



TS3.1- Faults and fractures in rocks : mechanics, occurrence, dating, stress history and fluid flow

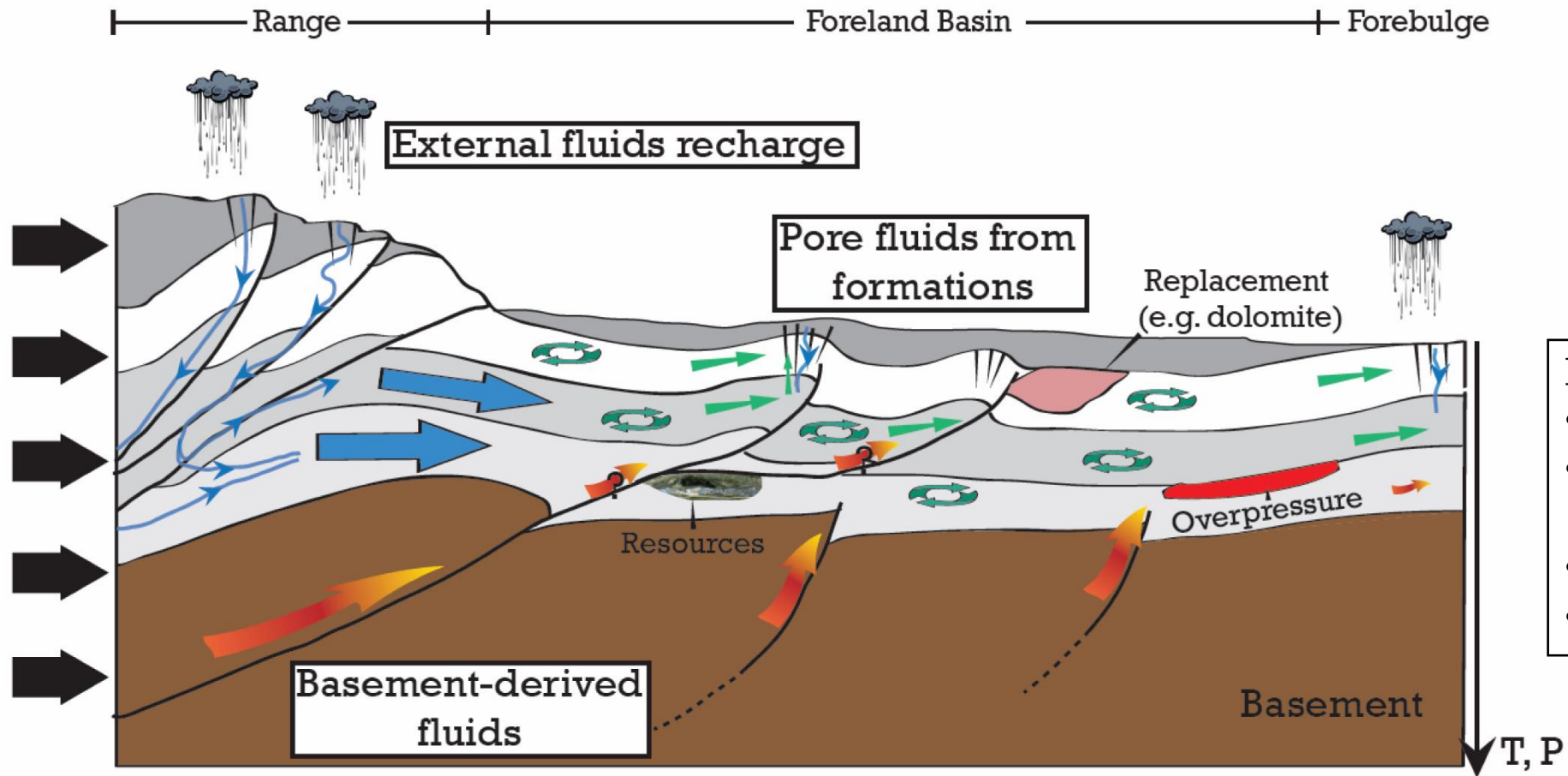
Regional-scale paleofluid system across the Tuscan Nappe – Umbria-Marche Apennine Ridge

Insights from mesostructural and isotopic analyses of stylolite-vein networks



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Introduction – Large-scale fluid flow in contractional context



Fluid system definition:

- Type of fluids?
- Timing and scale for fluid flow?
- Migration pathways?
- Reservoir connectivity?

Permeability of the upper crust / **Fluid rock interaction** / **Georesource** / **Long term elementary cycling**

Regional fluid flow by the Menu

Material & Methods

Where?

How to?

SRIT?

Burial model

Results

Deformation origin

Deformation timing

Fluid system

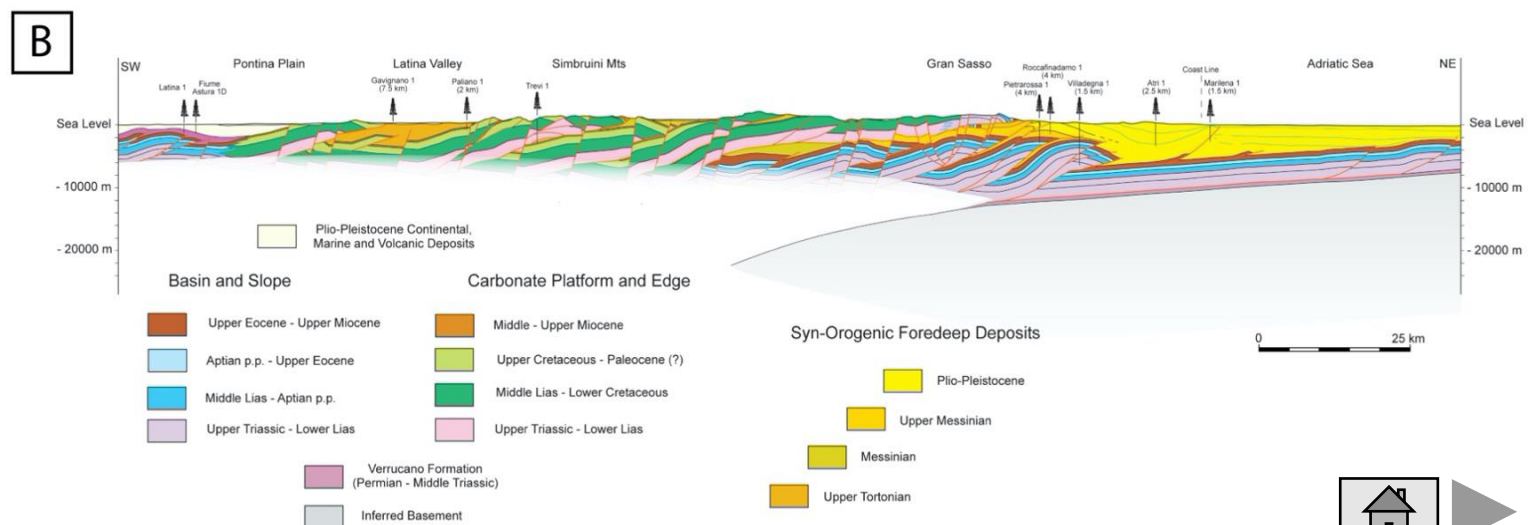
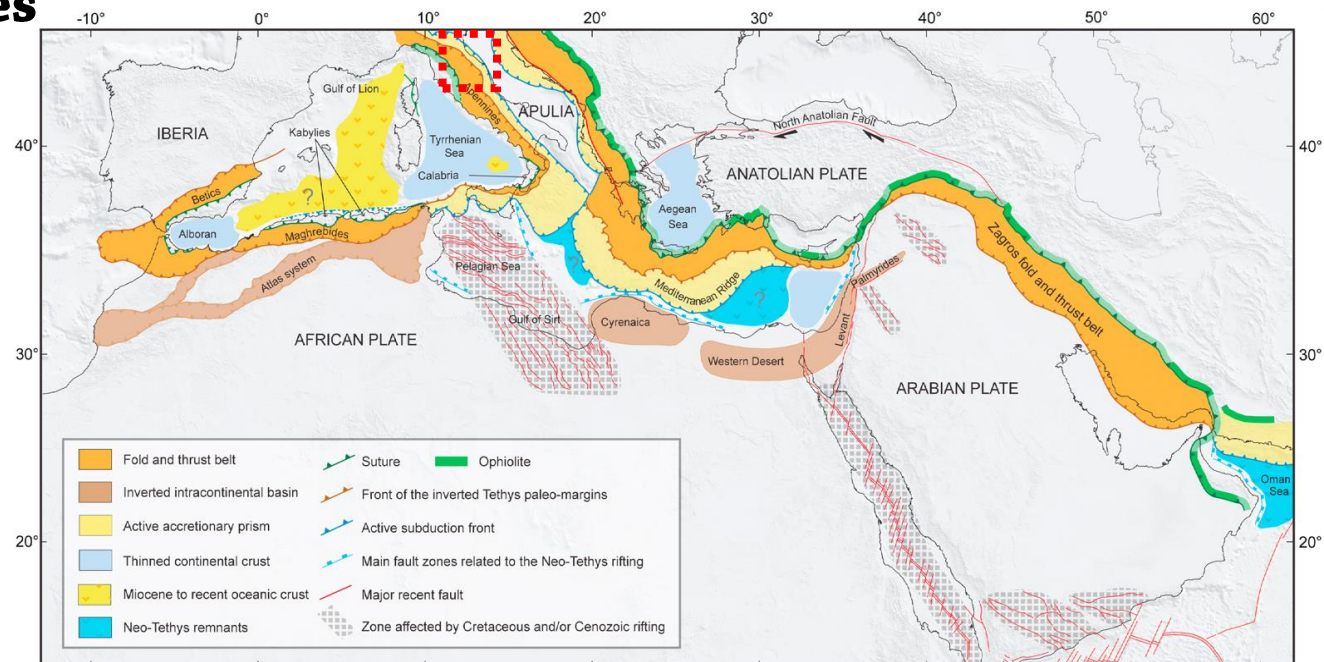
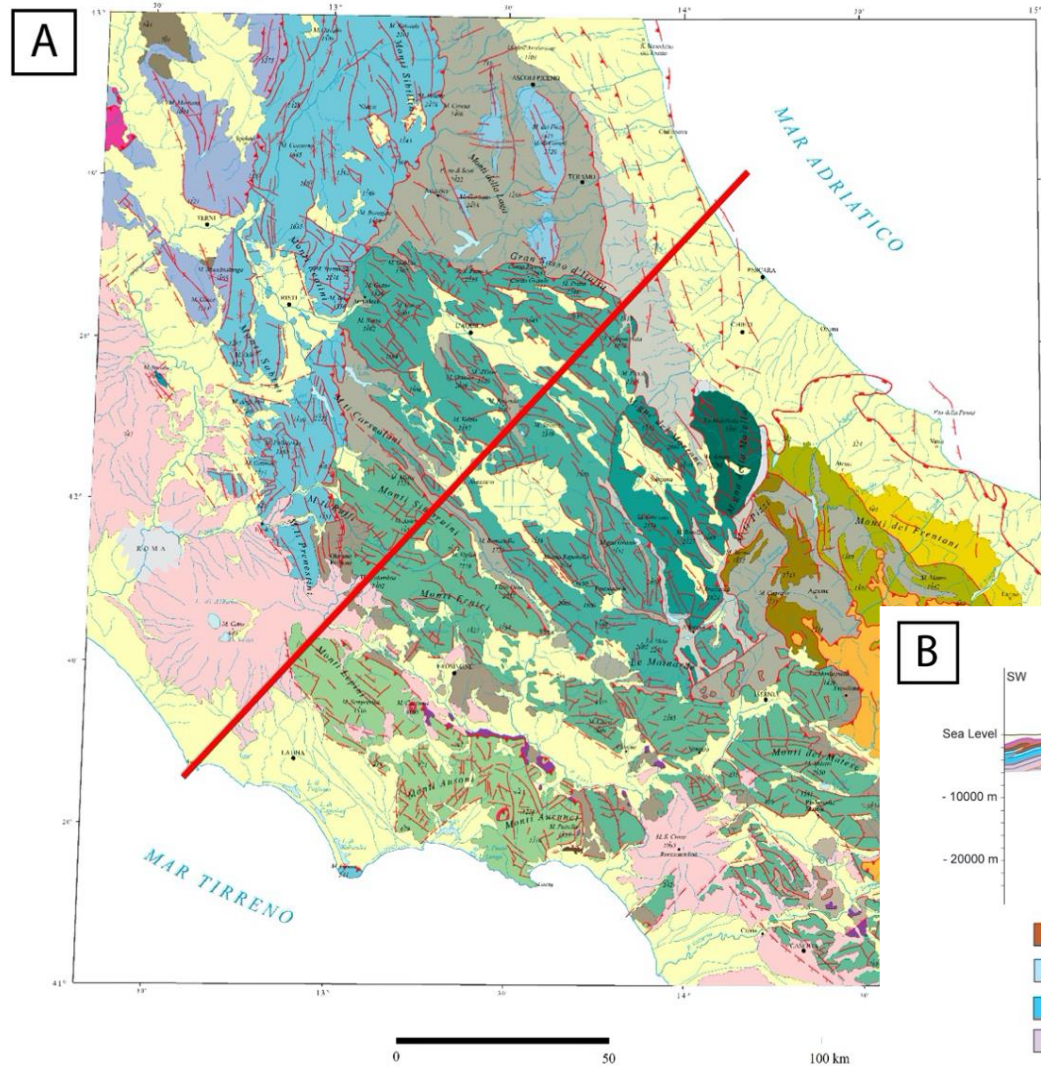
Discussion

