Structural characterization of fault damage zones in carbonates (Central Apennines, Italy)

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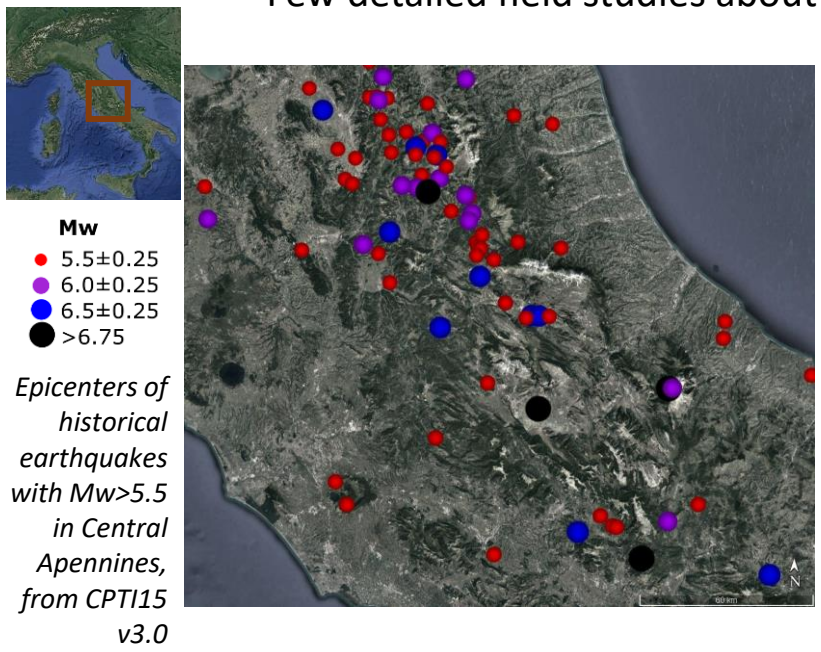
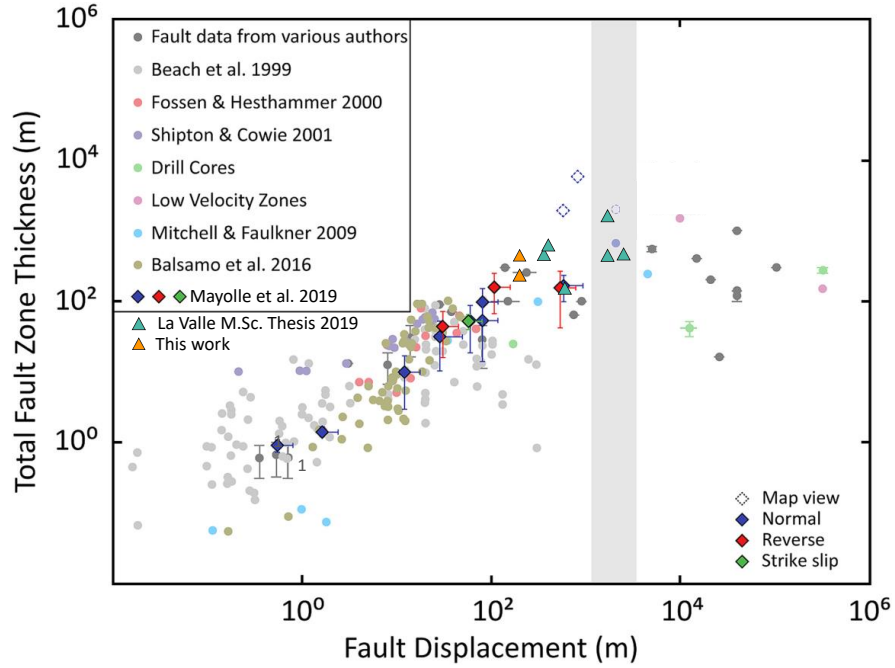
Motivations and state-of-art

- Very thick damage zones in Central Apennines: are they seismic related?
- How do these thick damage zones form?
- Few detailed field studies about fault damage zones in carbonates with displacement>10^2m



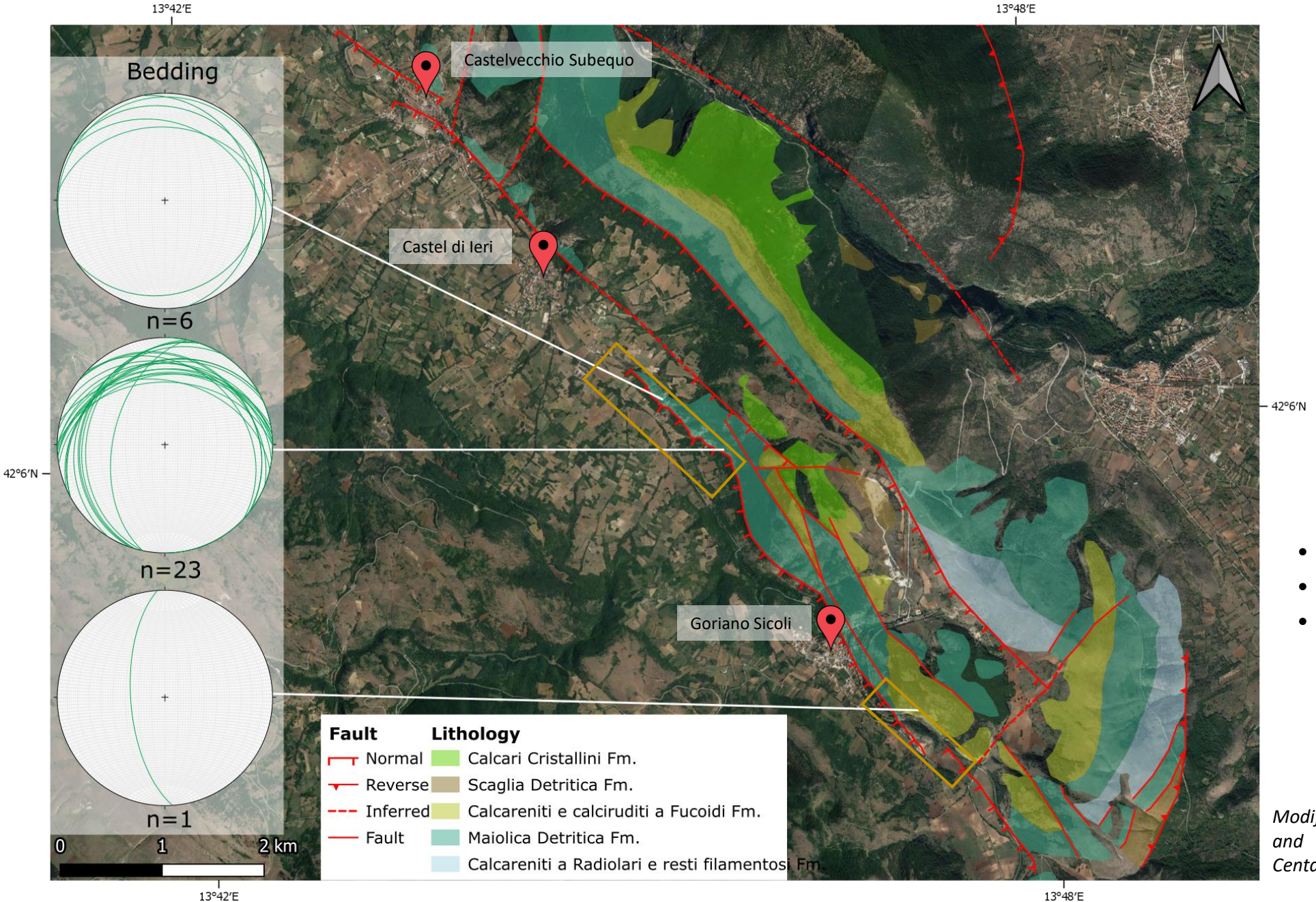
Epicenters of historical earthquakes with Mw>5.5 in Central Apennines, from CPTI15 v3.0

Monte Marine Fault, Central Apennines, Italy



Modified from Mayolle et al., 2019

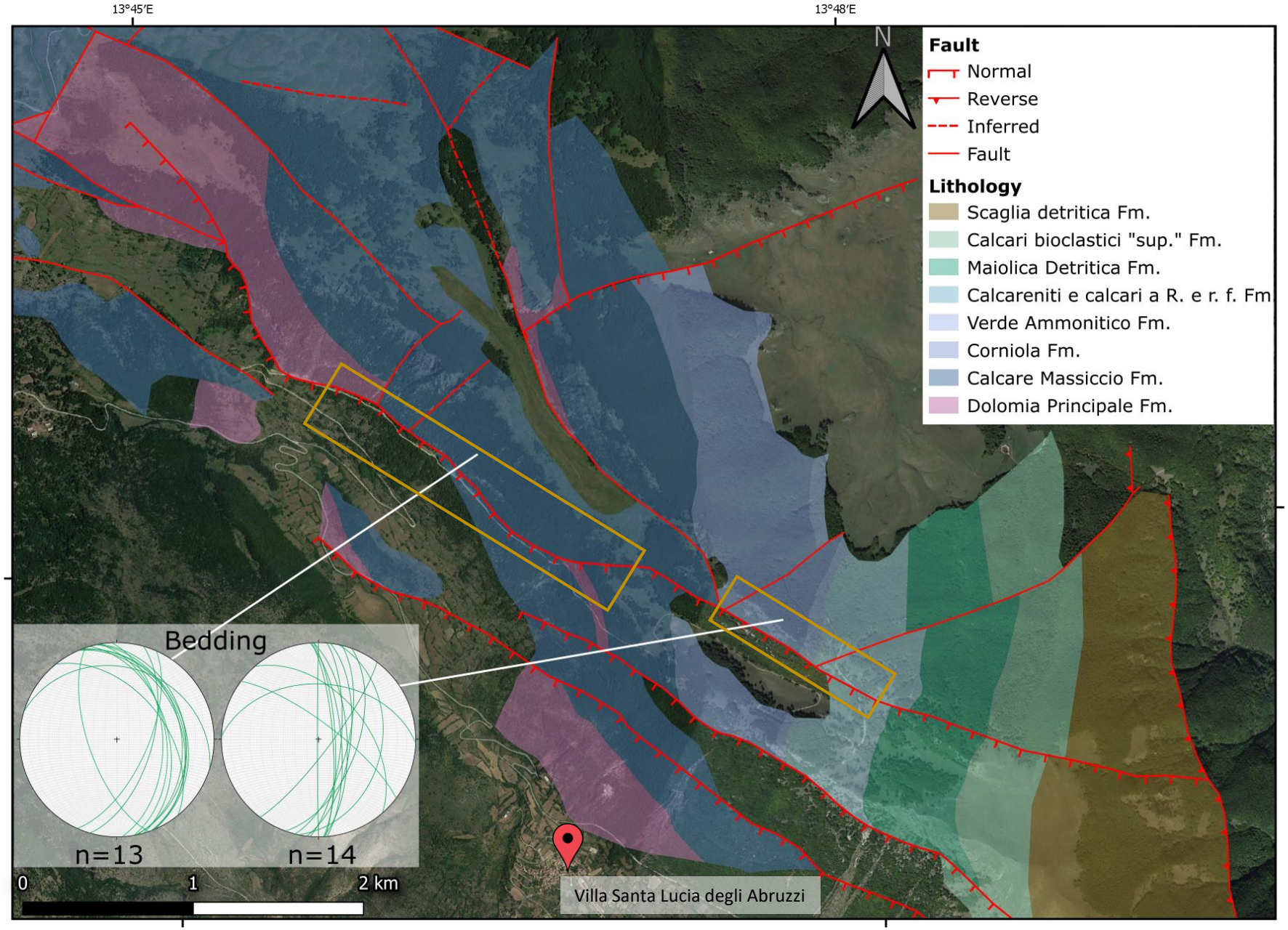
Geological setting – Subequana Valley Fault (SVF)



- Normal fault (N230/50° dipping)
- Displacement 200-300m
- 9-10km long, multiple segments in en-echelon array

Modified from Miccadei et al., 1998
and
Centamore et al., 2006, foglio 369 "Sulmona"

Geological setting – Capo di Serre Fault (CDSF)



- Normal fault (N225/70° dipping)
- Displacement 200-300m
- 8 km long

Modified from Centamore et al., 2006, foglio 360 "Torre de' Passeri"

Results: Fault rock domains

Defined after previous fieldwork on similar faults (Monte Marine Fault and Vado di Corno Fault), based on field observations about presence and intensity of fault-related structures (fractures, joints, secondary faults)

