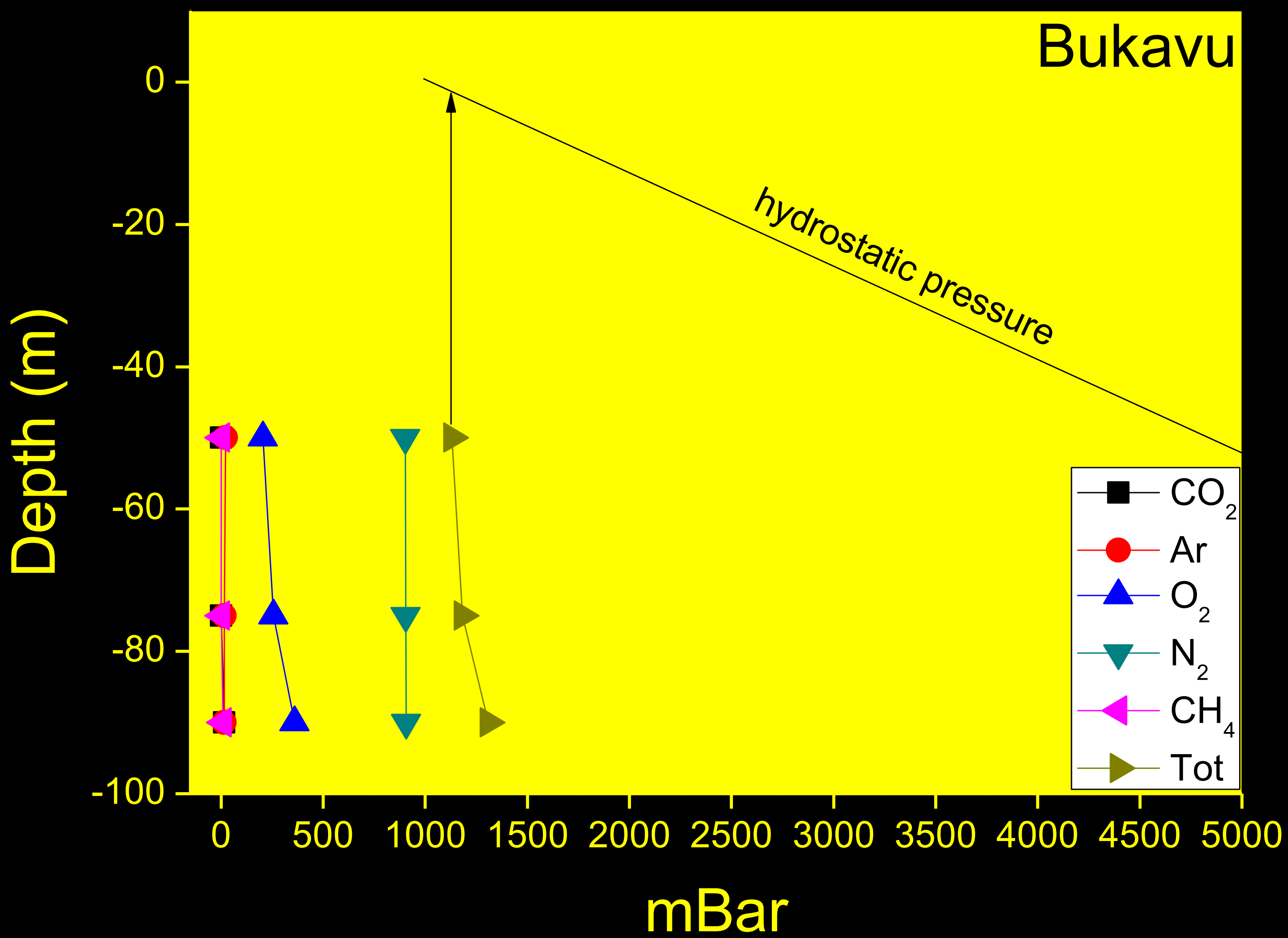
Parameters controlling lake stability: vertical distribution of the main dissolved gases (Kalehe basin)