Time-depth model of deformation

Large-scale fluid system

Take away remarks

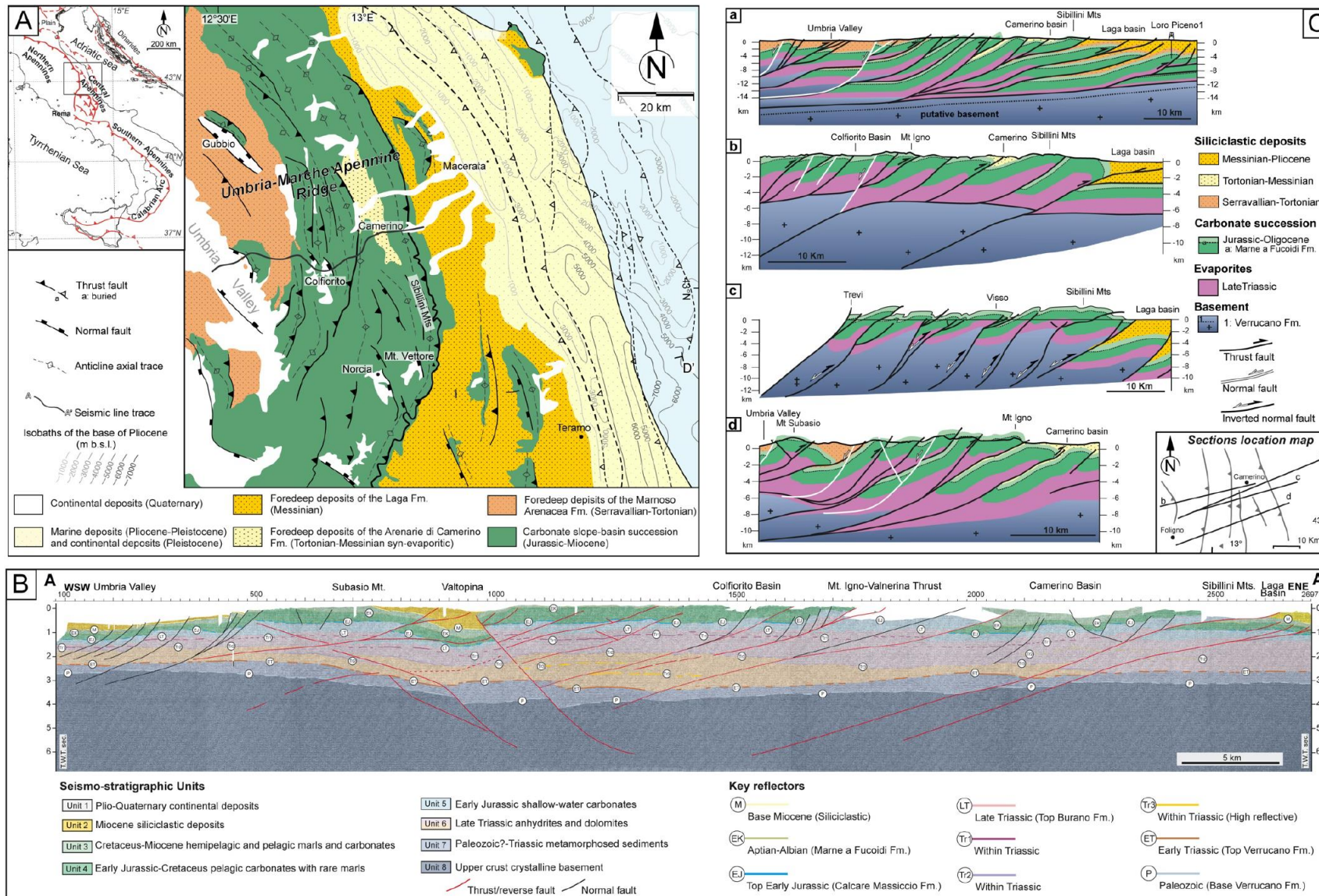
General overview of the central Apennines



Cosentino et al., 2010

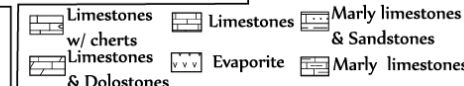
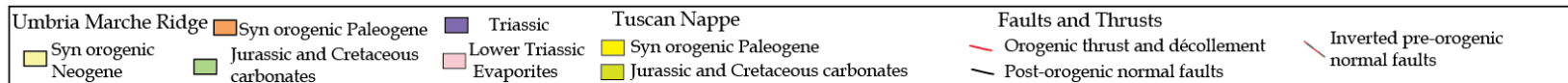
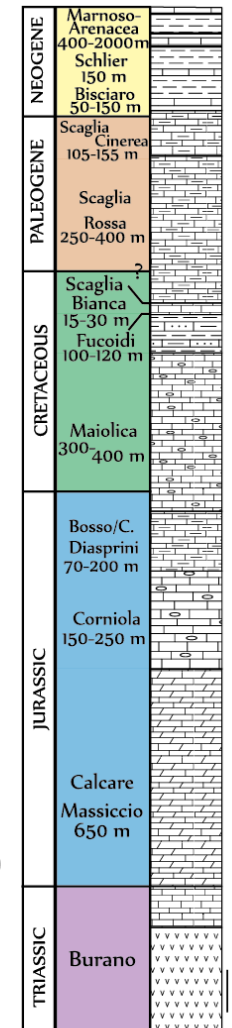
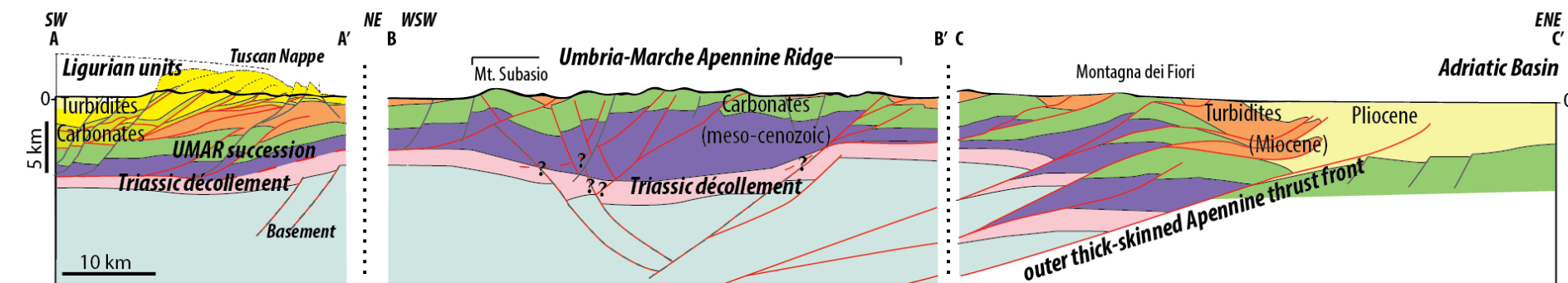
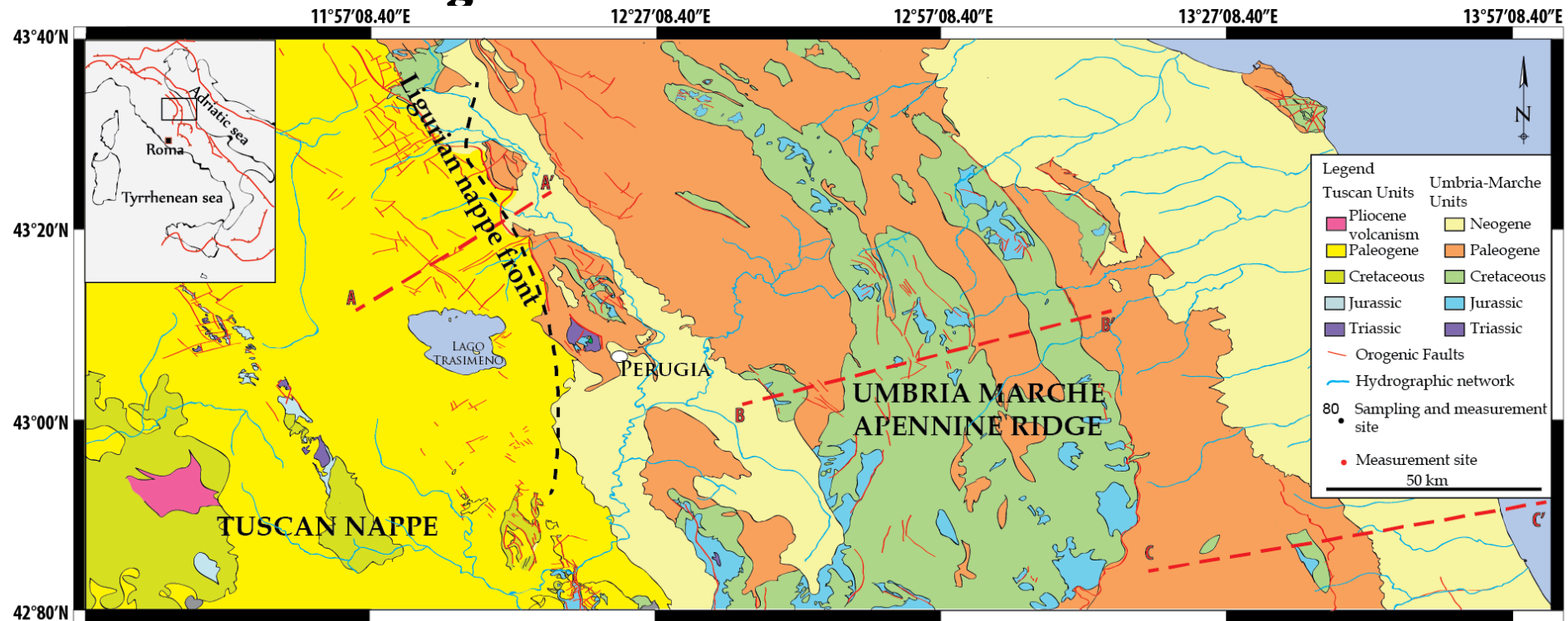


Umbria-Marche Ridge – structural style ?



Scisciani et al., 2014

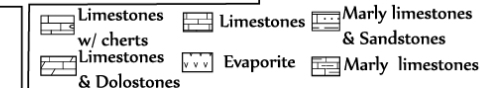
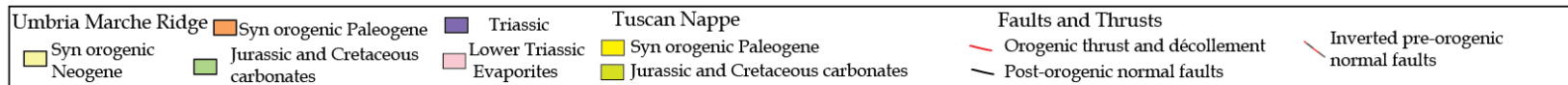
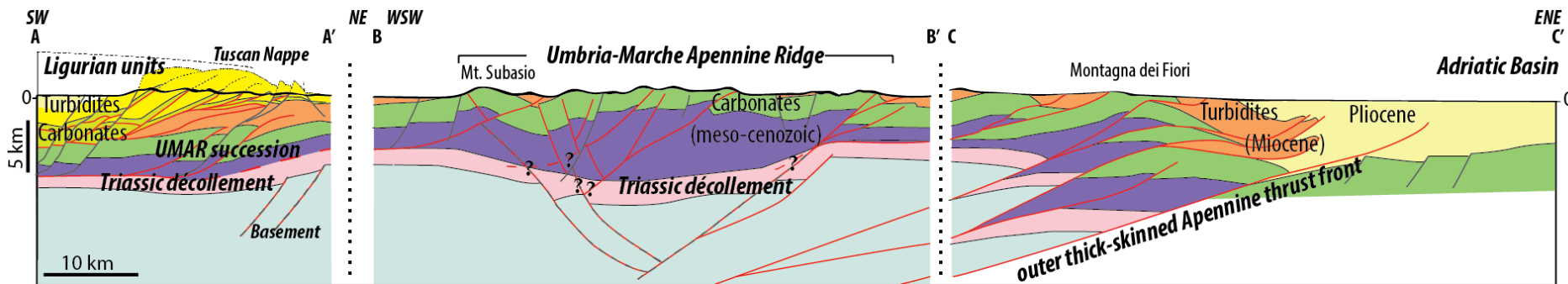
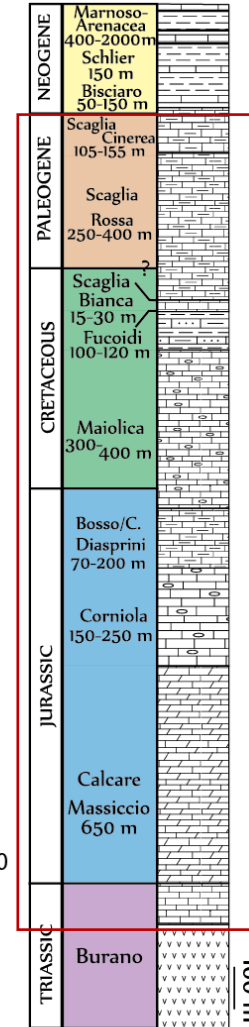
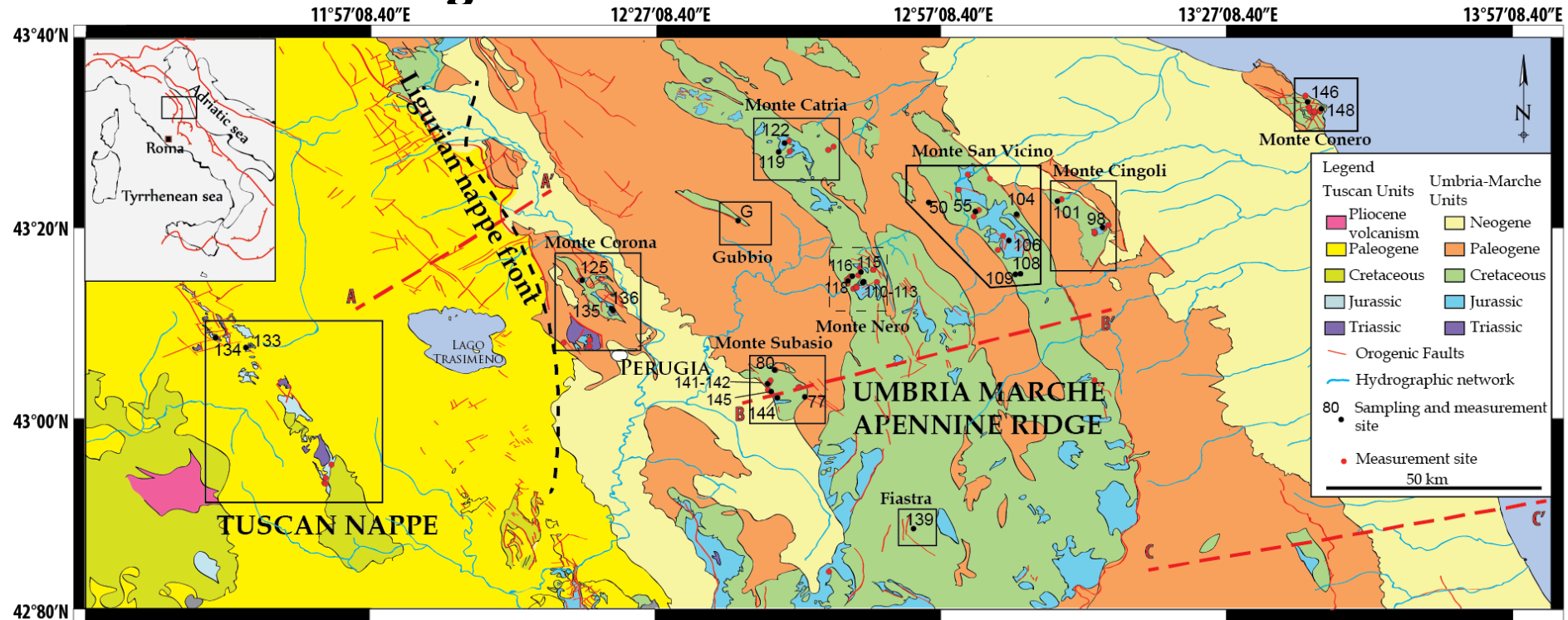
Umbria-Marche Ridge – a classic thrust-and-fold belt



