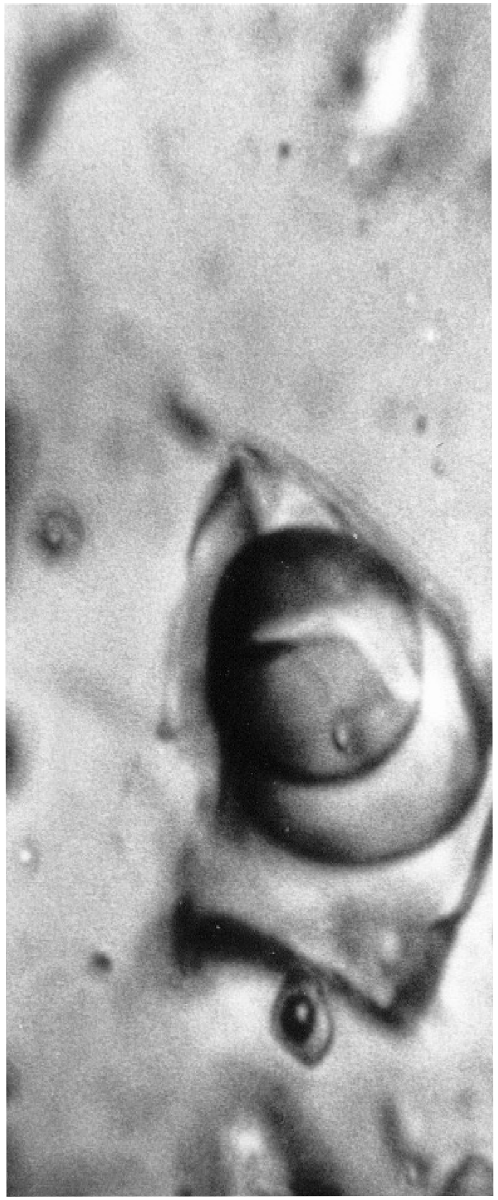


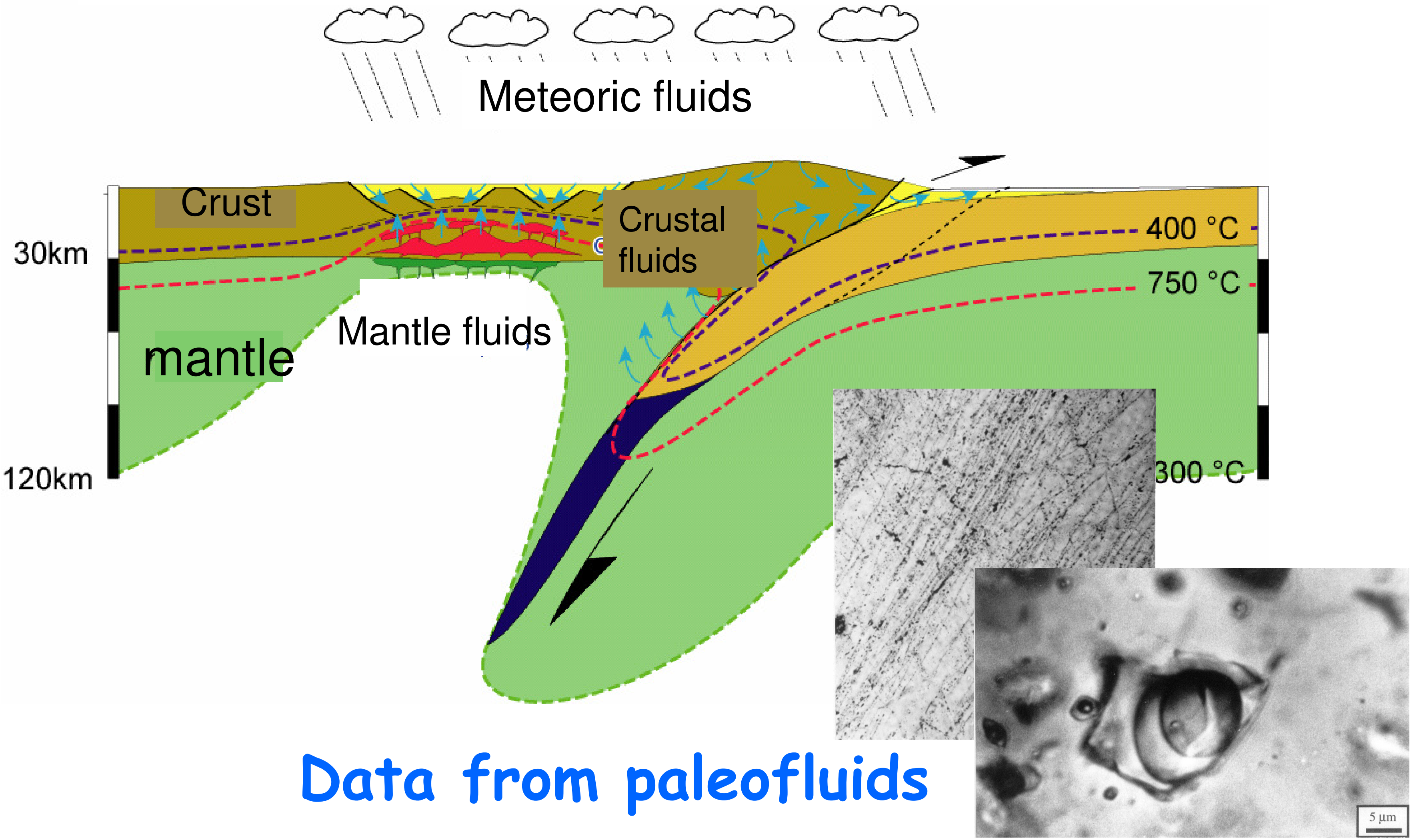
P-T-X evolution of paleo-hydrothermal systems related to granites and active geothermal systems : the data from fluid inclusion studies

M. Cathelineau and M.C. Boiron

Thanks to coll. with CNR-IGG , G. Gianelli,
G. Ruggieri, M. Puxeddu
Works on Larderello geothermal system from 1986 to 2007
and Alpi Apuane (Ch. Montomoli, Pisa Univ.)

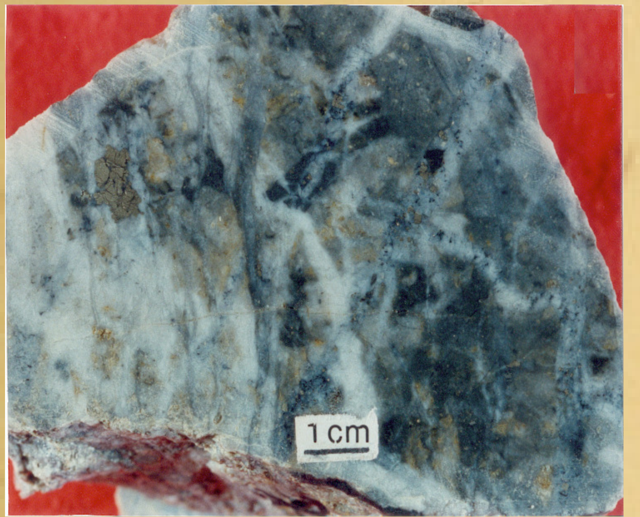
and coll. with O. Vanderhaeghe, J. Vallance,
A.S. André on paleo-hydrothermal systems

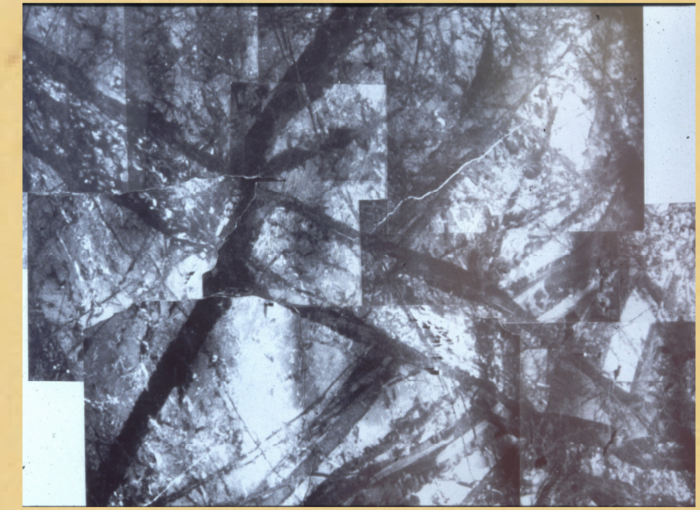
Mass and heat transfer in the continental crust:

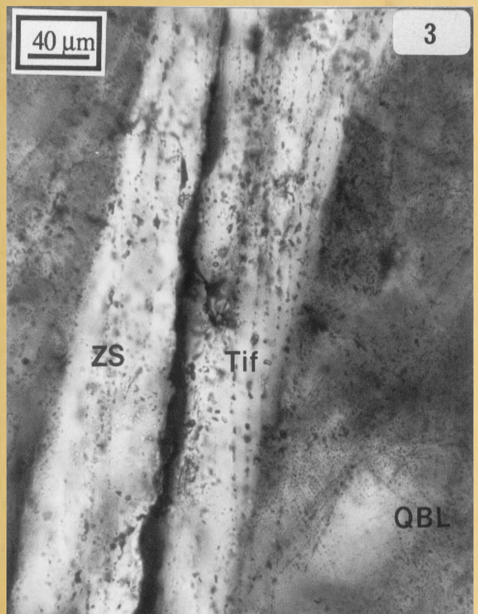


Data from paleofluids

From quartz vein to fluid inclusion







Paleofluids and deformation
methodology

Petrography, CL

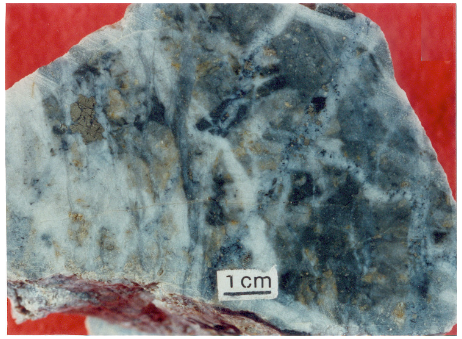
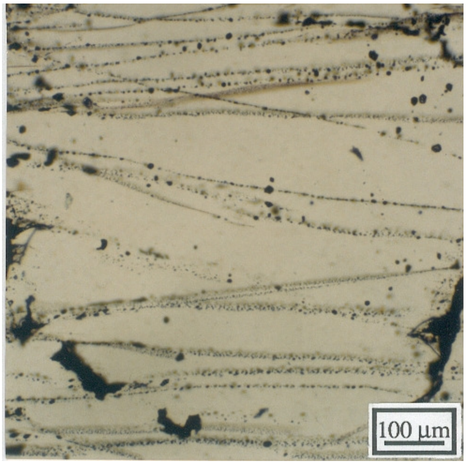
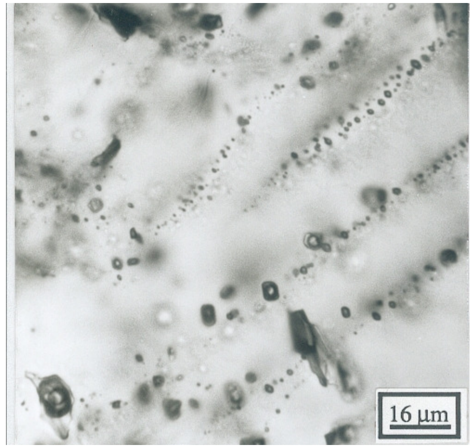
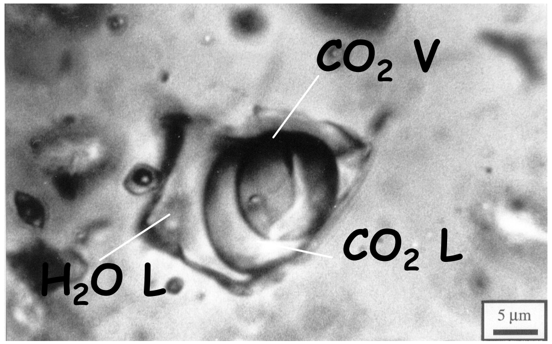


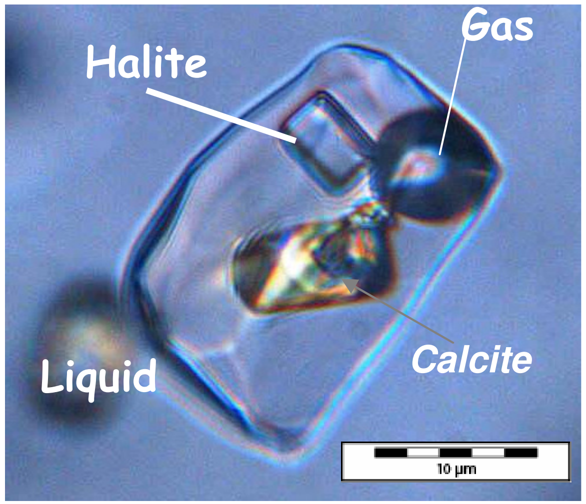
Image analysis

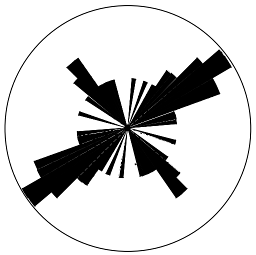


Typology and chronology of fluid events



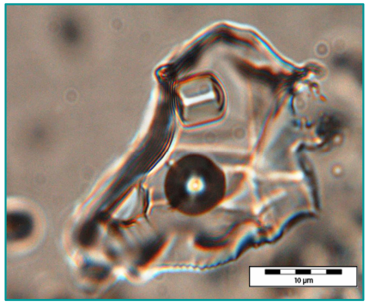




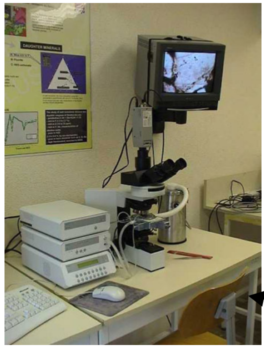


Fluid inclusion plane distribution
fluid-deformation relationships

Paleofluid density, composition, and P-T trapping conditions



Crush-leach method
Cations /anions /trace elements/ halogens

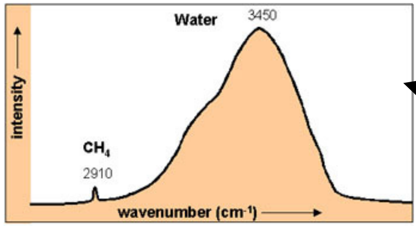


Optical microscopy, IR, UV

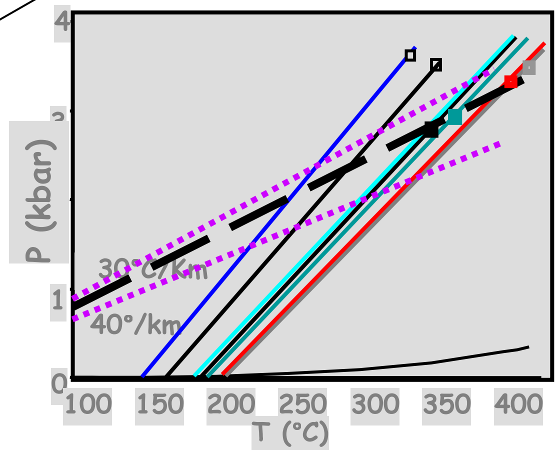
microthermometry

PTX

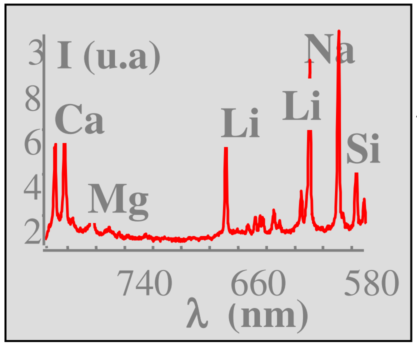
Water-gas-salt system



Raman : gas, Cl



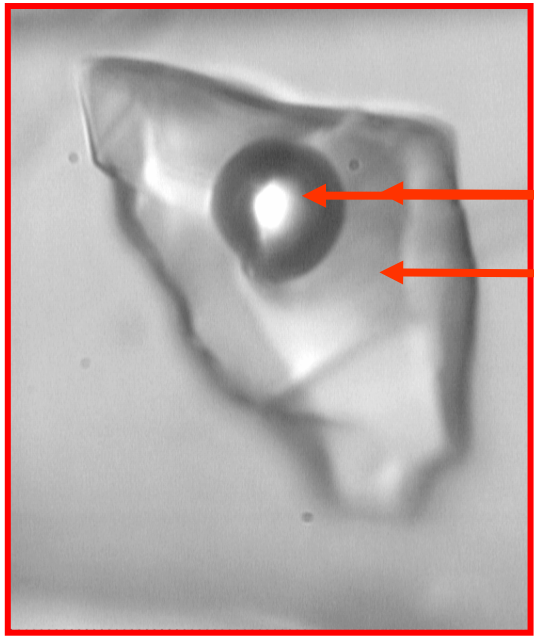
LIBS : cations, trace elts



EOS
Liquid-Vapour modelling

Stable Isotopes (C, O, H)

Paleo-hydrochemistry



Gas ?

Cations ? Anions ? Metals ?

pH ? fO_2 ? fS_2 ?