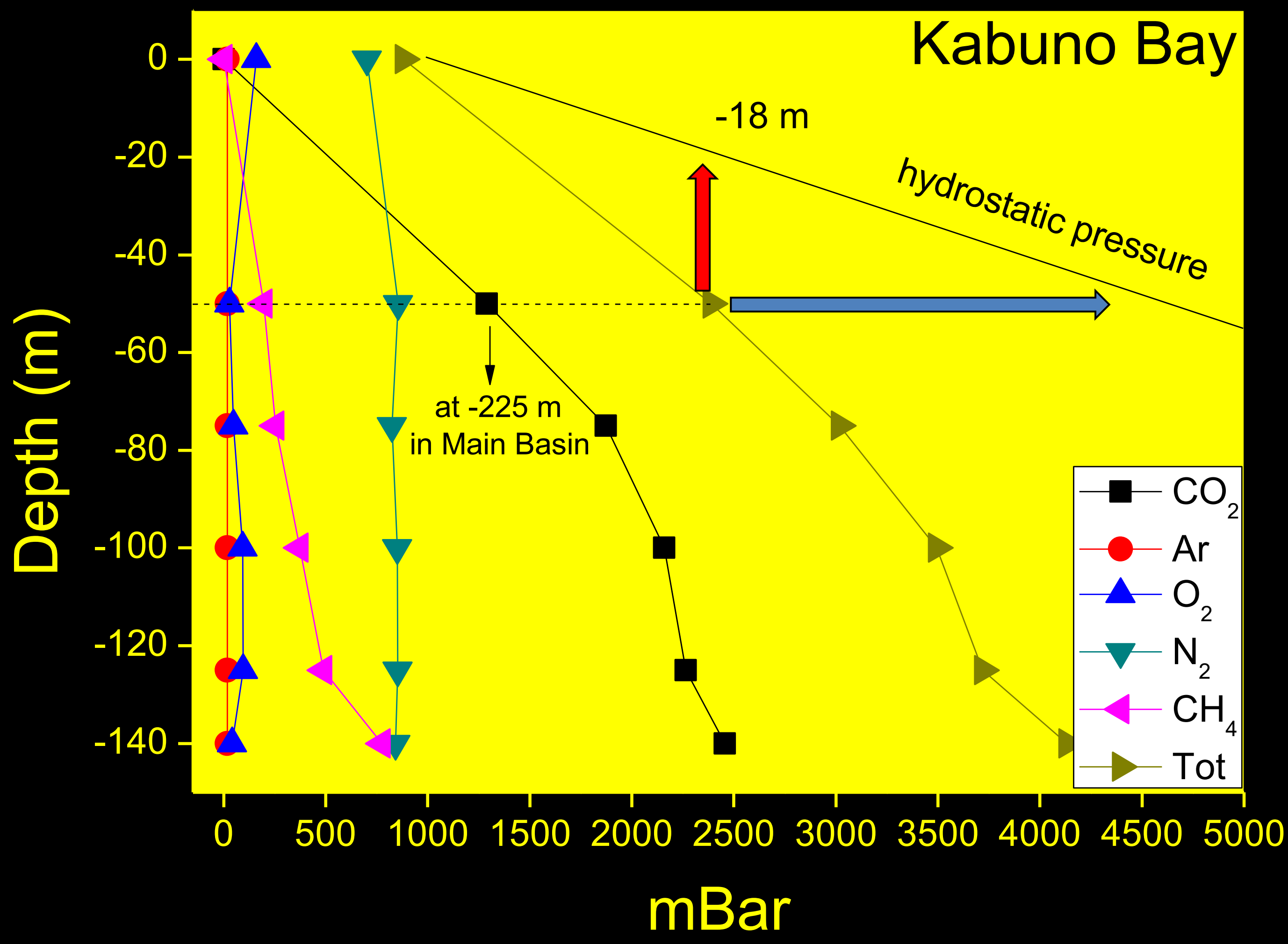
Parameters controlling lake stability: vertical distribution of the main dissolved gases (Ishungu basin)