Damage Zone

HSDZ

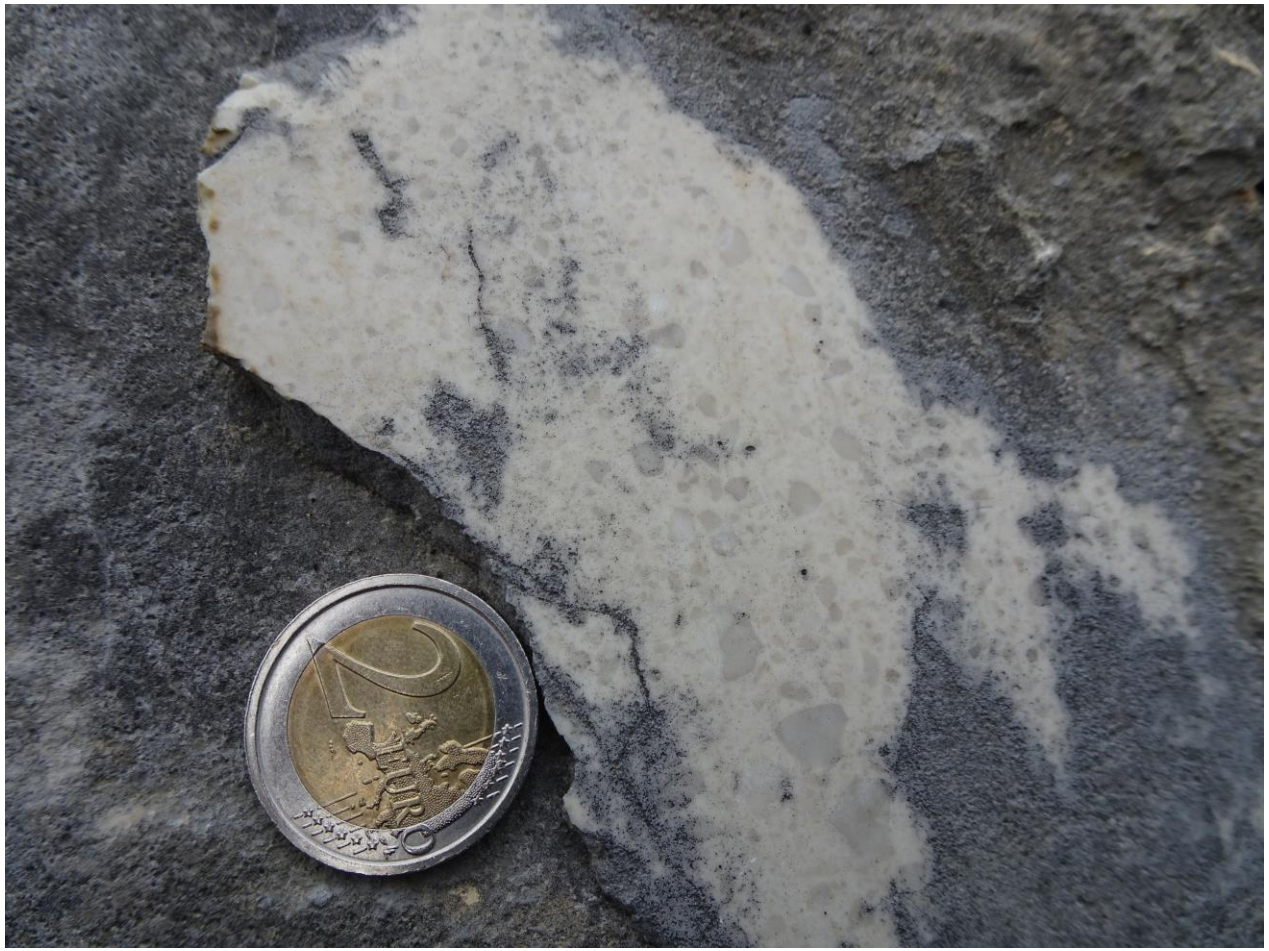
LSDZ

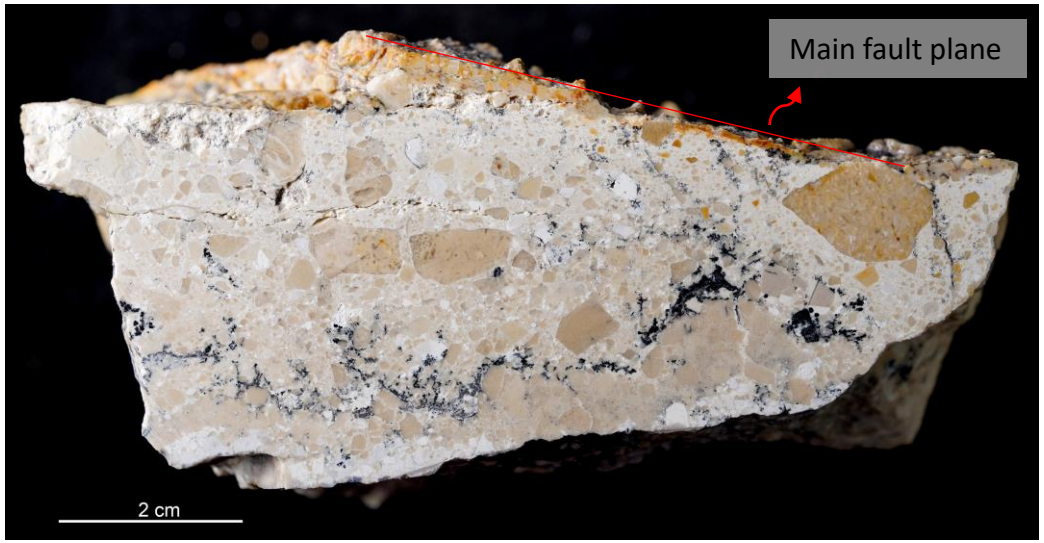
1. **Fault Core:** ultra-cataclastic, cataclastic and proto-cataclastic facies of the main fault core, quantity of matrix decreases further from the PSZ;
2. **Protobreccia type 2**: sub-cm spaced joints, breccia with embryonic fabric *(Billi et al., 2010 JSG)*; in contact angular clasts, no matrix; joint sets locally still recognizable;
3. **Intense fractured rock:** 1-3 cm spaced joints, joint-sets well recognizable;
   - 3.1 Protobreccia type 1: not well recognizable joint sets, breccia with rounded and indented clasts;
4. **Fractured rock:** 10-20 cm spaced joints;
5. **Undeformed host rock:** background fracture density, no fault-related deformation structures.

HSDZ (High Strain Damage Zone); LSDZ (Low Strain Damage Zone)

Results: Fault rock domains

1. Fault Core: ultra-cataclastic, cataclastic and proto-cataclastic facies of the main fault core, quantity of matrix decreases further from the PSZ;





Subequana Valley Fault

Capo di Serre Fault

Results: Fault rock domains

High Strain Damage Zone

2. Protobreccia type 2: sub-cm spaced joints, breccia with embryonic fabric *(Billi et al., 2010 JSG)*; in contact angular clasts, no matrix; joint sets locally still recognizable;

Results: Fault rock domains

High Strain Damage Zone

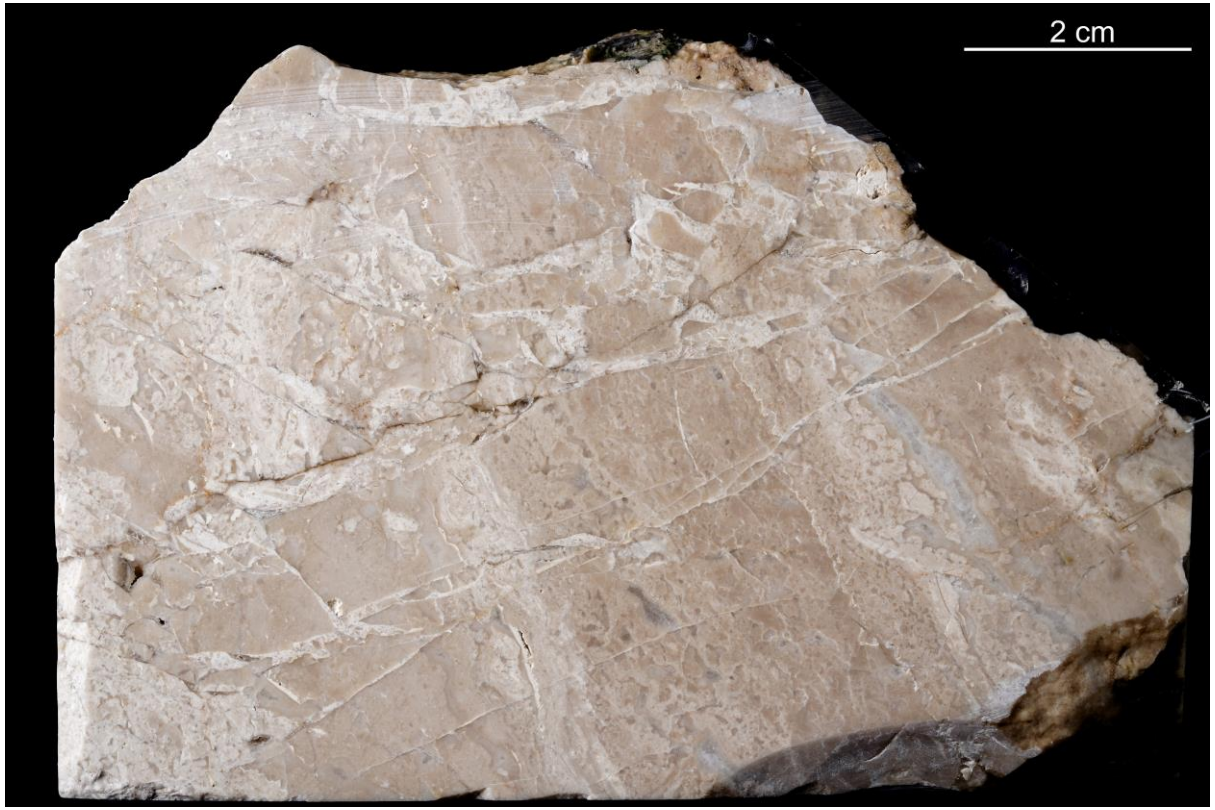
3. Intense fractured rock: 1-3 cm spaced joints, joint-sets well recognizable;