Paleo-hydrogeochemistry on 10^{-9} g of paleofluid

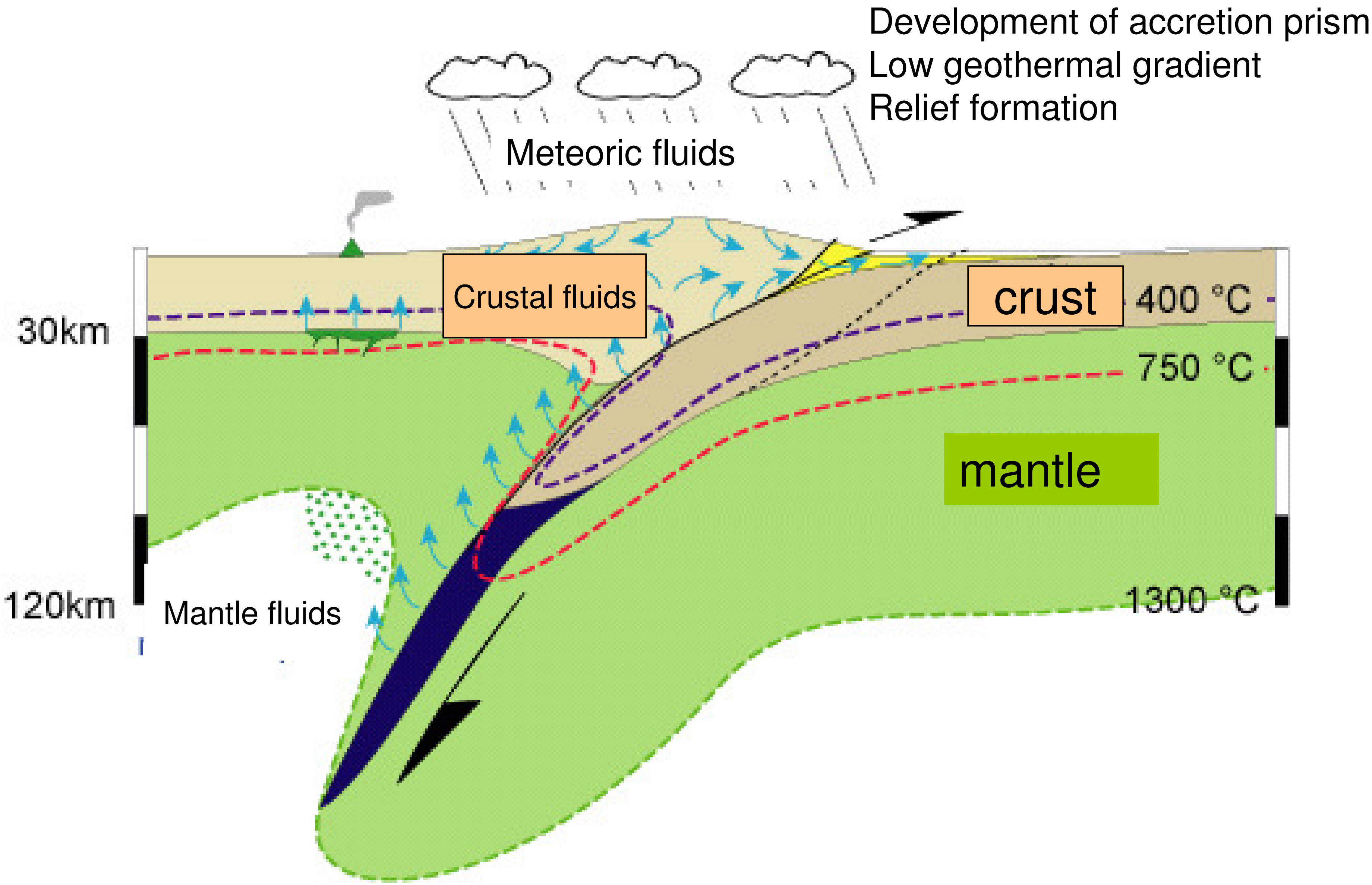
Controls of paloefluid chemistry?

Fluid- mineral equilibria/ disequilibria ?

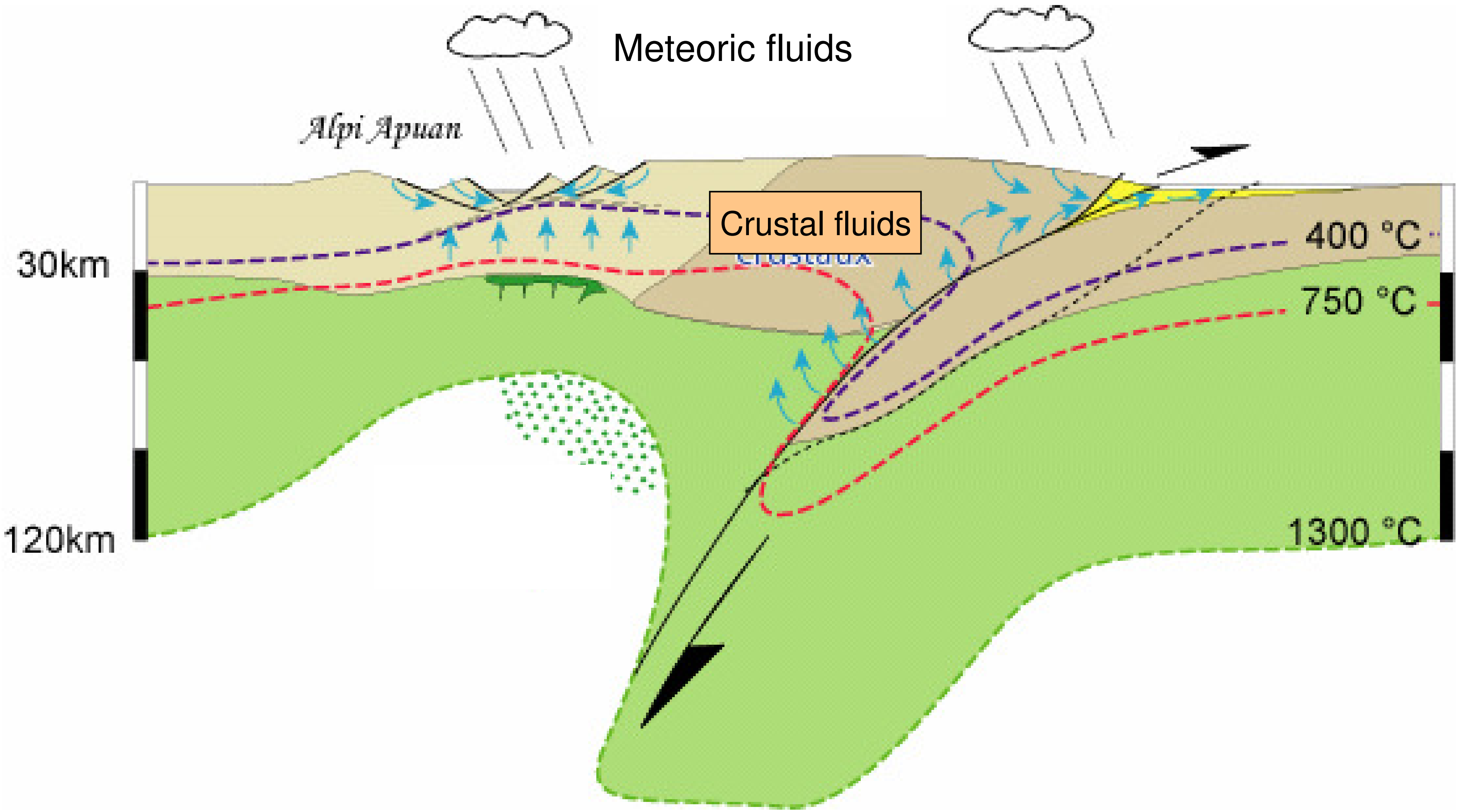
Immiscibility, fluid mixing ?

Fluid Sources

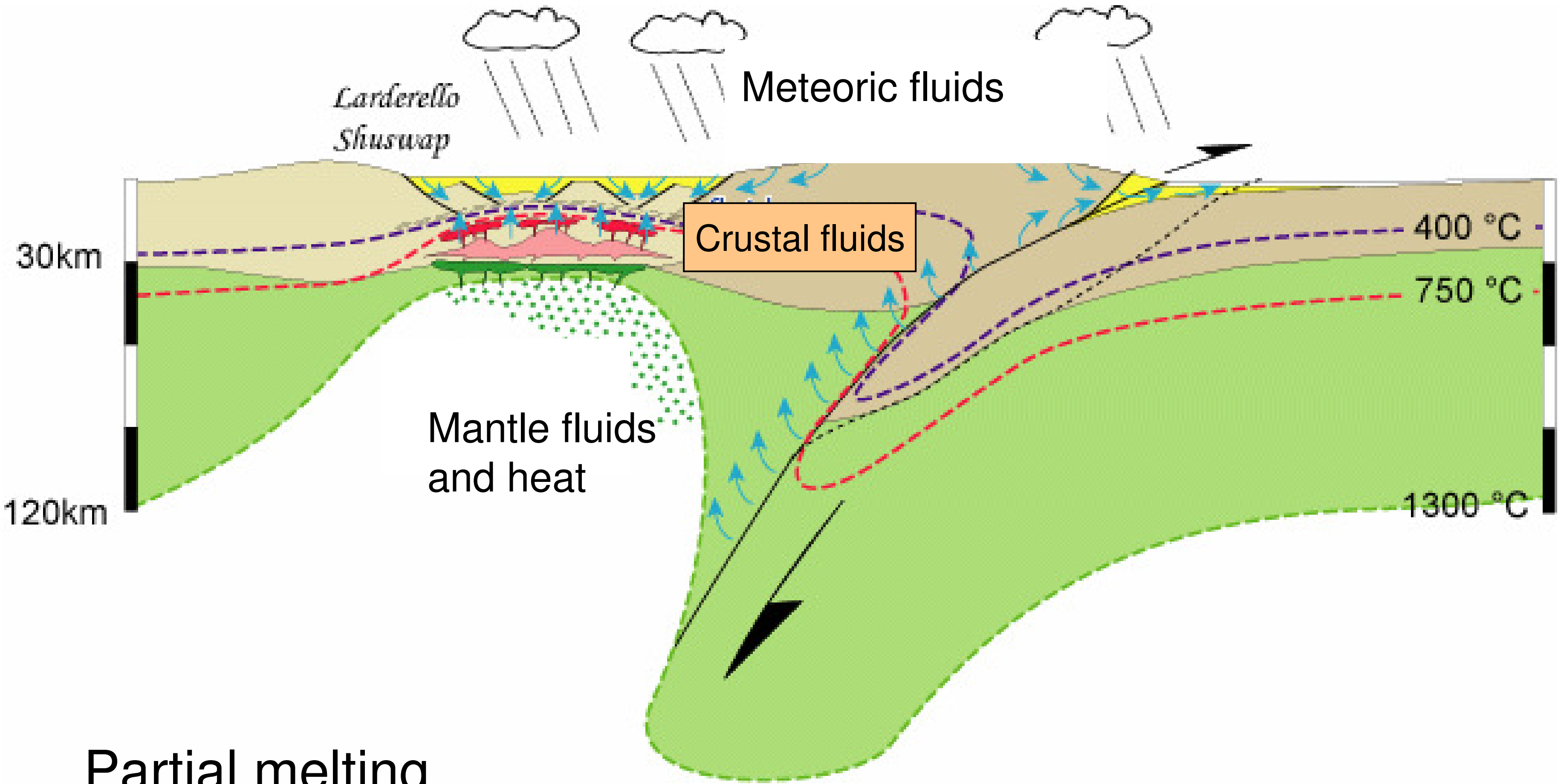
P ? T ? Depth? Thermal gradient? Heat exchange ?



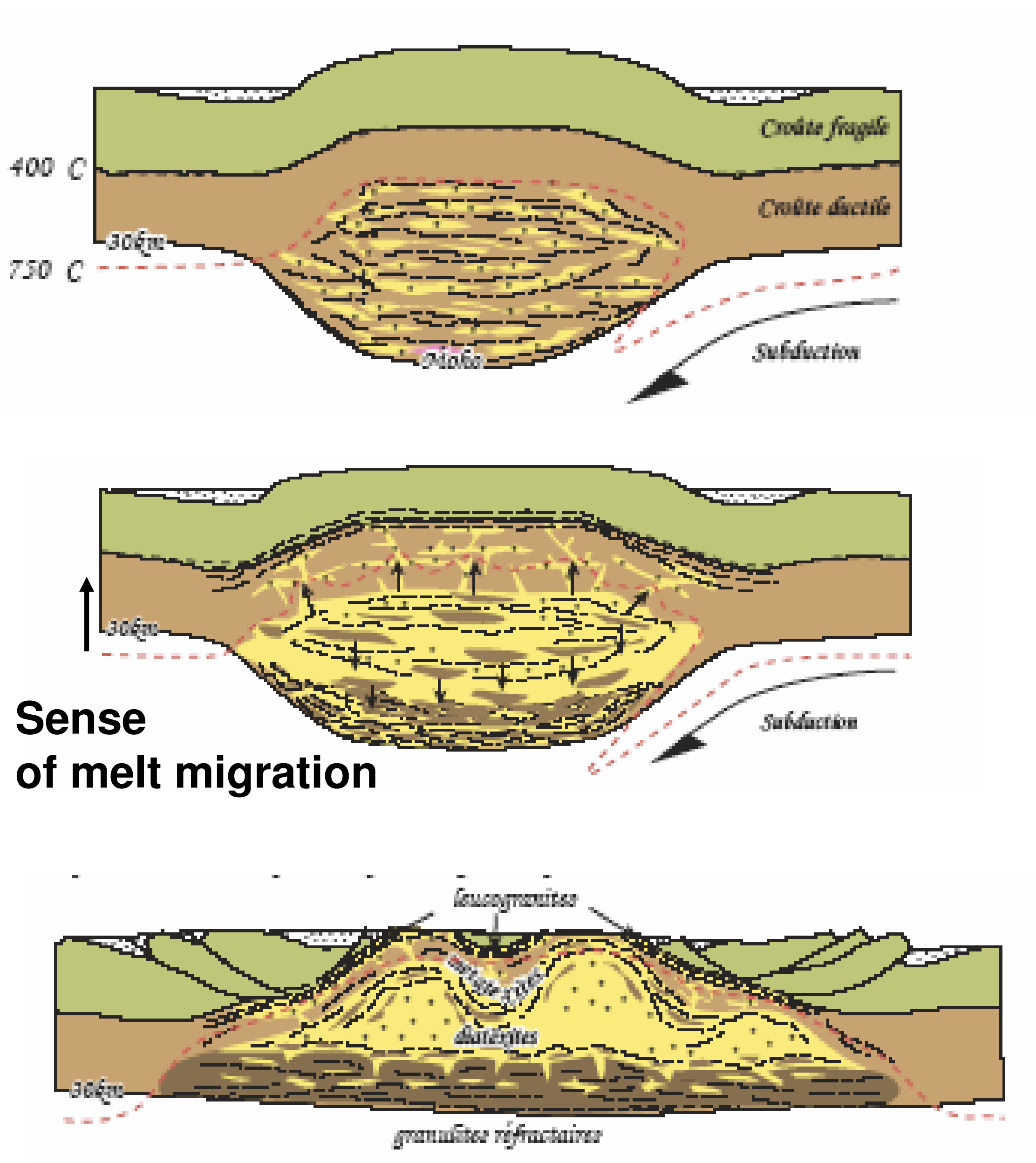
Thermal evolution of the continental crust in subduction zones



Transition from crustal thickening to crustal thinning
formation of metamorphic core complexes, horts and grabens,
crustal cooling during thinning



Partial melting
High geothermal gradients
Gravitational collapse

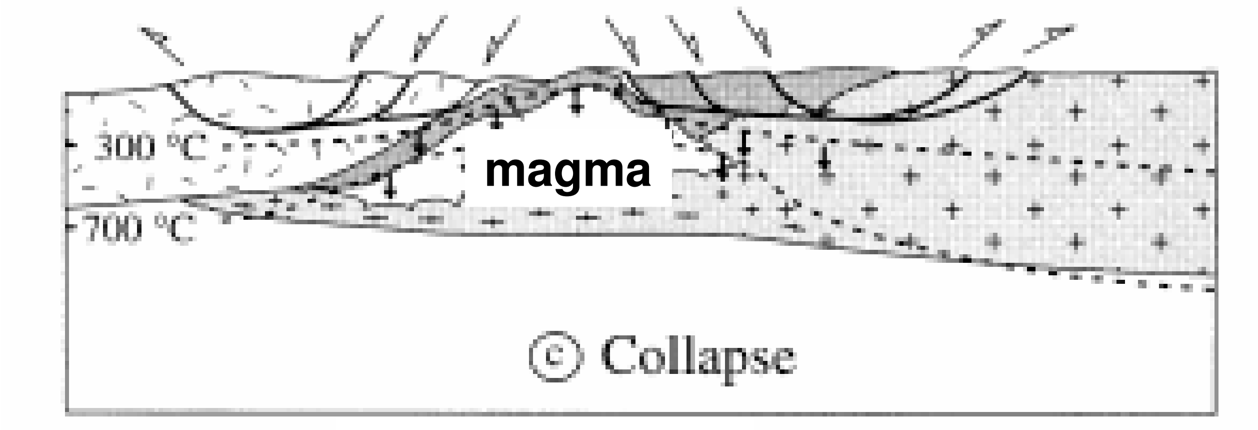


Vanderhaeghe, 2001

Continental convergence
Thickening, and accretion
Incipient melting
Increase of temperature
due to radioactive decay

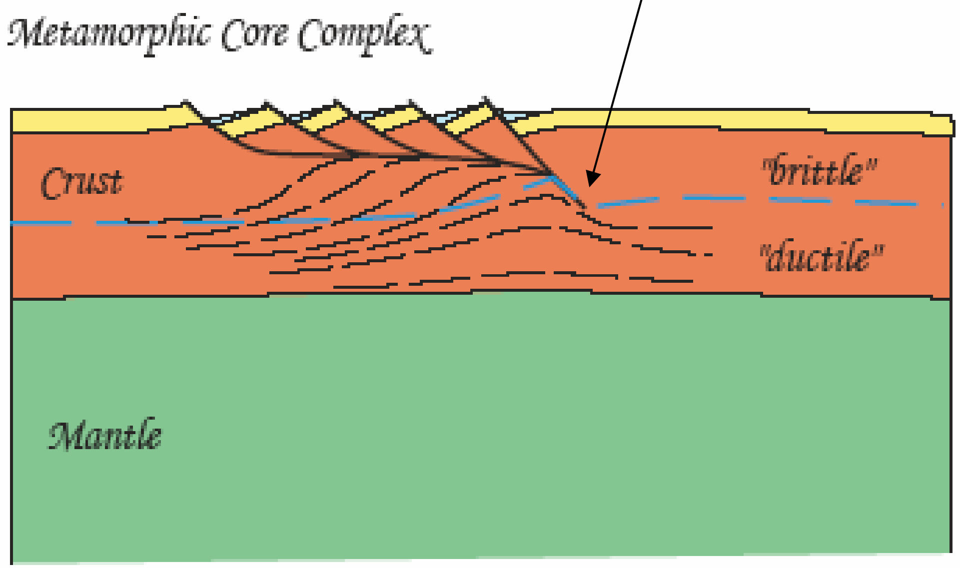
Partial melting
Formation of an anatectic layer
Pervasive melt migration
Network of granitic veins
(sills/ dykes feeding larger Intrusions)

Exhumation / crystallization of the partially molten crust
Orogenic collapse
Extension of the upper crust



Divergent collapse (Vanderhaeghe and Teyssier, 2001)