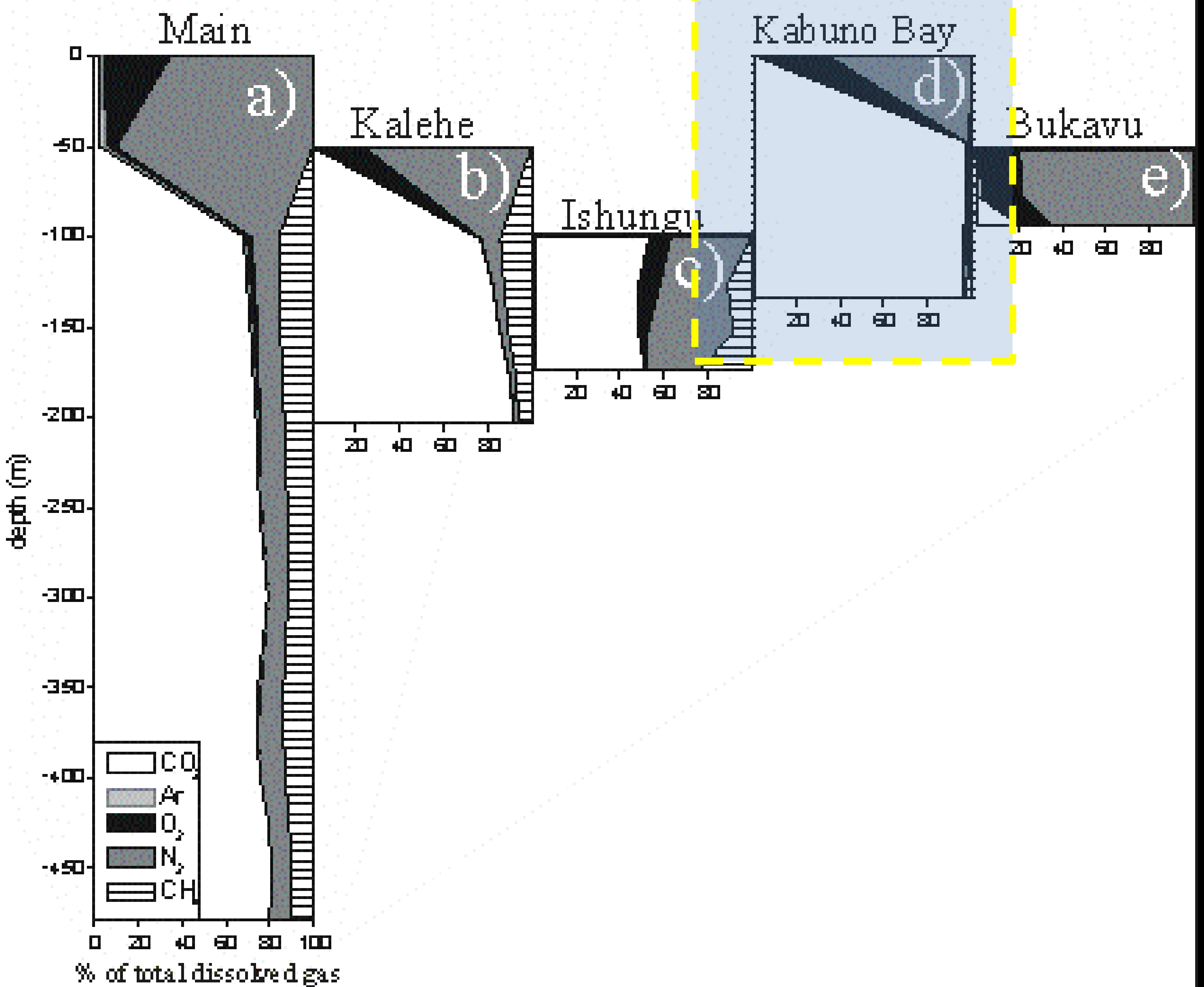


Parameters controlling lake stability: vertical distribution of the main dissolved gases (Bukavu basin)

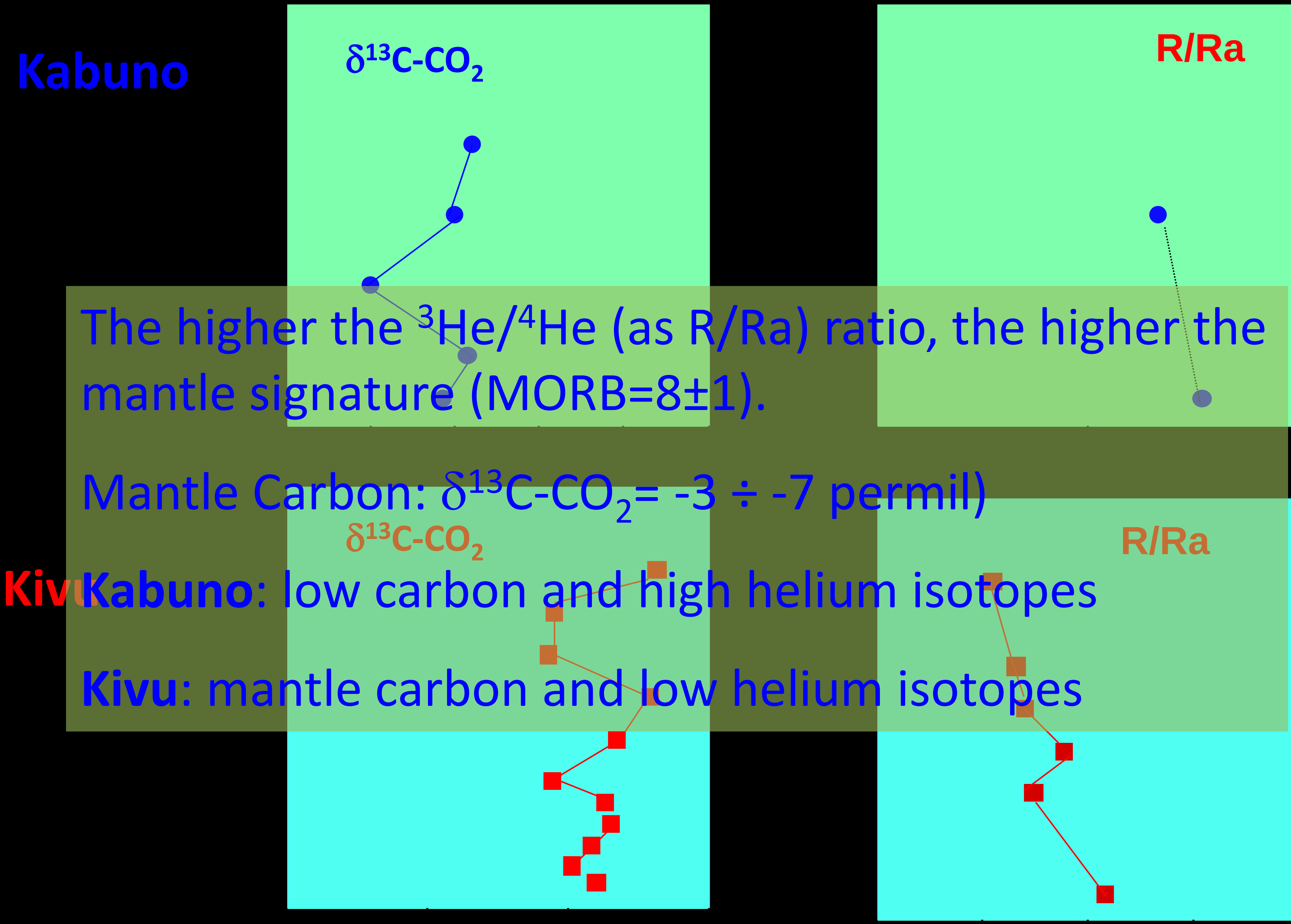


Parameters controlling lake stability: vertical distribution of the main dissolved gases (Kabuno Bay basin)





Main
a)
Kalehe
b)
Ishungu
c)
Kabuno Bay
d)
Bukavu
e)
depth (m)
% of total dissolved gas
CO2
Ar
O2
N2
CH4



The higher the $^3He/^4He$ (as R/Ra) ratio, the higher the mantle signature (MORB=8±1).

