DOMENICO LIOTTA

d.liotta@geo.uniba.it

THE CONTRIBUTE OF REGIONAL GEOLOGY: FOSSIL VS. ACTIVE GEOTHERMAL SYSTEMS IN SOUTHERN TUSCANY

Dipartimento di Scienze della Terra e Geoambientali
Università di Bari (Italy)

FIELD GEOLOGY

methodology

integration of data

1

GEOLOGIC SURVEY FOR GEOTHERMAL EXPLORATION: FRACTURES AND STRUCTURAL CHANNELS FOR FLUID FLOW

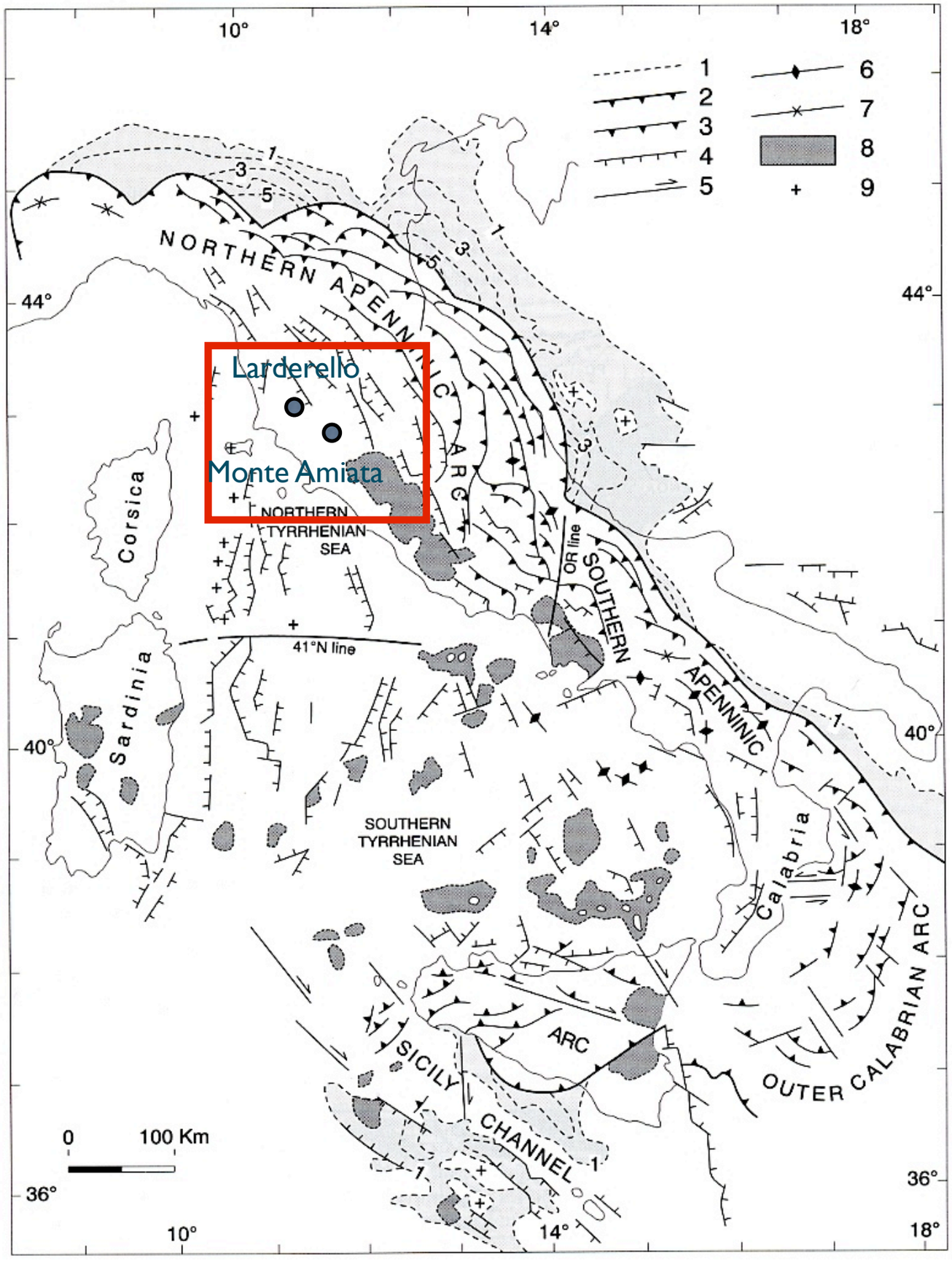
2

THE CONTRIBUTE OF REGIONAL GEOLOGY: FOSSIL VS. ACTIVE GEOTHERMAL SYSTEMS IN SOUTHERN TUSCANY

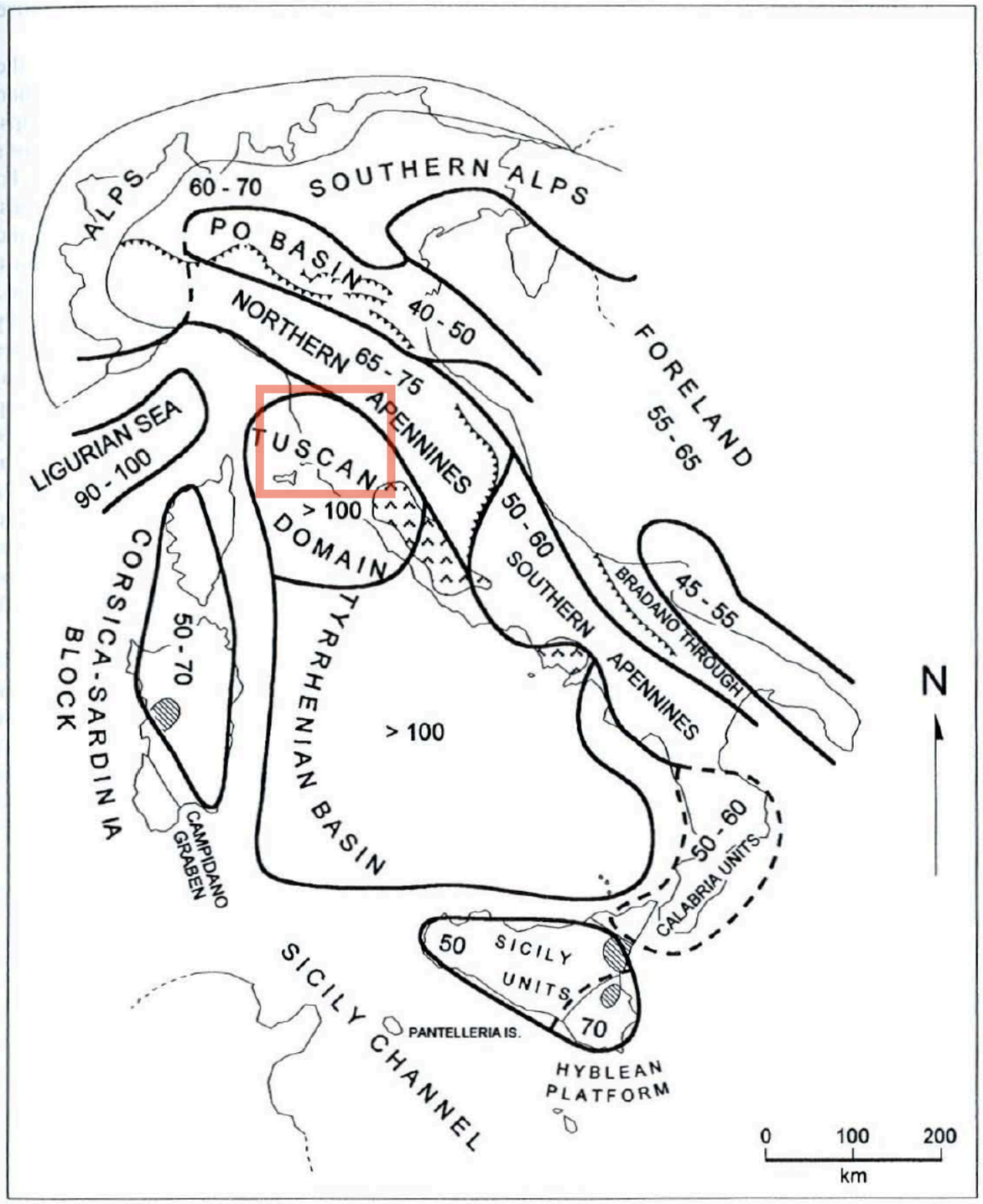
conceptual model on the relationships between geothermal resources and geological structures

D. Liotta - international school on geothermal exploration

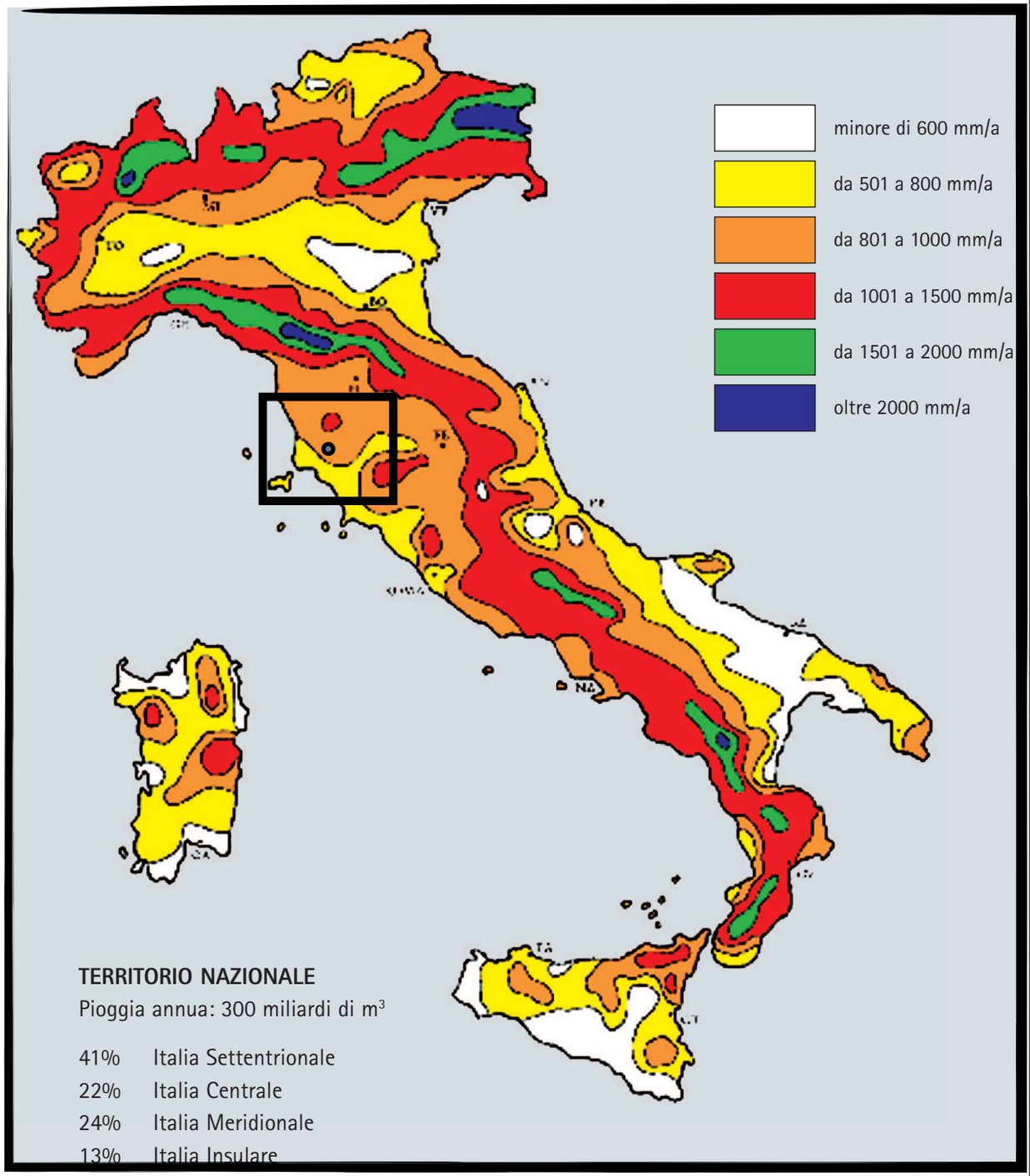
structural sketch map



heat flow map (mW/m^2)



average annual rainfall



INDEX

tectonic evolution of southern *Tuscany*

paleogeography

Alpine collision (Cretaceous-Oligocene)

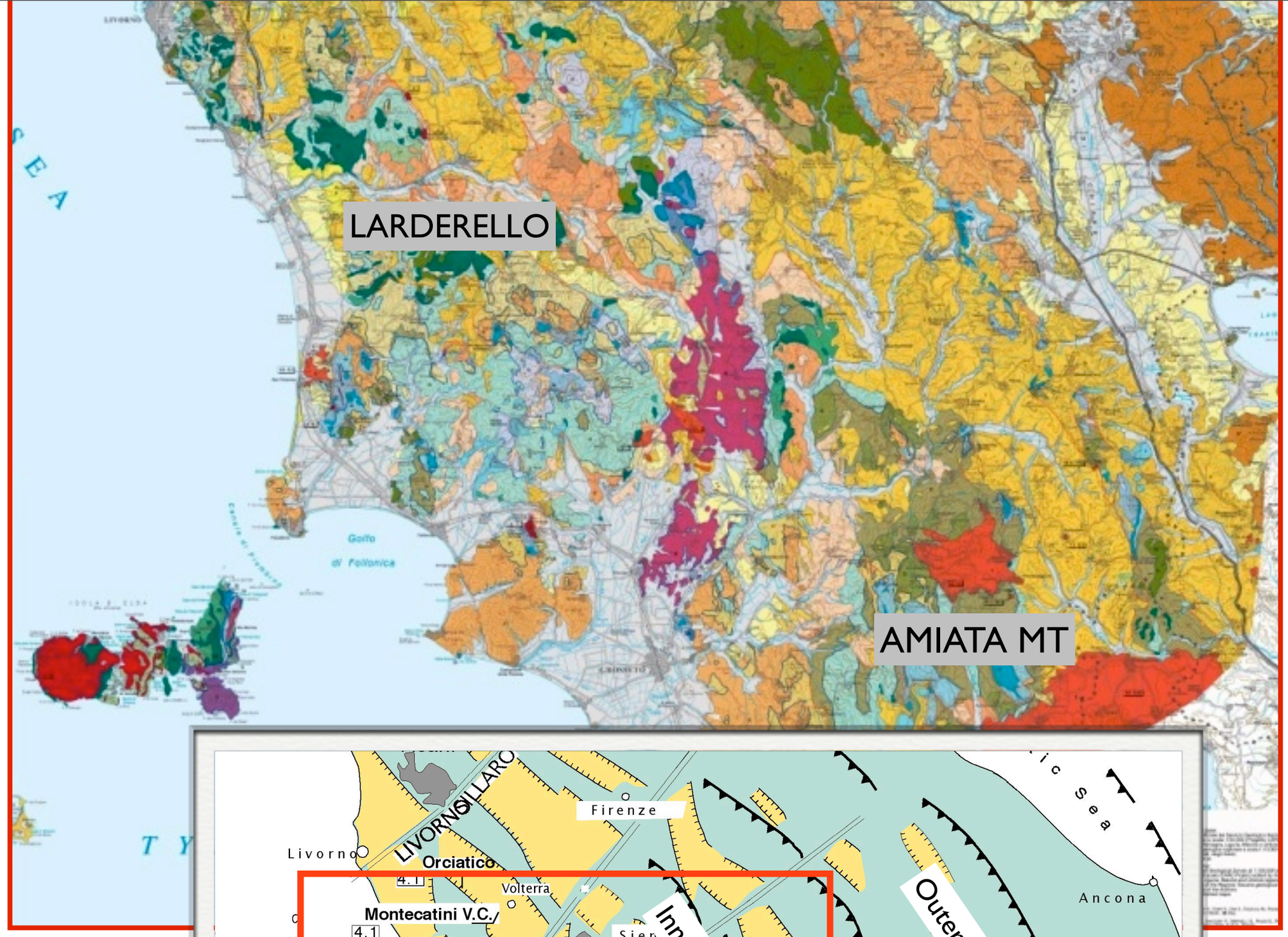
post-collisional extensional tectonics (MIOCENE)

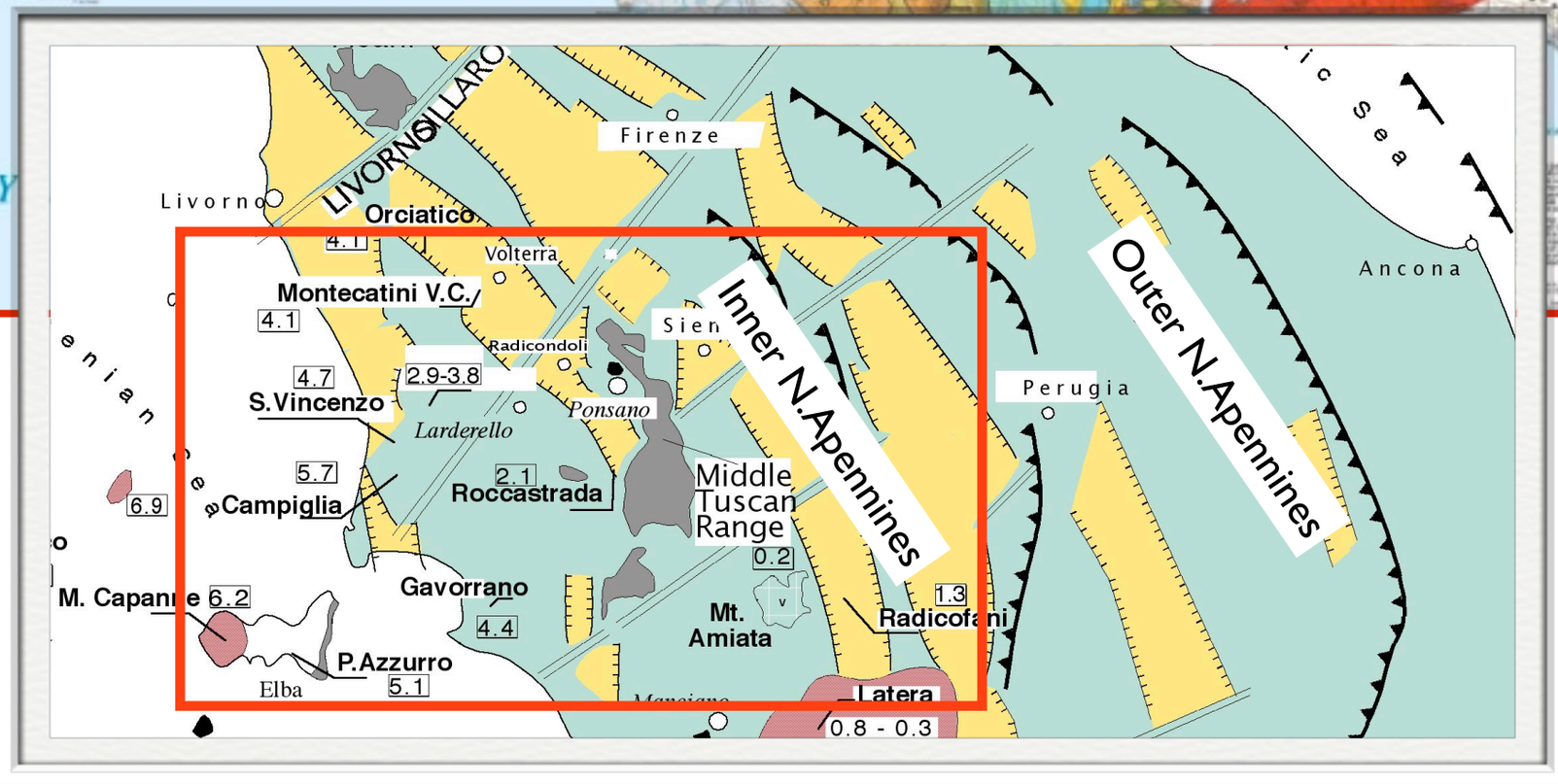
extension and magmatism (Pliocene - Present)

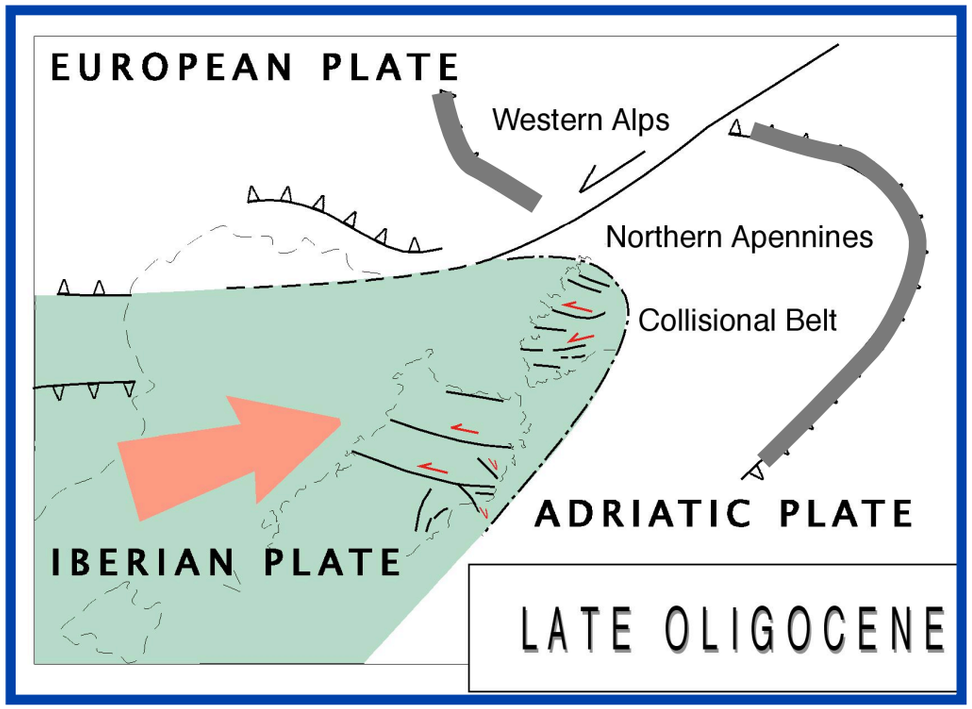
fossil geothermal systems (mineralizations)

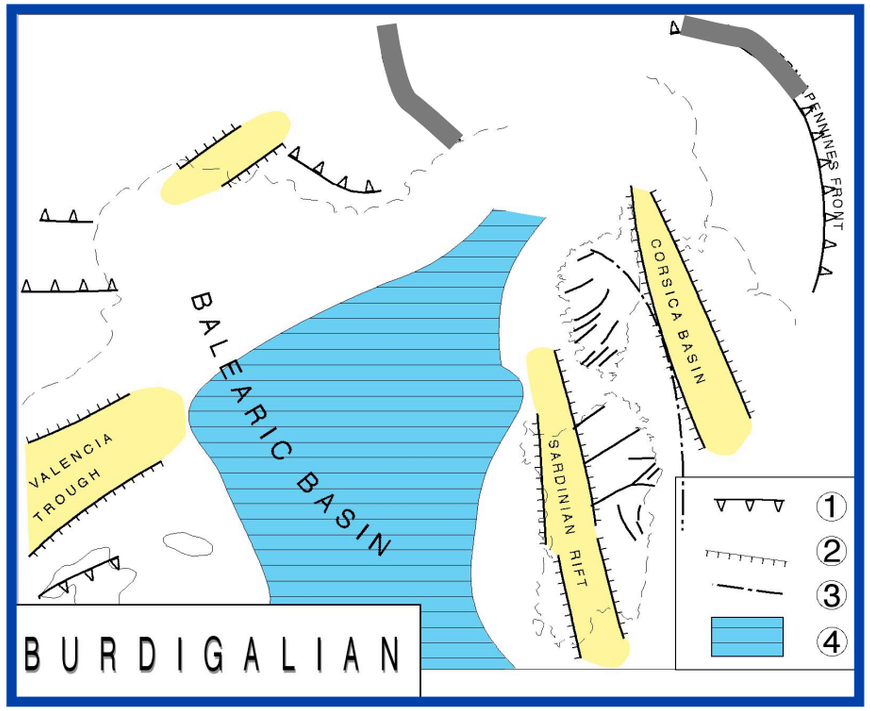
active geothermal systems (Larderello and Monte Amiata)

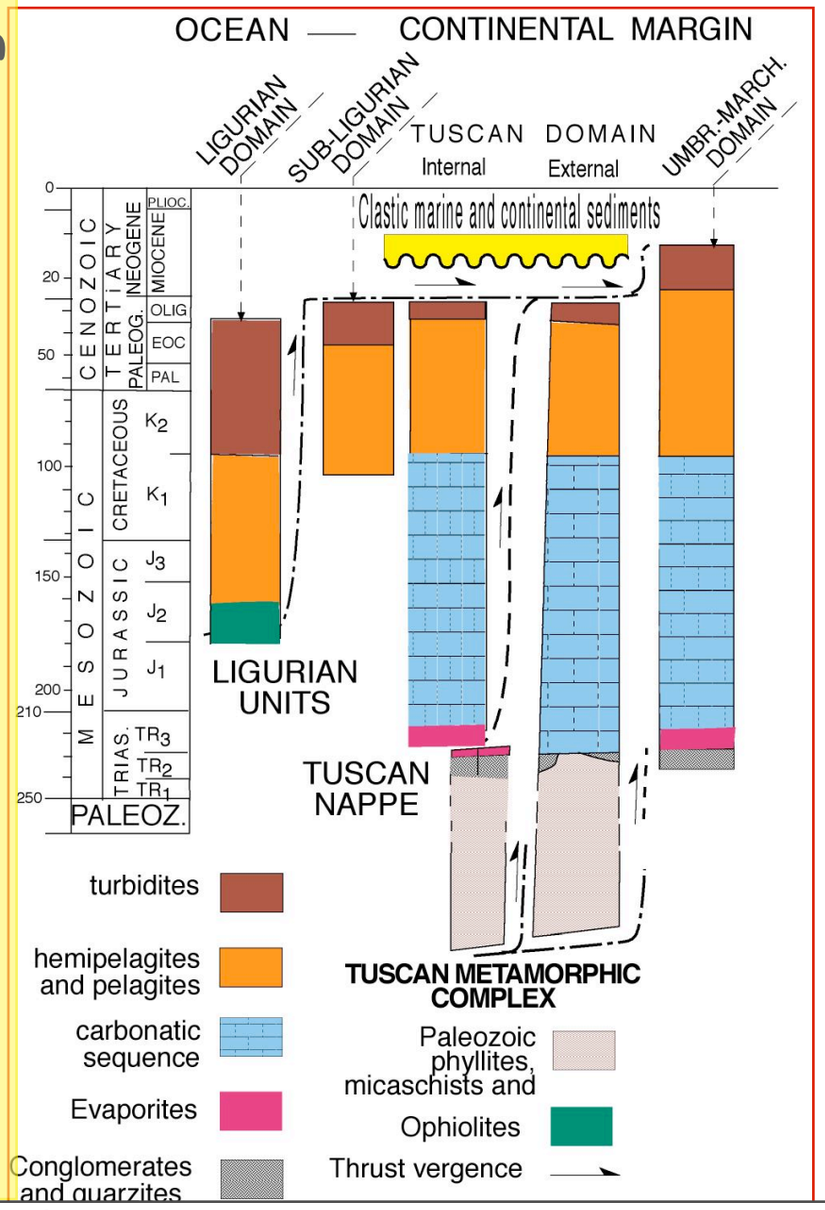
Conceptual model

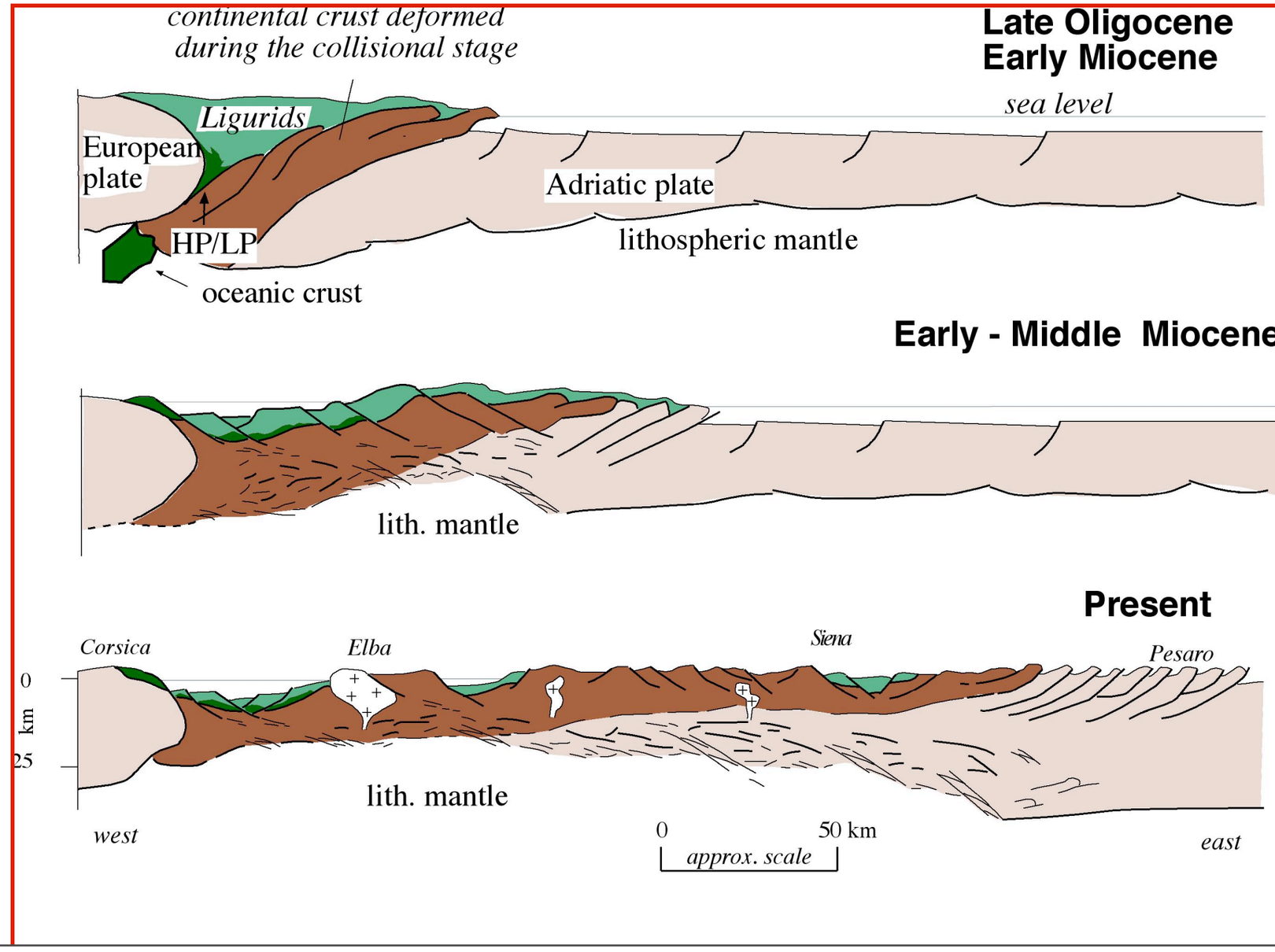

LARDERELLO
AMIATA MT
Golfo
di Follonica


LIVORNO-SILLARO
Firenze
Livorno
Orciatico
4.1
Volterra
Montecatini V.C.
4.1
Radicondoli
4.7
S.Vincenzo
2.9-3.8
Ponsano
Larderello
5.7
Campiglia
6.9
2.1
Roccastrada
Middle Tuscan Range
0.2
Gavorrano
4.4
M. Capanne 6.2
P.Azzurro
5.1
Elba
Mt. Amiata
1.3
Radicofani
Latera
0.8 - 0.3
Inner N.Apennines
Outer N.Apennines
Perugia
Ancona


EUROPEAN PLATE
Western Alps
Northern Apennines
Collisional Belt
ADRIATIC PLATE
IBERIAN PLATE
LATE OLIGOCENE

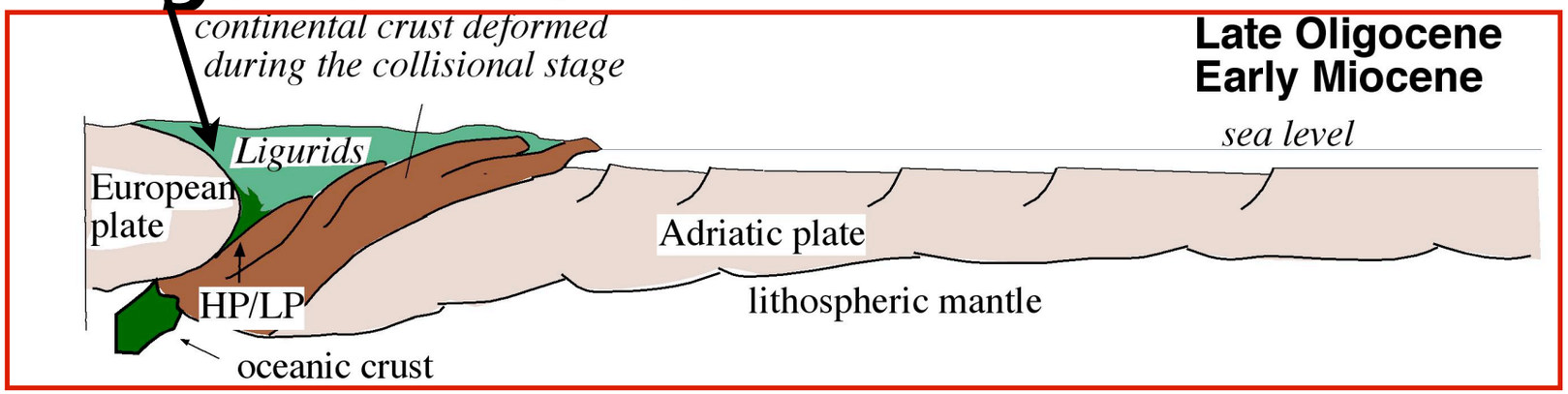

PENNINES FRONT
CORSICA BASIN
BALEARIC BASIN
VALENCIA TROUGH
SARDINIAN RIFT
1
2
3
4
BURDIGALIAN

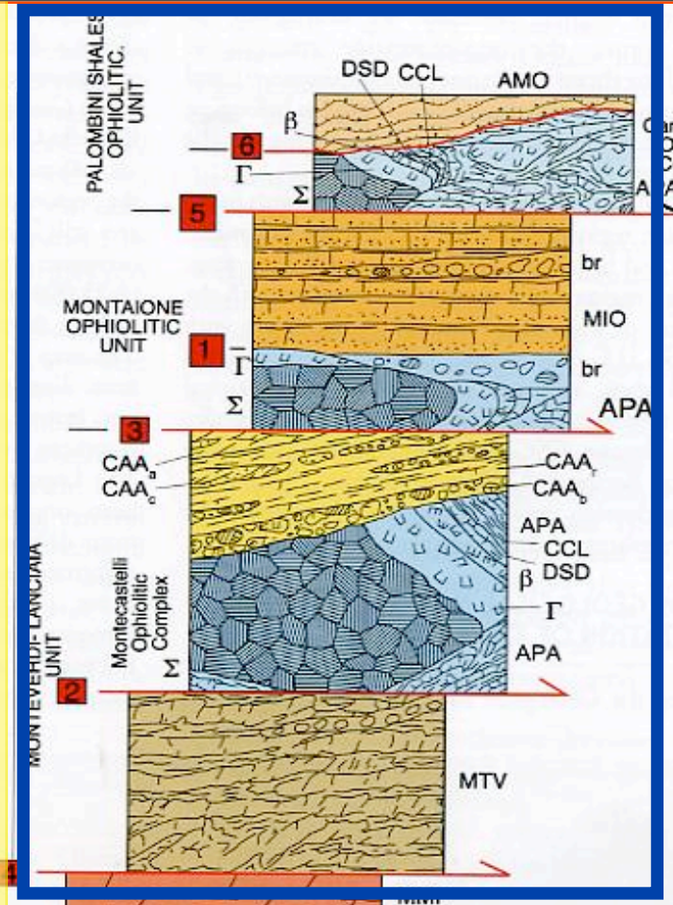

OCEAN — CONTINENTAL MARGIN
LIGURIAN DOMAIN
SUB-LIGURIAN DOMAIN
TUSCAN DOMAIN
Internal
External
UMBR.-MARCH. DOMAIN
Clastic marine and continental sediments
CENOZOIC
TERTIARY
NEOGENE
PLIOC.
MIOCENE
PALEOG.
OLIG
EOC
PAL
MESOZOIC
CRETACEOUS
K2
K1
JURASSIC
J3
J2
J1
TRIAS.
TR3
TR2
TR1
PALEOZ.
0
20
50
100
150
200
210
250
LIGURIAN UNITS
TUSCAN NAPPE
TUSCAN METAMORPHIC COMPLEX
turbidites
hemipelagites and pelagites
carbonatic sequence
Evaporites
Conglomerates and quarzites
Paleozoic phyllites, micaschists and
Ophiolites
Thrust vergence


continental crust deformed during the collisional stage
Late Oligocene
Early Miocene
sea level
Ligurids
European plate
Adriatic plate
HP/LP
oceanic crust
lithospheric mantle
Early - Middle Miocene
lith. mantle
Present
Corsica
Elba
Siena
Pesaro
0
25
km
lith. mantle
west
0
50 km
approx. scale
east

Oceanic crust - Ligurian Domain

COLLISION





magmatic rocks and related sedimentary cover

Jurassic - Cretaceous

LIGURIAN UNITS

F. delle Argille a Palombini
Aptian -Cenomanian

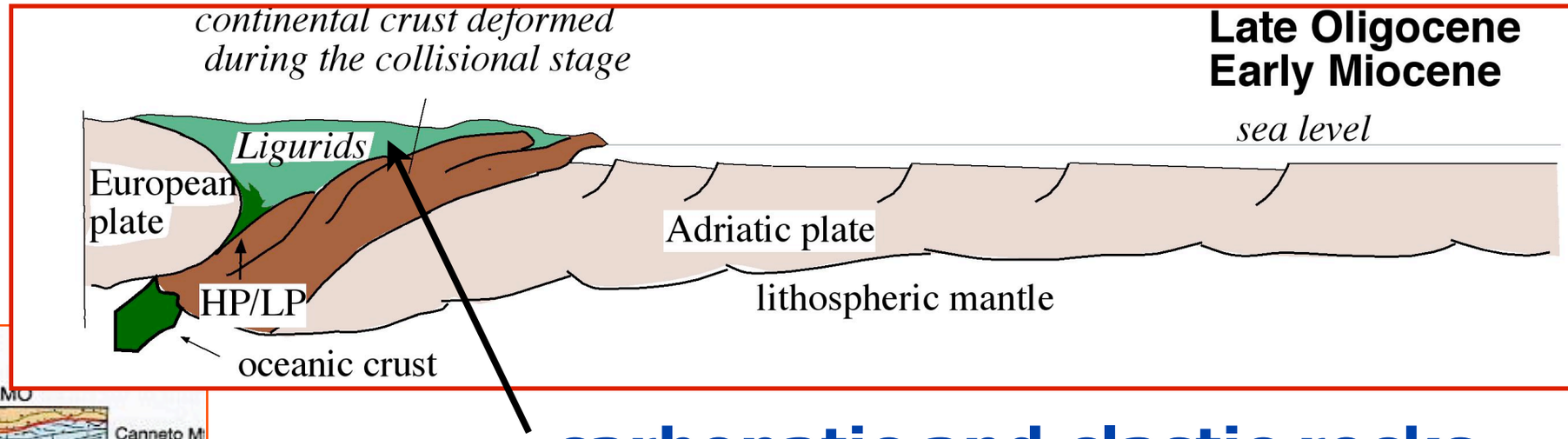
pillow basalts

Unità Monteverdi-Lanciaia:
F. di Lanciaia
Early- Middle Eocene

Unità Monteverdi-Lanciaia:
F. di Monteverdi M.mo
Campanian - Maastrichtian

TRANSITIONAL CRUST - Subligurian Domain

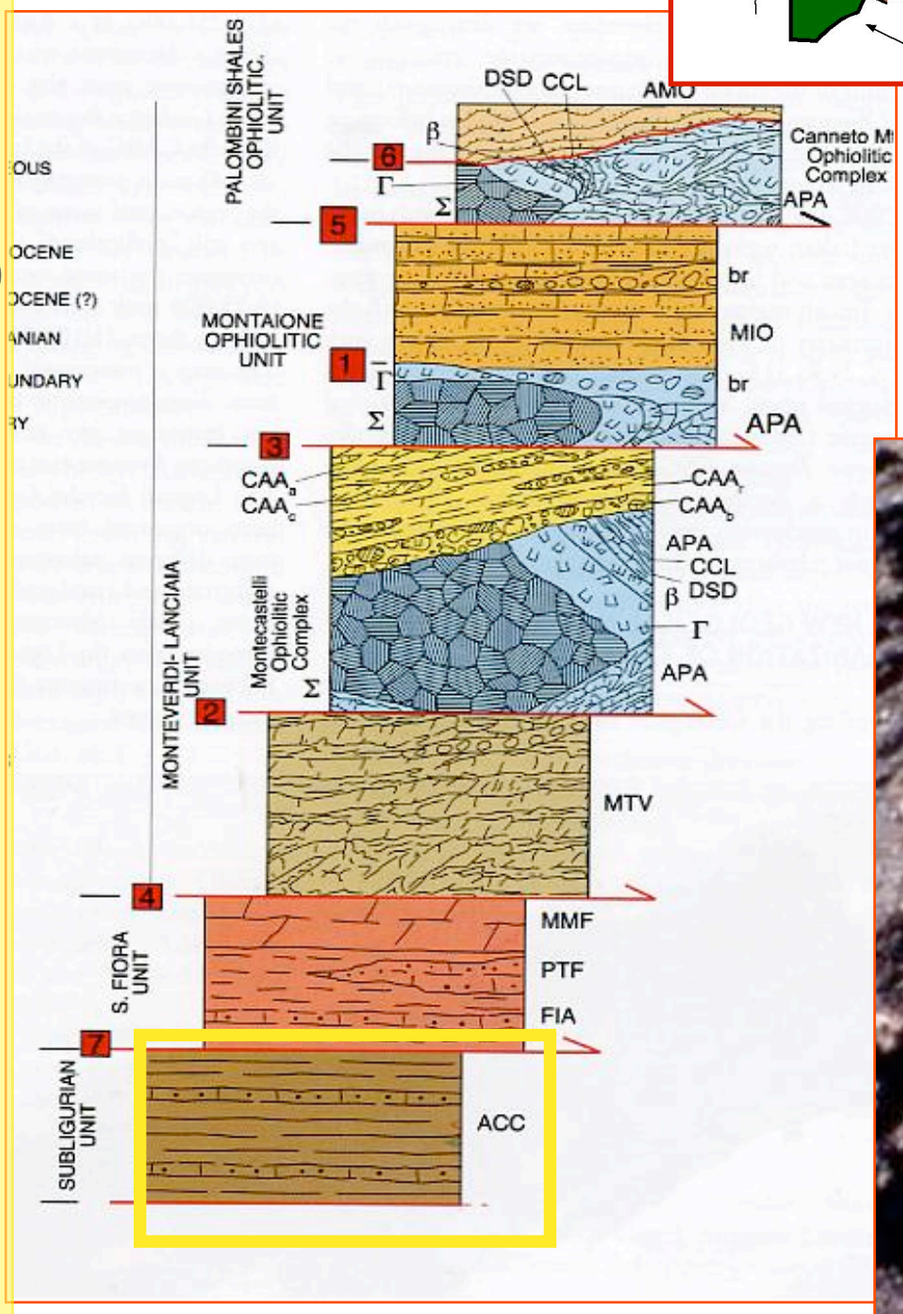
COLLISION



carbonatic and clastic rocks

SUBLIGURIAN UNITS

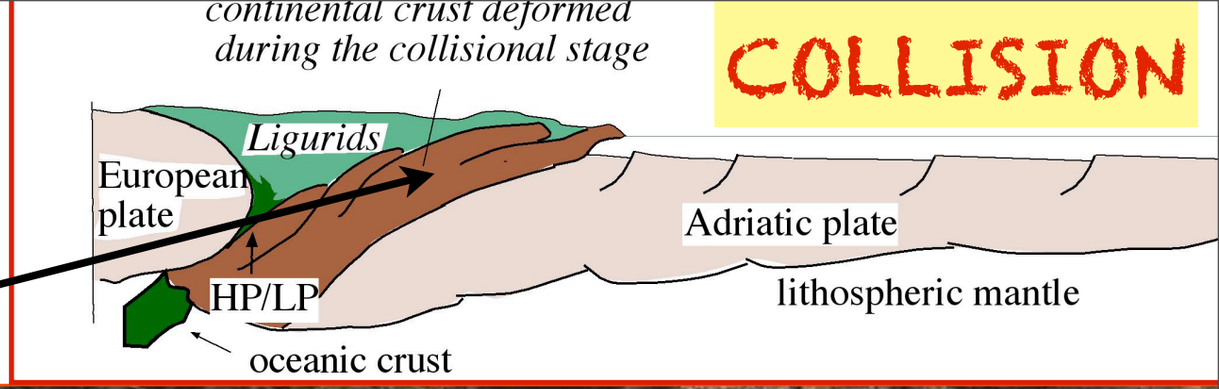
Oligocene



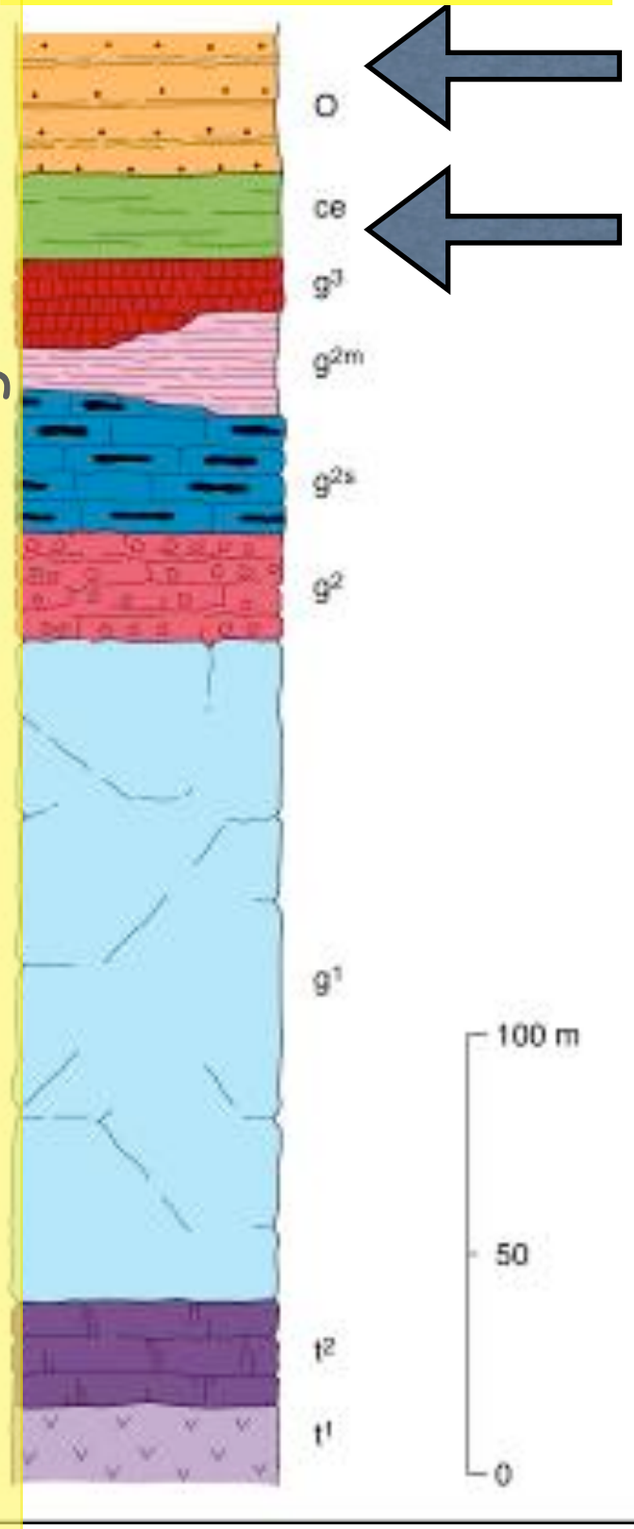
F. delle Argille e calcari - *Oligocene*