Beaudoin et al., 2020



Umbria-Marche Ridge :



Beaudoin et al., 2020



Deciphering fluid flow from mesostructures



Veins, stylolites, mesoscale faults:

- Access to the deformation history through definition of sets
- Can predate, be related to, postdate large-scale deformation
- Access to past pressures (stress)

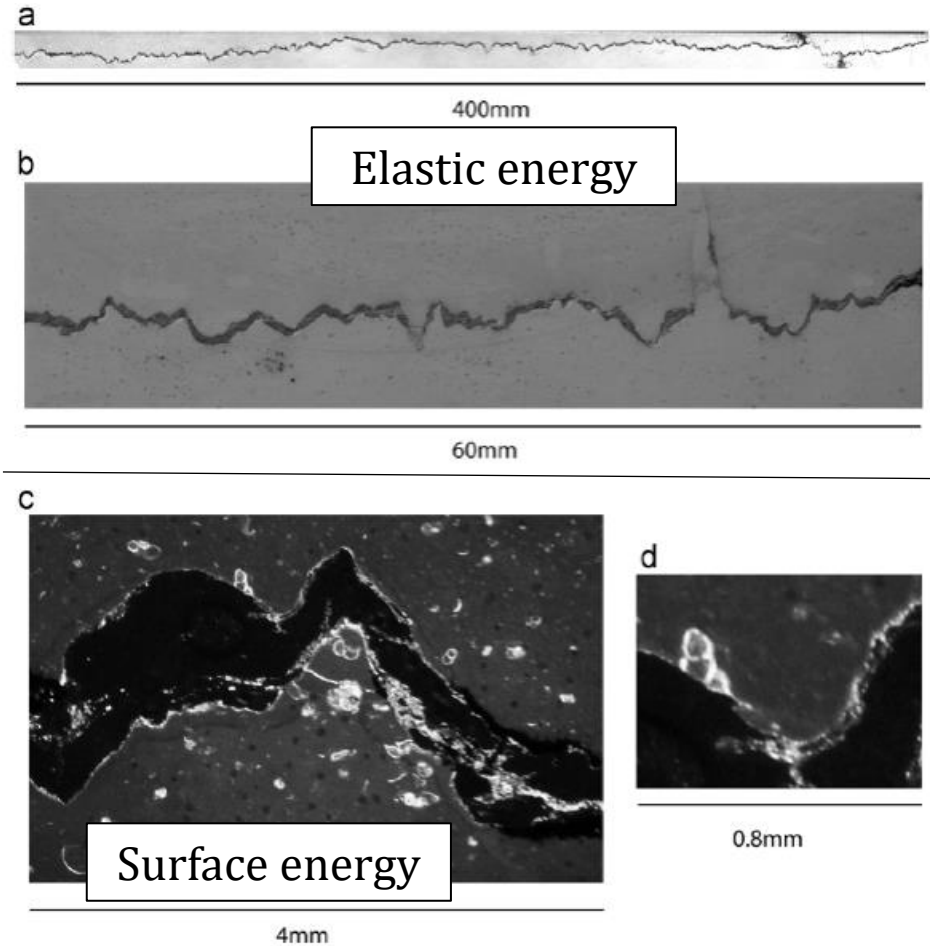
Carbonate filling:

- Access to fluid chemistry and temperature (*isotopes O, C, CO₂, trace elements, fluid inclusions*)
- Access to absolute age of precipitation (*U-Pb*)
- Access to fluid origin (*Sr isotopes*)

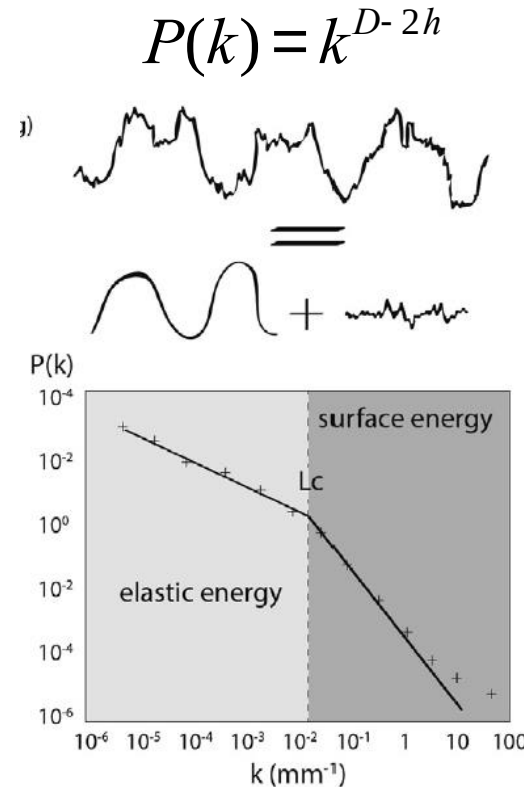


Stylolite Roughness Inversion Technique

Roughness has self affine properties:



Koehn et al., 2012



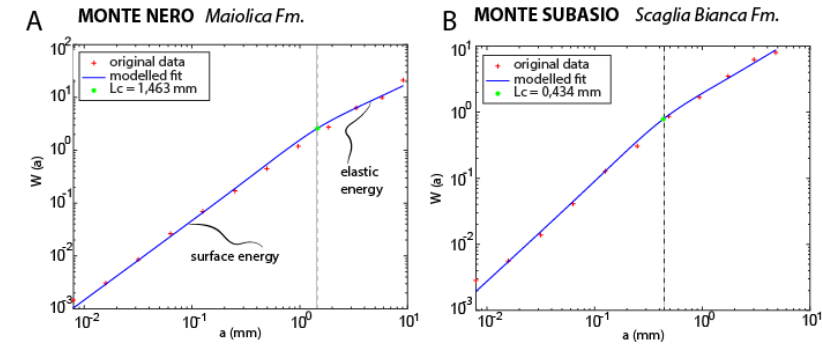
Cross-over length scales with stress

$$L = \frac{gE}{bs_m s_d}$$

E, β : mechanical p.
 γ chemical p.

Schmittbuhl et al., 2004

Some regional examples:



Some published studies with bedding parallel stylolites:

1. original method

2. first application

3. natural laboratory of Bures

4. Paris basin

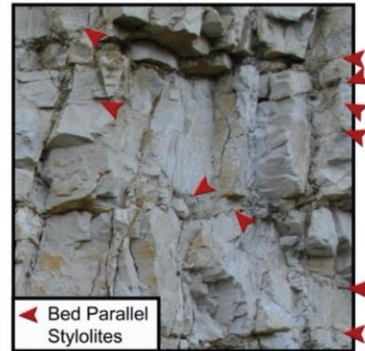
5. Bighorn basin



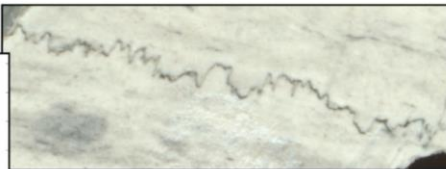
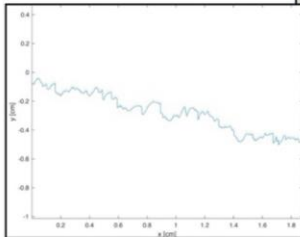
Depth-time model construction in the western part of the UM

Chemical compaction estimate

STEP 1 : measurement of the number of stylolites per metre : **N**



STEP 2 : computer treatment



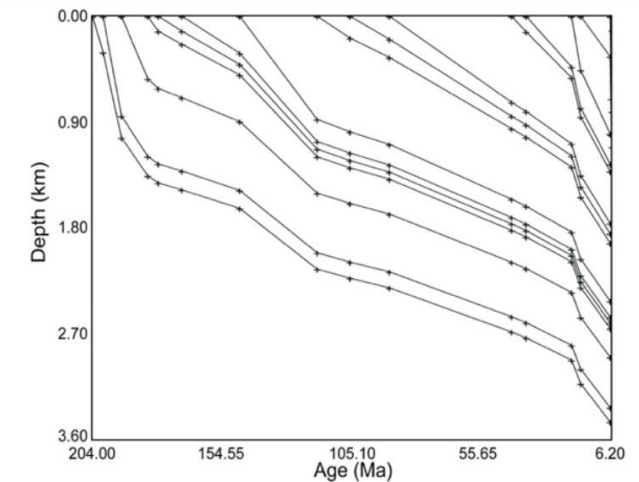
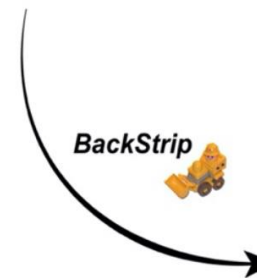
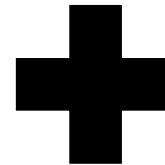
Compaction
Search for the maximum amplitude value for each samples ; then calculation of the average : **Amax**

STEP 3 : calculation of chemical compaction

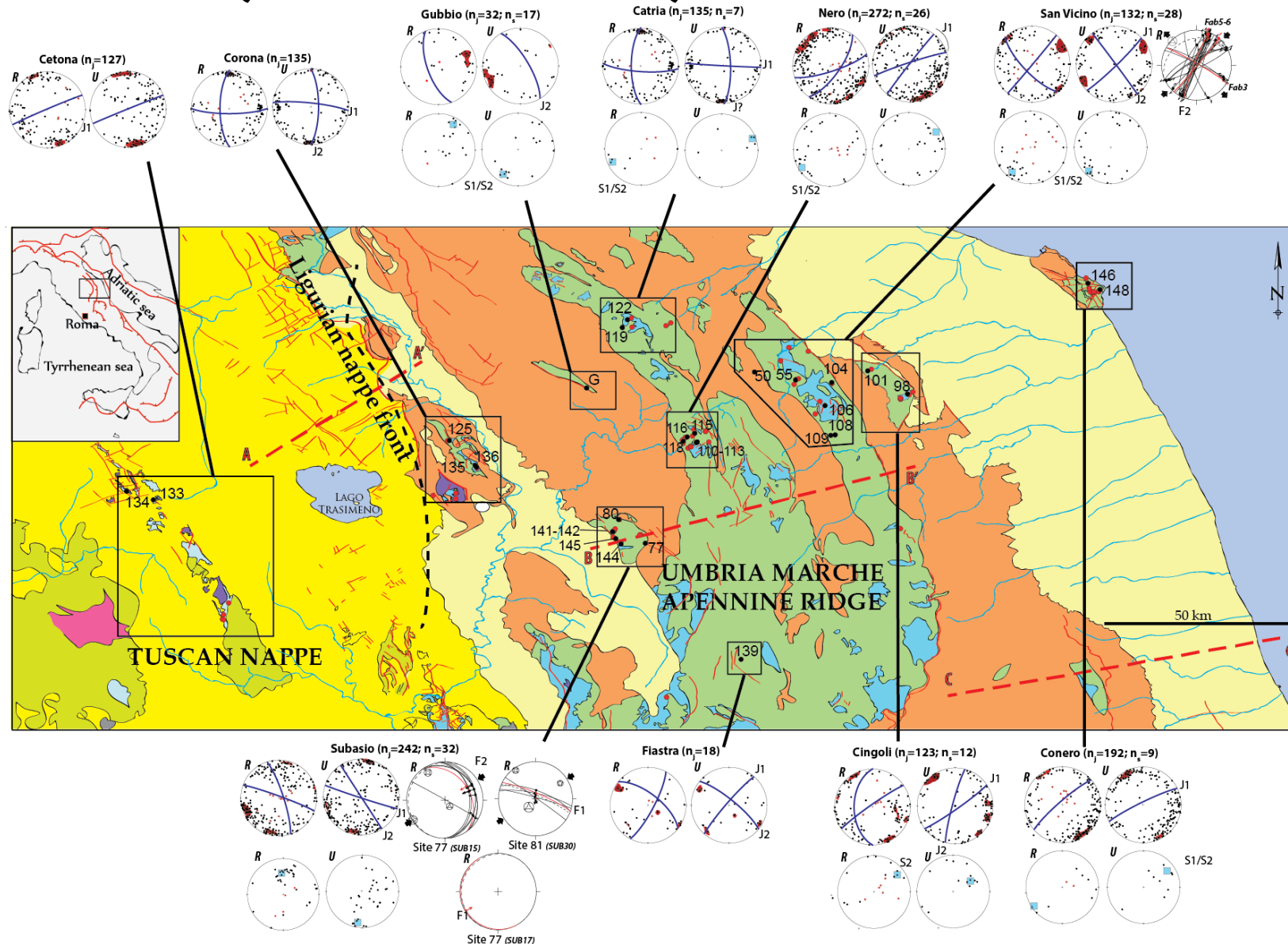
$$\text{Chemical compaction} = N \times A_{\text{max}}$$