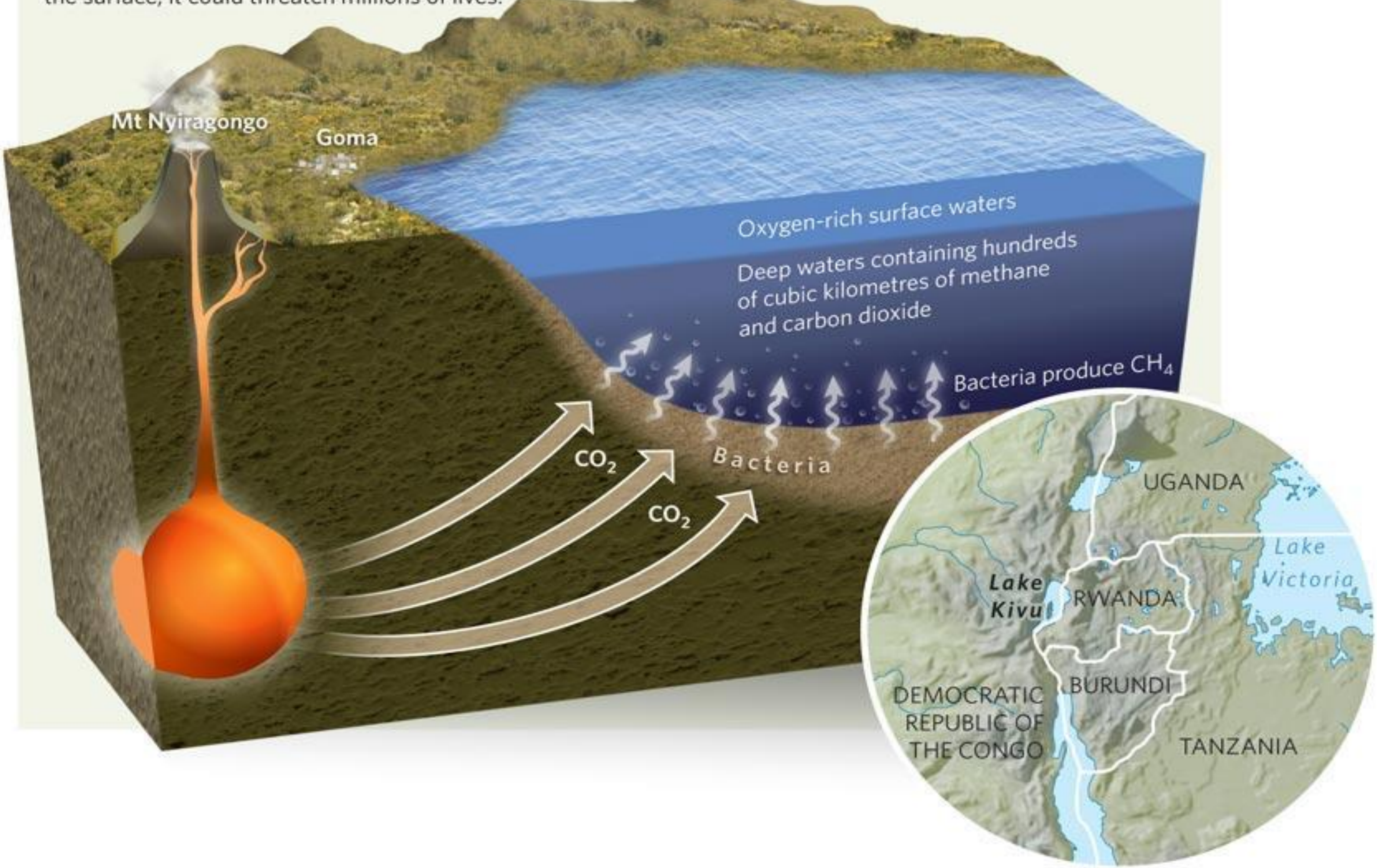
Mantle Carbon: $\delta^{13}C$-CO_2= -3 ÷ -7 permil)