CONTINENTAL CRUST - Tuscan Domain

inner Tuscan Domain



TUSCAN NAPPE



F. Del Macigno - *Late Oligocene Early Miocene*

quartz-arenaceous flysch

Late Oligocene-Early Miocene

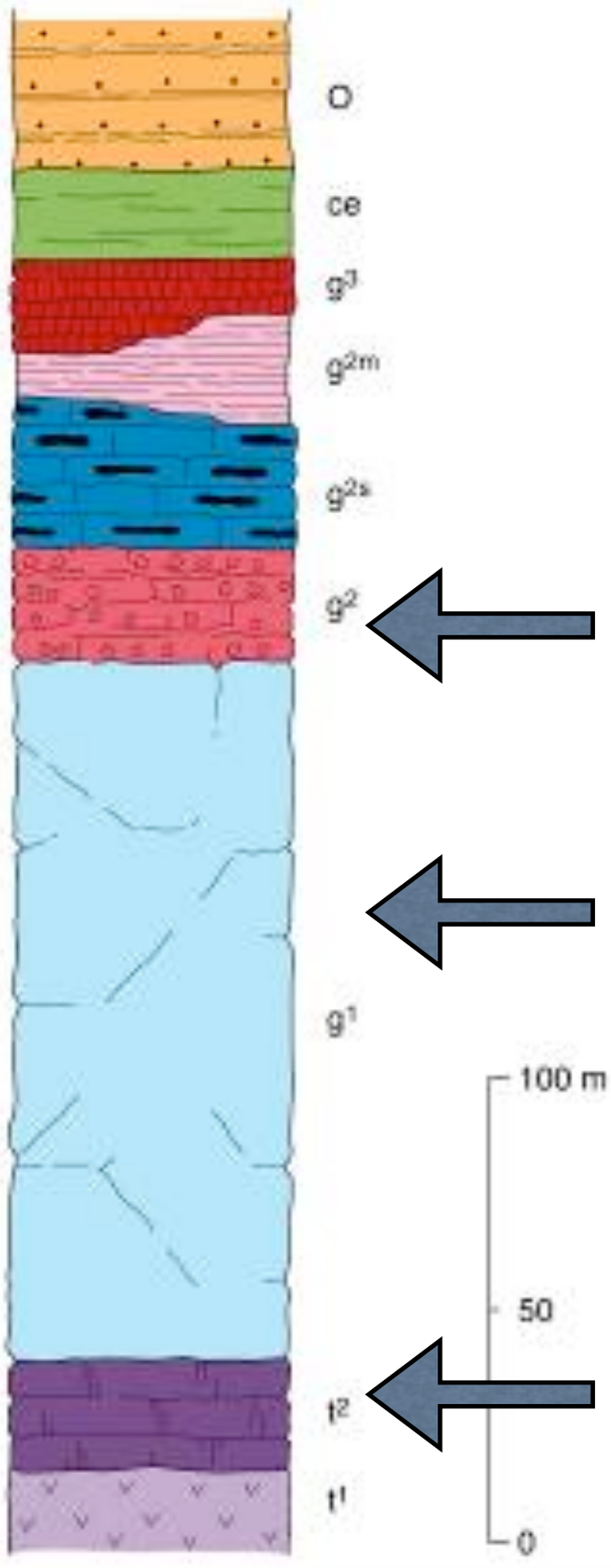
pelitic sequence

Cretaceous - Oligocene

F.della Scaglia Toscana: *Cretaceous - Oligocene*

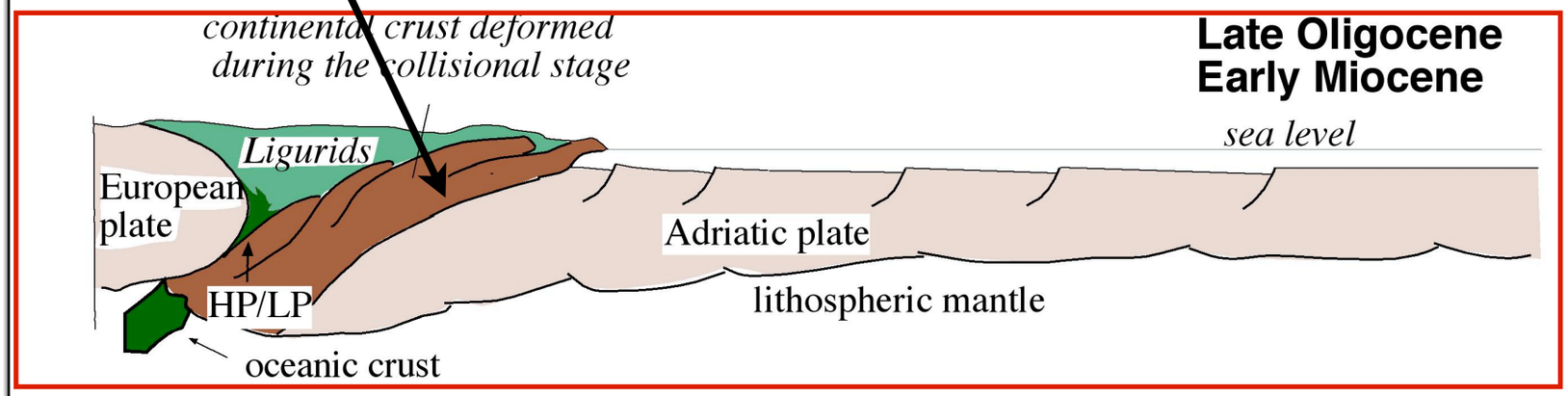
D. Liotta - international school on geothermal exploration

TUSCAN NAPPE



Inner Tuscan Domain

COLLISION

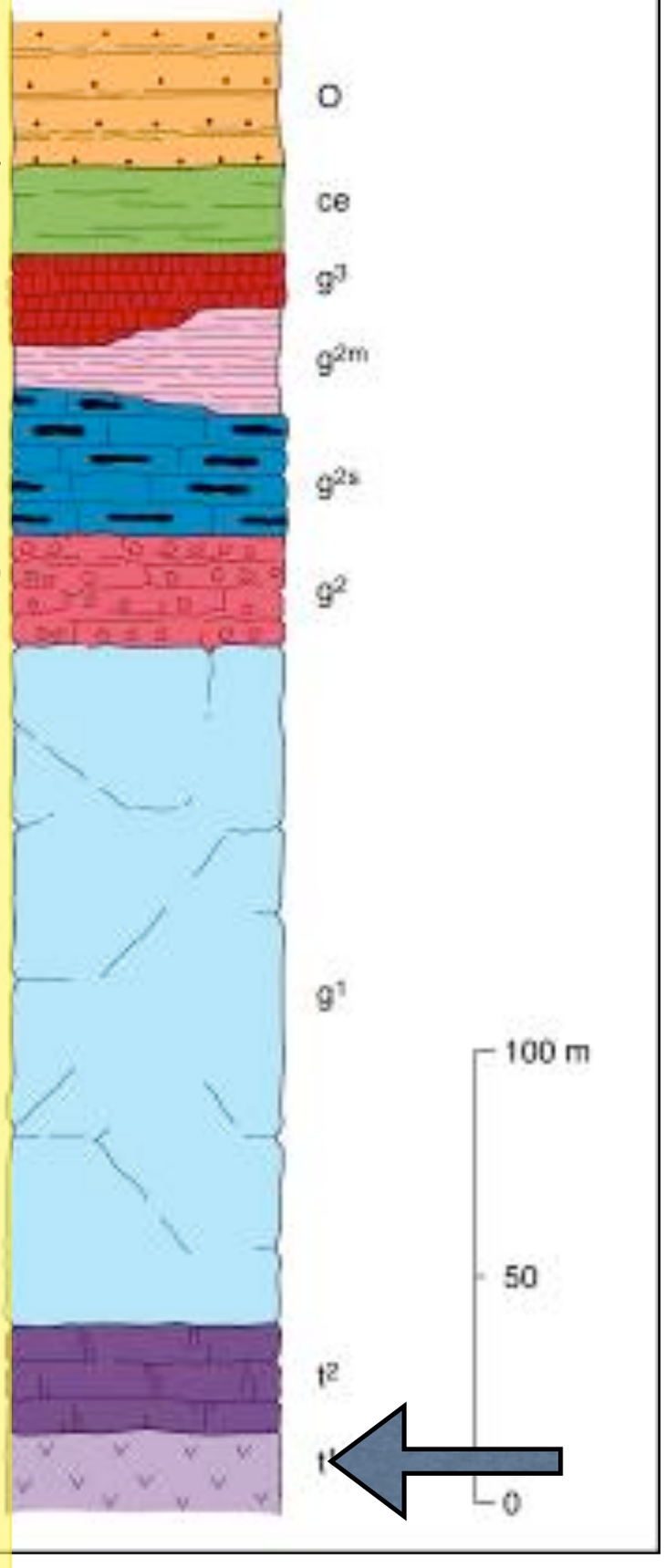


Rosso ammonitico, Calcare Massiccio, Calcari a Rhaet. Contorta: *Late Trias- Middle Lias*

carbonate platform

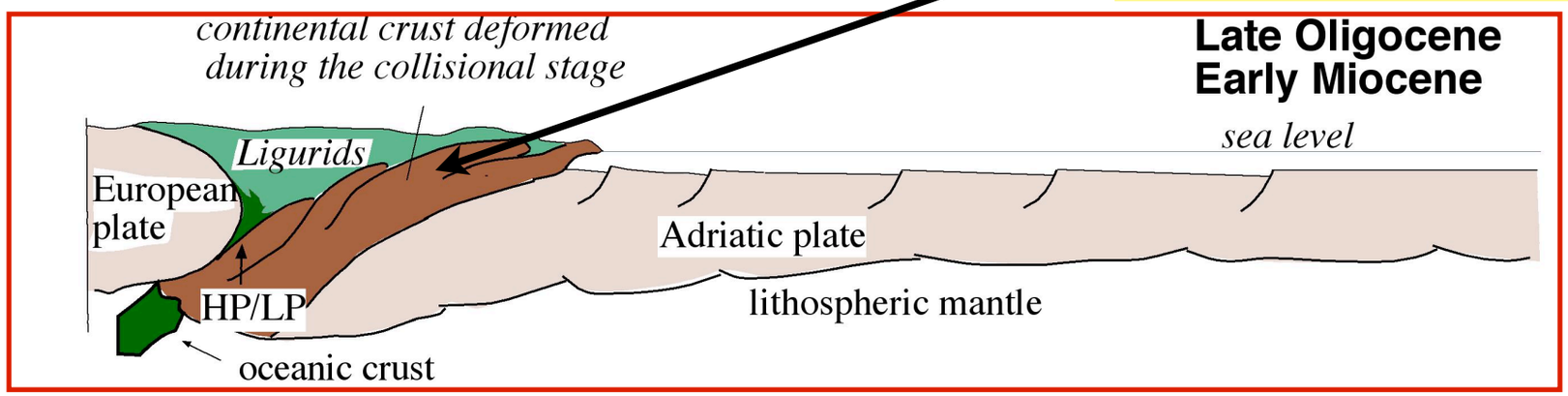
Late Trias - Jurassic

TUSCAN NAPPE



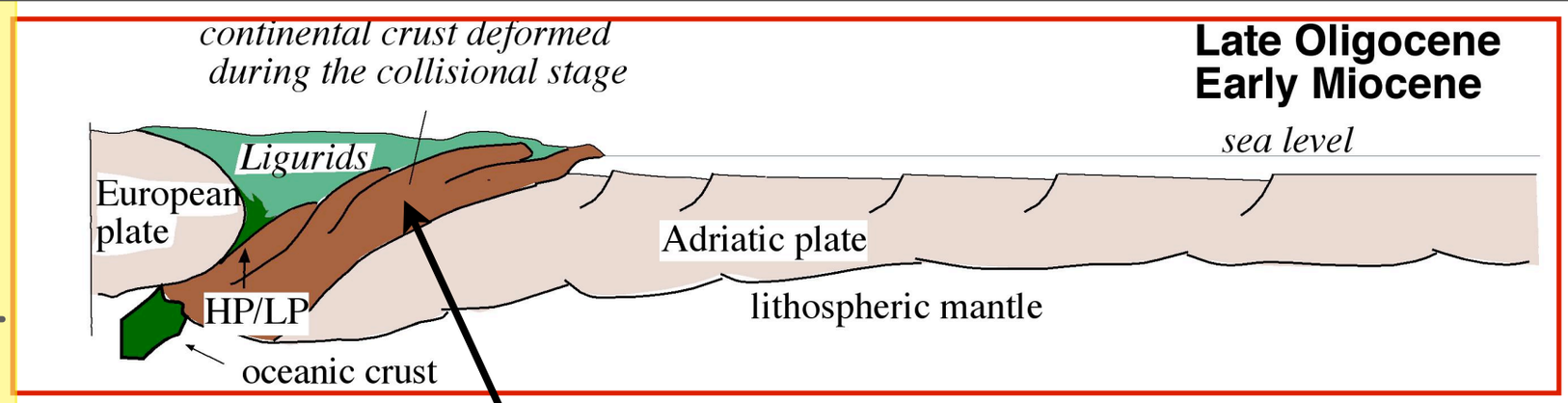
Inner Tuscan Domain

COLLISION



evaporite environment

Late Trias



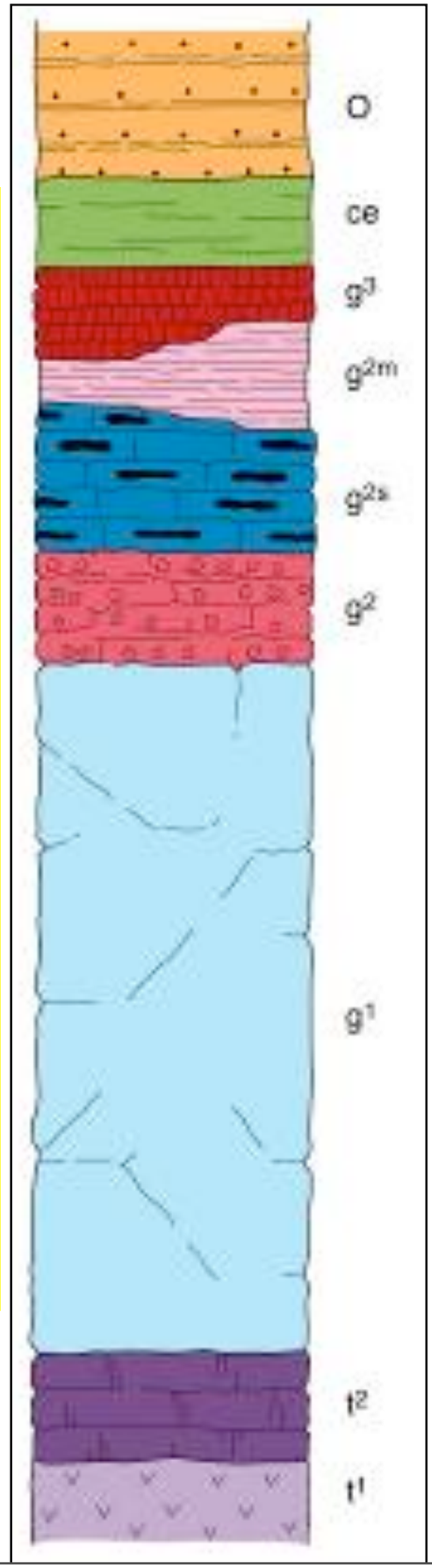
COLLISION

Outer Tuscan Domain

metamorphic rocks (green schists facies)

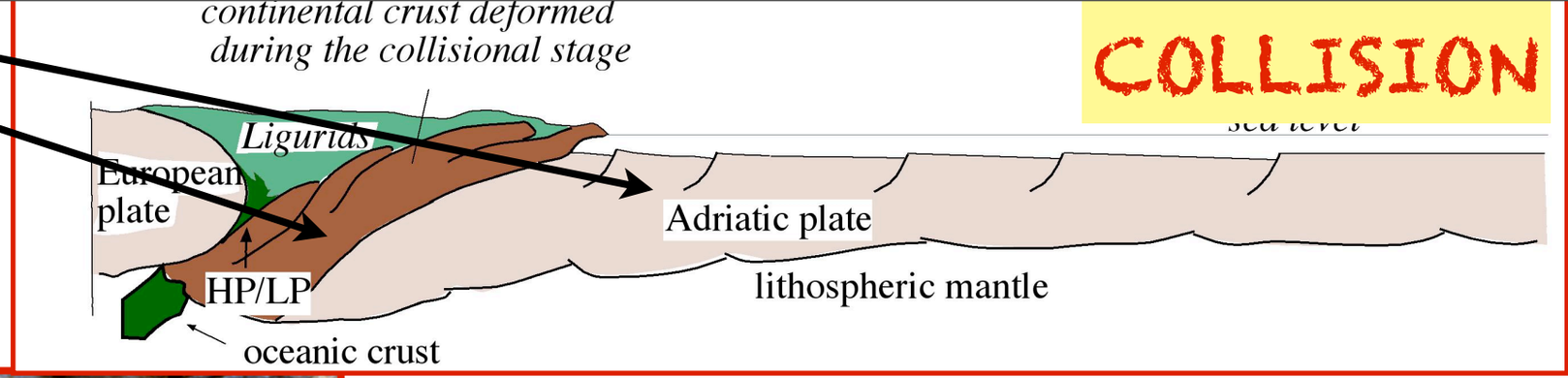
age of metamorphism:
Late Oligocene - Early Miocene

METAMORPHIC TUSCAN UNIT



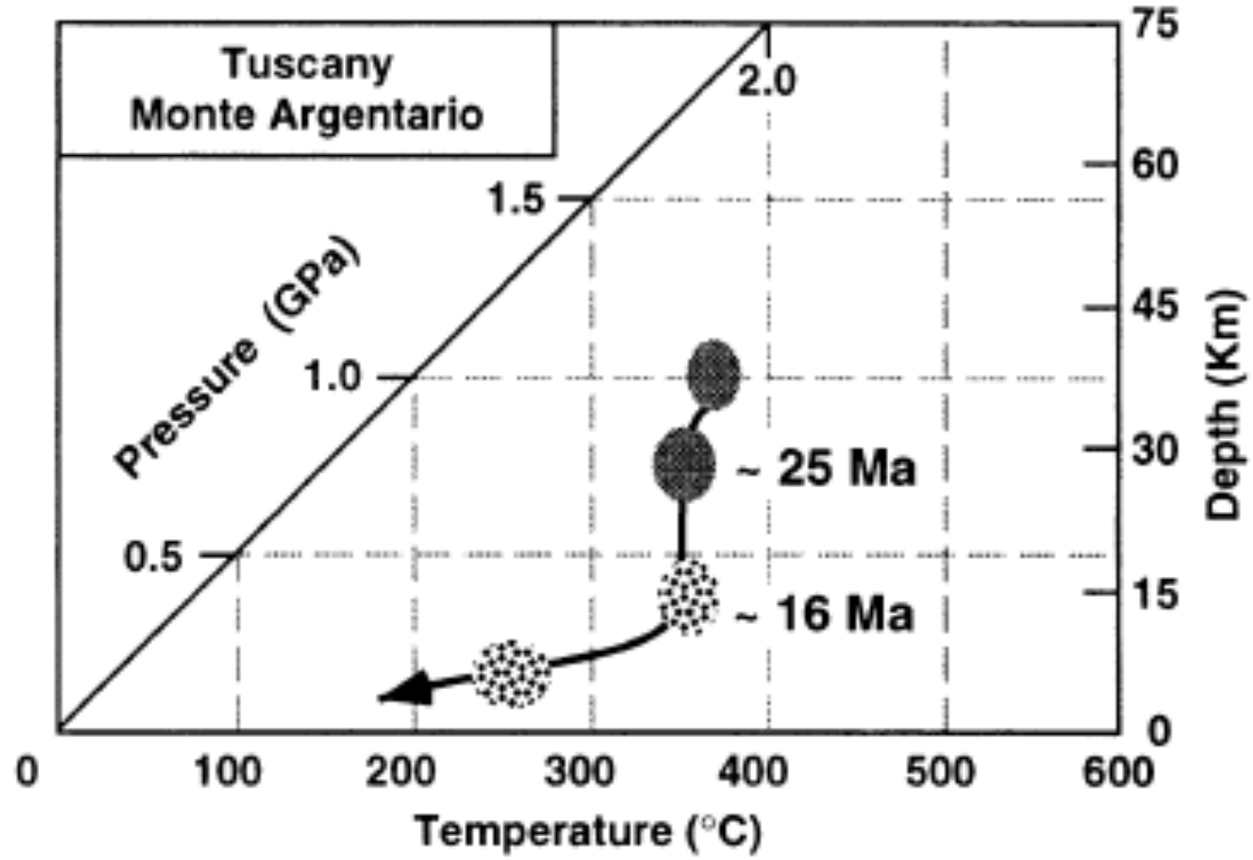
Basement

continental environment



Verrucano Group *Trias*

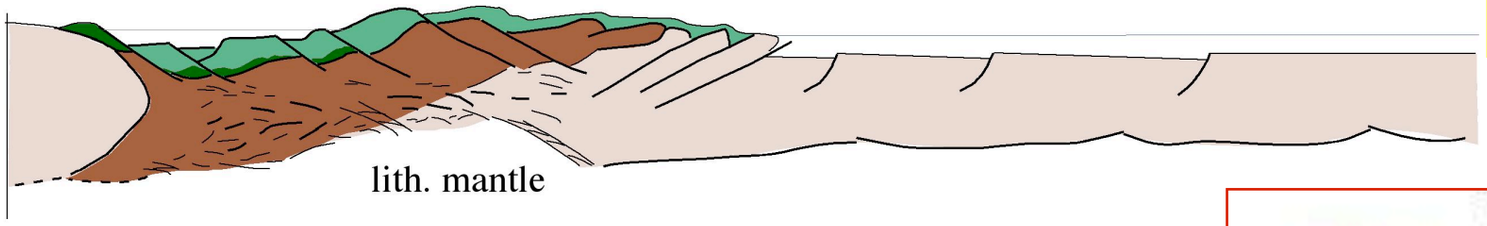
phyllite- Carboniferous

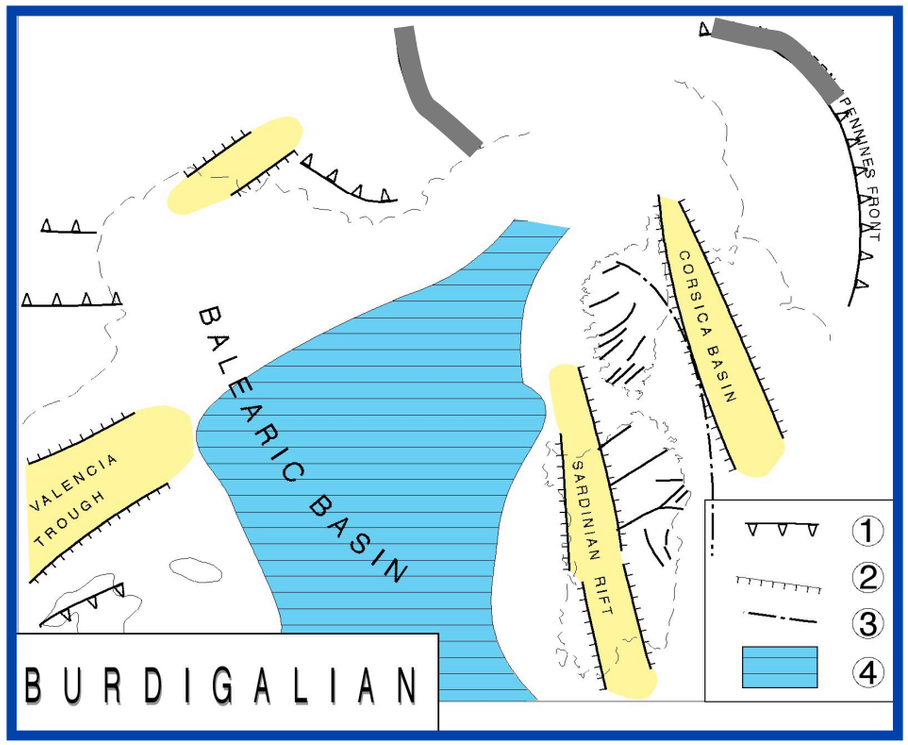


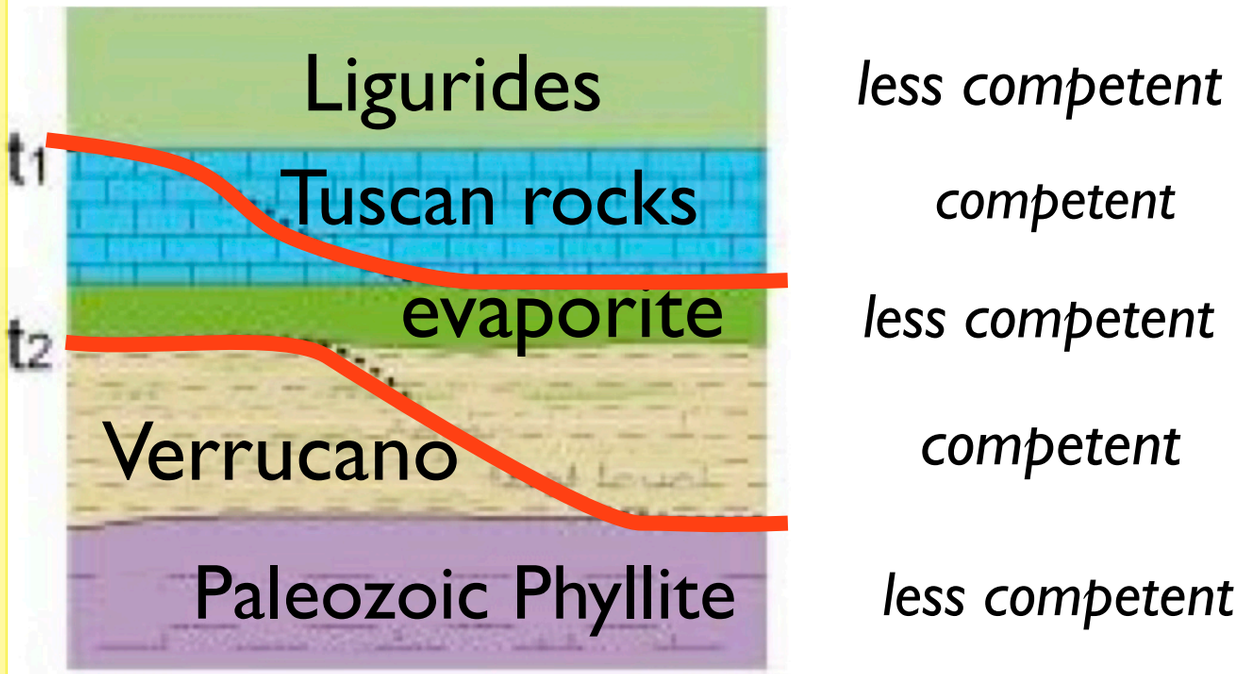
Micaschist and gneiss

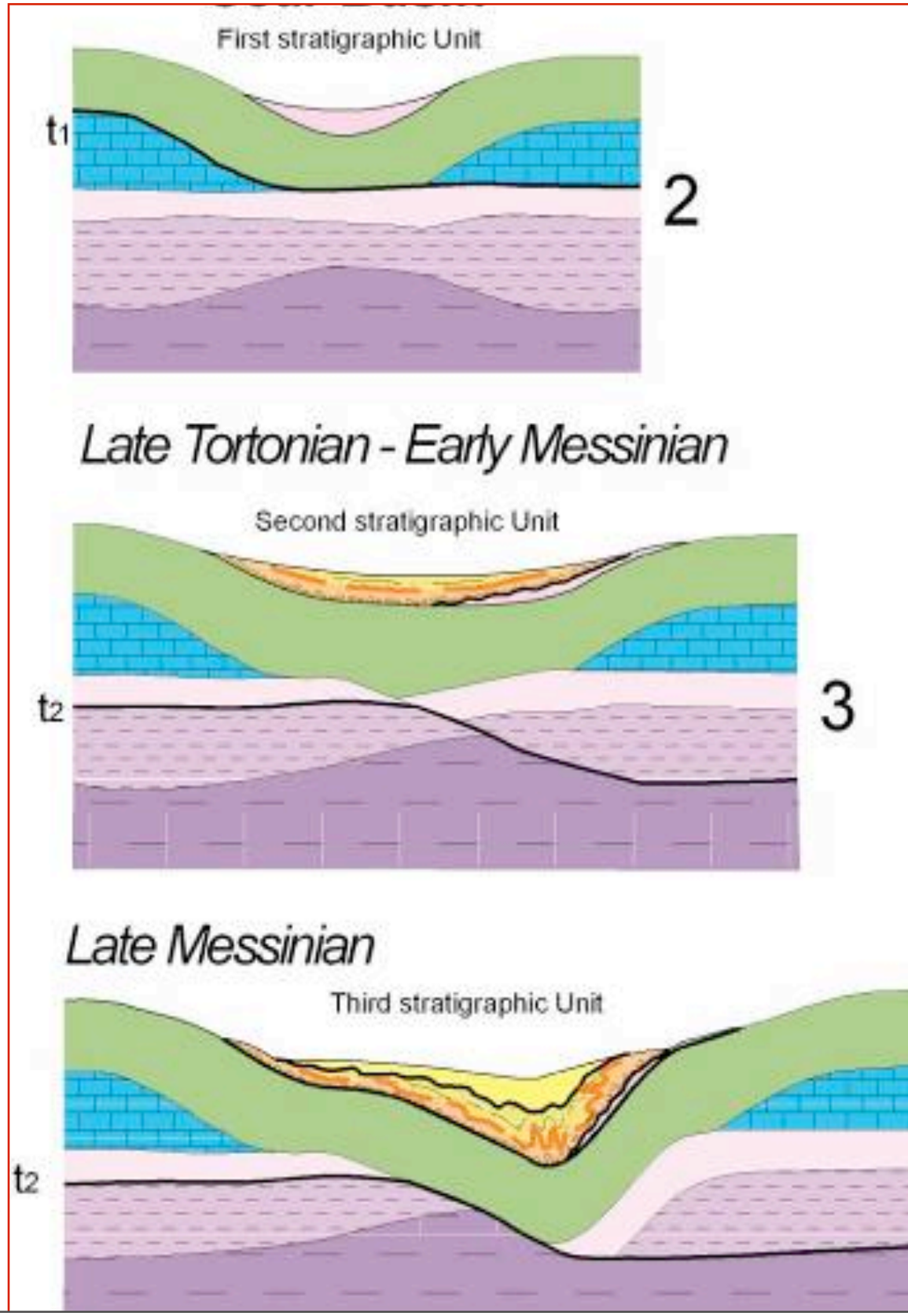
MIOCENE EXTENSION

Early - Middle Miocene

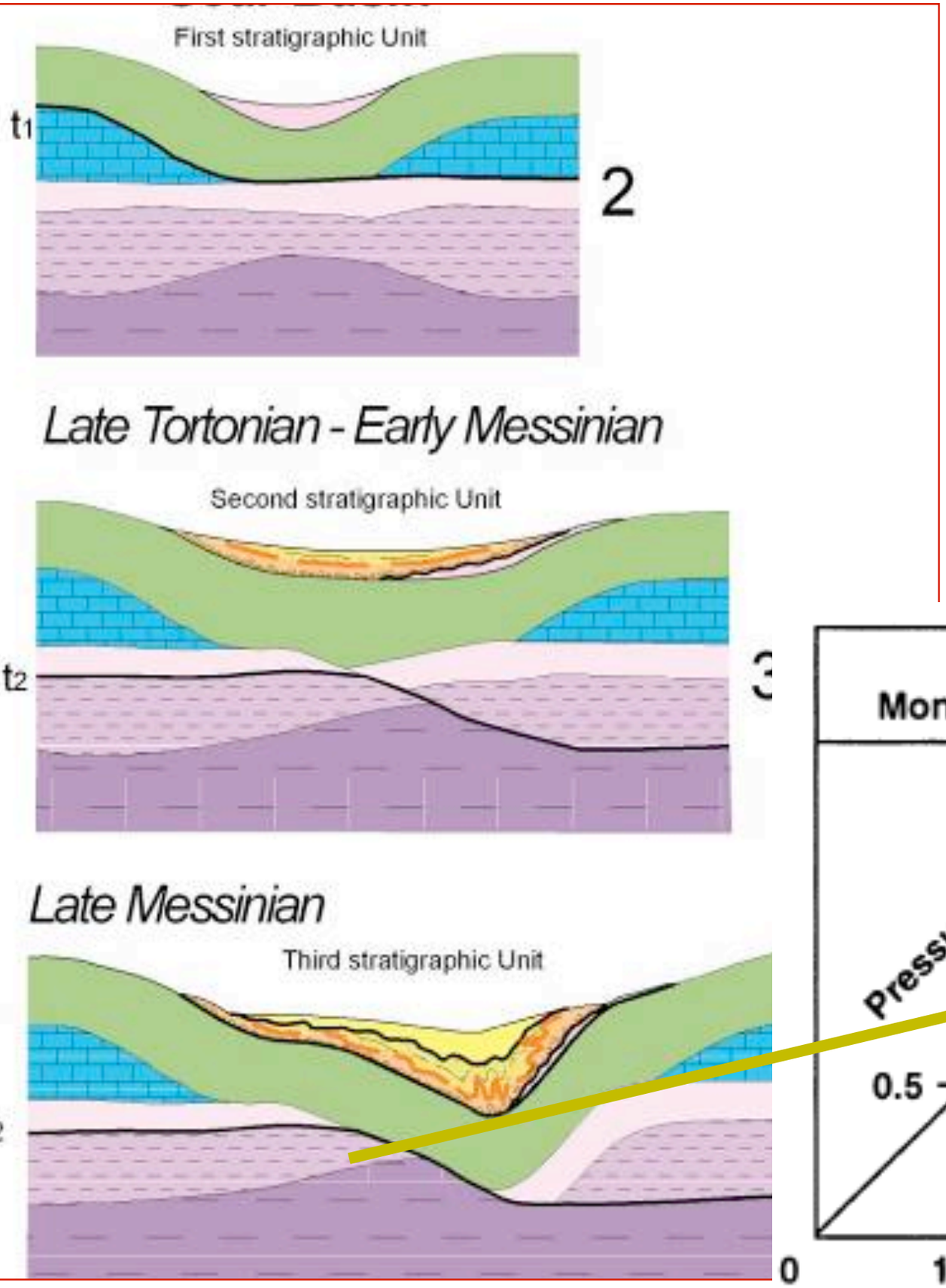




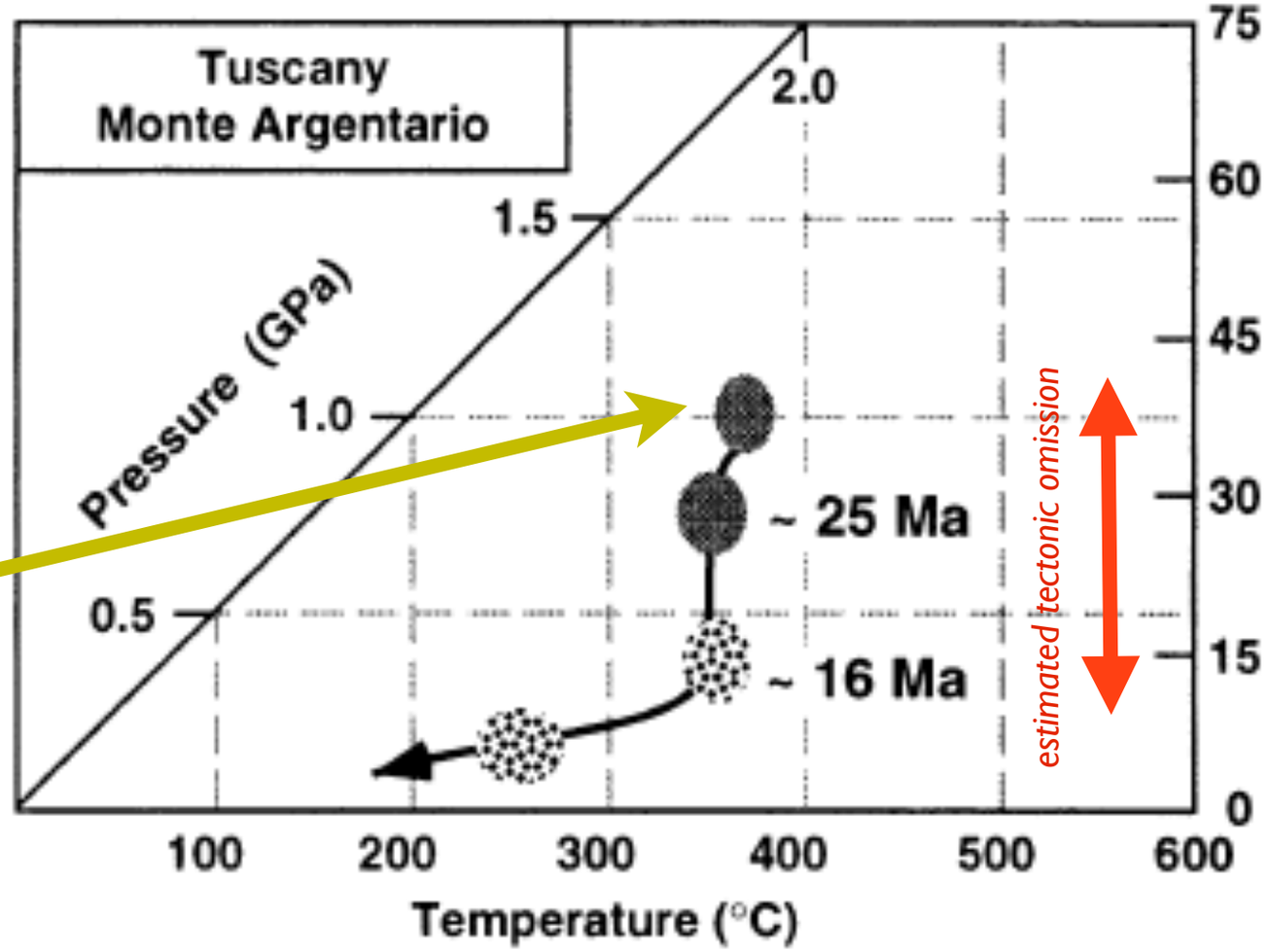




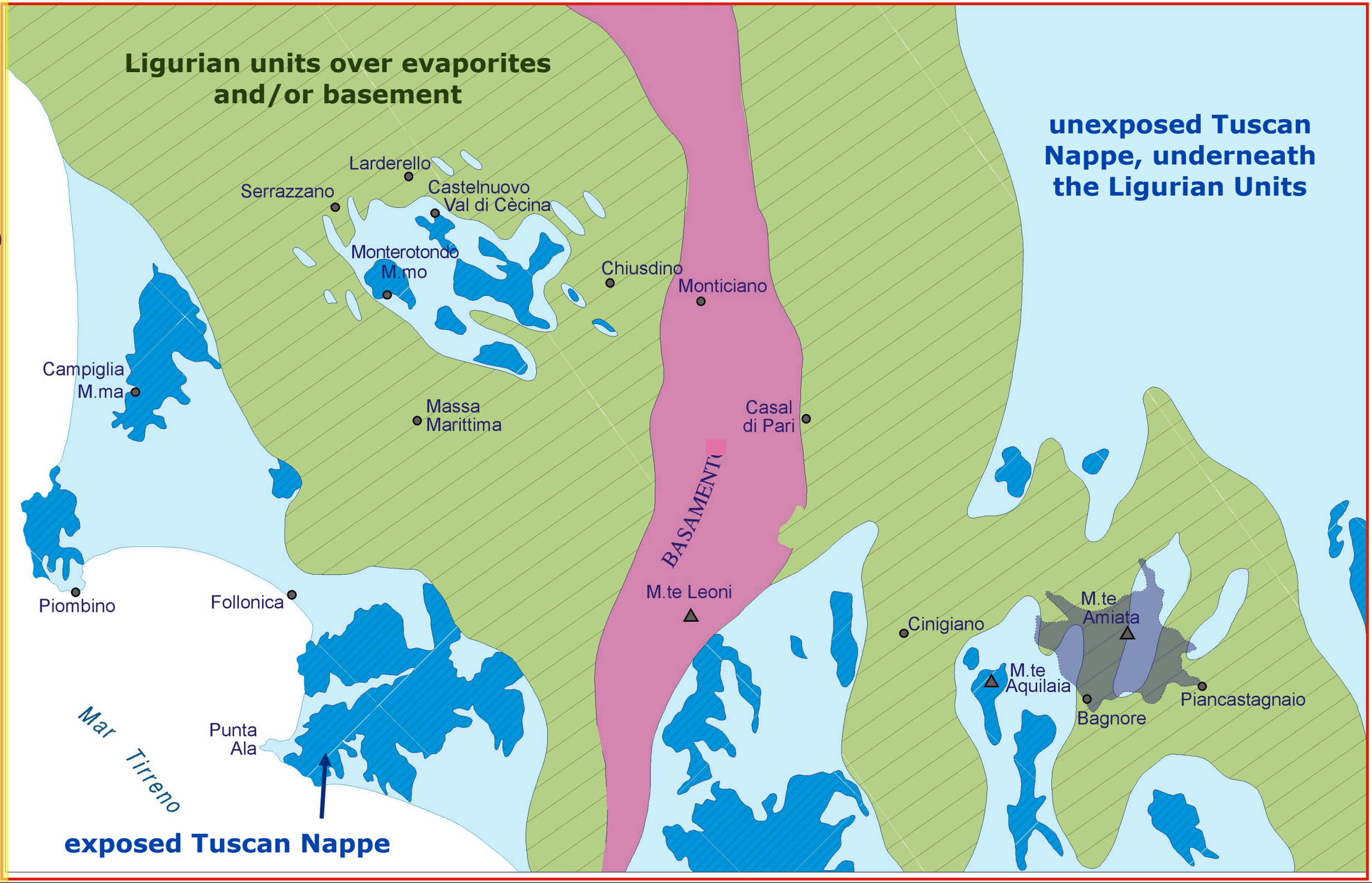
EXTENSION



Extension determined a tectonic omission of about 20 km, at least and exhumation of deeper structural levels



STRUCTURAL SKETCH MAP ILLUSTRATING THE AREAS WHERE THE LIGURIAN UNITS LYE DIRECTLY ON THE LATE TRIASSIC EVAPORITES AND/OR BASEMENT



Ligurian Units resting on Triass
evaporites or metamorphic roc
Palaezoic-Cretaceous
metamorphic rocks
not exposed Tuscan Nappe
exposed Tuscan Nappe
not exposed Miocene sedimen
exposed Miocene sediments
Volcanic rocks
0
10 km
Tyrrhenian Sea
LARDERELLO
Radicondoli Basin
Serrazzano
Serrazzano Basin
Chiusdino
Monticiano
Palaeozoic-Cretaceous metamorphic rocks
Campiglia M.ma
Massa Marittima
Velona Basin
Monte Amiata
Cinigiano
Cinigiano-Baccinello Basin
M.te Aquilaia
Bagnore
M.te Labbro
Punta Ala
boundary of the Tuscan Nappe boudin
inferred boundary of the Tuscan Nappe boudin
Pliocene normal fault

Ligurian Units resting on Triassic evaporites or metamorphic rocks
Palaezoic-Cretaceous metamorphic rocks
not exposed Tuscan Nappe
exposed Tuscan Nappe
not exposed Miocene sediments
exposed Miocene sediments
Volcanic rocks
0 10 km