3.1 Protobreccia type 1: not well recognizable joint sets, breccia with rounded and indented clasts;

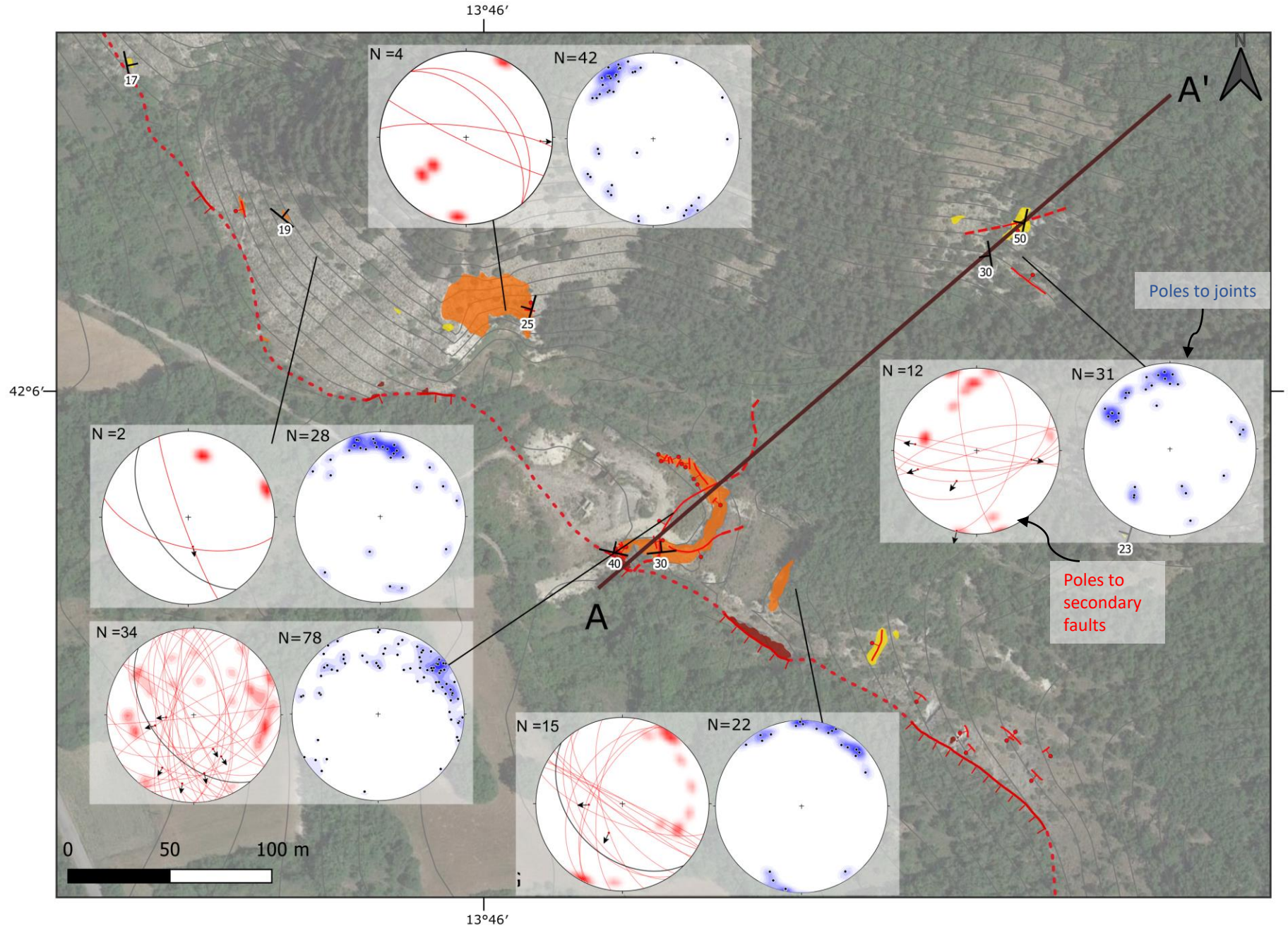
Results: Fault rock domains

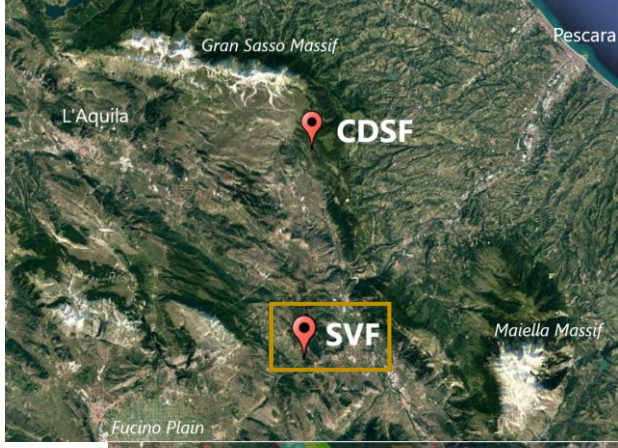
Low Strain Damage Zone

4. Fractured rock: 10-20 cm spaced joints;



Results: Structural map and data - SVF





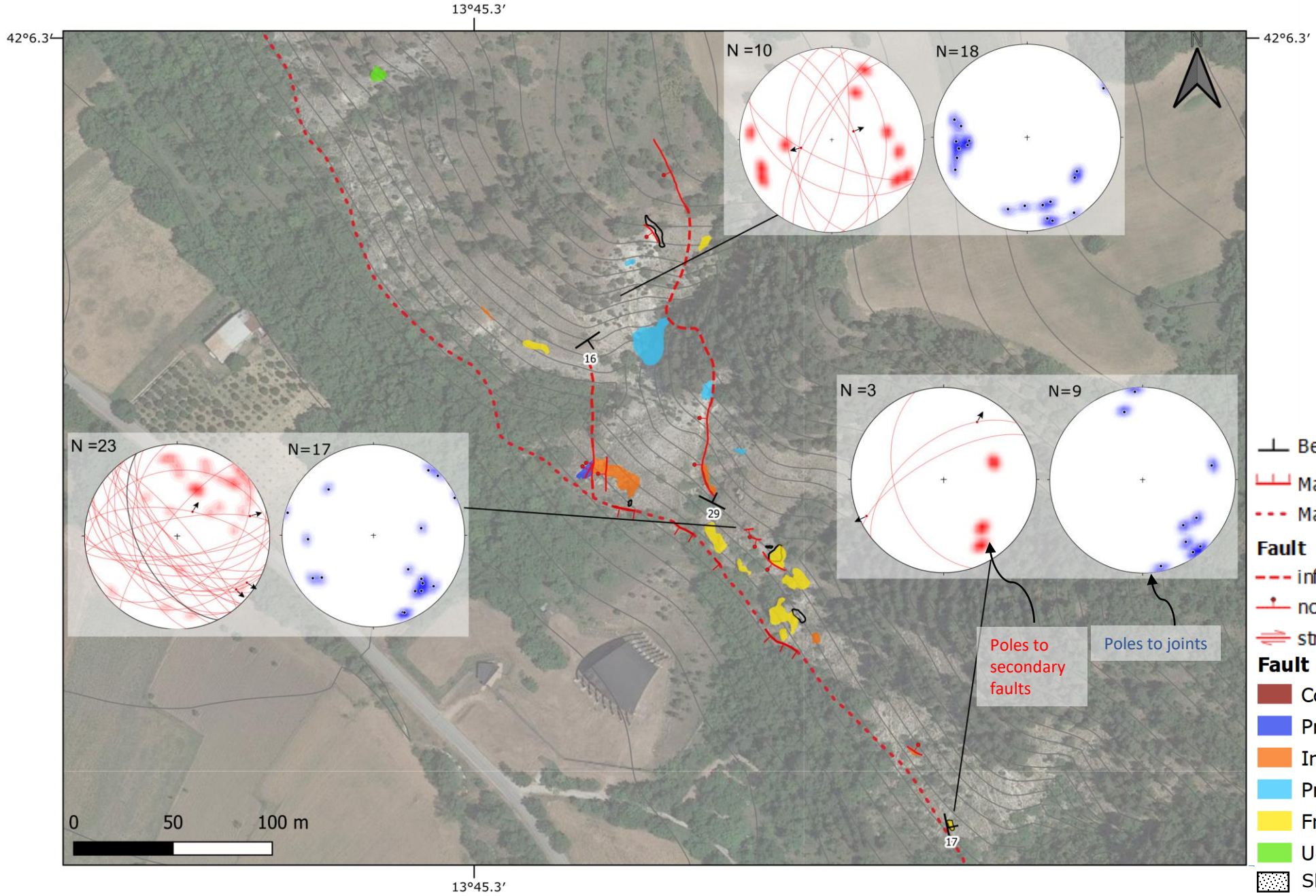
Bedding
Main Fault
Main fault inferred

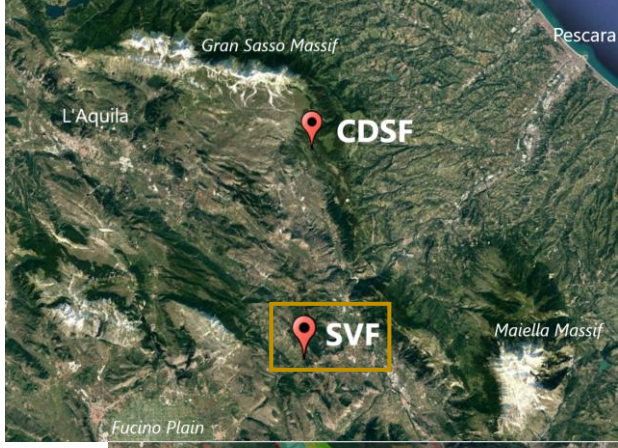
Fault
inferred
normal
strike-slip

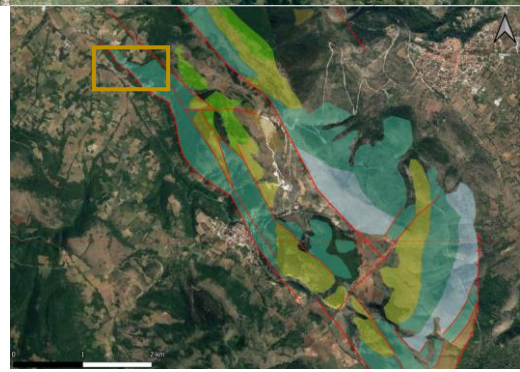
Fault rocks
Core
Intense fractured rock
Fractured rock
Slope breccia

Stereonet:
Faults
Joints
Main fault plane
Secondary fault plane
HW slip direction

Results: Structural map and data - SVF







Bedding
Main Fault
Main fault inferred

Fault
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Fault rocks
Core
Protobreccia type 2
Intense fractured rock
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Undeformed host rock
Slope breccia

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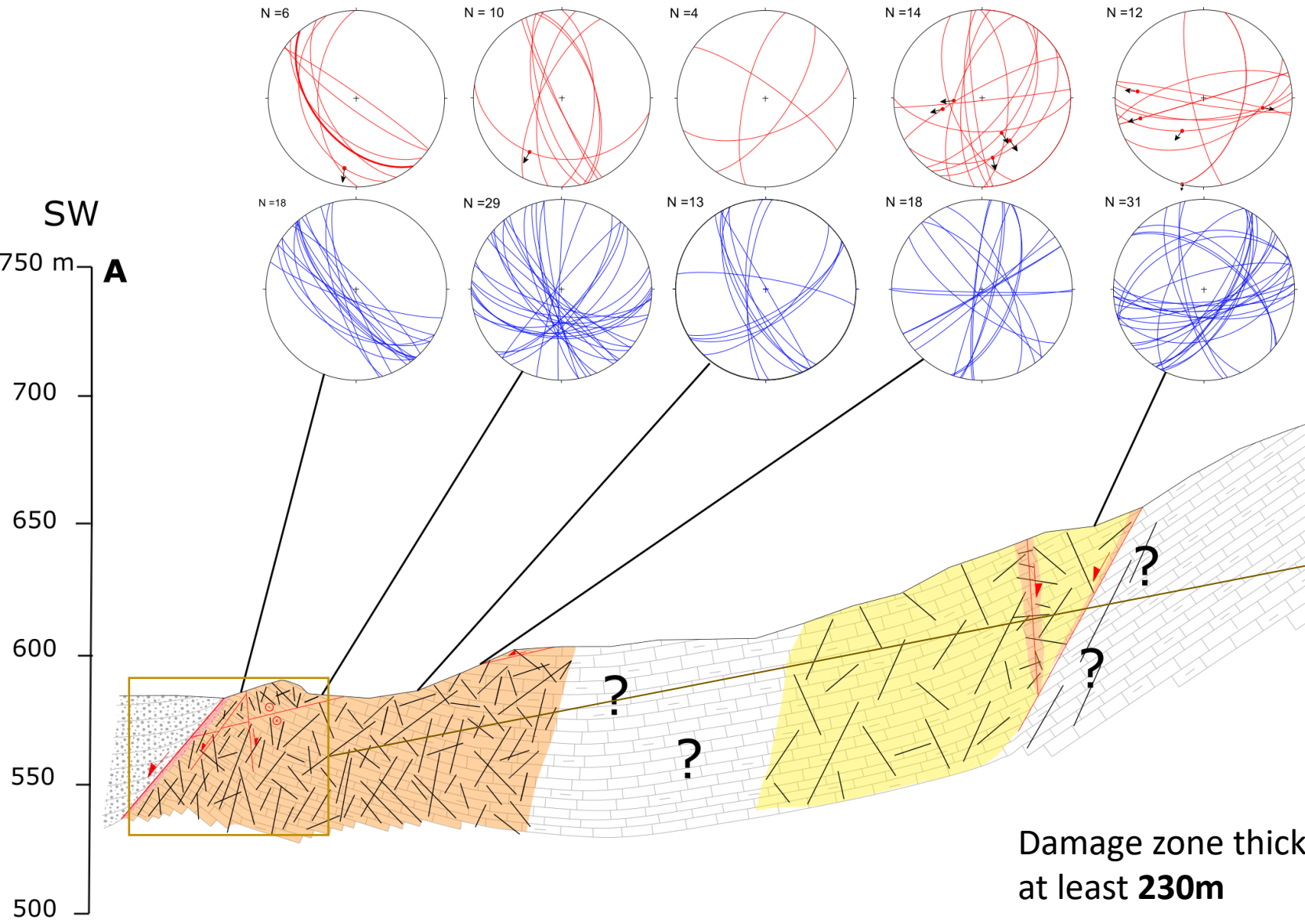
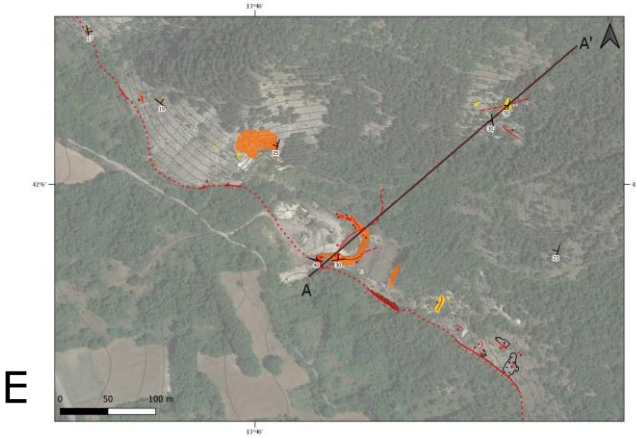
HW slip direction

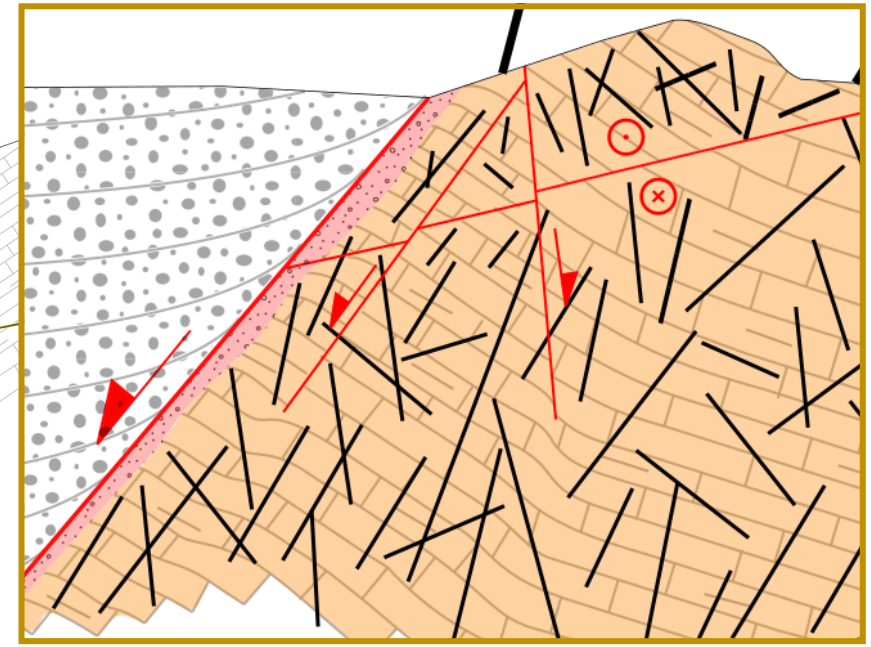
Results: Geological cross-section - SVF





NE

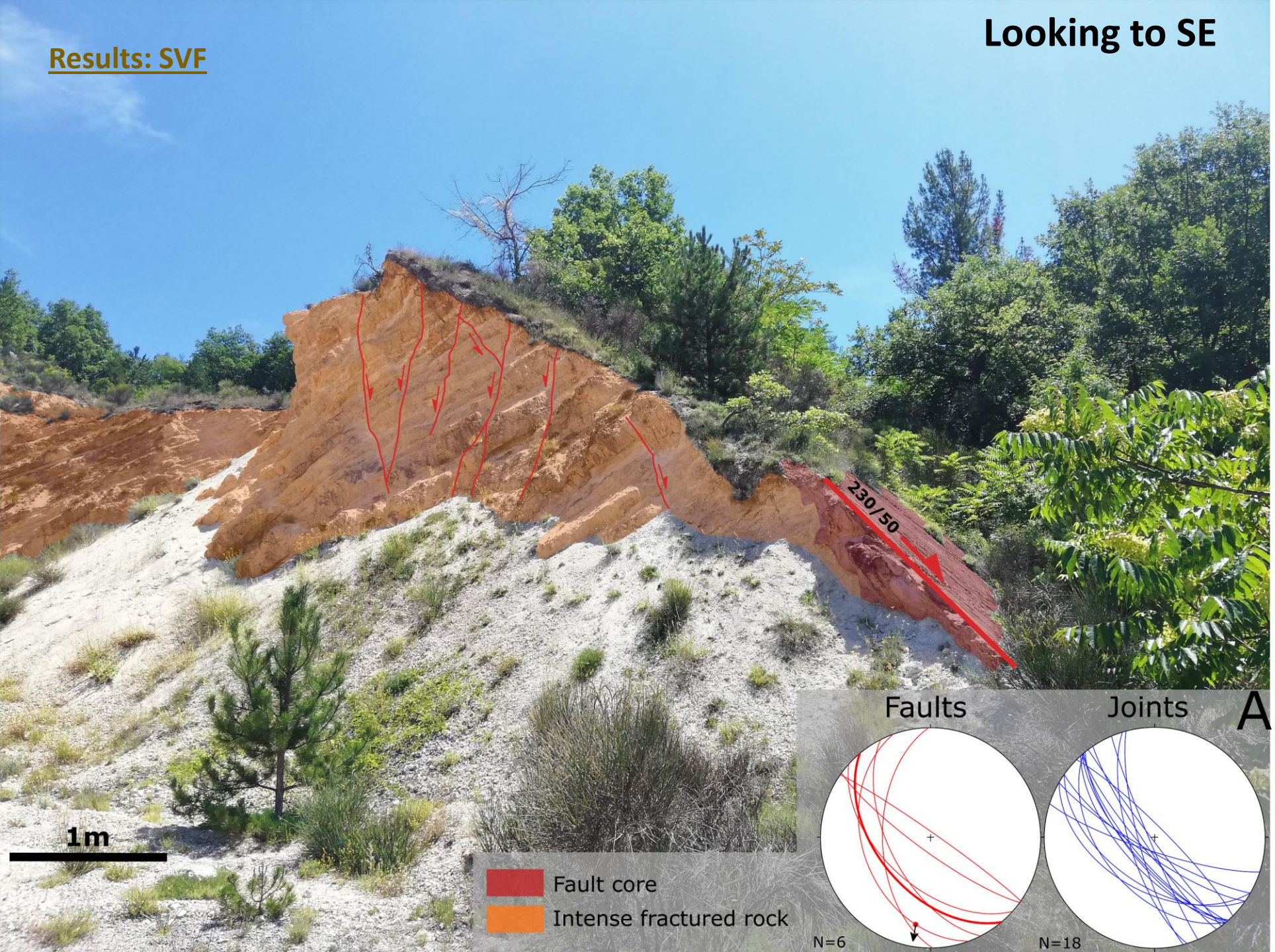
A'