Shallow brittle
to ductile transition

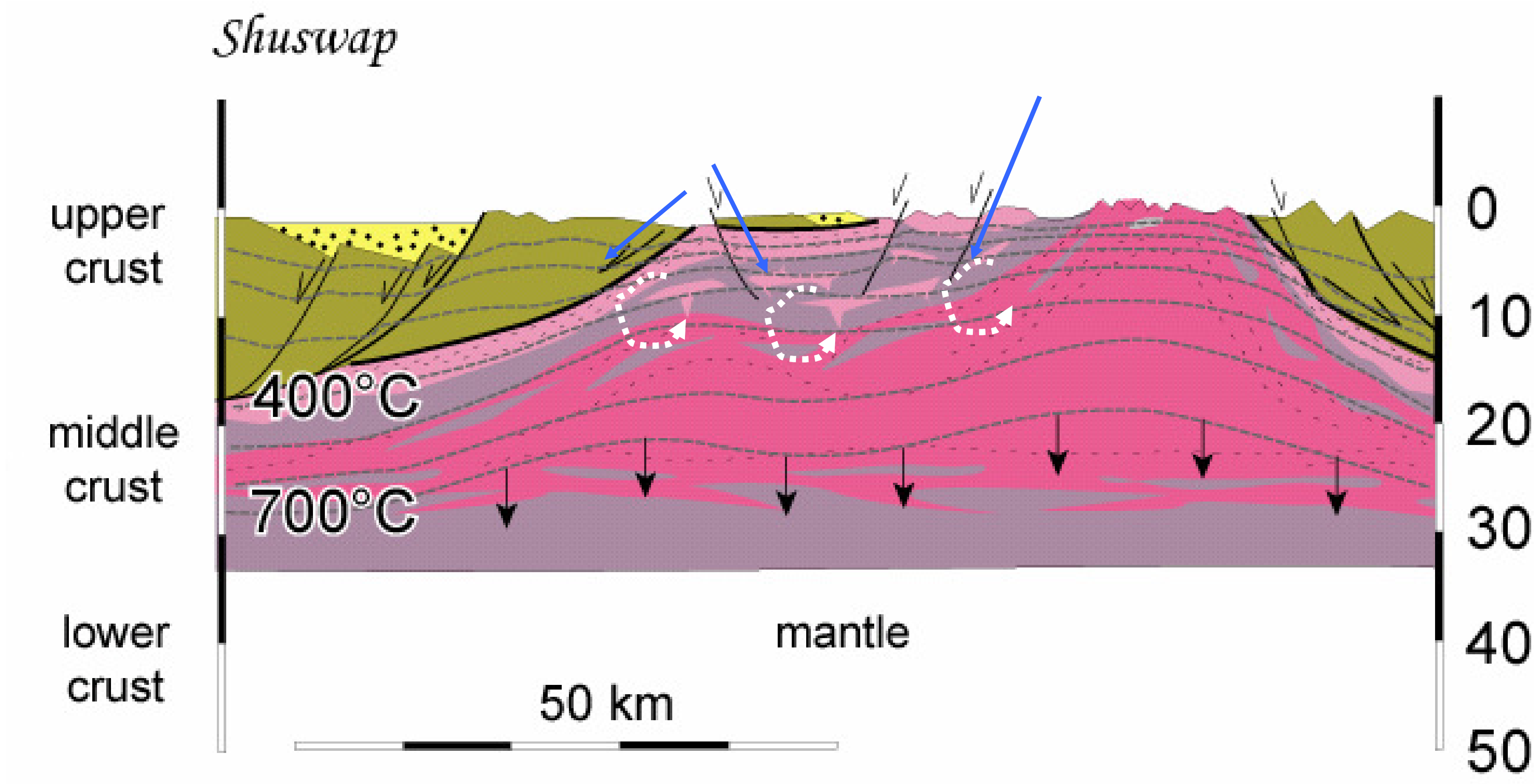


synchronous with late exhumation
gravitanional collapse of the overthickened crust
may be divergent or convergent

with or without (brittle) extension o the upper crust
Normal faulting

Ductile thinning of the lower crust

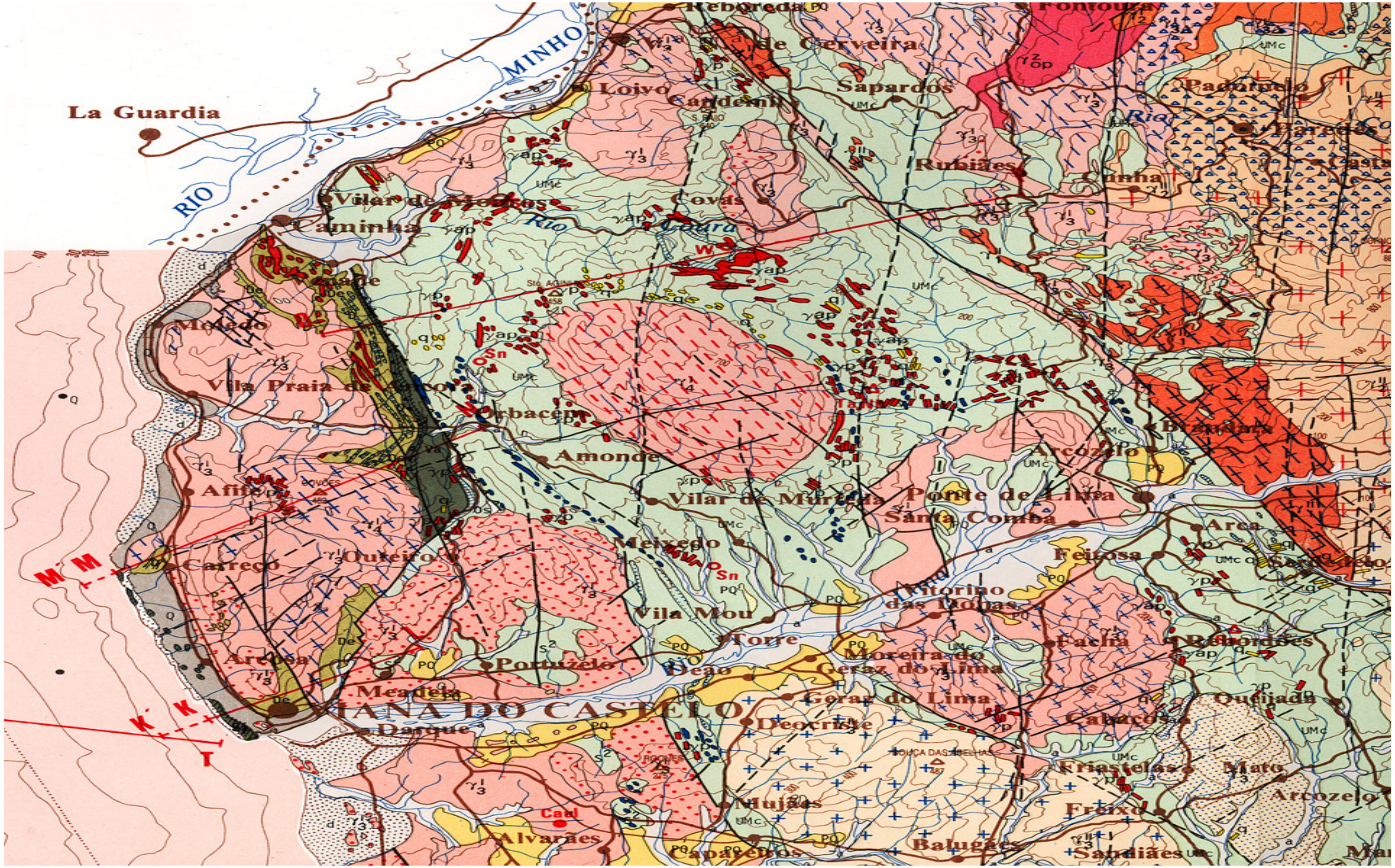
>> nearly isothermal decompression, followed by rapid cooling



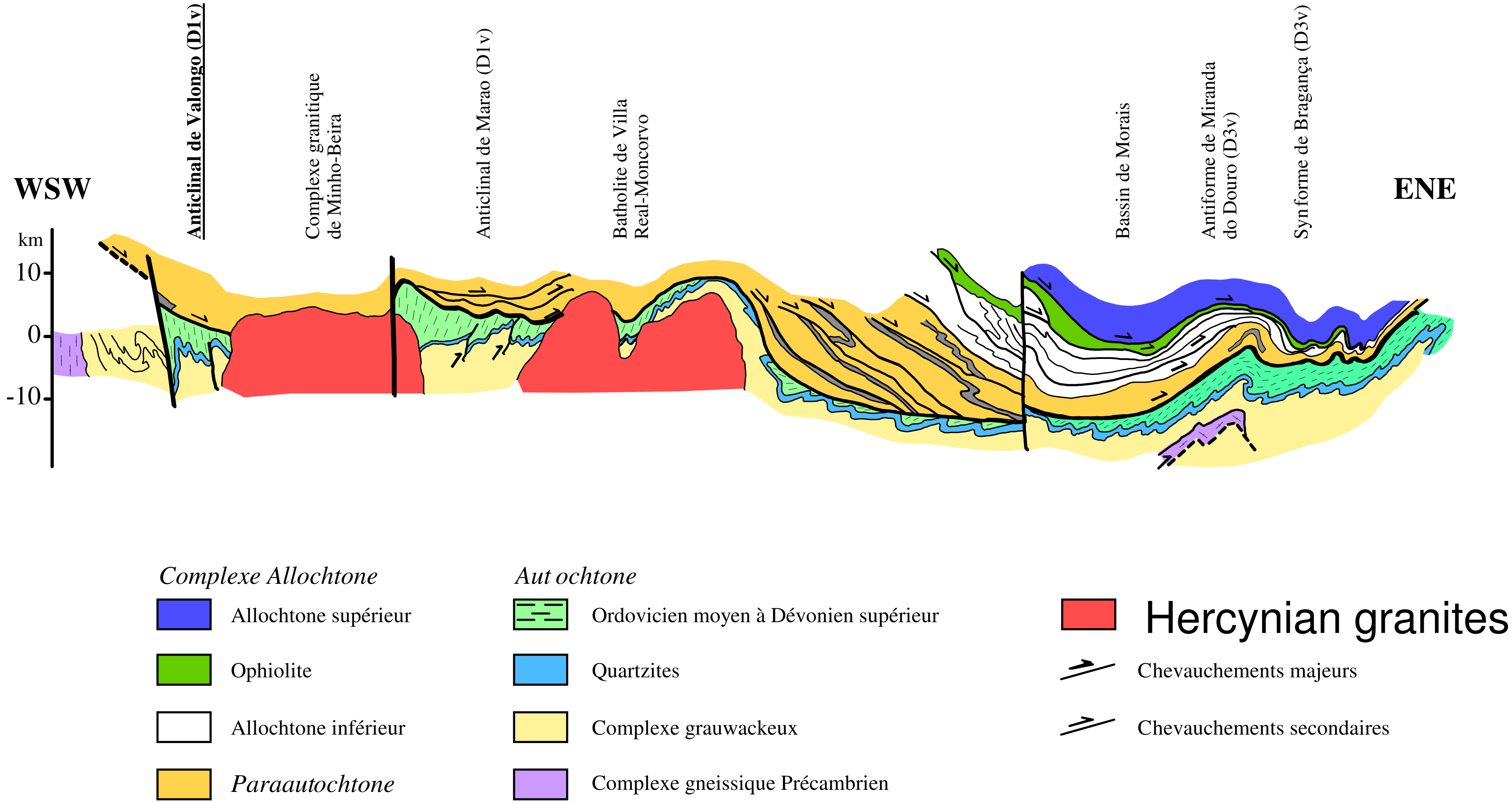
Gravitational collapse accompanied by shallow intrusion of leucogranites