Tyrrhenian Sea
LARDERELLO
Serrazzano
Radicondoli Basin
Serrazzano Basin
Chiusdino
Monticiano
Palaeozoic-Cretaceous metamorphic rocks
Campiglia M.ma
Massa Marittima
Velona Basin
Cinigiano
Monte Amiata

boundary of the Tuscan Nappe boudin

Late Tortonian - Early Messinian
Second stratigraphic Unit
3

Late Messinian
Third stratigraphic Unit
t2
4

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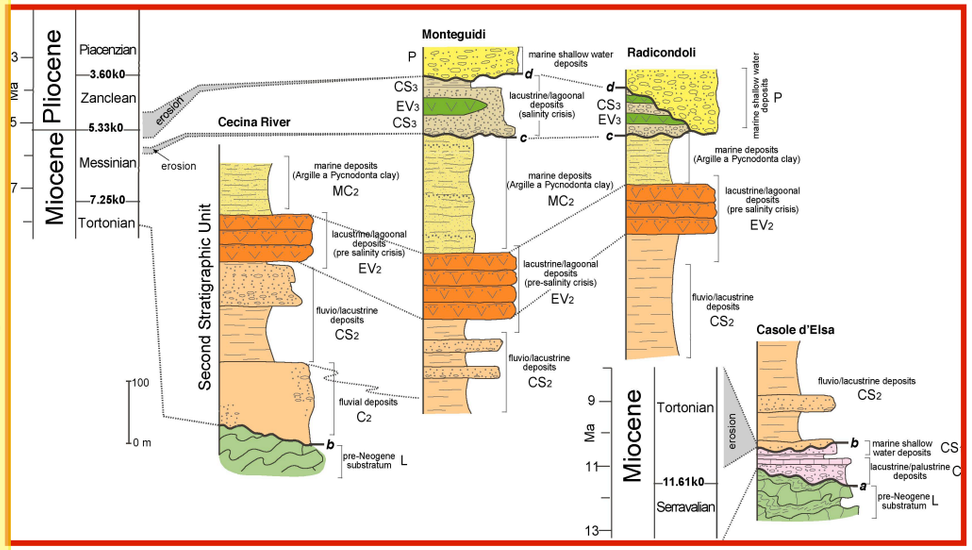
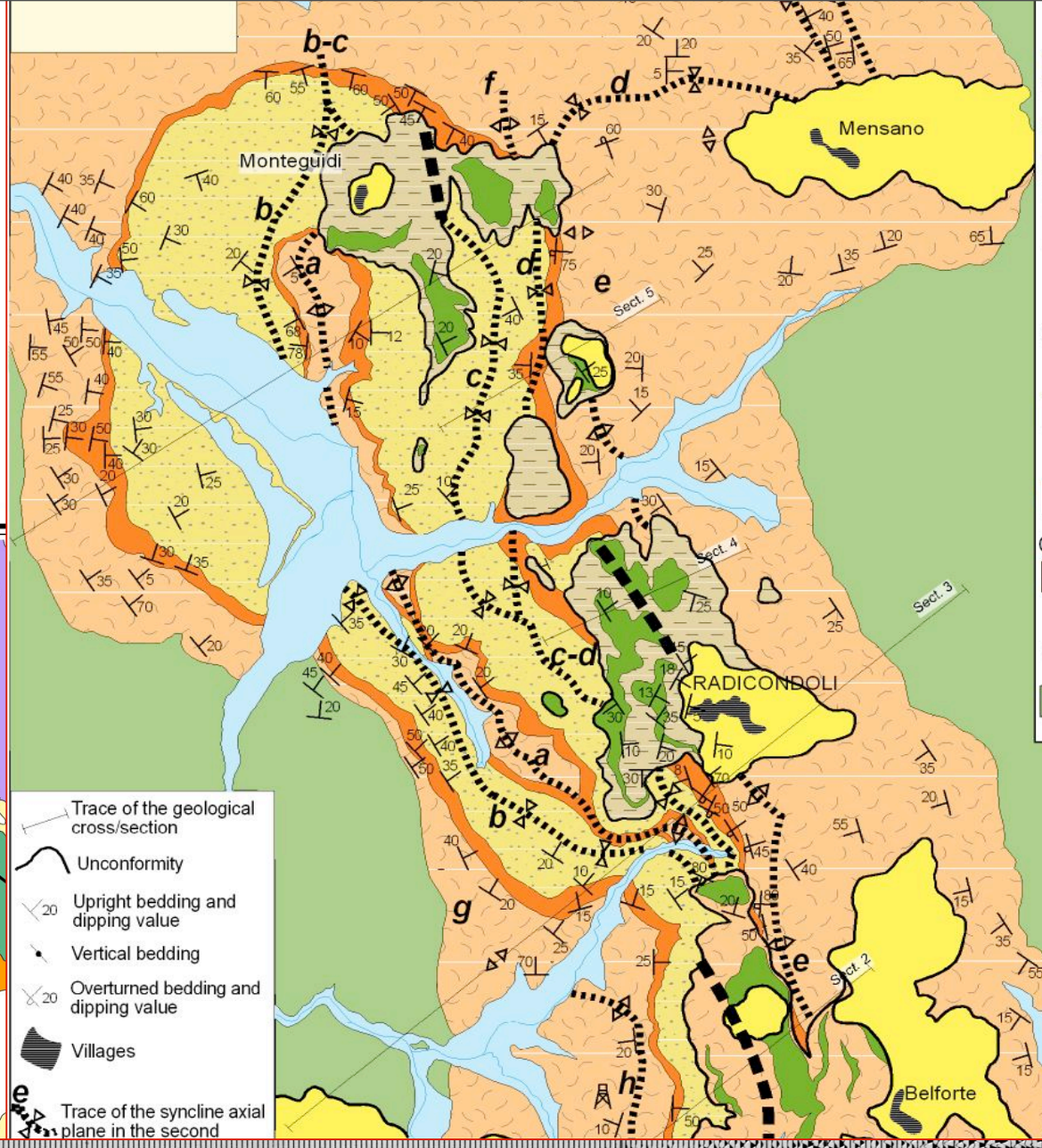
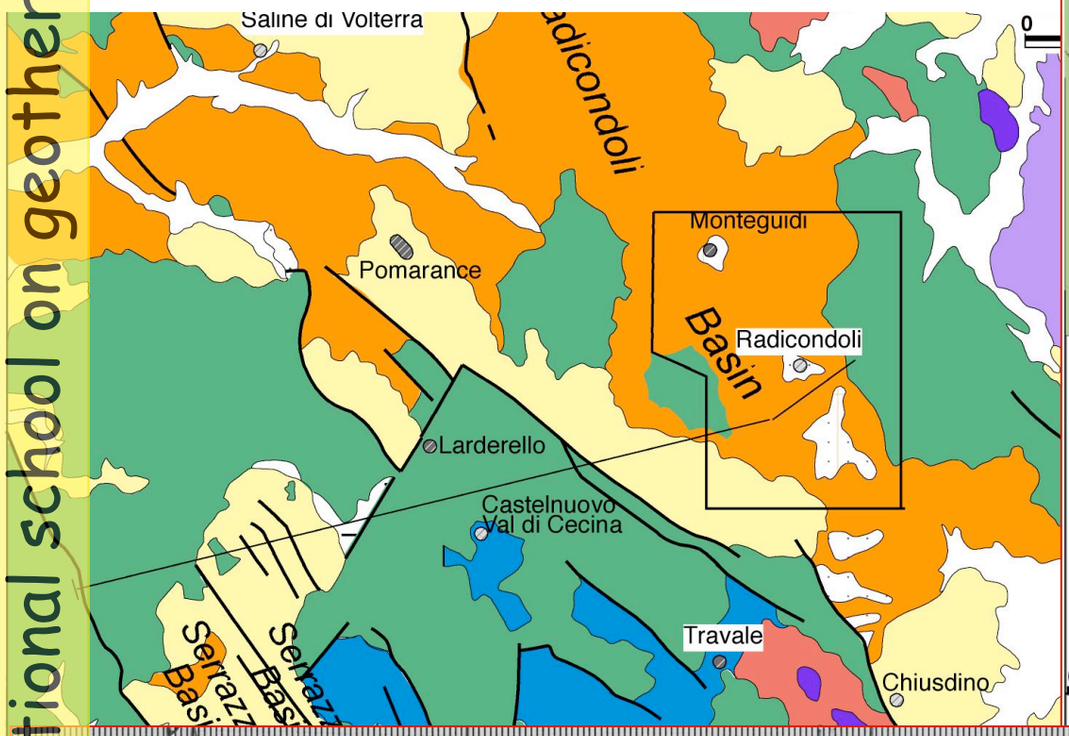
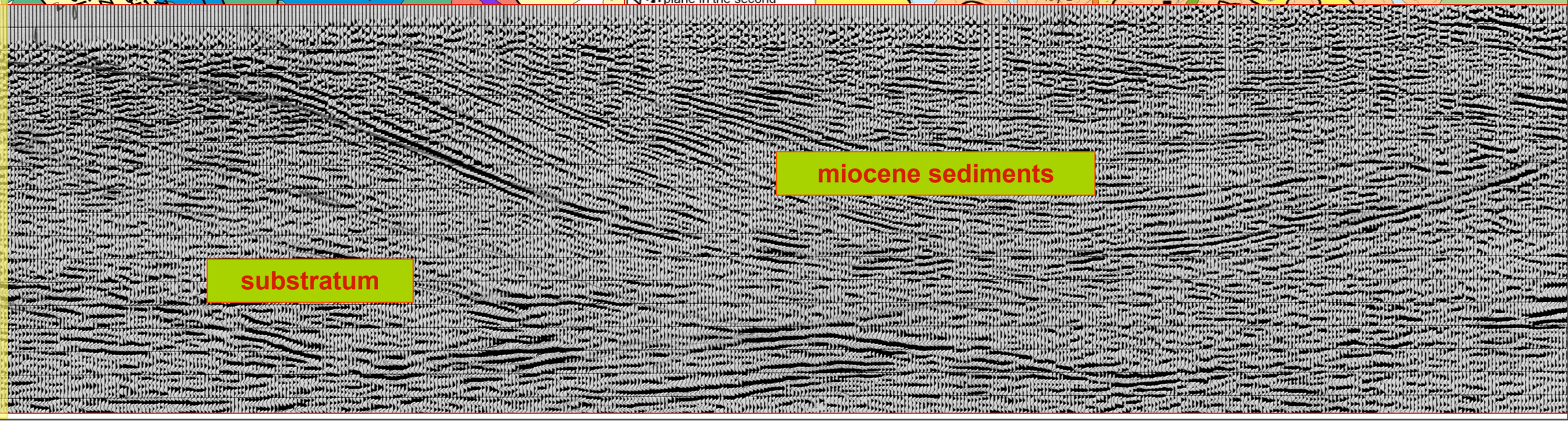
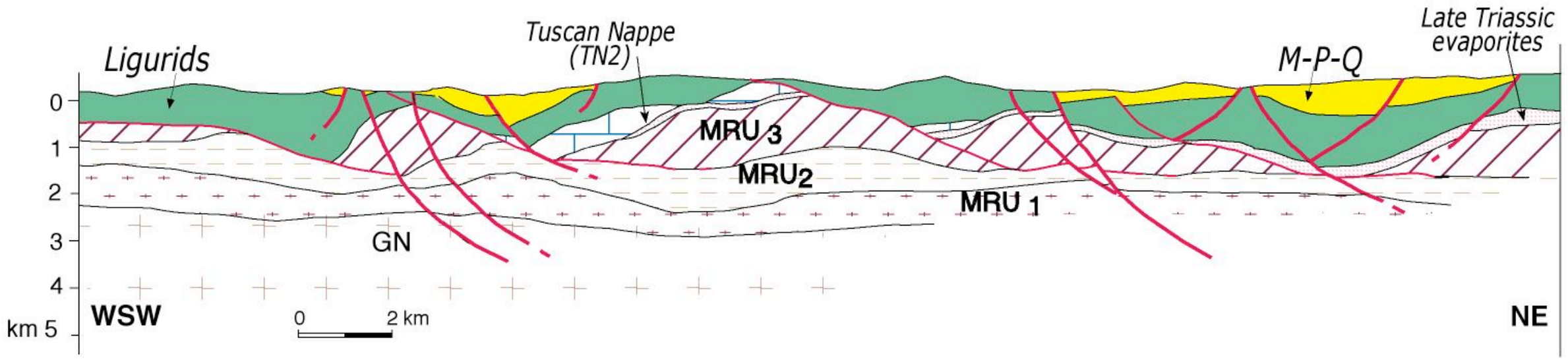


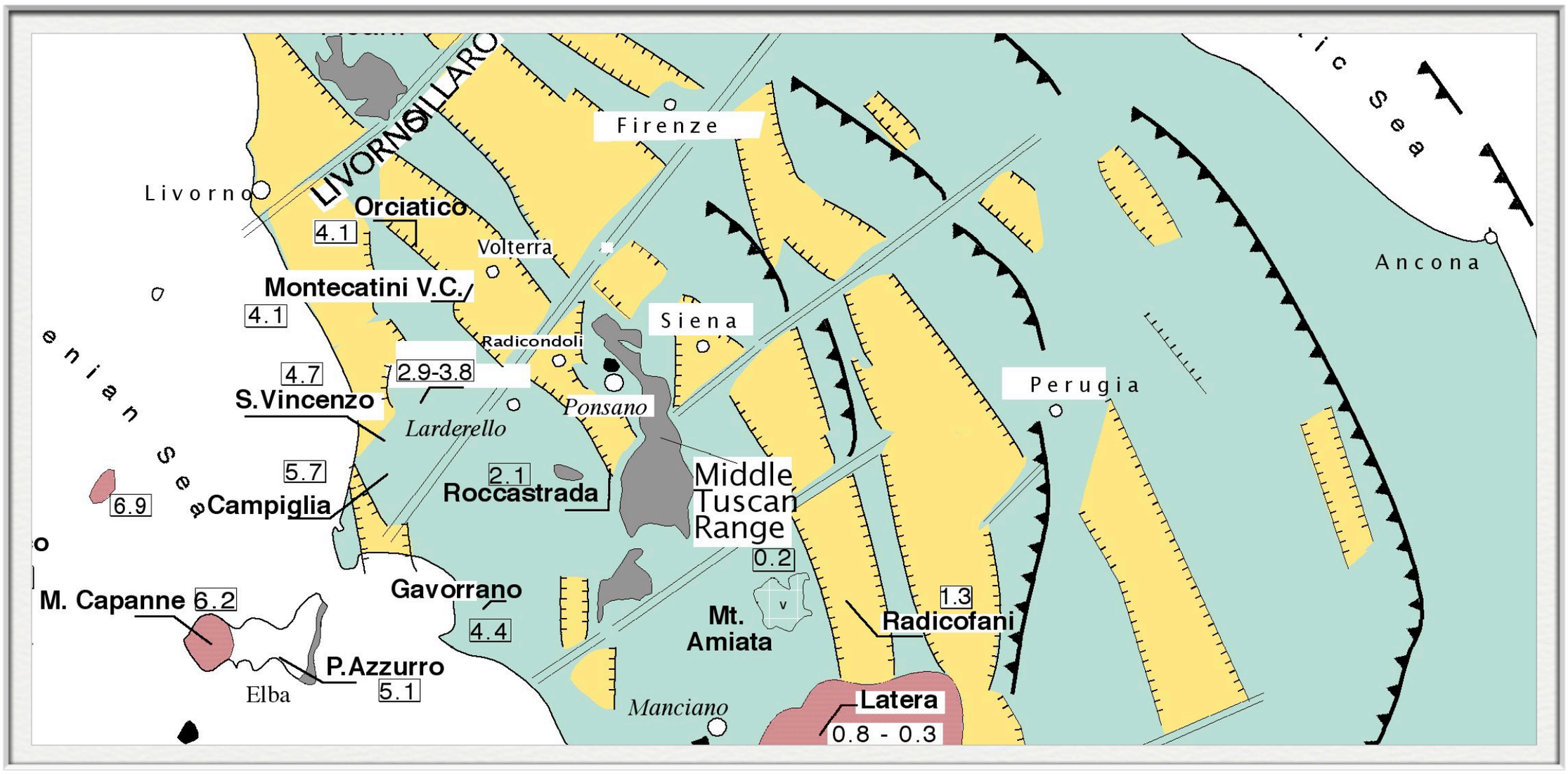






PLIOCENE-PRESENT EXTENSION





R. GIANNINI, A. LAZZAROTTO, R. SIGNORINI

CARTA GEOLOGICA DELLA TOSCANA MERIDIONALE

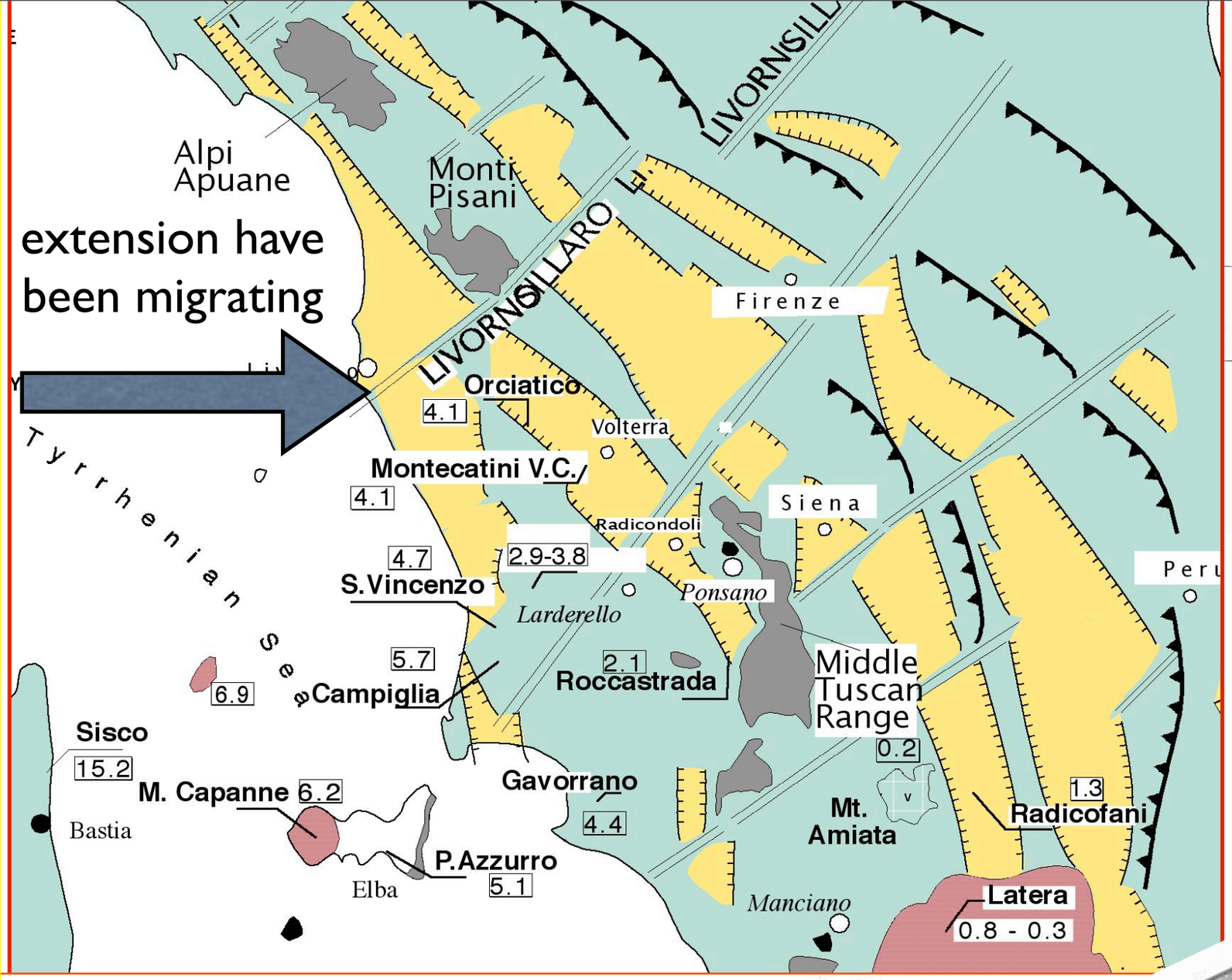
SCALA 1:200.000

LEGENDA

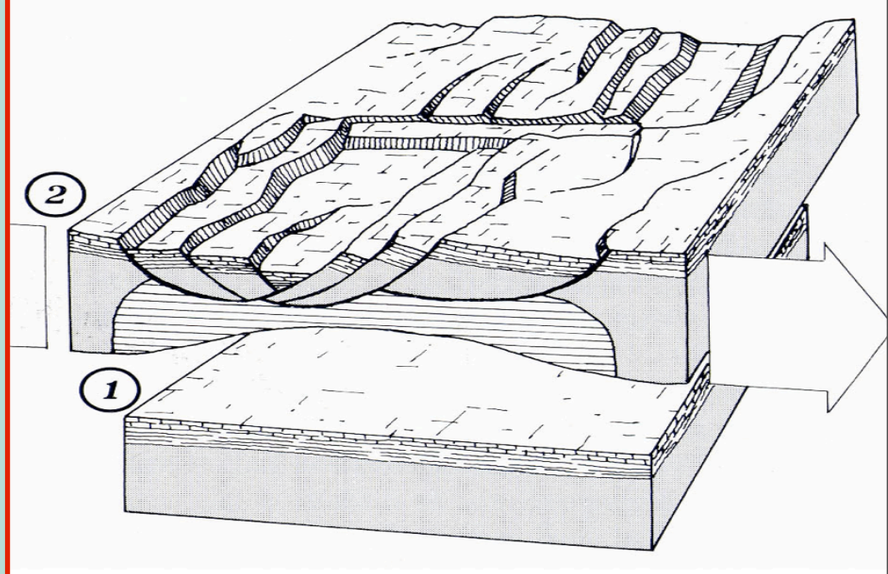
PLIOCENE RADICOFANI BASIN

normal fault

Pliocene clay and sand

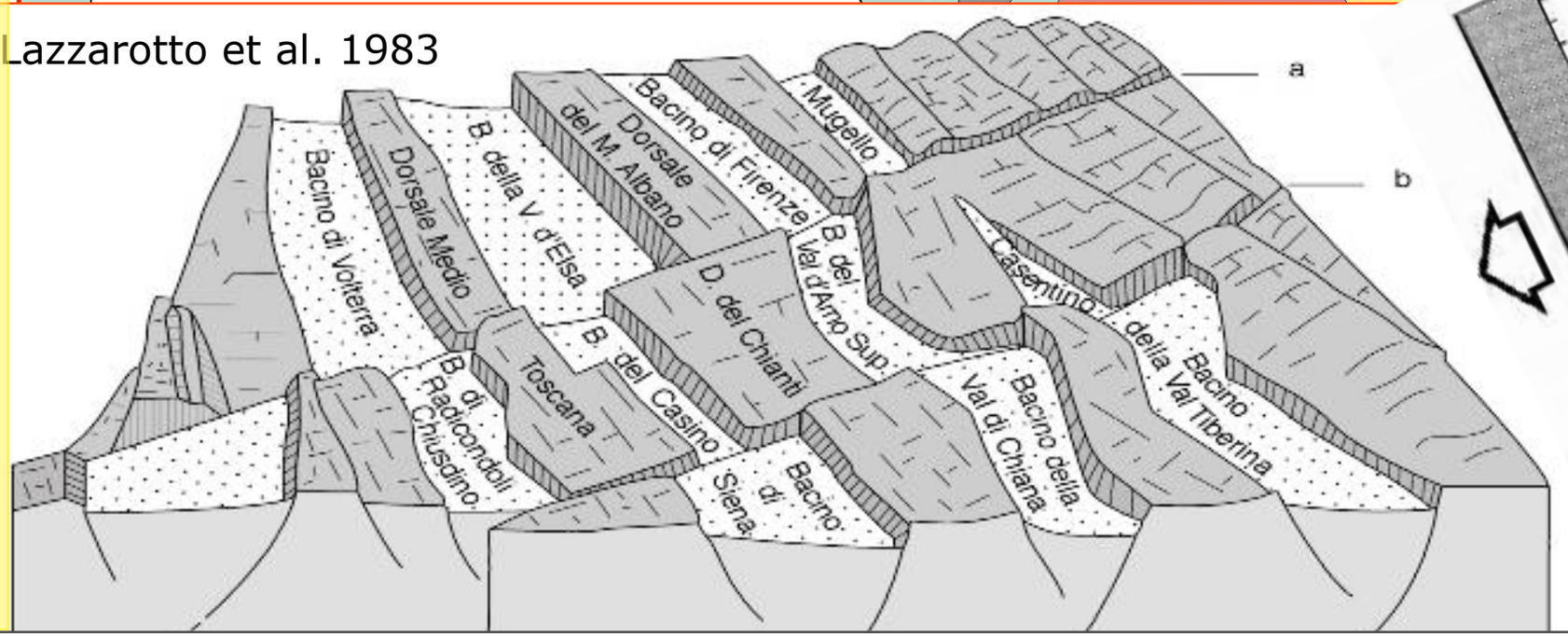


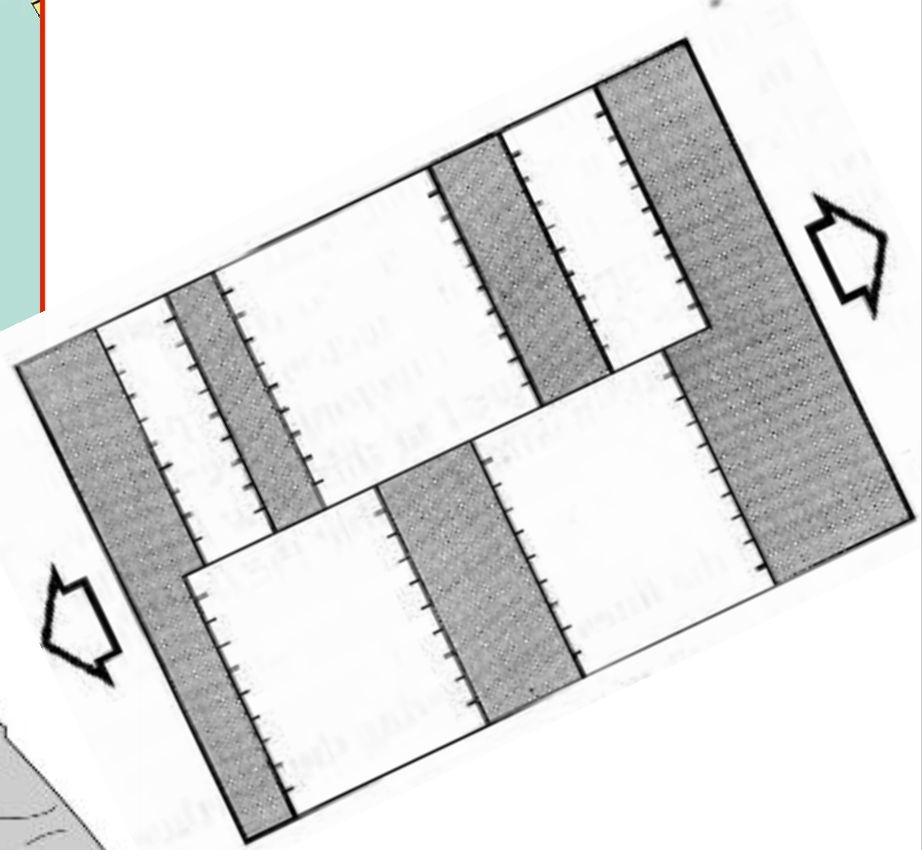
extension have been migrating



Bally, 1981

Lazzarotto et al. 1983



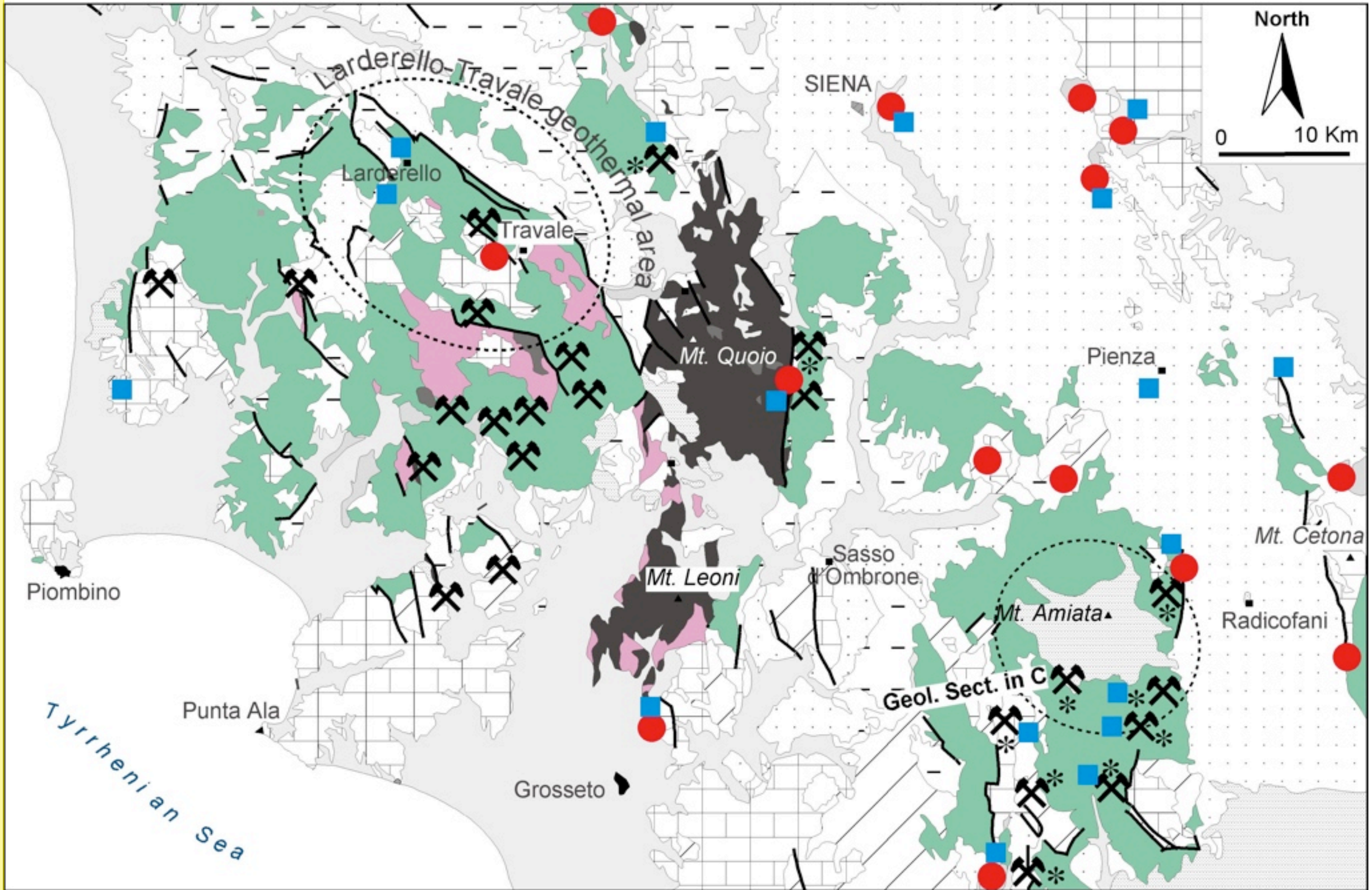


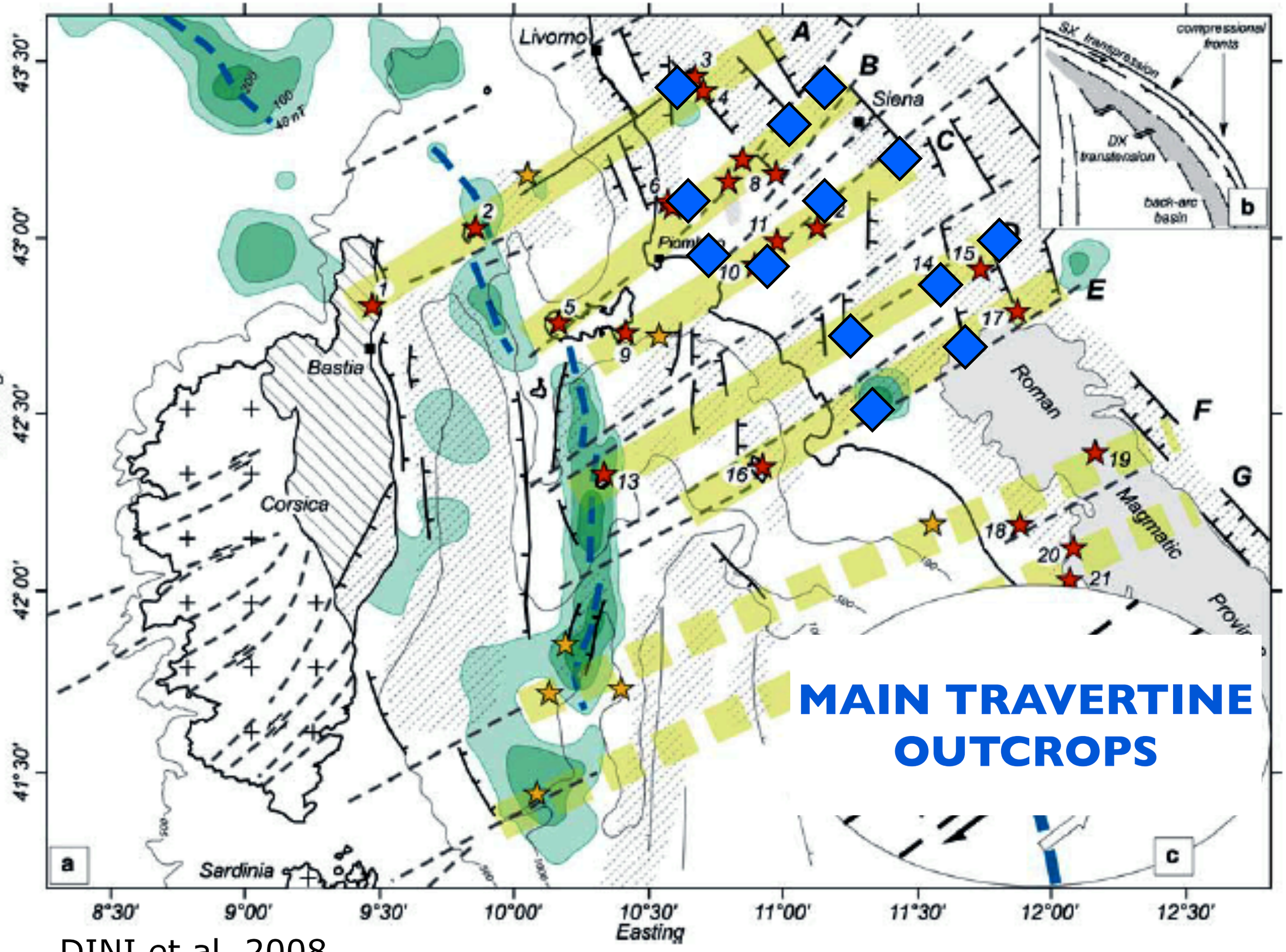
Liotta,1990

Magmatic younging direction

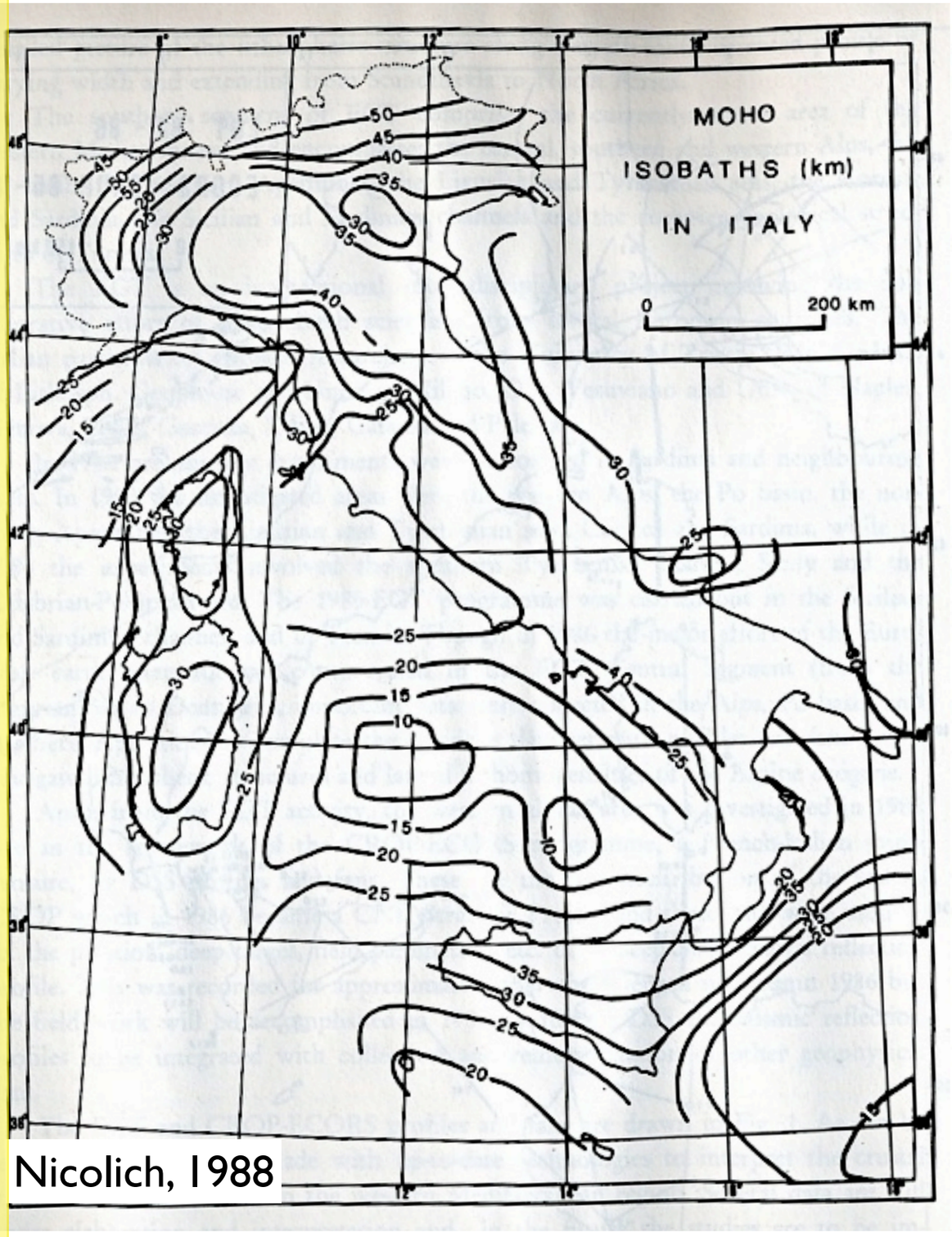
14 Ma - 0.2 Ma

DINI et al. 2008


North
0
10 Km
Larderello-Travale geothermal area
Larderello
Travale
SIENA
Mt. Quoio
Pienza
Mt. Cetona
Sasso d'Ombrone
Mt. Leoni
Mt. Amiata
Radicofani
Geol. Sect. in C
Piombino
Punta Ala
Tyrrhenian Sea
Grosseto
Quaternary continental deposits
Quaternary magmatic rocks
Early/Middle Pliocene marine sediments
Late Miocene continental sediments
Ligurian Units (Middle Jurassic/Eocene)
Subligurian Units (Paleocene/Eocene)
Tuscan Nappe: carbonate succession (Late Trias/Cretaceous)
Tuscan Nappe: evaporitic succession (Late Trias)
Monticiano-Roccastrada Unit (Palaeozoic - Eocene)
Main Pliocene - Quaternary normal fault
Hg and Sb mines
Fe, Cu, Pb, Zn mines
Gas emission (CO_2, CH_4, H_2S)
Travertines