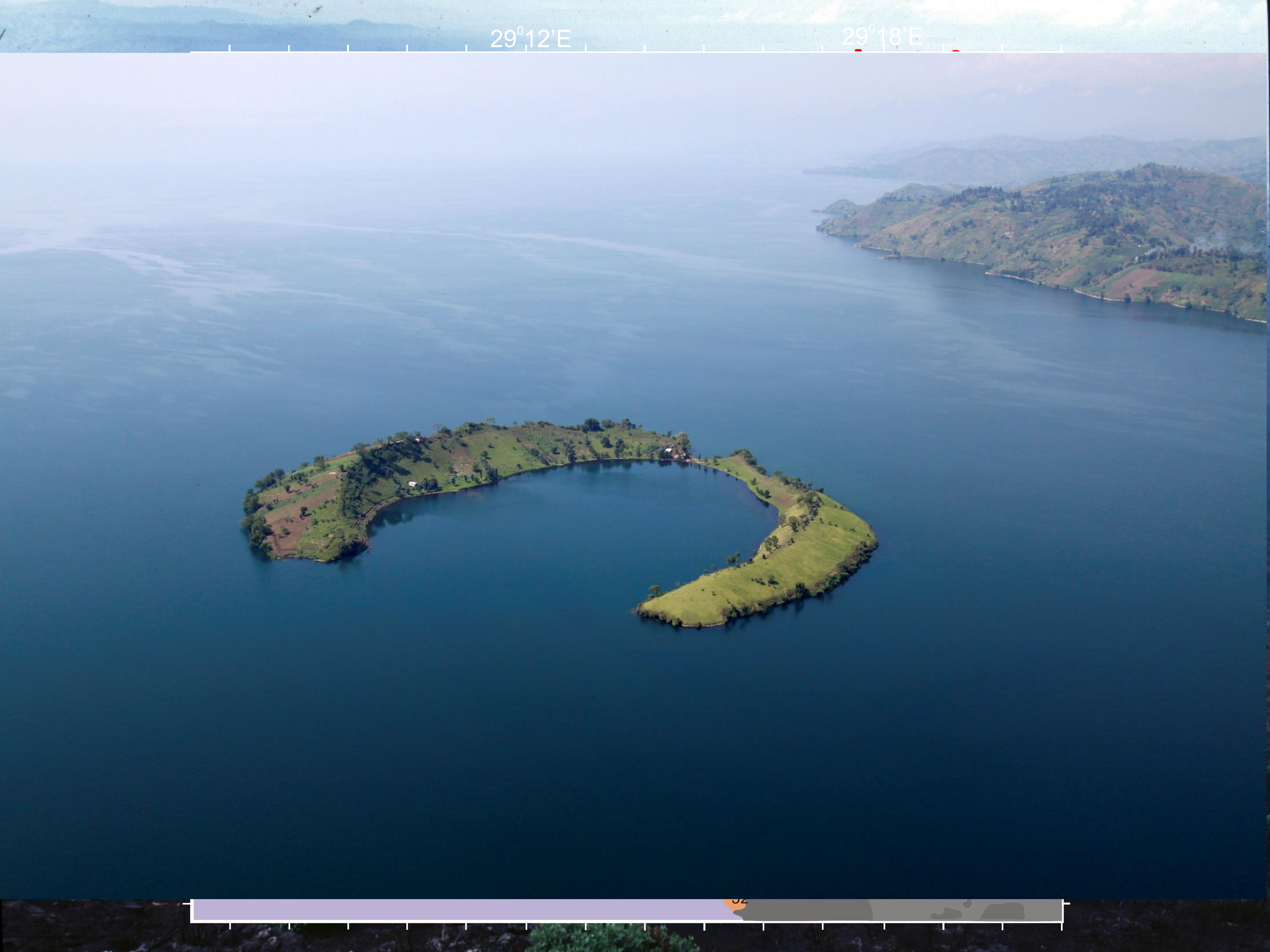
Kabuno: low carbon and high helium isotopes

Kivu: mantle carbon and low helium isotopes

THE UNDERWATER THREAT

If the dissolved gas accumulating in the depths of Lake Kivu bursts to the surface, it could threaten millions of lives.




29°12'E
29°18'E

A first consideration

The risk of limnic eruption at Kabuno Bay is greater (100 times ? Tietze suggests) than at the Main basin, although the total gas content is much less than that of the main basin.

How can this hazard be evaluated (quantified) ?...

“A huge CO_2 cloud was suddenly released from the lake…“

…and then ?

Hazards related to a limnic eruption

"The Nyos limnic eruption in 1986 culminated with a roaring gas-water jet breaking the surface that reached 80-100 metres into the air and created surface waves up to 25 metres high."

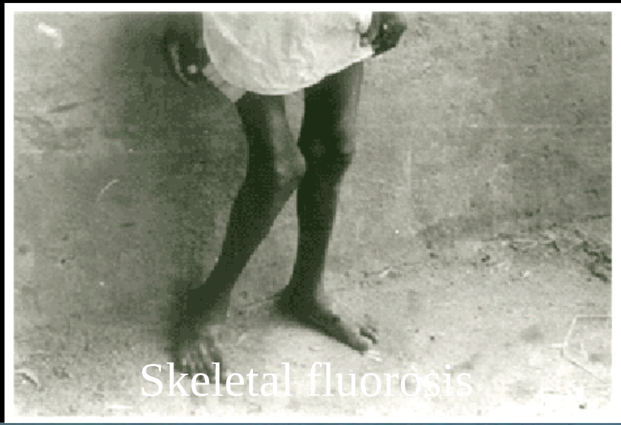
Tsunami hazard ??