>> **nature of the fluids involved in the local heat transfer, and cooling ??**

Fluid typology in past geothermal systems related to granites

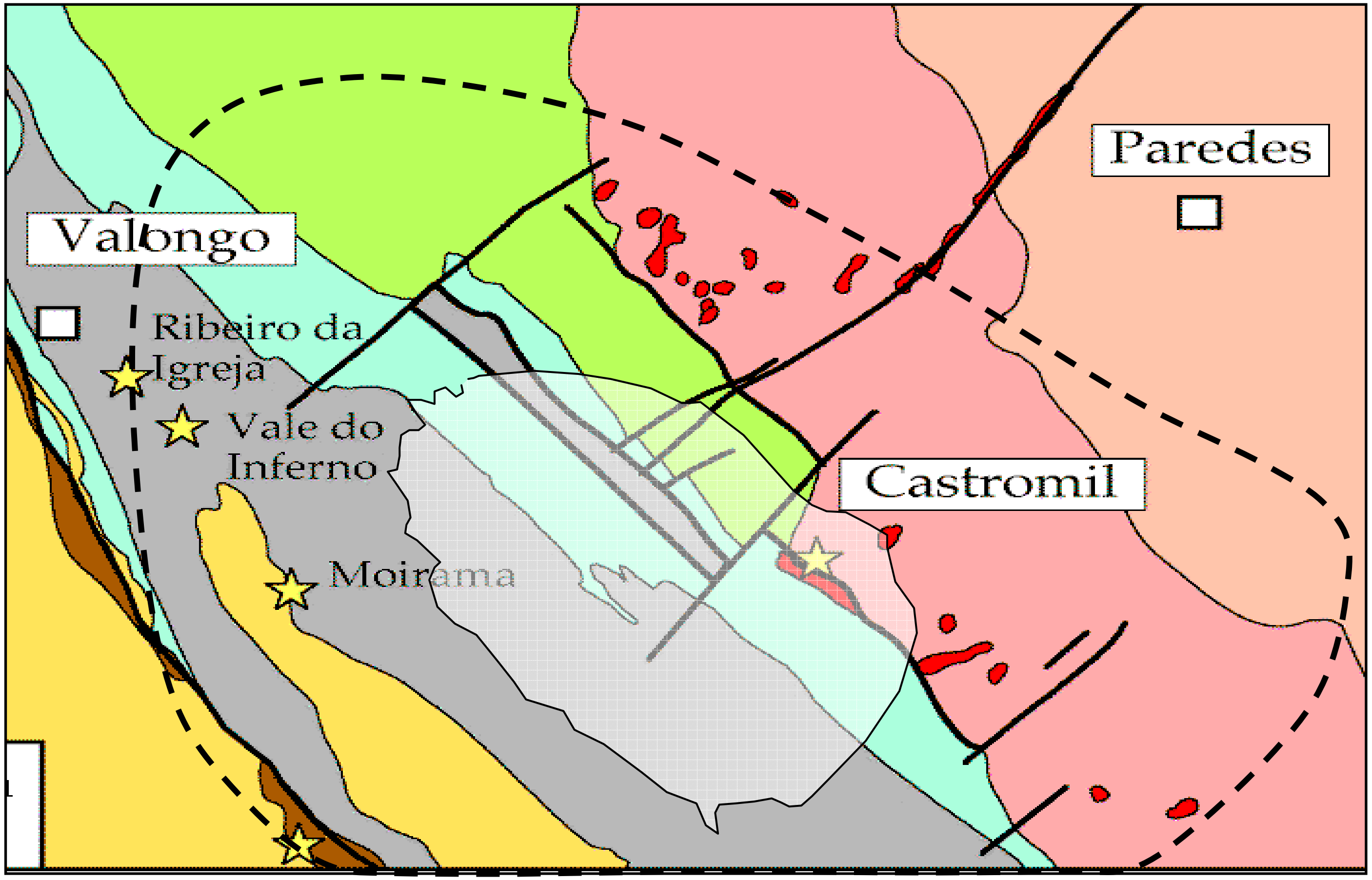


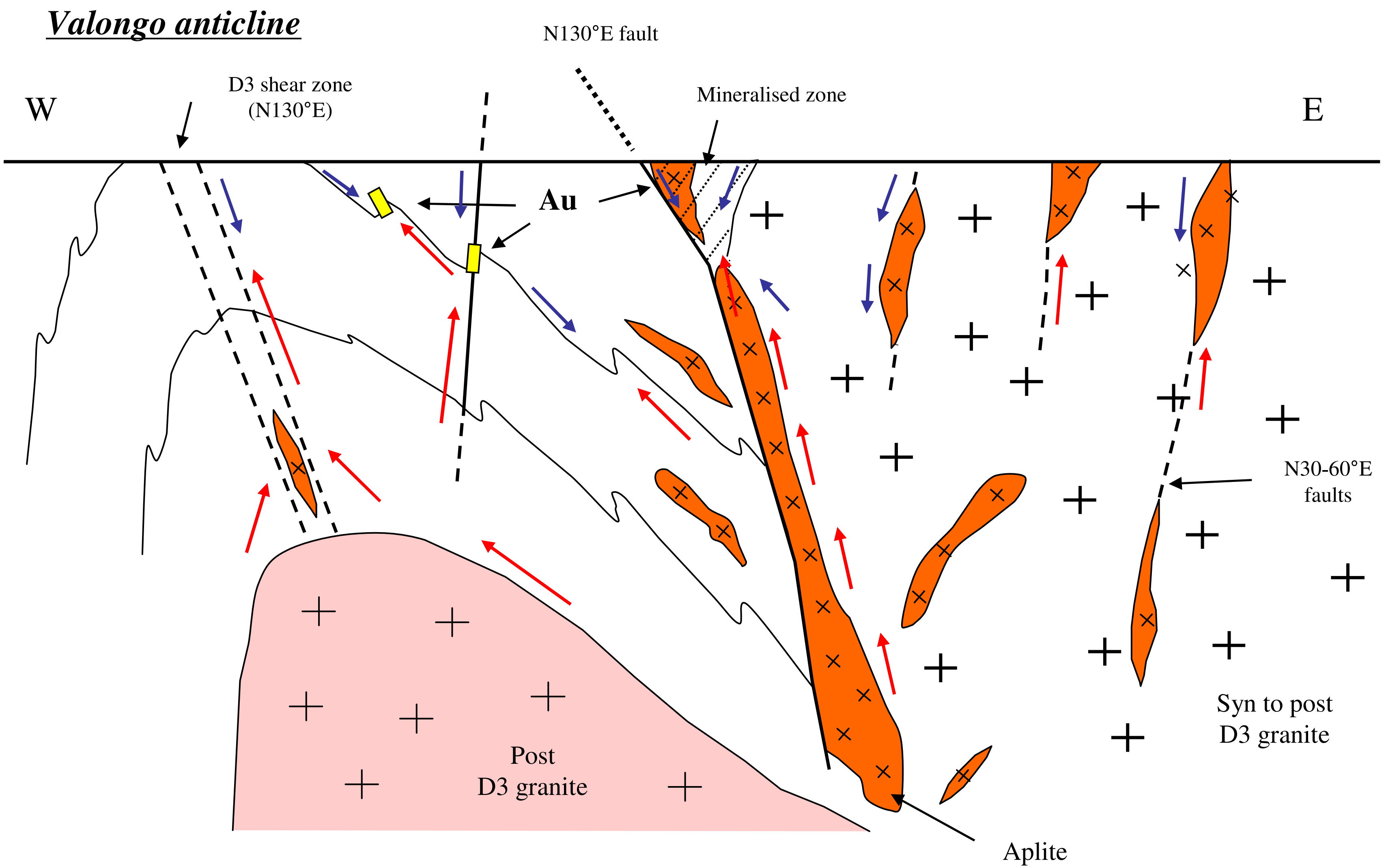
Northern Portugal



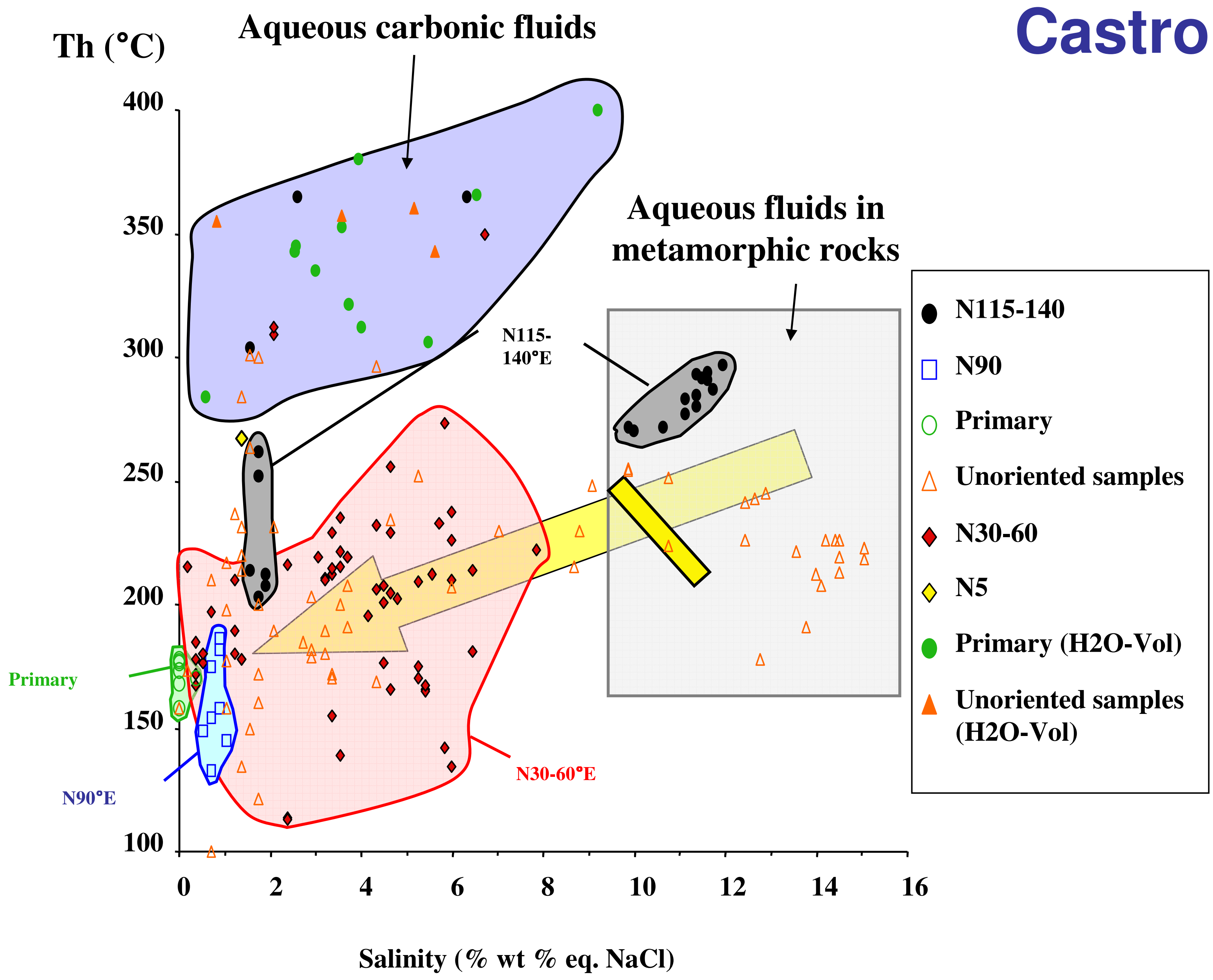
Northern Portugal (Miranda do Douro-Porto cross-section; after Ribeiro et al., 90)

Northern Portugal

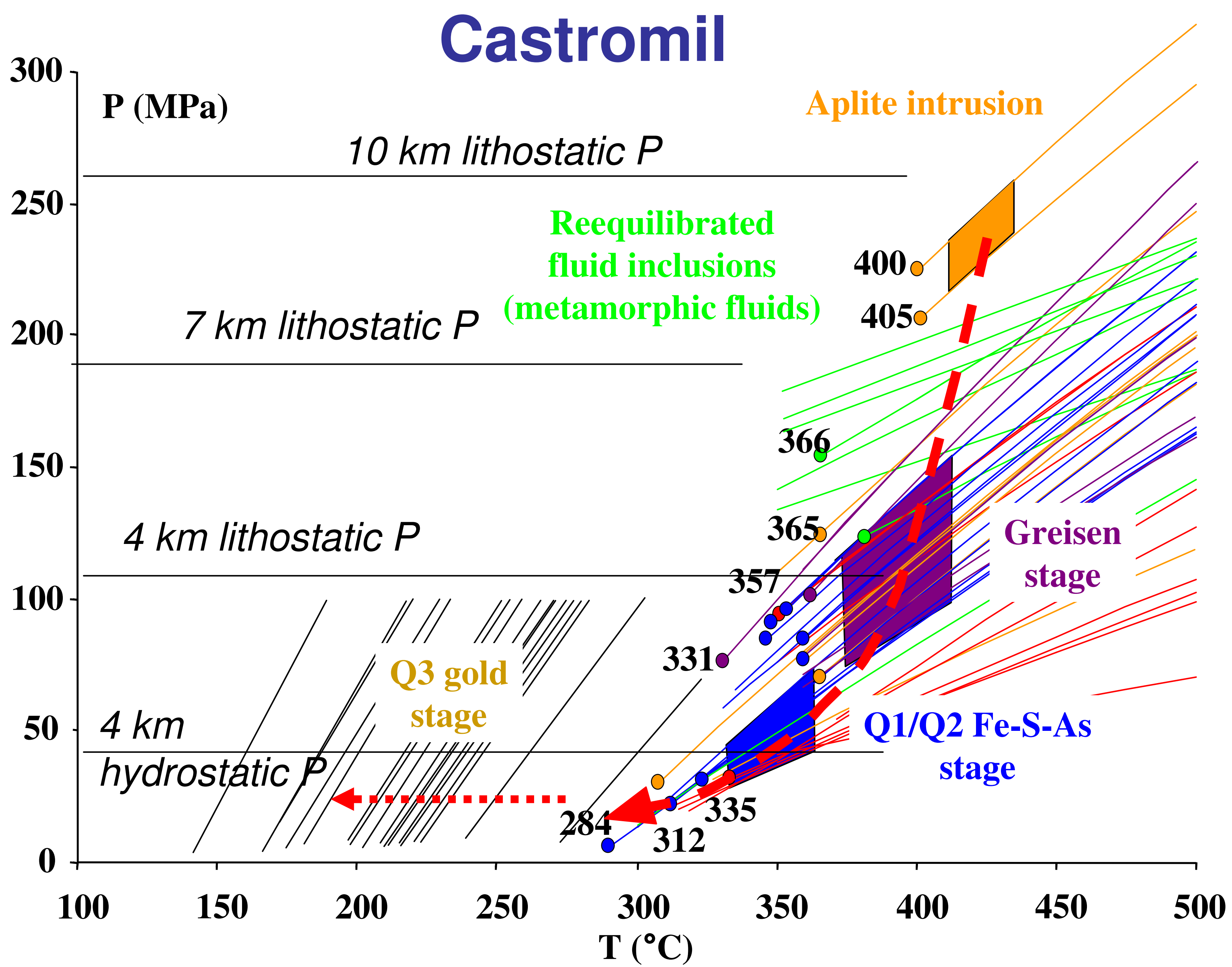



Valongo anticline
N130°E fault
D3 shear zone
(N130°E)
Mineralised zone
W
E
Au
N30-60°E
faults
Syn to post
D3 granite
Post
D3 granite
Aplite

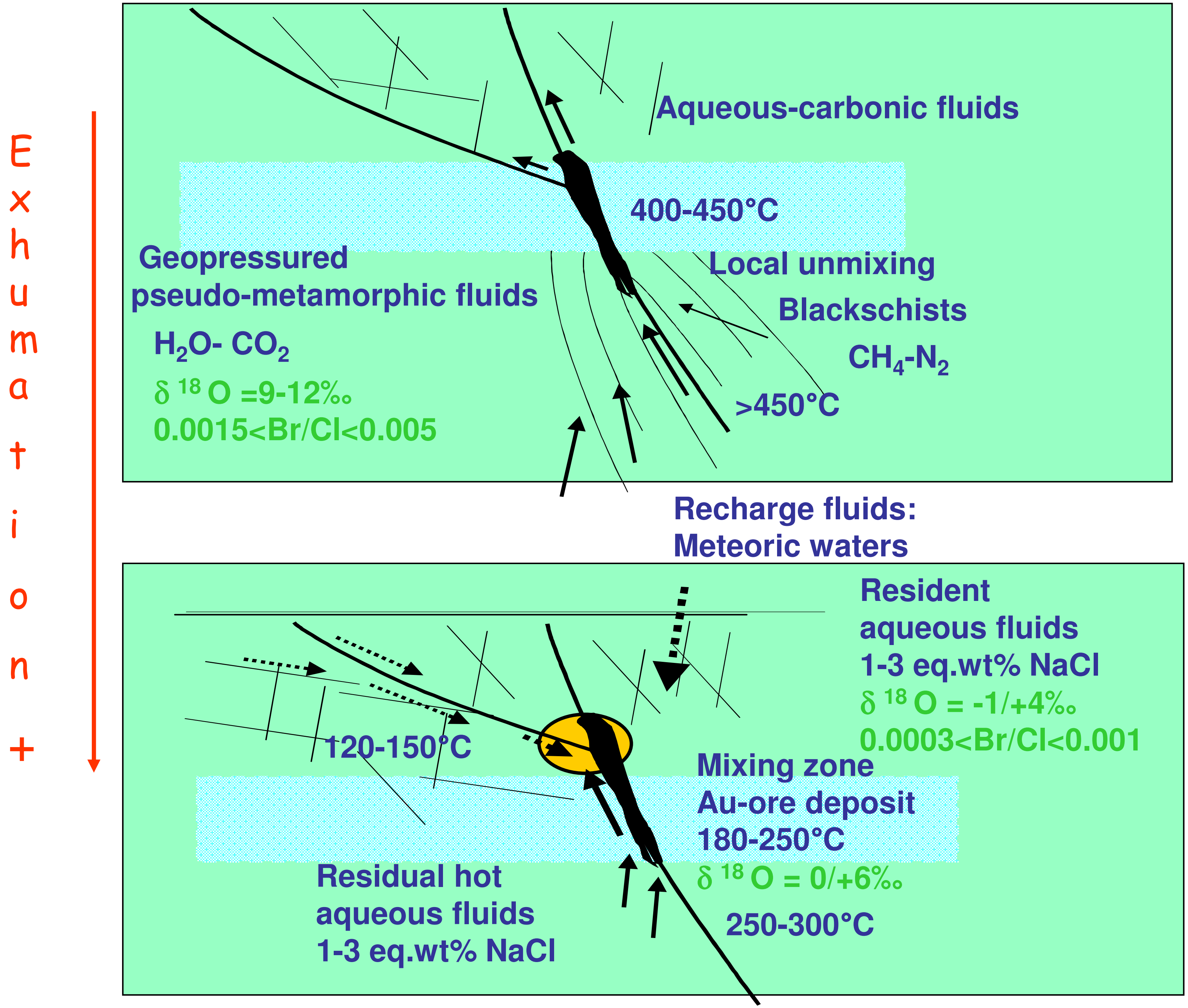
Castromil



Aqueous carbonic fluids
Th (°C)
400
350
300
250
200
150
100
Aqueous fluids in metamorphic rocks
N115-140°E
Primary
N90°E
N30-60°E
0
2
4
6
8
10
12
14
16
Salinity (% wt % eq. NaCl)
N115-140
N90
Primary
Unoriented samples
N30-60
N5
Primary (H2O-Vol)
Unoriented samples (H2O-Vol)

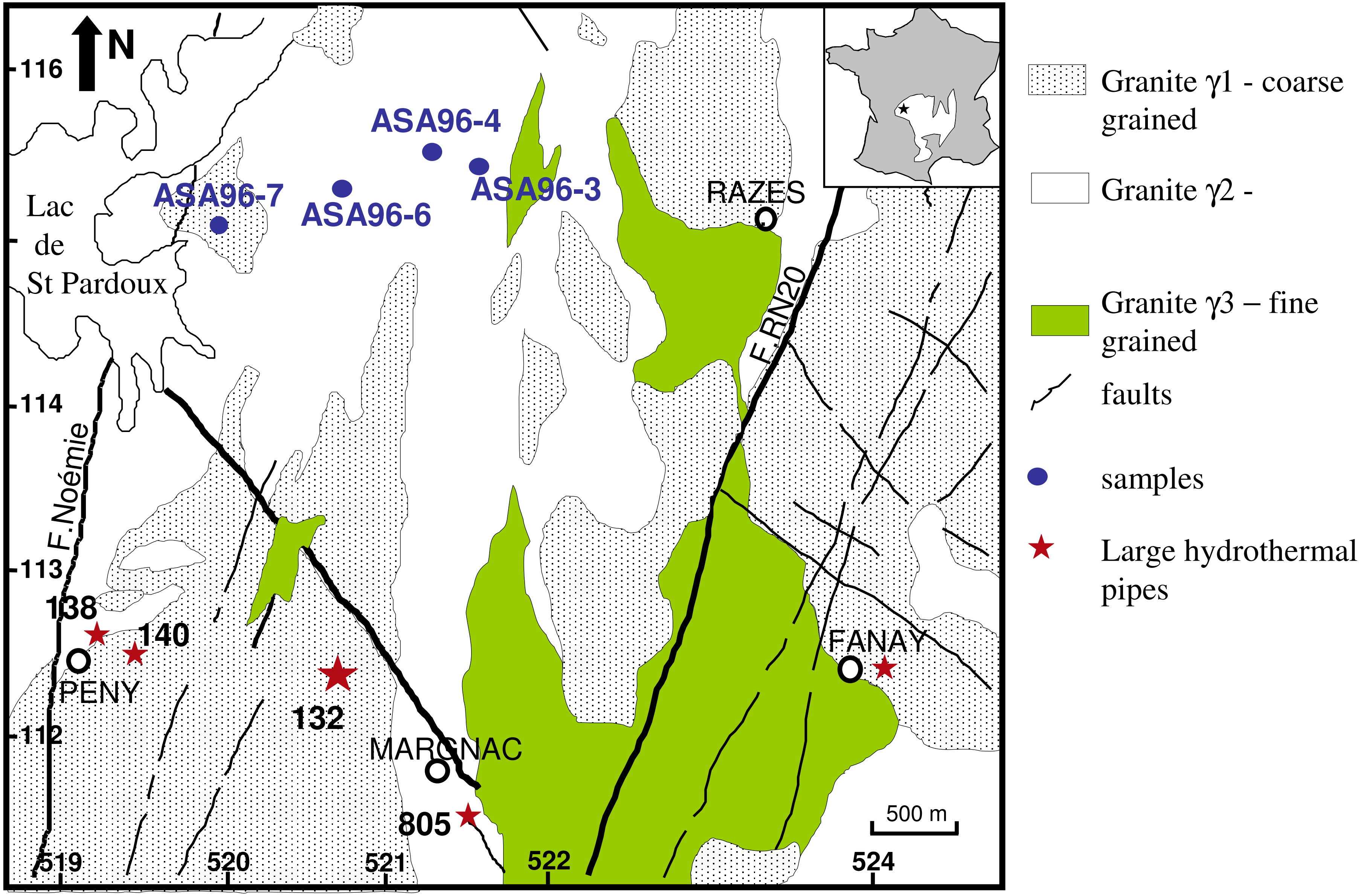


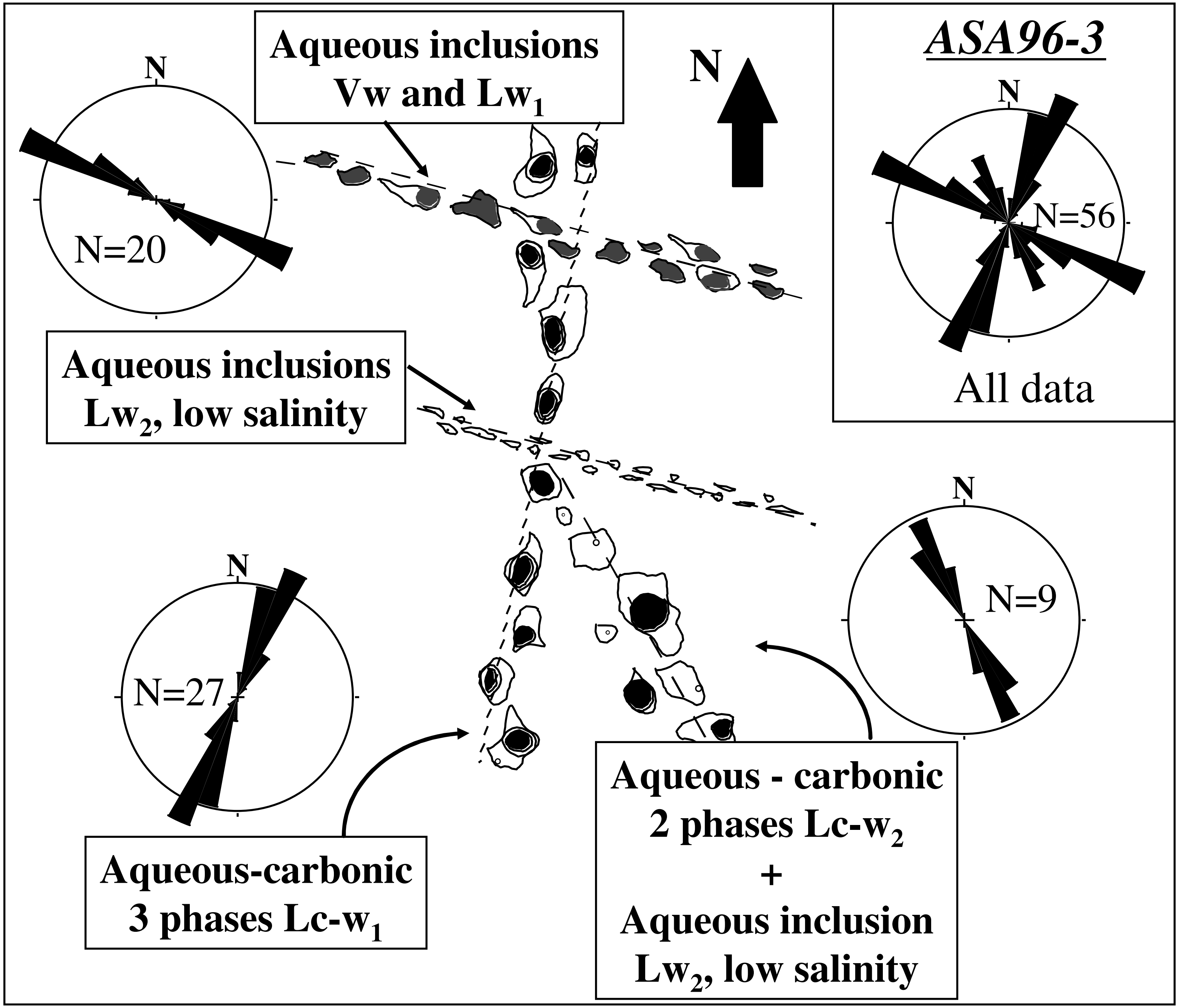
Castromil
P (MPa)
300
250
200
150
100
50
0
10 km lithostatic P
7 km lithostatic P
4 km lithostatic P
4 km
hydrostatic P
Aplite intrusion
Reequilibrated
fluid inclusions
(metamorphic fluids)
Greisen
stage
Q1/Q2 Fe-S-As
stage
Q3 gold
stage
400
405
366
365
357
331
335
312
284
100
150
200
250
300
350
400
450
500
T (°C)