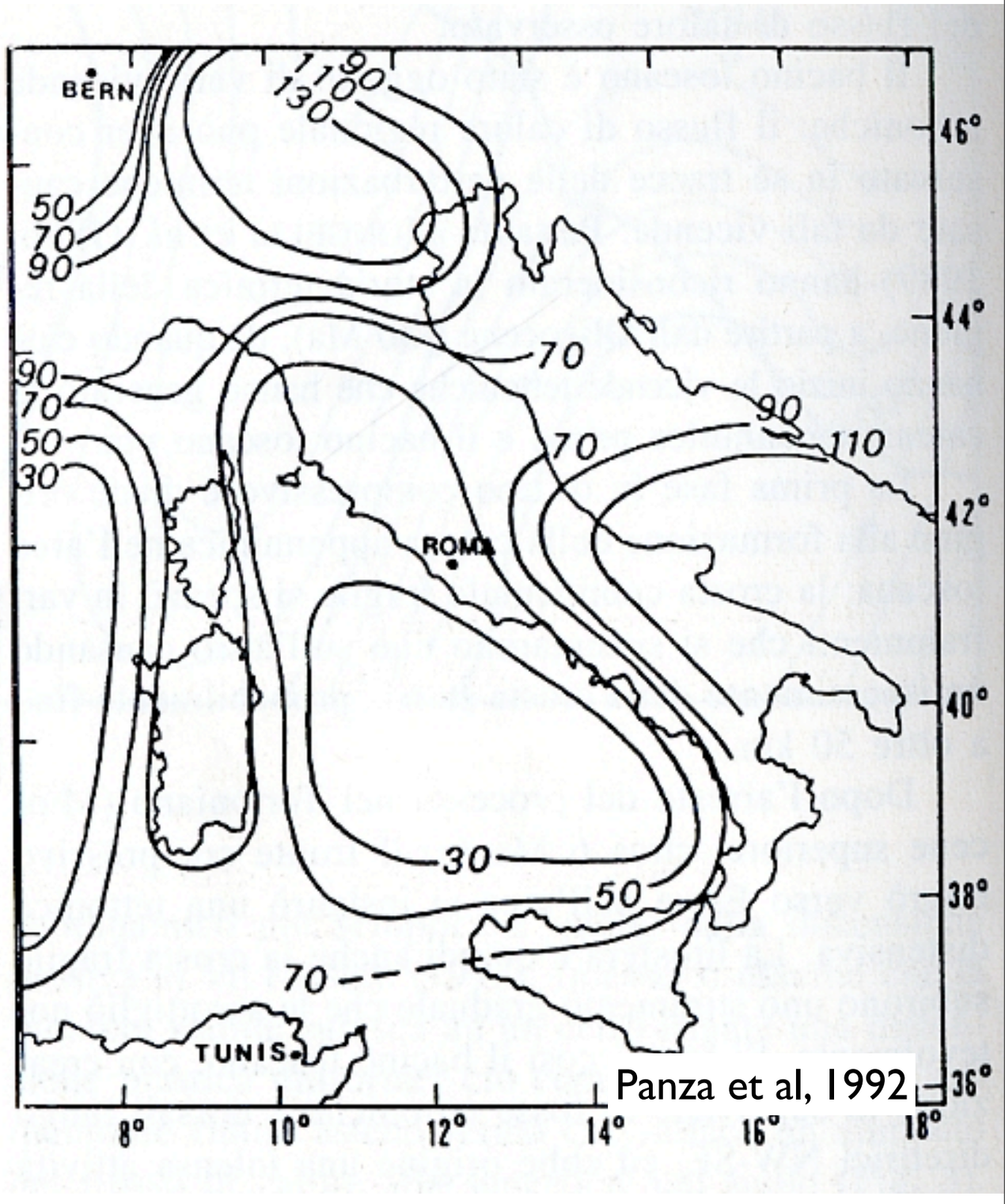


DINI et al. 2008



Nicolich, 1988

Crust thickness is about 25 km in southern Tuscany

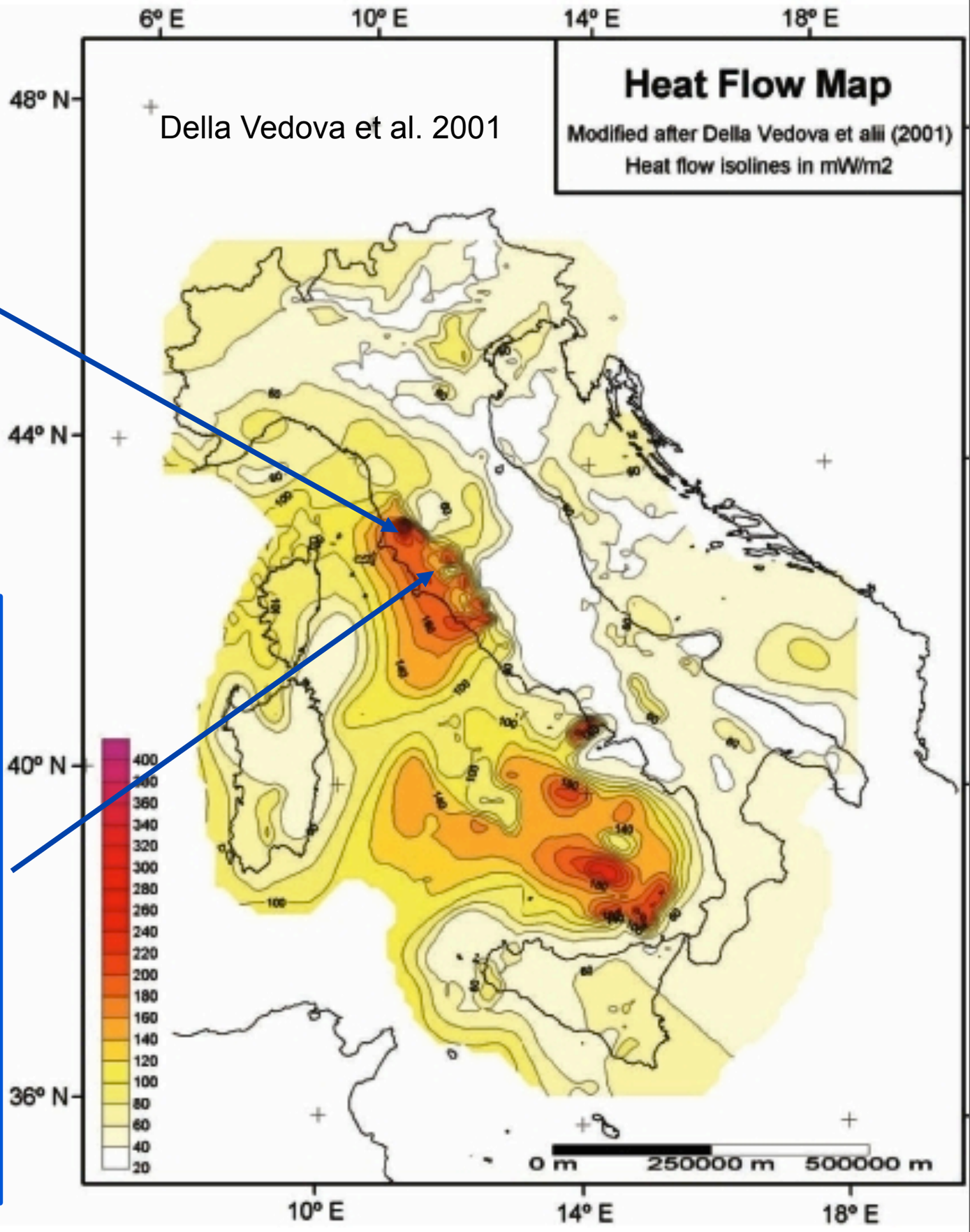


Lithosphere thickness is about 40 km in southern Tuscany

FIELD AREAS

LARDERELLO

MT. AMIATA



LIGURIAN SEA

LARDERELLO

MT. AMIATA

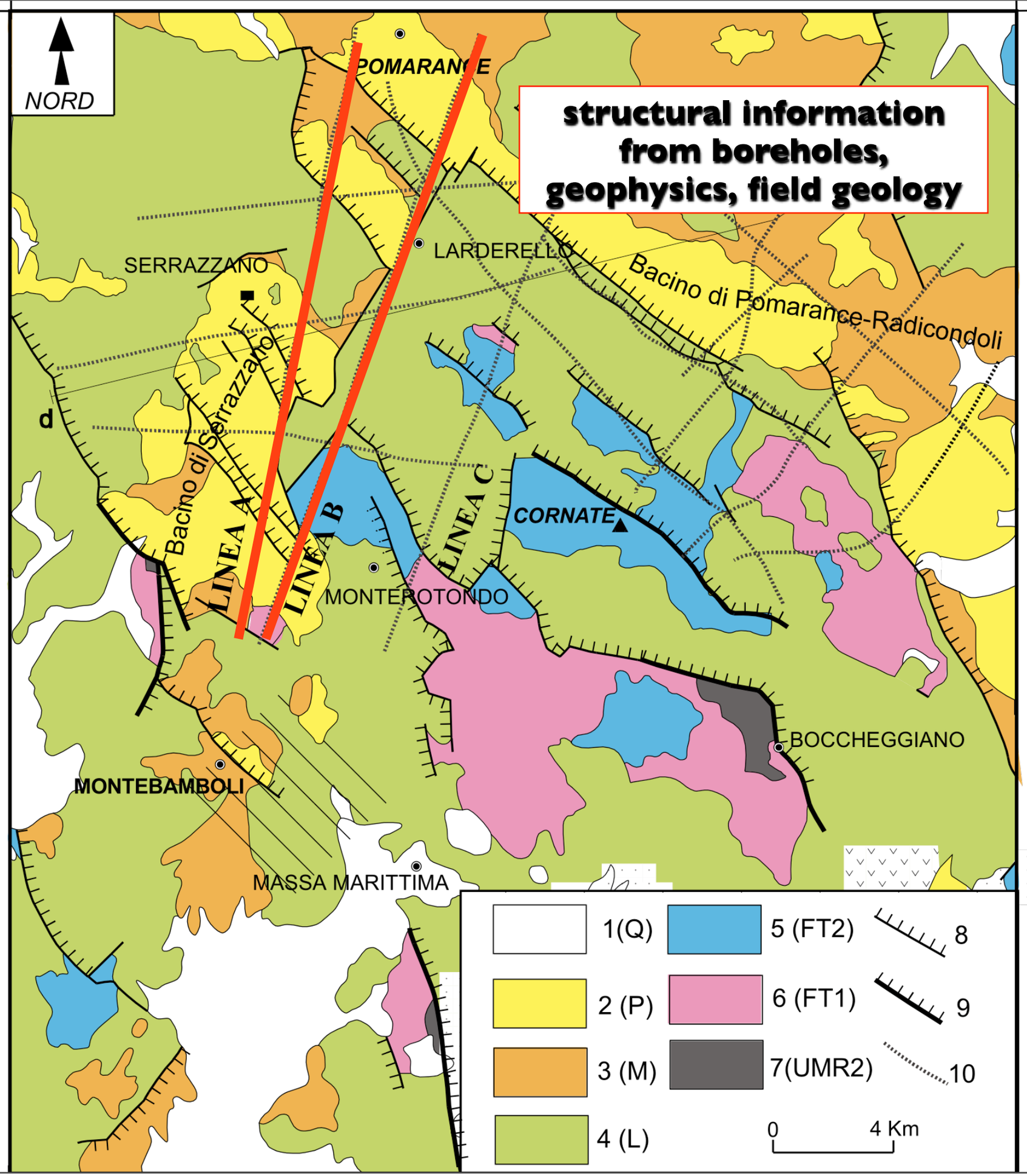
Golfo di Follonica

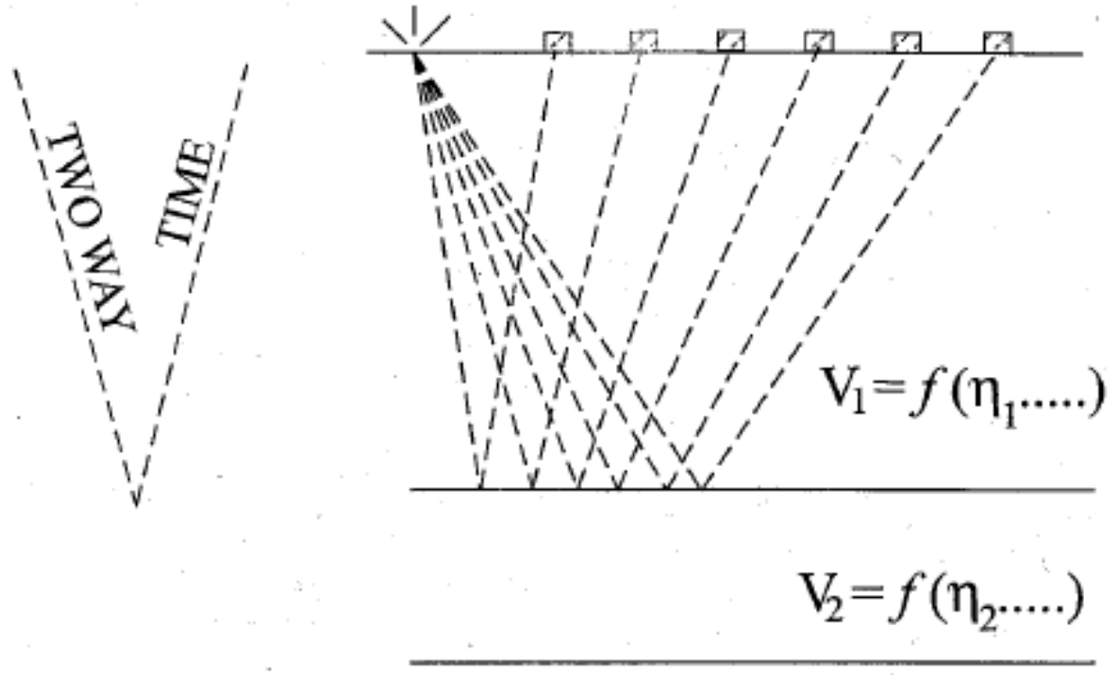
TYRRHENIAN

D. Liotta - international school on geothermal exploration

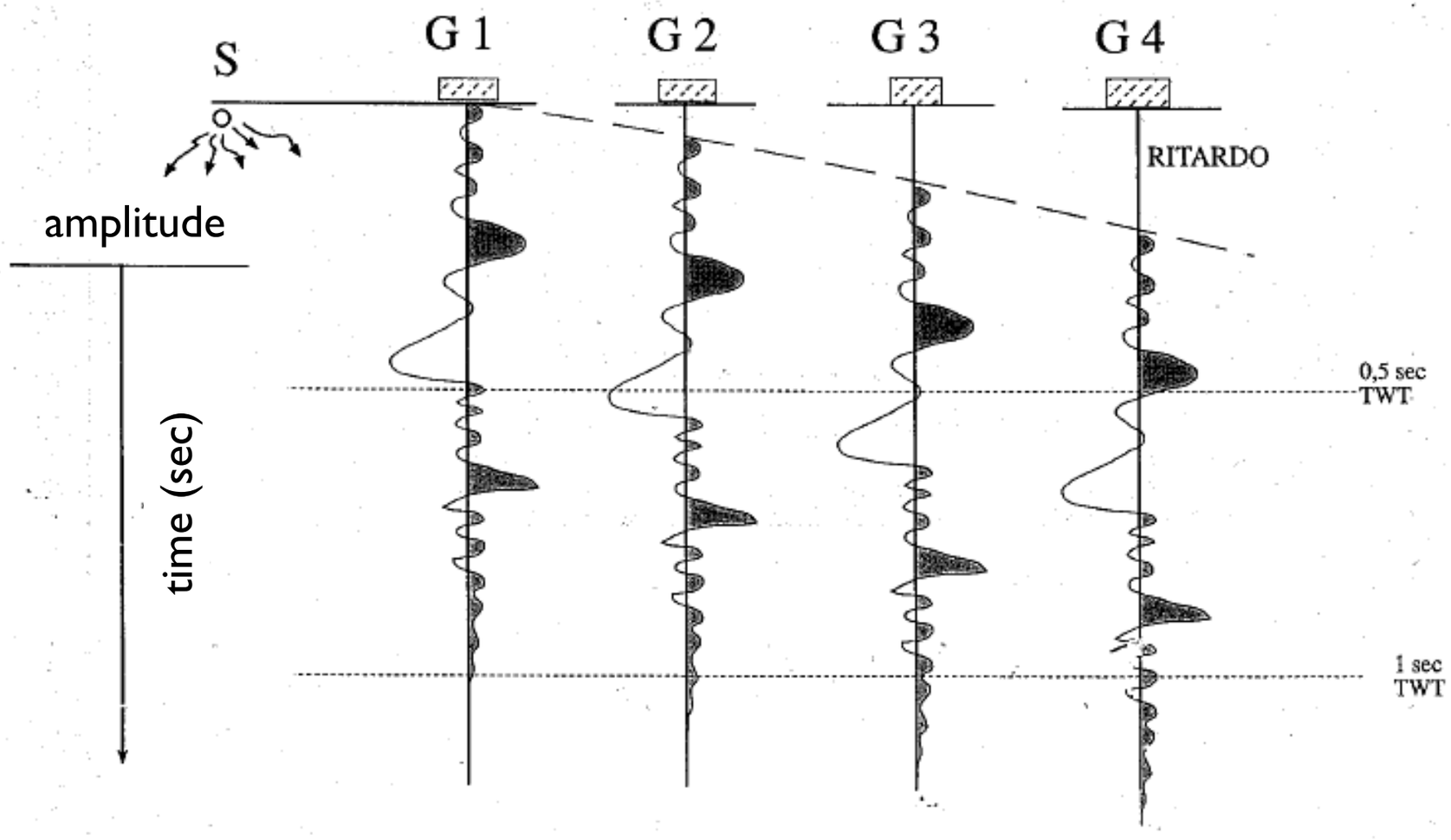
LARDERELLO

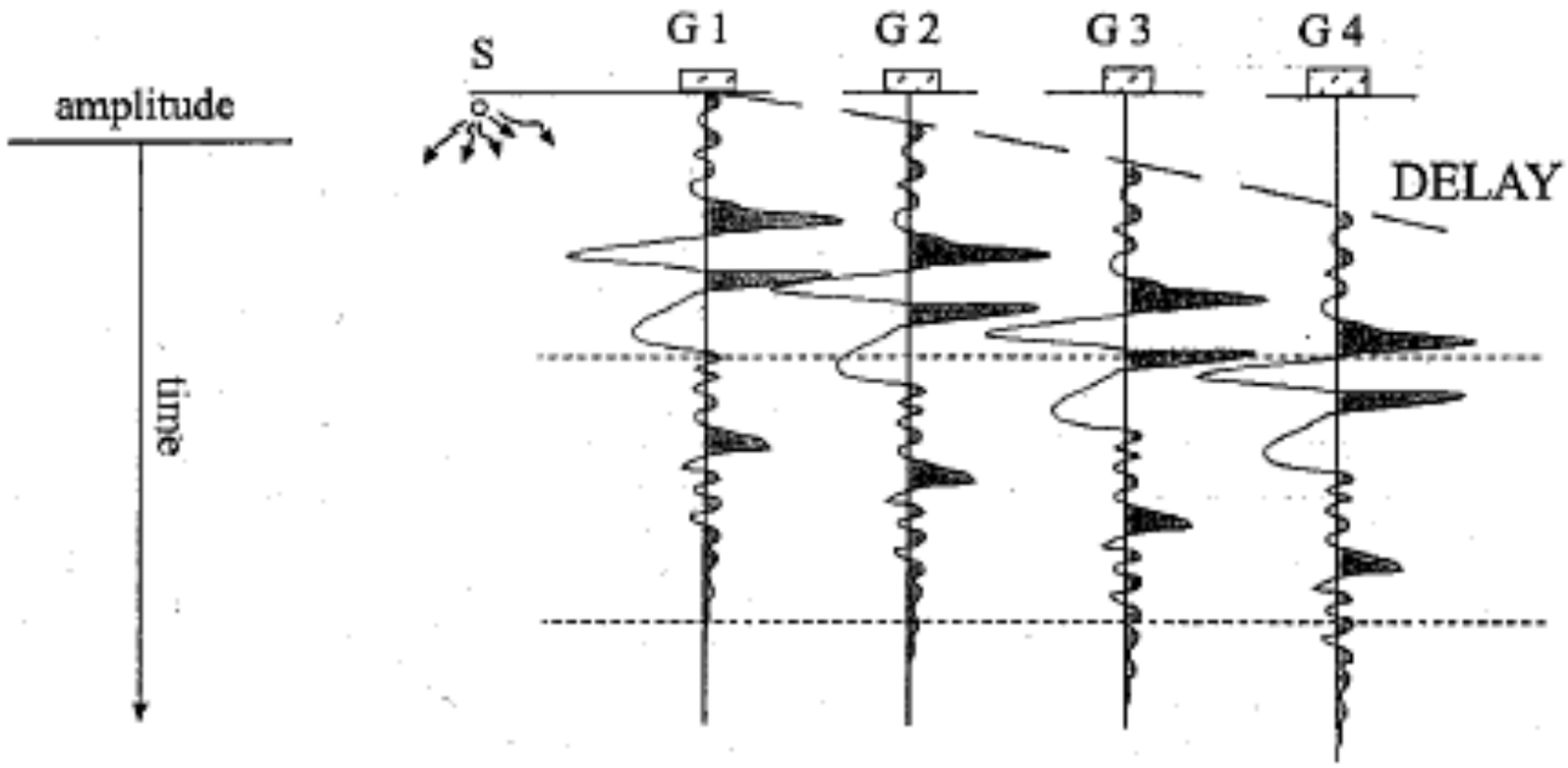
43° 18'



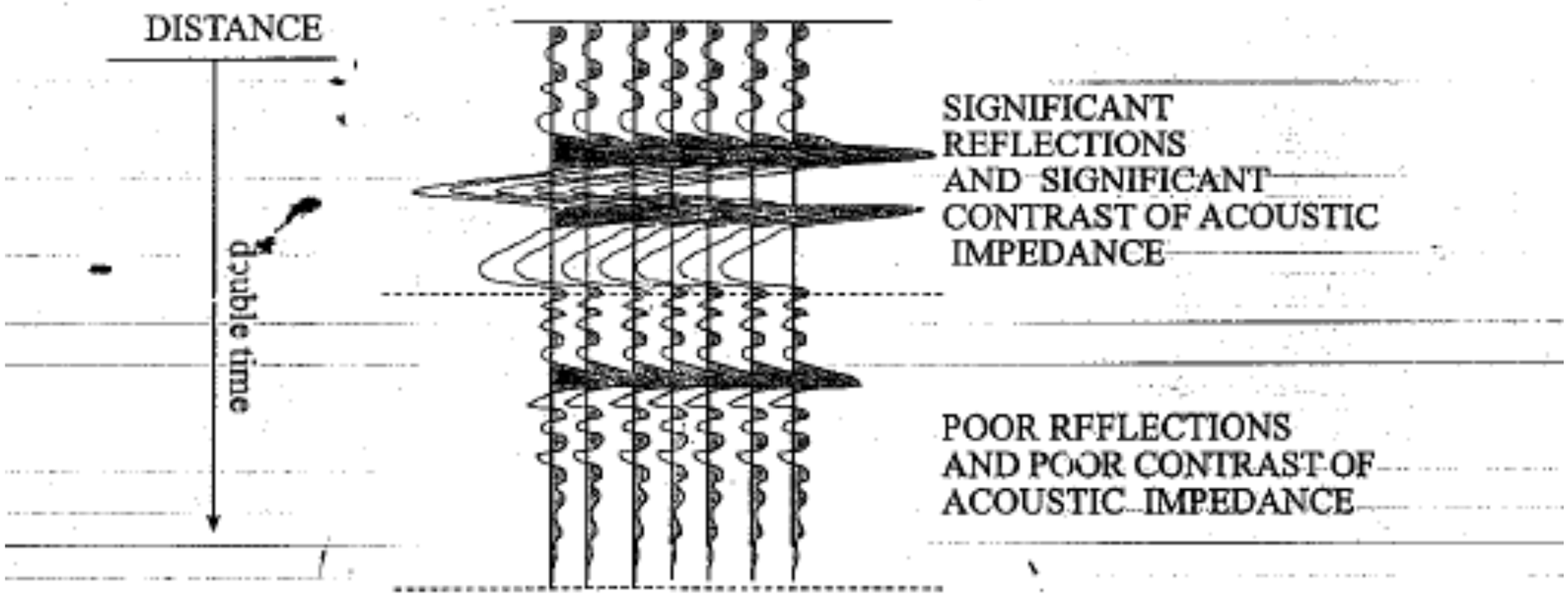


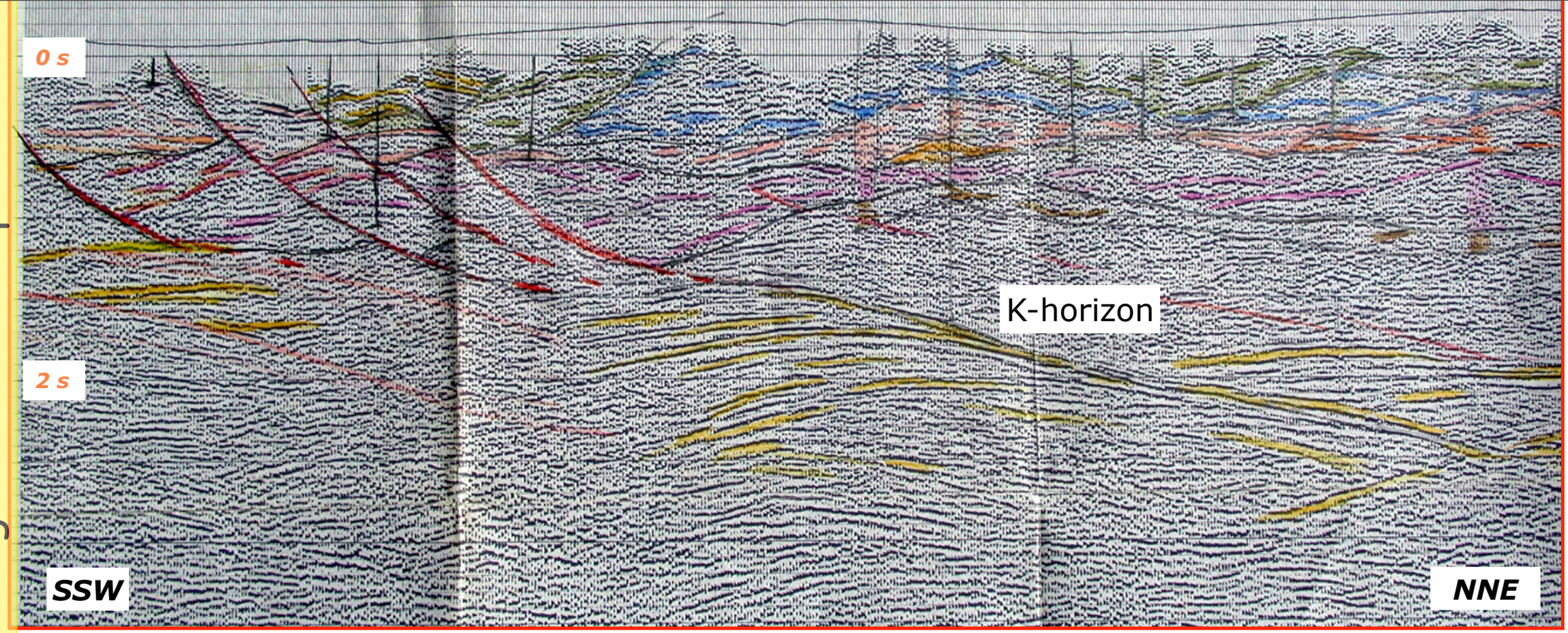
ACOUSTIC IMPEDANCE = VELOCITY x DENSITY

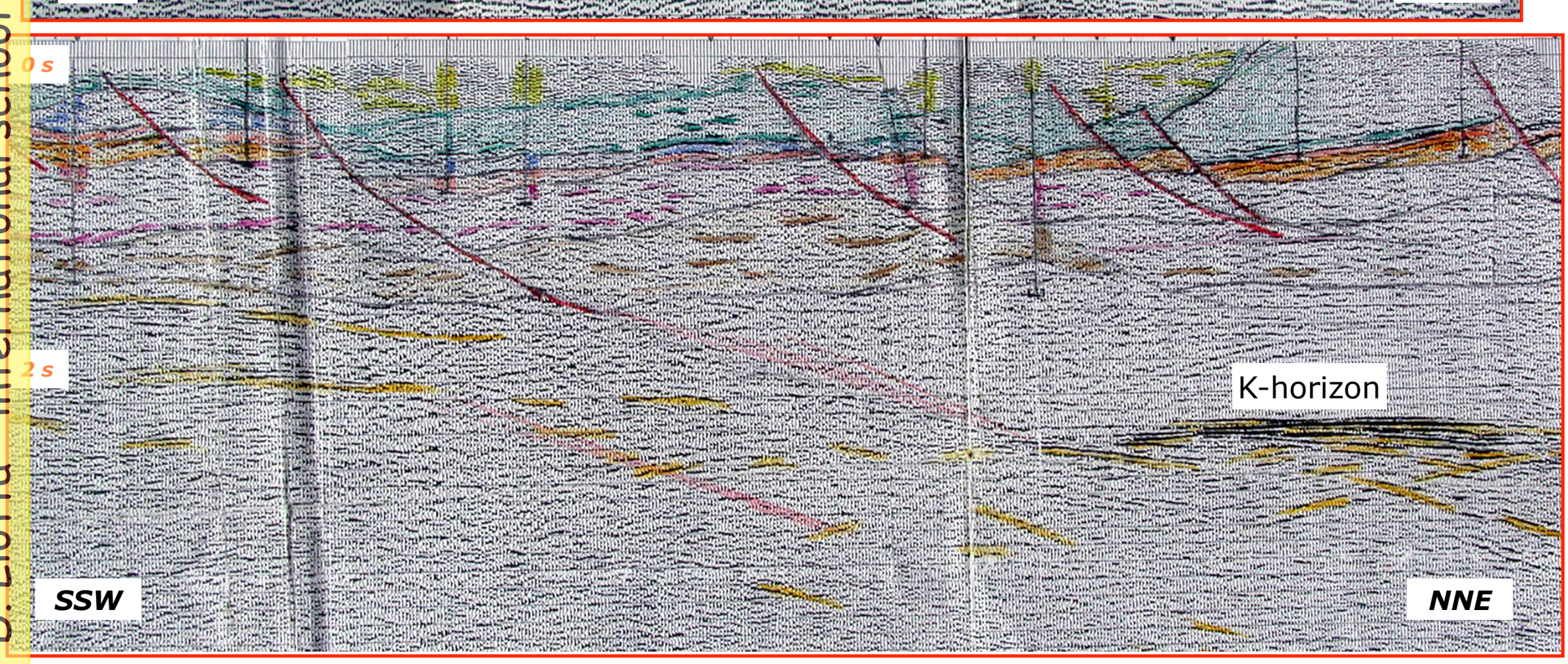


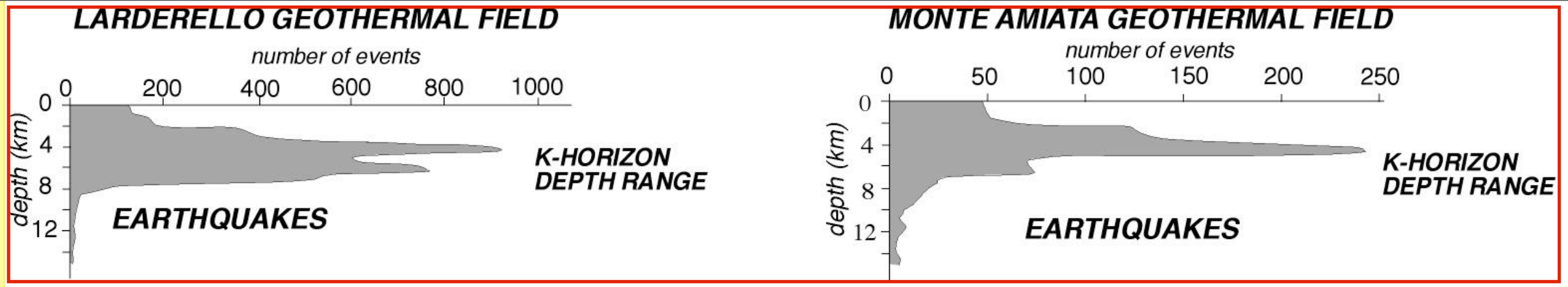


to obtain a reflection seismic line, the original data need to be processed

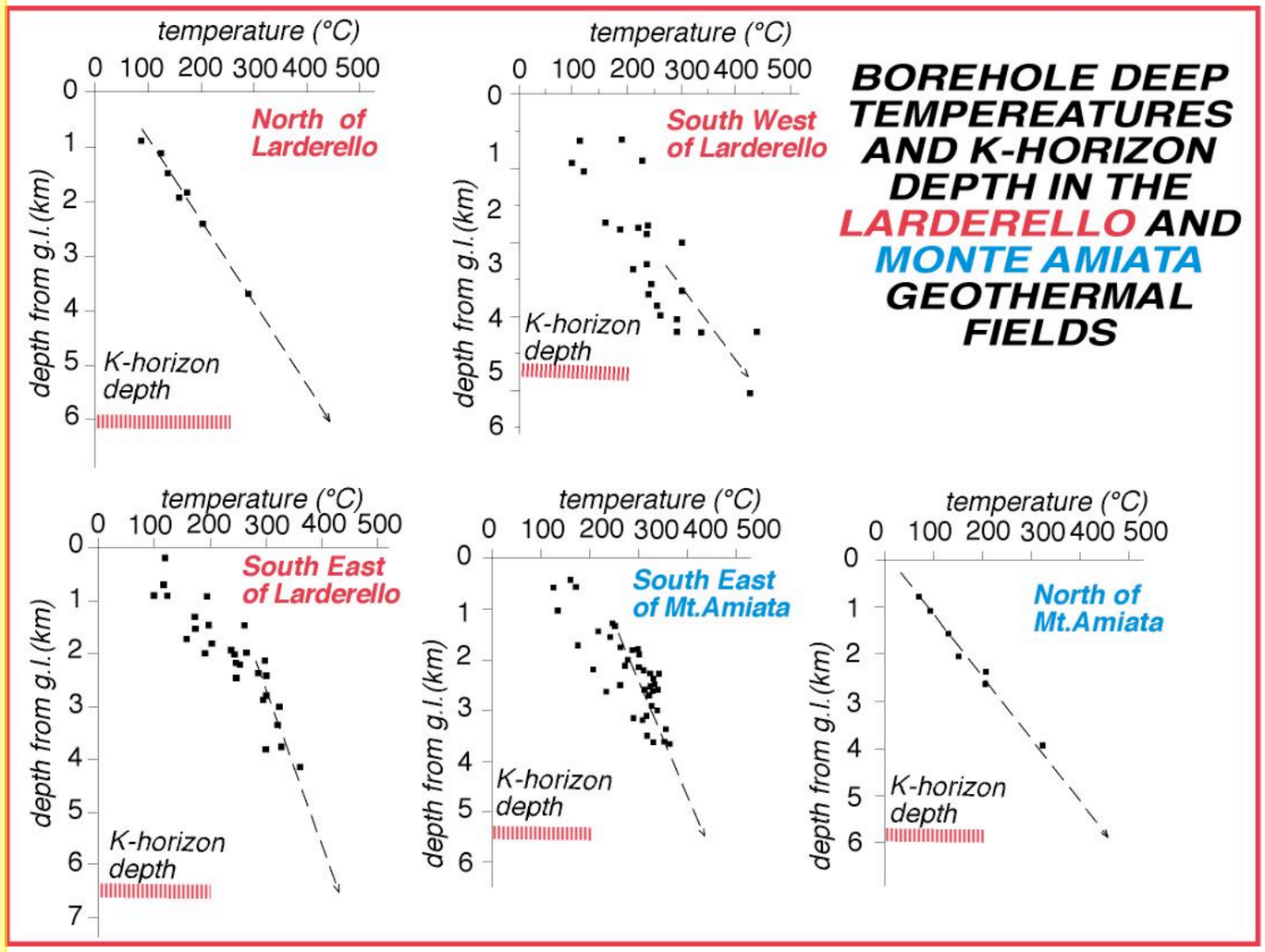



0 s
2 s
K-horizon
SSW
NNE

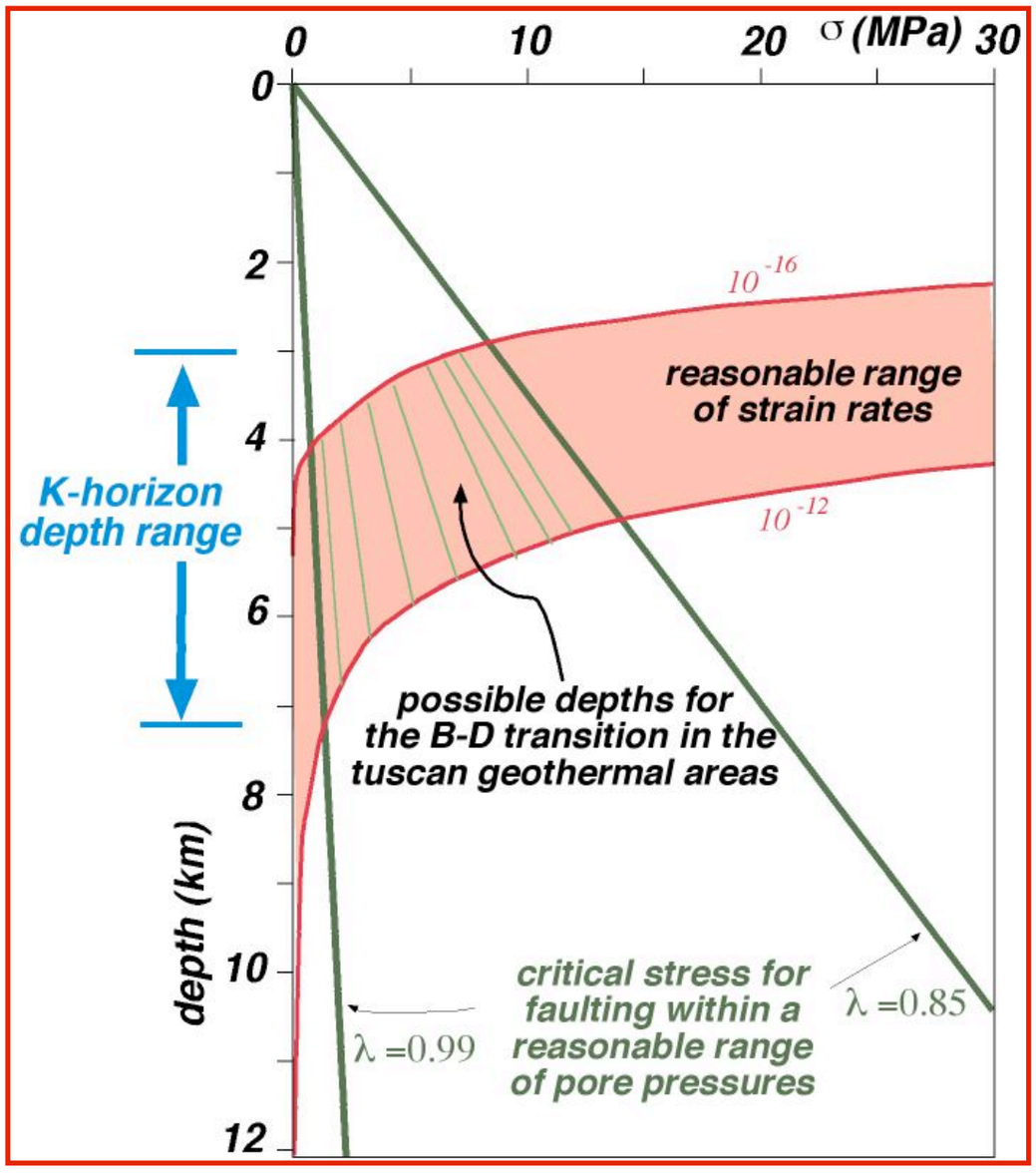

0 s
2 s
K-horizon
SSW
NNE



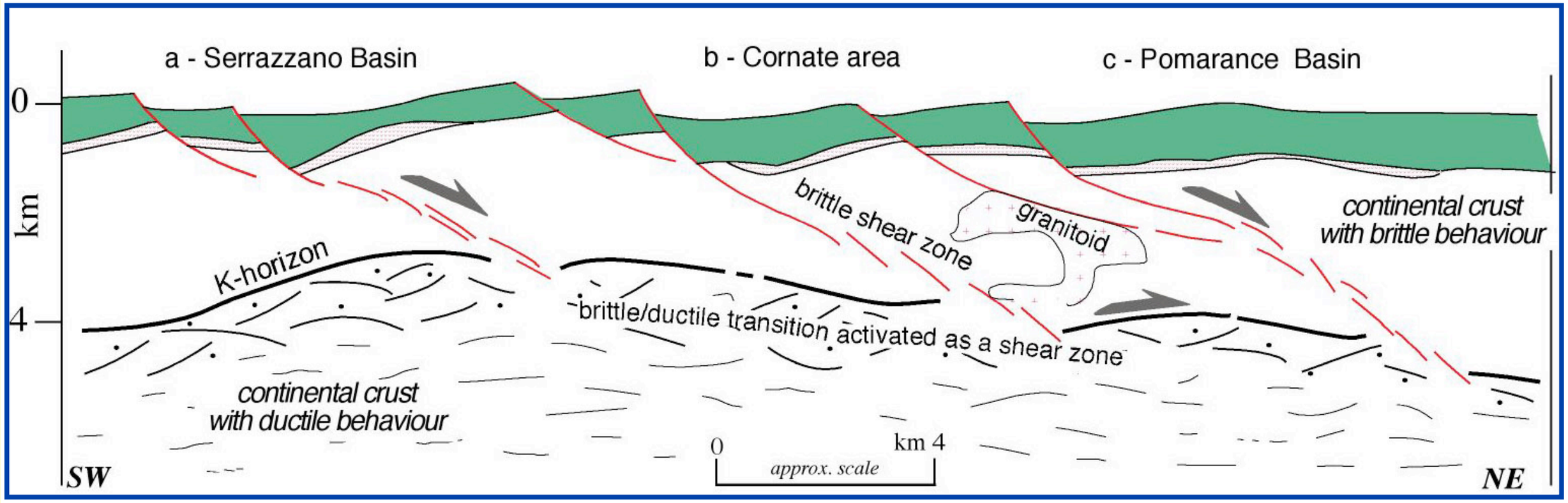
Local epicentres are mostly concentrated at the K-horizon depth

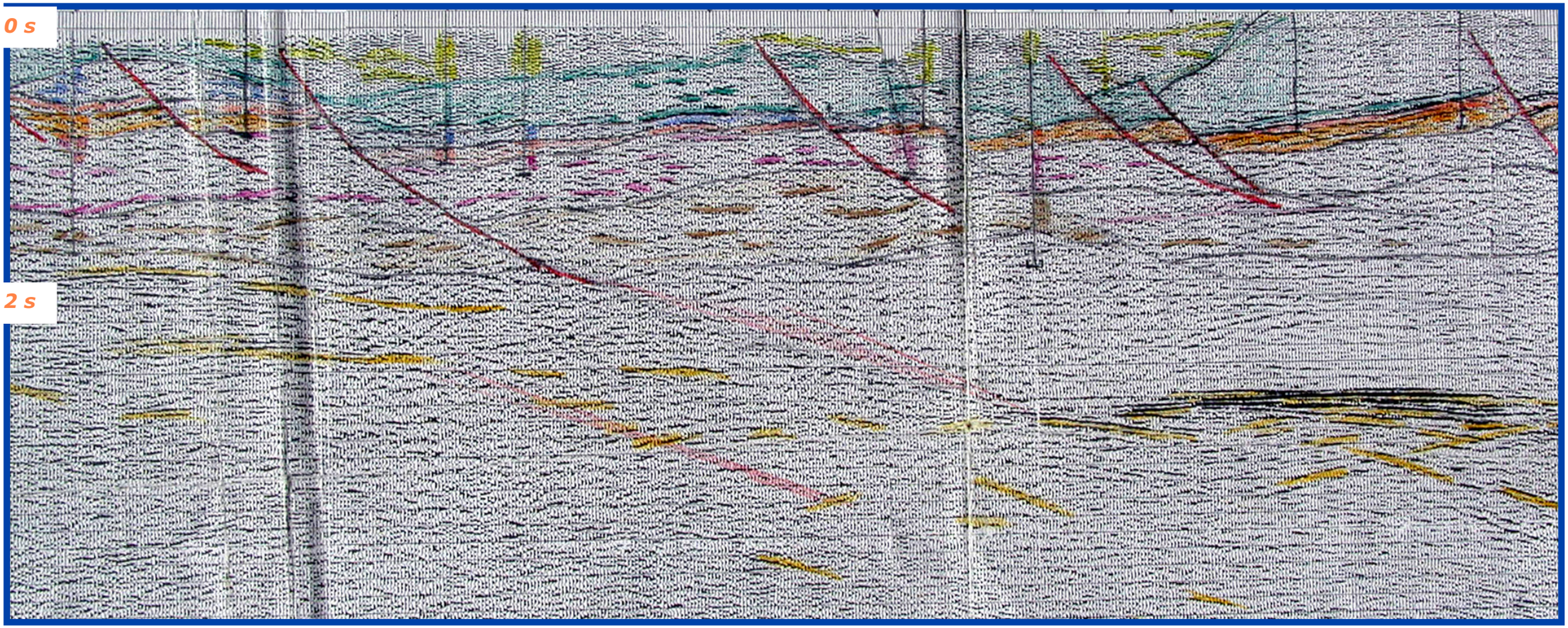


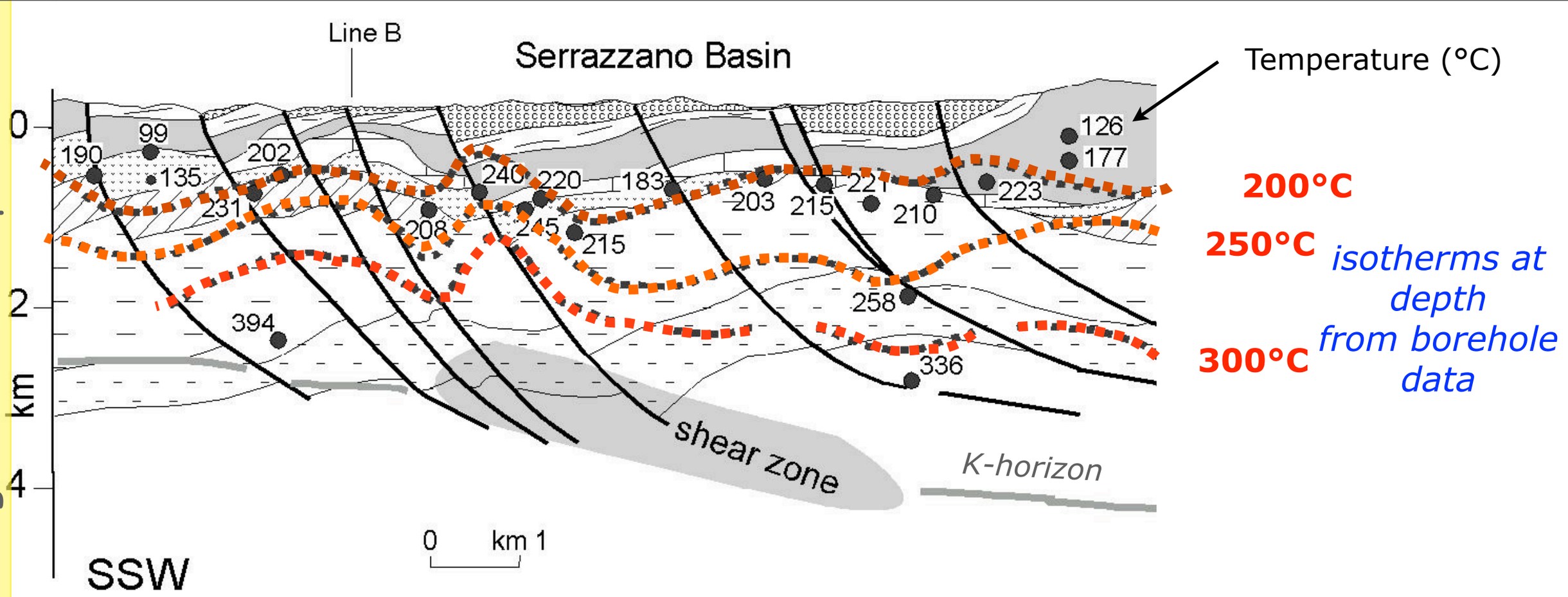
Estimated temperature is 400-450°C at the K-horizon depth

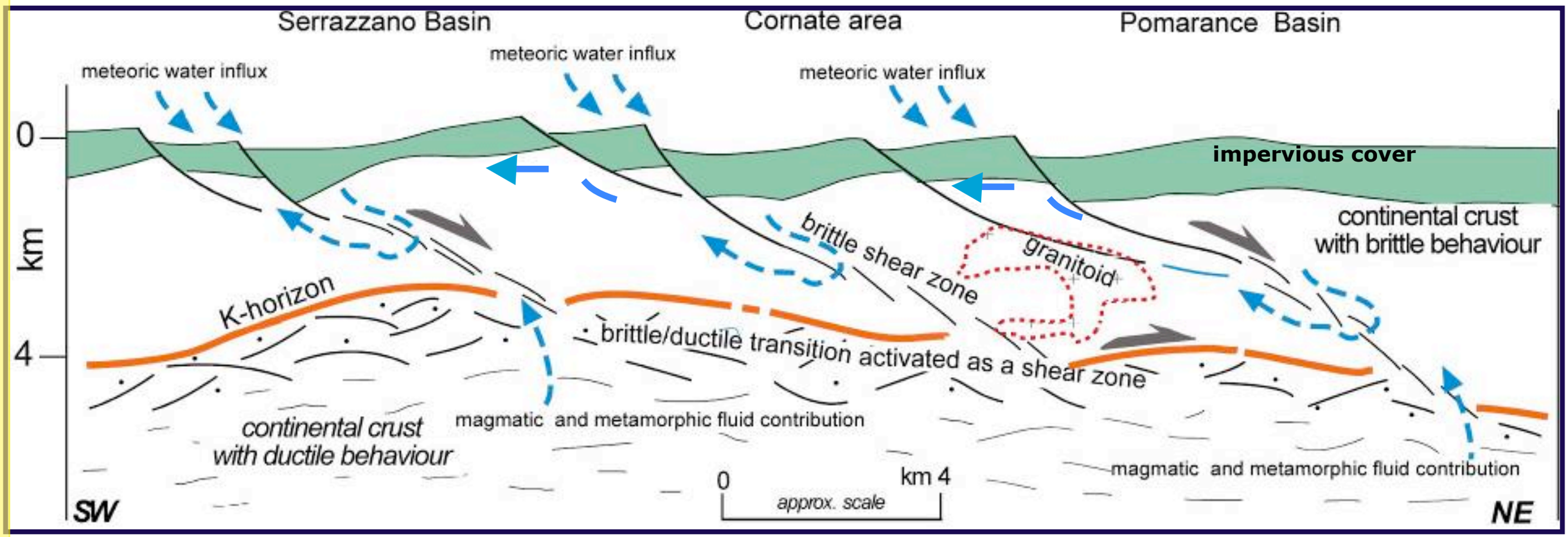


Rheological predictions

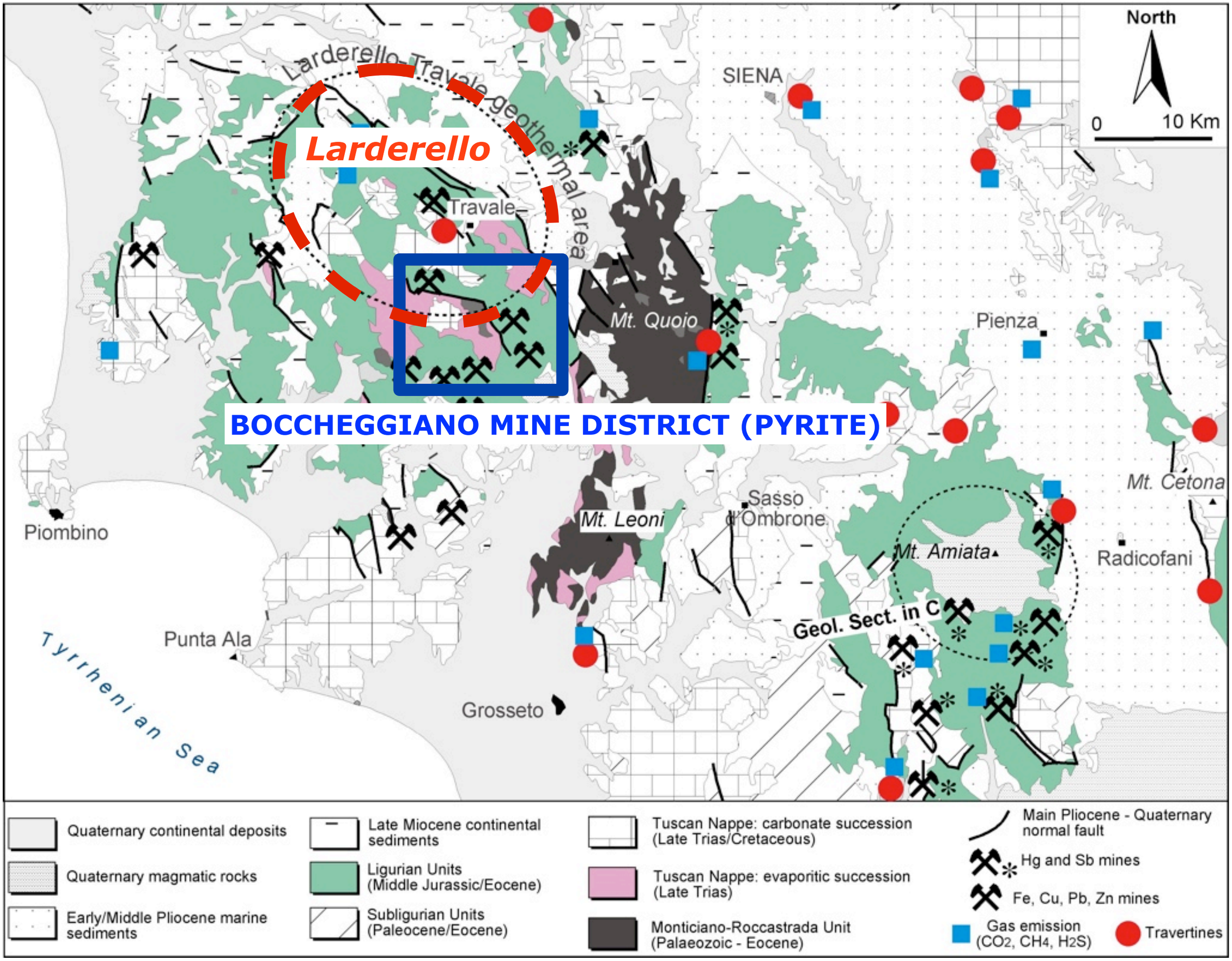

a - Serrazzano Basin
b - Cornate area
c - Pomarance Basin
0
km
4
K-horizon
brittle shear zone
granitoid
continental crust
with brittle behaviour
brittle/ductile transition activated as a shear zone
continental crust
with ductile behaviour
SW
0
km 4
approx. scale
NE