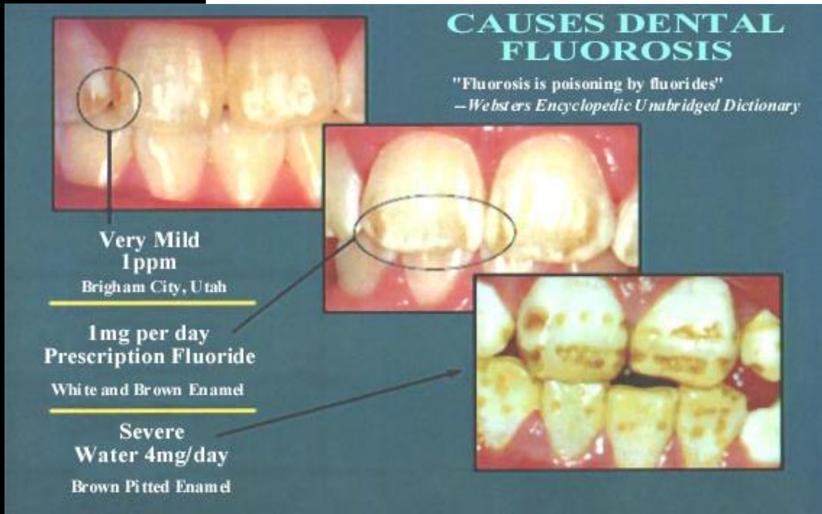
Hazard related to a limnic eruption

<u>…an area of limited water resources</u>

Water stored in banana's trees is typically used during dry season. However, during erutpions this water is stronlgy polluted by ashes.

<u>Rainwater</u> has high F concentrations caused by the volcanic plume.





Hazard related to a limnic eruption at Kabuno Bay

The lake is an important water resource, but…

Lake Nyos prior (1985) and after (1986) the liminc erutpion.

Where does the CO_2 cloud escape ?

Why so much CO_2 at Kabuno Bay ?

…geochemical evidences lead to open questions

CO_2/CH_4 ratios: similarities and differences among the basins

Main, Ishungu, Kalehe basins		Kabuno Bay basin
CO_2/CH_4 = 6-10 (at the bottoms)	↘	
CO_2/CH_4 = 4-8 (at -140 m)	→	CO_2/CH_4 = 35 (at the bottom)
CO_2/CH_4 = 15-20 (at -75)	→	CO_2/CH_4 = 85 (at -75)