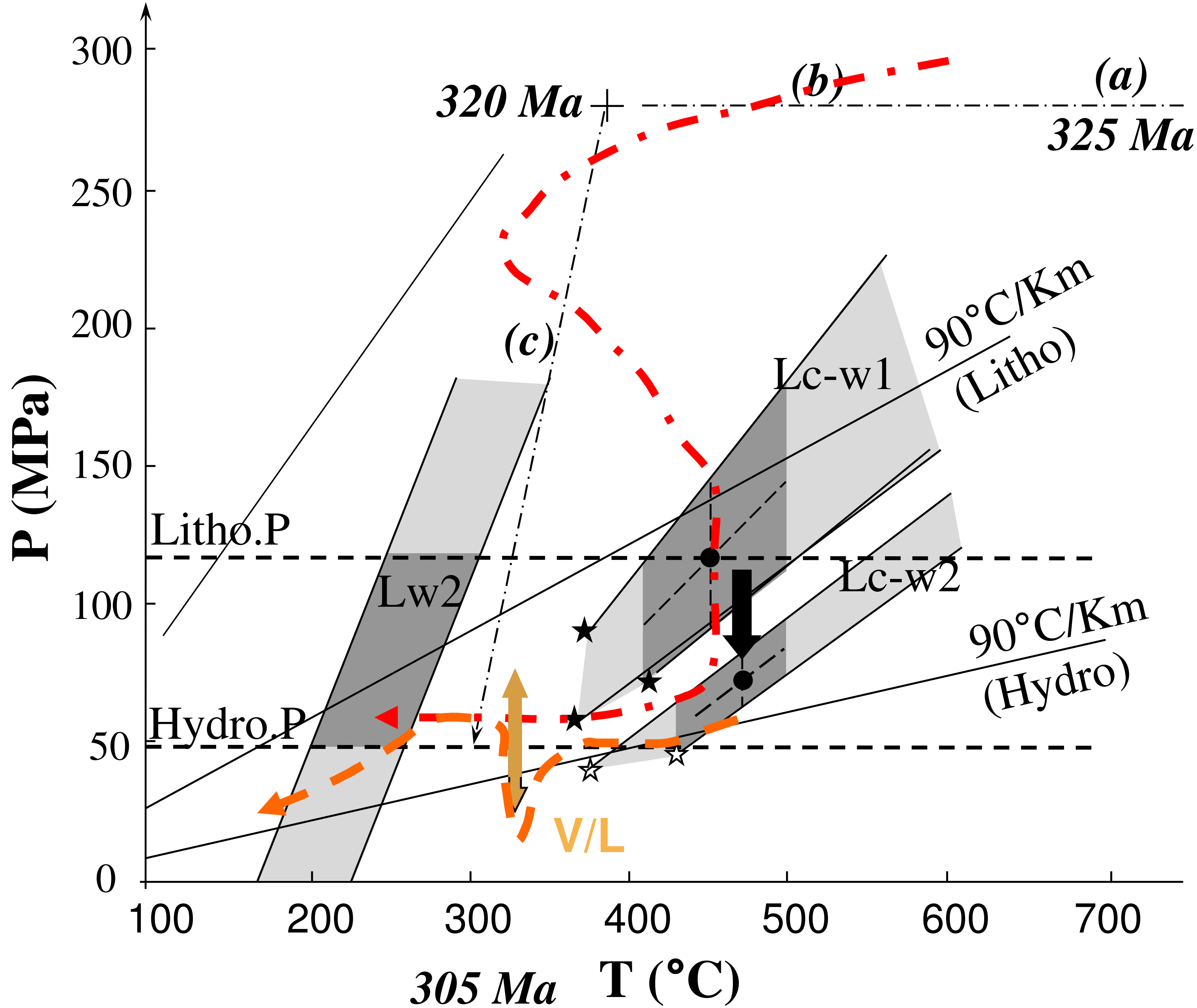
Exhumation
Aqueous-carbonic fluids
400-450°C
Geopressured
pseudo-metamorphic fluids
H_2O- CO_2
$\delta^{18}O$ =9-12‰
0.0015<Br/Cl<0.005
Local unmixing
Blackschists
CH_4-N_2
>450°C
Recharge fluids:
Meteoric waters
Resident
aqueous fluids
1-3 eq.wt% NaCl
$\delta^{18}O$ = -1/+4‰
0.0003<Br/Cl<0.001
120-150°C
Mixing zone
Au-ore deposit
180-250°C
$\delta^{18}O$ = 0/+6‰
250-300°C
Residual hot
aqueous fluids
1-3 eq.wt% NaCl

Late intrusion in French Massif Central : Intense microfracturing and fluid percolation

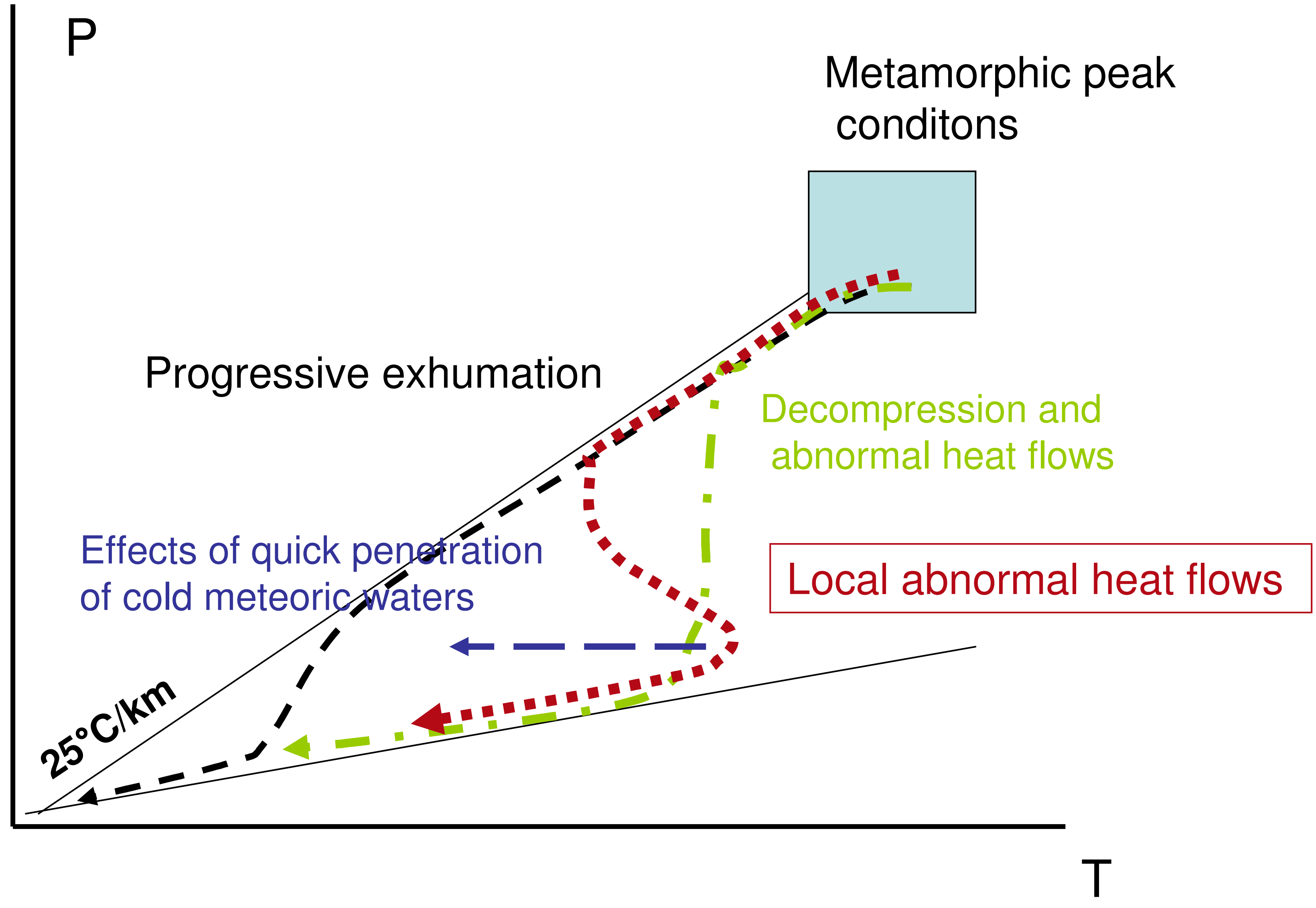




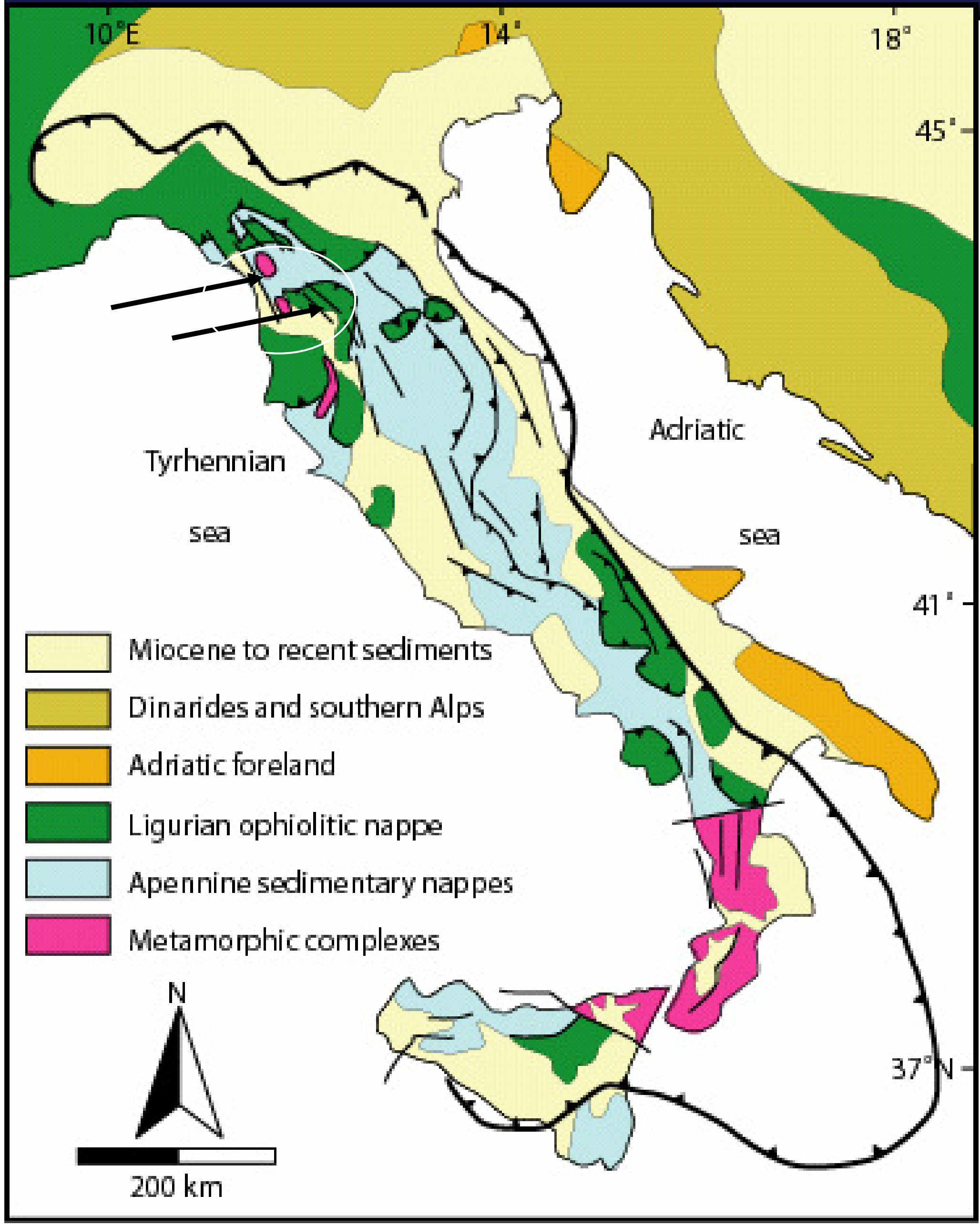
ASA96-3
N
N=56
All data
N
N=20
Aqueous inclusions
Vw and Lw_1
N
Aqueous inclusions
Lw_2, low salinity
N
N=9
N
N=27
Aqueous-carbonic
3 phases $Lc\text{-}w_1$
Aqueous - carbonic
2 phases $Lc\text{-}w_2$
+
Aqueous inclusion
Lw_2, low salinity



P (MPa)
300
250
200
150
100
50
0
100
200
300
400
500
600
700
T (°C)
305 Ma
320 Ma
325 Ma
(a)
(b)
(c)
Litho.P
Hydro.P
Lw2
Lc-w1
Lc-w2
90°C/Km
(Litho)
90°C/Km
(Hydro)
V/L


P
Metamorphic peak
conditons
Progressive exhumation
Decompression and
abnormal heat flows
Effects of quick penetration
of cold meteoric waters
Local abnormal heat flows
25°C/km
T

Northern Apennines belt

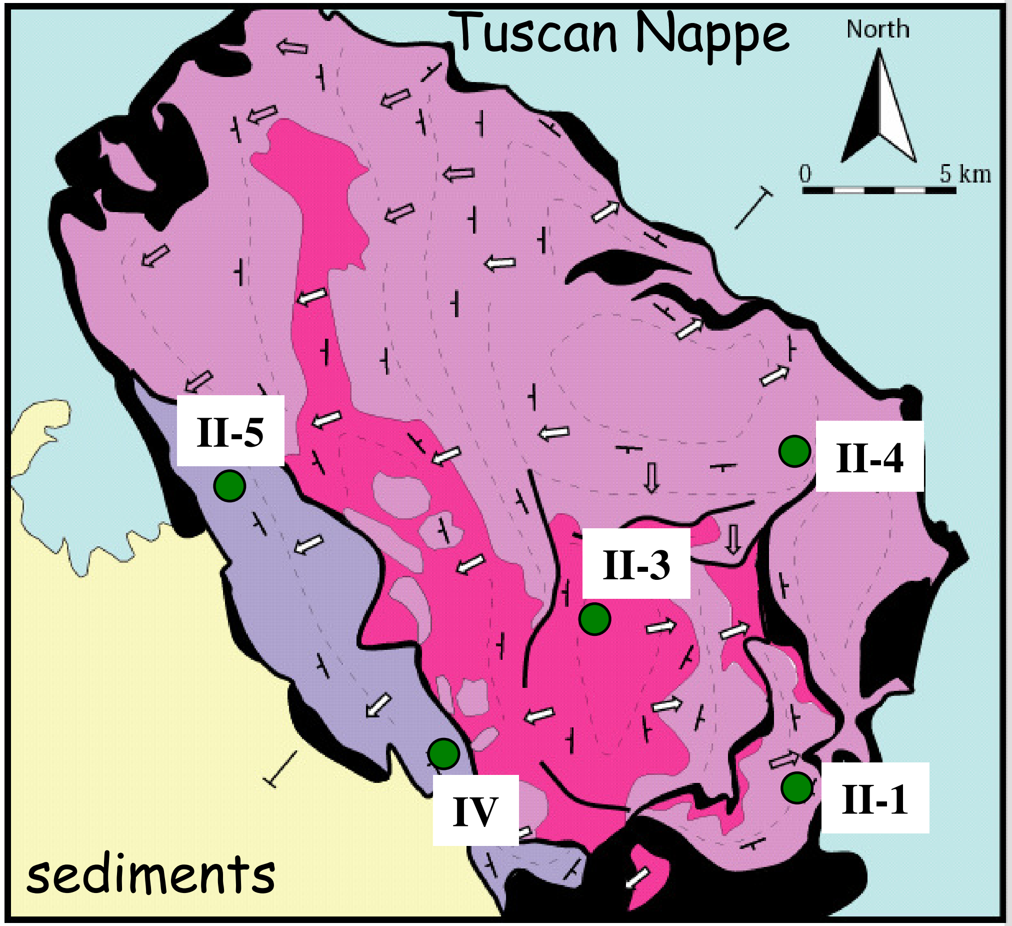


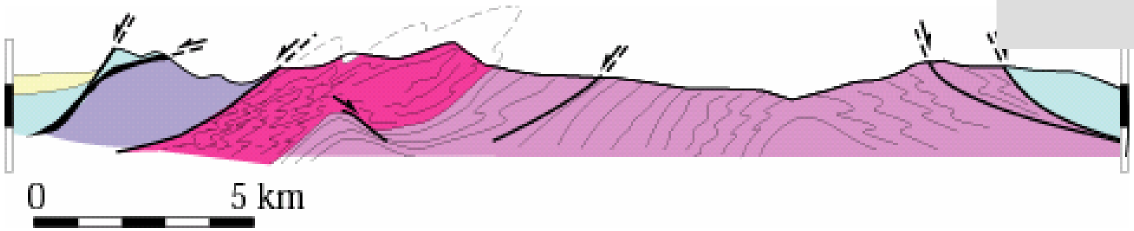
continental collision
Europe (Sardinia-Corsica) /Africa (Adria)

Late stages
1- exhumation of the MCC complexes

2- melting, granite intrusions and large thermal anomalies

The Apuan MCC





Tuscan nappe

Sediments (Trias-Miocene)- marls, limestones

Post D1 veins coeval of folds, and Crosscutting the foliation (Macigno formation)

Apuan metamorphic complex:

- **Apuan Unit**

sample II-1: pseudo-macigno formation.

sample II-4: Scisti sericitici group.