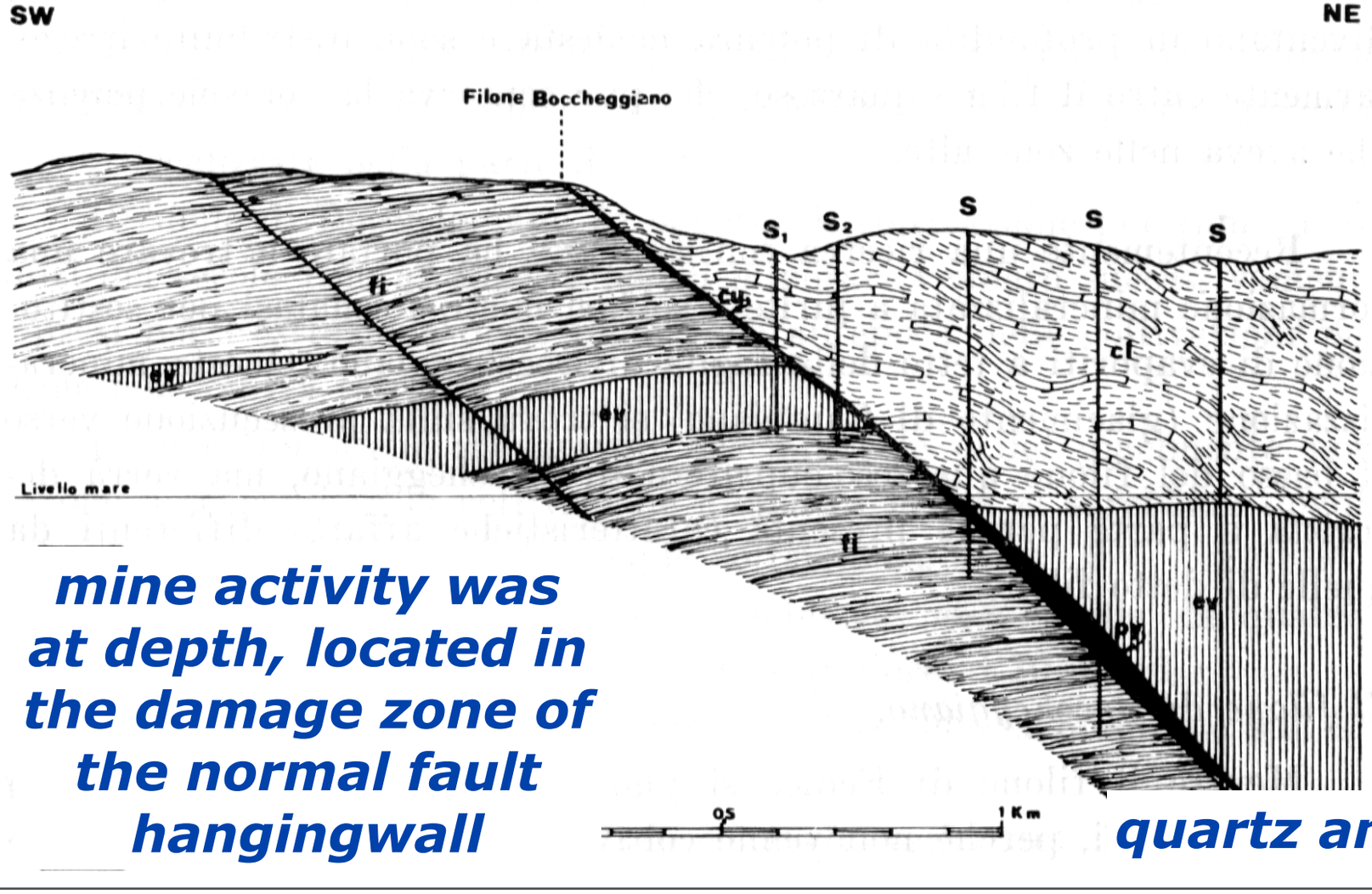

0 s
2 s


Line B
Serrazzano Basin
Temperature (°C)
0
2
km
4
190
99
135
202
231
208
240
220
245
215
183
203
215
221
210
223
126
177
394
258
336
200°C
250°C
300°C
isotherms at depth from borehole data
shear zone
K-horizon
0 km 1
SSW

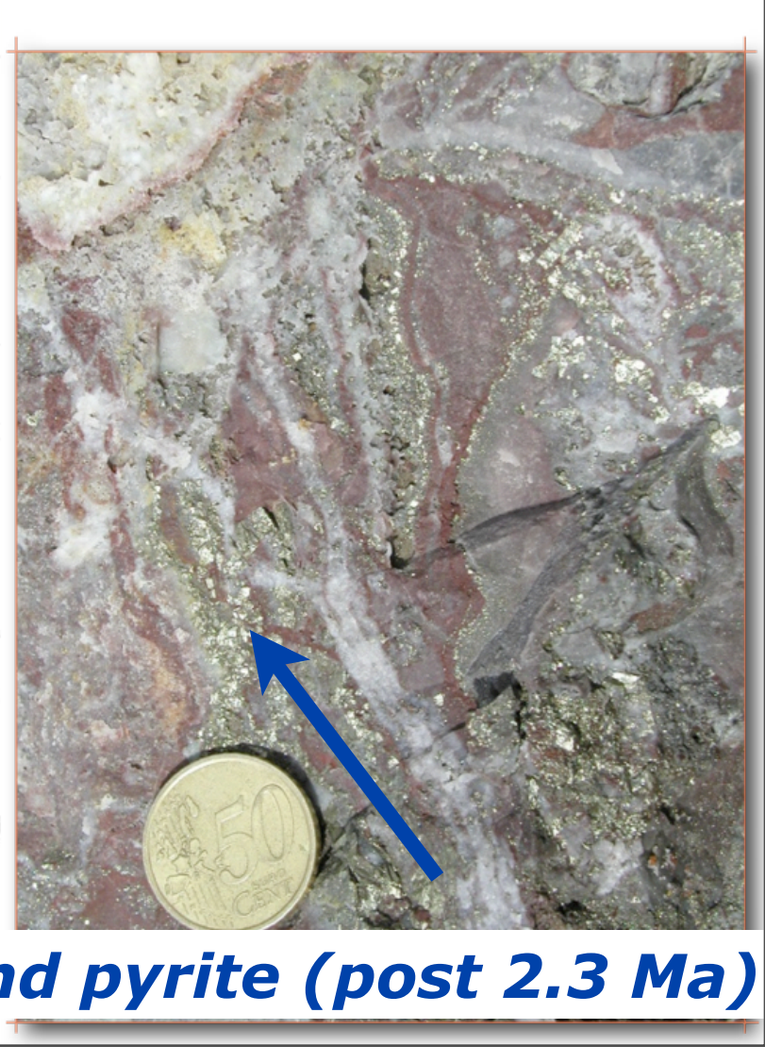

Serrazzano Basin
Cornate area
Pomarance Basin
meteoric water influx
meteoric water influx
meteoric water influx
impervious cover
0
km
4
brittle shear zone
granitoid
continental crust with brittle behaviour
K-horizon
brittle/ductile transition activated as a shear zone
magmatic and metamorphic fluid contribution
continental crust with ductile behaviour
magmatic and metamorphic fluid contribution
0 km 4
approx. scale
SW
NE

comparison with a fossil geothermal system





mine activity was at depth, located in the damage zone of the normal fault hangingwall



quartz and pyrite (post 2.3 Ma)

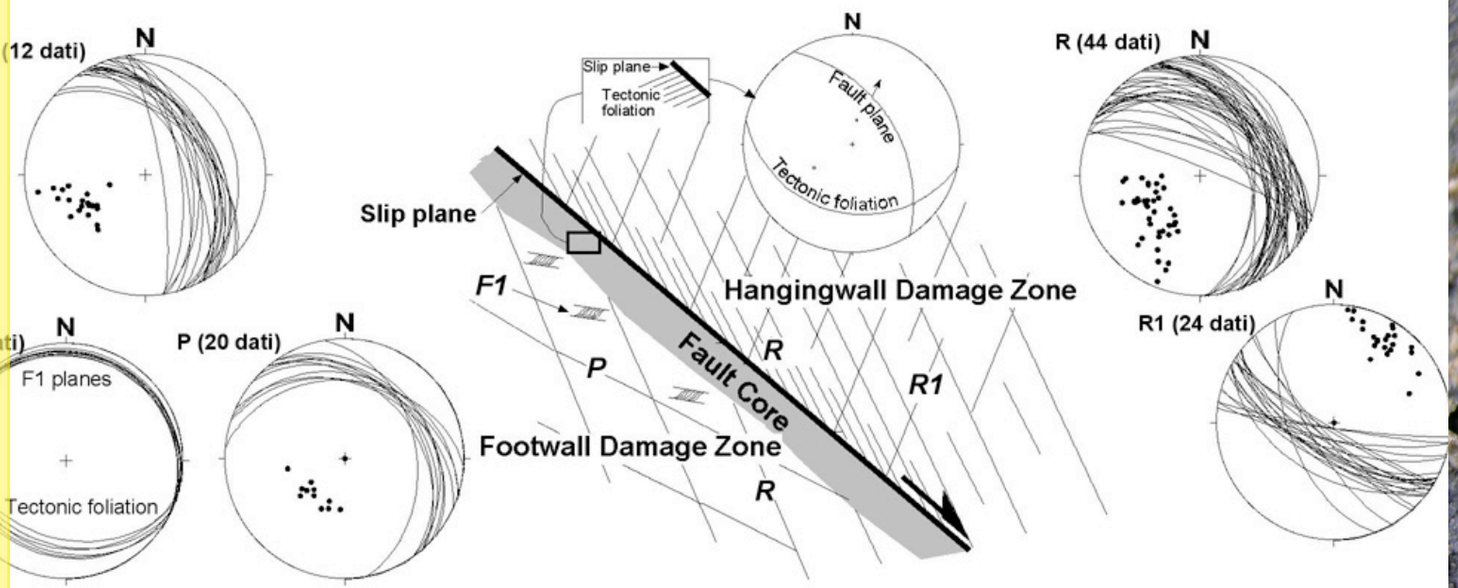
FAULT ARCHITECTURE

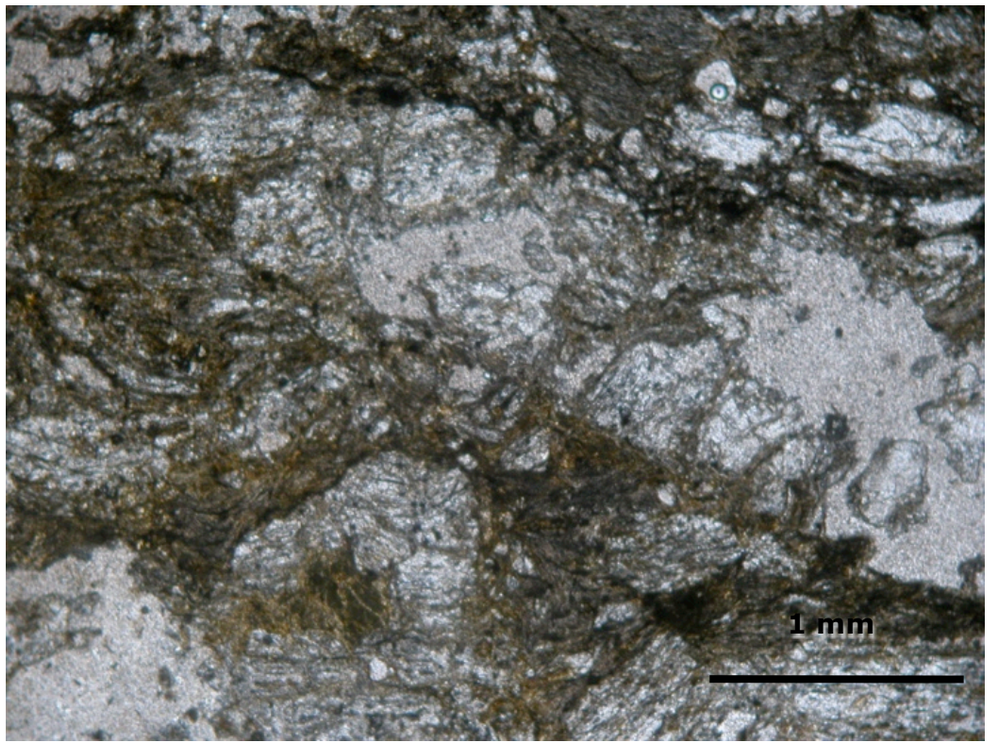
PATTERN OF FRACTURES

DISTRIBUTION, TEXTURE AND STRUCTURE OF VEINS

FLUID INCLUSIONS IN QUARTZ

FAULT ARCHITECTURE

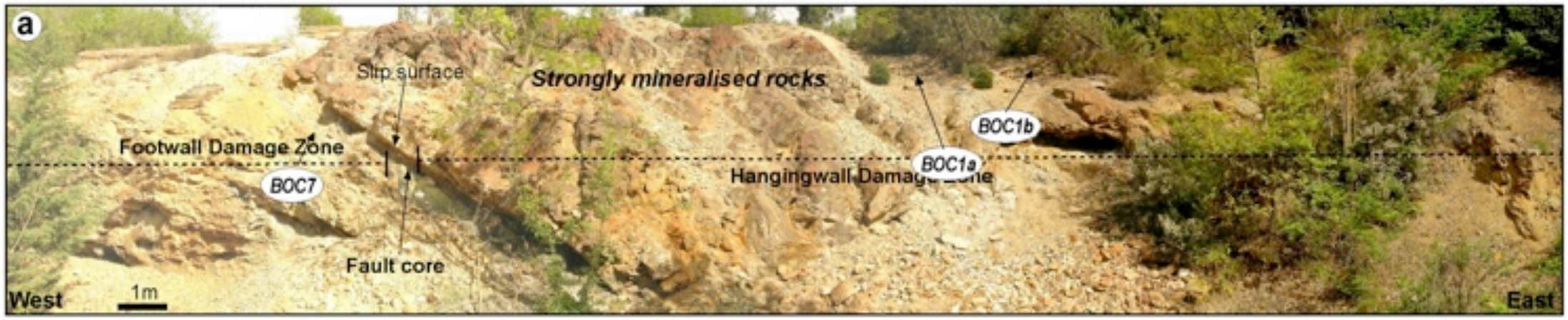


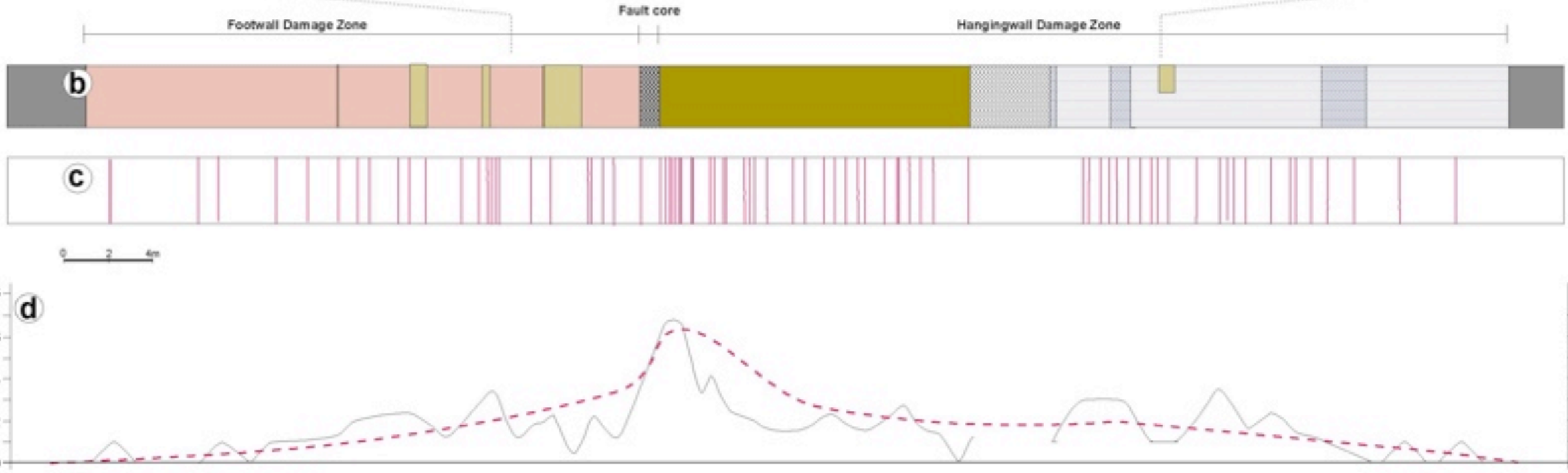


vertical throw: 930 m

horizontal throw: 520 m

PATTERN AND DISTRIBUTION OF FRACTURES





Footwall Damage Zone

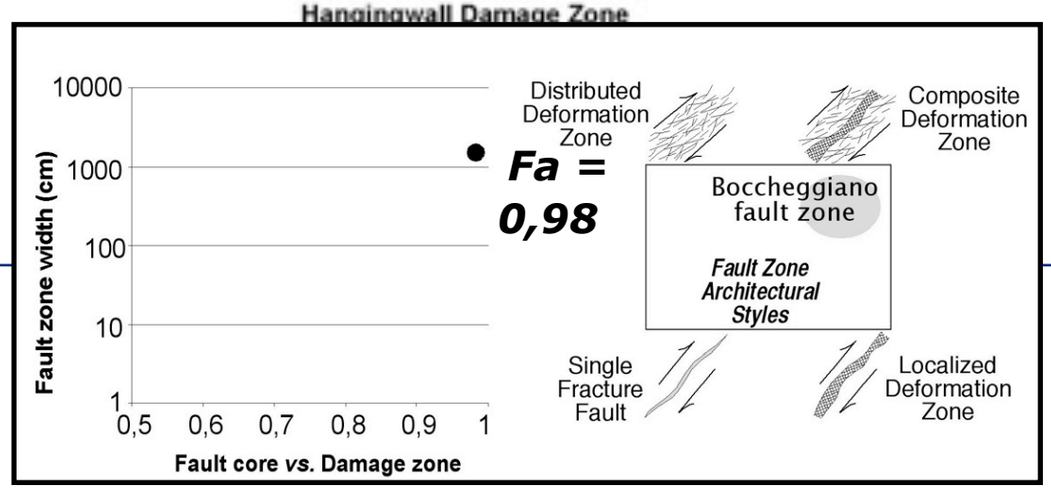
Protolith

Gap

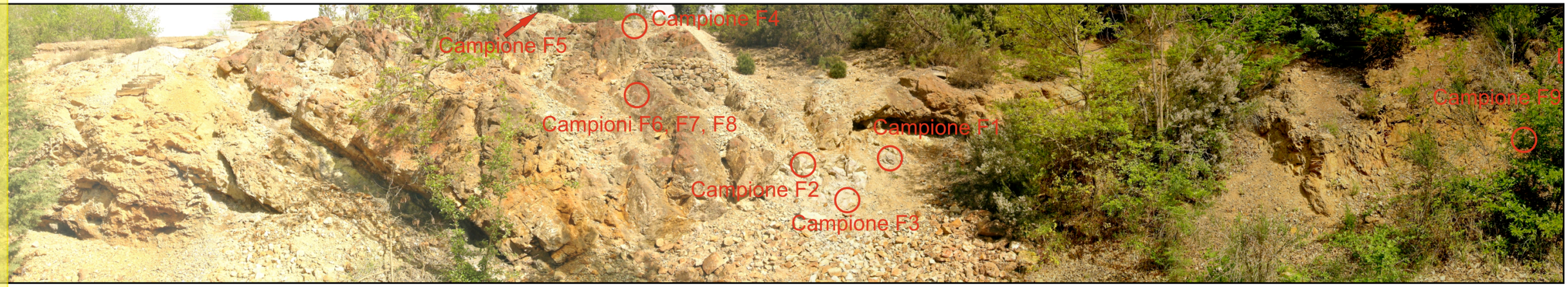
Quartz veins with pyrite

Palaeozoic phyllite

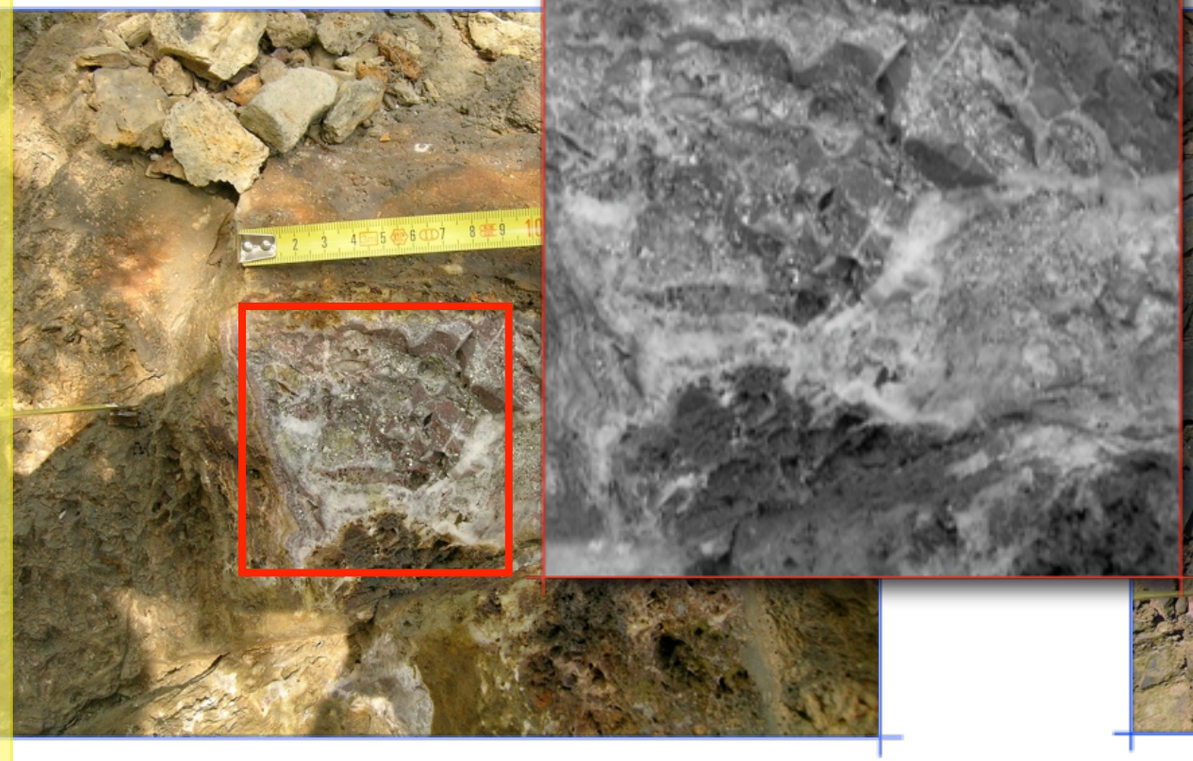
Hangingwall Damage Zone



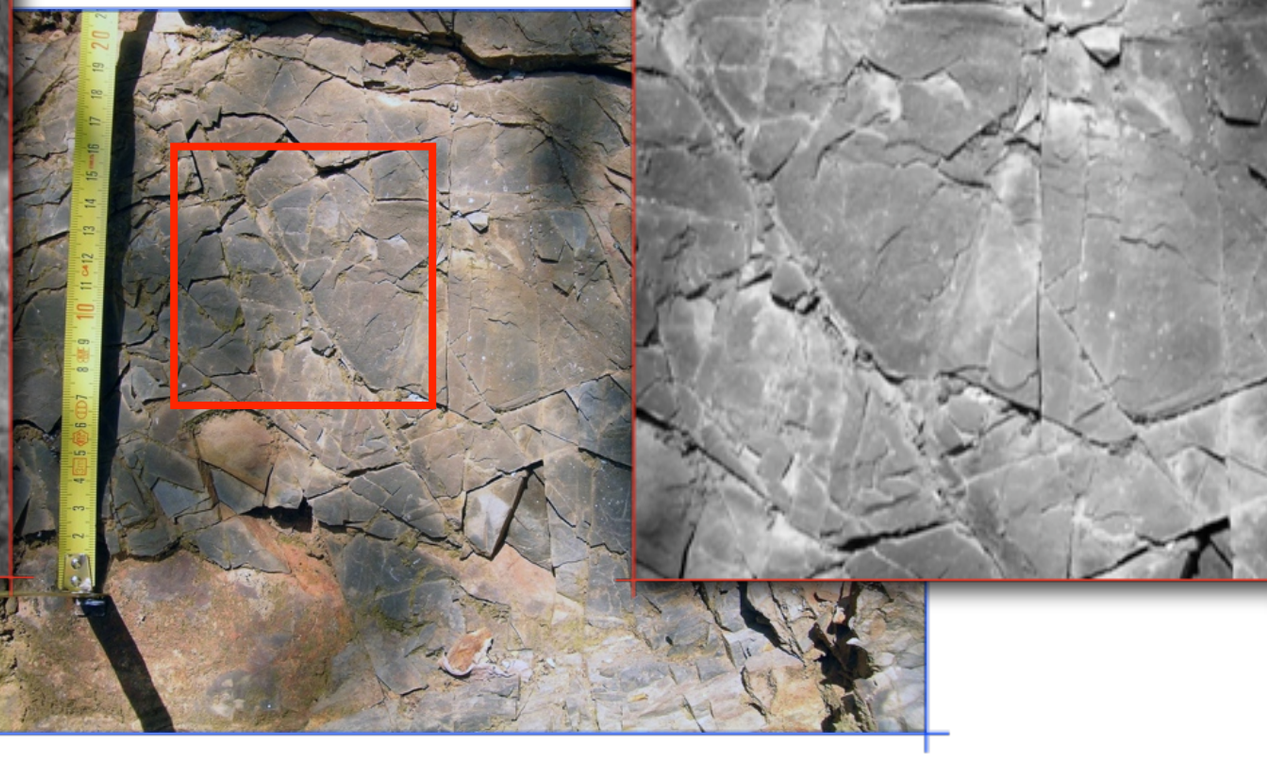
DISTRIBUTION OF VEINS

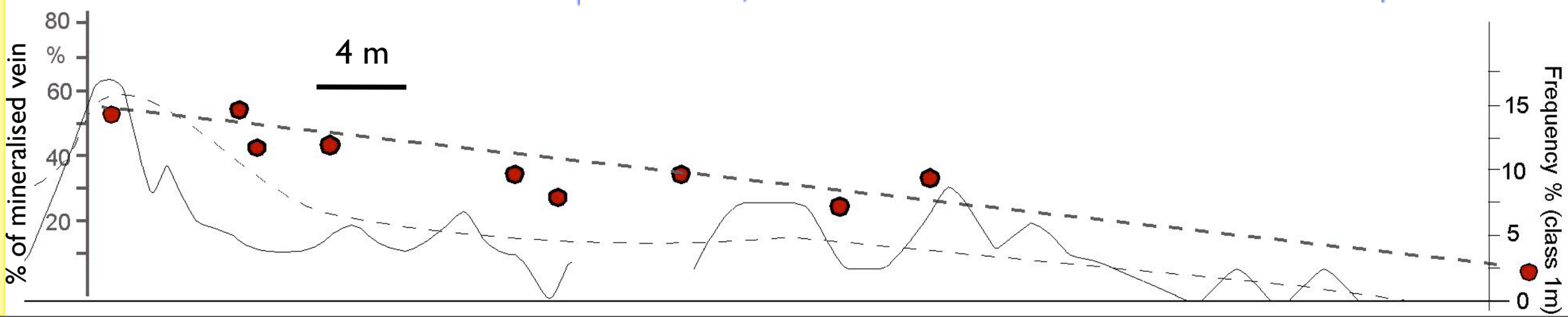


Campione F5

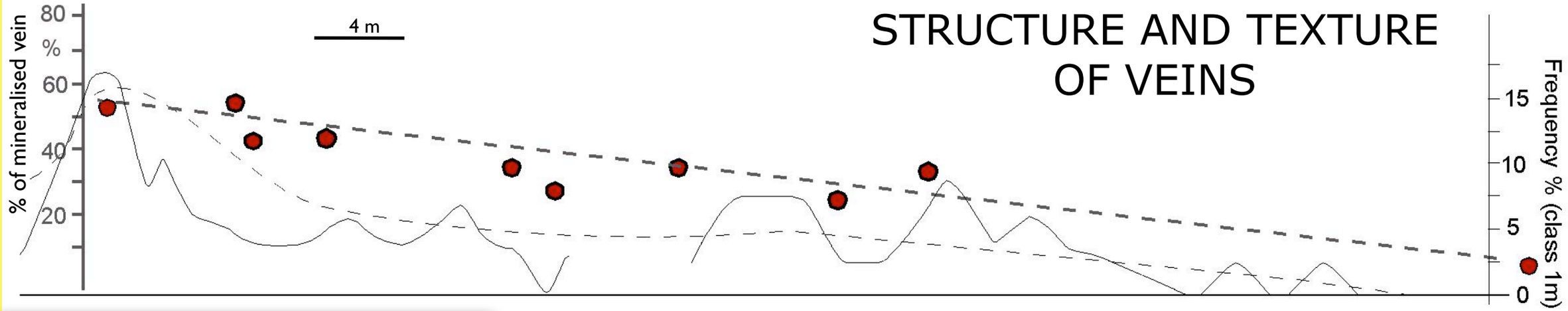


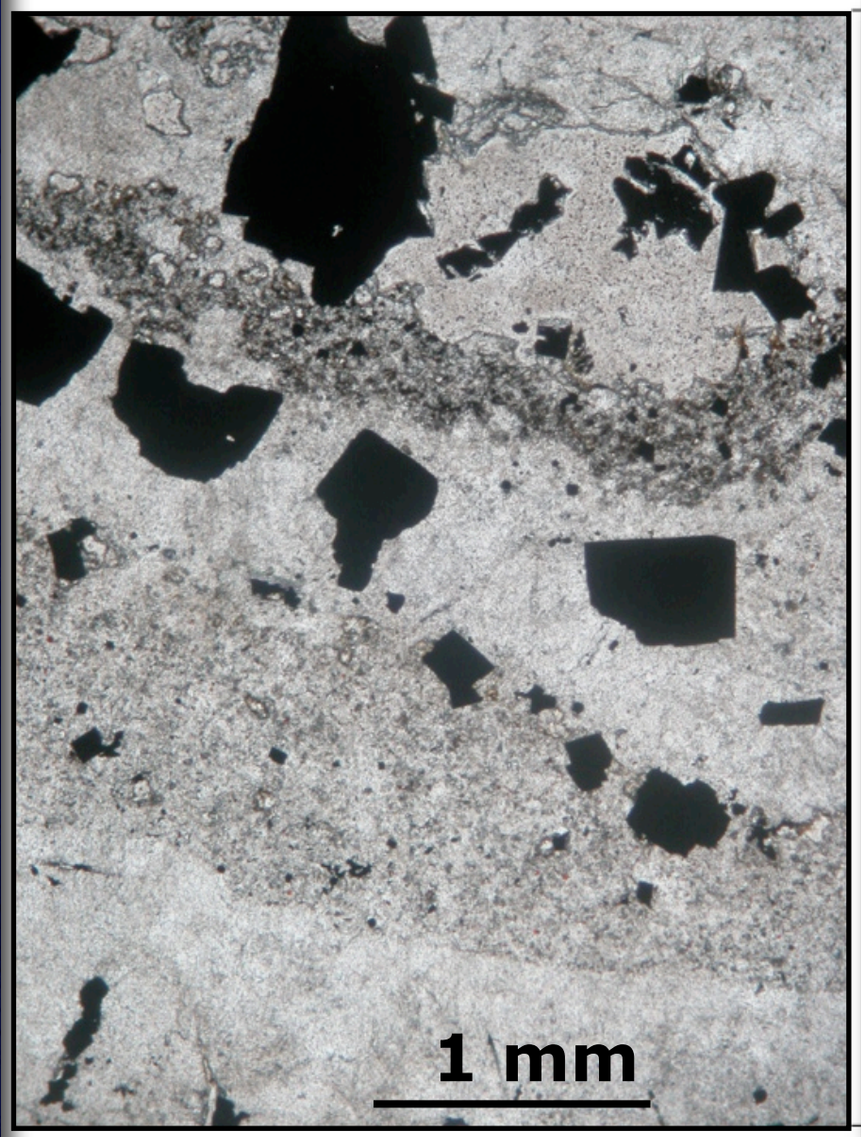
Campione F9





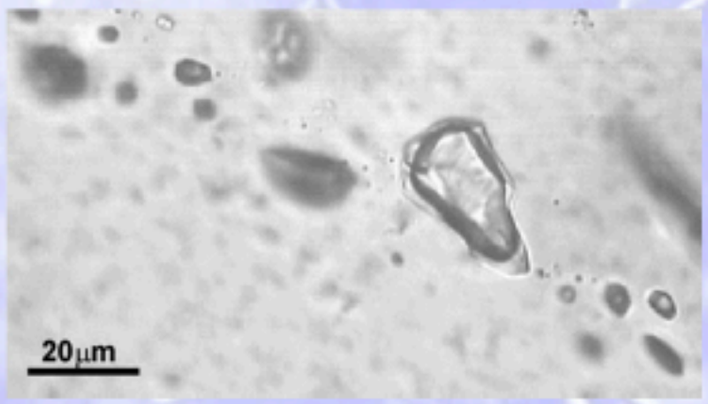
STRUCTURE AND TEXTURE OF VEINS

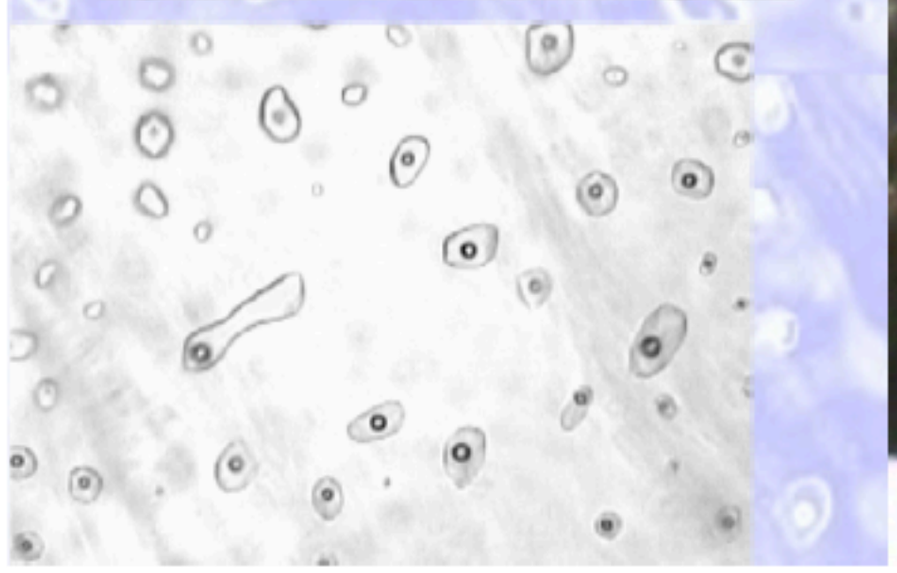


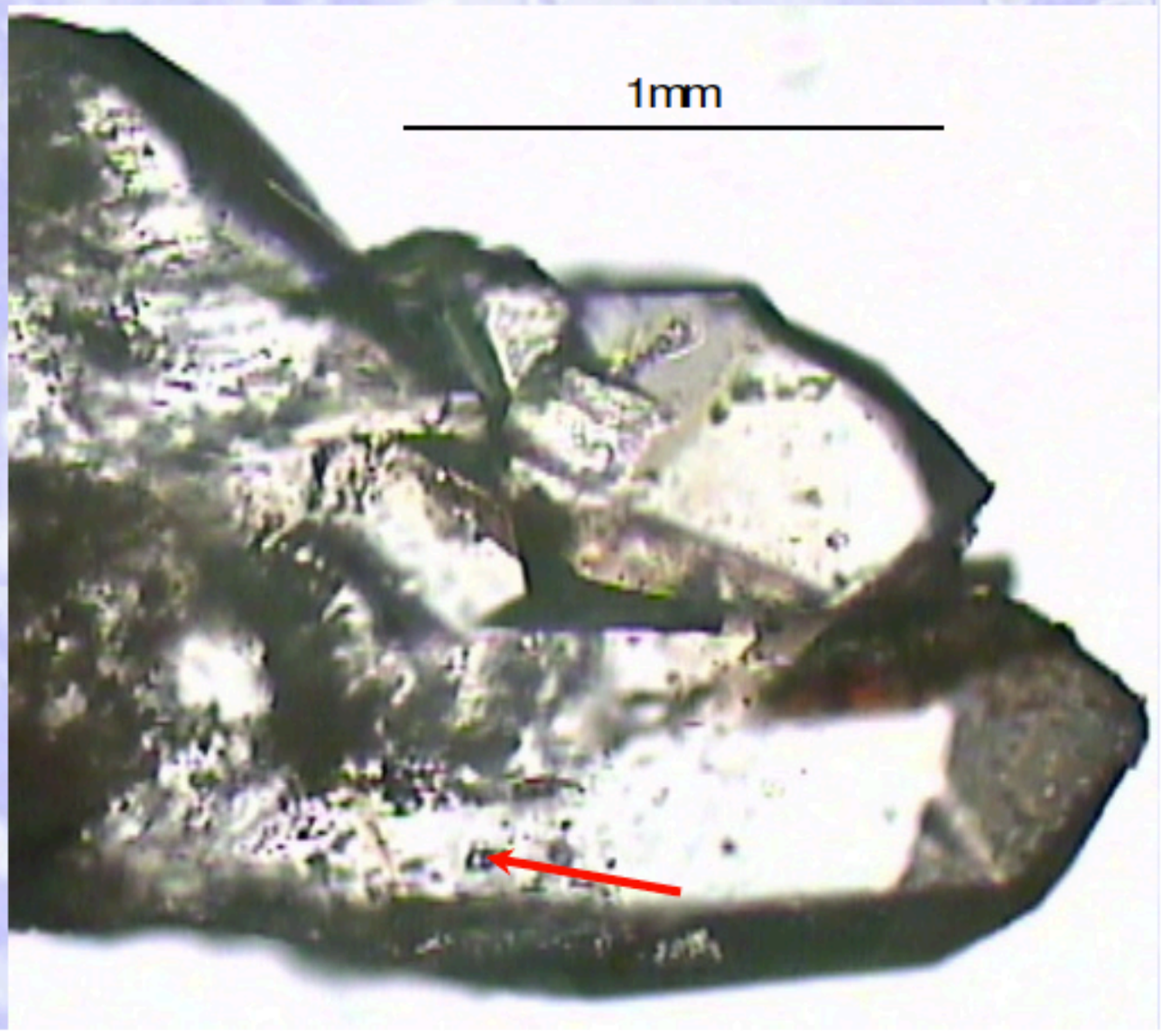


FLUID INCLUSIONS

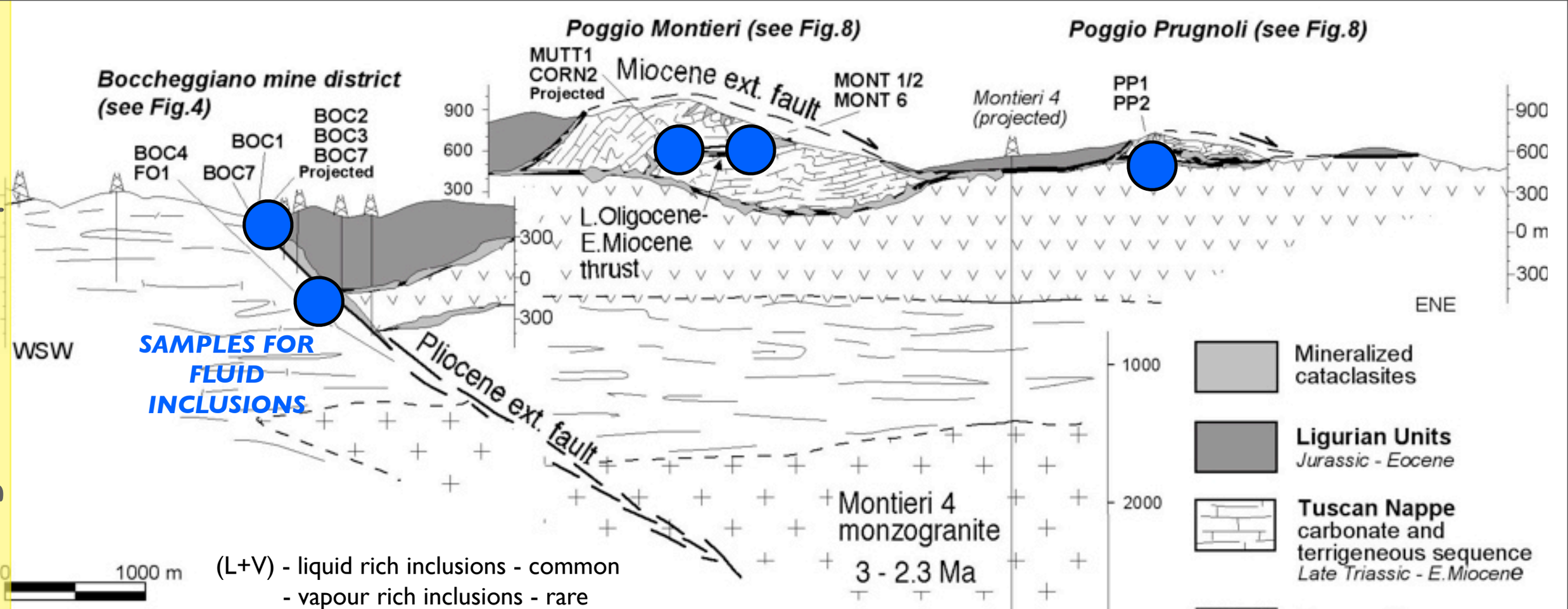
Fluid inclusions are small portions of fluid trapped within crystals during or after their growth