Carbon isotopic signature

Main, Ishungu, Kalehe basins

$\delta^{13}C-CO_2$ between -3.9 and -5.5 ‰PBD

Kabuno Bay basin

$\delta^{13}C-CO_2$ between -8.7 and -11.2 ‰PBD

≠

$d^{13}C-CO_2$ (mantle) ~ -3 and -7 ‰PBD

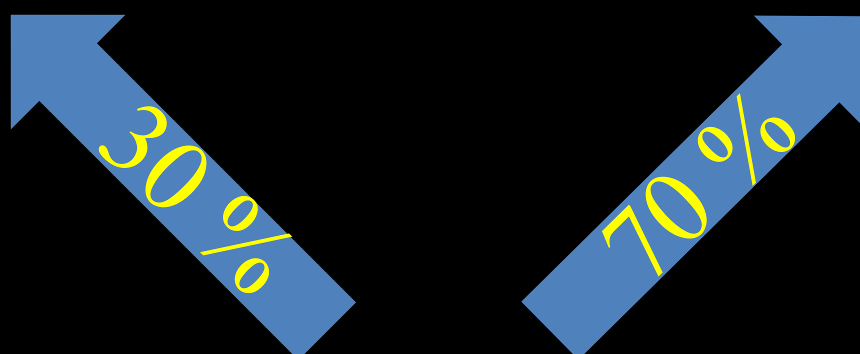
Helium isotopic signature

Main, Ishungu, Kalehe basins

Kabuno Bay basin

R/Ra ~ 2.5

R/Ra ~ 5.5



R/Ra (MORB) ~ 8

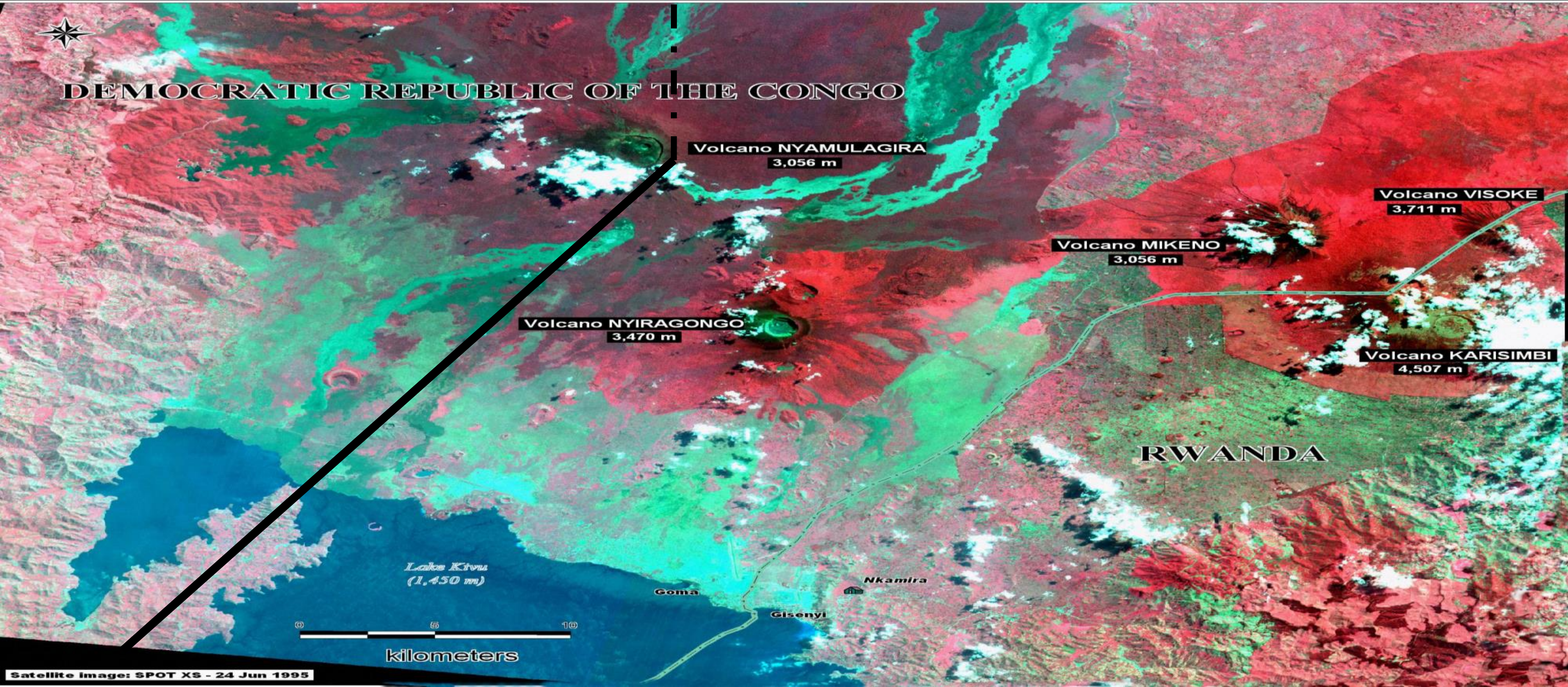
Two different domains

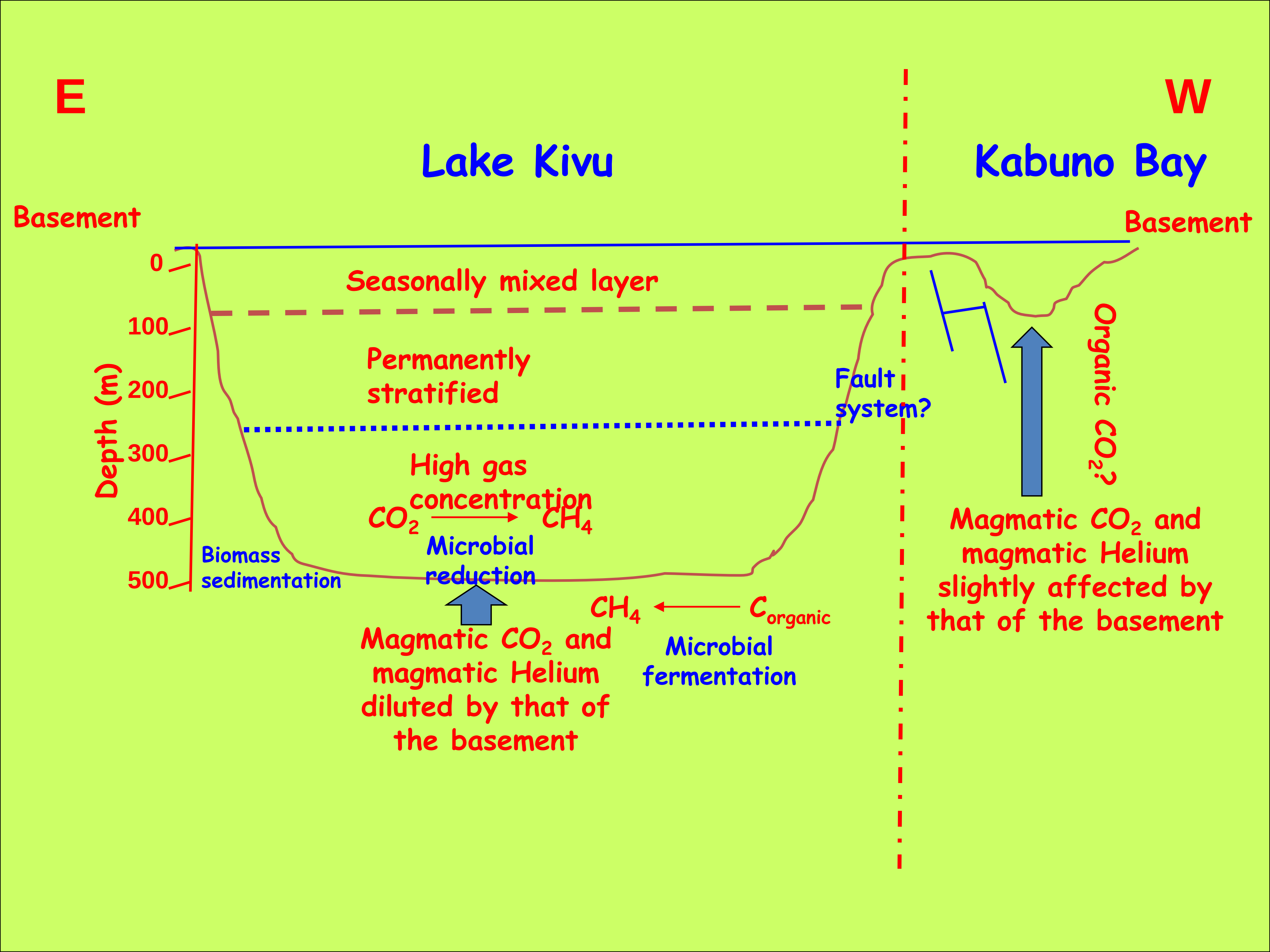
<u>Kabuno Bay and Sake area</u>

high Mantle contribution
vs.
organic CO_2 ? Less CH_4 !!

<u>Main Kivu and Goma area</u>

low Mantle contribution (+ crustal)
vs.
magmatic CO_2




E
W
Lake Kivu
Kabuno Bay
Basement
Basement
0
100
200
300
400
500
Depth (m)
Seasonally mixed layer
Permanently stratified
Fault system?
High gas concentration
CO_2 → CH_4
Microbial reduction
Biomass sedimentation