Physical compaction estimate

Name	Base	Ageb	SLb	WDb	Top	Agec	SLt	WDt	pc	c	Φo	type
Rhaetavivula conto	3.988	204.0	0.000	0.000	3.854	200.0	0.000	0.000	2.7	0.580	70.0%	0
Massiccio	3.854	200.0	0.000	0.000	3.385	193.0	0.000	0.000	2.7	0.580	70.0%	0
Corniola	3.385	193.0	0.000	0.000	3.117	183.0	0.000	0.000	2.7	0.580	70.0%	0
Rosso Ammonitico	3.117	183.0	0.000	0.000	3.063	179.0	0.000	0.000	2.7	0.580	70.0%	0
Calcare a Posidoni	3.063	179.0	0.000	0.000	3.009	170.0	0.000	0.000	2.7	0.580	70.0%	0
Calcare Diasprini	3.009	170.0	0.000	0.000	2.862	148.0	0.000	0.000	2.7	0.580	70.0%	0
Maiolica	2.862	148.0	0.000	0.000	2.326	118.5	0.000	0.000	2.7	0.580	70.0%	0
Fucoidi	2.326	118.5	0.000	0.000	2.239	106.0	0.000	0.000	2.7	0.580	70.0%	0
Scaglia Bianca	2.239	106.0	0.000	0.000	2.145	91.0	0.000	0.000	2.7	0.580	70.0%	0
Scaglia Rossa	2.145	91.0	0.000	0.000	1.676	44.5	0.000	0.000	2.7	0.580	70.0%	0
Scaglia Variegata	1.676	44.5	0.000	0.000	1.609	39.0	0.000	0.000	2.7	0.580	70.0%	0
Scaglia Cinera	1.609	39.0	0.000	0.000	1.341	21.7	0.000	0.000	2.7	0.580	70.0%	0
Schlier-Biscario	1.341	21.7	0.000	0.000	0.898	7.0	0.000	0.000	1.9	0.300	40.0%	0
Della Laga	0.898	7.0	0.000	0.000	0.134	6.6	0.000	0.000	1.9	0.300	40.0%	0
Gessoso-Solfifera	0.134	6.6	0.000	0.000	0.000	6.2	0.000	0.000	1.9	0.300	40.0%	0
END	0.000	6.2	0.000	0.000	0.000	0.0	0.000	0.000	0.0	0.000	0.0%	0



Fracture-stylolite network analysis



1st order pattern:

- Mode 1 fractures are either perpendicular to the fold axis (J1) or parallel to the fold axis (J2) with respect to the curvature
- Stylolites are mainly showing NE-SW contraction (S1 prefolding, S2 postfolding)
- Striated fault inversion return pre folding (F1) and post folding (F2) NE-SW contraction

3 events of deformation:

1. Prefolding LPS (J1 + S1+F1)
2. Folding (J2)
3. Postfolding LSFT (S2+F2)

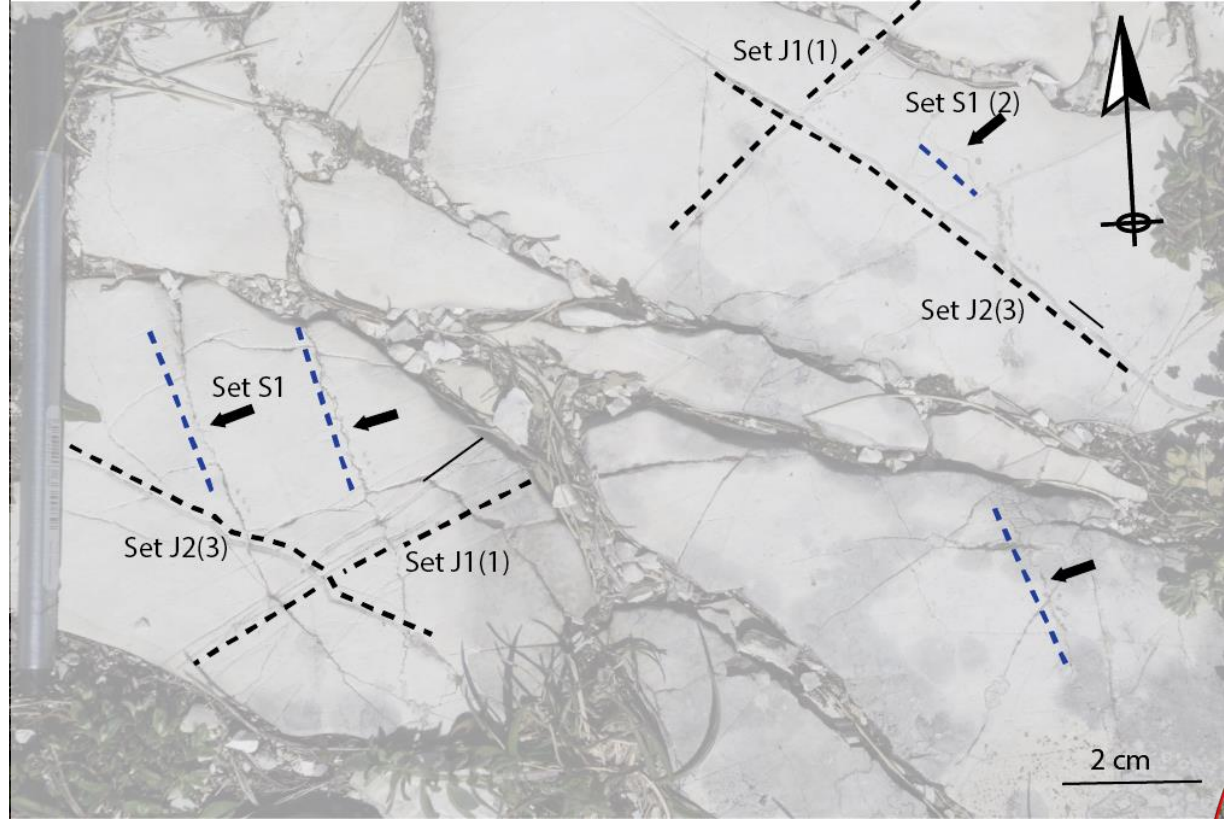


Umbria-Marche Ridge – Fracture-stylolite network

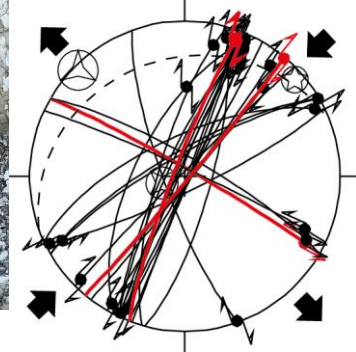
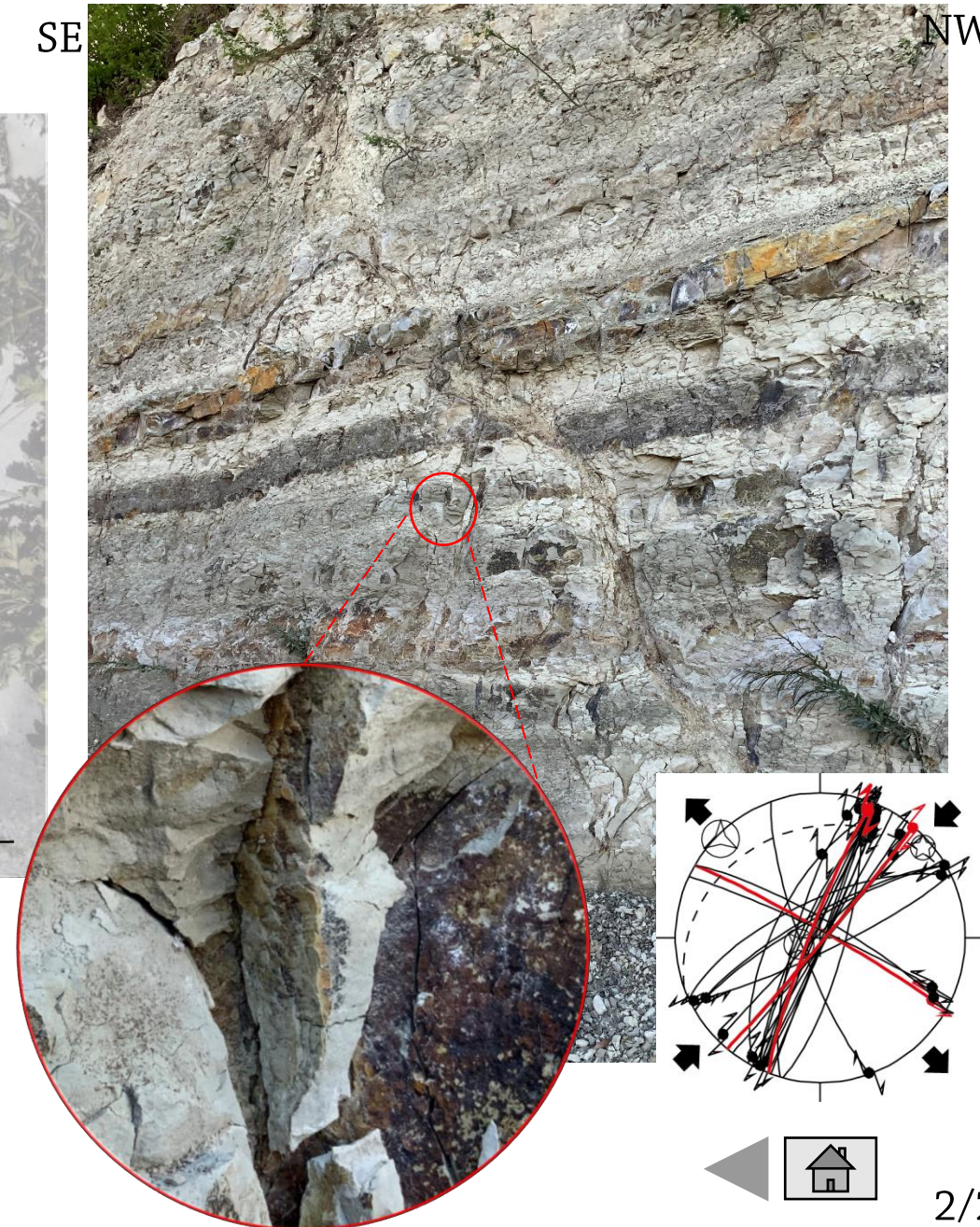
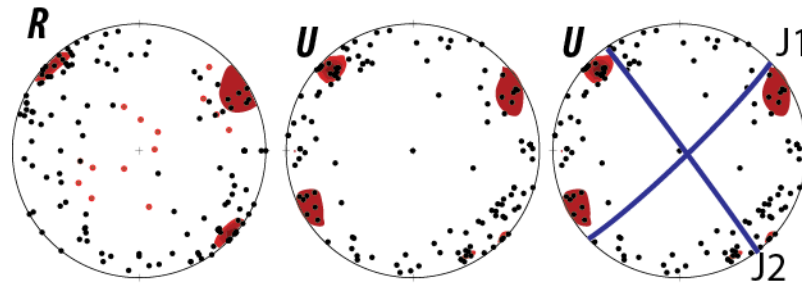
SE

NW

NEOGENE	Marnoso-Arenacea (400-2000 m)
	Schlier (150 m) Bisciaro (50-150 m)
PALEOGENE	Scaglia Cinera (105-155 m)
	Scaglia Rossa (250-400 m)
	Scaglia Bianca (15-30 m) Fucoidi (100-120 m)
CRETACEOUS	Maliolica (300-400 m)
	Bosso/C. Diasprini (70-200 m)
JURASSIC	Corniola (150-250 m)
	Calcare Massiccio (650 m)
TRIASSIC	Contorta
	Burano