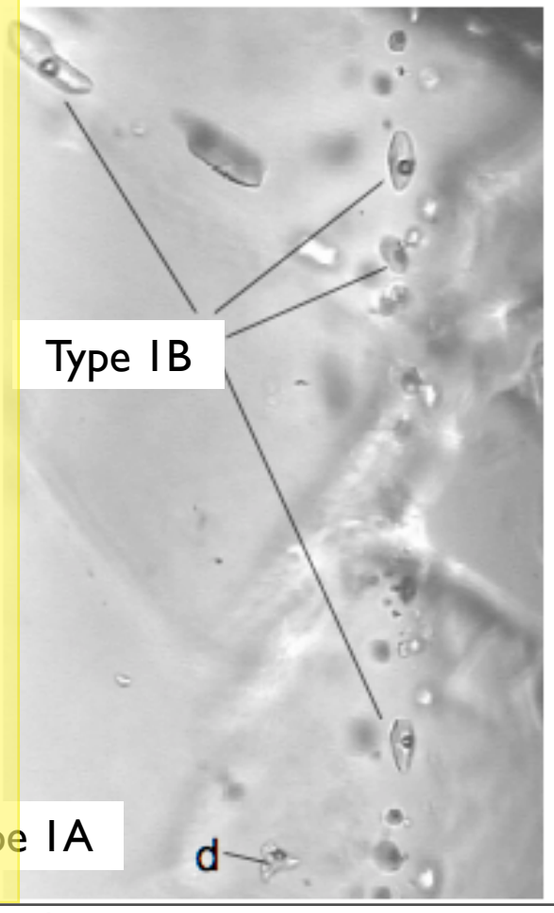


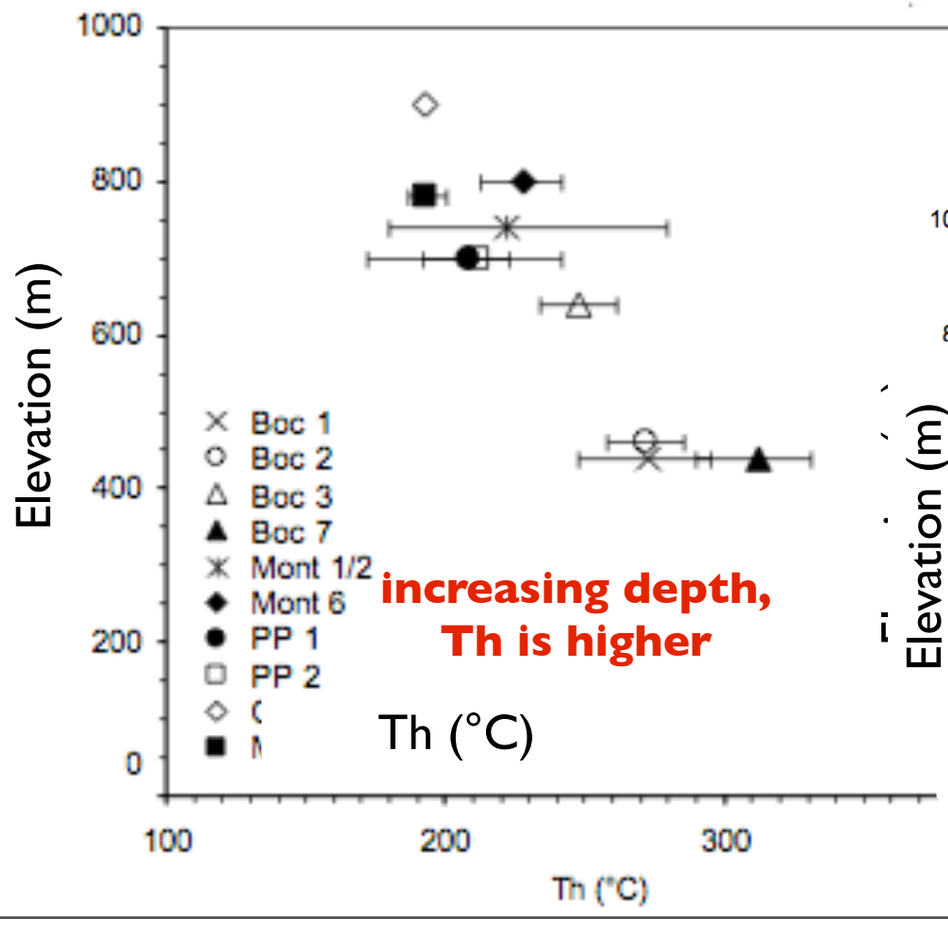


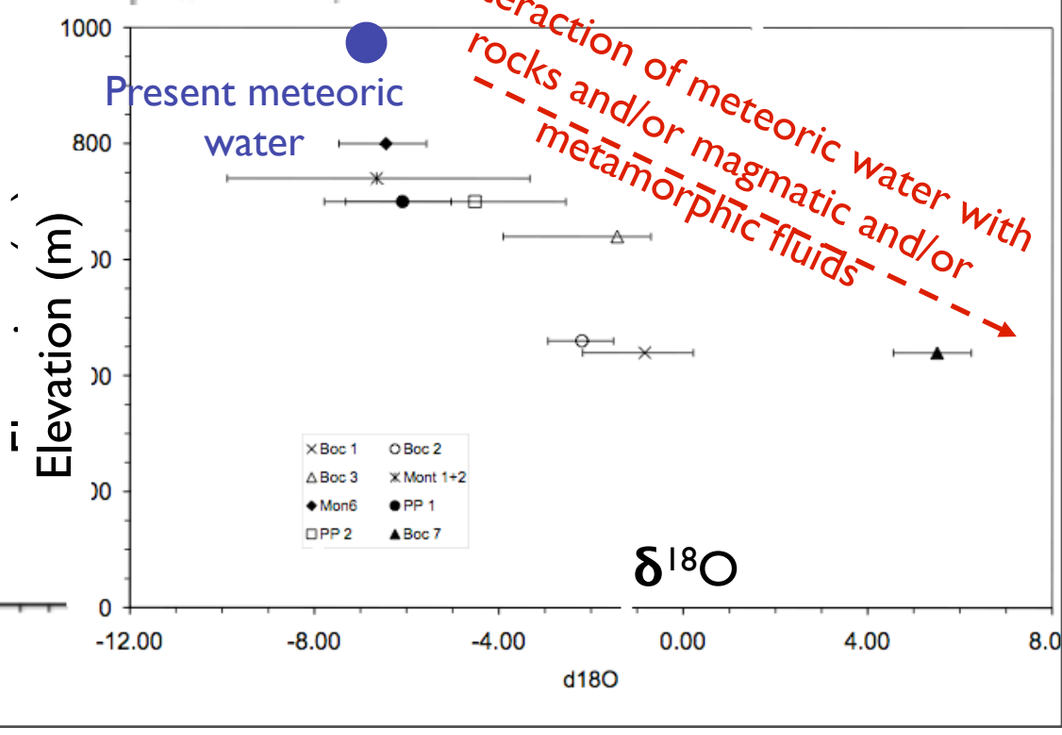


courtesy G. Ruggieri

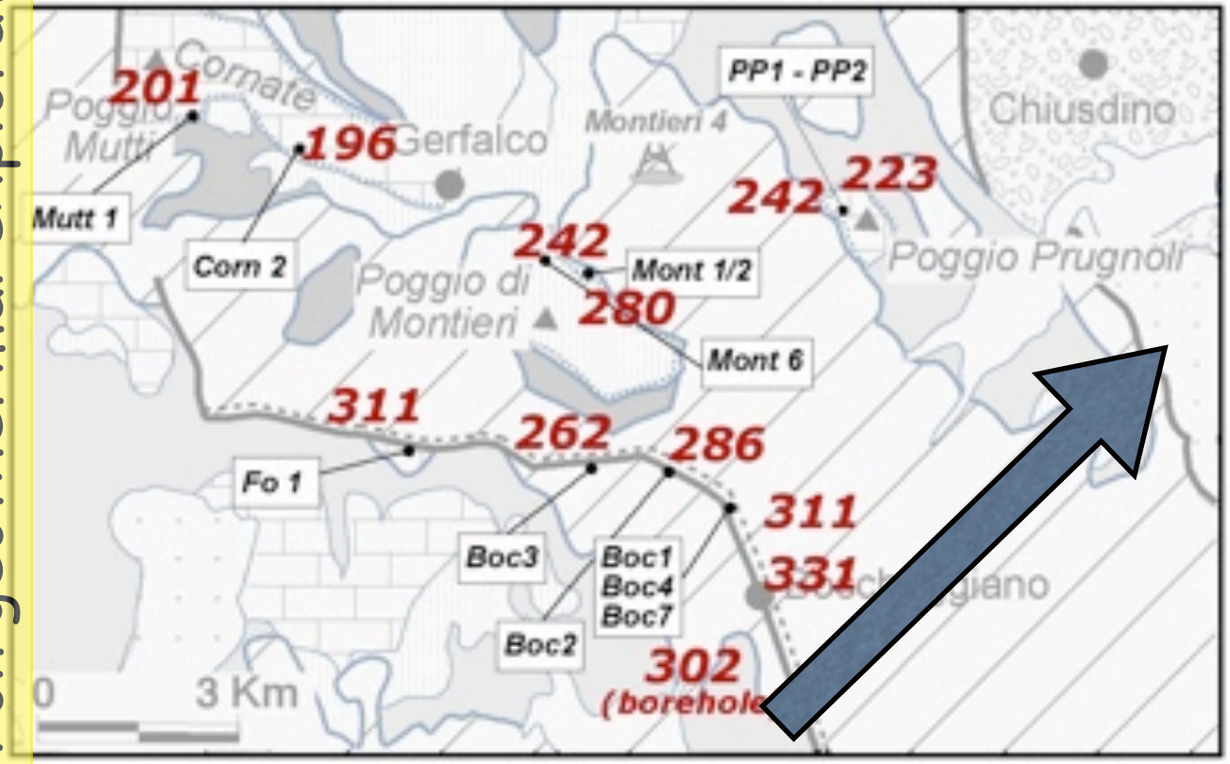

Poggio Montieri (see Fig.8)
Poggio Prugnoli (see Fig.8)
Boccheggiano mine district
(see Fig.4)
MUTT1
CORN2
Projected
Miocene ext. fault
MONT 1/2
MONT 6
Montieri 4
(projected)
PP1
PP2
BOC4
FO1
BOC7
BOC1
BOC2
BOC3
BOC7
Projected
900
600
300
0 m
L.Oligocene-
E.Miocene
thrust
WSW
ENE
SAMPLES FOR
FLUID
INCLUSIONS
Pliocene ext. fault
Montieri 4
monzogranite
3 - 2.3 Ma
1000
2000
3000
Mineralized
cataclasites
Ligurian Units
Jurassic - Eocene
Tuscan Nappe
carbonate and
terrigeneous sequence
Late Triassic - E.Miocene
Tuscan Nappe
evaporitic sequence
Late Triassic
Phyllite
Palaeozoic
1000 m
(L+V) - liquid rich inclusions - common
- vapour rich inclusions - rare


Type 1B
Type 1A
d

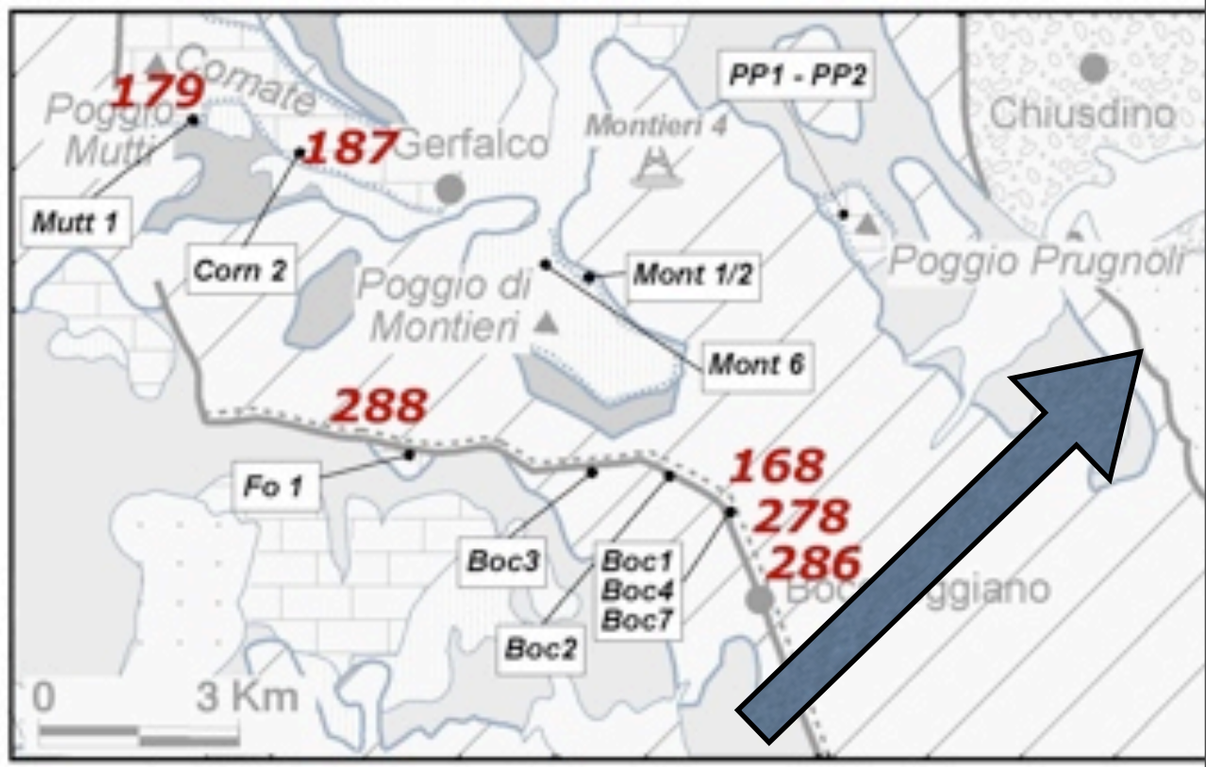

Elevation (m)
1000
800
600
400
200
0
100
200
300
Th (°C)
Boc 1
Boc 2
Boc 3
Boc 7
Mont 1/2
Mont 6
PP 1
PP 2
increasing depth,
Th is higher
Th (°C)


Present meteoric
water
interaction of meteoric water with
rocks and/or magmatic and/or
metamorphic fluids
Elevation (m)
1000
800
-12.00
-8.00
-4.00
0.00
4.00
d18O
Boc 1
Boc 2
Boc 3
Mont 1+2
Mon6
PP 1
PP 2
Boc 7
δ18O

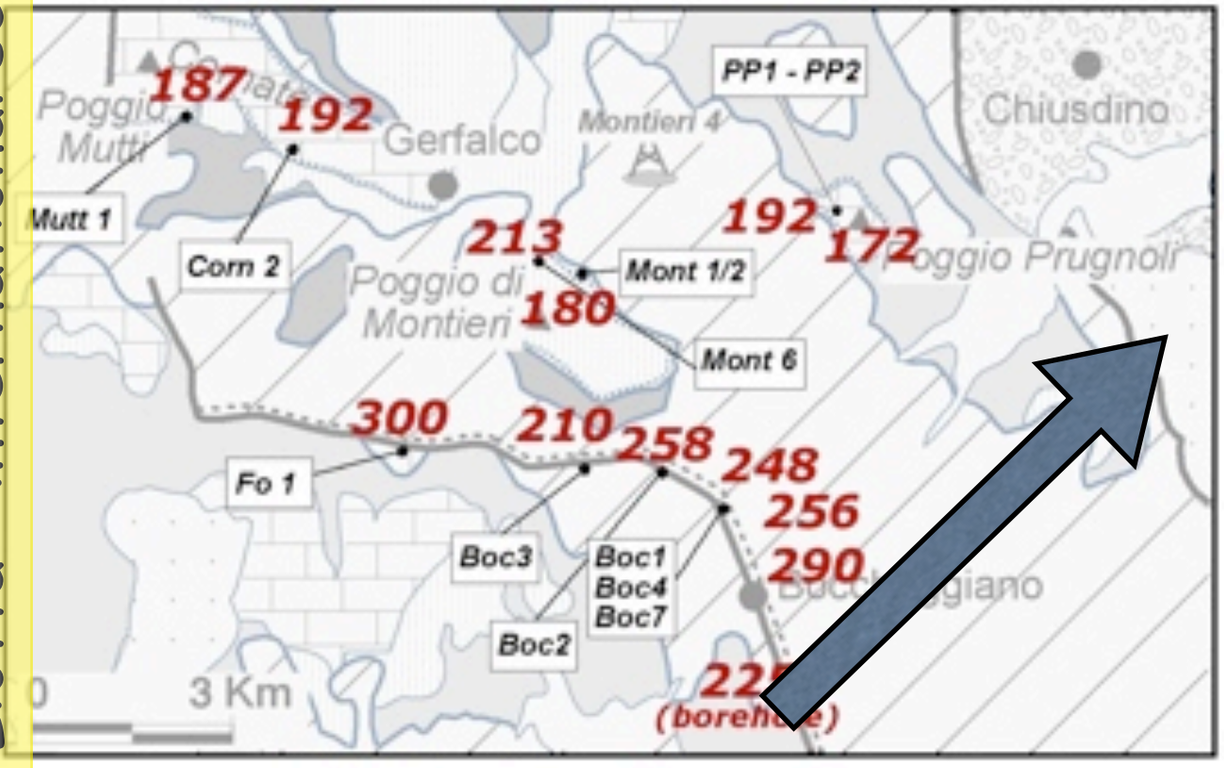
Th max: type 1a



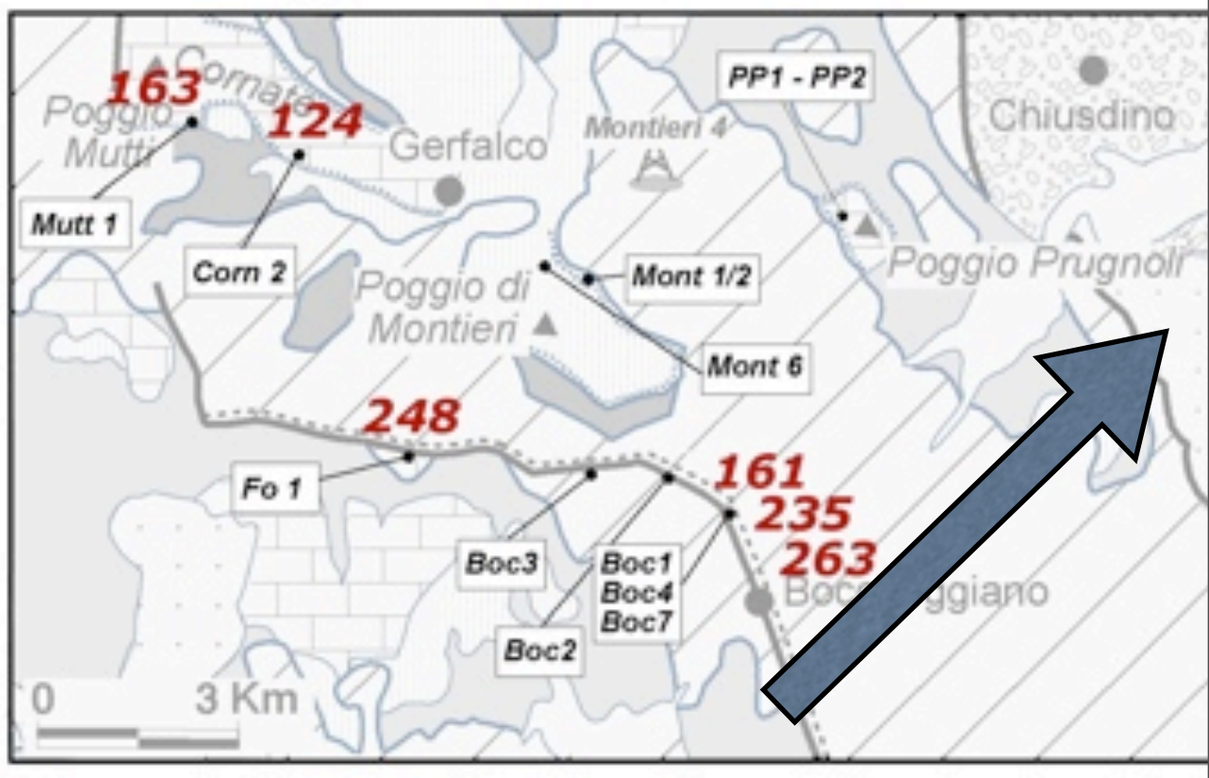
Th max: type 1b



Th min: type 1a



Th min: type 1b



METEORIC WATER

permeable Tuscan Nappe

RECHARGE AREA

Th values decreasing
100°C / 10 km

Pliocene cataclasite

DAMAGE ZONE

imperveous cover

Ligurian Units

mineralised Late Oligocene cataclasite

mineralised cataclasite within the Late Triassic evaporite

meteoric water

present level of erosion

increase of salinity flowing through the evaporite cataclasite

fluids mixing

PALAEOZOIC PHYLLITE

mineralised cataclasite

hot fluids

fluids mixing

Th values of 270±60°C

hot fluids

MONZOGRANITE
3 – 2.3 Ma

PALAEOZOIC PHYLLITE

PALAEOZOIC PHYLLITE

saline hot fluids

SW

NE

LIGURIAN SEA

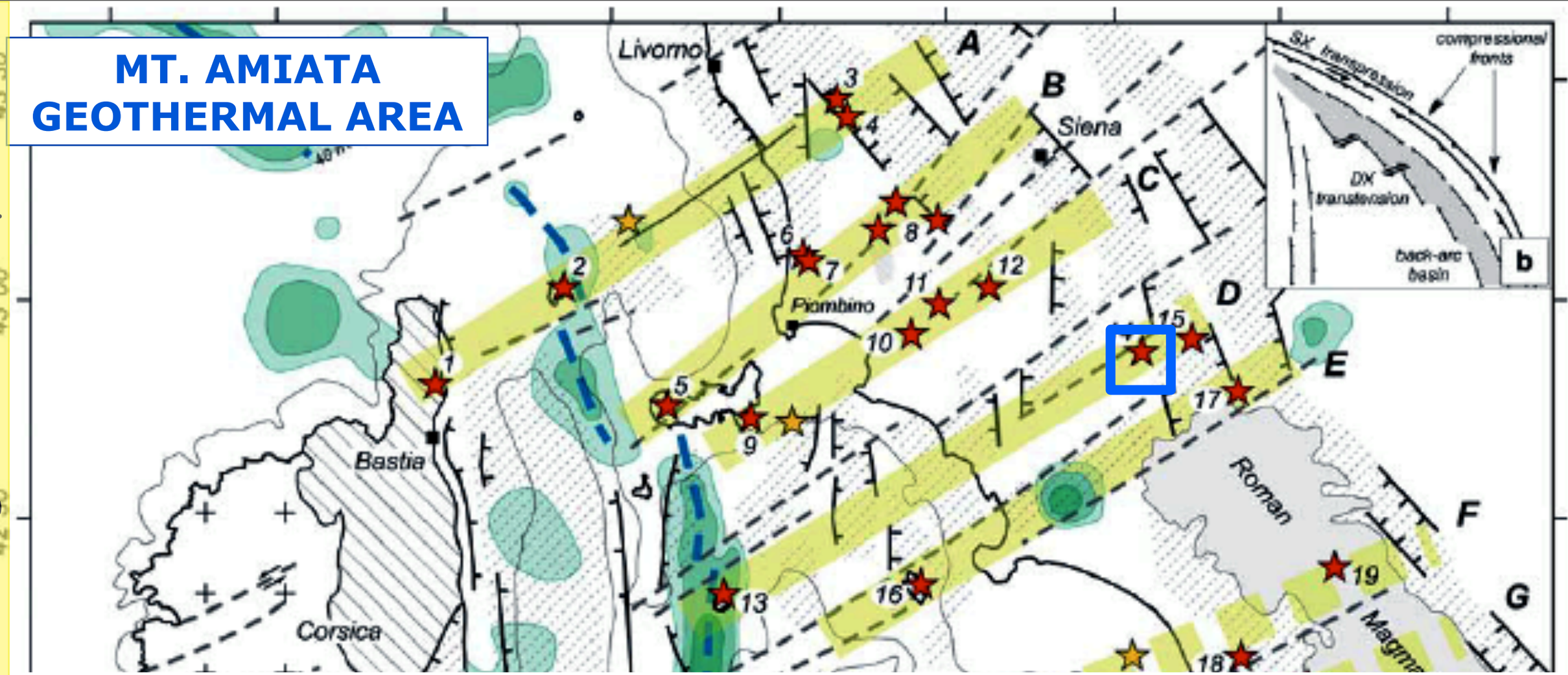
LARDERELLO

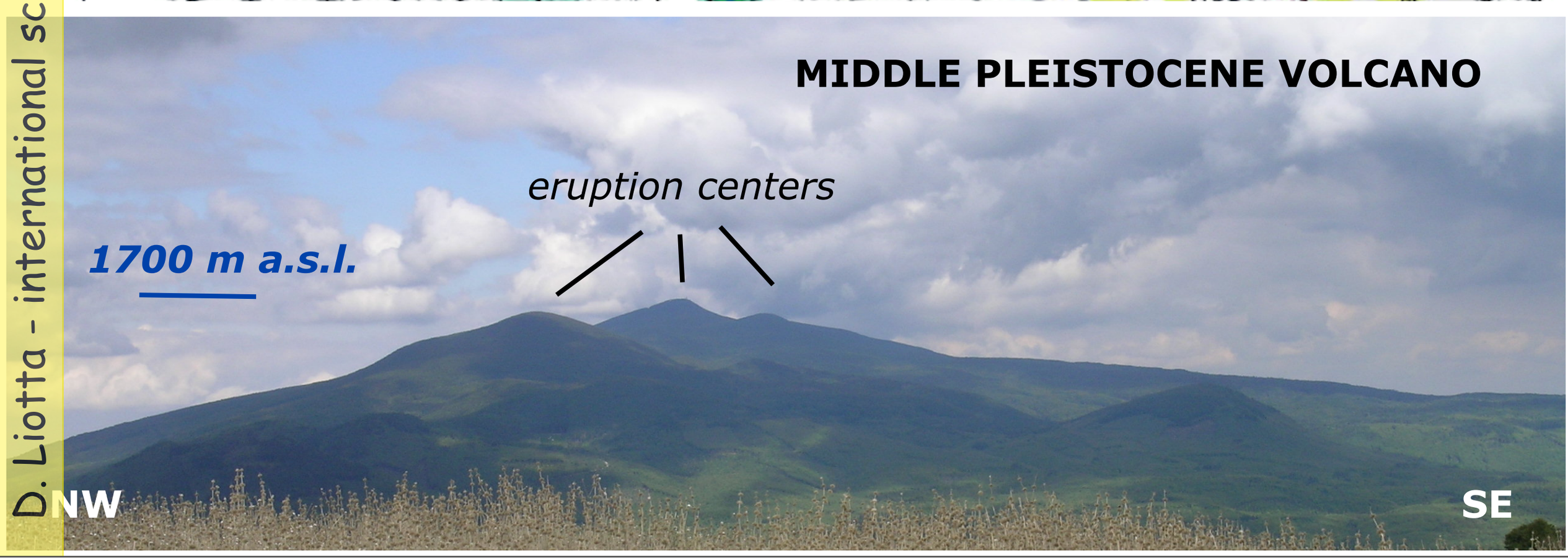
MT. AMIATA

Golfo di Follonica

TYRRHENIAN SEA

MT. AMIATA GEOTHERMAL AREA





MT.AMIATA AREA

Velona Basin
Castiglione d'Orcia
Val d'Orcia Basin
Sasso d'Ombrone
CROP18
Cinigiano
Baccinello Basin
Seggiano
Mt. Amiata
Radicofani
1.3 - 0.9 Ma
Radicofani Basin
Cetona Fault system
Mt. Cetona
S. Casciano dei Bagni
Roccalbegna
Castell'Azzara
AM01
AM02
AM03
AM04
AM05
AM06
AM07
SIF11
SIF12
SIF13
Pia21
Pia22
Pia19
Pia17
Pia18
Pia16
Pia13
Bag1
Bag3
Bag4
Bag5
Bag6
Am01
RA01
0
7 Km
N

Late Miocene continental
Tuscan Nappe: pelagic/turbiditic succession
Stratigraphic boundary

LIGURIAN UNITS

TUSCAN NAPPE

Travertines

N

Leccio

Castel del Piano

volcanic center

Ermeta

Abbadia S. Salvatore

La Montagnola

Corno di Bellaria

Poggio della Pescina

Poggio Lombardo

Poggio Trauzzolo

MIDDLE PLEISTOCENE LAVAS

Quarantana

Bagnore

Piancastagnaio

Santa Fiora

Pliocene marine sediments

TUSCAN NAPPE

DIPARTIMENTO DI SCIENZE DELLA TERRA

0 500 m

N
W E
S

S10 Sondaggi e pozzi minerari

Evidenze di mineralizzazioni a cinabro in superficie

Emanazioni di gas

Faglie ad alto angolo quaternarie

Faglie a basso angolo neogeniche

Contatto stratigrafico

20 (20) Giaciture di strato

Ce + Ox

Py + Ox

P. S. Luigi

P. Rondinaia

LEGENDA

Depositi continentali quaternari

Travertini
55Ka (Minissale comunicazione orale) -Attuale

Depositi marini pliocenici

Argille Plioceniche
Pliocene inf.

Conglomerati Pliocenici
Pliocene inf.

Unità Liguri

Unità ofiolitifera

Argille a Palombini
Cretaceo inf.

Unità di S. Fiora

Pietraforte
Cretaceo sup.

S. Fiora
Cretaceo sup.

Falda Toscana

Calcareniti di Montegrossi
Eocene sup.

Marne del Sugame
Cretacoco sup.-Eocene

Maiolica
Cretacico inf.

Marne a Posidonia
Dogger

Calcare Rosso Ammonitico
Lias medio

Calcare a *Rhaetavicula* contorta
Retico

Argilliti e calcareniti di Dudda

Argilliti di Brolio

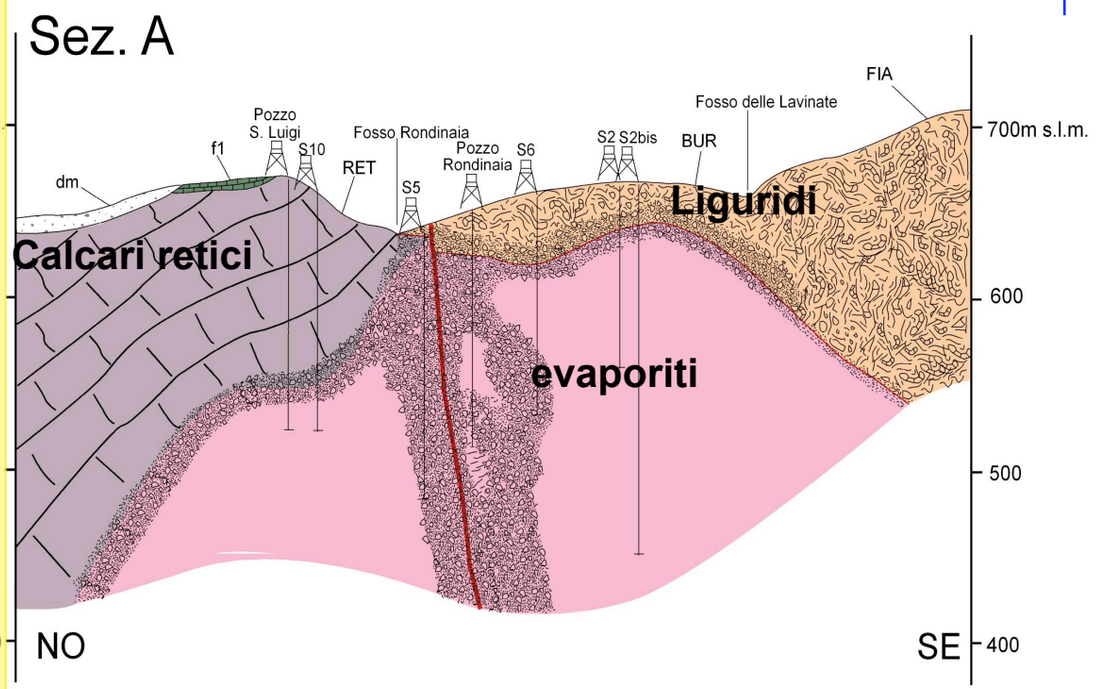
Diaspri

Calcare Selcifero di Limano
Lias medio-sup.

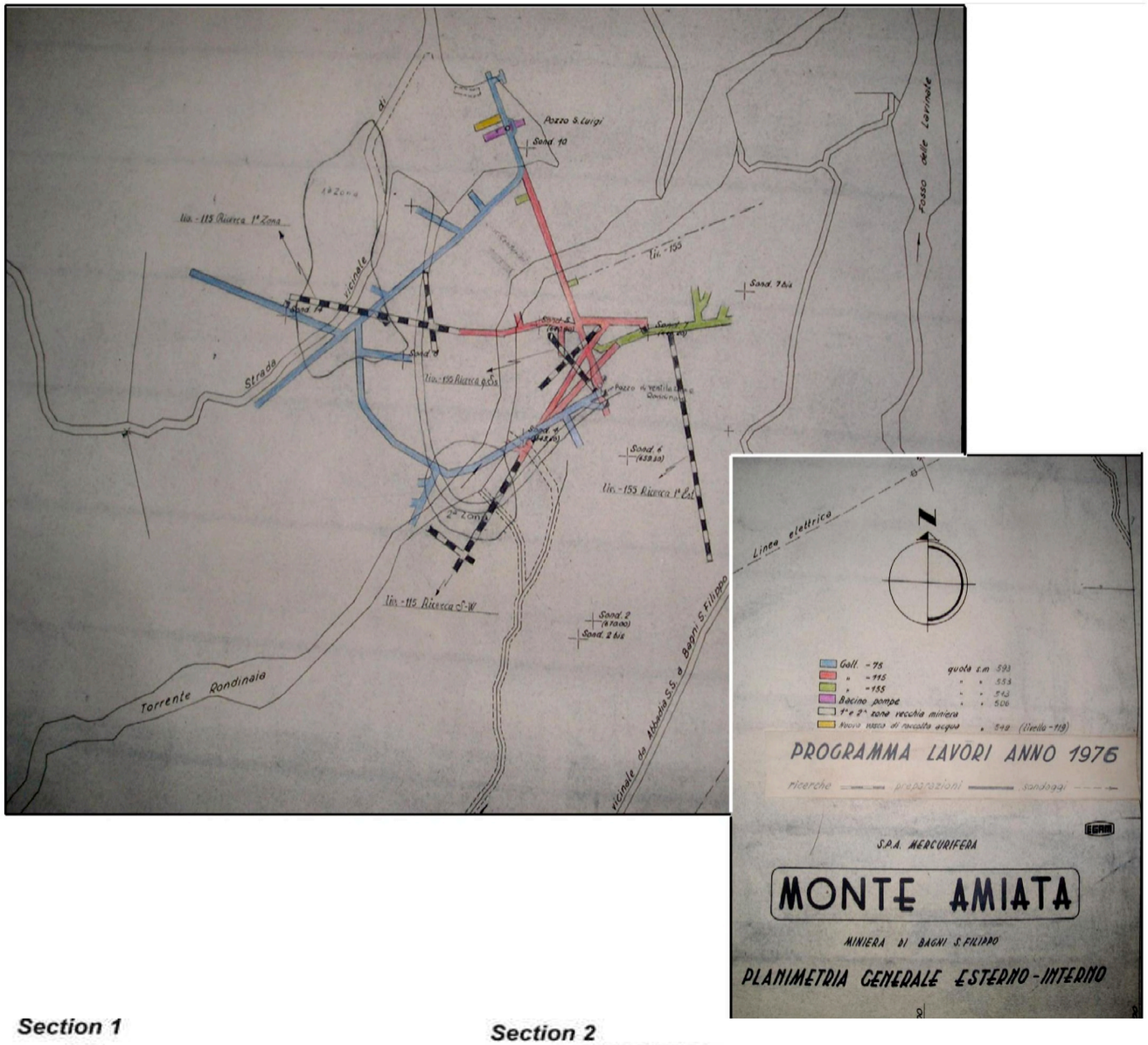
Calcare Massiccio
Lias inf.

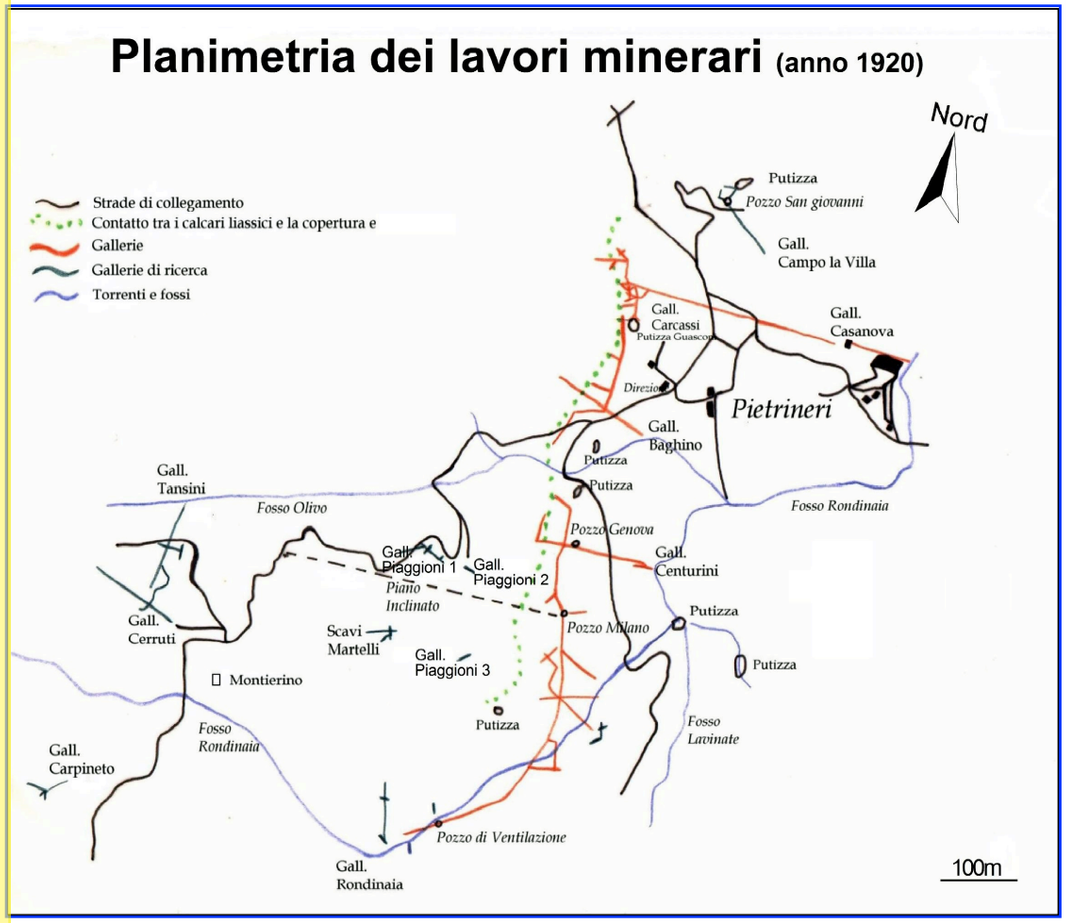
Anidriti di Burano
Norico

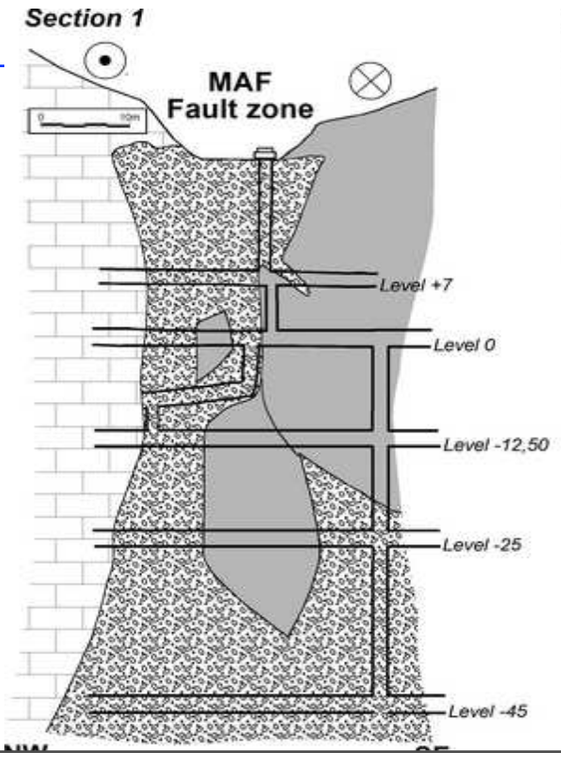
Brogi and Fabbrini, 2010

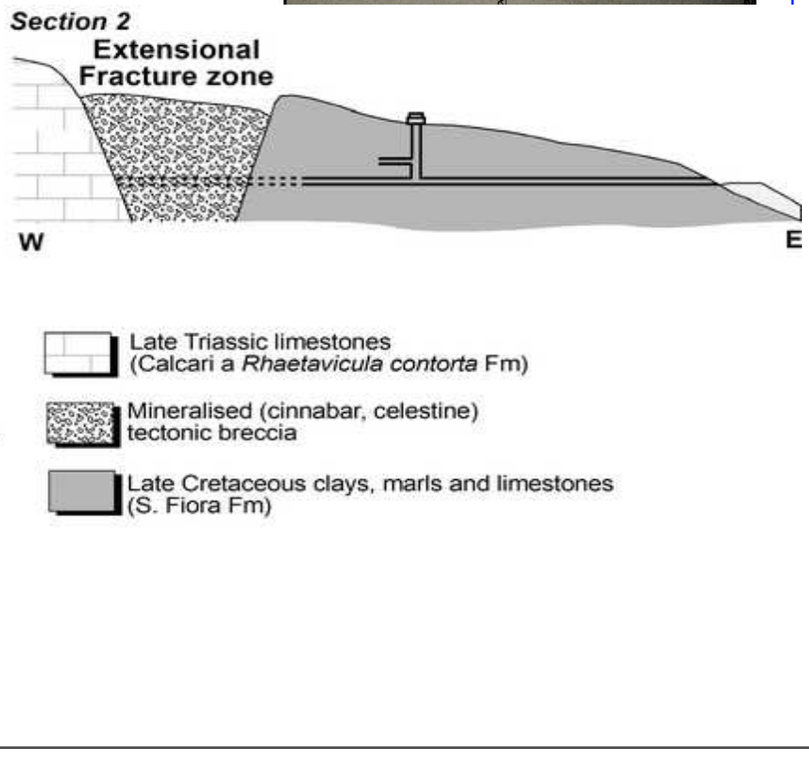


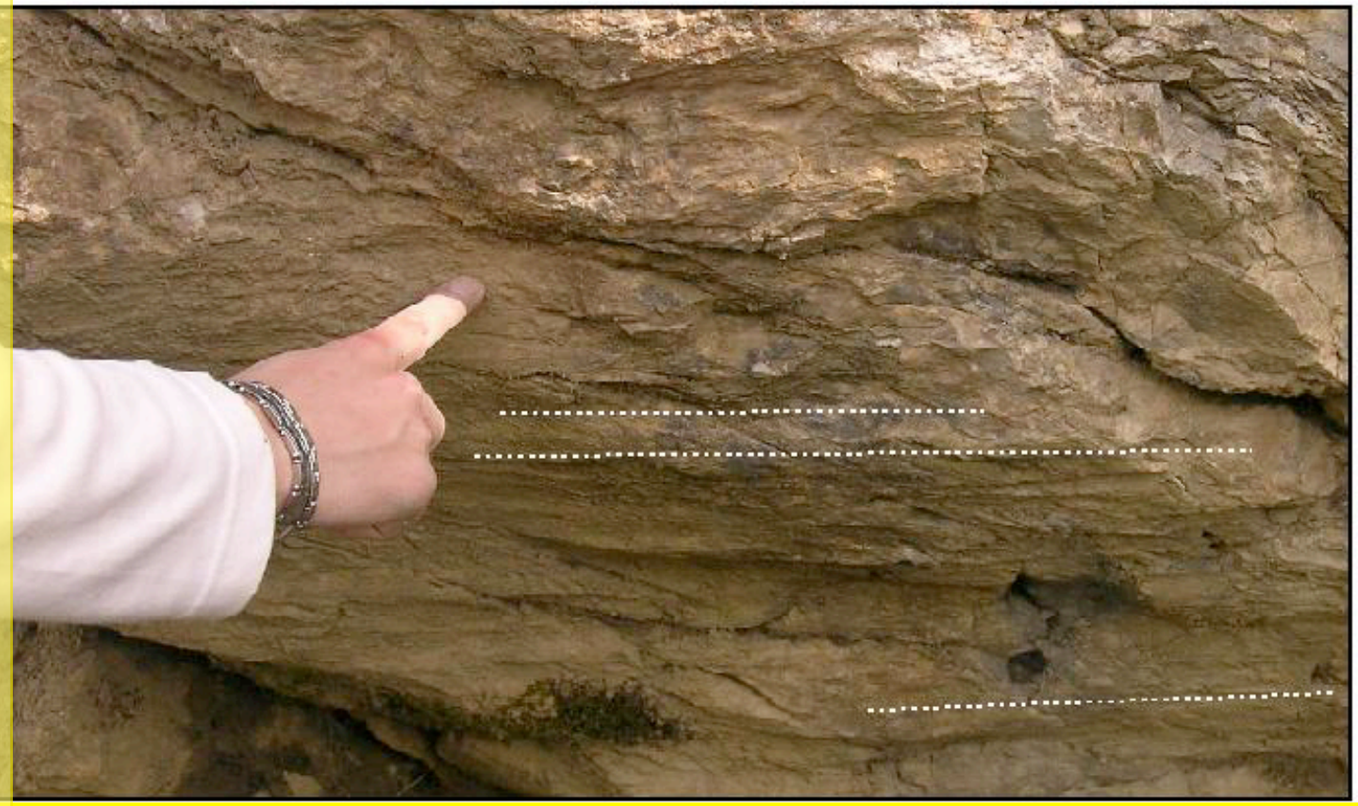
Brogi e Fabbrini, 2010







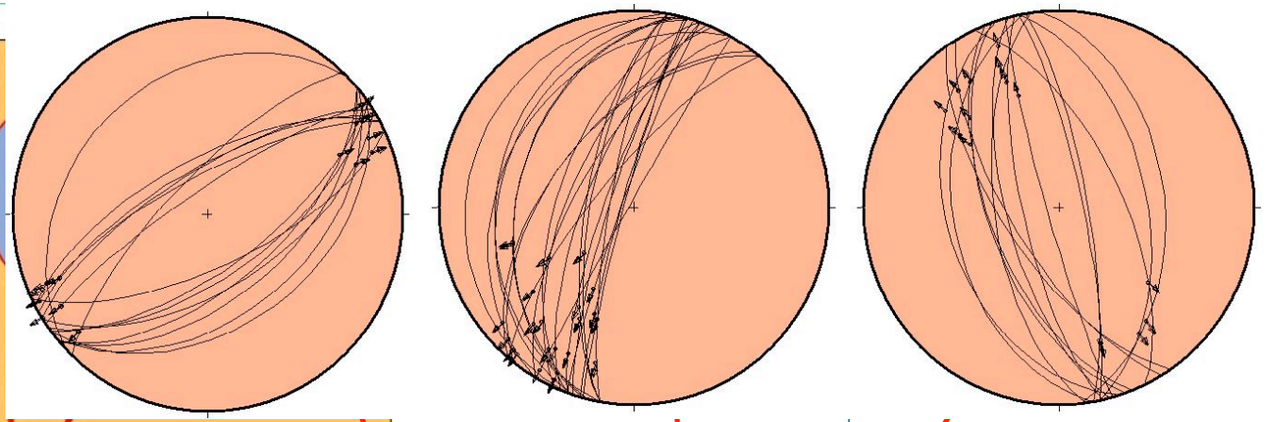




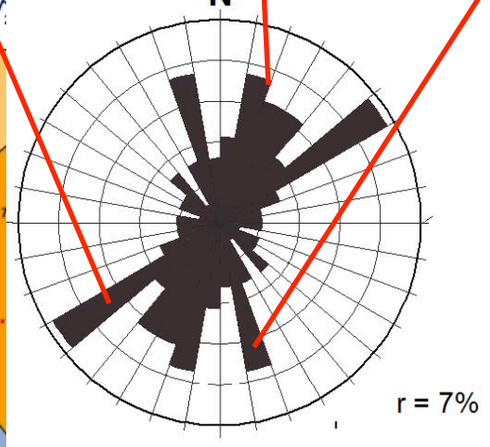
UNIVERSITA' DEGLI STUDI DI SIENA
DIPARTIMENTO DI SCIENZE DELLA TERRA

0 500 m

N
W E
S



Contatto stratigrafico



LEGENDA

Depositi continentali quaternari
- Travertini — *55Ka (Minissale comunicazione orale) -Attuale*

Depositi marini pliocenici
- Argille Plioceniche — *Pliocene inf.*
- Conglomerati Pliocenici — *Pliocene inf.*

Unità Liguri

Unità ofiolitifera
- Argille a Palombini — *Cretaceo inf.*

Unità di S. Fiora
- Pietraforte — *Cretaceo sup.*
- S. Fiora — *Cretaceo sup.*

Falda Toscana
- Calcareniti di Montegrossi — *Eocene sup.*
- Marne del Sugame — *Cretacoco sup.-Eocene*
- Maiolica — *Cretacico inf.*
- Marne a Posidonia — *Dogger*
- Calcare Rosso Ammonitico — *Lias medio*
- Calcare a *Rhaetavicula* contorta
- Argilliti e calcareniti di Dudda
- Argilliti di Brolio
- Diaspri
- Calcare Selcifero di Limano — *Lias medio-sup.*
- Calcare Massiccio — *Lias inf.*
- Anidriti di Burano

Brogi & Fabbrini, 2010

DIPARTIMENTO DI SCIENZE DELLA TERRA

0 500 m

N
W E
S

S10 Sondaggi e pozzi minerari

Evidenze di mineralizzazioni a cinabro in superficie

Emanazioni di gas

Faglie ad alto angolo quaternarie

Faglie a basso angolo neogeniche

Contatto stratigrafico

20 (20) Giaciture di strato

Ce + Ox

Py + Ox

P. S. Luigi

P. Rondinaia

LEGENDA

Depositi continentali quaternari

- Travertini — *55Ka (Minissale comunicazione orale) -Attuale*

Depositi marini pliocenici

- Argille Plioceniche — *Pliocene inf.*
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Unità ofiolitifera