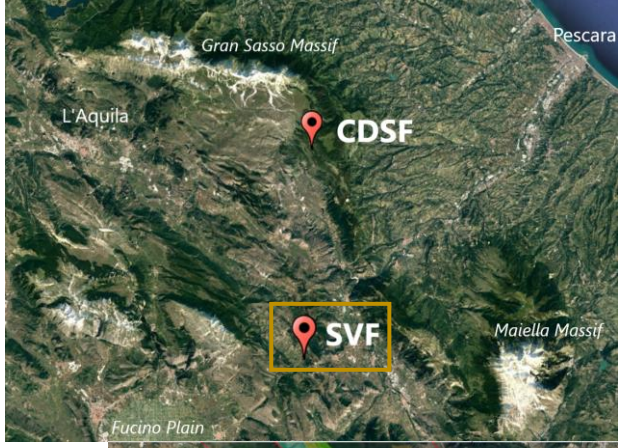


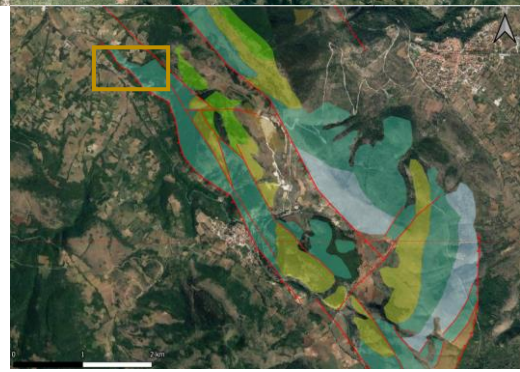
Damage zone thickness:
at least **230m**

Results: SVF

Looking to SE

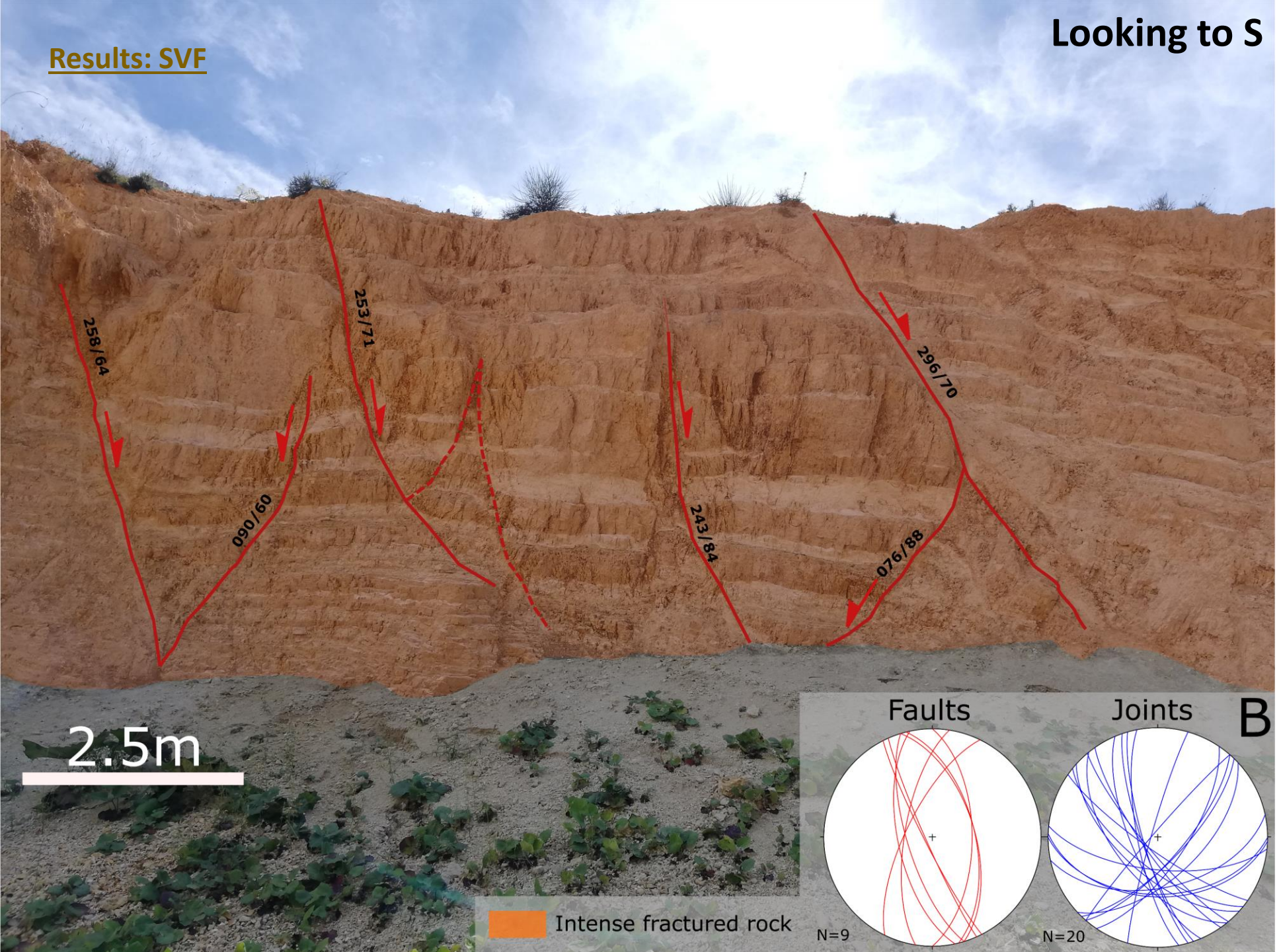


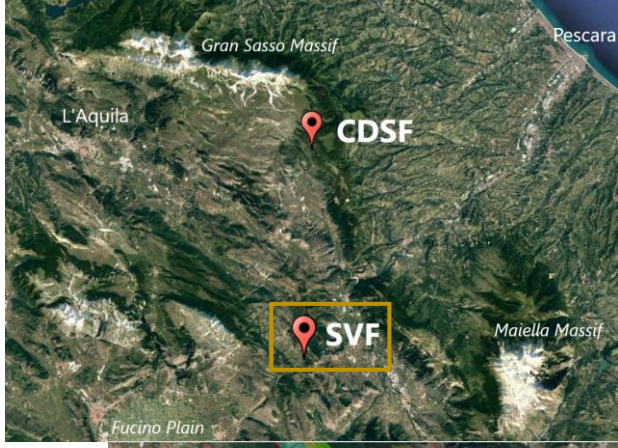


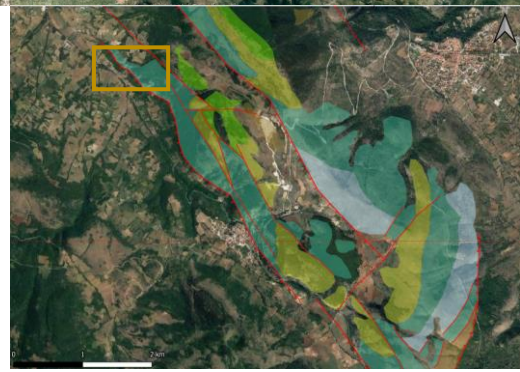


Results: SVF

Looking to S







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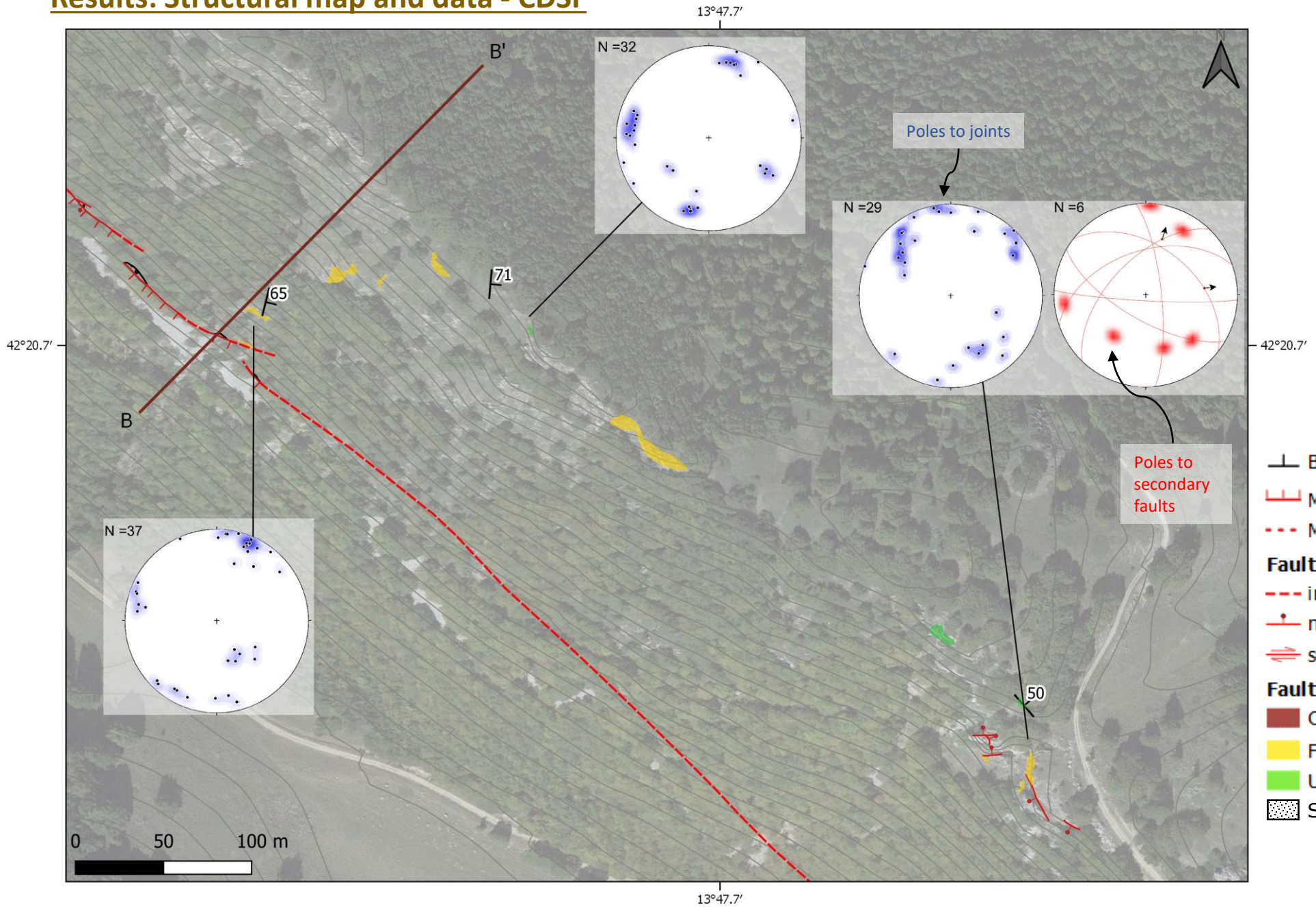

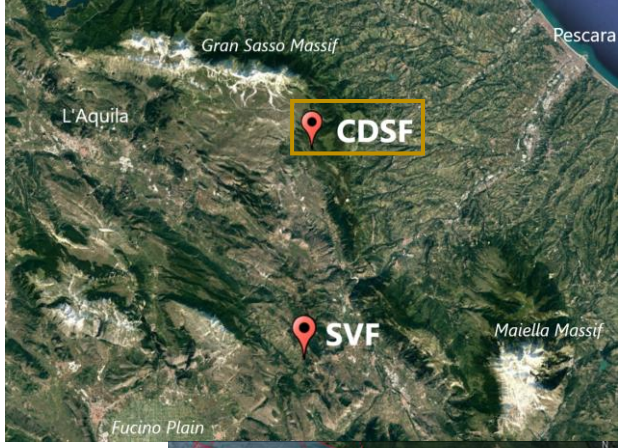

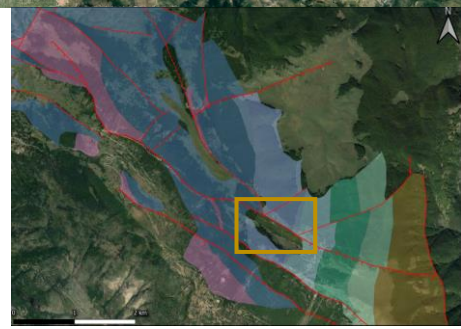

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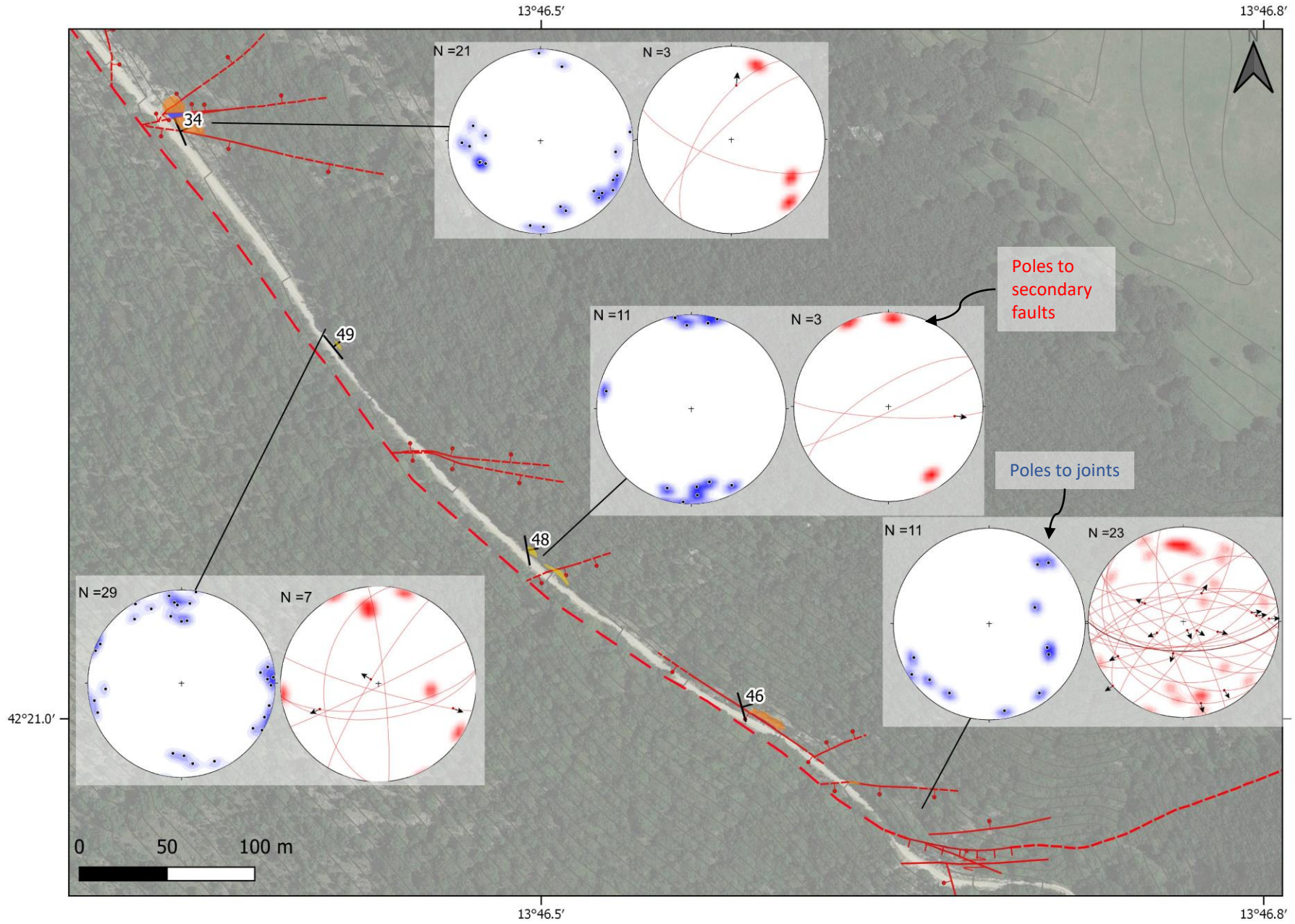