- **Massa Unit (siliclastic sequence)**

sample IV: Rippa mine (hydrothermal veins, Hg)

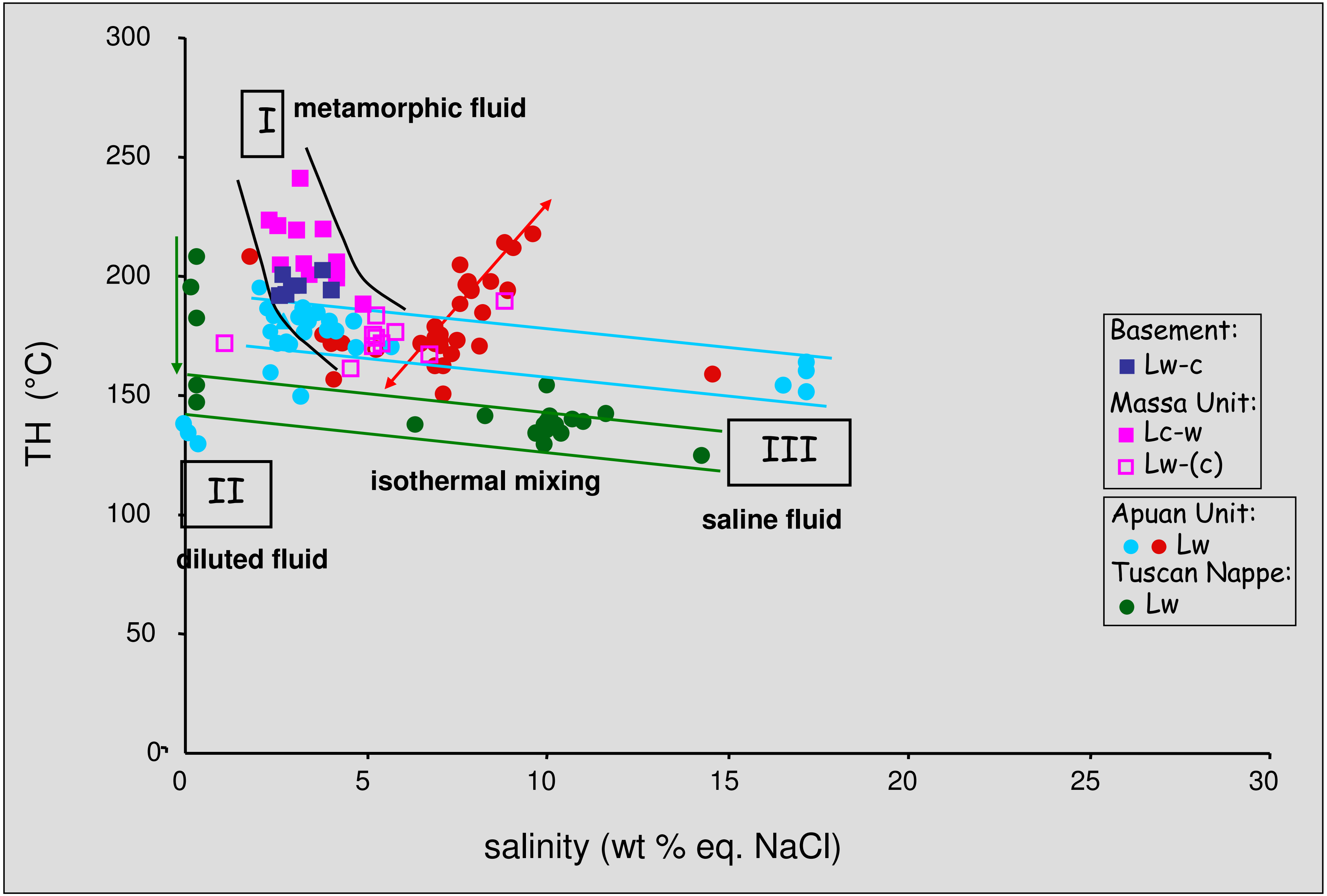
sample II-5: Breccia level (detachment fault)

- **Basement** (phyllites,quartzites, schists) sample II-3.

Works in progress
in coll. C. Montomoli, G. Ruggieri

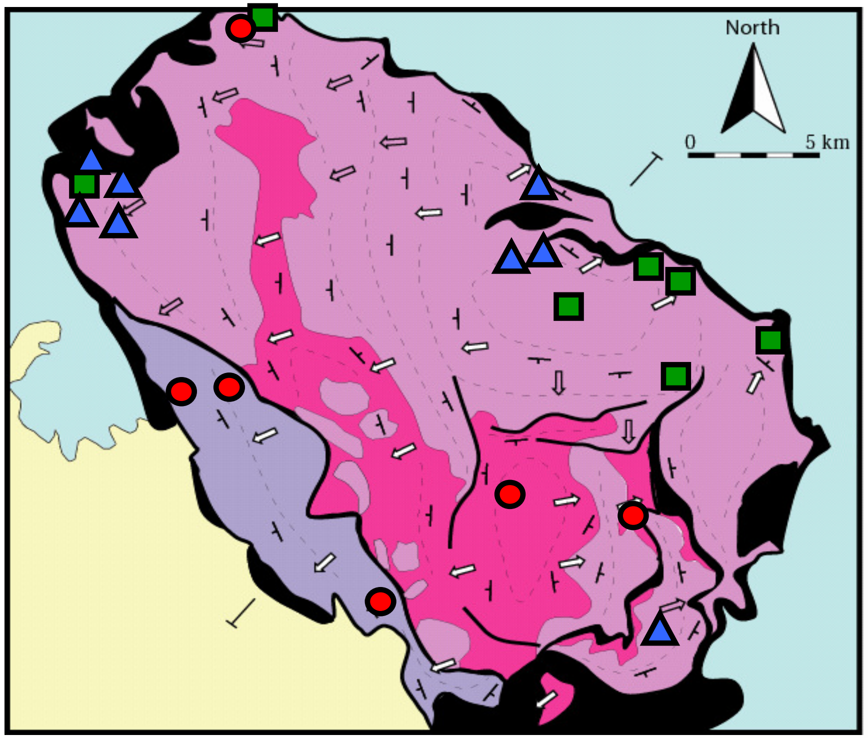
Salinity-TH evolution

Northern Apennines

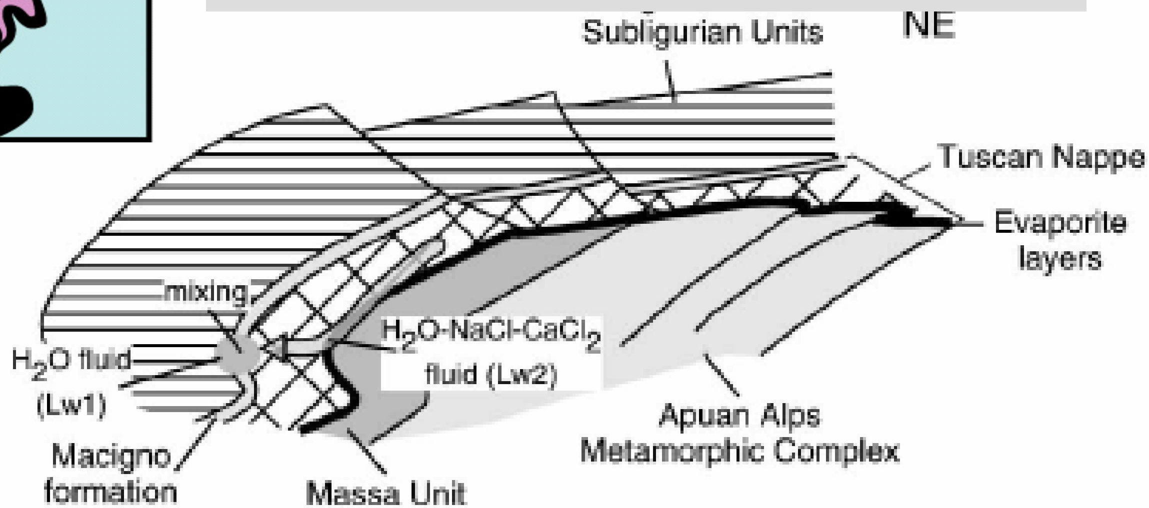


Fluid distribution in the Alpi Apuan

Northern Apennines



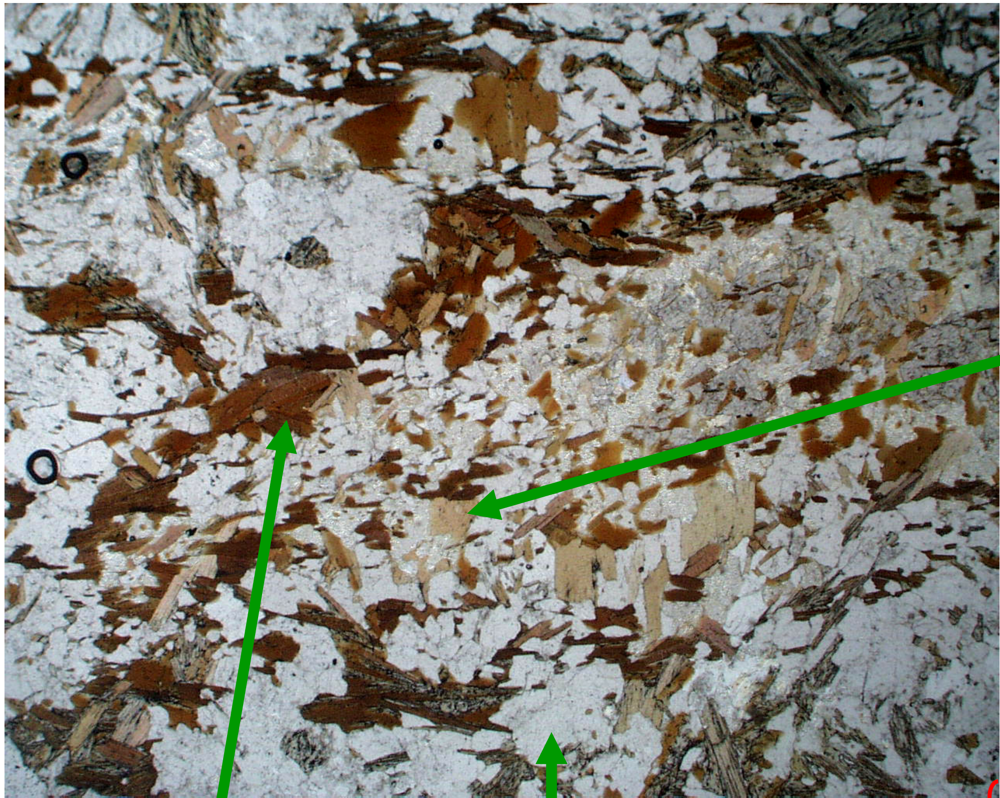
- **Massa Unit**, **Basement**:
  aqueous-carbonic fluid,
- cataclasite zone:
  saline fluid,
- **Apuan Unit**:
  aqueous fluid
- Tuscan nappe : H_2O-CH_4/ H_2O-salts



Montomoli et al., 2001

Biotite zone : veins and recrystallized quartz lenses *(Larderello)*

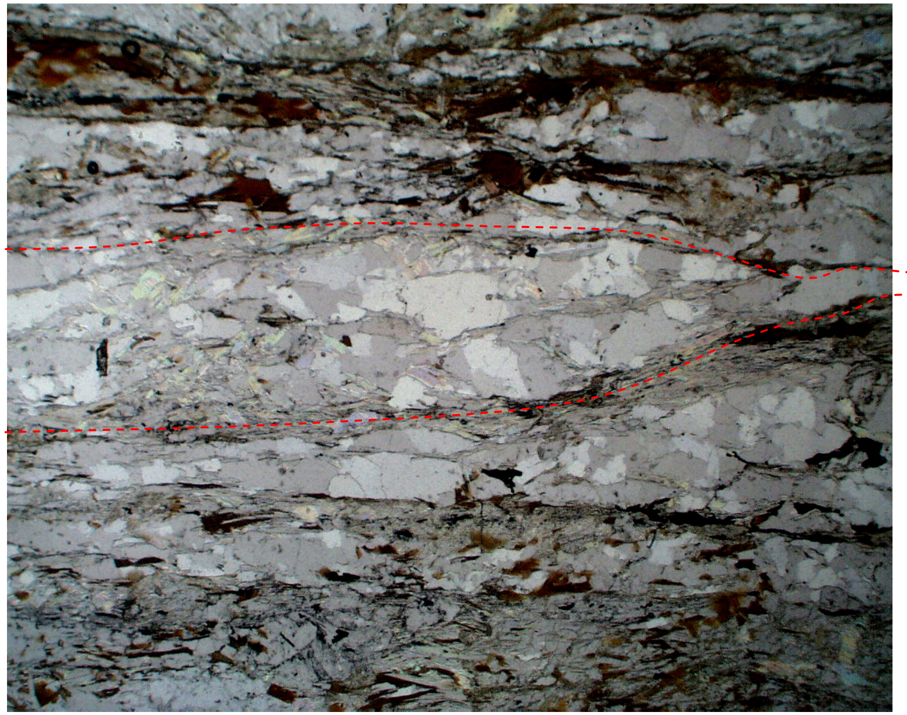
Biotite-Tourmaline-pyrite-Graphite-rec. Qz



Tourmaline

Biotite

Quartz

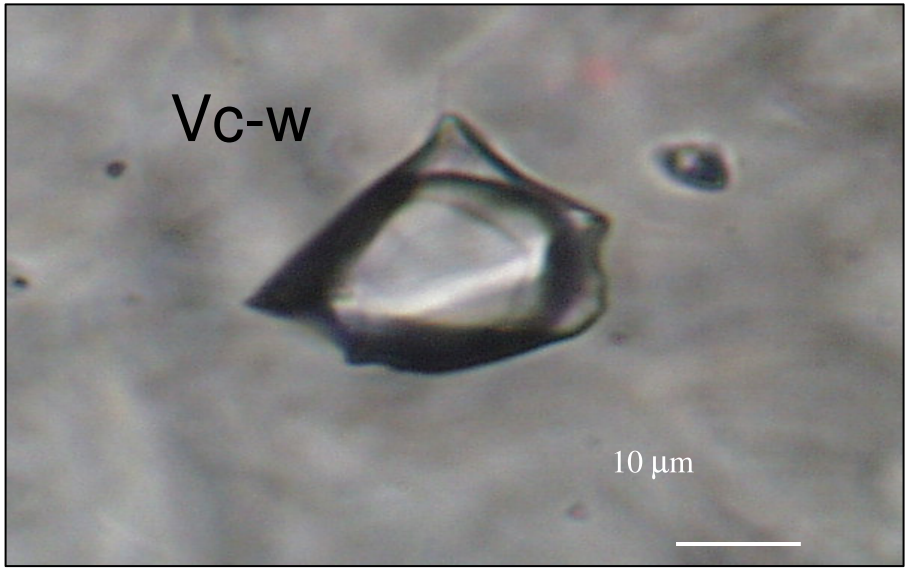


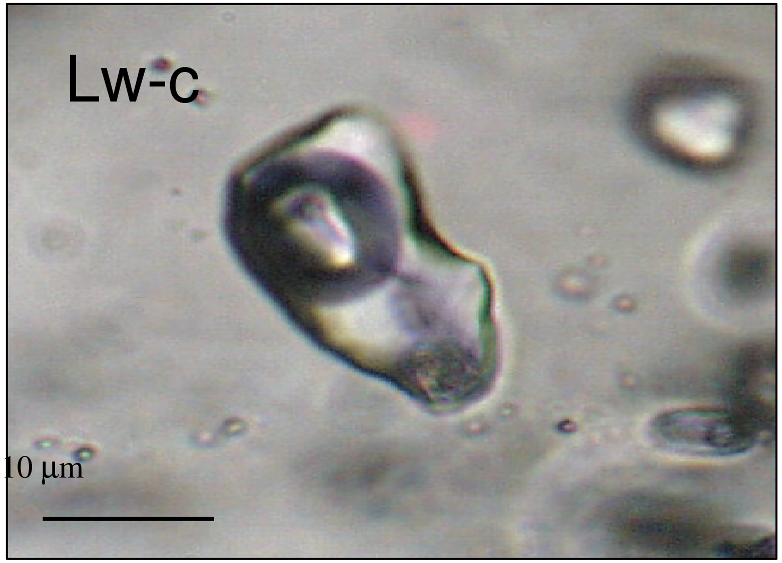
Quartz lens

Fluid inclusion types

Larderello

Aqueous carbonic inclusions





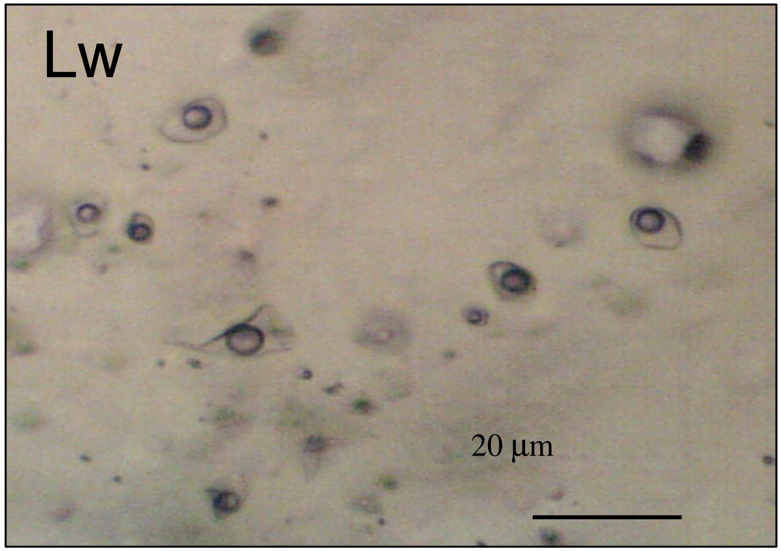
Saline inclusions

Lw- c -h

QuickTime™ et un décompresseur
Photo - JPEG sont requis pour visualiser
cette image.