- Argille a Palombini — *Cretaceo inf.*

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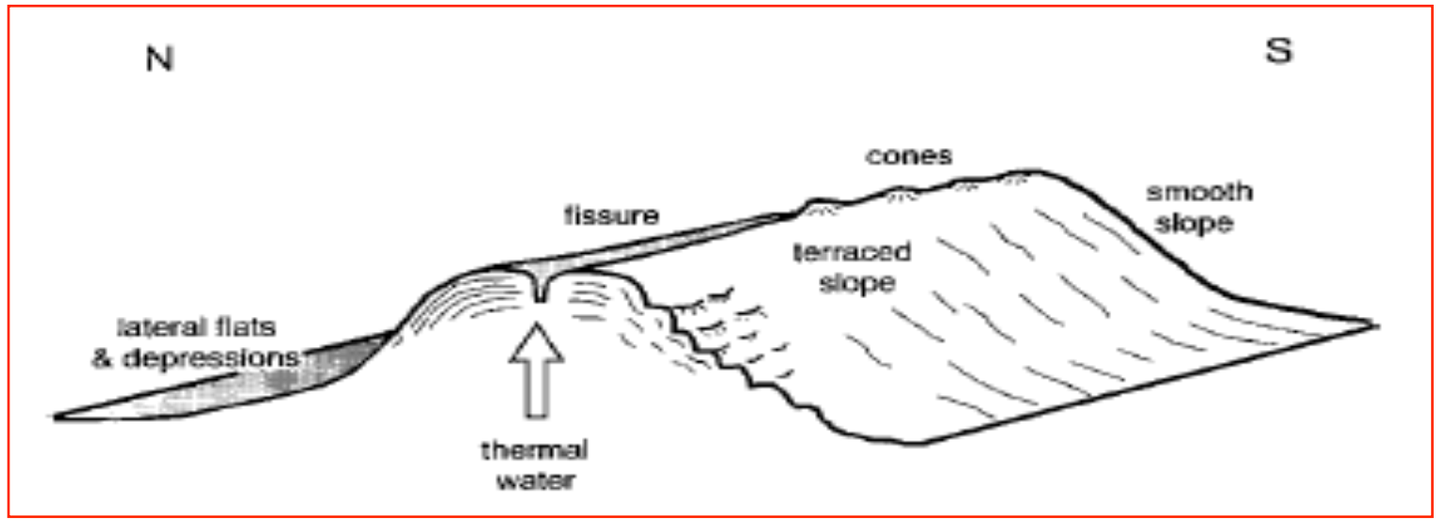
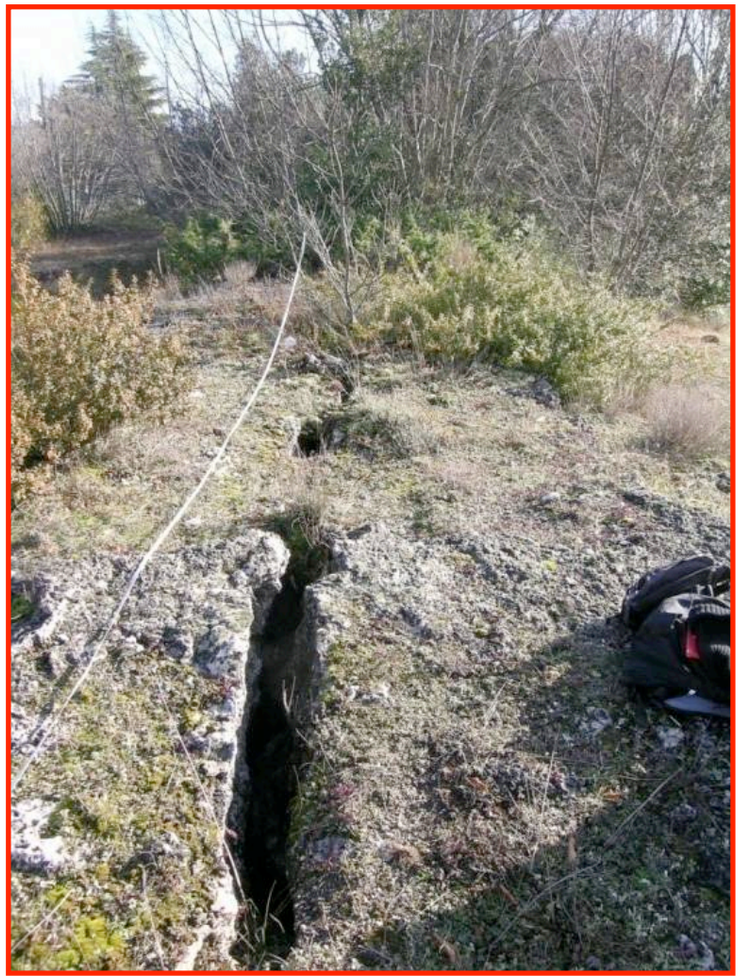
- Pietraforte — *Cretaceo sup.*
- S. Fiora — *Cretaceo sup.*

Falda Toscana

- Calcareniti di Montegrossi — *Eocene sup.*
- Marne del Sugame — *Cretacoco sup.-Eocene*
- Maiolica — *Cretacico inf.*
- Marne a Posidonia — *Dogger*
- Calcare Rosso Ammonitico — *Lias medio*
- Calcare a *Rhaetavicula* contorta — *Retico*
- Argilliti e calcareniti di Dudda
- Argilliti di Brolio
- Diaspri
- Calcare Selcifero di Limano — *Lias medio-sup.*
- Calcare Massiccio — *Lias inf.*
- Anidriti di Burano — *Norico*


N
S
cones
fissure
smooth slope
terraced slope
lateral flats & depressions
thermal water



LIGURIAN UNITS

TUSCAN NAPPE

Travertines

N

Leccio

Castel del Piano

volcanic center

La Valle

Ermeta

Abbadia S. Salvatore

Corno di Bellaria

La Montagnola

Poggio della Pescina

Poggio Lombardo

Poggio Trauzzolo

YOUNGING DIRECTION

MIDDLE PLEISTOCENE LAVAS

Quaranta

Bagnore

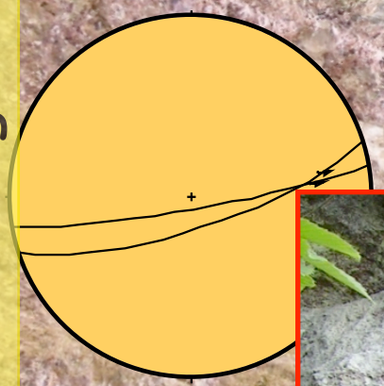
Piancastagnaio

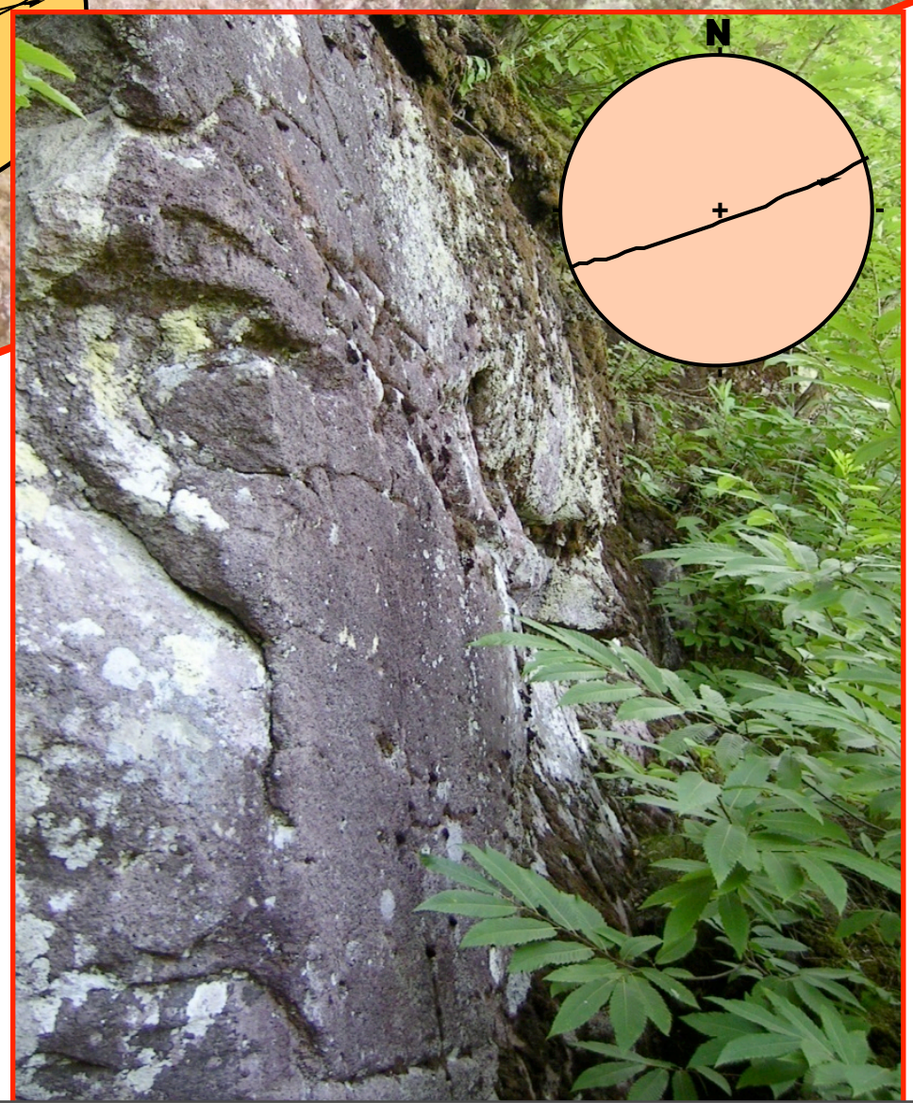
Santa Fiora

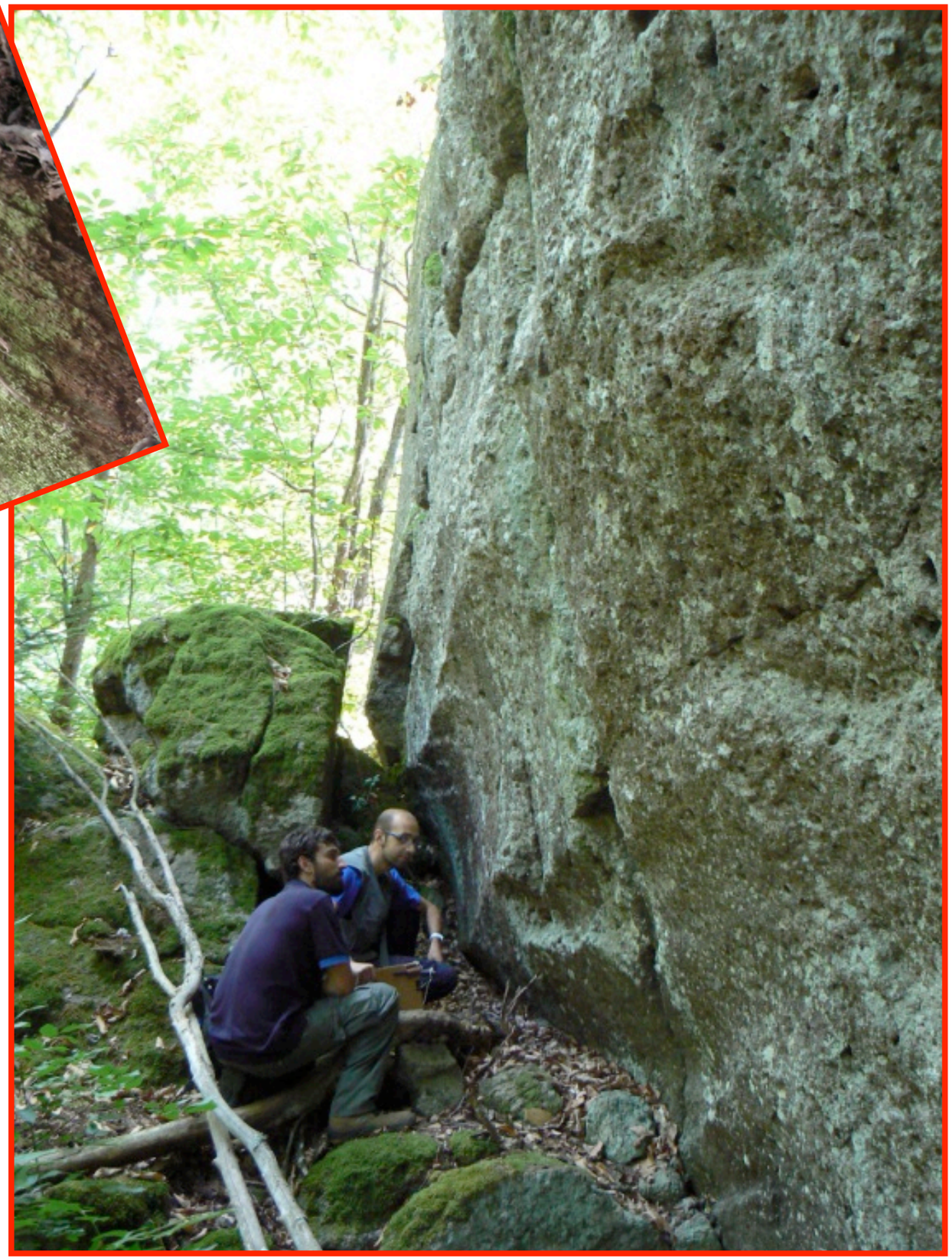
Pliocene marine sediments

TUSCAN NAPPE


orizzontale




N



A

N n=1 N n=6 N n=7

N n=2 N n=1 N n=14 N n=9

N n=2 N n=5 N n=3

N n=1 N n=1 N n=6 N n=7

N n=3 N n=4 N n=4 N n=8

N n=5 N n=12

N n=1

N n=8 N n=7

N n=2 N n=9 N n=11

N n=5 N n=14 N n=15

N n=6 N n=6

N n=2 N n=13 N n=5

N n=1 N n=18 N n=8

N n=2 N n=21

B

① N n=25

② N n=251

1.6 %
2.4 %
3.6 %
5.6 %
6.0 %
6.4 %

③ N n=251

r=15%

11° 39'
42° 54'

11° 40'
42° 53'

11° 32'
42° 52'

42° 50'
11° 34'

Mt Amiata
1737m

La Montagnola

Corno di Bellaria

P. Pescina

P. Biello

P. Pinzi

N

1.5 km

Third volcanic complex: olivine-latite lava flow
209±0.29 ka

Second volcanic complex: phorphiritic rhyodacite dome and lava flow
from 300±0.04 ka to 190±0.23 ka

Upper Unit of the First volcanic complex: trachidacite
from318±0.08 ka to 217±0.01 ka

Lower Unit of the First volcanic complex: trachidacite
305±0.005 ka to 241±0.07 ka

Ligurian Units
Jurassic-Middle Eocene

* structural analysis stations

▲ eruption centers

A

N n=1 N n=6 N n=7

N n=2 N n=1 N n=14 N n=9

N n=2 N n=5 N n=3

N n=1 N n=1 N n=6 N n=7

N n=3 N n=4 N n=4 N n=8

N n=5 N n=12

N n=1

N n=8 N n=7

N n=2 N n=9 N n=11

B

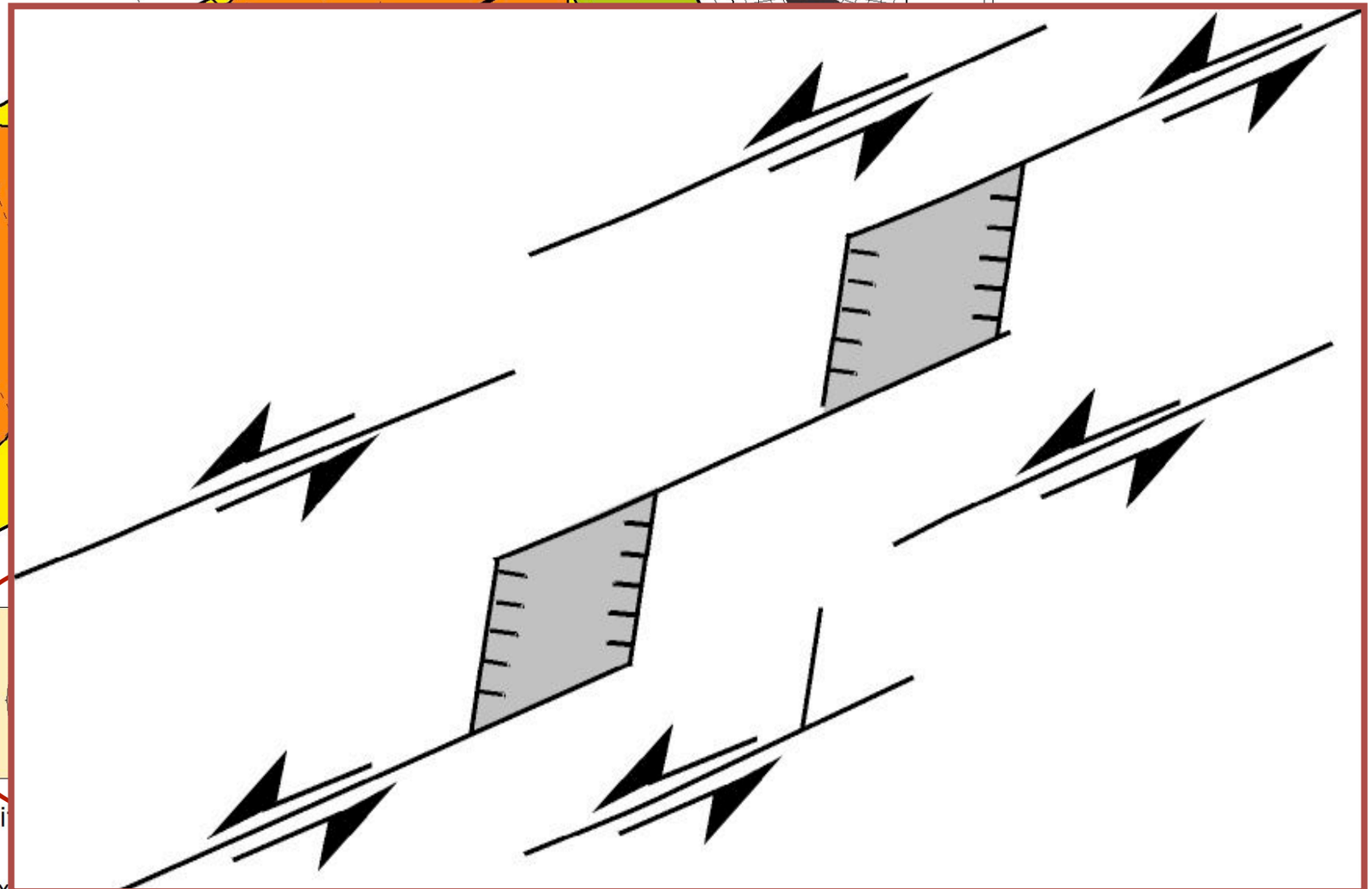
① N n=25

② N n=251

1.6 %
2.4 %
3.6 %
5.6 %
6.0 %
6.4 %

③ N n=251

11° 39'
42° 54'
11° 32'
42° 52'
42° 50'
11° 34'
P. Pescina
P. Pinzi



Third volcanic complex: olivine-lati
209±0.29 ka

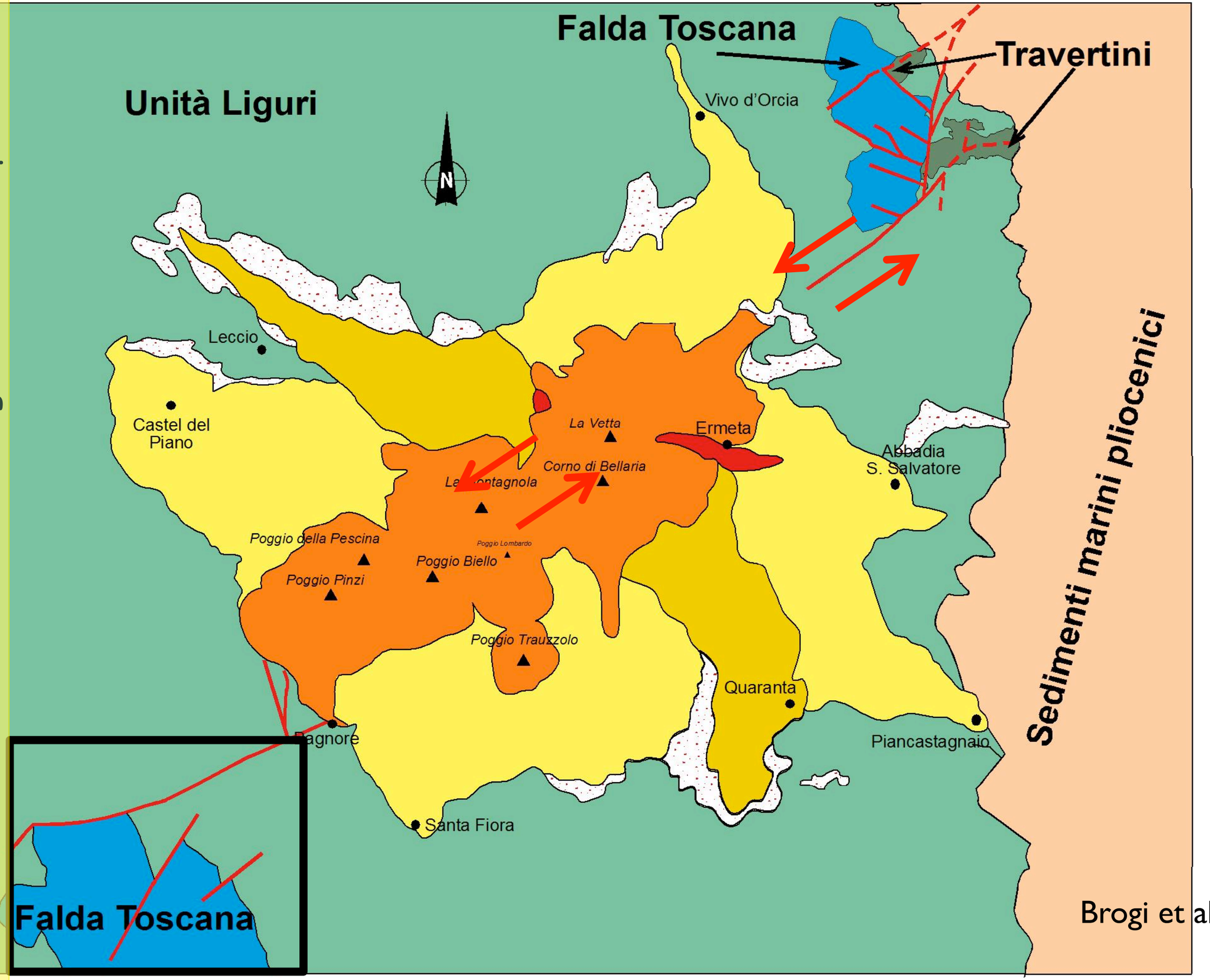
Upper Unit of the First volcanic complex: trachidacite
from318±0.08 ka to 217±0.01 ka

Lower Unit of the First volcanic complex: trachidacite
305±0.005 ka to 241±0.07 ka

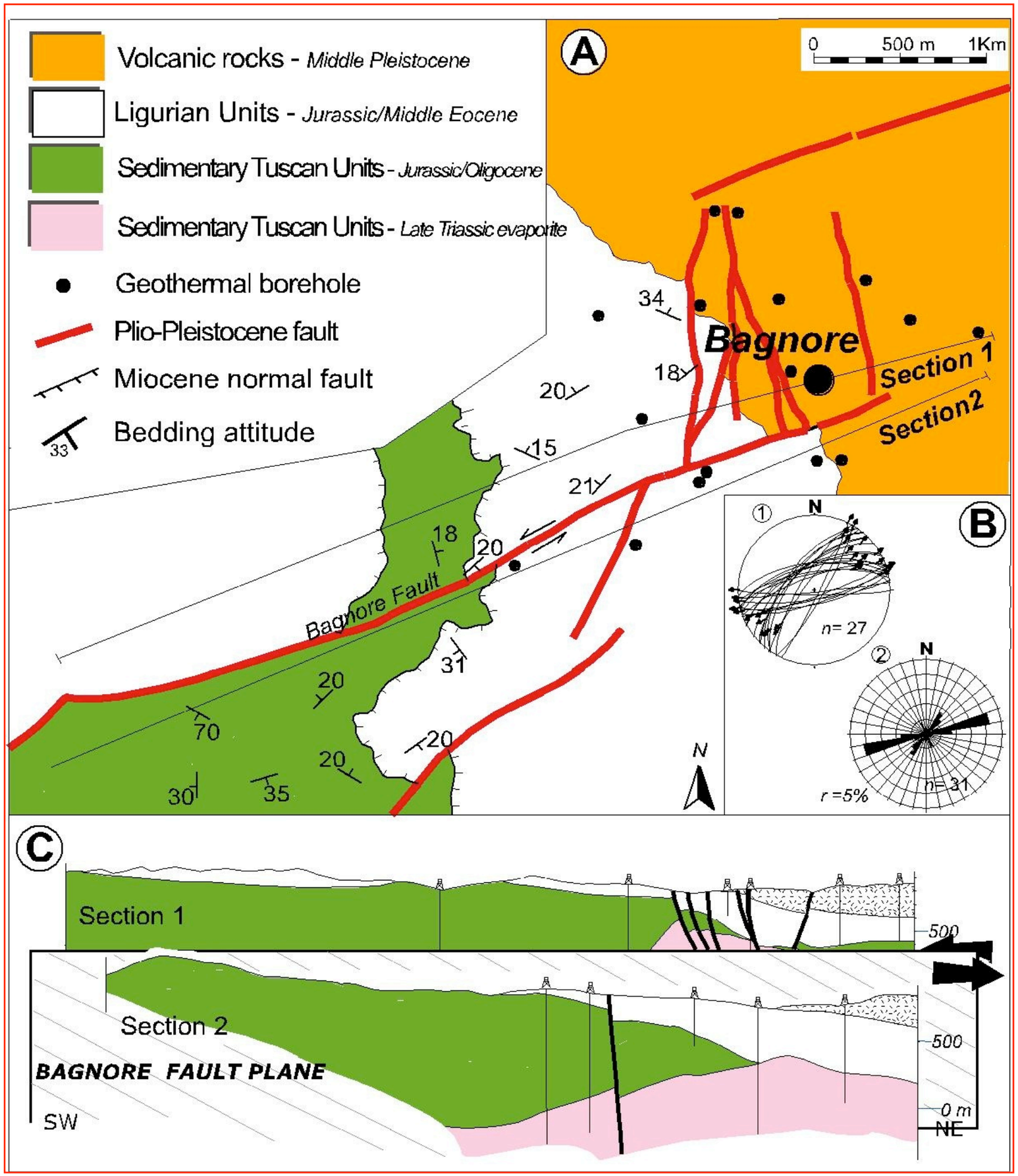
Ligurian Units
Jurassic-Middle Eocene

* structural analysis stations

▲ eruption centers



Brogi et al. 2010


Volcanic rocks - Middle Pleistocene
Ligurian Units - Jurassic/Middle Eocene
Sedimentary Tuscan Units - Jurassic/Oligocene
Sedimentary Tuscan Units - Late Triassic evaporite
Geothermal borehole
Plio-Pleistocene fault
Miocene normal fault
Bedding attitude
A
0 500 m 1Km
Bagnore
Section 1
Section2
Bagnore Fault
B
n= 27
n= 31
r =5%
N
C
Section 1
Section 2
BAGNORE FAULT PLANE
SW
NE
500
0 m


kavrnak * STUDIO * 2=B

Travertine deposits, Late Pleistocene-Holocene

Third volcanic complex: olivine-latite lava flow, 209 ± 0.29 ka

Second volcanic complex: phorphiritic rhyodacite dome and lava flow, from 300±0.04 ka to 190±0.23 ka

First volcanic complex, upper unit: trachidacite, from 318±0.08 to 217±0.01 ka

First volcanic complex, lower unit: trachidacite from 305±0.005 to 241±0.07 ka

Clay and sand, Early Pliocene

Ligurian Units, Jurassic-Middle Eocene

Tuscan Nappe, Late Triassic-Oligocene

▲ eruption centers

* station of structural analysis

42° 57'

Vivo d'Orcia

Poggio Zoccolino

Bagni S. Filippo

Bagni S. Filippo Fault

Sasso di Dante

Mt Amiata 1738 m

Abbadia San Salvatore

Castel del Piano

La Montagnola

Corno di Bellaria

Arcidosso

P. Pescina

P. Lombardo

P. Pinzi

P. Biello

P. Trauzzolo

Bagnore

Piancastagnaio

Saragiolo

S.Piero

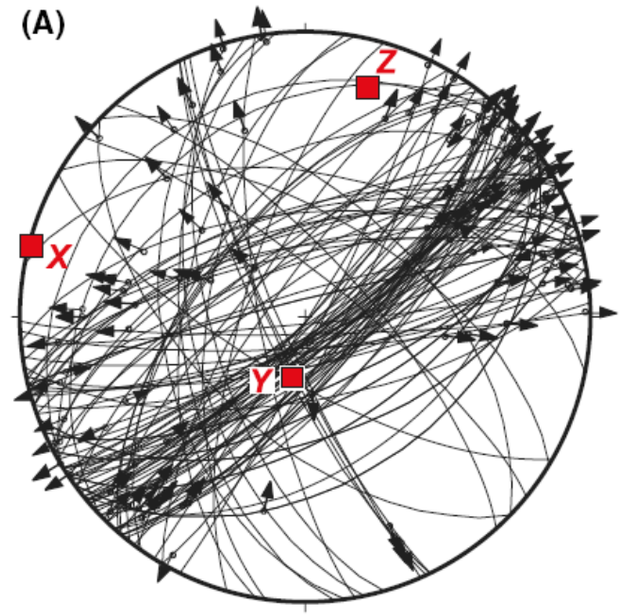
Bagnore Fault

N

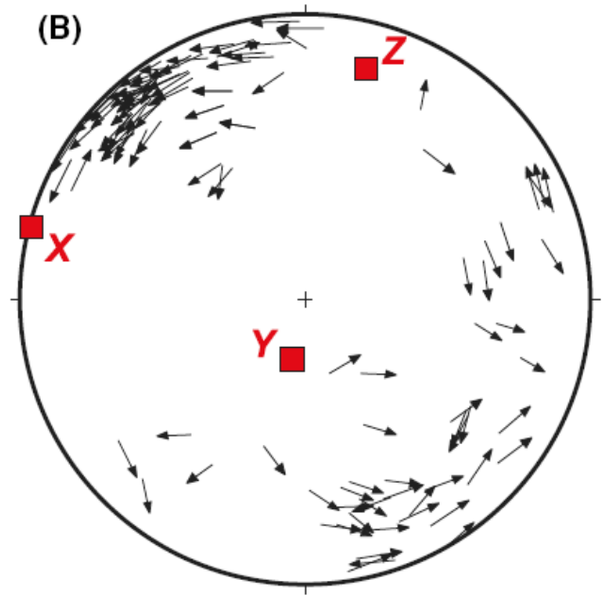
2.5 km

11° 42'

42° 50'

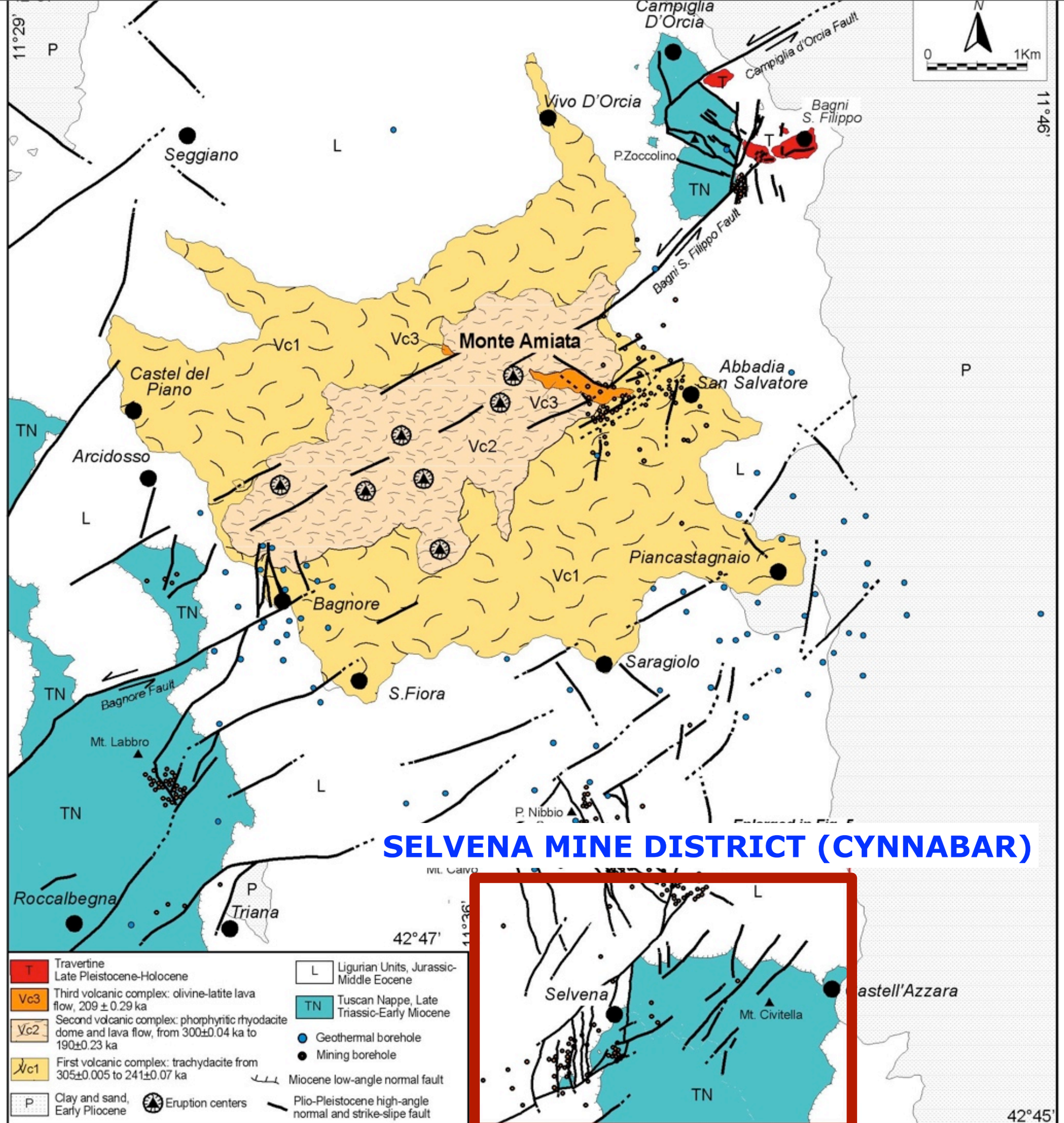


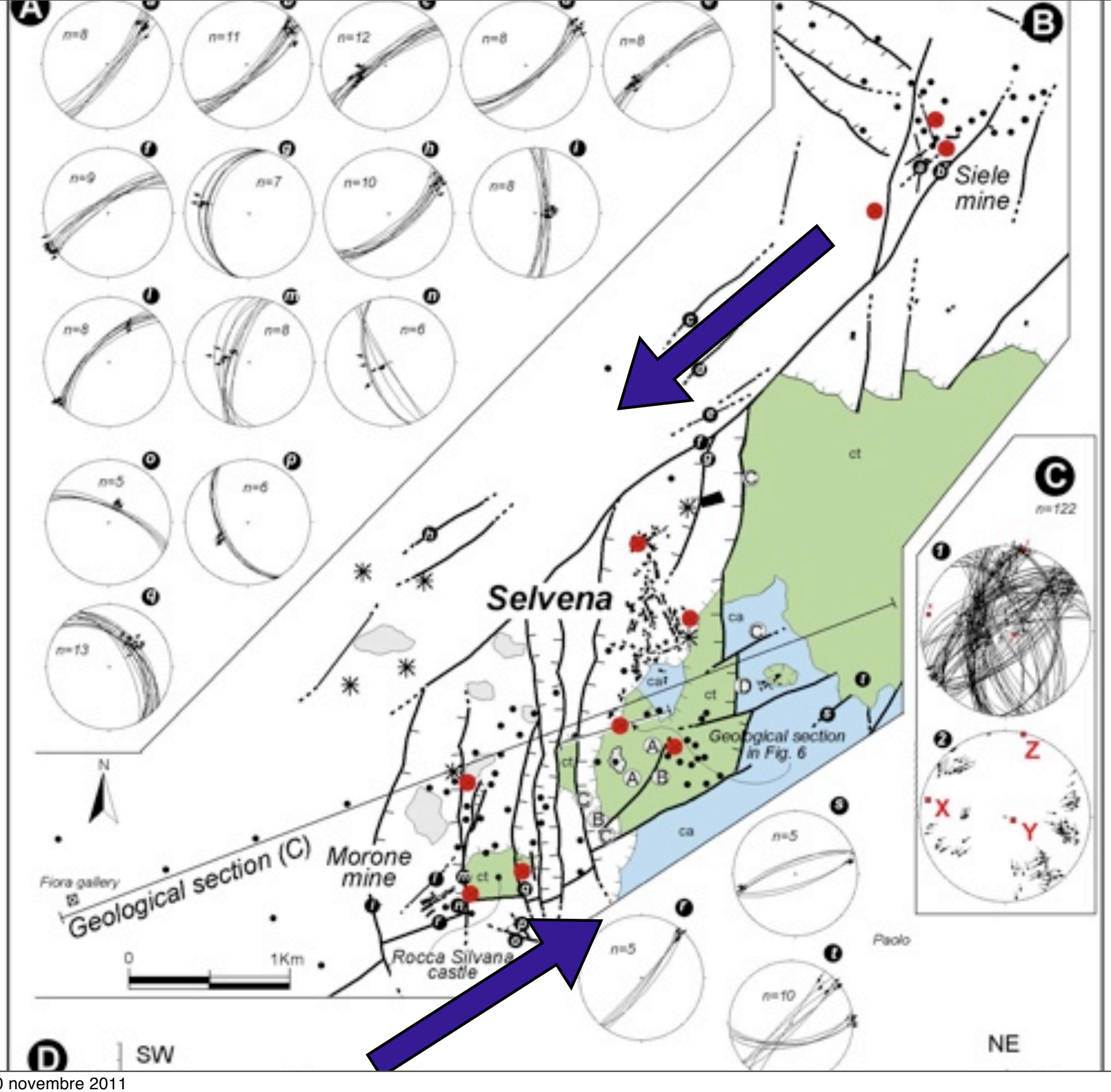
115 data



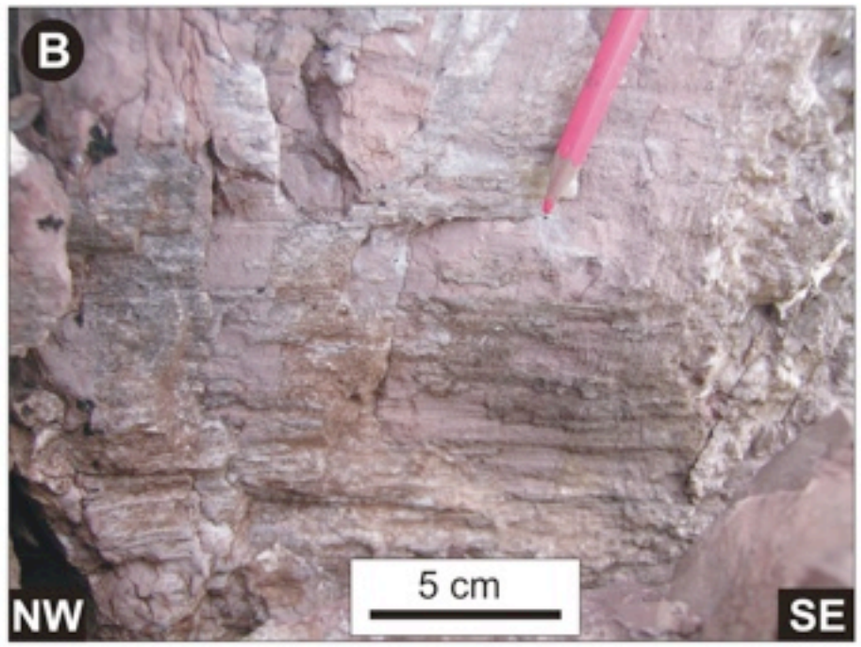
115 data

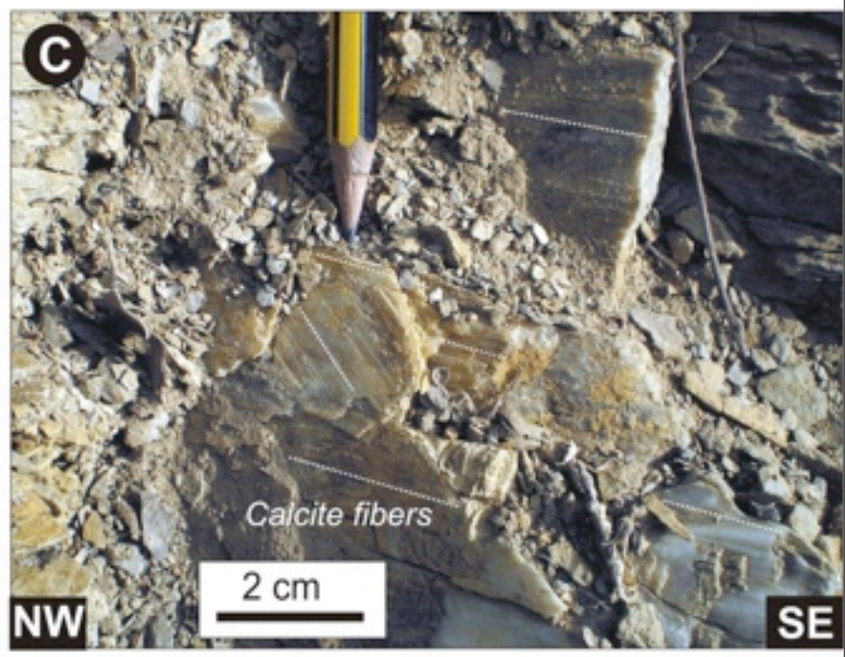
Age of deformation: from pre- to post- middle Pleistocene

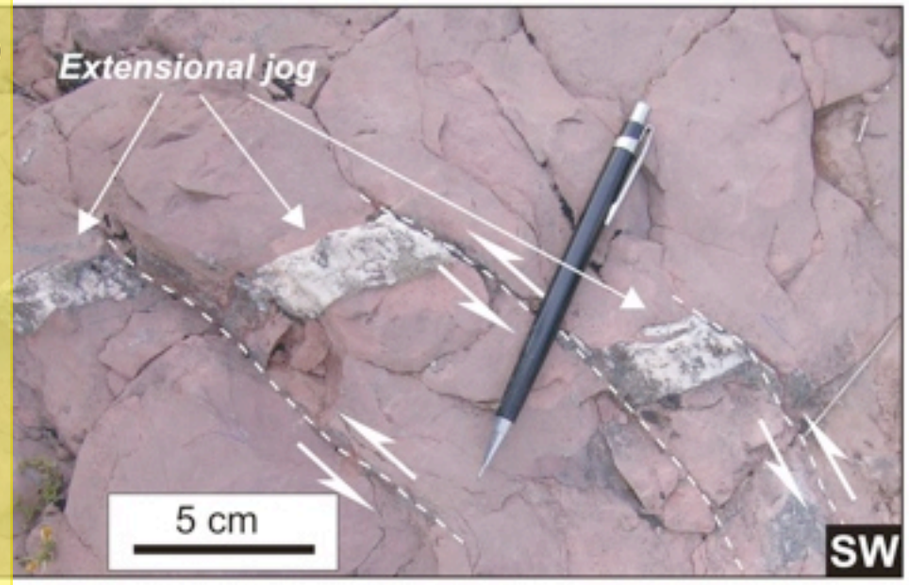

11°29'
11°46'
42°47'
42°45'
N
0
1Km
Campiglia D'Orcia
Campiglia d'Orcia Fault
Vivo D'Orcia
Bagni S. Filippo
P.Zoccolino
Seggiano
Bagni S. Filippo Fault
Monte Amiata
Vc1
Vc2
Vc3
Castel del Piano
Abbadia San Salvatore
Arcidosso
Piancastagnaio
Bagnore
Saragiolo
S.Fiora
Bagnore Fault
Mt. Labbro
P. Nibbio
Roccalbegna
Triana
Selvena
Mt. Civitella
Castell'Azzara
SELVENA MINE DISTRICT (CYNNABAR)
T
TN
L
P
Travertine
Late Pleistocene-Holocene
Third volcanic complex: olivine-latite lava flow, 209 ± 0.29 ka
Second volcanic complex: phorphyritic rhyodacite dome and lava flow, from 300±0.04 ka to 190±0.23 ka
First volcanic complex: trachydacite from 305±0.005 to 241±0.07 ka
Clay and sand, Early Pliocene
Eruption centers
Ligurian Units, Jurassic-Middle Eocene
Tuscan Nappe, Late Triassic-Early Miocene
Geothermal borehole
Mining borehole
Miocene low-angle normal fault
Plio-Pleistocene high-angle normal and strike-slipe fault

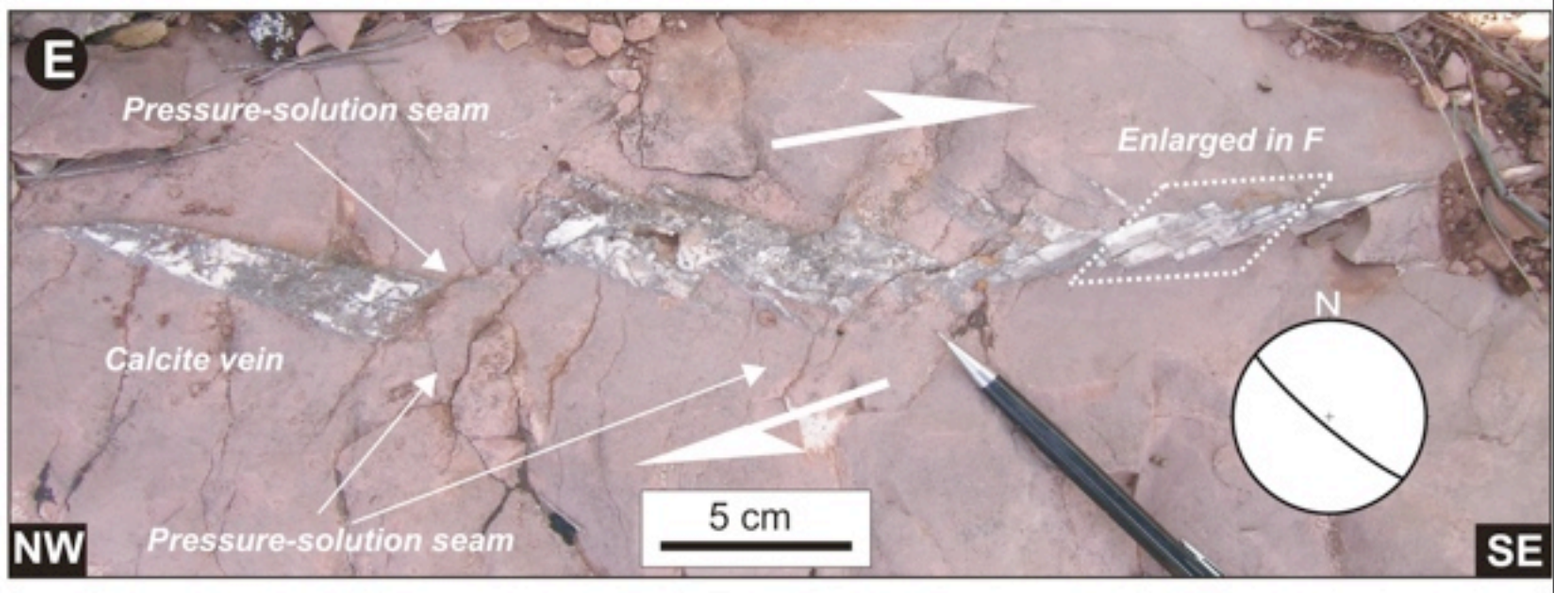

A
B
C
D
n=8
n=11
n=12
n=8
n=8
n=9
n=7
n=10
n=8
n=8
n=8
n=6
n=5
n=6
n=13
Siele mine
ct
ca
cat
Selvena
Geological section in Fig. 6
n=122
Z
X
Y
N
Fiora gallery
Geological section (C)
Morone mine
Rocca Silvana castle
0
1Km
n=5
n=5
n=10
Paolo
SW
NE