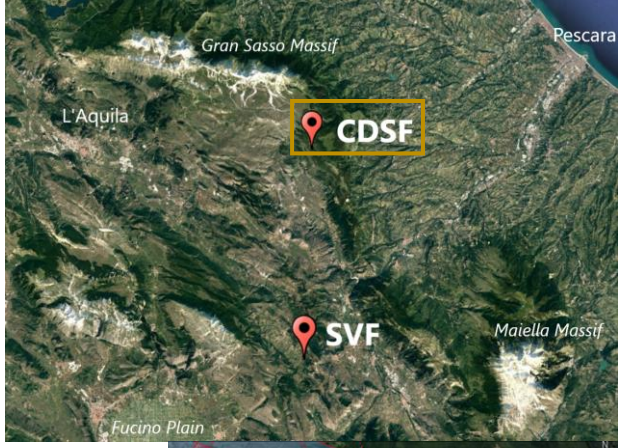

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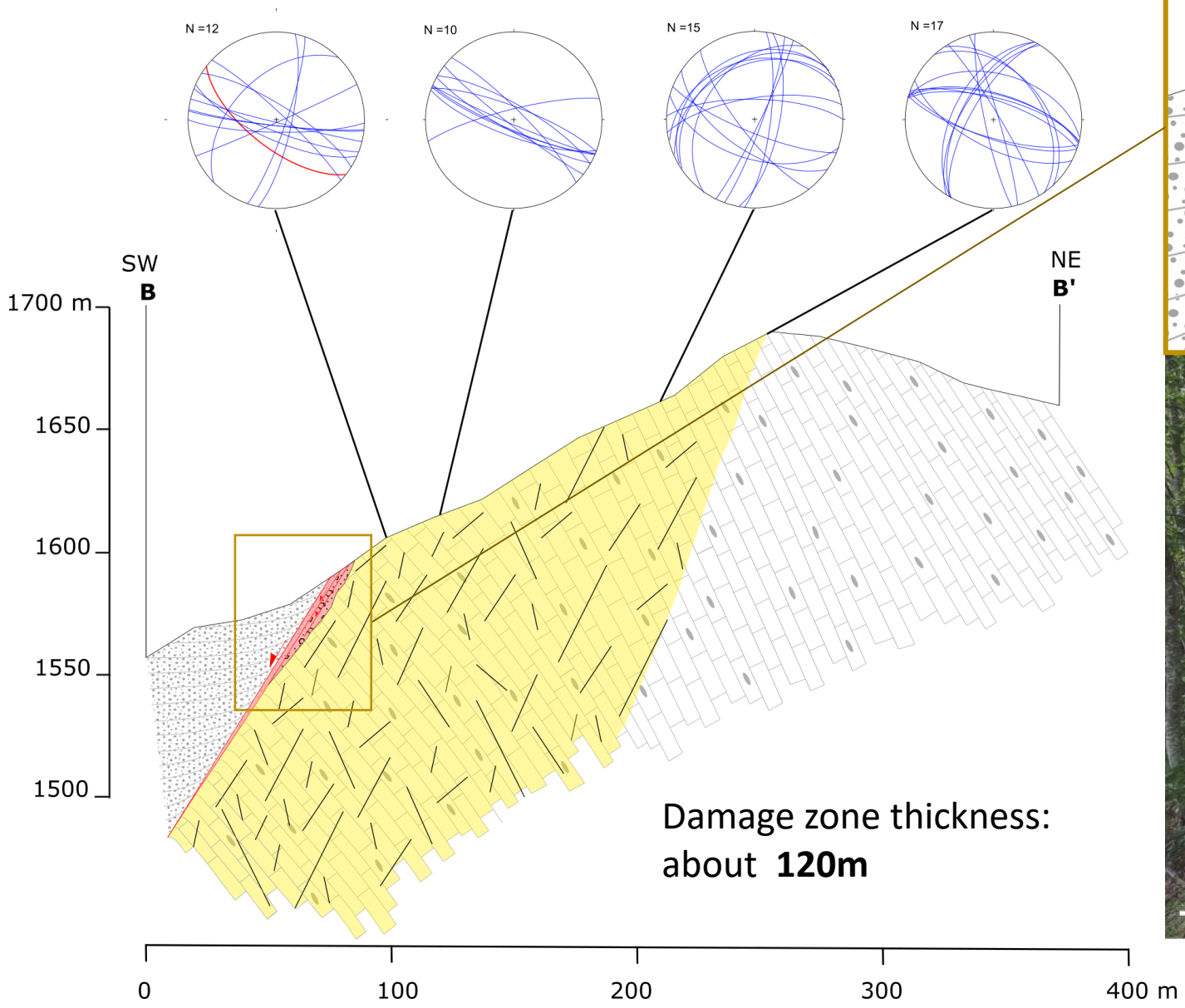
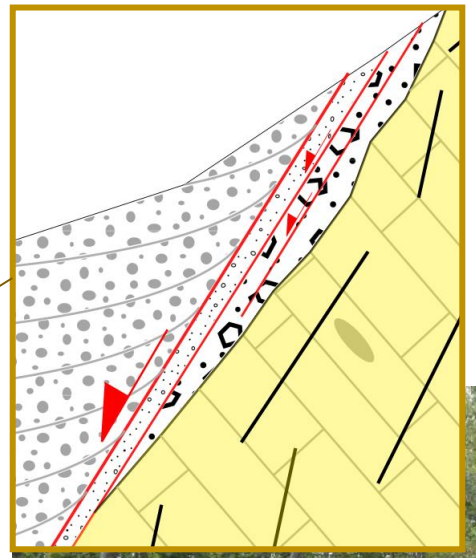
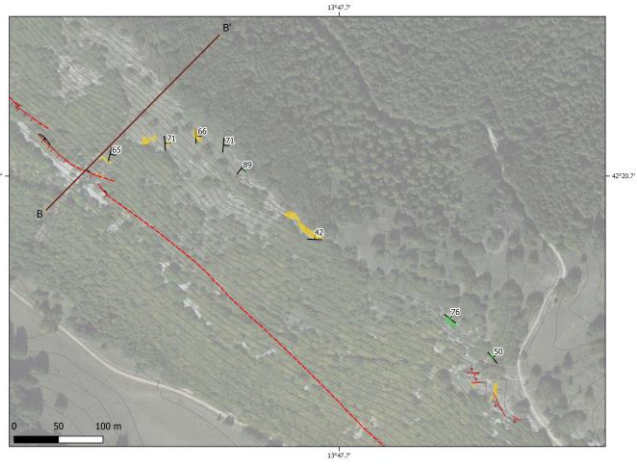
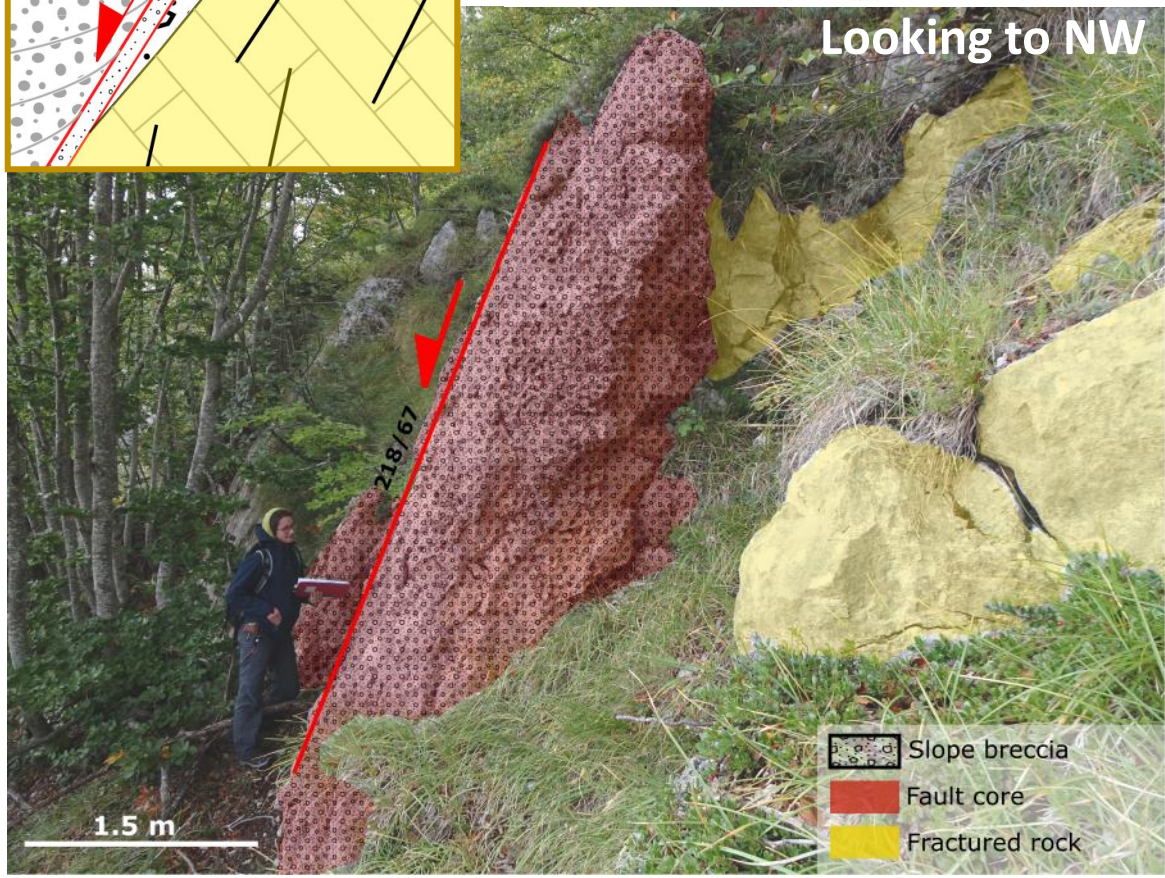


Damage zone thickness:
about **120m**





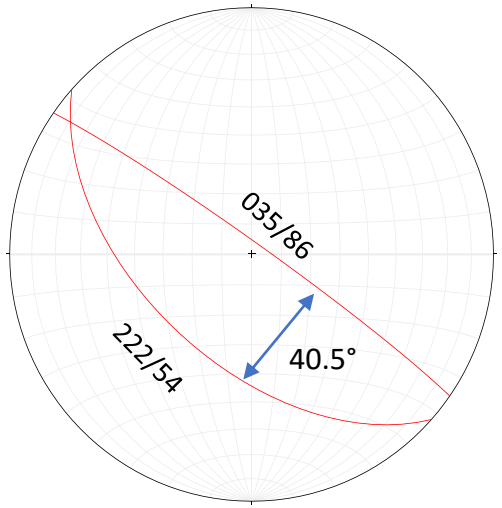


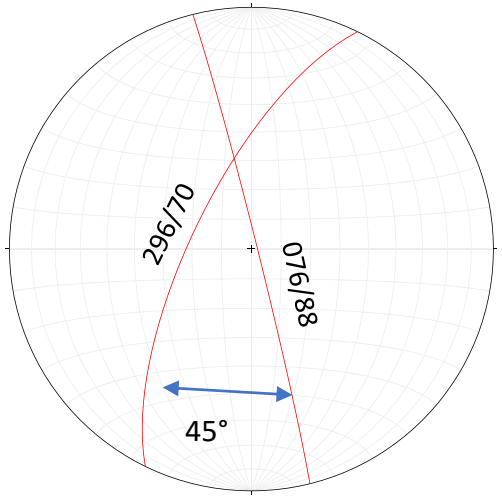
Discussion: SVF

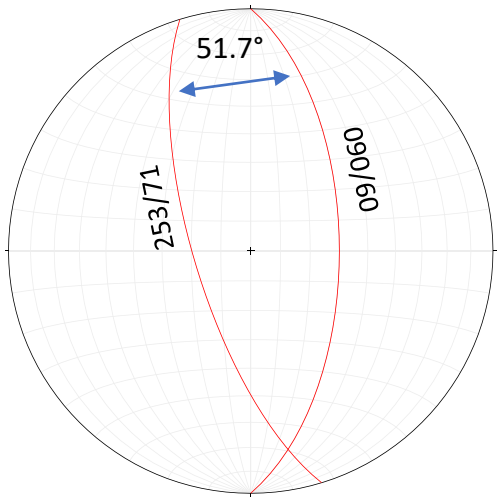
1. Dihedral angle of conjugate faults < 60°