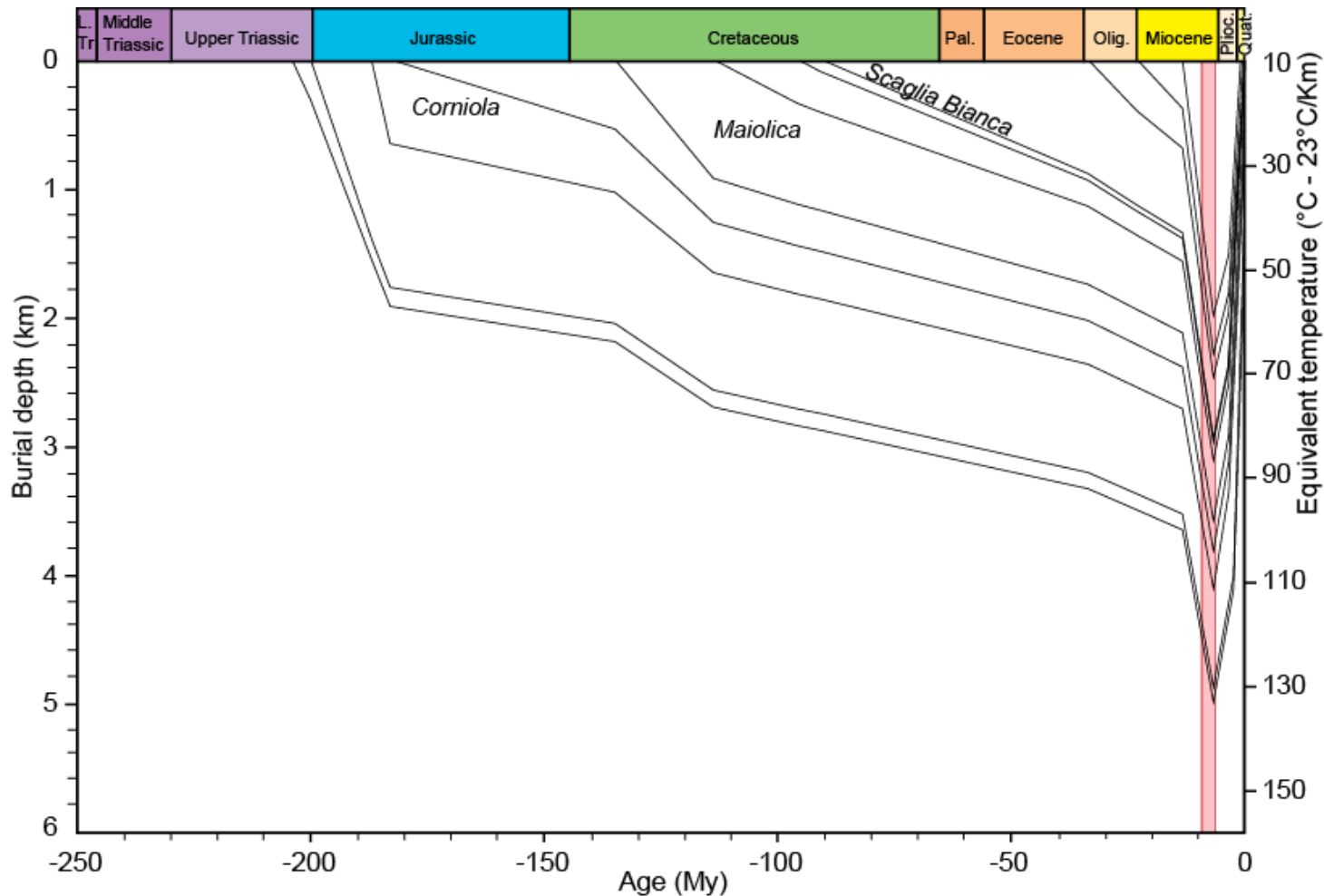


	Limestone & Marls alternation w/ turbidites
	Marly limestones & Sandstones
	Marly limestones
	Limestones w/ cherts
	Limestones & Dolostones
	Limestones
	Evaporite



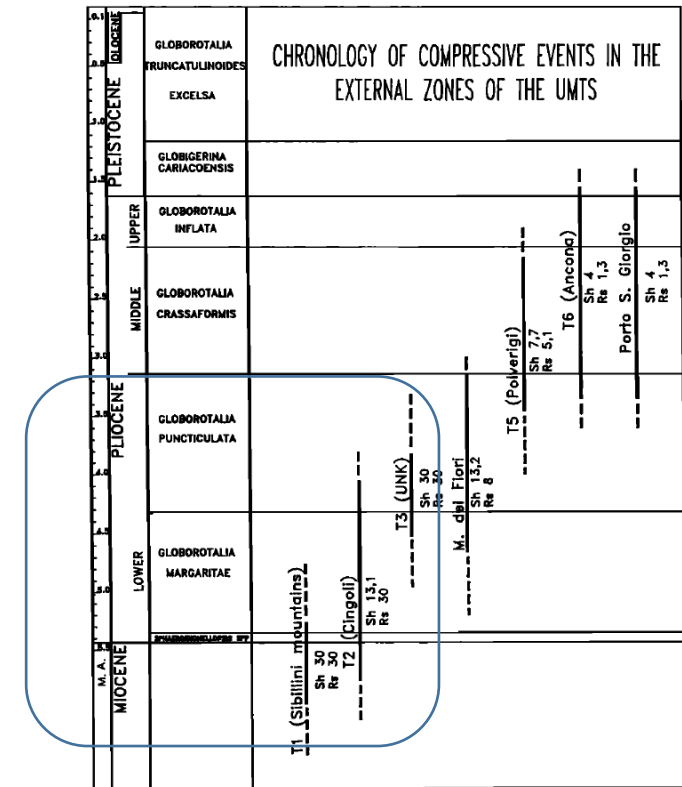
2/2

Depth-time model construction in the western part of the UM



How to constrain the timing of deformation?

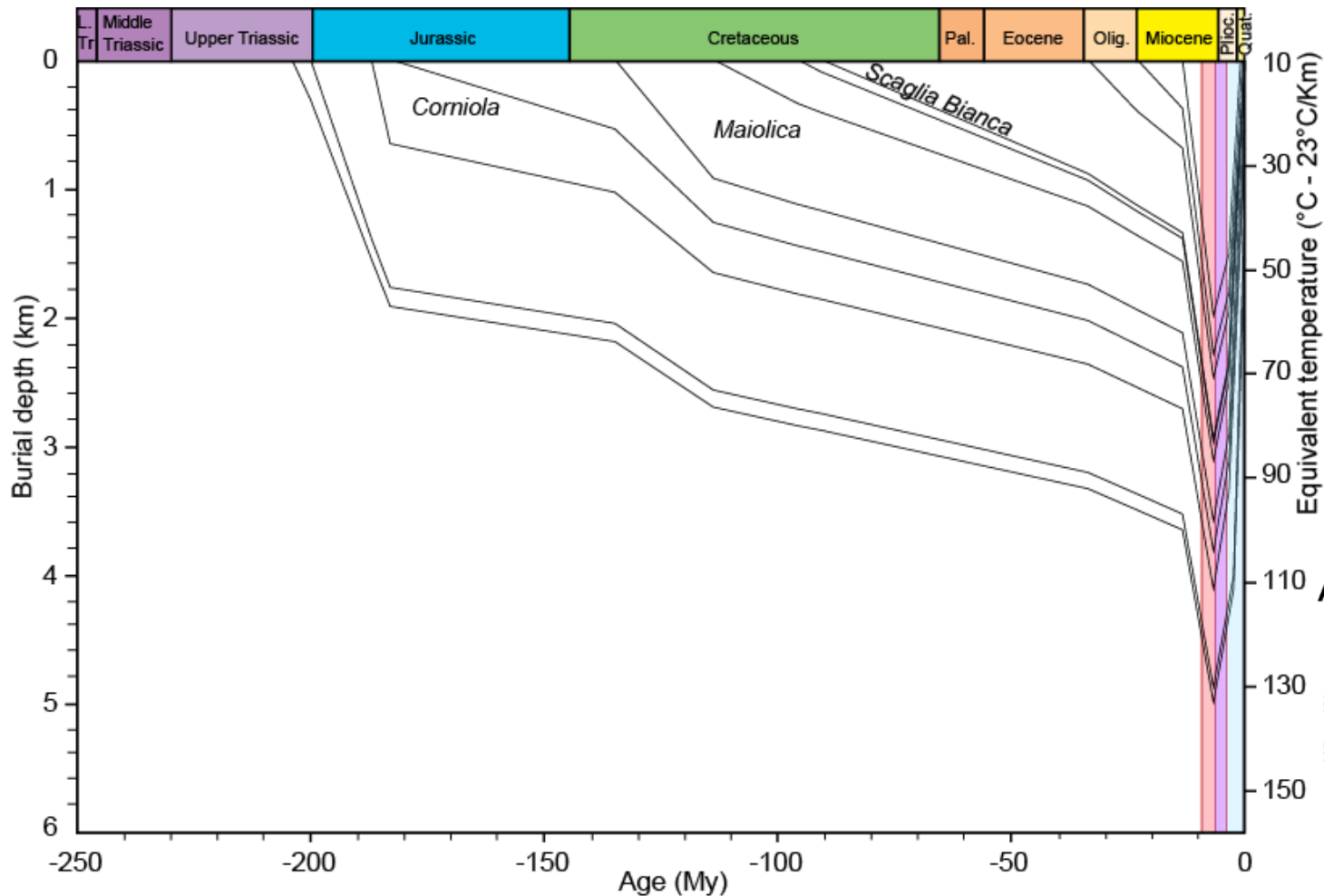
1. Syn folding strata / foredeep sediments
Tortonian – Messinian



Calamita et al., 1994



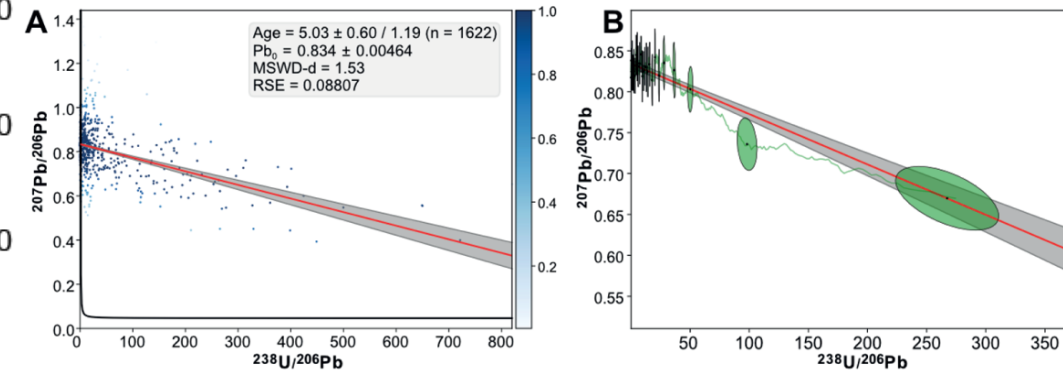
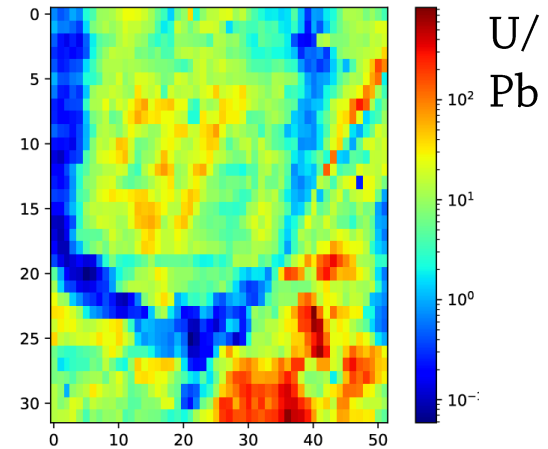
Depth-time model construction in the western part of the UM



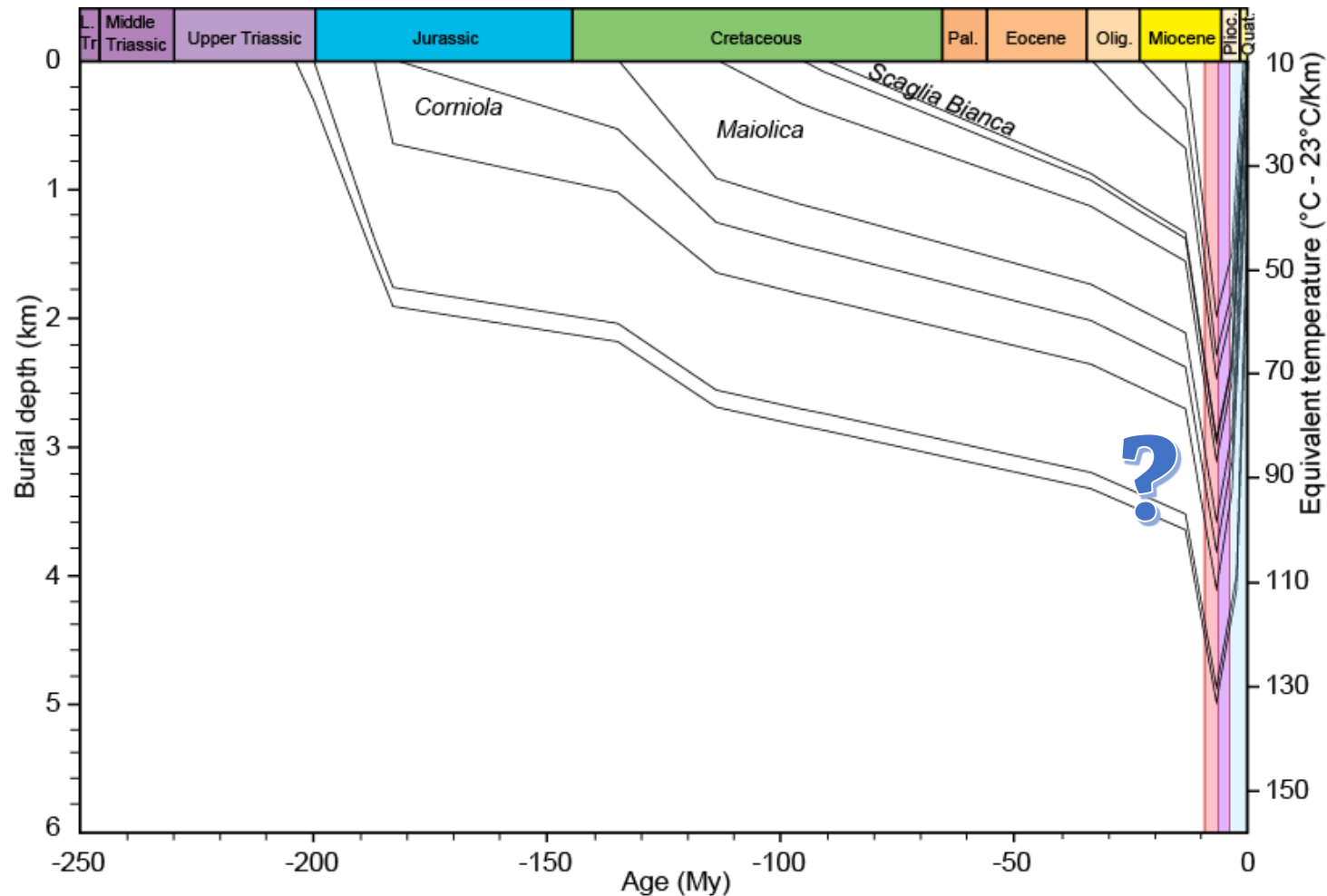
+ current extension started ~ 3,5 Ma in the western part

How to constrain the timing of deformation?