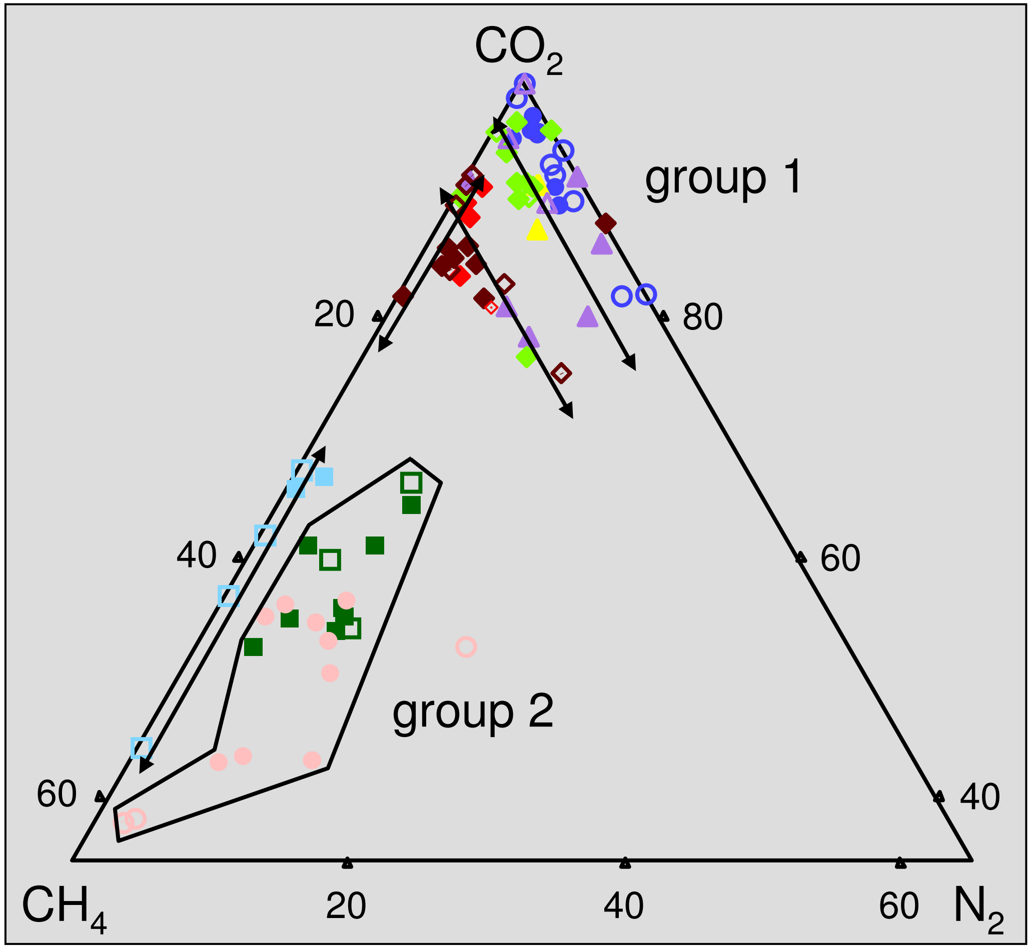
10 µm

Aqueous inclusions



Raman results

Larderello



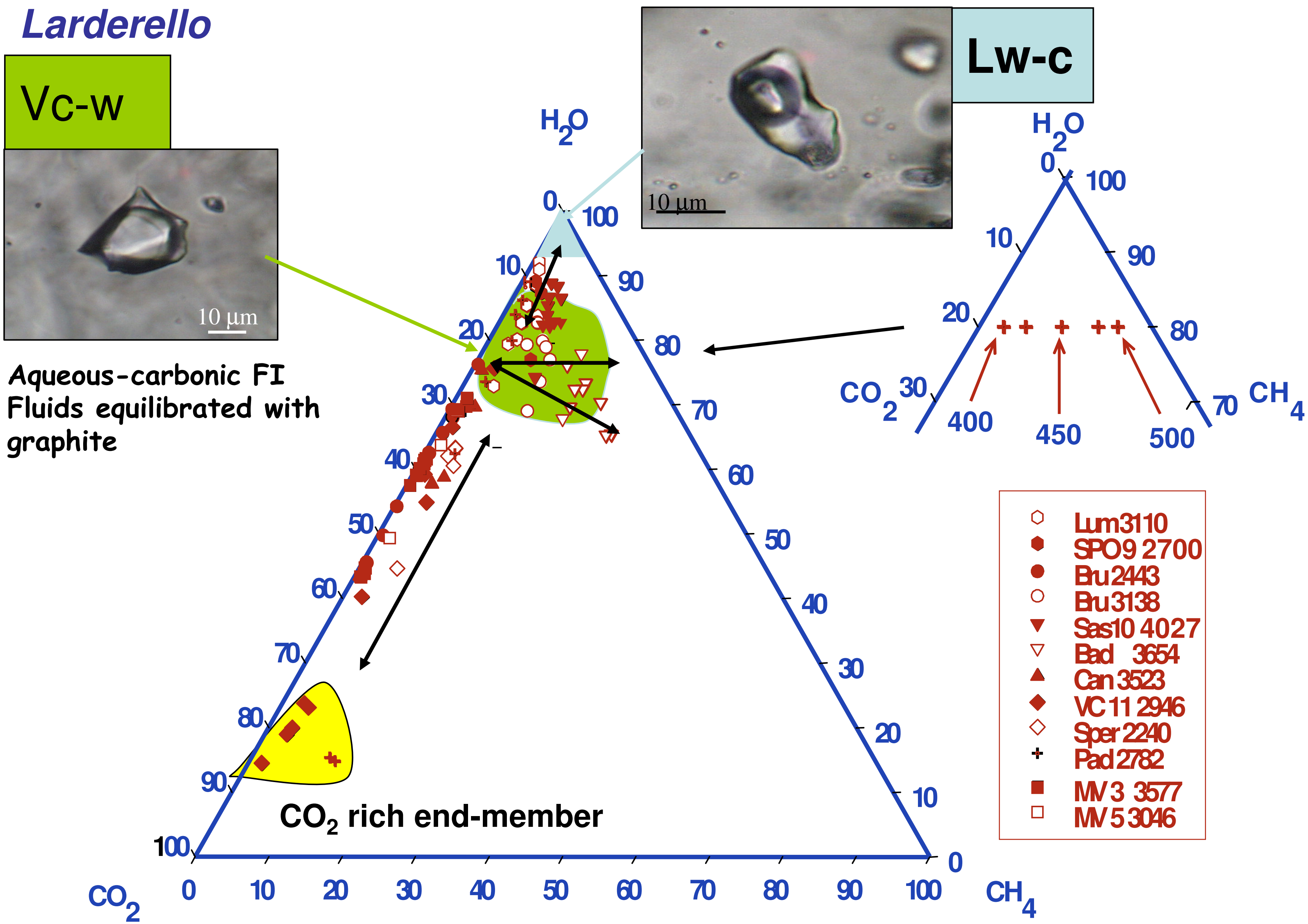
☞ 3 types of FI analysed:

● Vc-w, ○ Lw+/-c, ⊙ Lw-(c)-h

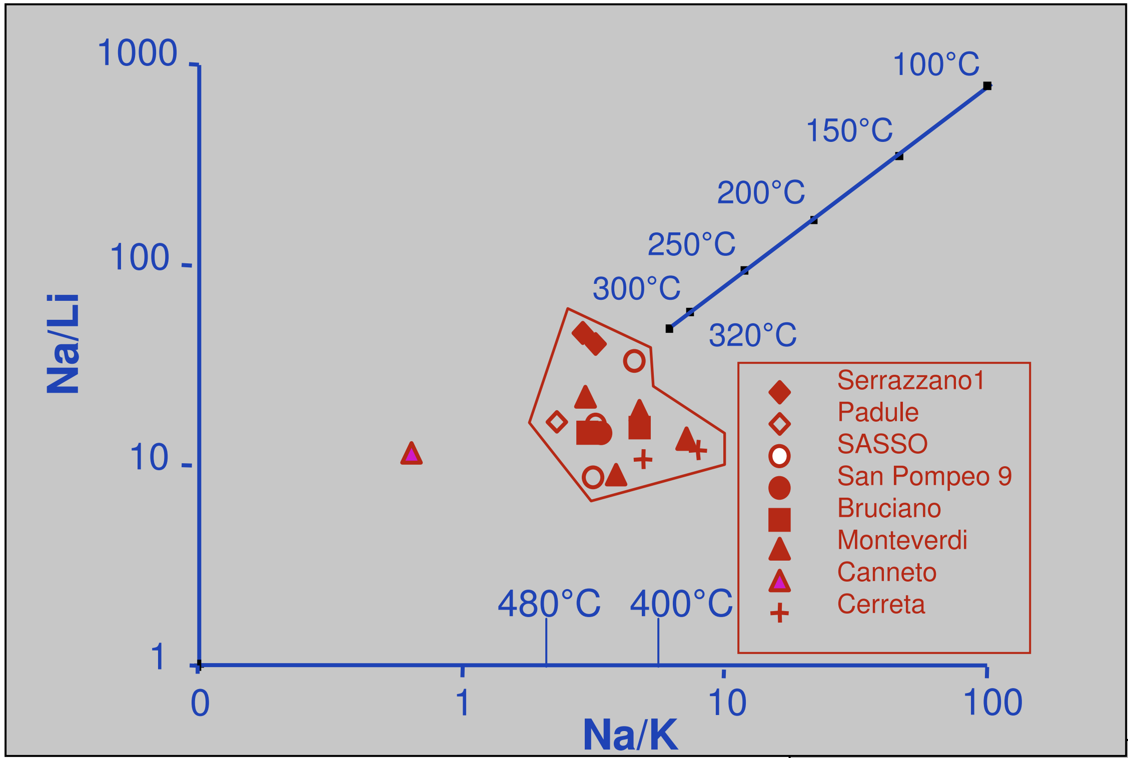
☞ main trend:
CO_2-CH_4 end-members

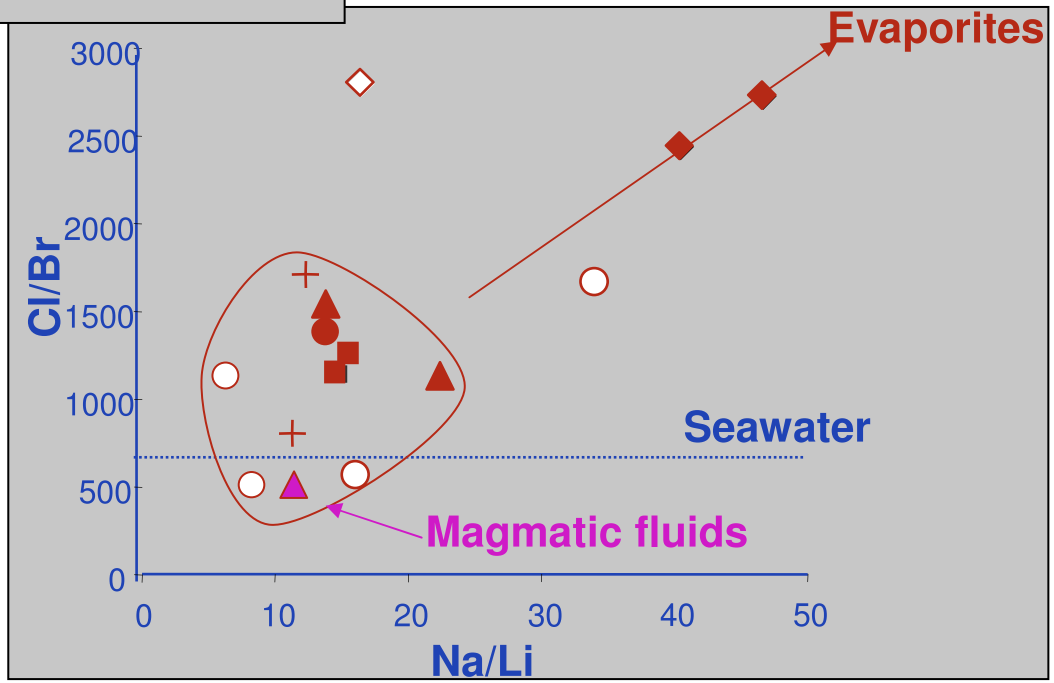
- group 1: CO_2 rich FI (> to 75 mol%), with several trends either parallel to the CO_2 - CH_4 axis or to the CO_2 - N_2 one.

- group 2: enrichment in CH_4 for Bru-3138, Sas 10-4027 and SPO 9-2900.


Larderello
Vc-w
10 µm
Aqueous-carbonic FI
Fluids equilibrated with
graphite
Lw-c
10 µm
H2O
CO2
CH4
CO2 rich end-member
400
450
500
Lum3110
SPO9 2700
Bru 2443
Bru 3138
Sas10 4027
Bad 3654
Can 3523
VC 11 2946
Sper 2240
Pad 2782
MV 3 3577
MV 5 3046

Ion Chemistry





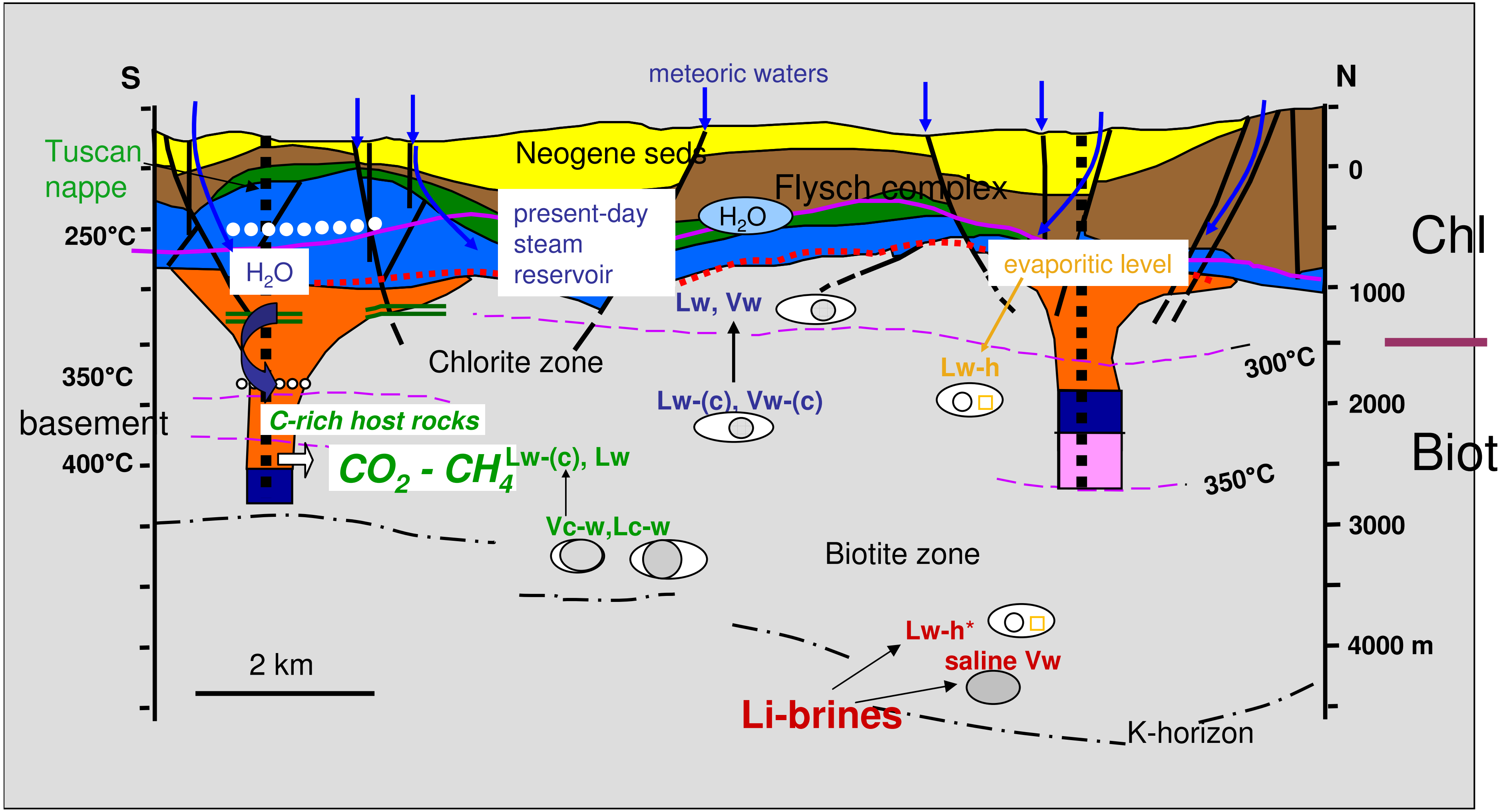
General trends

- **aqueous-carbonic fluid:**
CO_2 : origin in the carbonate levels under high T (>400°C), mixing with mantellic CO_2 (?)
$CO_2 + CH_4 + H_2O$: origin = deep fluid equilibrated with host rocks, fluid-graphite interaction.

- **aqueous fluid**: two end-members and products of mixings
  • high salinity: interaction with evaporitic levels.
  • low salinity and TH: meteoric fluid.
  intermediate salinity due to the dilution of brines
  + products of unmixing of aqueous-carbonic fluids

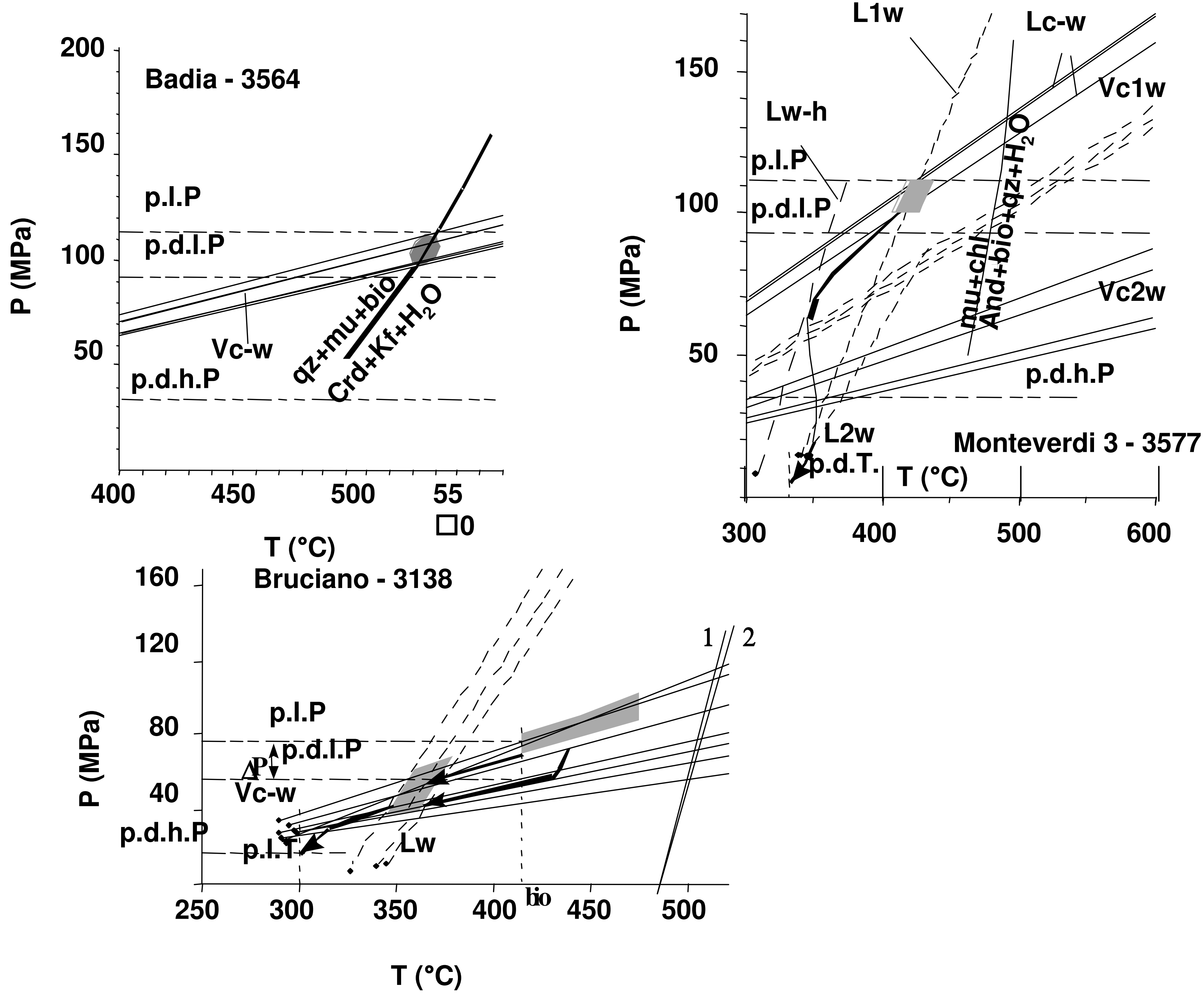
- penetration of surficial **fluid under high geothermic gradients** ⇒ **cooling** of the metamorphic pile

