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

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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

Image analysis

Fluid inclusion plane distribution
fluid-deformation relationships

Petrography, CL

Typology and chronology of fluid events

Calcite

Halite

Gas

Liquid

CO$_2$ L

CO$_2$ V

H$_2$O L

1 cm

100 μm

16 μm

5 μm

10 μm
Paleofluid density, composition, and P-T trapping conditions

Optical microscopy, IR, UV

microthermometry

Water-gas-salt system

Raman: gas, Cl

LIBS: cations, trace elts

EOS

Liquid-Vapour modelling

PTX

Stable Isotopes (C, O, H)

Crush-leach method
Cations/anions/trace elements/halogens
Paleo-hydrochemistry on $10^{-9}$ g of paleofluid

Controls of paleofluid chemistry?
Fluid- mineral equilibria/ disequilibria?
  Immiscibility, fluid mixing?
Fluid Sources

Thermal evolution of the continental crust in subduction zones

- Development of accretion prism
- Low geothermal gradient
- Relief formation

**Meteoric fluids**

**Crustal fluids**

**Mantle fluids**

**crust**

**mantle**
Transition from crustal thickening to crustal thinning
formation of metamorphic core complexes, horts and grabens,
crustal cooling during thinning
Meteoric fluids
Crustal fluids
Mantle fluids and heat

Partial melting
High geothermal gradients
Gravitational collapse
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

Vanderhaeghe, 2001
Divergent collapse (Vanderhaeghe and Teyssier, 2001)

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

with or without (brittle) extension of
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

D3 shear zone (N130°E)

Mineralised zone

Au

N130°E fault

N30-60°E faults

Syn to post D3 granite

Post D3 granite

Aplite
Aqueous carbonic fluids

Aqueous fluids in metamorphic rocks

Castromil

Salinity (% wt % eq. NaCl)

Th (°C)

- N115-140
- N90
- Primary
- Unoriented samples
- N30-60
- N5
- Primary (H2O-Vol)
- Unoriented samples (H2O-Vol)
250-300°C
Blackschists
>450°C

400-450°C
Geopressed pseudo-metamorphic fluids
H₂O- CO₂
δ¹⁸O = -9/-12‰
0.0015<Br/Cl<0.005

Local unmixing
Blackschists
CH₄-N₂
>450°C

Residual hot aqueous fluids
1-3 eq.wt% NaCl
δ¹⁸O = -1/+6‰
0.0003<Br/Cl<0.001

120-150°C
Residual hot aqueous fluids
1-3 eq.wt% NaCl

180-250°C
Mixing zone Au-ore deposit
Resident aqueous fluids
1-3 eq.wt% NaCl
δ¹⁸O = 0/+6‰
250-300°C

Recharge fluids:
Meteoric waters

Exhumation

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

Granite $\gamma_1$ - coarse grained
Granite $\gamma_2$
Granite $\gamma_3$ – fine grained
faults
samples
Large hydrothermal pipes
Aqueous-carbonic 3 phases Lc-w₁

Aqueous inclusion Lw₂, low salinity

Aqueous inclusions Vw and Lw₁

Aqueous - carbonic 2 phases Lc-w₂

Aqueous inclusion Lw₂, low salinity

ASA96-3

N=20

N=27

N=9

N=56

All data
Metamorphic peak conditions

Progressive exhumation

Decompression and abnormal heat flows

Effects of quick penetration of cold meteoric waters

Local abnormal heat flows

25°C/km
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

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

TH (°C)

metamorphic fluid

isostructural mixing

diluted fluid

saline fluid

Basement:
- Lw-c
- Massa Unit:
  - Lc-w
  - Lw-(c)
- Apuan Unit:
  - Lw
- Tuscan Nappe:
  - Lw

Salinity (wt % eq. NaCl)
Fluid distribution in the Alpi Apuan

- Massa Unit, Basement:
  - aqueous-carbonic fluid,
  - cataclasite zone:
    saline fluid,

- Apuan Unit:
  - aqueous fluid

Tuscan nappe: $\text{H}_2\text{O-CH}_4$/ $\text{H}_2\text{O}$-salts

Montomoli et al., 2001
Biotite zone: veins and recrystallized quartz lenses (*Larderello*)

- Biotite
- Tourmaline
- Pyrite
- Graphite
- Recrystallized quartz lenses

*Quartz lens*

*Tourmaline*
Fluid inclusion types

Aqueous carbonic inclusions

Larderello

Saline inclusions

Aqueous inclusions
3 types of FI analysed:
- Vc-w, Lw+/c, Lw-(c)-h

Main trend:
\( \text{CO}_2 - \text{CH}_4 \) end-members

- Group 1: \( \text{CO}_2 \) rich FI (> to 75 mol%), with several trends either parallel to the \( \text{CO}_2 - \text{CH}_4 \) axis or to the \( \text{CO}_2 - \text{N}_2 \) one.

- Group 2: enrichment in \( \text{CH}_4 \) for Bru-3138, Sas 10-4027 and SPO 9-2900.
Larderello

Vc-w

Aqueous-carbonic FI Fluids equilibrated with graphite

Lw-c

CO_2 rich end-member

CH_4

H_2O

CO_2 rich end-member
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 \( \Rightarrow \)
  cooling of the metamorphic pile
C-rich host rocks

Flysch complex

Neogene sediments

present-day steam reservoir

evaporitic level

meteoric waters

C-l-brines

saline Vw

K-horizon

2 km

Larderello

Tuscan nappe

Neogene sediments

Flysch complex

Chlorite zone

Biotite zone

Chl

Biot

Li-brines

H₂O

CO₂ - CH₄

Lw-h

Lw-(c), Lw-(c), Lw

Lw-h*
Chlorite zone (intermediate levels)

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

Ruggieri et al., 99
1- Early stages

$T^\circ C = f(\text{distance to the intrusion})$

P (Mpa)

T°C

Deep levels

Litho > hydro

hydro > L/V > vapor

Past L. P

p.d. L. P

p.d. H. P

Shallow levels

Deep levels

Litho > hydro

hydro > L/V > vapor

Shallow levels
1- Early stages

\[ T^\circ C = f(\text{distance to the intrusion}) \]

- Litho > hydro
- Hydro > L/V > vapor
- Reequilibrated fluid inclusions (metamorphic fluids)
- Greisen stage
- Q1/Q2 Fe-S-As stage

- Castromil
- Aplitic intrusion
- 10 km lithostatic P
- 7 km lithostatic P
- 4 km lithostatic P
- 4 km hydrostatic P

Deep levels

Shallow levels
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