2. U-Pb absolute age of post folding faults

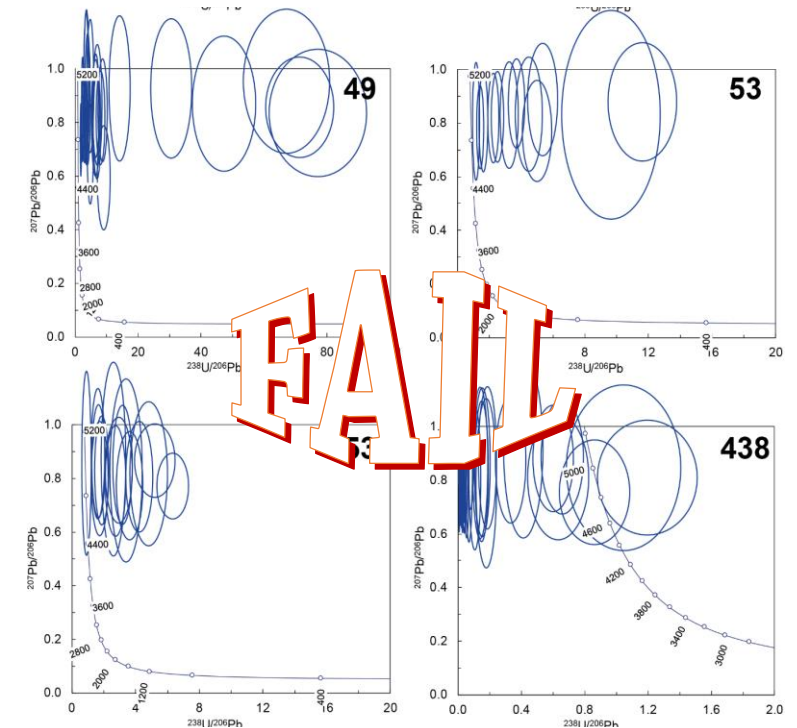


Depth-time model construction in the western part of the UM

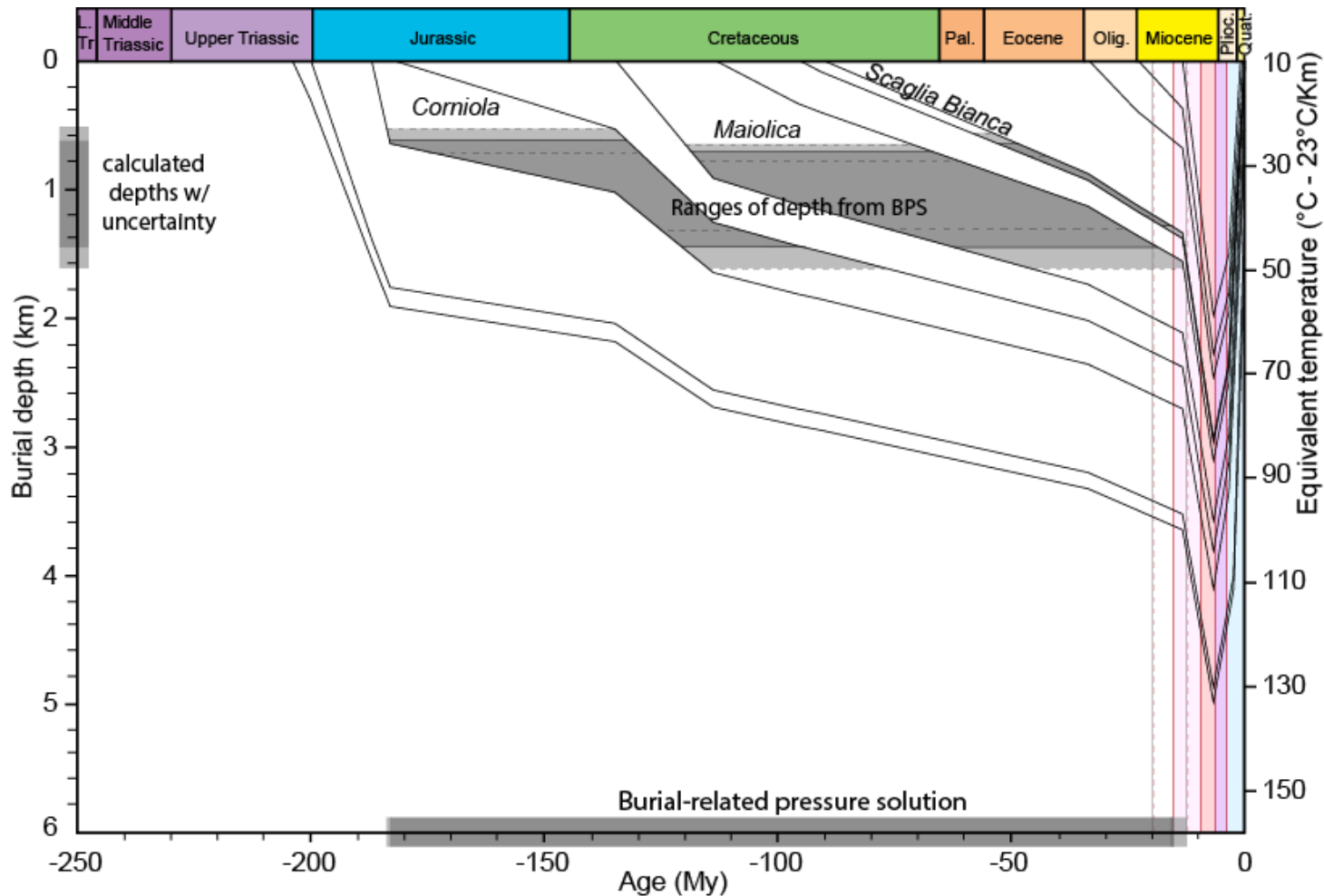


How to constrain the timing of deformation?

3. U-Pb absolute age of vein filling



Depth-time model construction in the western part of the UM



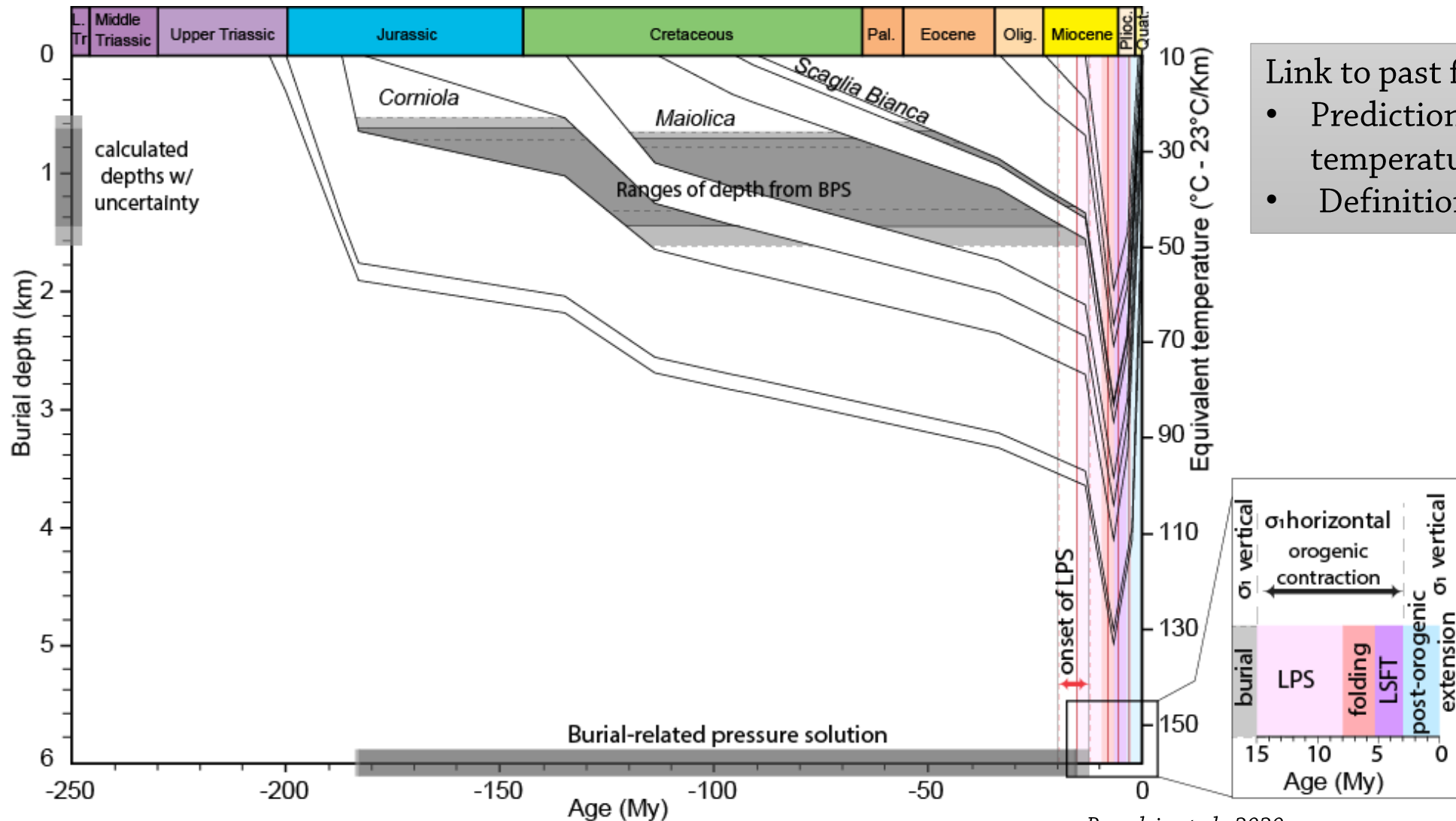
How to constrain the timing of deformation?

4. Use of bedding parallel stylolite to constrain the LPS

Sample	GPS	Structure	Formation	Dissolution (mm)	Lc (mm)*	E (GPa)	ν	γ	σ_v (Pa)	depth (m)
A165	165	Subasio	Scaglia Bianca	2,7	1,059	23,2	0,25	0,32	21811000	926
	165	Subasio	Scaglia Bianca	2,0	1,306	23,2	0,25	0,32	19640000	834
	165	Subasio	Scaglia Bianca	0,6	0,46	23,2	0,25	0,32	33093000	1406
	165	Subasio	Scaglia Bianca	0,5	0,486	23,2	0,25	0,32	32196000	1368
	165	Subasio	Scaglia Bianca	1,3	0,434	23,2	0,25	0,32	34070000	1447
	165	Subasio	Scaglia Bianca	3,1	0,971	23,2	0,25	0,32	22778000	967
	165	Subasio	Scaglia Bianca	1,3	1,488	23,2	0,25	0,32	18400000	782
AN26	110	Nero	Maiolica	3,1	1,073	23,2	0,25	0,32	21668000	920
	110	Nero	Maiolica	2,8	1,535	23,2	0,25	0,32	18116000	769
	110	Nero	Maiolica	1,7	1,463	23,2	0,25	0,32	18557000	788
	110	Nero	Maiolica	2,2	1,071	23,2	0,25	0,32	21688000	921
	110	Nero	Maiolica	3,0	1,29	23,2	0,25	0,32	19762000	839
	110	Nero	Maiolica	2,2	1,073	23,2	0,25	0,32	22661000	962
	110	Nero	Maiolica	1,8	1,596	23,2	0,25	0,32	17767000	755
AN16	110	Nero	Maiolica	6,4	0,659	23,2	0,25	0,32	27649000	1174
	110	Nero	Maiolica	2,7	0,696	23,2	0,25	0,32	26904000	1143
AN16	115	Nero	Maiolica	2,7	1,279	23,2	0,25	0,32	19847000	843
A137	148	Conero	Scaglia Bianca	5,2	2,073	23,2	0,25	0,32	15589000	662
A123-2	130	Gubbio	Corniola	2,1	0,428	23,2	0,25	0,32	34308000	1457
	130	Gubbio	Corniola	1,3	0,791	23,2	0,25	0,32	25237000	1072
A123	130	Gubbio	Corniola	1,8	2,35	23,2	0,25	0,32	14642000	622
	130	Gubbio	Corniola	2,3	1,457	23,2	0,25	0,32	18595000	790
A21	104	San Vincino	Maiolica	2,1	0,906	23,2	0,25	0,32	23581000	1002
	104	San Vincino	Maiolica	3,4	0,787	23,2	0,25	0,32	25414000	1079
A104	138	Spoletto	Scaglia Bianca	8,5	0,655	23,2	0,25	0,32	27733000	1178
	138	Spoletto	Scaglia Bianca	2,8	0,634	23,2	0,25	0,32	28189000	1197
	138	Spoletto	Scaglia Bianca	0,7	0,66	23,2	0,25	0,32	27628000	1174
	138	Spoletto	Scaglia Bianca	0,6	1,22	23,2	0,25	0,32	20321000	863
	138	Spoletto	Scaglia Bianca	3,4	0,749	23,2	0,25	0,32	25935000	1102
	138	Spoletto	Scaglia Bianca	2,5	1,322	23,2	0,25	0,32	19521000	829

*crossover length given within 23% uncertainty. Vertical stress σ_v given within 12% uncertainty using for Young Modulus $E = 23,2$ GPa (Beaudoin et al., 2014), Poisson ratio $\nu = 0,25$ and interfacial energy $\gamma = 0,32$ Jm⁻². Depth calculated using dry density of rock $d = 2400$ g.m⁻³, acceleration of the gravitational field $g = 9,81$ m.s⁻².