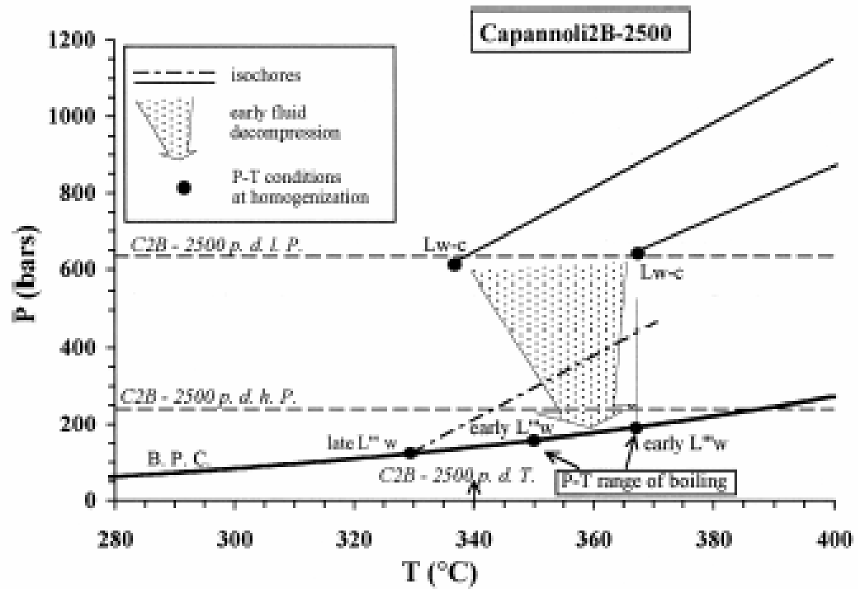
Larderello



S
N
meteoric waters
Tuscan nappe
Neogene seds
Flysch complex
present-day steam reservoir
H2O
H2O
250°C
350°C
400°C
basement
evaporitic level
Lw, Vw
Chlorite zone
Lw-(c), Vw-(c)
Lw-h
300°C
C-rich host rocks
CO2 - CH4
Lw-(c), Lw
350°C
Vc-w,Lc-w
Biotite zone
Lw-h*
saline Vw
Li-brines
K-horizon
2 km
0
1000
2000
3000
4000 m

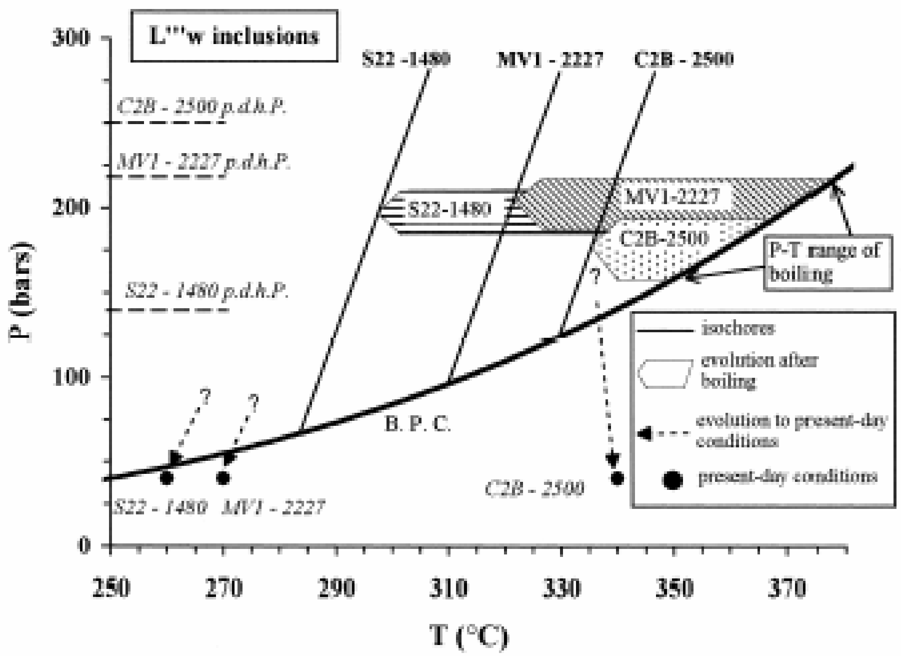
Chl
Biot


Badia - 3564
P (MPa)
200
150
100
50
p.l.P
p.d.l.P
Vc-w
p.d.h.P
qz+mu+bio
Crd+Kf+H2O
400
450
500
55
□0
T (°C)
Monteverdi 3 - 3577
L1w
Lc-w
Vc1w
Lw-h
p.l.P
p.d.l.P
mu+chl
And+bio+qz+H2O
Vc2w
p.d.h.P
L2w
p.d.T.
P (MPa)
150
100
50
300
400
500
600
T (°C)
Bruciano - 3138
P (MPa)
160
120
80
40
p.l.P
p.d.l.P
ΔP
Vc-w
p.d.h.P
p.l.T
Lw
bio
1
2
250
300
350
400
450
500
T (°C)

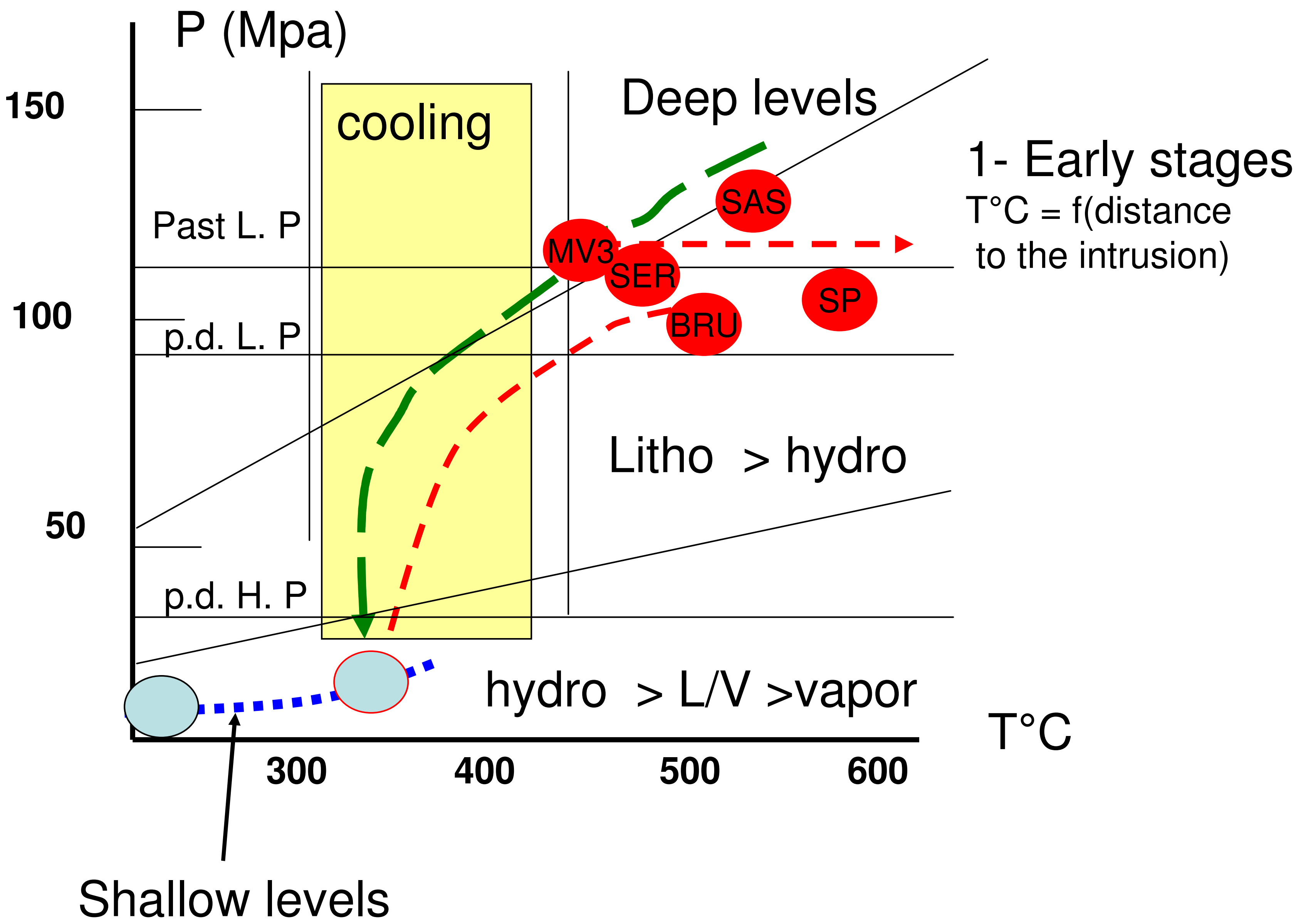


Chlorite zone
(intermediate levels)

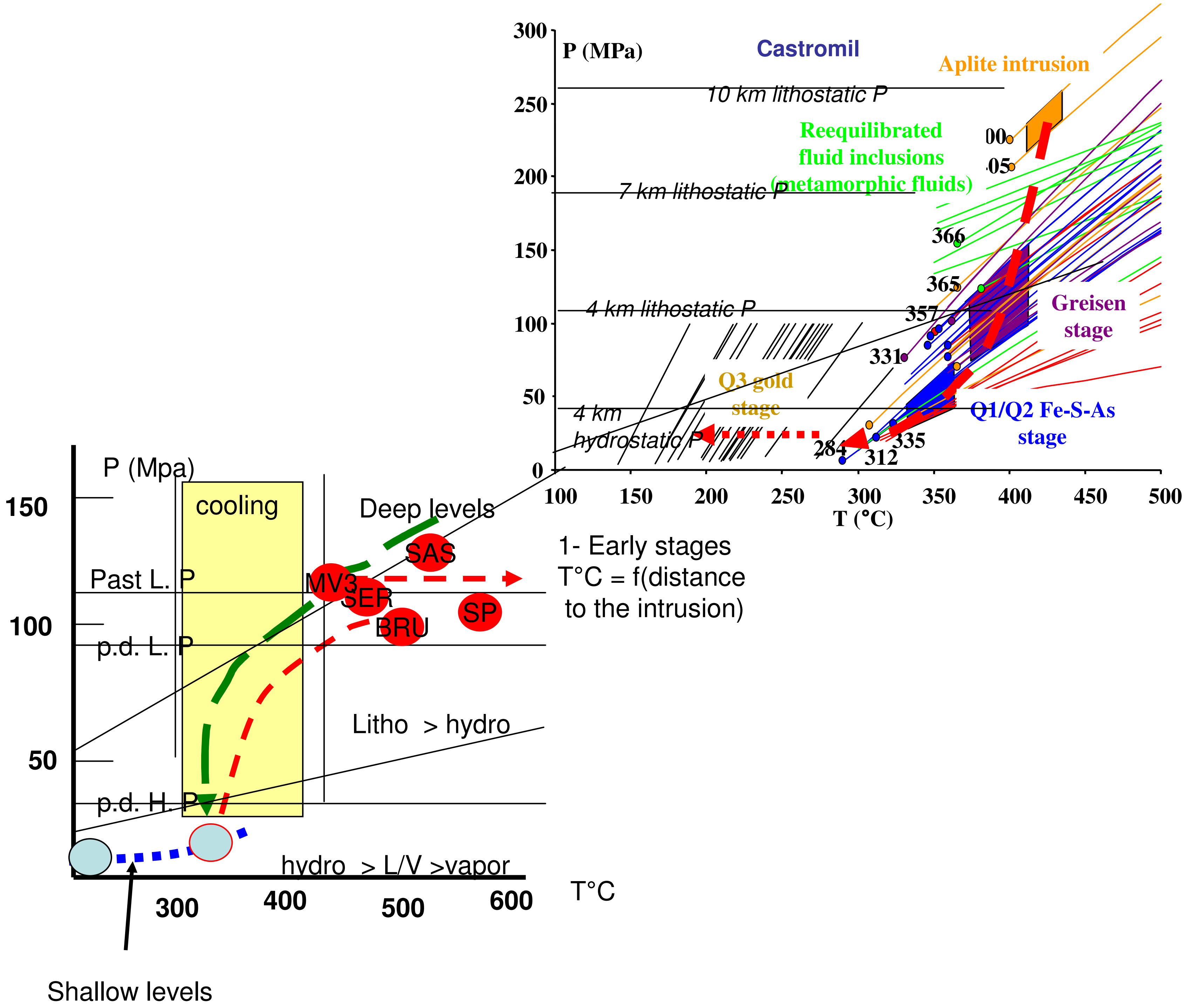
Boiling and fluid mixing
(condensation, mixing of the products
of boiling, and parent fluids



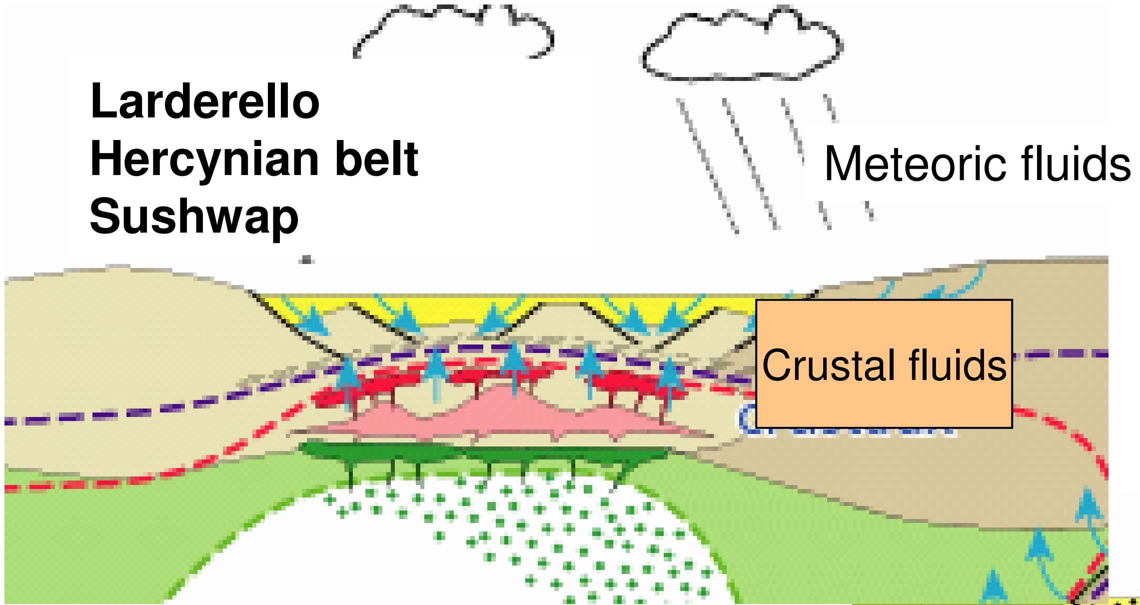
Ruggieri et al.,99

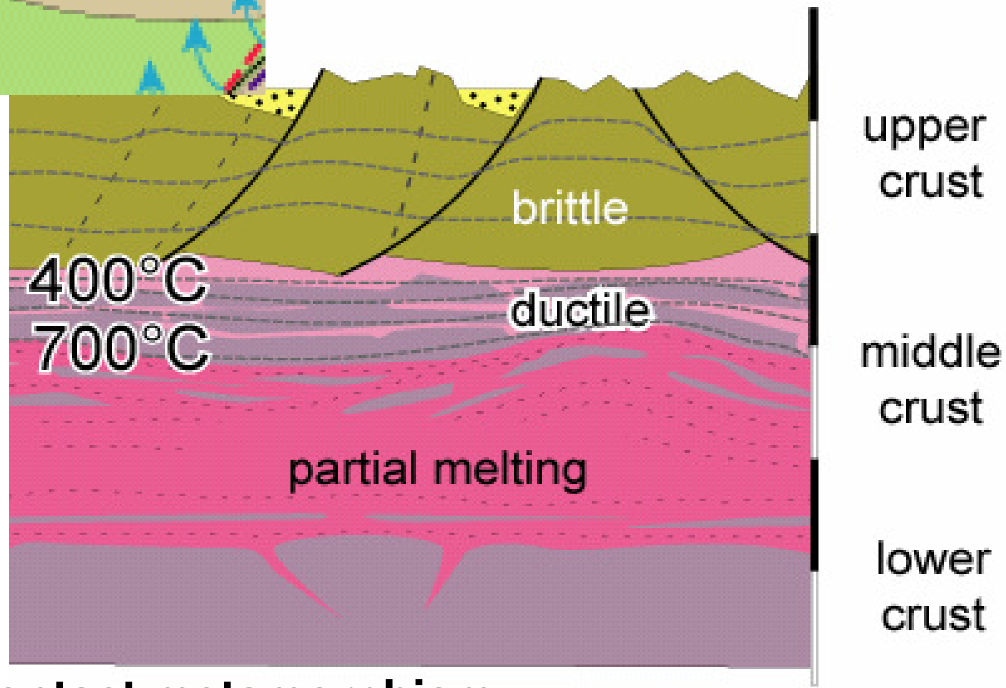


P (Mpa)
150
100
50
cooling
Deep levels
1- Early stages
T°C = f(distance
to the intrusion)
Past L. P
p.d. L. P
p.d. H. P
SAS
MV3
SER
BRU
SP
Litho > hydro
hydro > L/V >vapor
T°C
300
400
500
600
Shallow levels


P (MPa)
Castromil
Aplite intrusion
10 km lithostatic P
Reequilibrated
fluid inclusions
(metamorphic fluids)
7 km lithostatic P
366
365
357
331
4 km lithostatic P
Greisen
stage
Q3 gold
stage
4 km
hydrostatic P
284
312
335
Q1/Q2 Fe-S-As
stage
300
250
200
150
100
50
0
100
150
200
250
300
350
400
450
500
T (°C)
P (Mpa)
cooling
Deep levels
150
100
50
Past L. P
p.d. L. P
p.d. H. P
MV3
SER
SAS
SP
BRU
Litho > hydro
hydro > L/V >vapor
300
400
500
600
T°C
Shallow levels
1- Early stages
T°C = f(distance
to the intrusion)

Larderello
Hercynian belt
Sushwap





Similarities between
old and active geothermal areas

Link with collision events,
and MCC style deformation
Abnormal heat flows in relation
with late partial melting
Penetration of cold meteoric waters
and cooling of the overheated crust
Mixing of pseudo-metamorphic or contact metamorphism
fluids with meteoric waters (and secondary brines when evaporites)
Geometry of active systems (size, fluid percolation style)
may be deduced from past systems and conversely