CH_4 ← $C_{organic}$
Microbial fermentation
Magmatic CO_2 and magmatic Helium diluted by that of the basement
Organic CO_2?
Magmatic CO_2 and magmatic Helium slightly affected by that of the basement

Two different feeding systems ?

Kabuno Bay and Sake area:

Nyamuragira fluid circulating system
High CO_2 recharge rate

Main Kivu and Goma area:

Nyiragongo fluid circulating system
Low CO_2 recharge rate

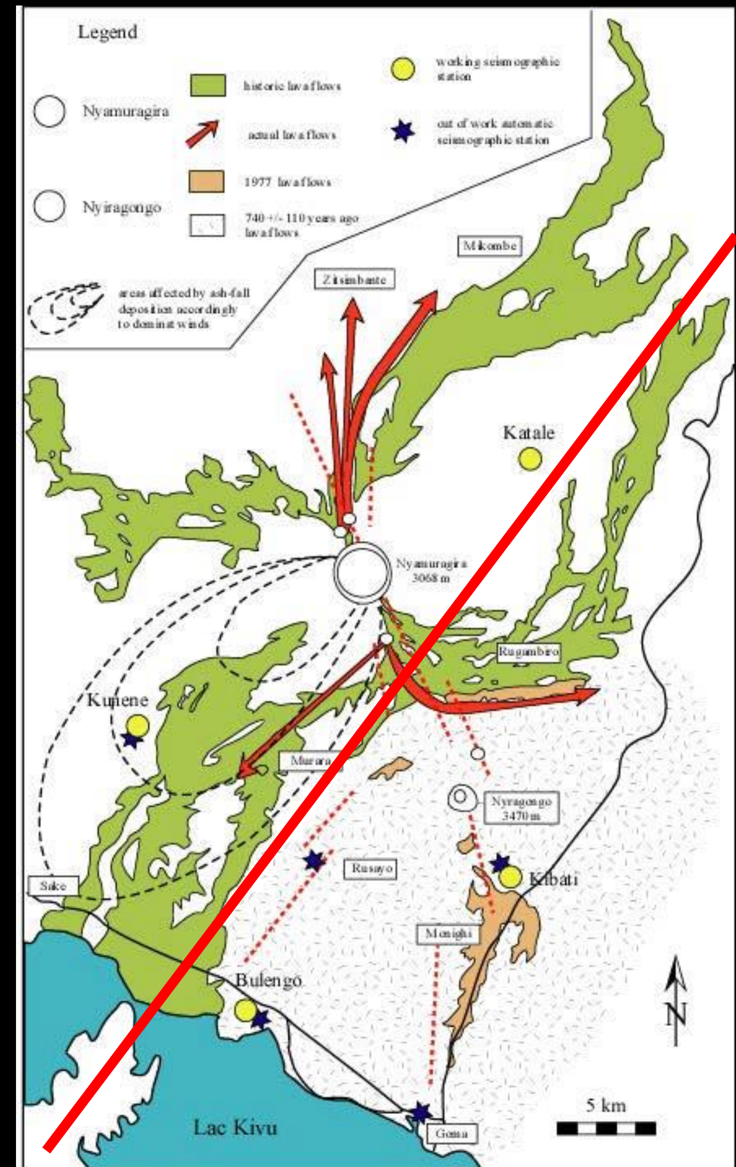


Fig. 1: schematic map of the Virunga volcanic area with direction of the present Nyamuragiira lava flows

The CO_2 hazard inland Kabuno Bay

CO_2 dry emissions (mazukus) and CO_2-rich springs are present in several location close to both the Kabuno Bay and Main basins shoreline…

The CO_2 hazard inland Kabuno Bay

At Sake village, CO_2 concentrations up to several % were measured indoor (1/2 m from the ground)…