Depth-time model construction in the western part of the UM



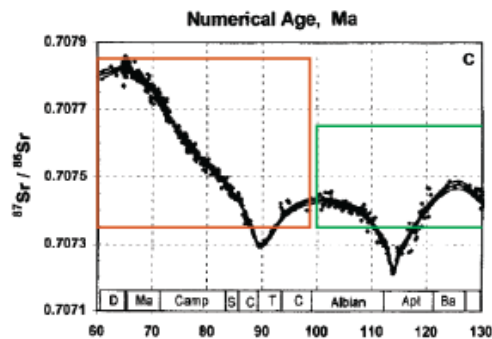
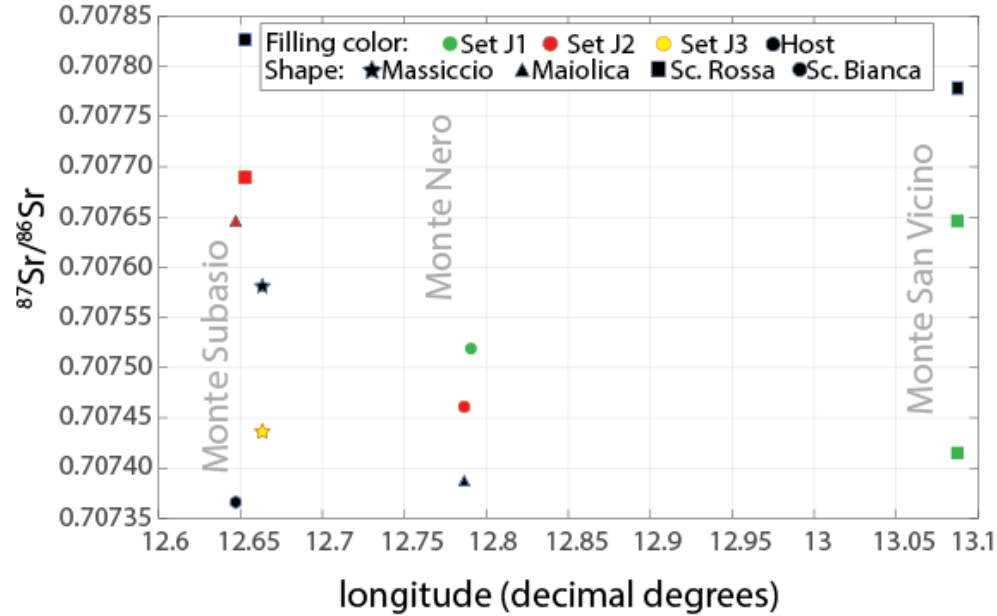
Link to past fluid flow:

- Prediction of expected local temperature during history.
- Definition of **hydrothermal**

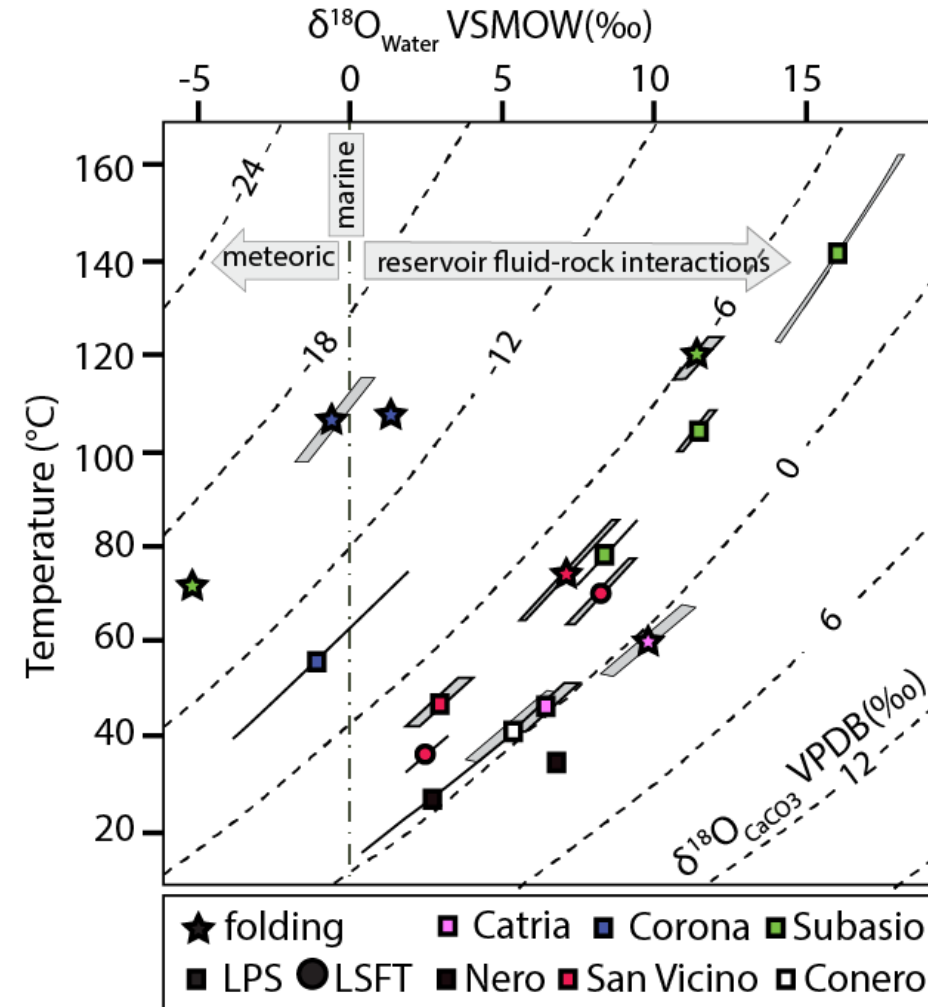
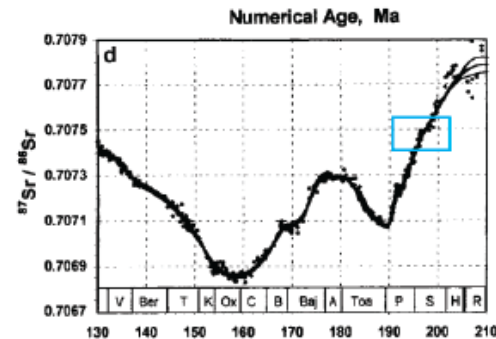
Beaudoin et al., 2020



Past fluid system in the Umbria-Marche



McArthur et al., 2001

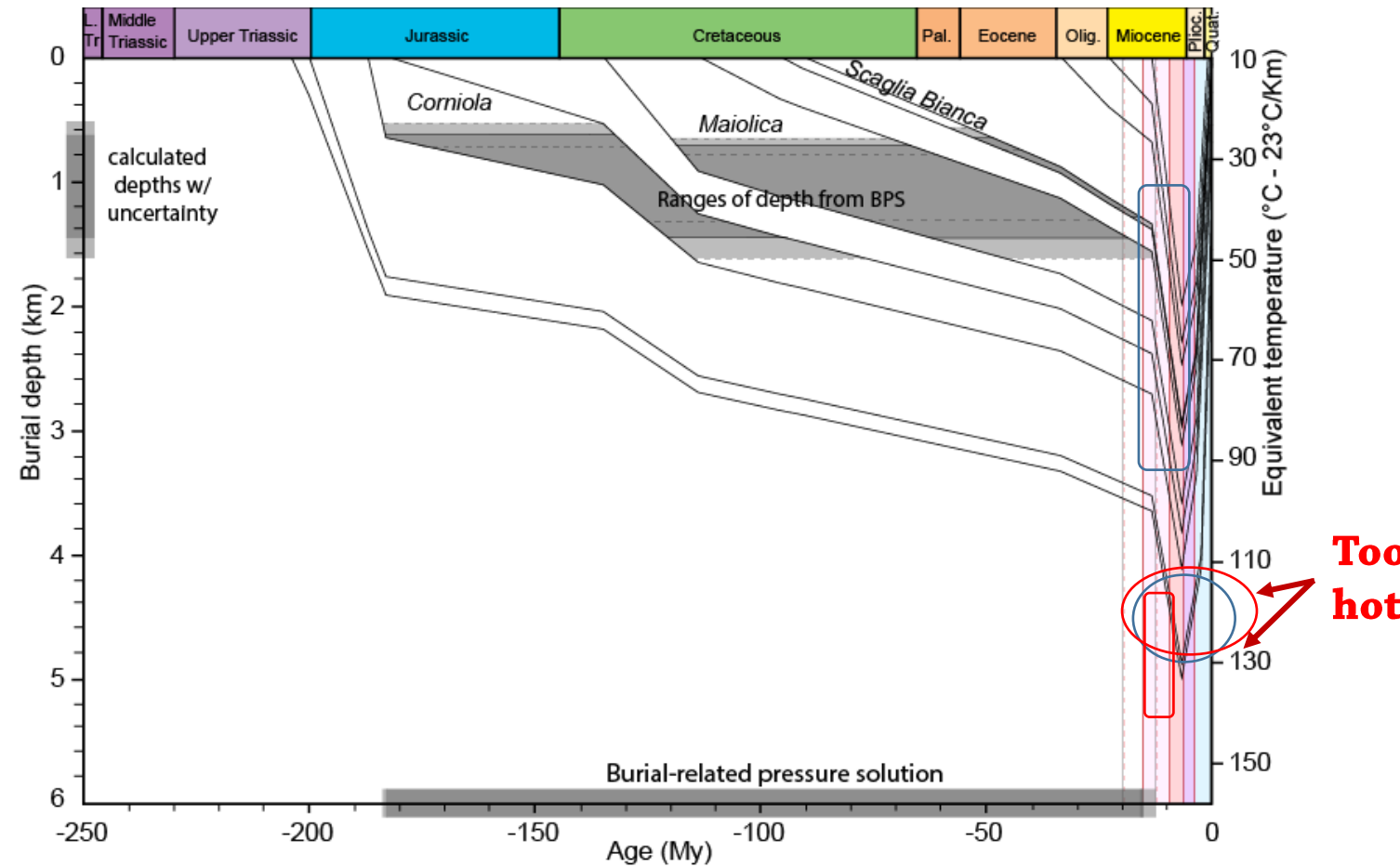
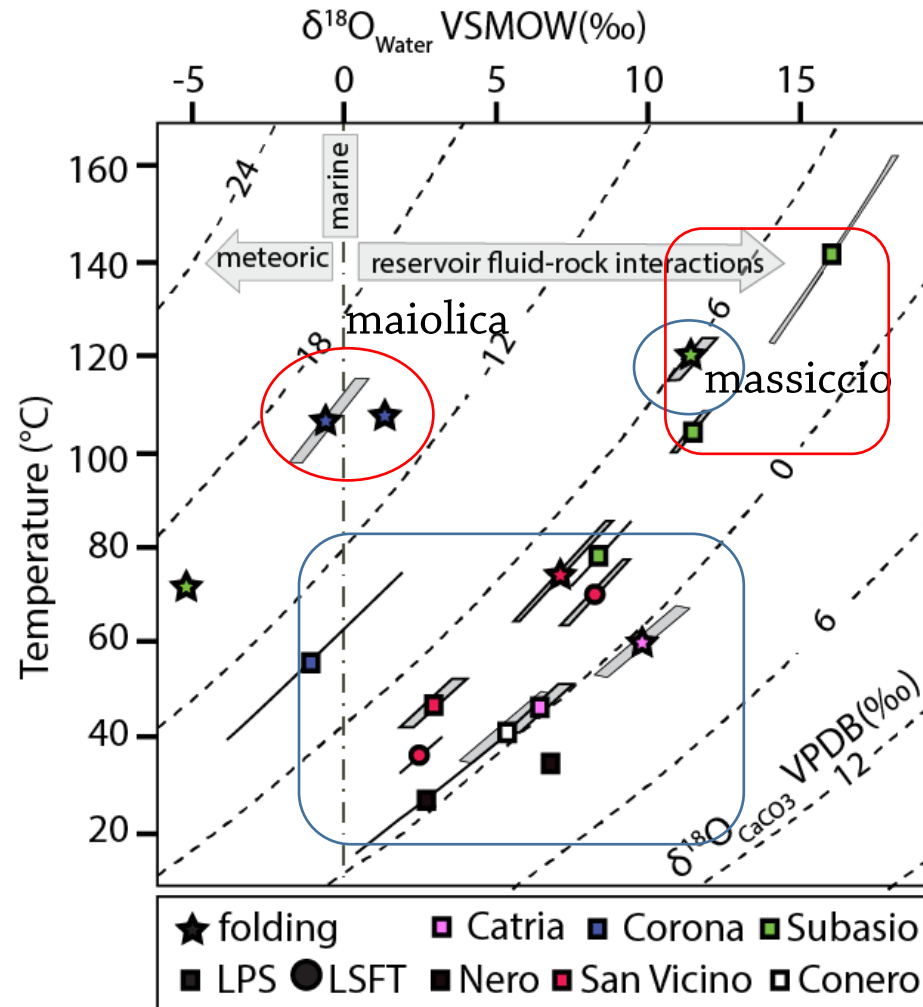