2. Stratigraphic constraints
   (Maiolica Detritica Fm. exumed from depth <1km)

→ **Evidences of shallow structures**

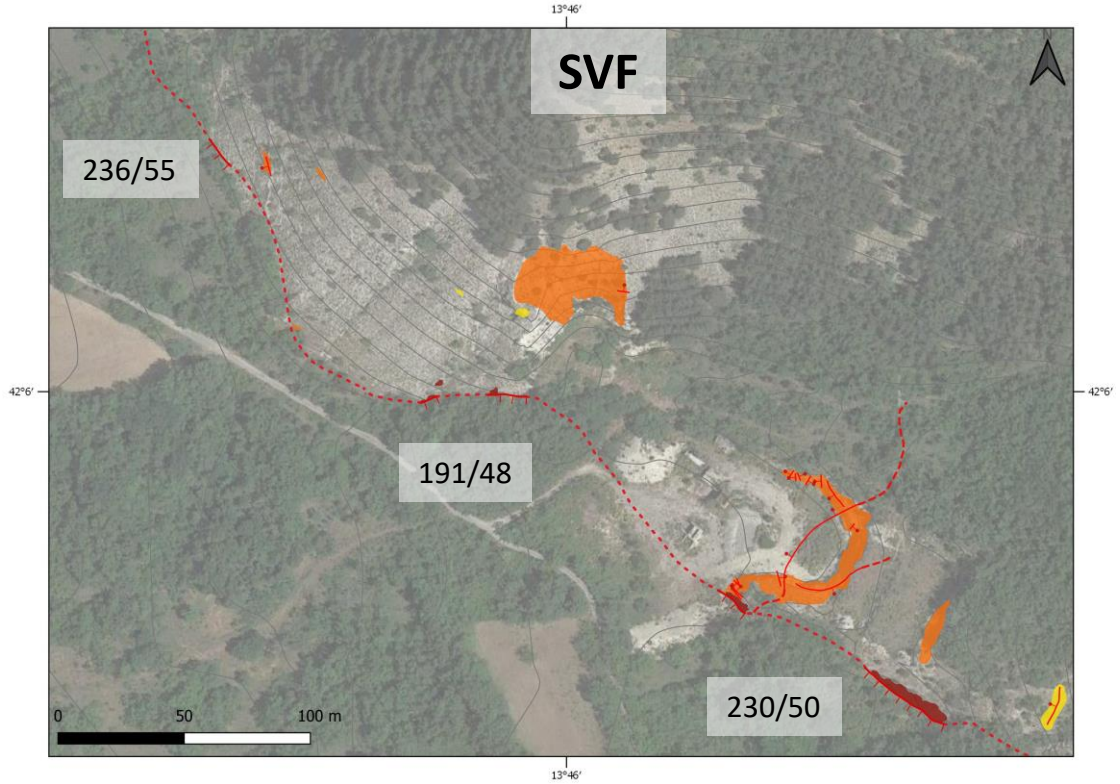


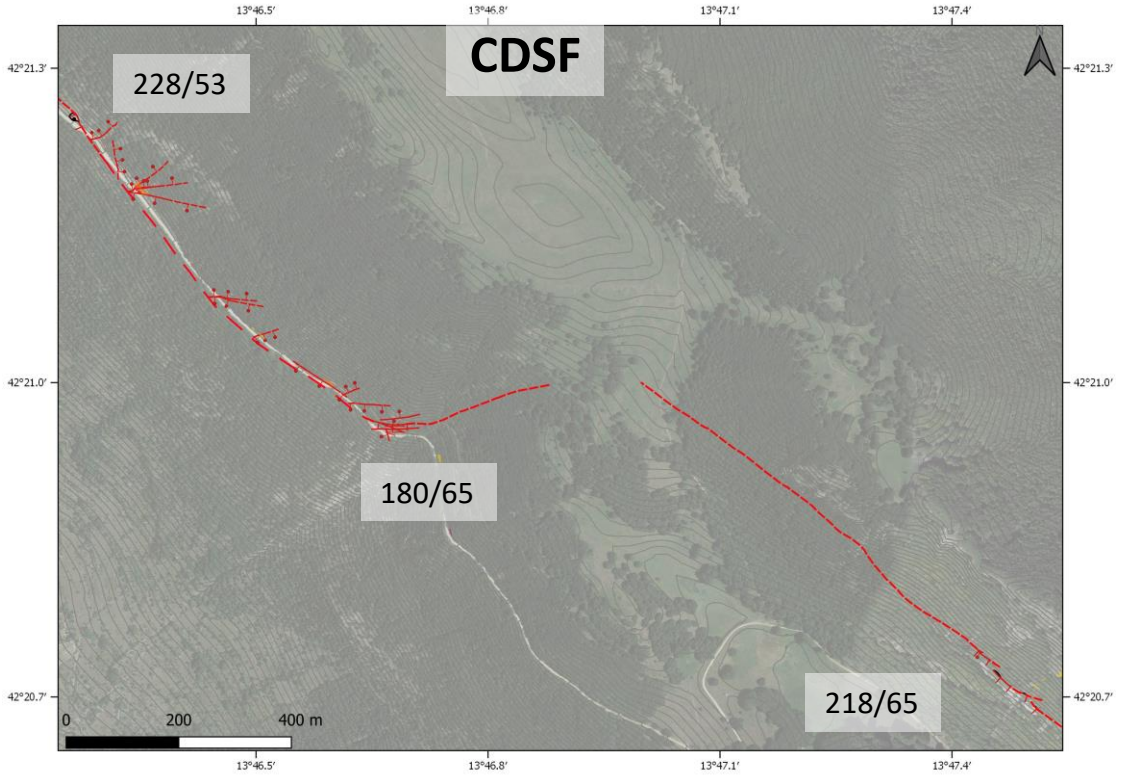




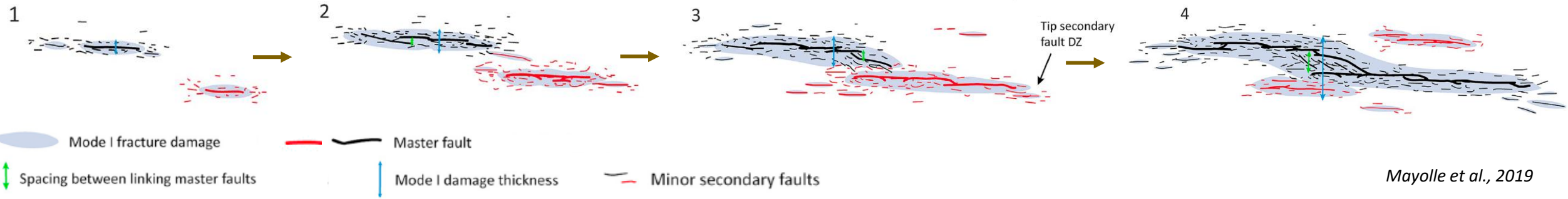
Discussion

- Variation of the main fault plane direction





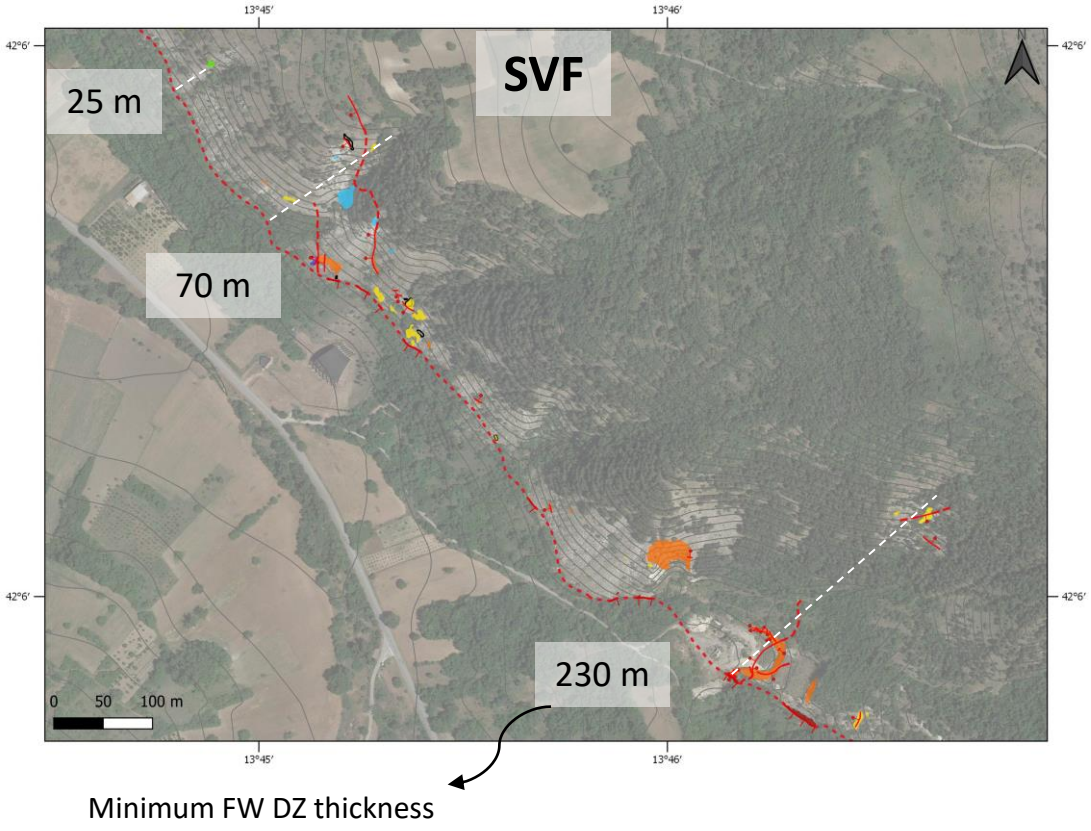
Evidence of fault growth by segment linkage



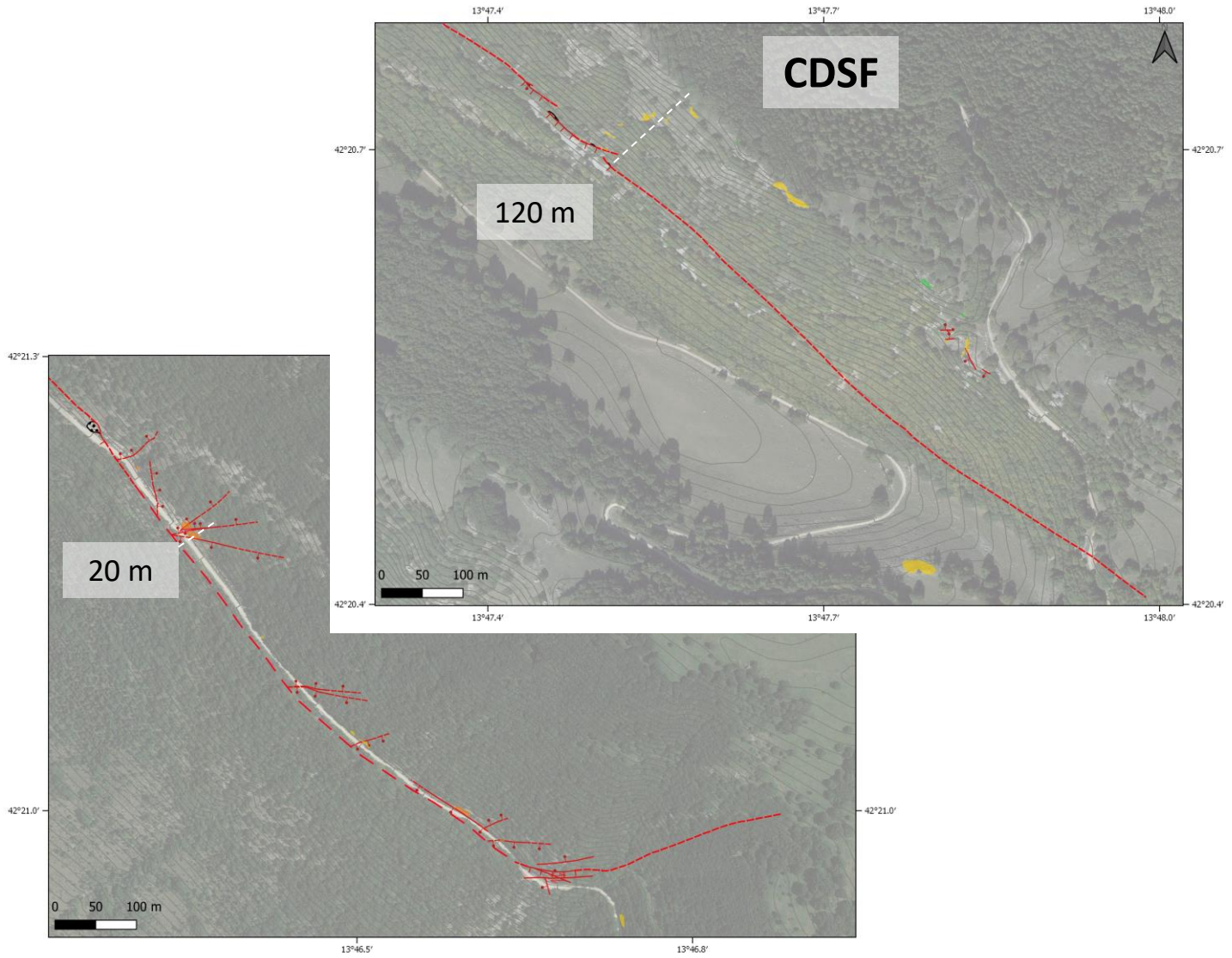
Mayolle et al., 2019

Discussion

- Footwall Damage Zone thickness in SVF e CDSF



Minimum FW DZ thickness

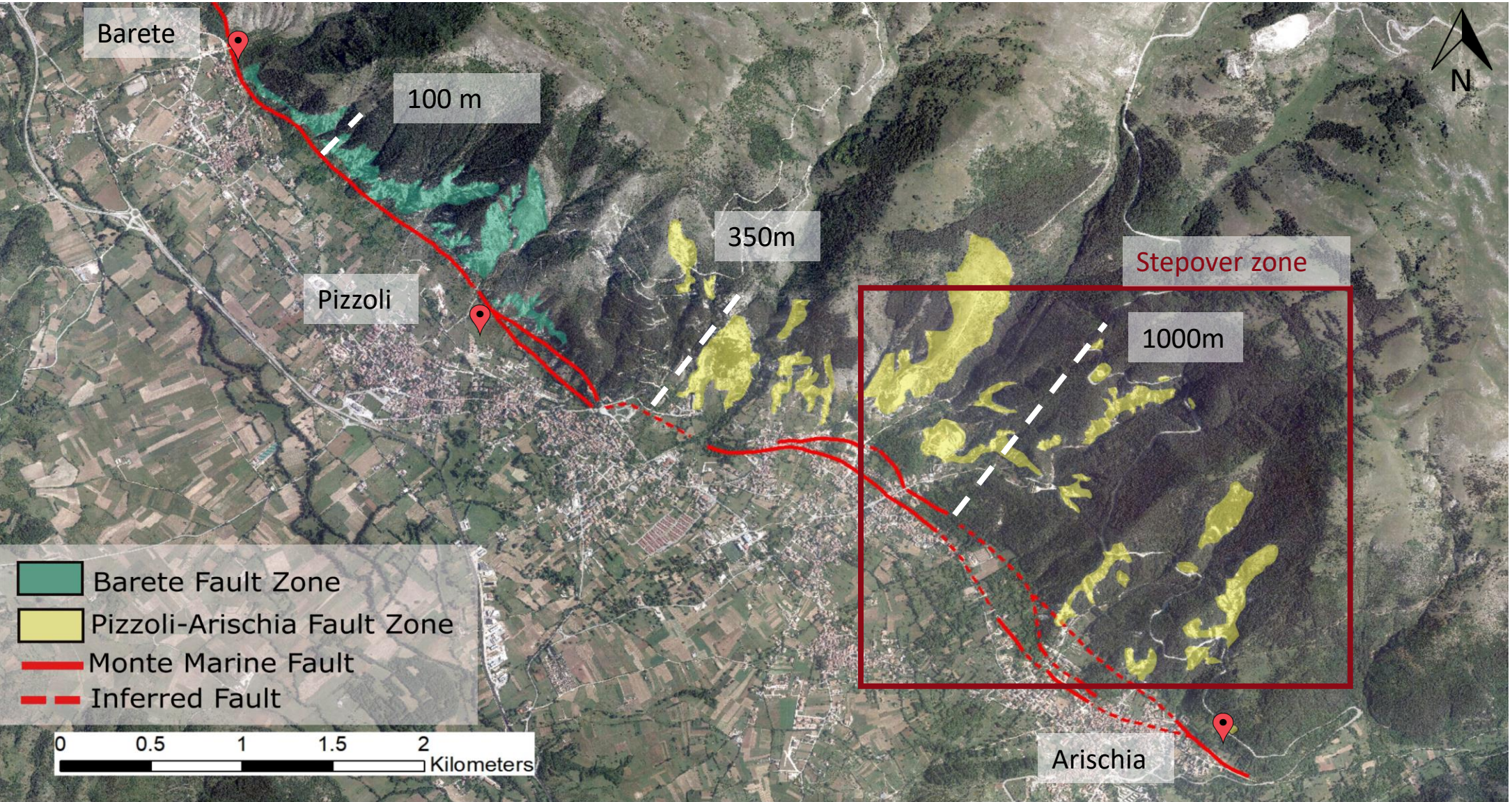


Damage zone thickness up to hundreds of meters in correspondence of secondary faults

Few reachable outcrops perpendicular to main fault- strike

Discussion

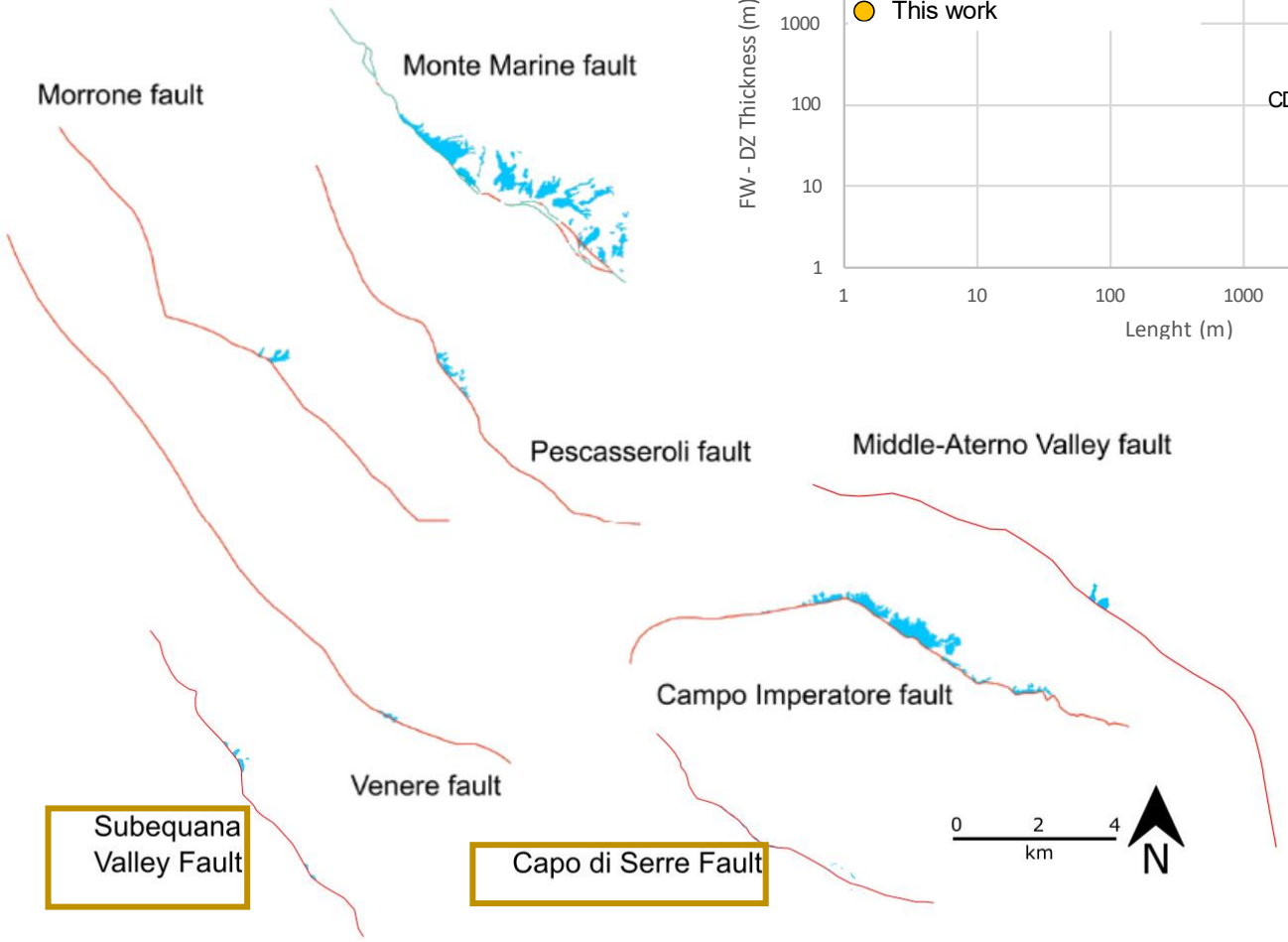
Studied areas of the Monte Marine Fault Zone → max FW DZ thickness: **850 m** in the stepover zone

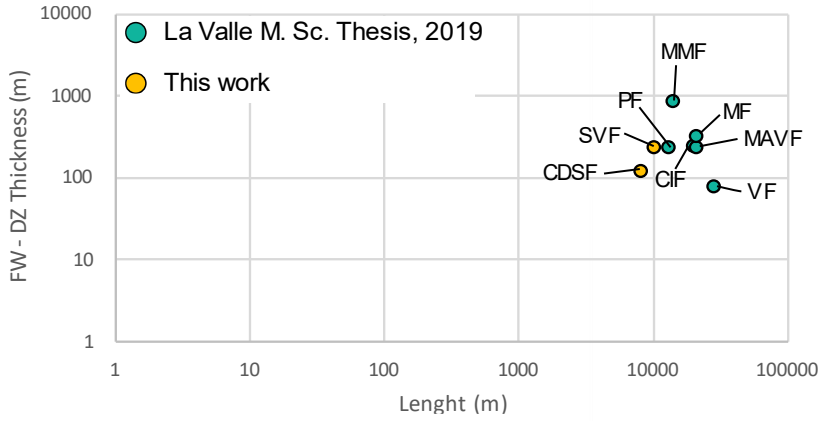


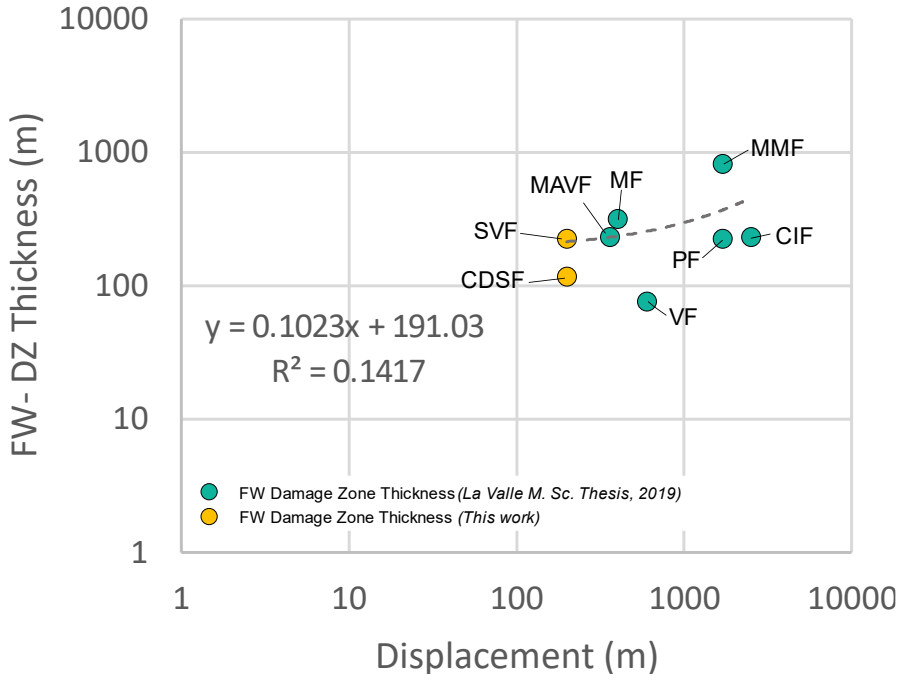
Fabio LaValle and Silvia Cortinovis M.Sc. And Ph.D. projects

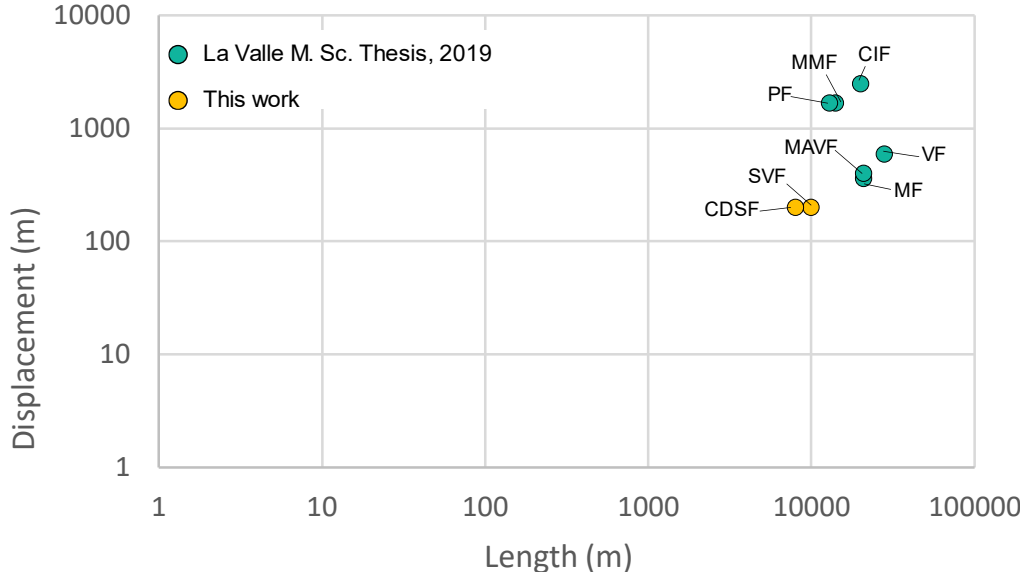
Discussion: fault-scaling relationships

Recent studies about normal fault damage zones in carbonates in Central Apennines
FW – DZ Thickness: measured Footwall damage thickness







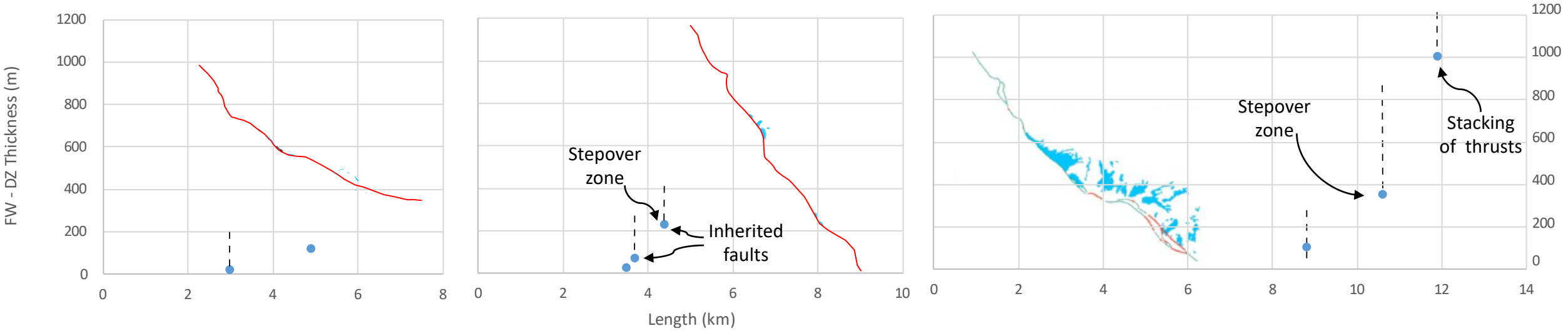


Discussion: fault-scaling relationships

FW – DZ Thickness: **measured Footwall damage thickness**

- In the point of maximum thickness along strike
- Minimum thickness because we almost never found undeformed host rock in the point of maximum DZ thickness

FW – DZ thickness variation along strike



Capo Di Serre Fault

Subequana Valley Fault

Monte Marine Fault

error bars

0 2 4 km

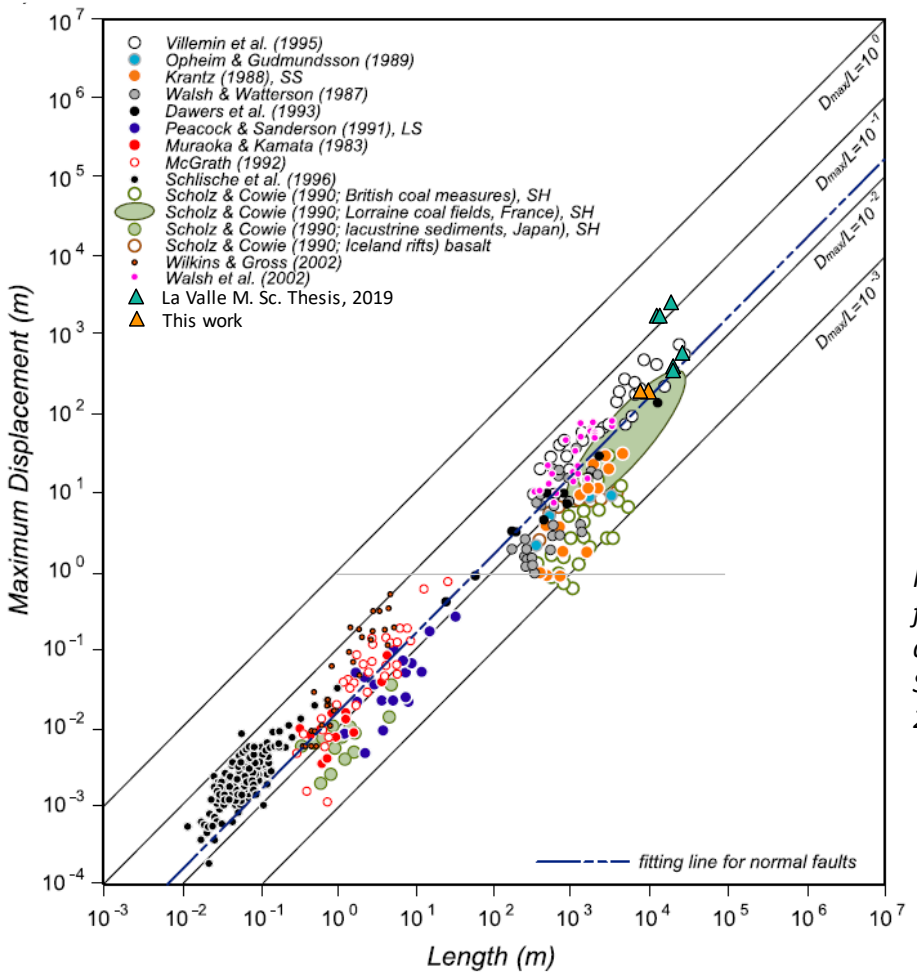
N

Discussion: fault-scaling relationships

Recent studies from Central Apennines compared to data from literature

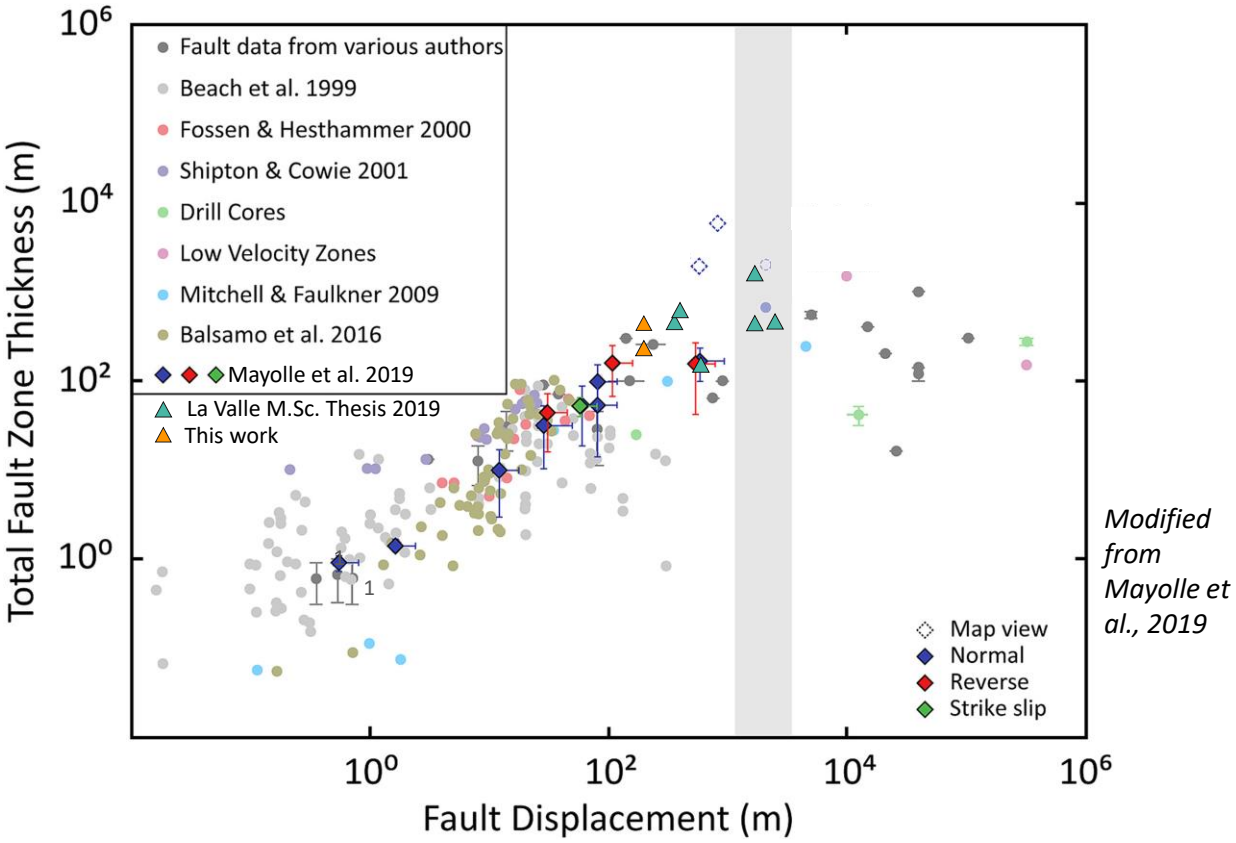
Several problems in comparing →

- Different lithologies, not only carbonates
- Normal, reverse and strike-slip faults
- Different boundaries of DZ
- Thickness doubled for FT and HW



Modified from Kim and Sanderson, 2005

Relationship between Length (L) and Maximum displacement (Dmax) is of the form $Dmax = cL^n$



Modified from Mayolle et al., 2019

- Linear D-T scaling between 0 and 100m, saturation of DZ thickness over 10 km in length
- Damage thickness tends to saturate with displacements larger than 100m

Conclusions

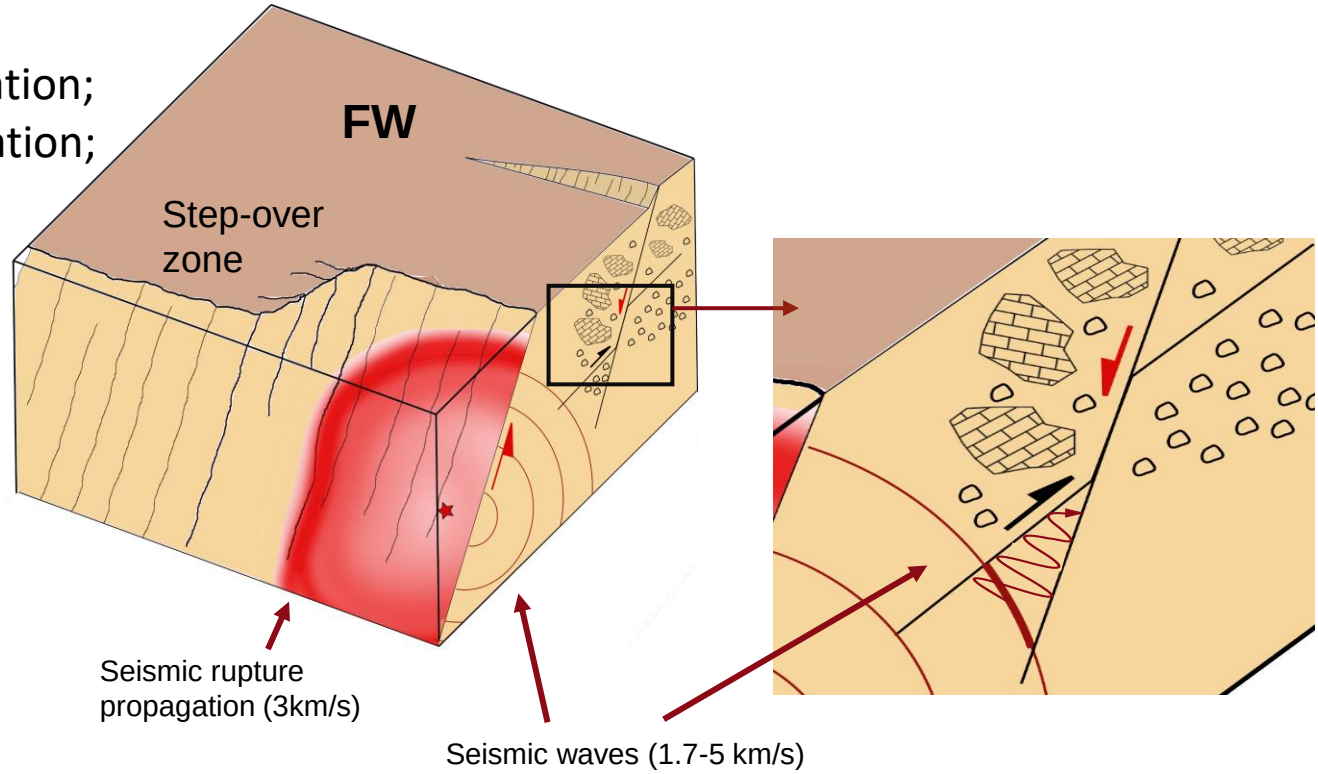
- SVF and CDSF are similar in length, lithology and displacement, but they develop different damage zones: SVF damage zone is thicker and with higher fracture density compared to the CDSF damage zone;

- Inherited structures is the main factor controlling thickness of DZ that varies along main fault strike;

- Differences in DZ characteristics could be related to carbonates with different mechanical properties (pelagic vs platform carbonates);

- Other possible factors controlling DZ thickness:
  - Low confining pressure related to low depth exumation;
  - Barrier effect of step-over zones in rupture propagation;
  - Trapped seismic waves in inherited structures.

Problems:
- Difficulty to constrain DZ thickness due to few and unreachable outcrops perpendicular to the main fault;
- Inaccurate fault displacement data;
- Few constraints about damage in the HW (symmetrical or not?)



References

- Agosta, F., and D. L. Kirschner, 2003. “Fluid Conduits in Carbonate-Hosted Seismogenic Normal Faults of Central Italy.” *Journal of Geophysical Research: Solid Earth* 108 (B4). https://doi.org/10.1029/2002jb002013.
- Allmendinger, R. W., Cardozo, N. C., and Fisher, D., 2013, Structural Geology Algorithms: Vectors & Tensors: Cambridge, England, Cambridge University Press, 289 pp.
- Billi, A., 2010. “Microtectonics of Low-P Low-T Carbonate Fault Rocks.” *Journal of Structural Geology* 32 (9): 1392–1402. https://doi.org/10.1016/j.jsg.2009.05.007.
- Cardozo, N., and Allmendinger, R. W., 2013, Spherical projections with OSXStereonet: Computers & Geosciences, v. 51, no. 0, p. 193 - 205, doi: 10.1016/j.cageo.2012.07.021
- Centamore E., Crescenti U., Dramis F., 2006. Note Illustrative del Foglio 369 “Sulmona” della Carta Geologica d'Italia alla scala 1: 50.000. ISPRA, Roma.
- Centamore E., Crescenti U., Dramis F., 2006. Note Illustrative del Foglio 360 “Torre de’ Passeri” della Carta Geologica d'Italia alla scala 1: 50.000. ISPRA, Roma
- Demurtas M., Fondriest M., Balsamo F., Clemenzi L., Storti F., Bistacchi A., and Di Toro G., 2016. “Structure of a Normal Seismogenic Fault Zone in Carbonates: The Vado Di Corno Fault, Campo Imperatore, Central Apennines (Italy).” *Journal of Structural Geology* 90: 185–206. https://doi.org/10.1016/j.jsg.2016.08.004 .
- Falcucci, E., Gori S., Moro M., Pisani A., Melini D., Galadini, F. and Fredi P., 2011. “The 2009 L’Aquila Earthquake (Italy): What’s next in the Region? Hints from Stress Diffusion Analysis and Normal Fault Activity.” *Earth and Planetary Science Letters* 305 (3–4): 350–58. https://doi.org/10.1016/j.epsl.2011.03.016 .
- Falcucci, E., Gori S., Moro M., G. Fubelli, M. Saroli, C. Chiarabba, and F. Galadini, 2015. “Deep Reaching versus Vertically Restricted Quaternary Normal Faults: Implications on Seismic Potential Assessment in Tectonically Active Regions: Lessons from the Middle Aterno Valley Fault System, Central Italy.” *Tectonophysics* 651: 186–98. https://doi.org/10.1016/j.tecto.2015.03.021.
- Galadini, F., and Messina P., 2001. “Plio-Quaternary Changes of the Normal Fault Architecture in the Central Apennines (Italy).” *Geodinamica Acta* 14 (6): 321–44. https://doi.org/10.1080/09853111.2001.10510727.
- Kim, Y.-S., D. C.P. Peacock, D. J. Sanderson, 2004. “Fault Damage Zones.” *Journal of Structural Geology* 26 (3): 503–17. https://doi.org/10.1016/j.jsg.2003.08.002.
- Mayolle, S., Soliva R., Caniven Y., Wibberley C., Ballas G., Milesi G. and Dominguez S., 2019. “Scaling of Fault Damage Zones in Carbonate Rocks.” *Journal of Structural Geology* 124 (March): 35–50. https://doi.org/10.1016/j.jsg.2019.03.007.
- Miccadei E., Parotto M., and Piacentini T., 1998. “Assetto Geologico-Strutturale Dei Monti Della Conca Subequana (Appennino Abruzzese, Italia Centrale).” *Geologica Romana* 34 (1): 31–50.
- *Rovida A., Locati M., Camassi R., Lolli B., Gasperini P. (2020). The Italian earthquake catalogue CPTI15. Bulletin of Earthquake Engineering, 18(7), 2953-2984. https://doi.org/10.1007/s10518-020-00818-y*