Enlarged in B
Damage Zone
Damage Zone
Fault Core
50 cm
SE

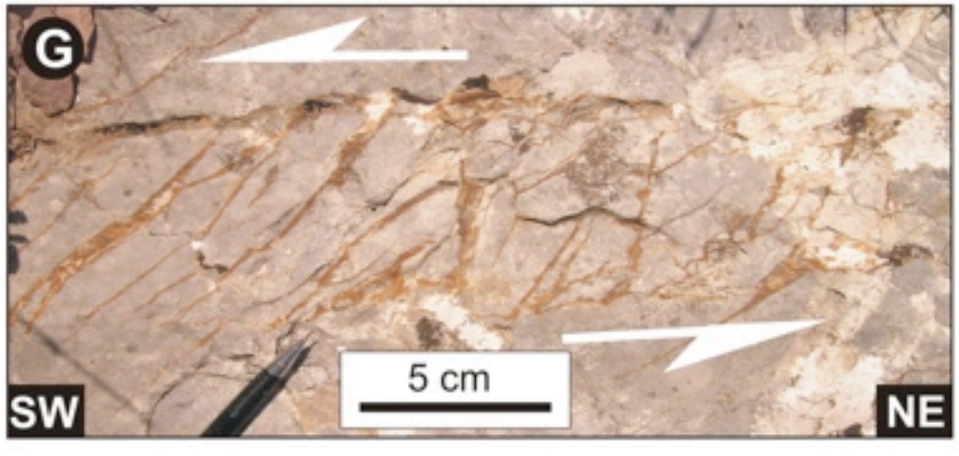

B
5 cm
NW
SE

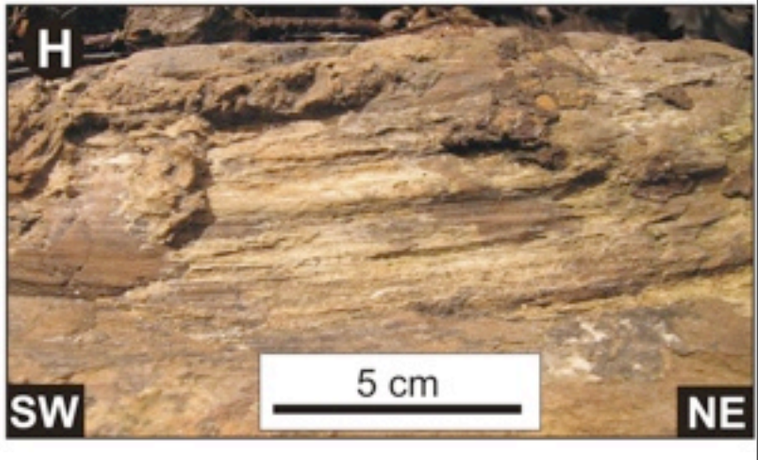

C
Calcite fibers
2 cm
NW
SE


Extensional jog
5 cm
SW


E
Pressure-solution seam
Enlarged in F
N
Calcite vein
5 cm
NW
Pressure-solution seam
SE


1 cm
SE


G
5 cm
SW
NE


H
5 cm
SW
NE

N

0 1Km

Pliocene-Quaternary strike-slip faults

Pliocene-Quaternary normal faults

Occurrence of Hg in the soil

Exploited cinnabar at depth

Mine Borehole

Mine gallery

Gas vent

Main outcrops of cinnabar mineralizatio

Main outcrops of jasperoid

Main outcrops of losima

Main outcrops of Fe-hydroxide

Main outcrops of hydrothermal alteration

OCCURENCE OF Hg IN THE SOIL (1953)

Siele mine

Mt. Penna

Selvena

Morone mine

MINE (AT DEPTH)

chief and minor infiltration path of meteoric water

path of hot and saline hydrothermal fluids

impervious cover

migrating tip zone

b

c

d

c

Ligurian Units

a

Mesozoic carbonate rocks

LateTriassic evaporite

Palaeozoic phyllite

Palaeozoic phyllite

a Middle-Late Miocene cataclasite

b Middle-Late Miocene mineralized cataclasite

c Plio-Pleistocene mineralized cataclasite of normal fault

d Plio-Pleistocene mineralized cataclasite at the tip zone

e Plio-Pleistocene mineralized cataclasite of strike-slip fault

Sb-Hg mineralization

fluid flow path along surface faults

trace of Middle-Late Miocene normal fault

trace of Plio-Plistocene left strike-slip fault

deep reflection seismic lines CROsta Profonda Project

D. Liotta - international school on geothermal exploration

Larderello

Siena

CROP 18A

LARDERELLO
geothermal fields

Mt. AMIATA
geothermal field

CROP 3

CROP 18B

CROP 3

4 s

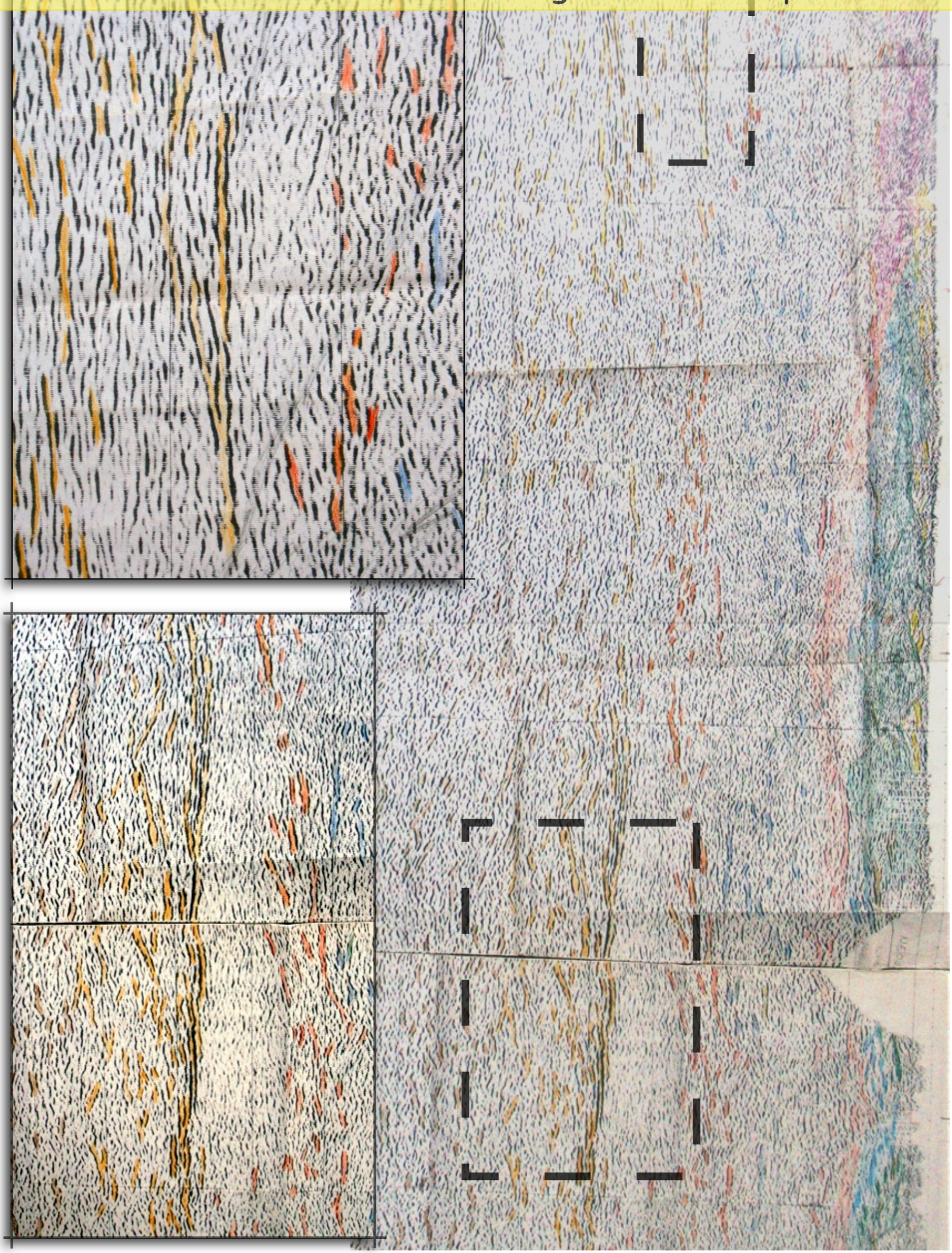
7 s

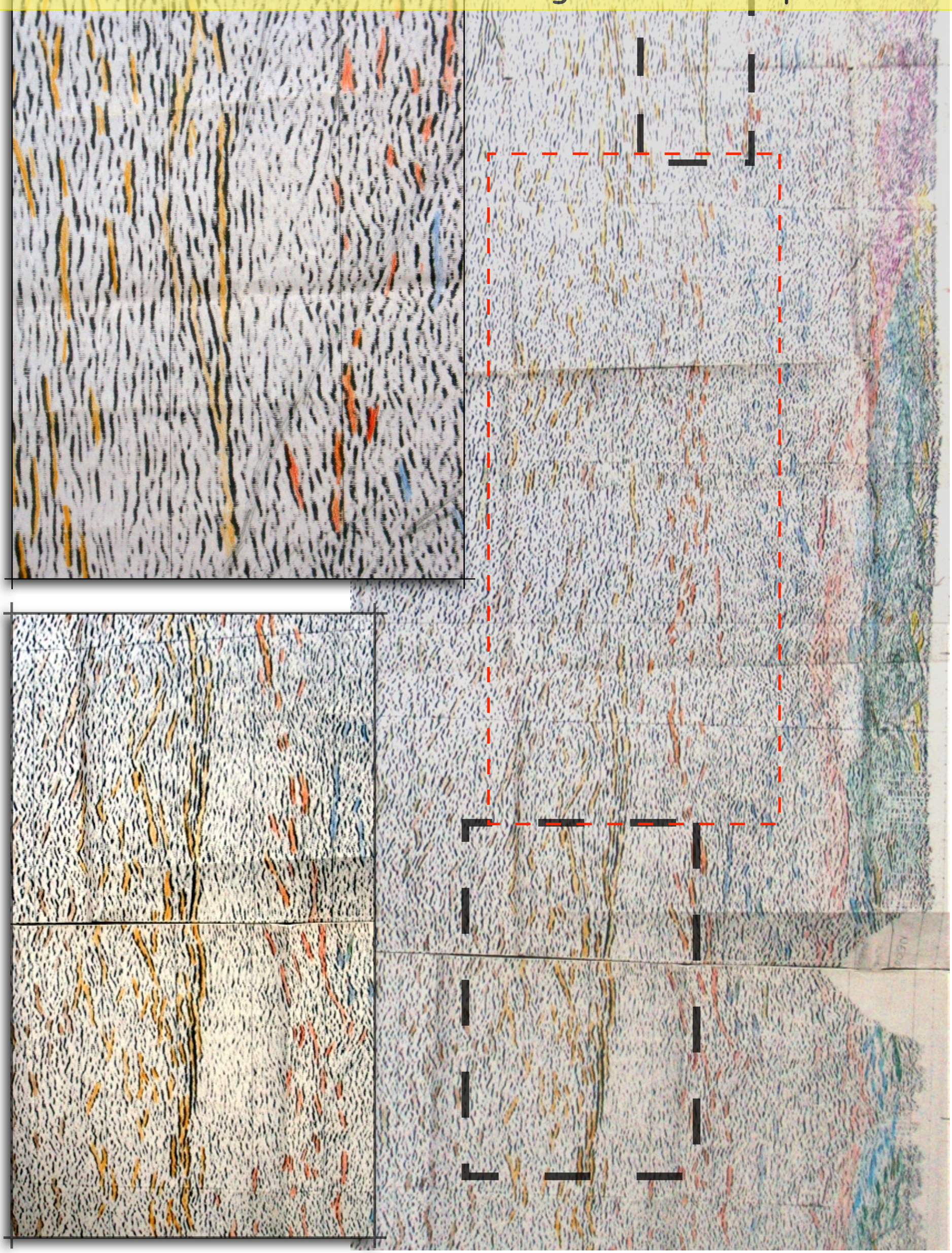
15 km

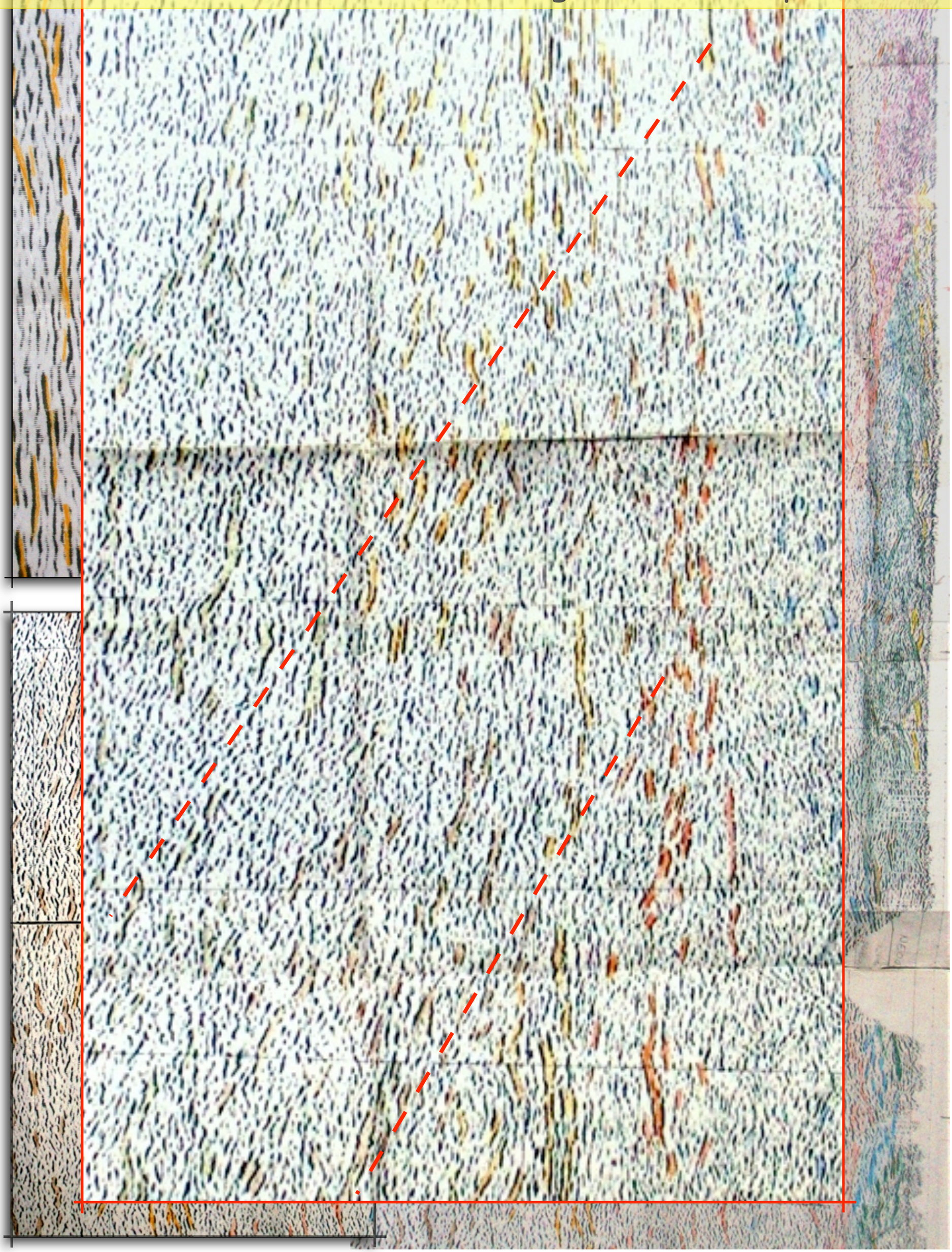
SW

NE


K - horizon
4 s





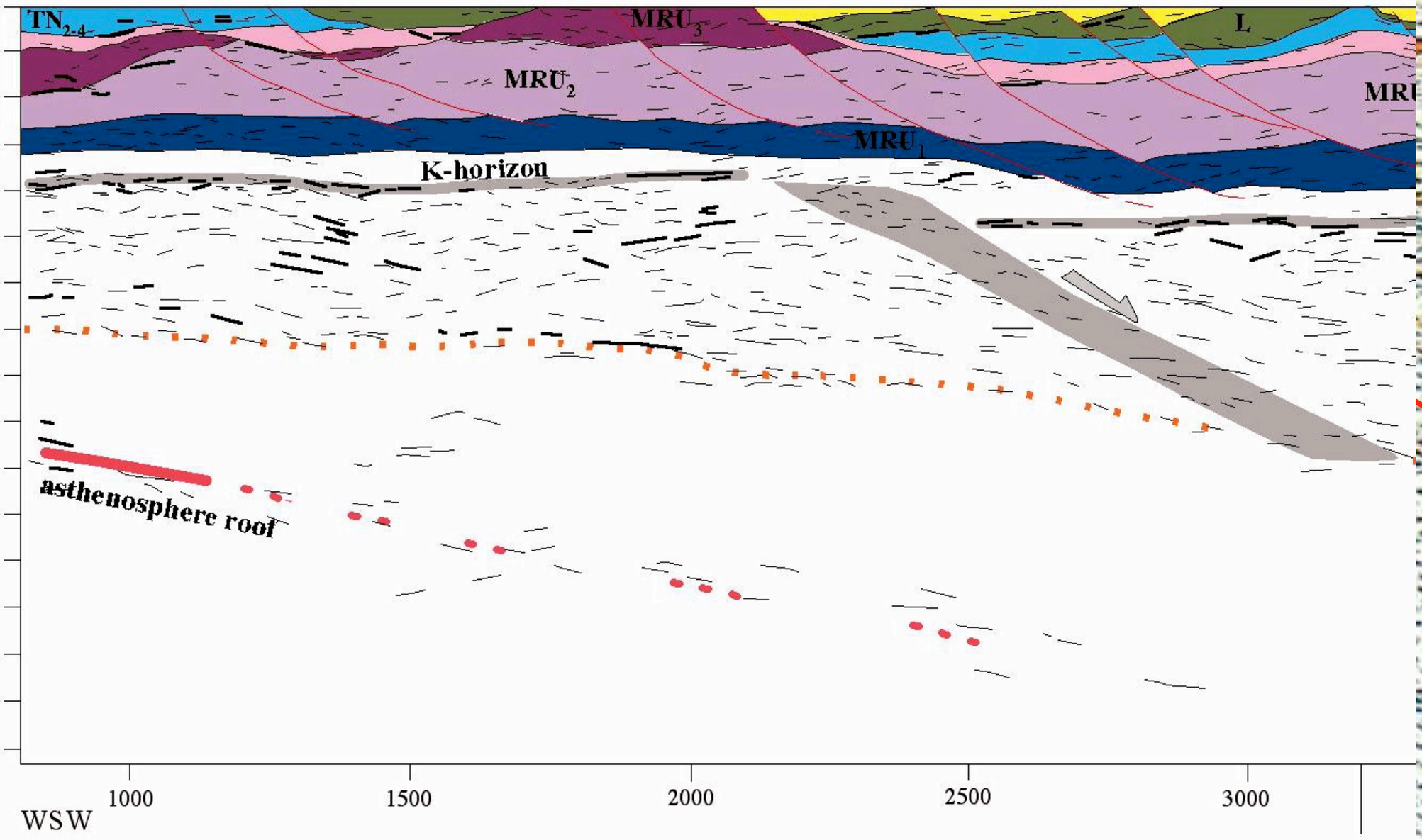


16

WSW 1000 1500 2000 2500 3000 ENE SSW

Larderello (projected)

Tyrrhenian coast



deep reflection seismic lines CROsta Profonda Project

D. Liotta - international school on geothermal exploration

Larderello

Siena

CROP 18A

LARDERELLO geothermal fields

Mt. AMIATA geothermal field

CROP 3

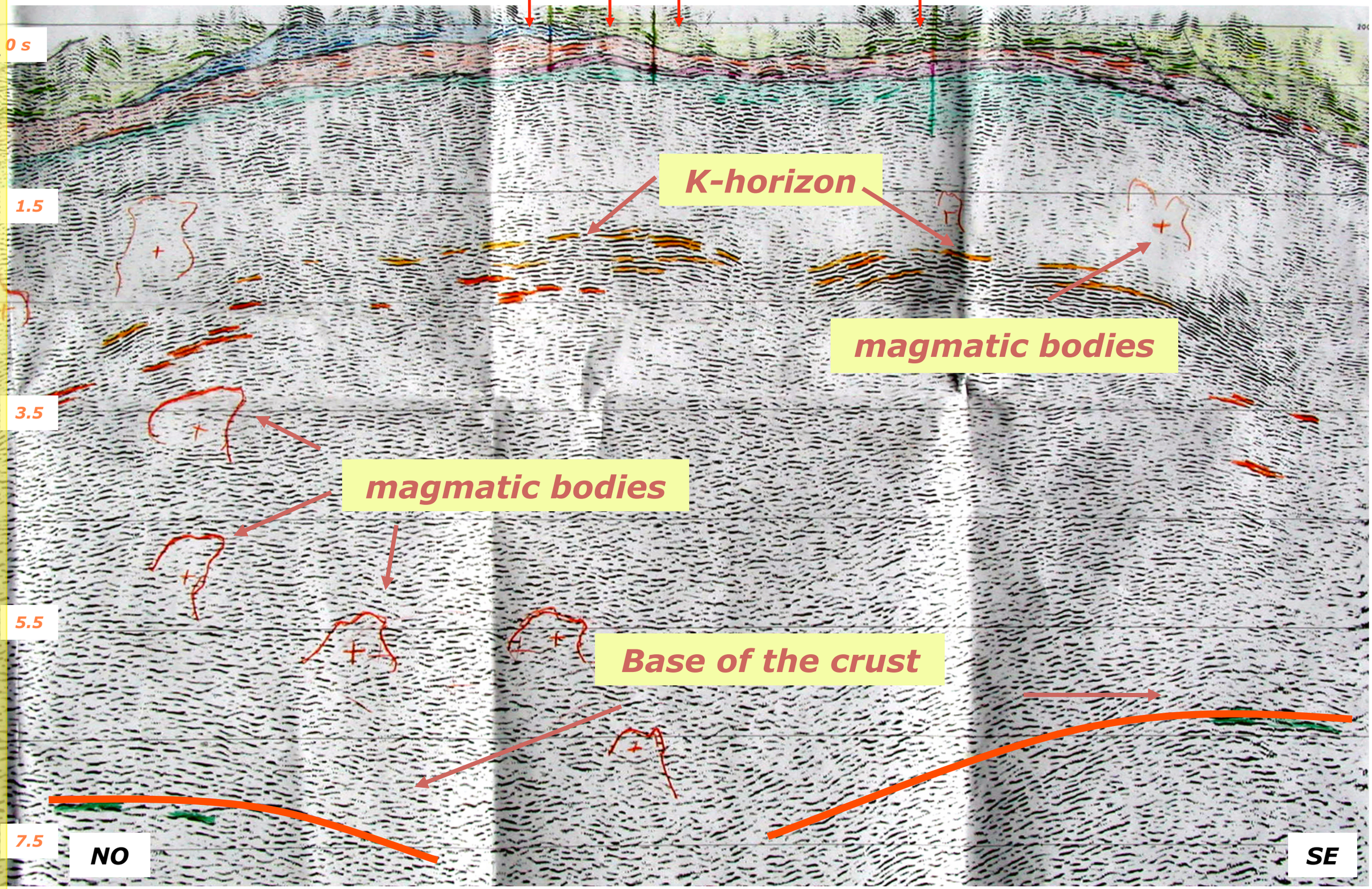
CROP 18B

CRUSTAL STRUCTURE

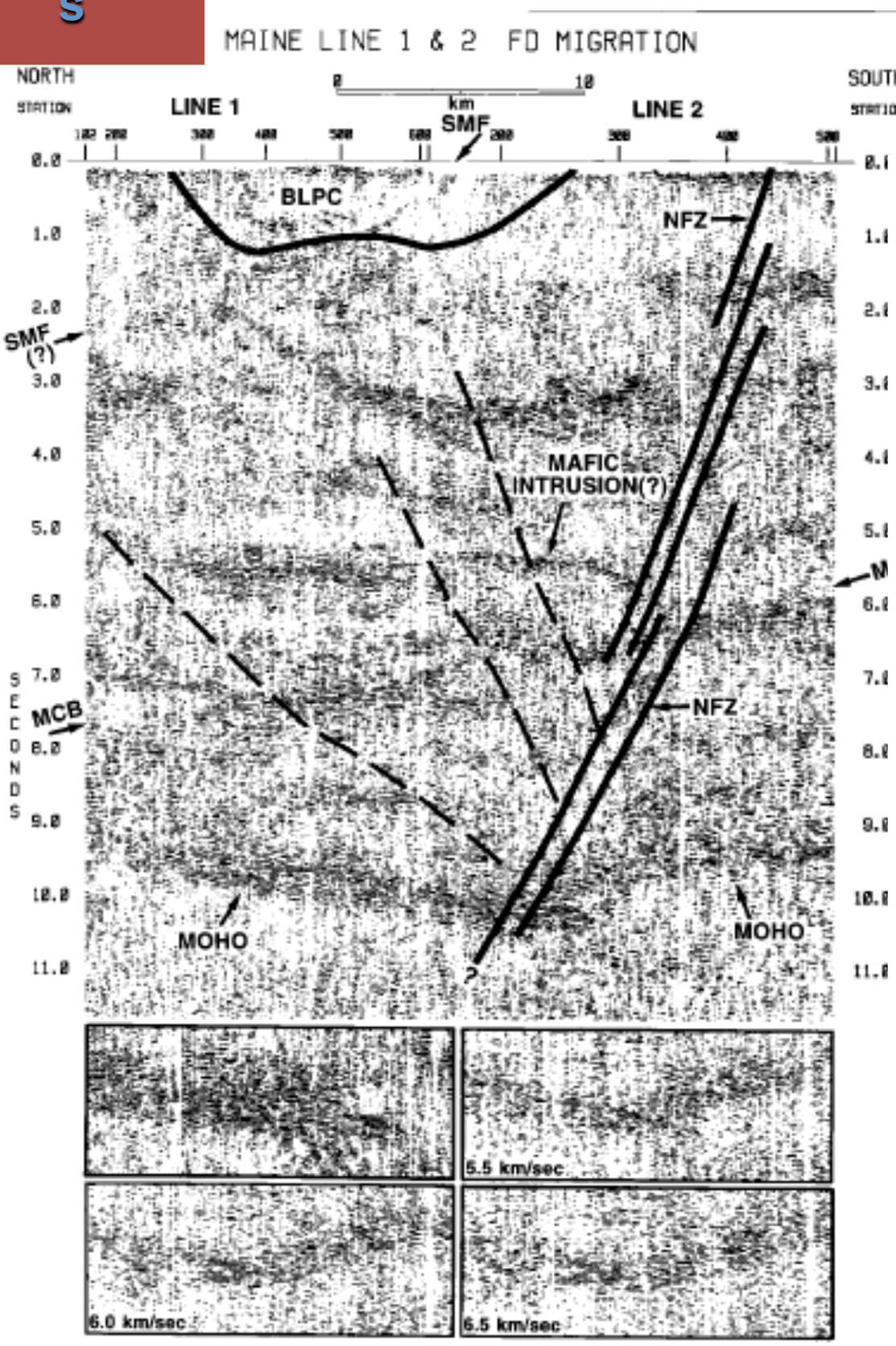
Bagnore geoth. field

CROP 18 B – Mt. Amiata area

intersection with other seismic profiles sismici

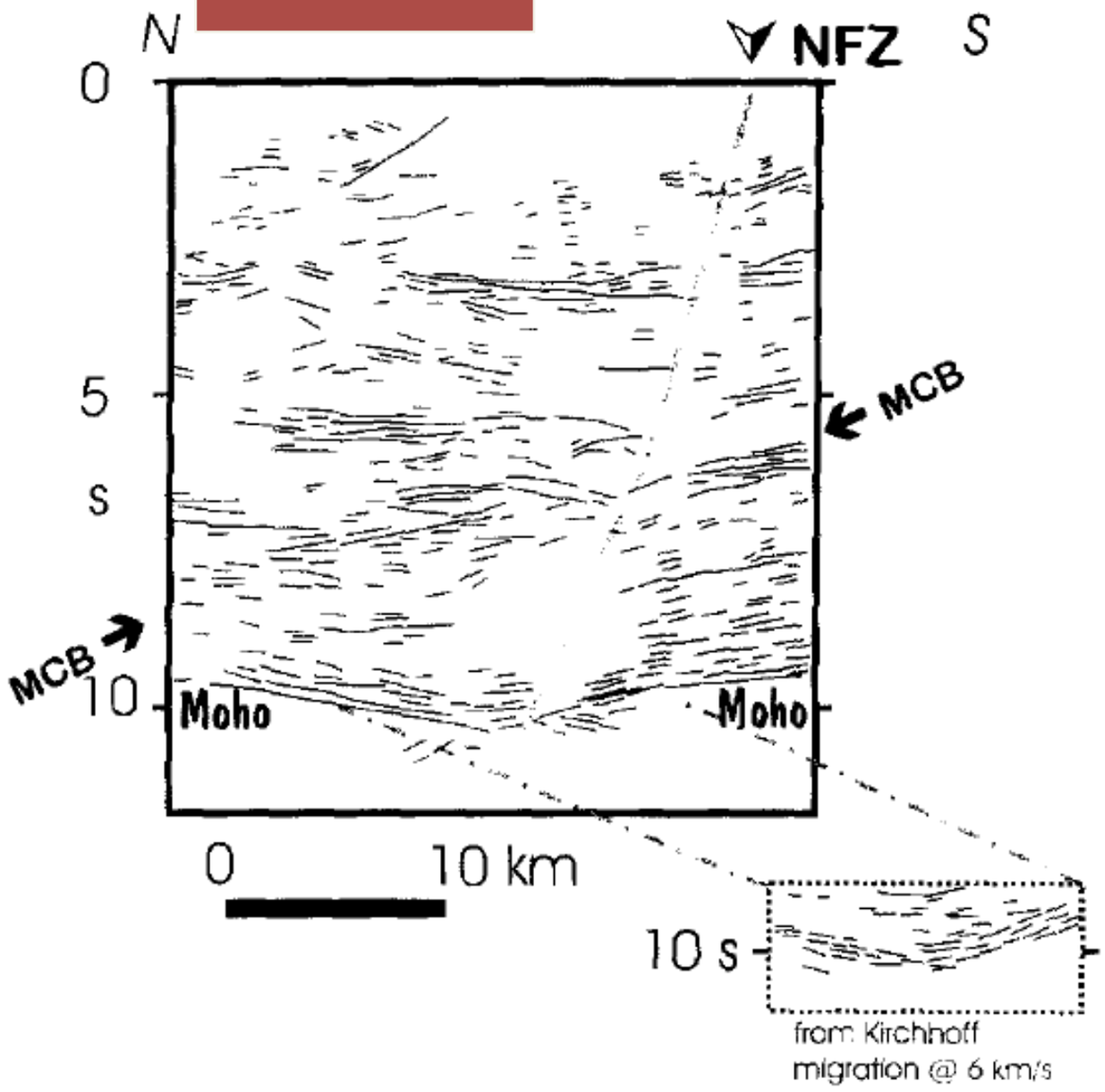


S



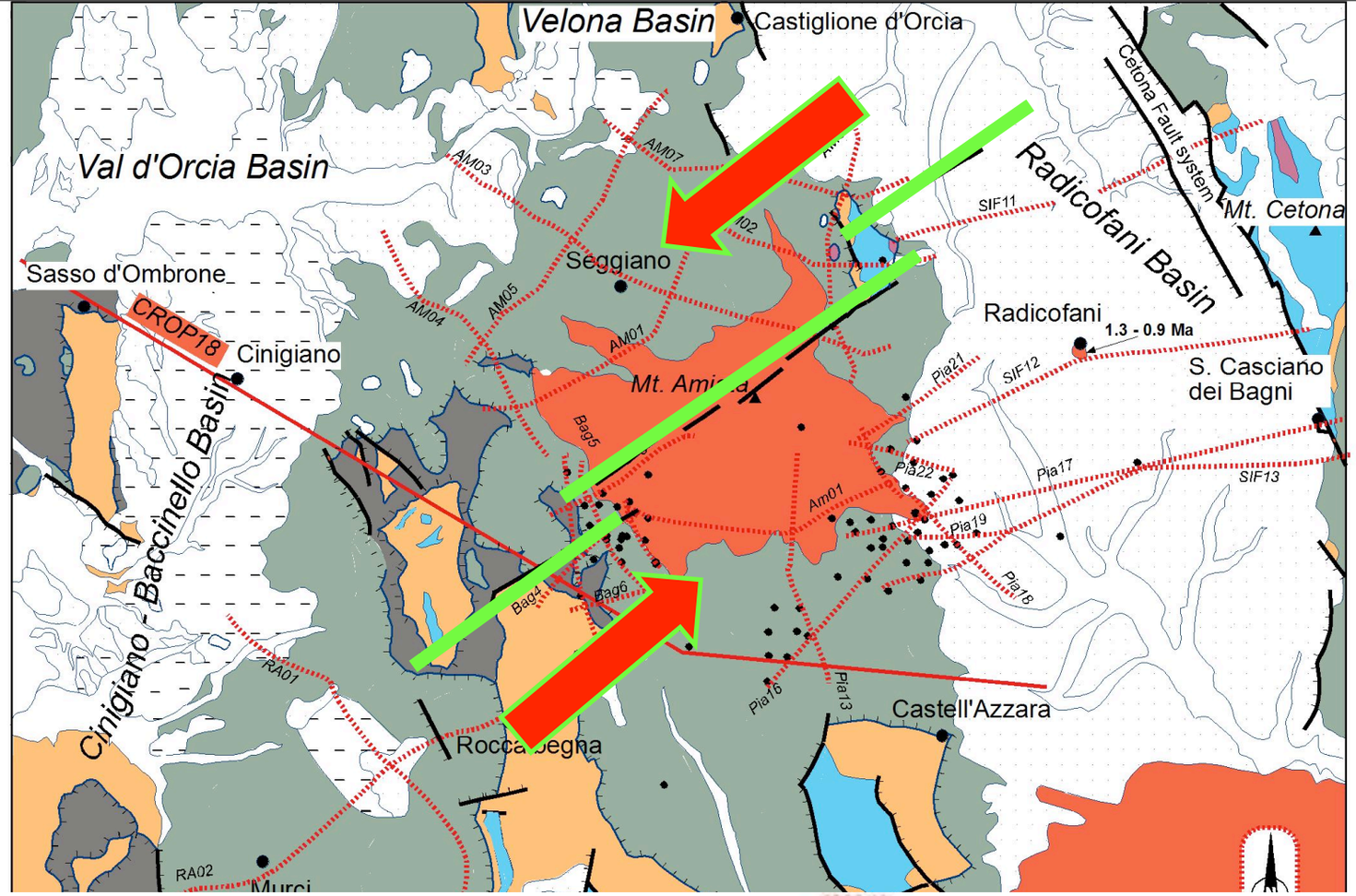
Doll et al., 1996 - Geology

Nuova Zelanda

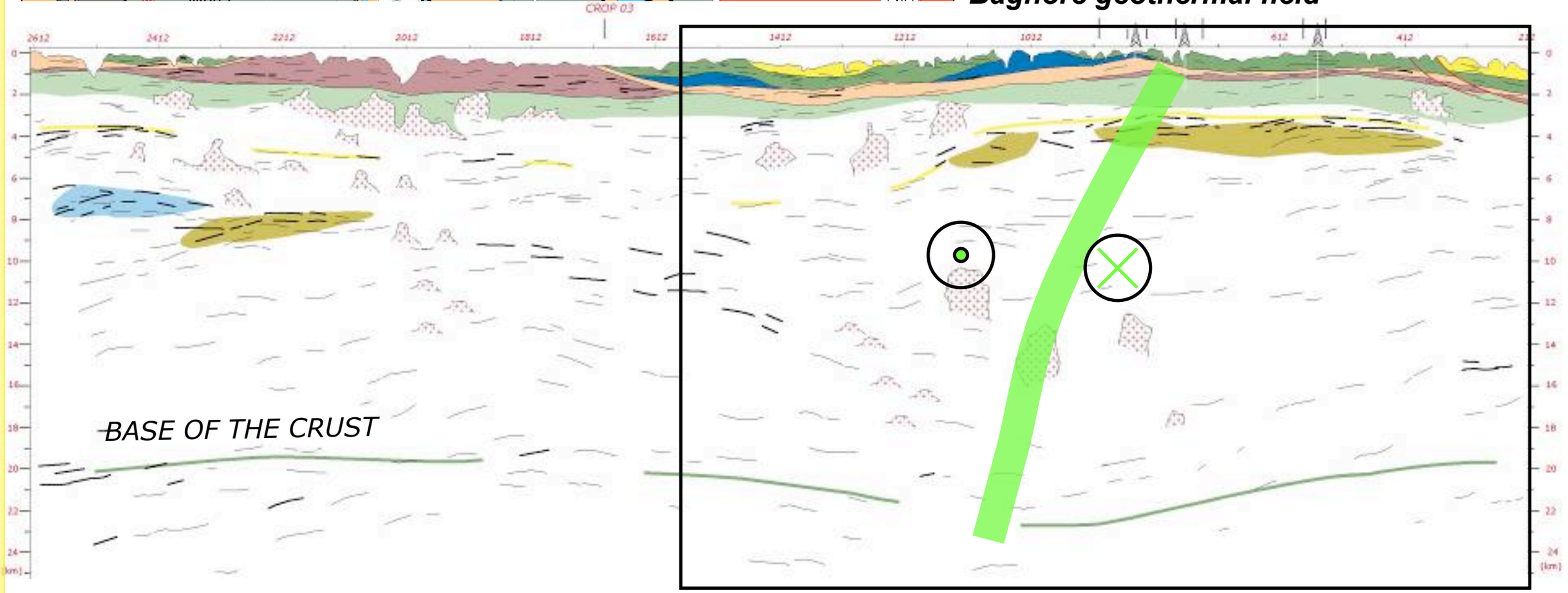


Stern and McBride et al., 1998 - Tectonophysics

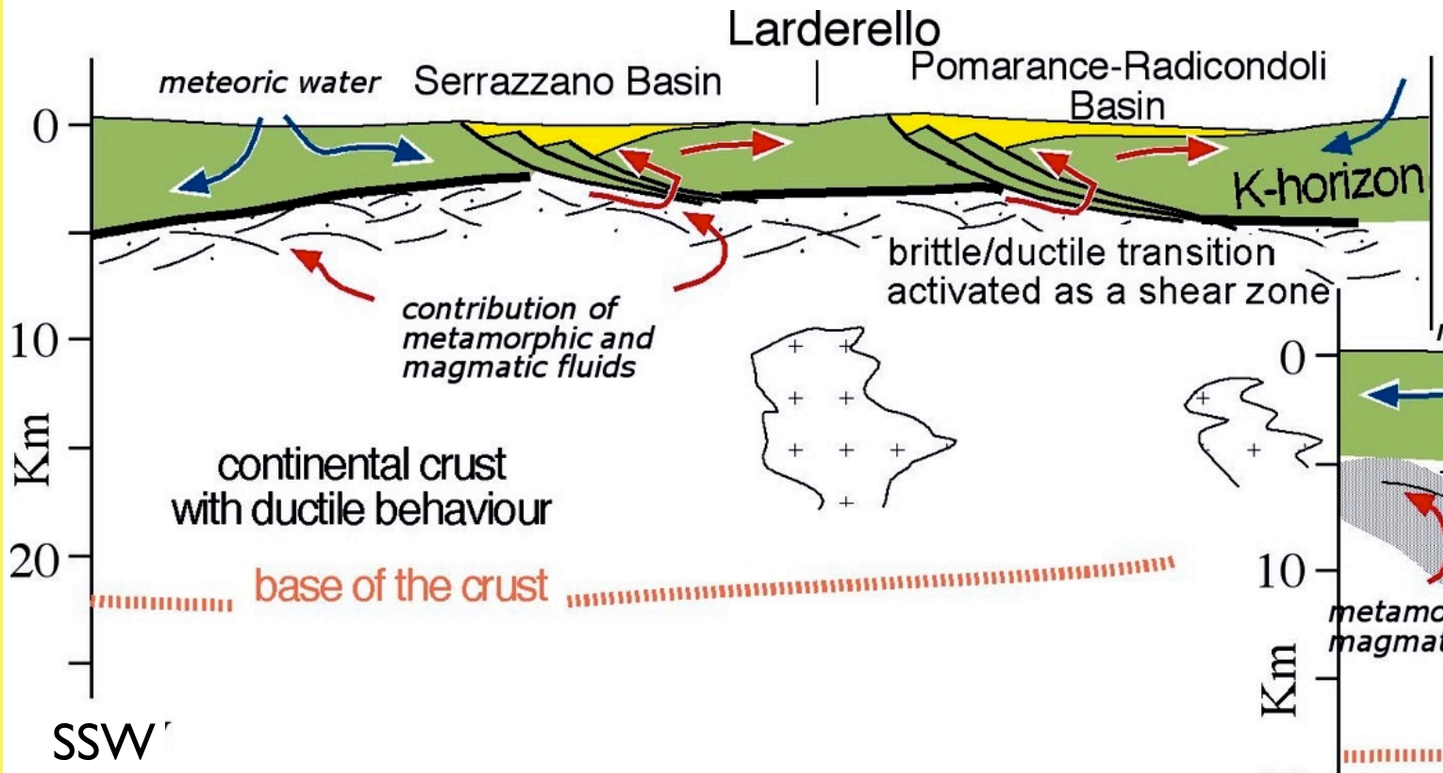
Typical feature of crustal strike-slip tectonic environments

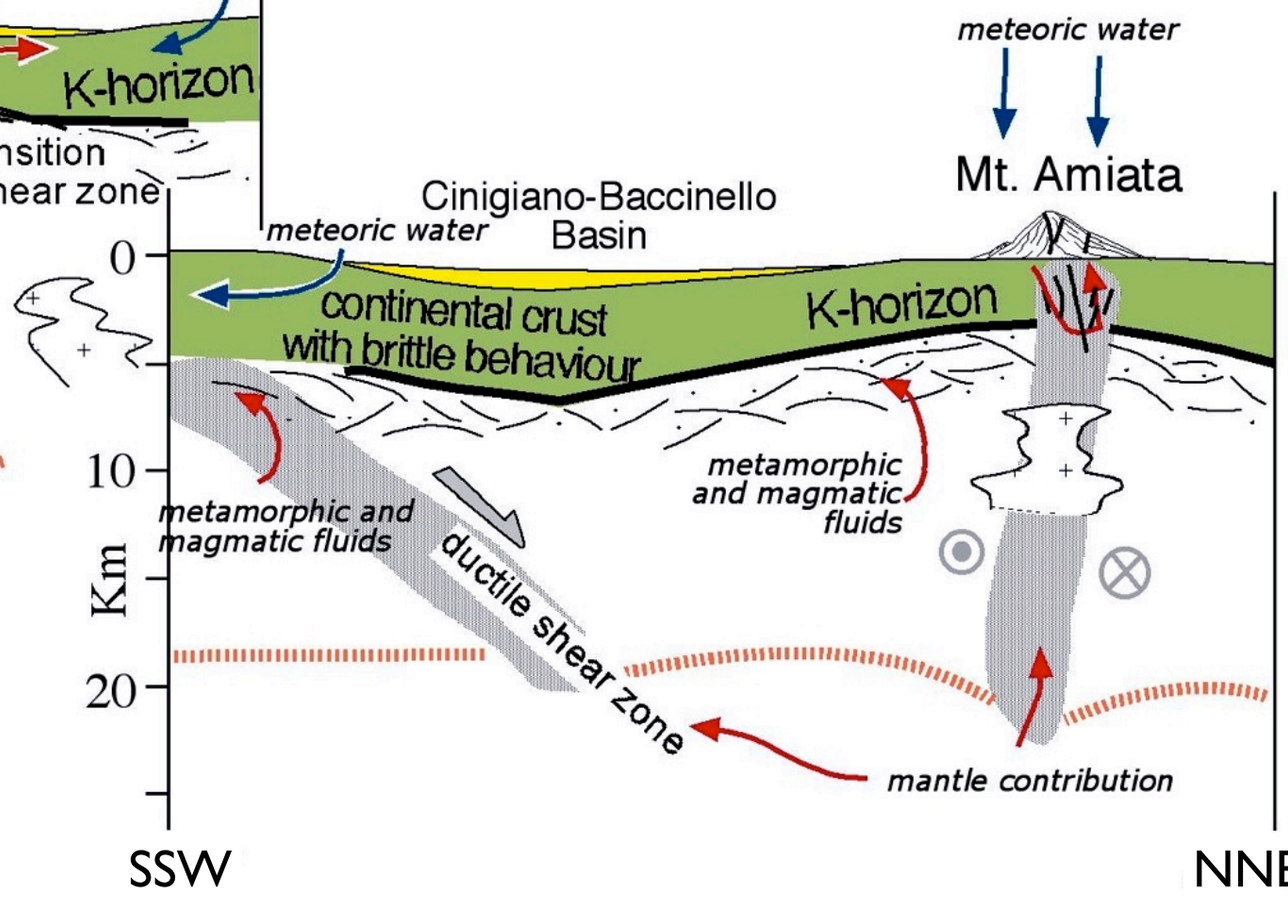


Bagnore geothermal field



CONCLUSIONS





studying the Past to understand the Present

normal and transtensive faults are the most favourable to channel fluids flow

multidisciplinary approach

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