Beaudoin et al., 2020

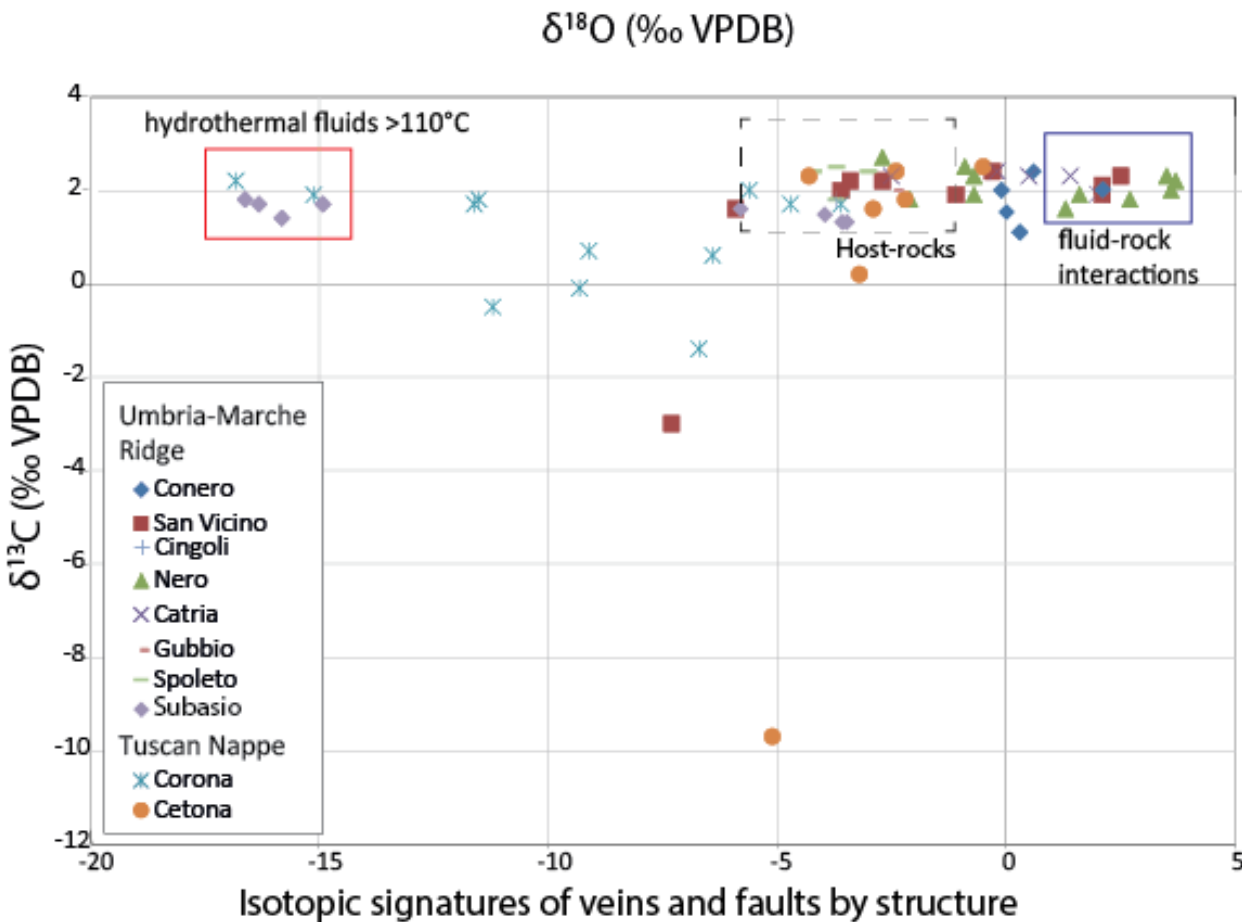
Mostly **reservoir fluids** with more or less F/R interactions



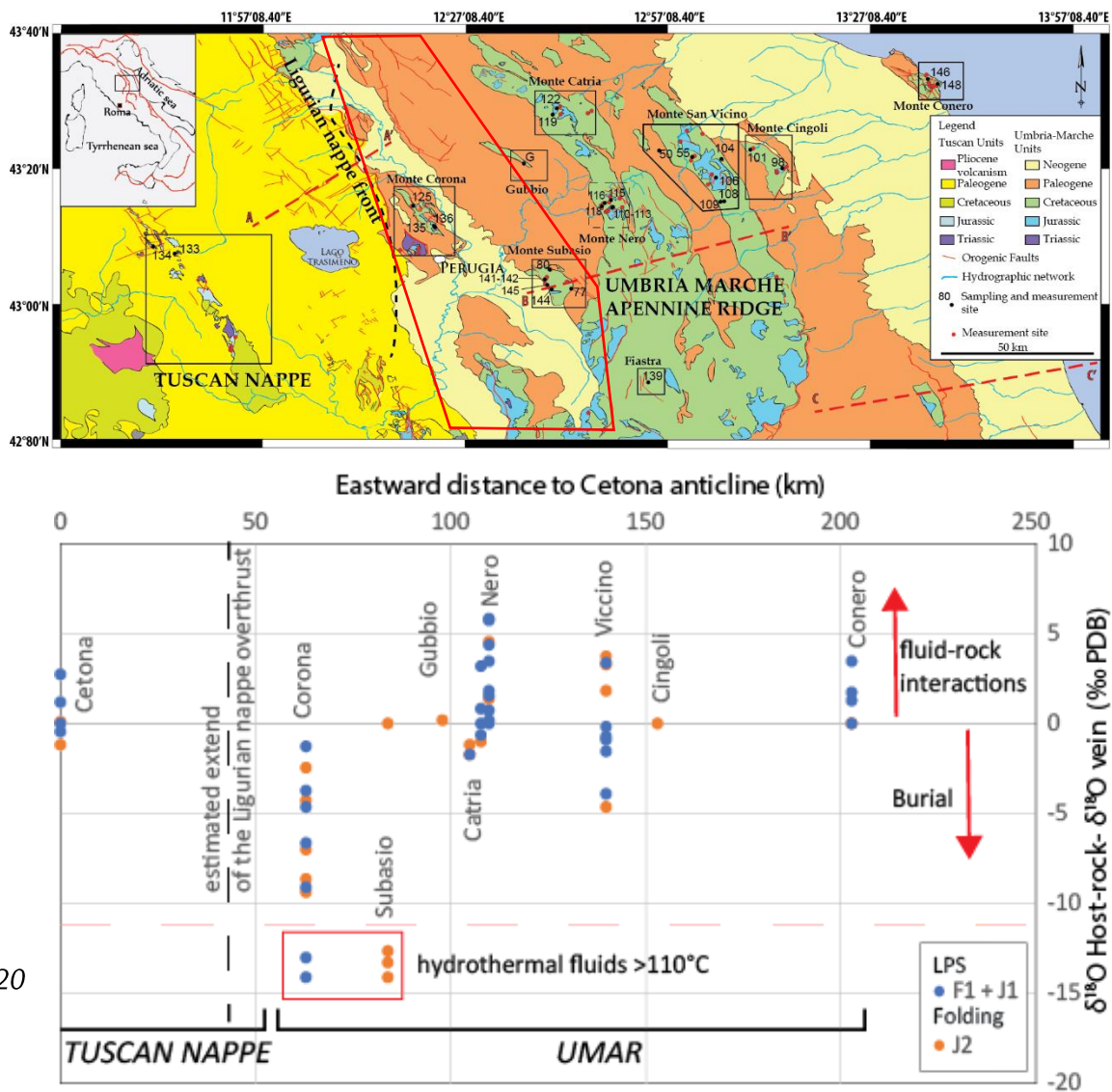
Past fluid system in the Umbria-Marche



Past fluid system in the Umbria-Marche



Beaudoin et al., 2020

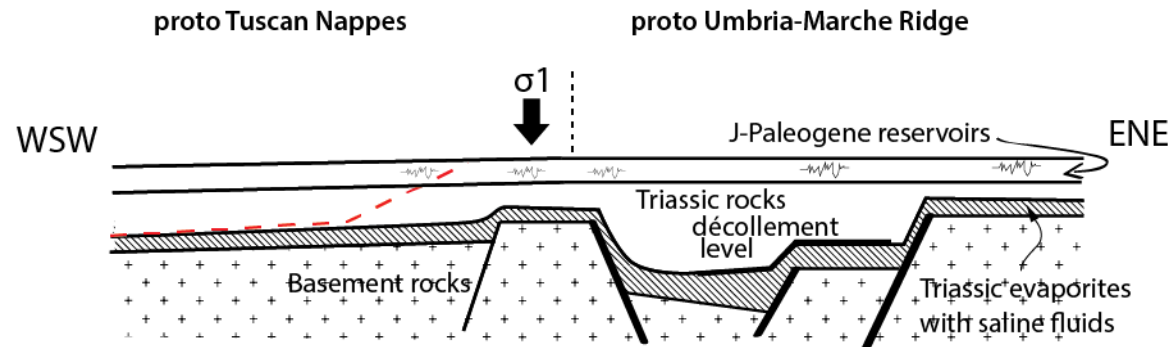


Hydrothermal overprinting in the westernmost part of the UMAR

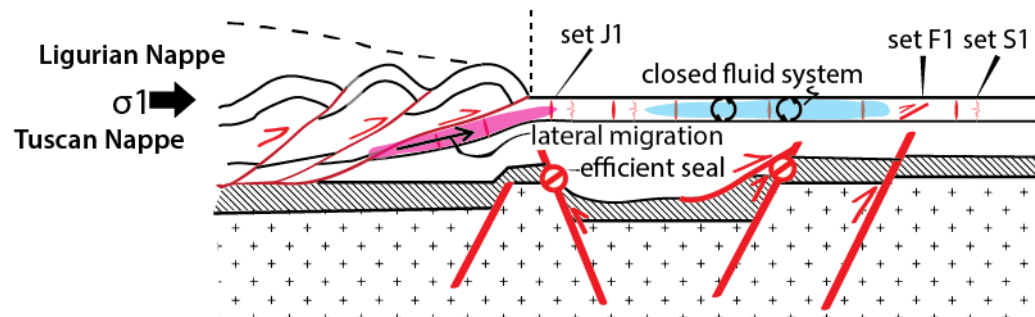


Past fluid system in the Umbria Marche – Large scale squeegee?

a) Burial up to Burdigalian - Serravalian (15 ± 3 Ma)

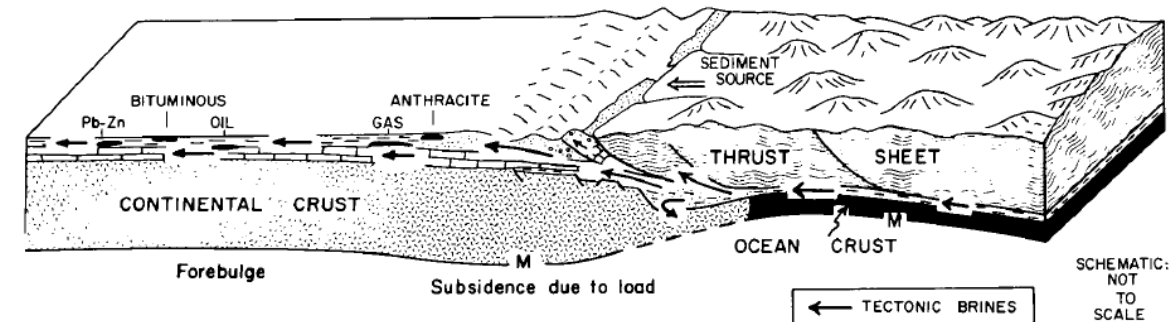
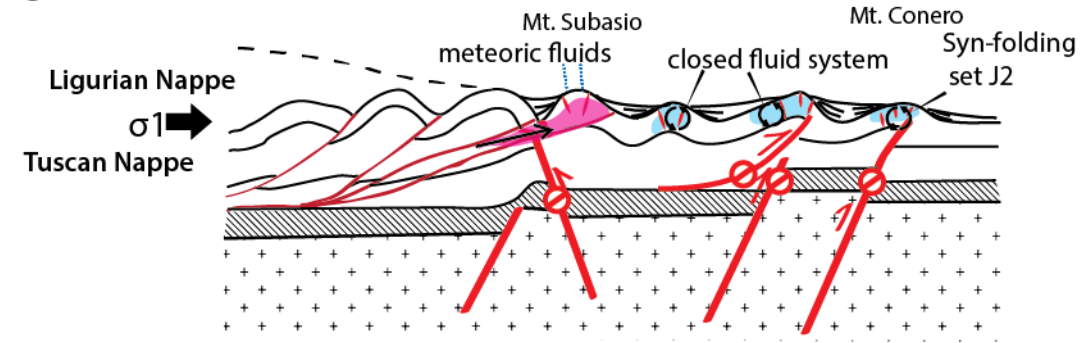


b) LPS in the UMAR from Serravalian to Tortonian (~8Ma)



Lack of triassic fluids: hint toward thick-skinned?

c) Folding in the UMAR from Tortonian to ~Messinian (5.5 Ma)



Oliver, 1986

Squeegee type fluid flow + table top difference



Take-home conclusions

- **Definition of a « paleohydrological » system different from the structural system**
- **Highlights the role of large-scale tectonics on the fluid flow since LPS**
- **Evolution of the methodological workflow that combines paleopiezometry and isotopic analysis to reconstruct the depth-T-t evolution of the sedimentary strata and fluid involved in the deformation**



This work



Related work



Fundings:

