Fault Displacement Hazards Analysis Workshop
December 8 - 9, 2016
US Geological Survey Campus Menlo Park, CA

SURFACE RUPTURE OF THE 2016 EARTHQUAKE SEQUENCE IN CENTRAL ITALY

AUGUST 24TH Mw 6.0 AMATRICE - OCTOBER 26th Mw 5.9 VISSO - OCTOBER 30th Mw 6.5 CASTELLUCCIO

*Francesca R. Cinti**

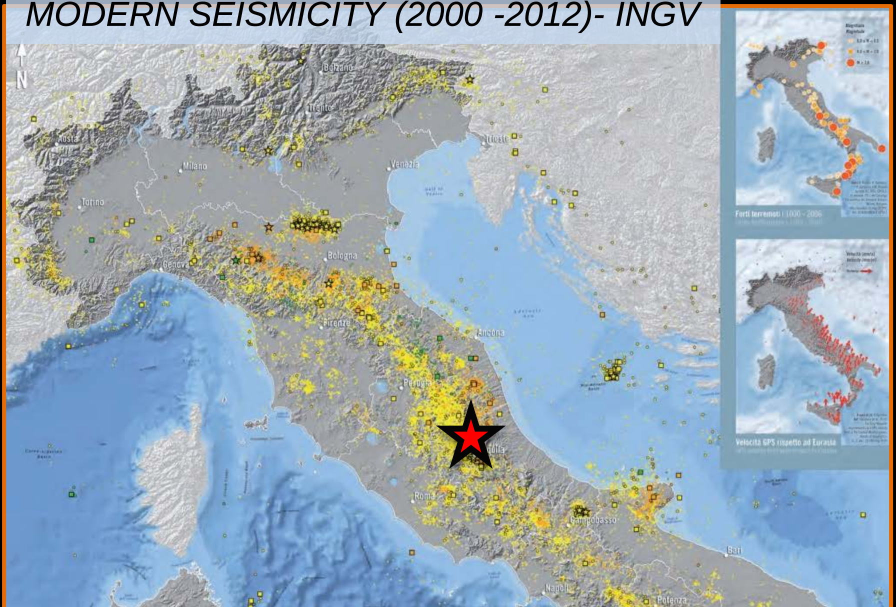
Emergeo Working Group, ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA*

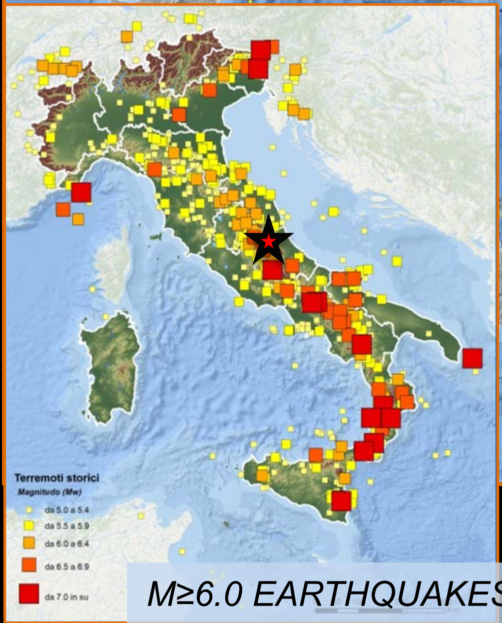
collaboration: *ISPRA, UniChieti, UnInsubria, UniCassino, UniCam, Univ. L'Aquila, CNR, ENEA, IRSN, CNRS, Birbeck Univ., Leeds Univ., Univ. College London, London Univ., Geos. Res.Ltd., Durham Univ.*

http://emergeo.ingv.it

THE APENNINES ARE AN ACTIVELY EXTENDING MOUNTAIN BELT

MODERN SEISMICITY (2000 -2012)- INGV



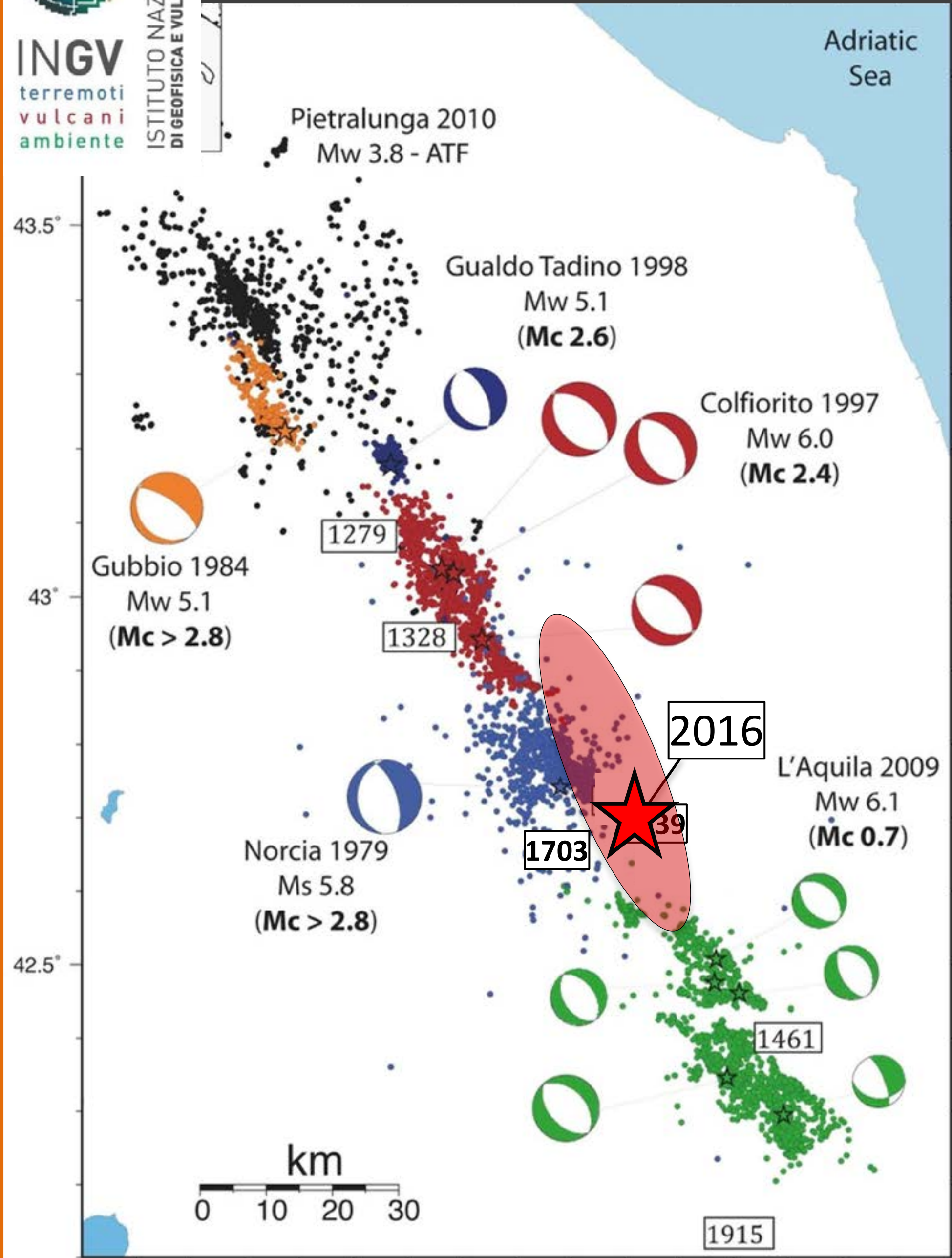


M≥6.0 EARTHQUAKES (1000 -2006)- INGV

ITHACA- ITaly HAzard from CApable faults (ISPRA)

THE 2016 SEISMOGENIC AREA

INGV terremoti vulcani ambiente
ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

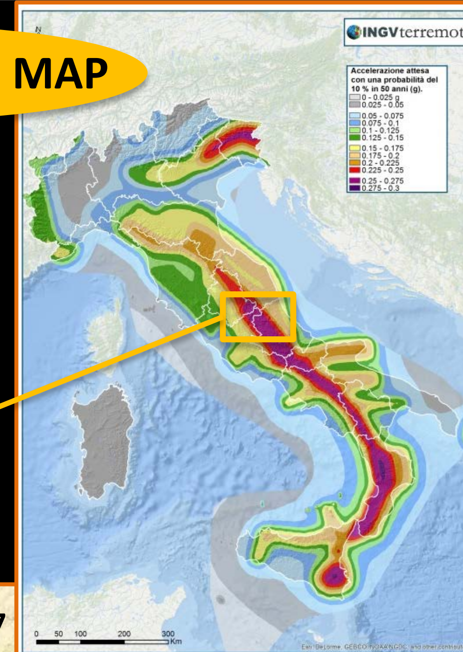


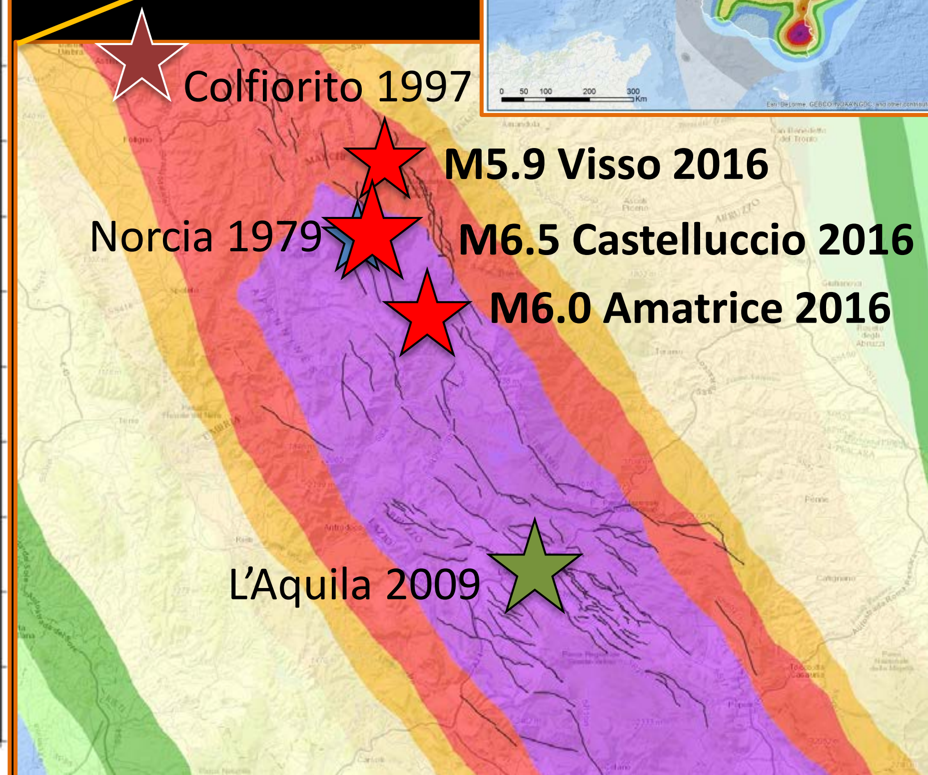
Chiaraluce JSG 2012

SEISMIC HAZARD MAP

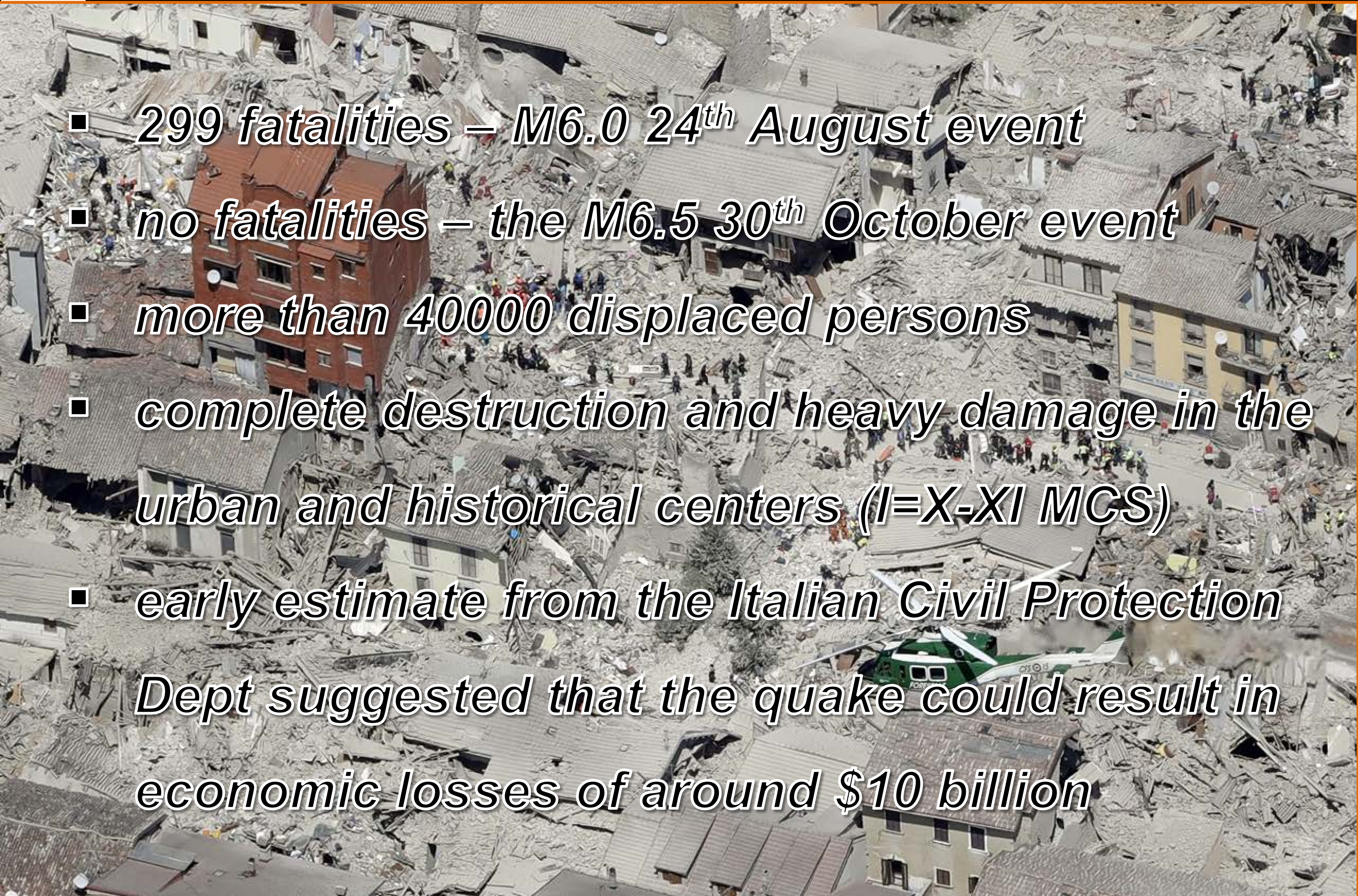
Highest Seismic Hazard Level

maximum ground shaking (0.250-0.275 g) seismic hazard for 10% probability of exceedance in 50 year

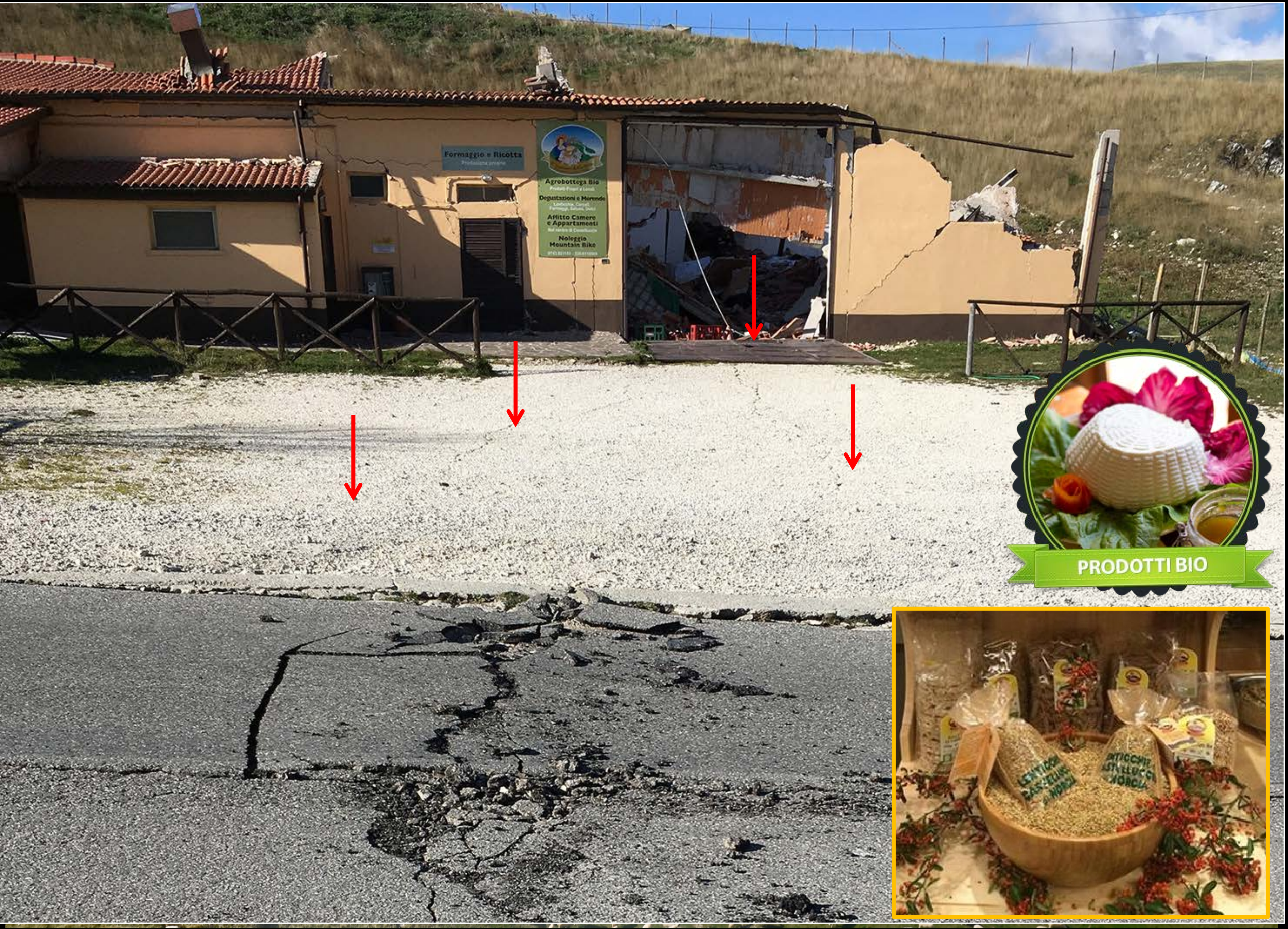




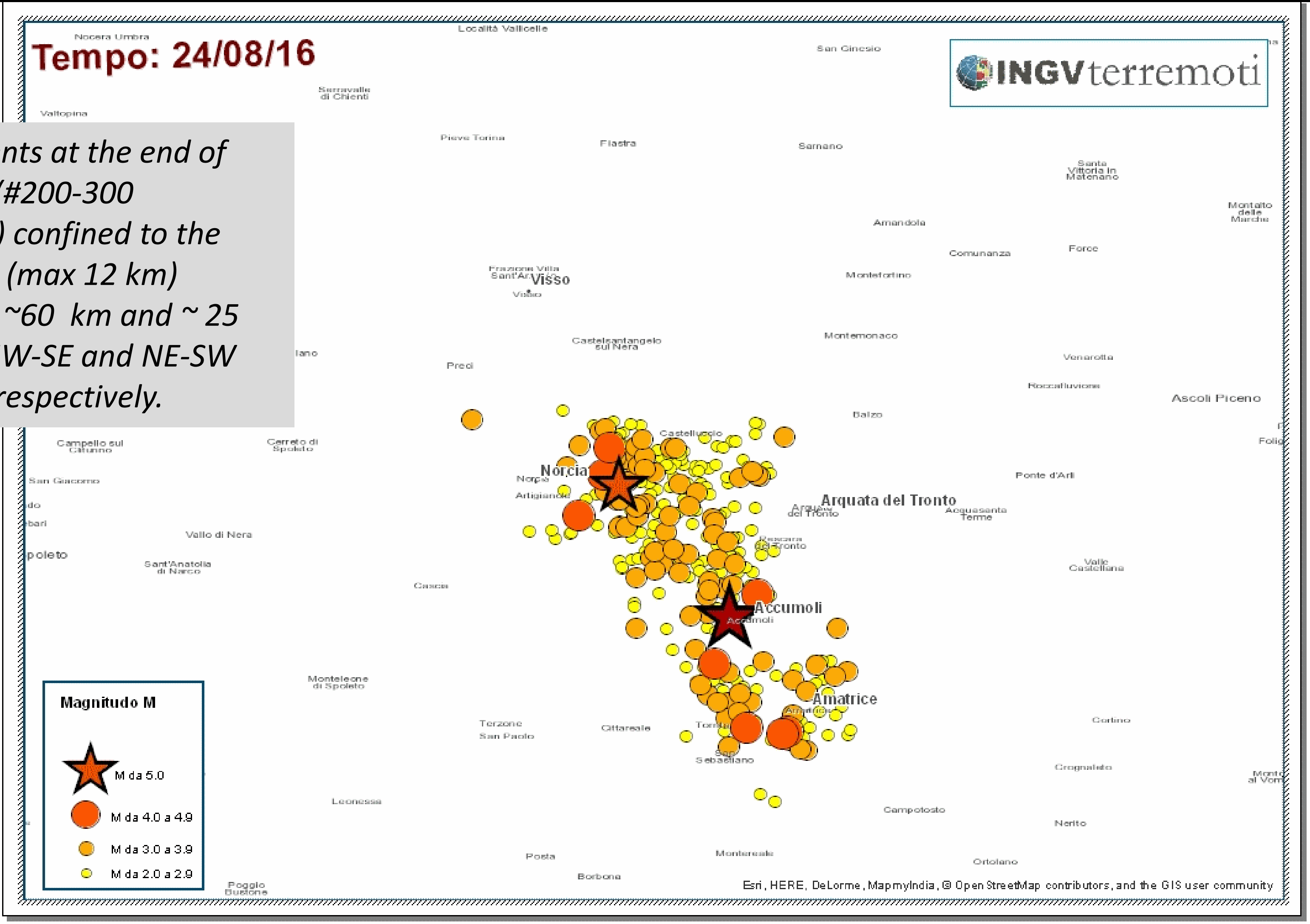
HUMAN AND ECONOMIC LOSSES



- *299 fatalities – M6.0 24th August event*
- *no fatalities – the M6.5 30th October event*
- *more than 40000 displaced persons*
- *complete destruction and heavy damage in the urban and historical centers (I=X-XI MCS)*
- *early estimate from the Italian Civil Protection Dept suggested that the quake could result in economic losses of around $10 billion*


Formaggio e Ricotta
Agrobottega Bio
Degustazioni e Merende
Affitto Camere
e Appartamenti
Noleggio
Mountain Bike
PRODOTTI BIO

~30000 events at the end of November (#200-300 events/day) confined to the upper crust (max 12 km) extends for ~60 km and ~ 25 km in the NW-SE and NE-SW directions, respectively.



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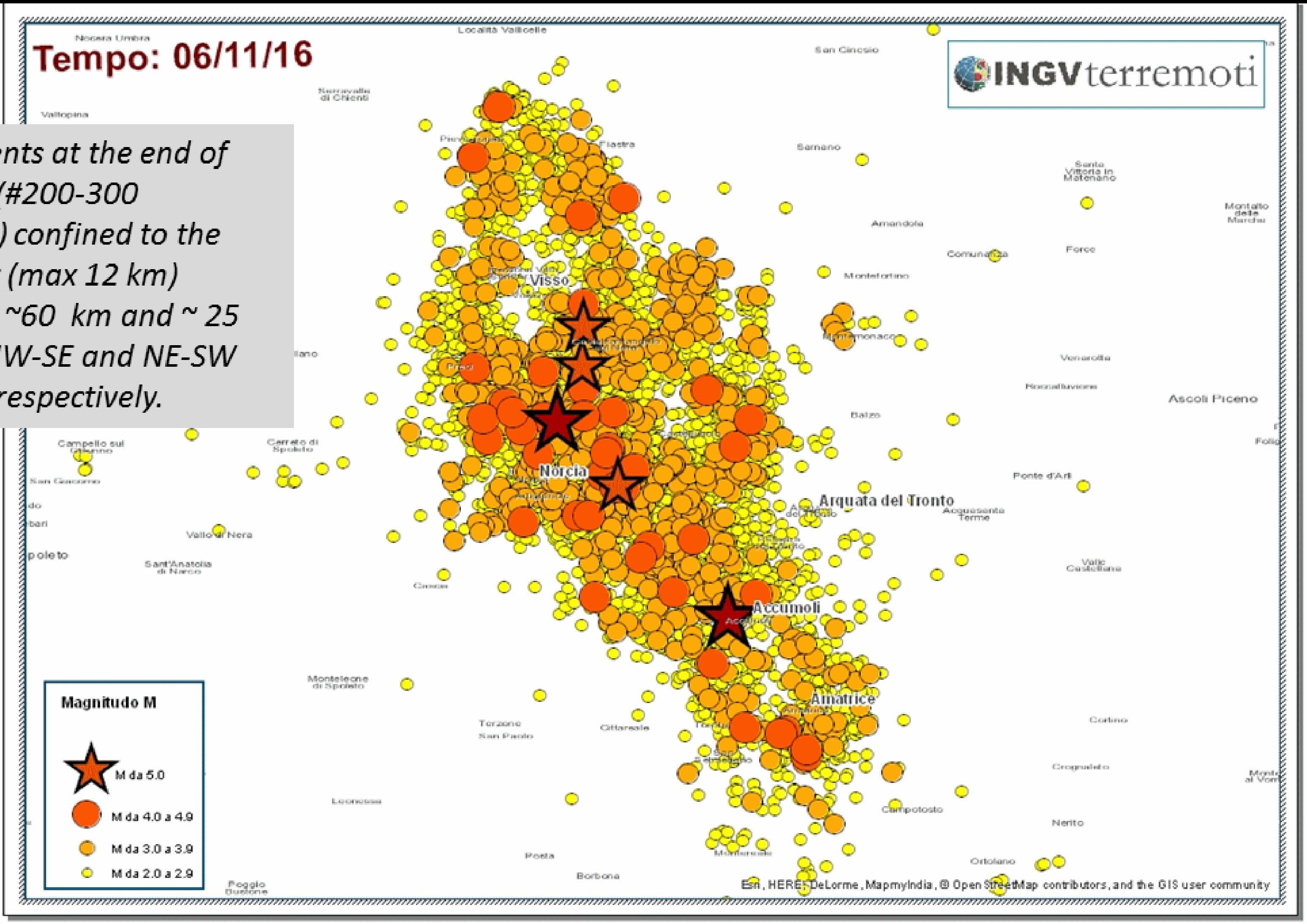
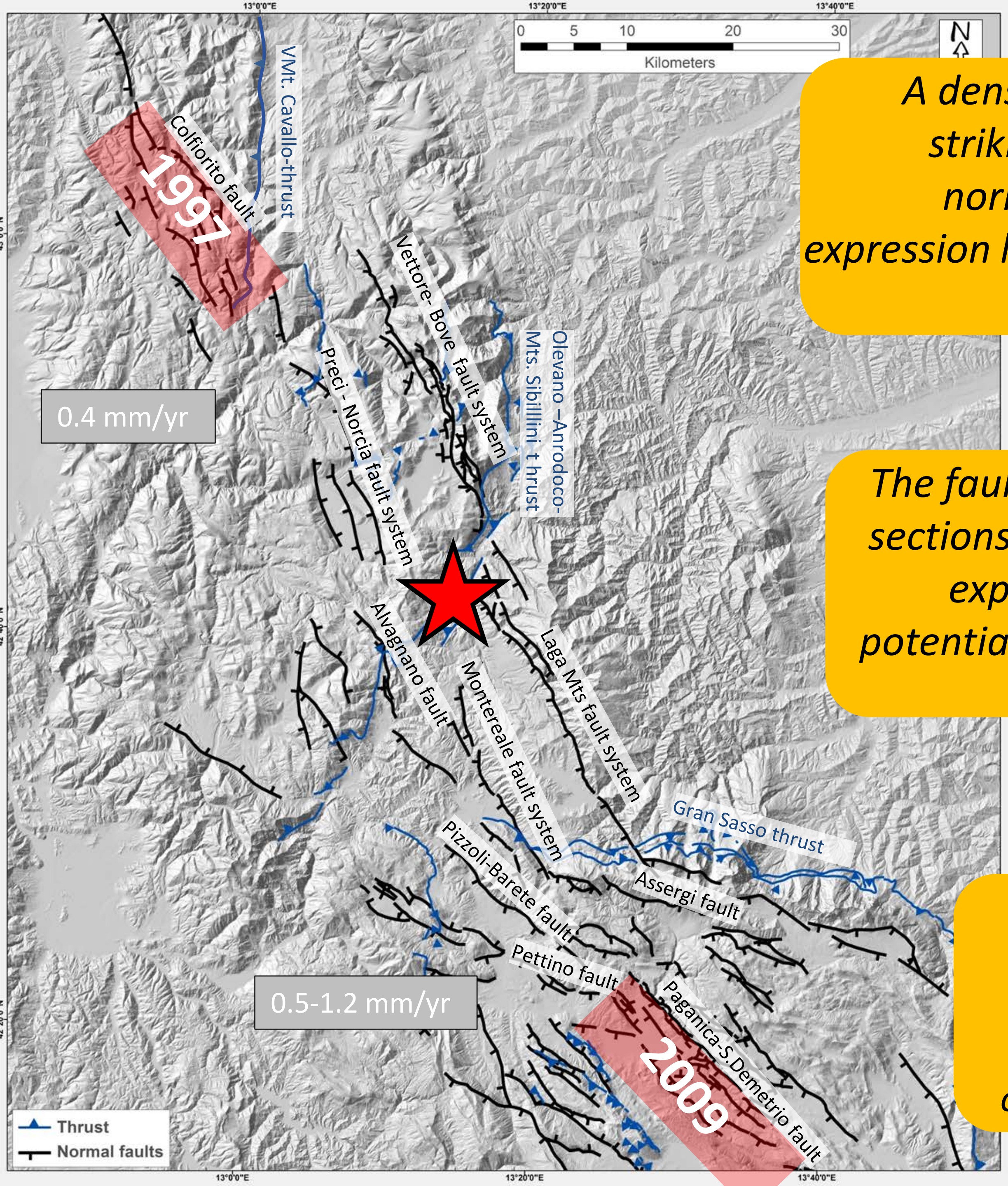




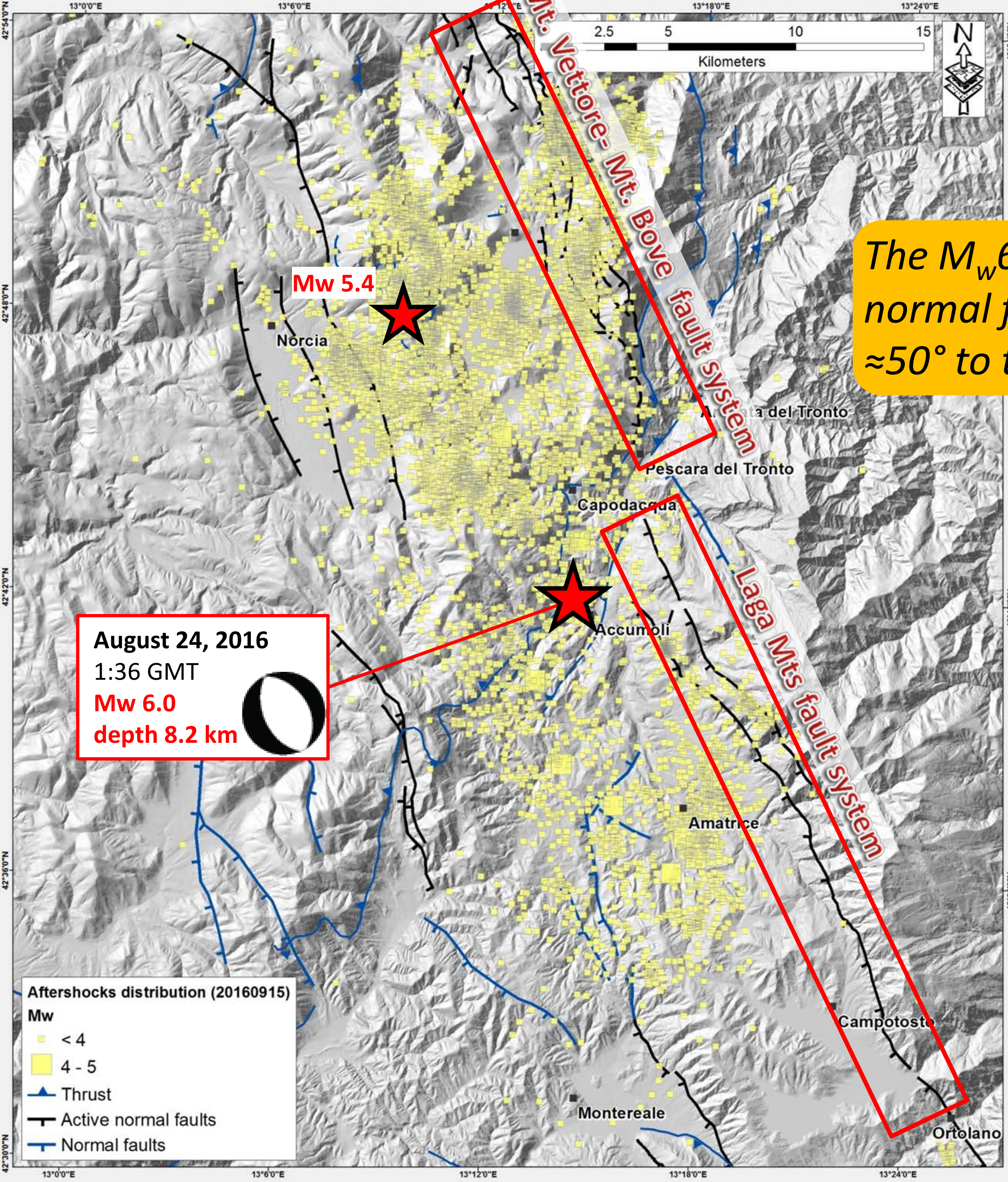
A dense array of NW-SE to NNW-SSE striking, mostly SW- dipping, active normal fault systems, with surface expression longer 20-30 km, made of fault sections 5-10 km long

The fault systems and the related fault sections likely represent the superficial expression of seismogenic sources potentially responsible for earthquakes with M between 5.5 and 7.0

The major NNE-SSW and ESE-WNW striking faults represent the principal pre-existing cross-structures with respect to the axis of Quaternary extensional faulting

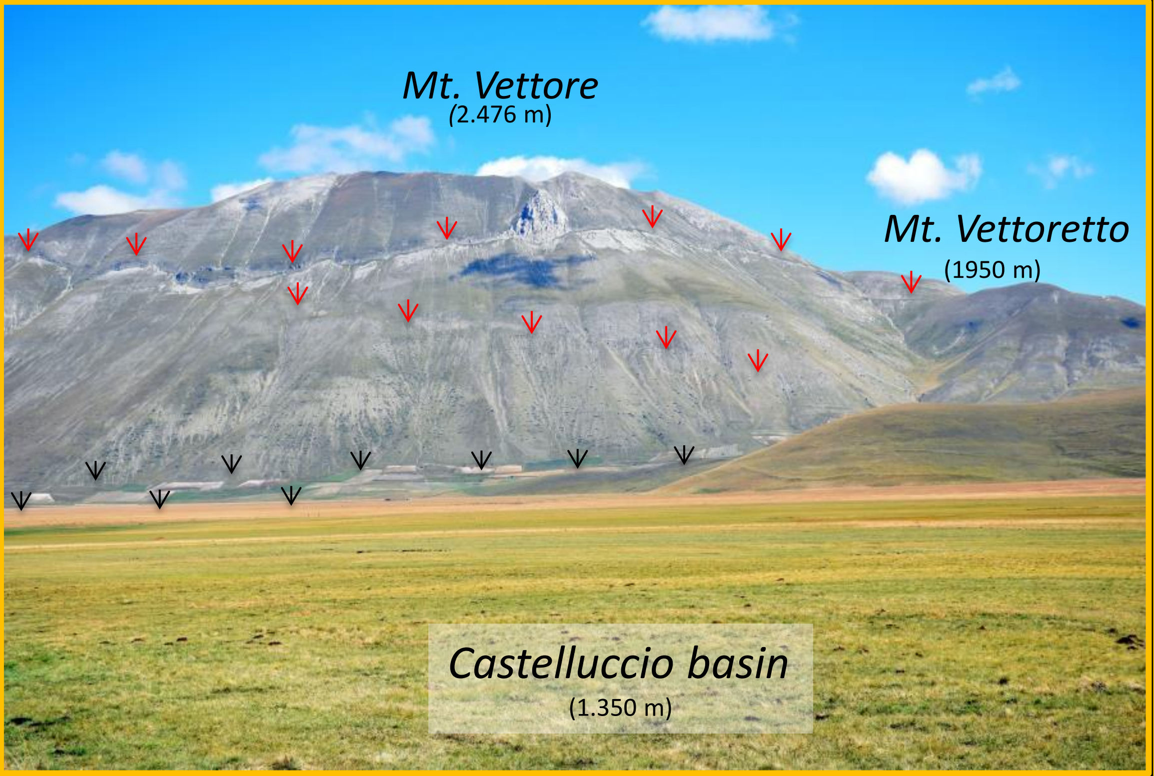
THE 24th AUGUST 2016 Mw6.0

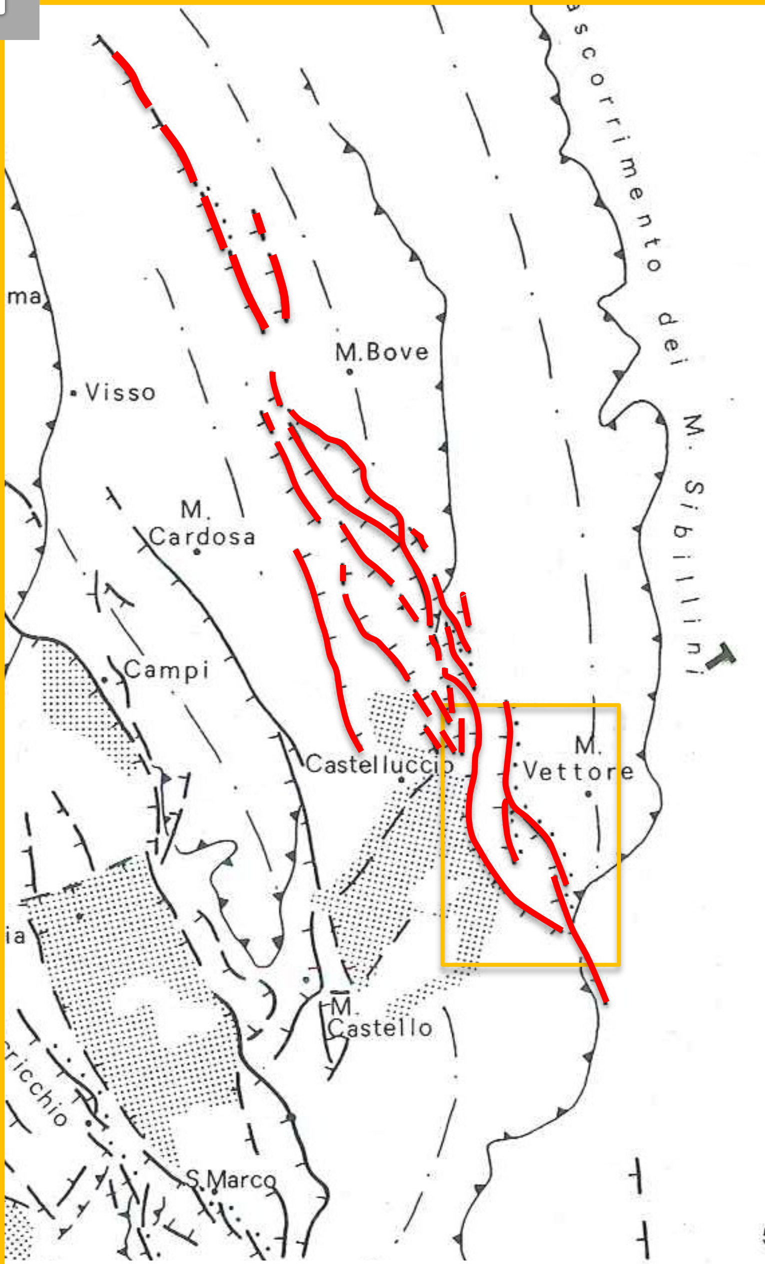
The M_w6.0 main shock ruptured a normal fault striking ≅155° and dipping ≈50° to the SW



THE Mt. VETTORE- Mt. BOVE FAULT SYSTEM

Well mapped extensional tectonic element
NNW-SSE trending, SW dipping normal faults

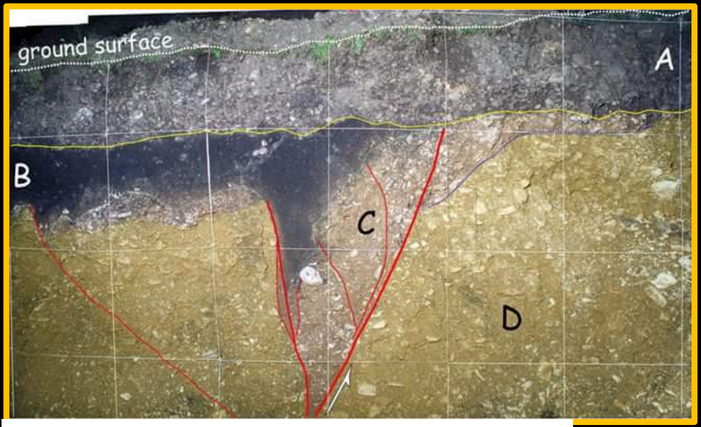




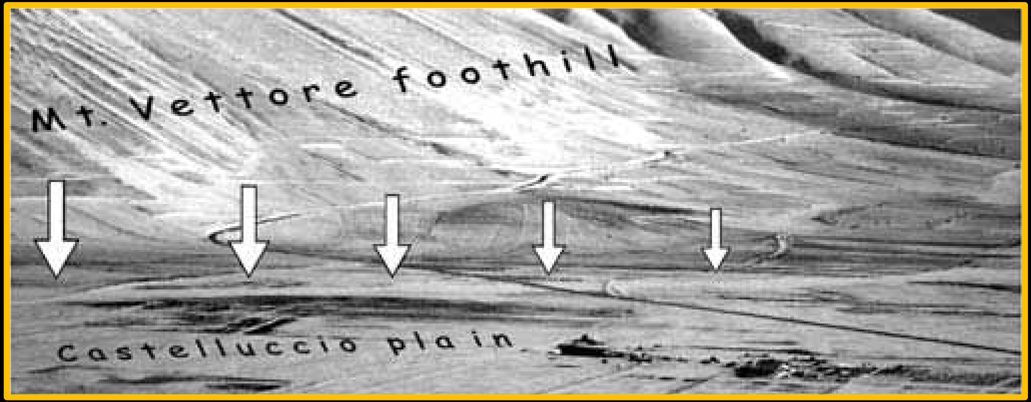
Calamita & Pizzi, SGC, 1992

The cumulative fault scarps along the slope are made by bedrock at the footwall (mostly Corniola Fm.) and by highly fractured bedrock as well as unconsolidated deposits (generally cryoclastic debris) at the hanging wall.

THE Mt. VETTORE-Mt. BOVE FAULT SYSTEM



Galadini & Galli, Ann. Geophys, 2003



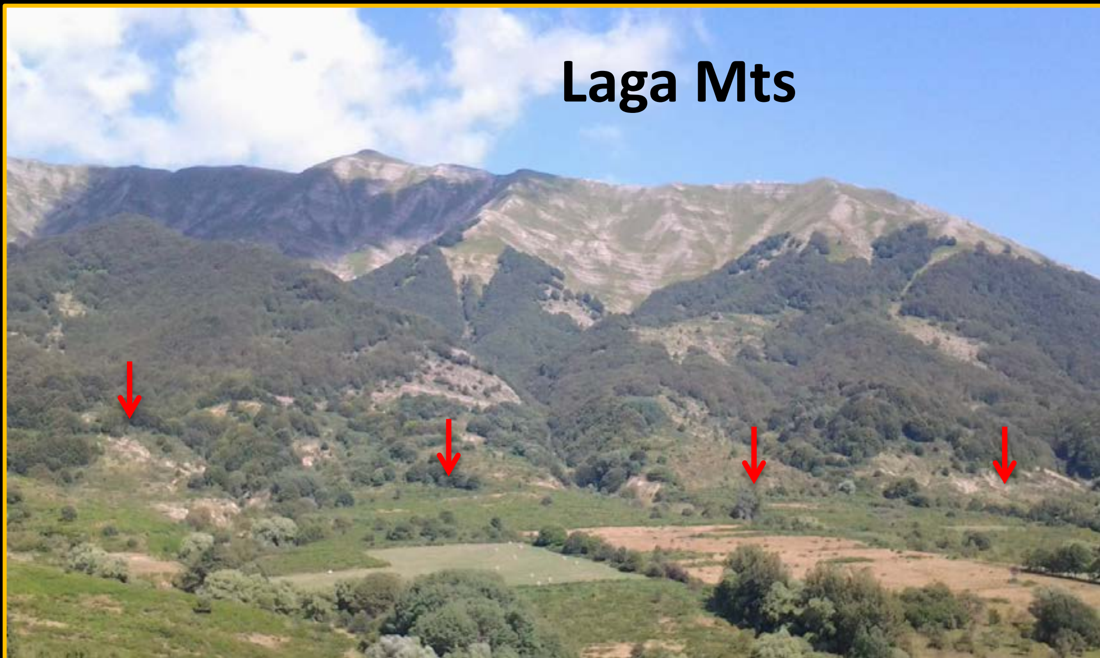
EXPECTED MAGNITUDE
M 6.5

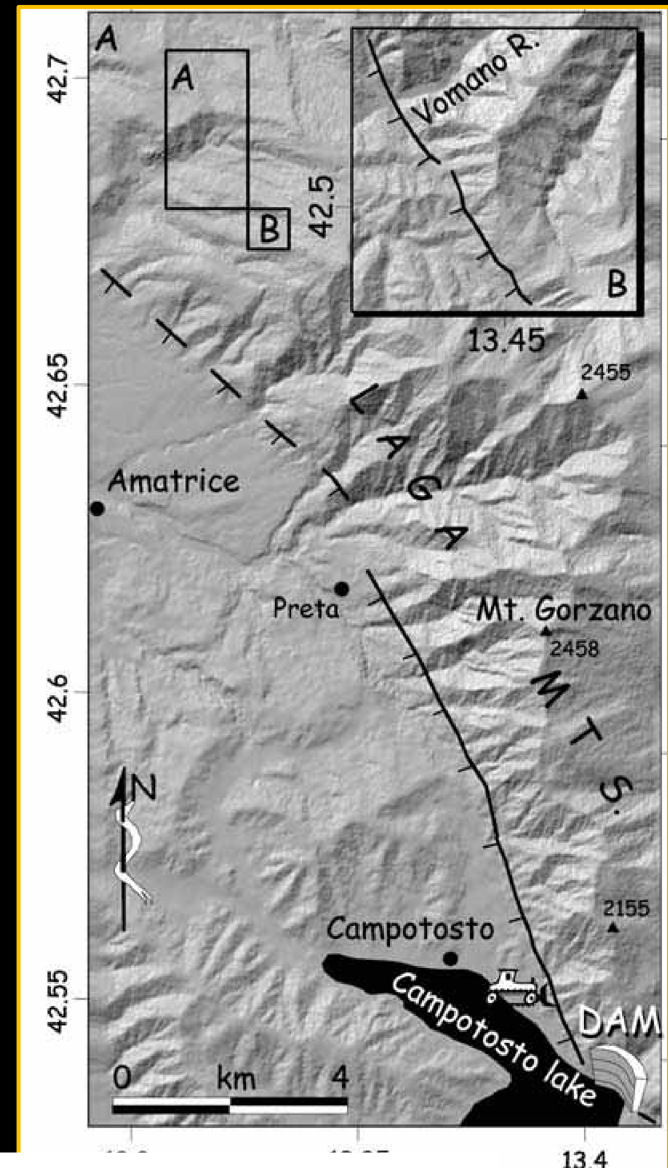
MIN ELAPSED TIME
1300-1500 yr

SILENT FAULT

THE LAGA Mts FAULT SYSTEM

NW-SE-trending, 30 km long, parallel fault splays affecting the Laga Mts. SW slope at different height



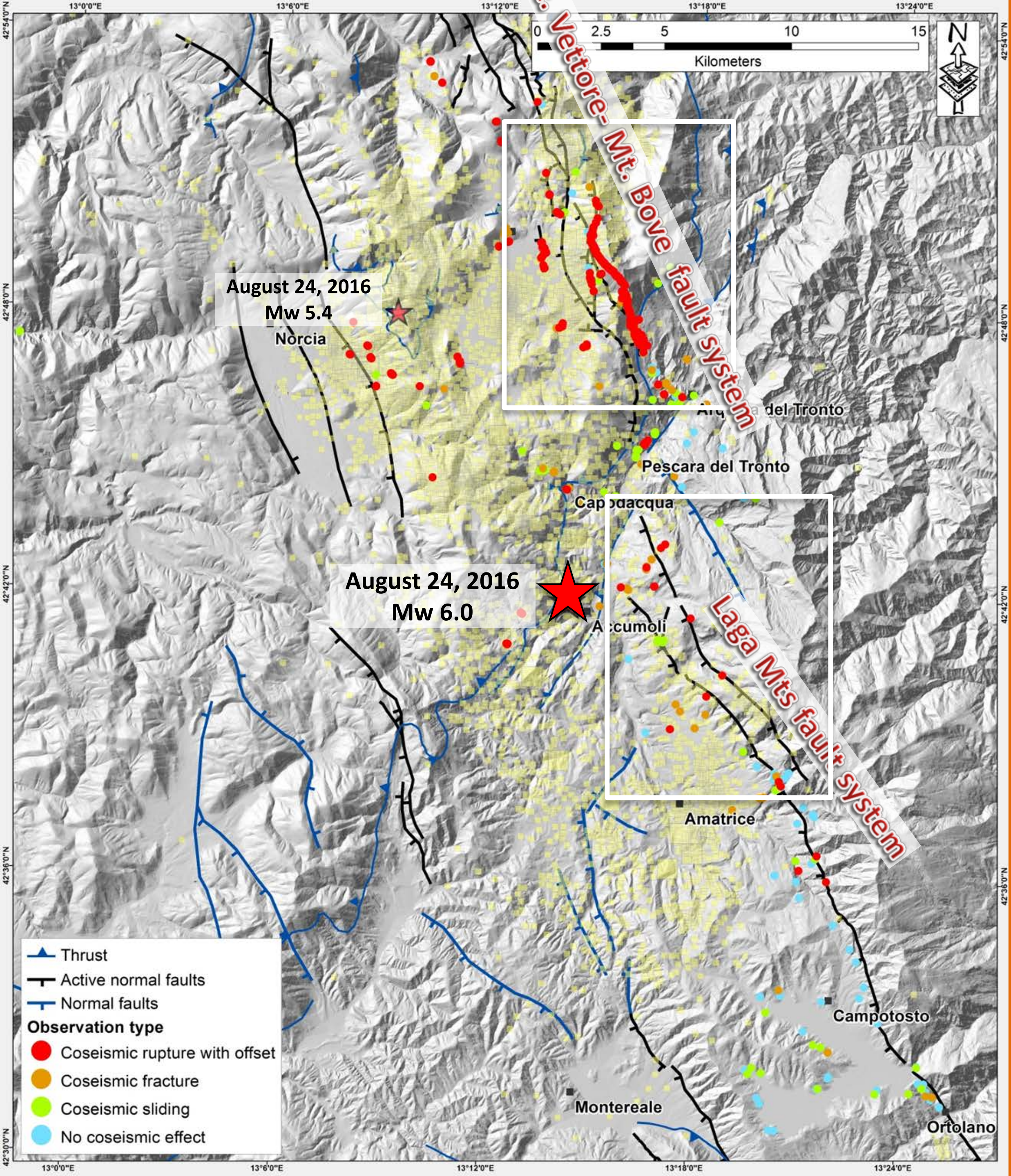


EXPECTED MAGNITUDE
M 6.6

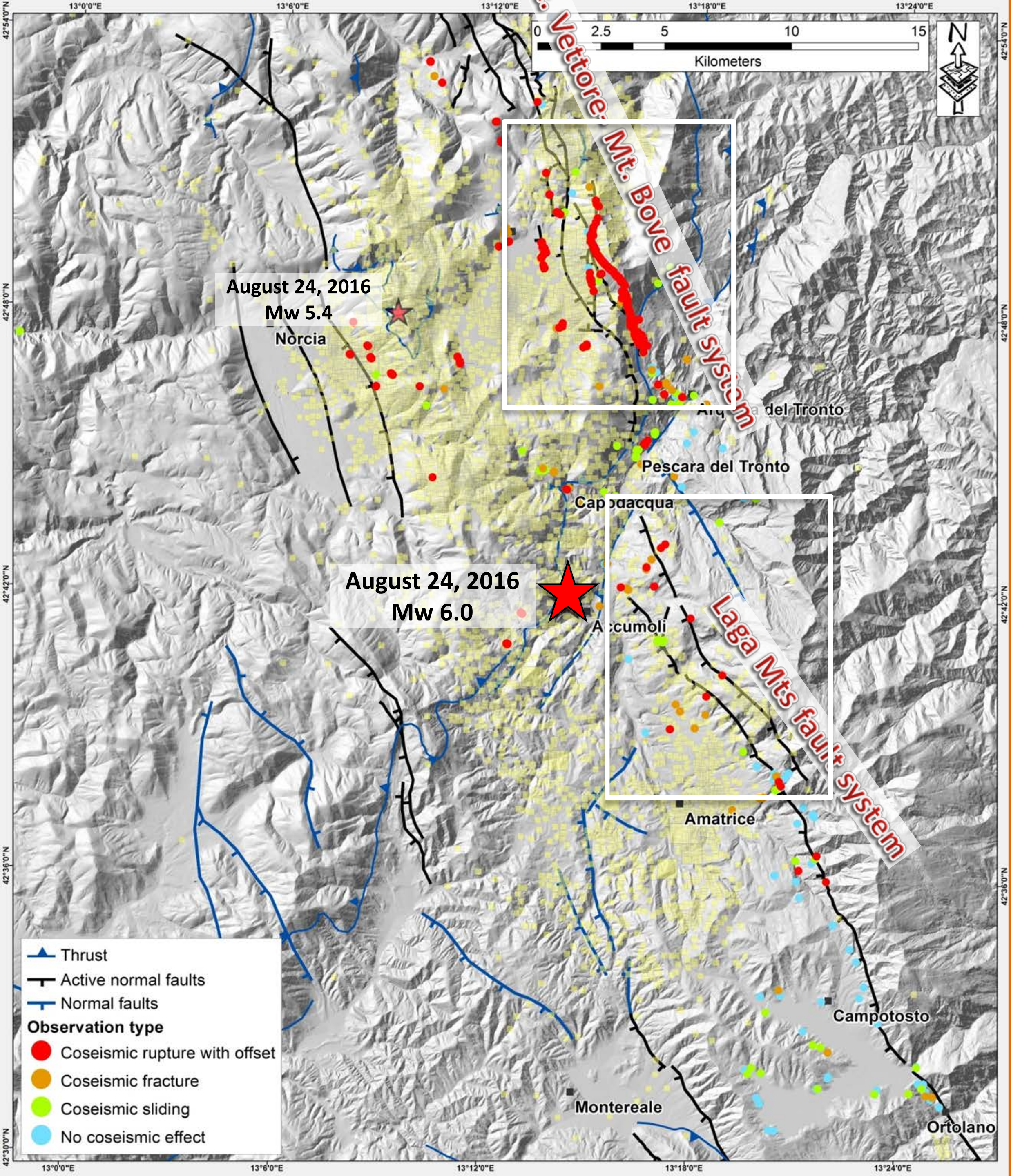
SILENT FAULT

Galadini & Galli, Ann. Geophys, 2003

OBSERVATIONS RELATIVE TO THE 24TH AUGUST 2016

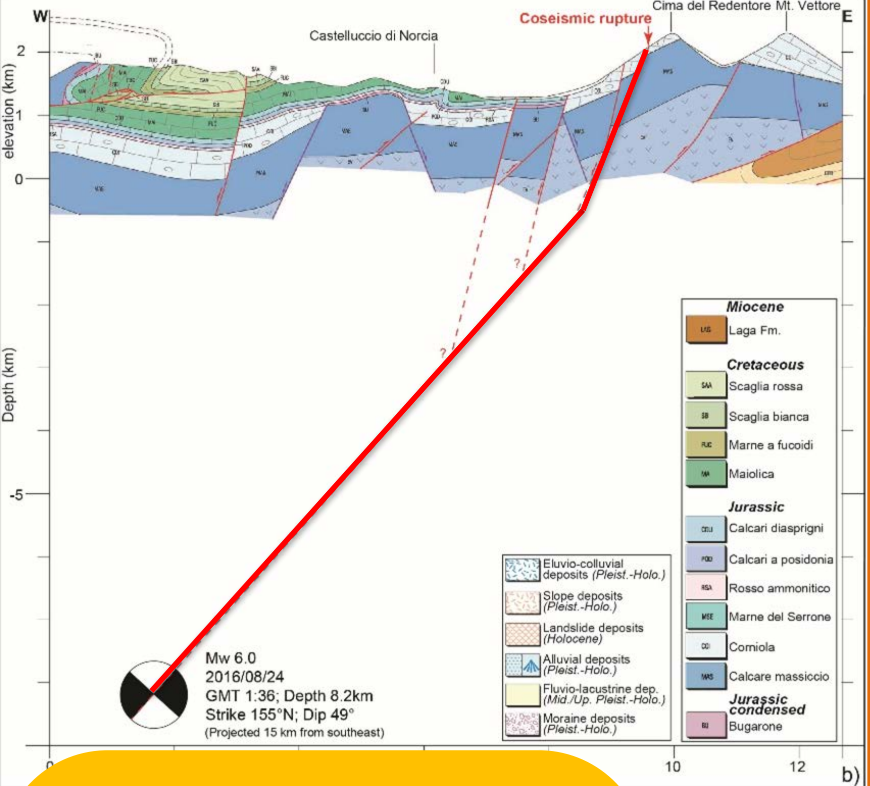


~750 km^2 wide area, recording measurements of coseismic ruptures (i.e. surface cracks exhibiting both vertical displacements and opening >1cm), fractures (i.e. small surface open cracks exhibiting displacement <1 cm), landslides, clast extrusions, soil remobilization, remobilized DGSD

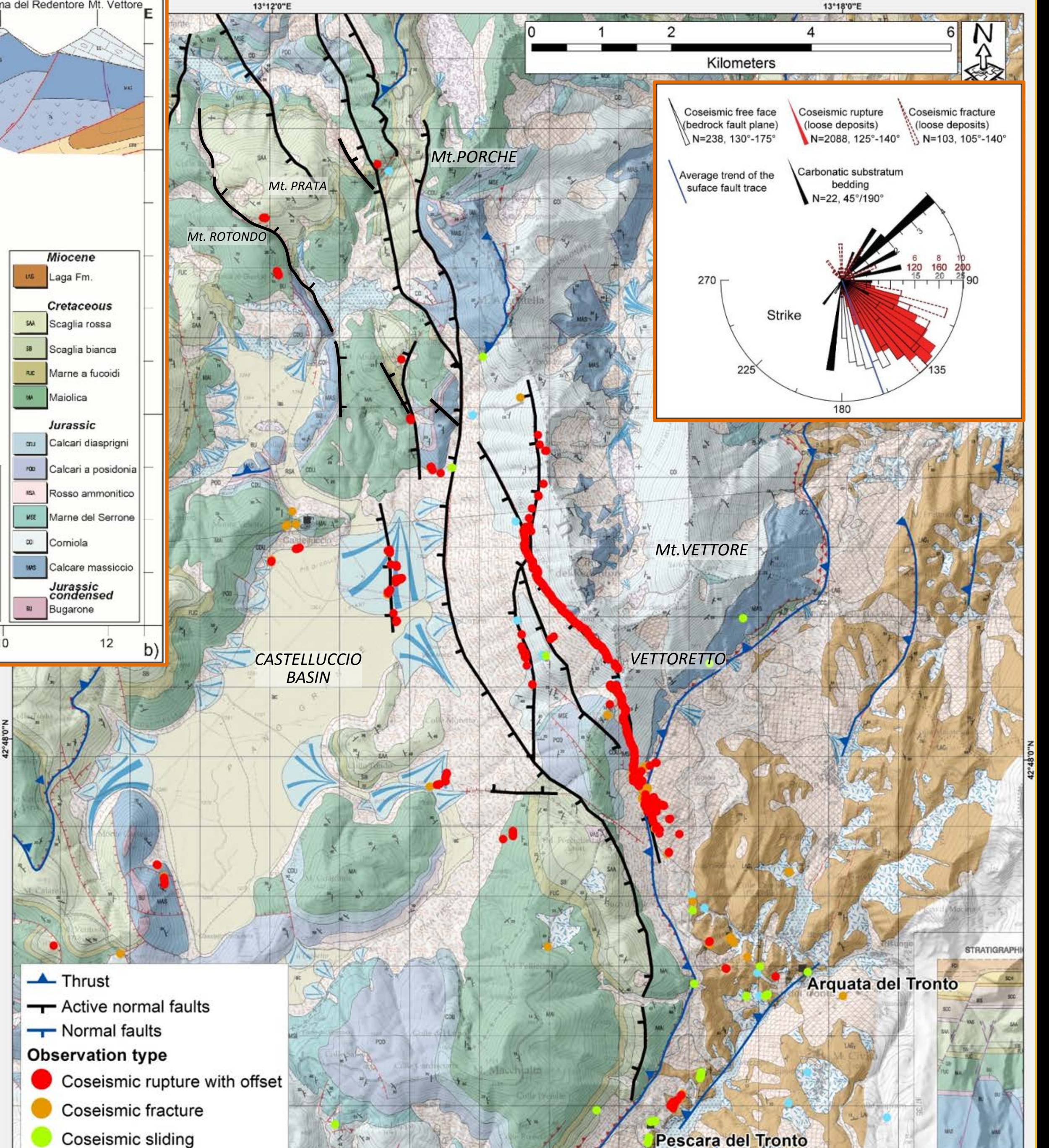


OBSERVATIONS RELATIVE TO THE 24TH AUGUST 2016

LAGA Mts fault system: discontinuous (maximum 300 m-long) coseismic ruptures with small displacements (maximum 5 cm), mostly concentrated along its northern sector.



Vettore Mt.-Bove Mt. fault system SURFACE FAULTING: continuous alignment of ruptures, minimum total length ~5.2 km, N155°-striking, SW side down, following the base of the cumulative tectonic scarps of the Vettore-Bove fault system.

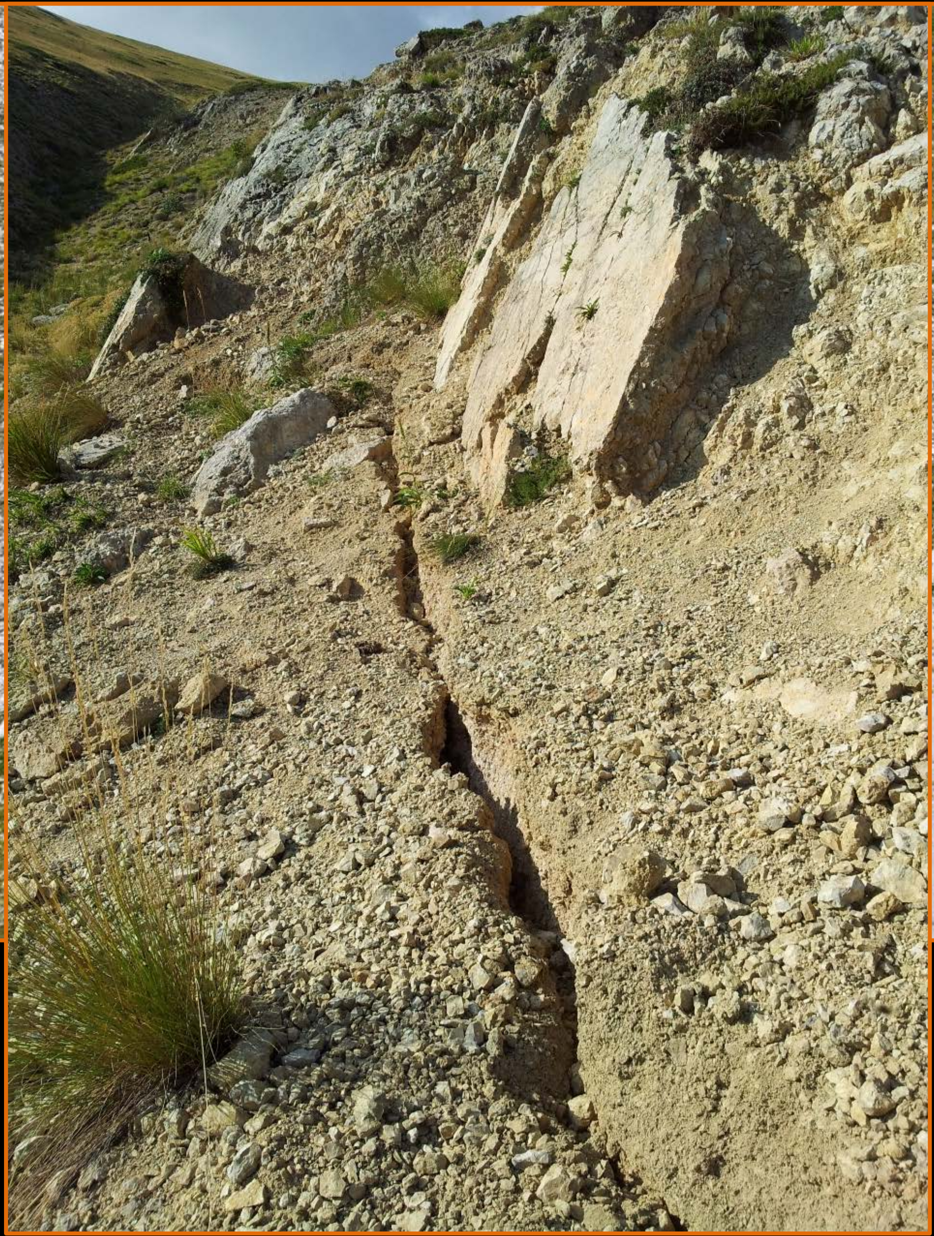


Emergeo Working Group, Ann. Geophys., 2016

V 10 cm
O 8 cm

en-echelon rupture affecting unconsolidated slope deposits and a trail

On bedrock fault planes, the newly formed free face looks like a fresh, light-coloured stripe of rejuvenated bedrock surface, with soil shade and no lichens



Continuous and narrow rupture at the hanging wall of the bedrock fault plane

The rupture trace preserves its trend, regardless of the affected deposits, linking aligned and dissected fault mirrors

SPATIAL PATTERN OF THE DISPLACEMENT

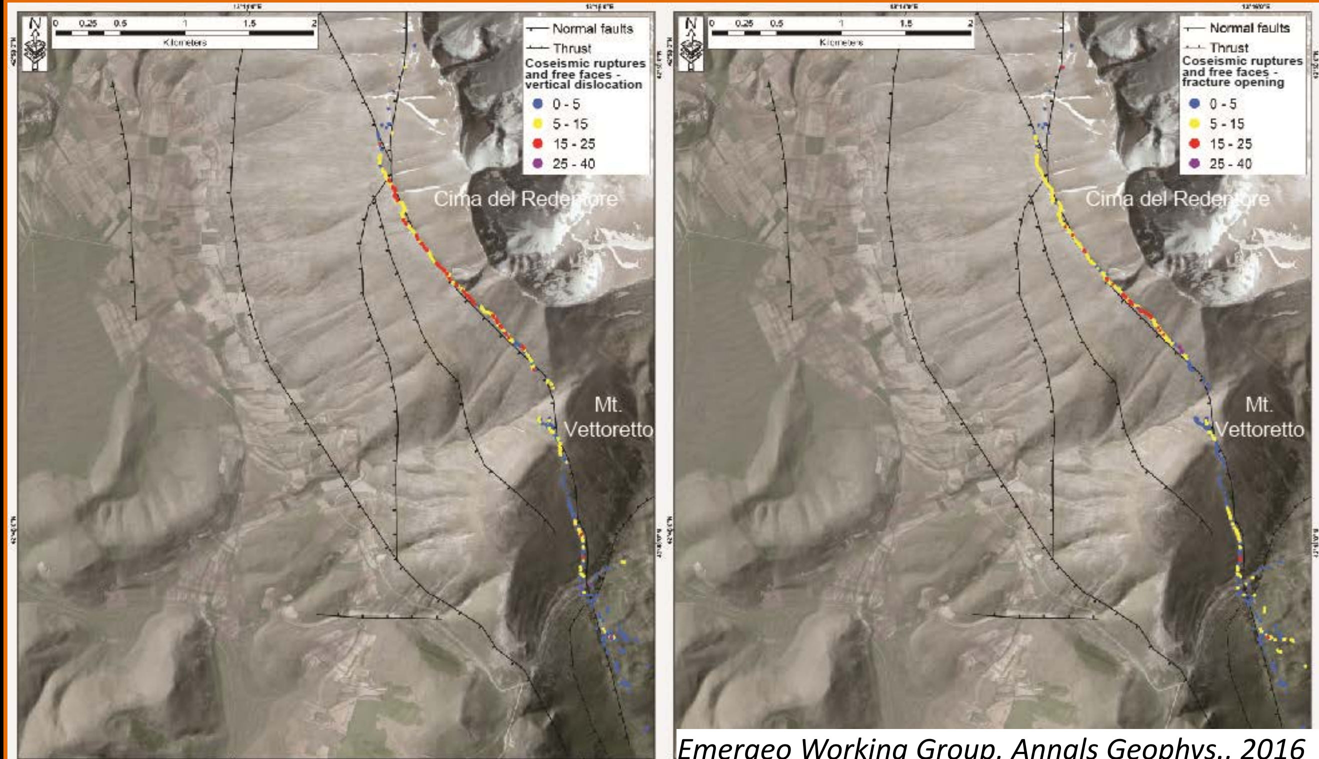
dataset N = 1465
av. spacing of measurements ~4.5 m

The displacement of the ruptures in loose deposits is mostly lower than 16 cm (max 28-30 cm). The free face when in bedrock is generally higher, in the range of 14-20 cm. Both vertical and opening values show the maxima along the central portion of the SR.

Along-strike distribution of median values of the displacement (red line) and of the opening (blue line)

VERTICAL DISLOCATION

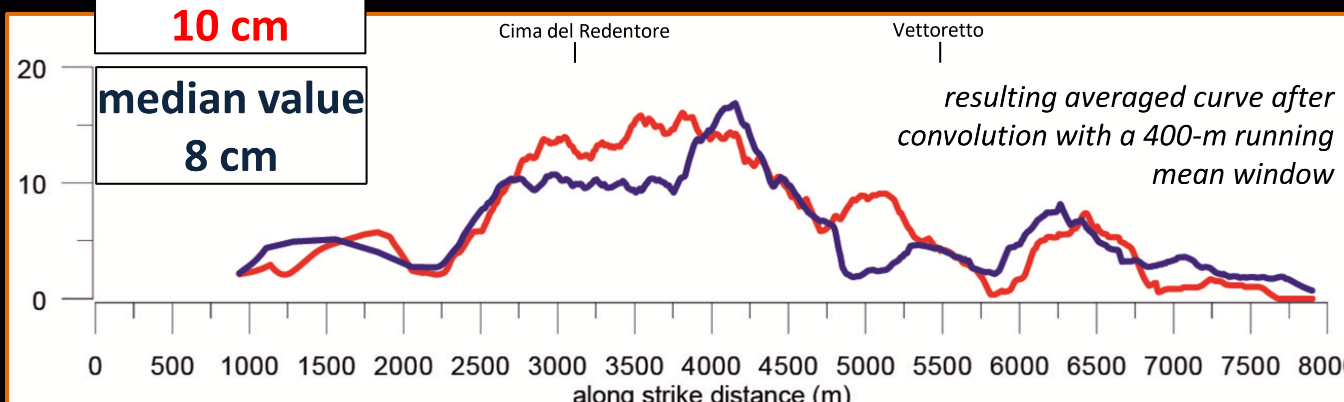
OPENING

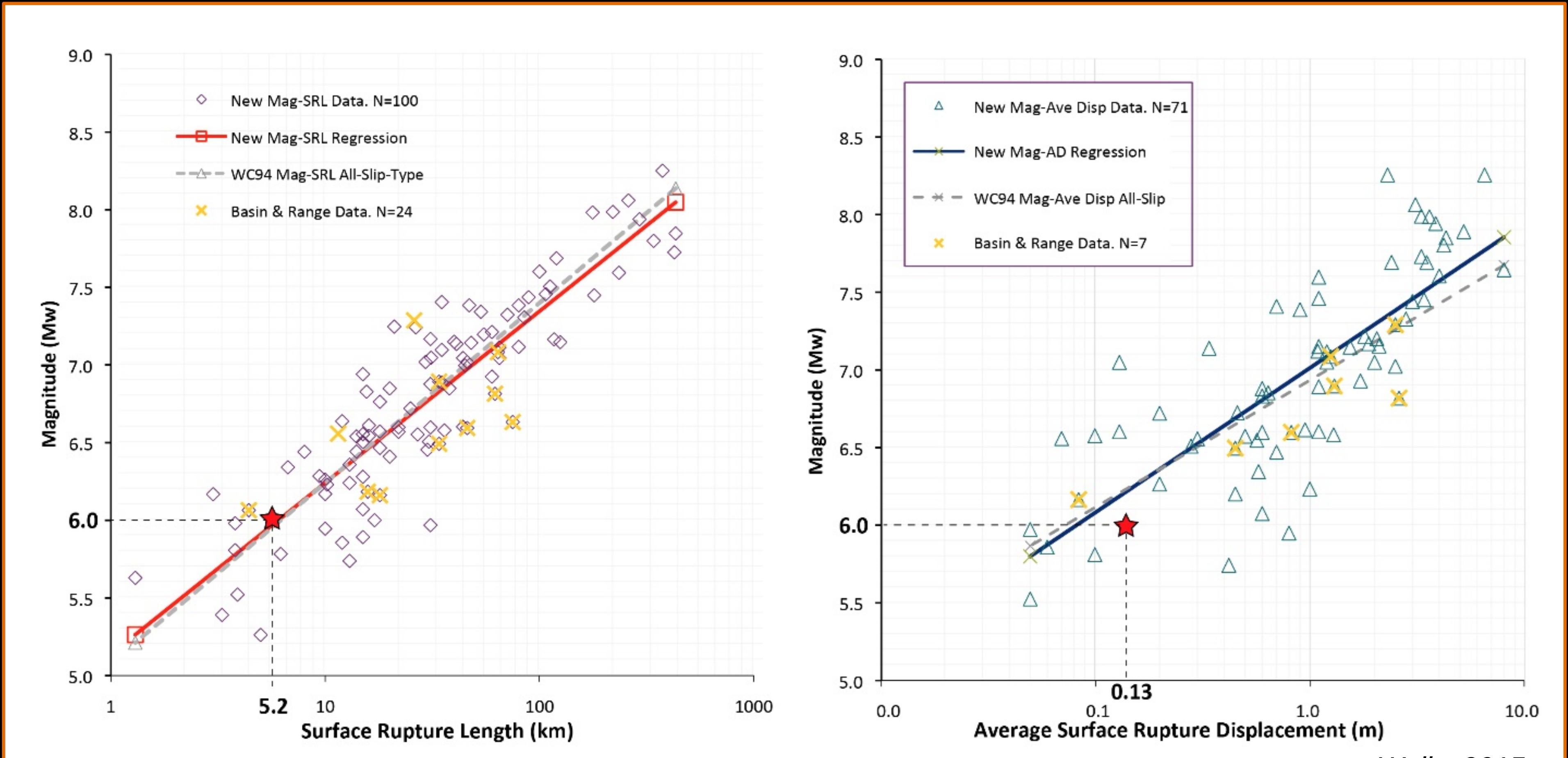


Emergeo Working Group, Annals Geophys., 2016

median value 10 cm

median value 8 cm

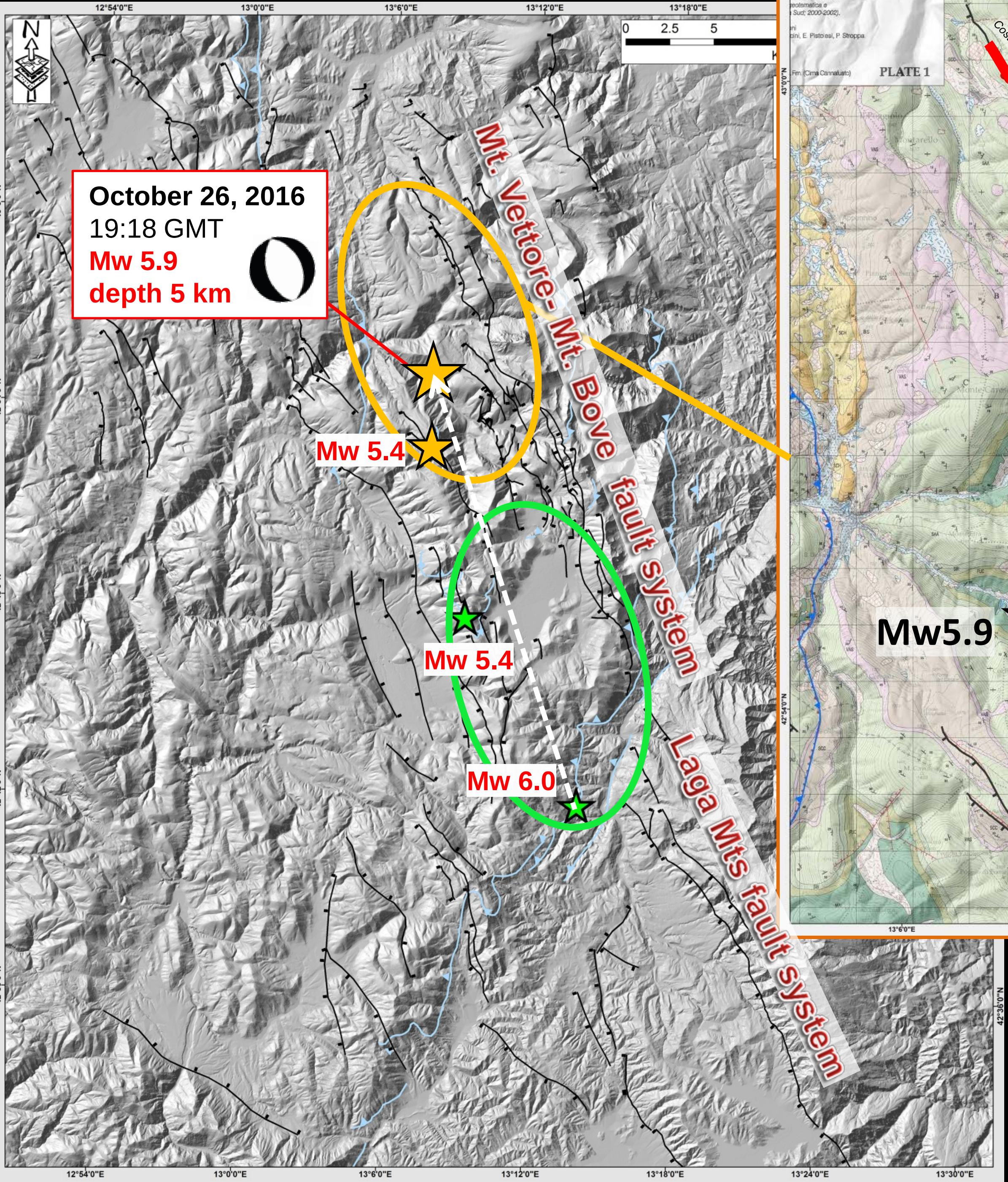


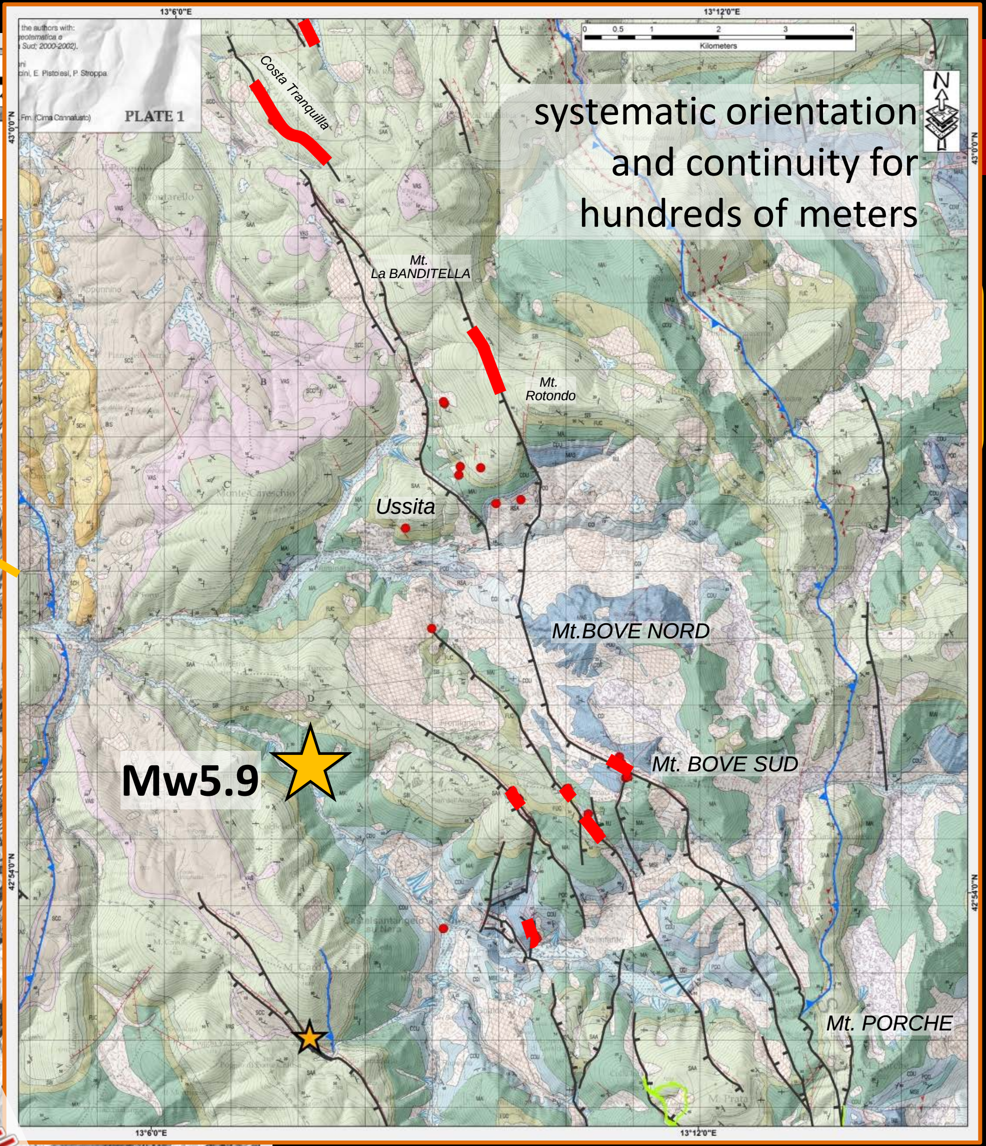


Wells, 2015

The ruptures fit quite well the empirical displacement-length relations for M 6 normal-faulting earthquakes

The average coseismic surface displacement is slightly higher with respect to the predicted value, likely due to the contribution of shallow gravitational movements





OBSERVATIONS RELATIVE TO THE 26TH OCTOBER 2016

newly formed free face on
bedrock fault plane and on
slope debris

V 10 cm
O 8 cm

av. Vertical displ. 8 cm

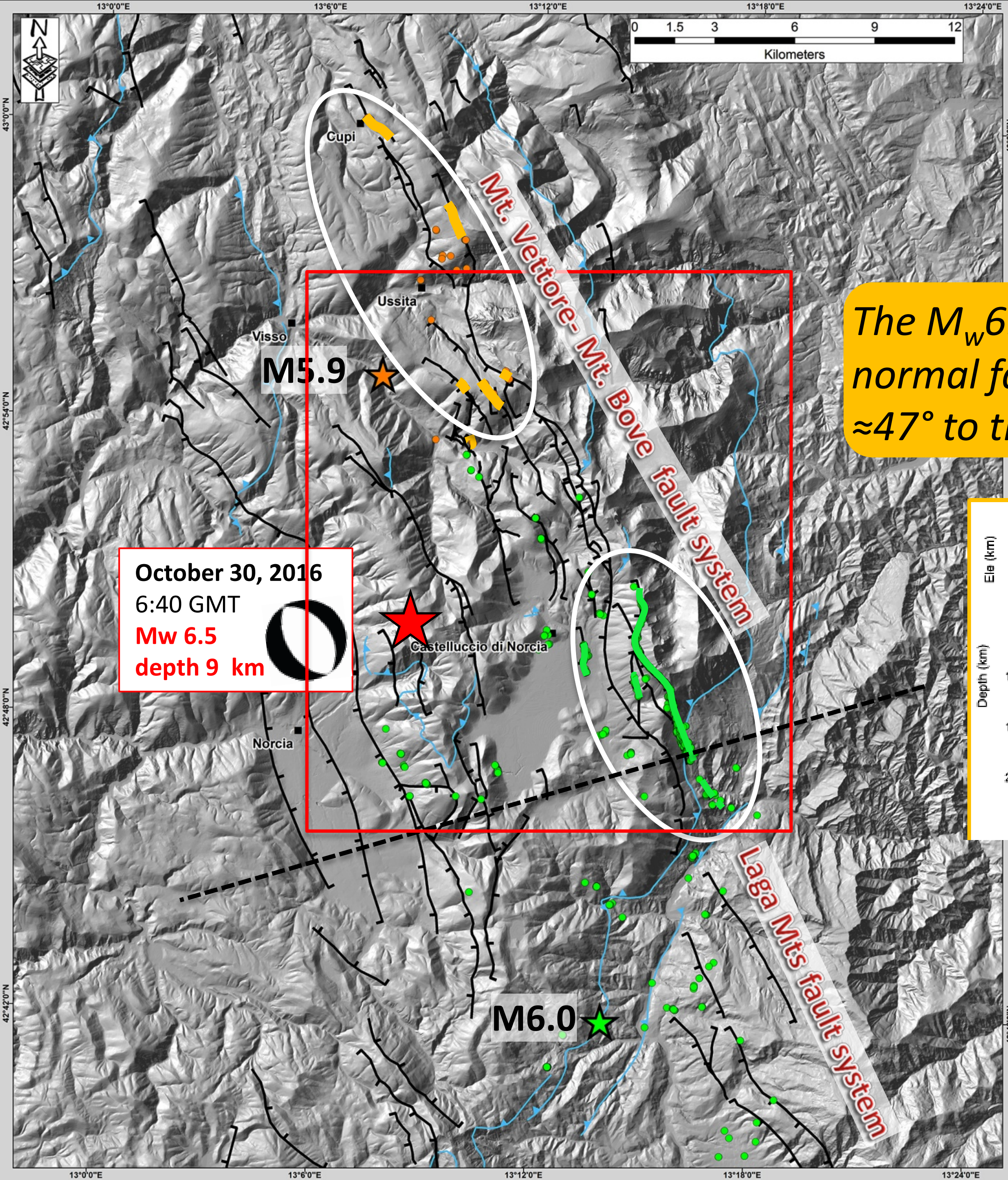
av. Opening 4 to 5 cm

The displacement of the ruptures rarely exceeds 20 cm, remaining mostly lower than 10 cm

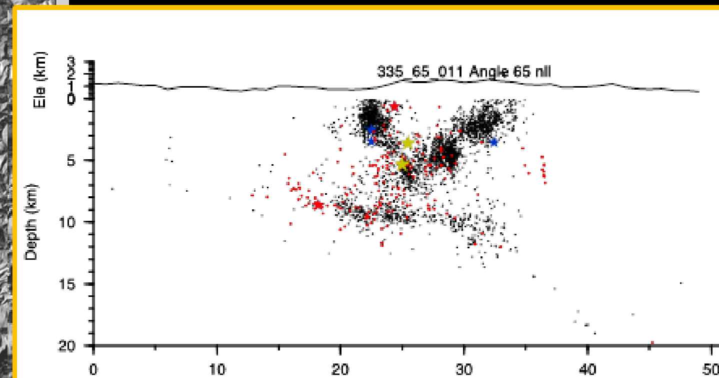
V max 15 cm

O max 20 cm

THE 30th OCTOBER 2016 Mw6.5



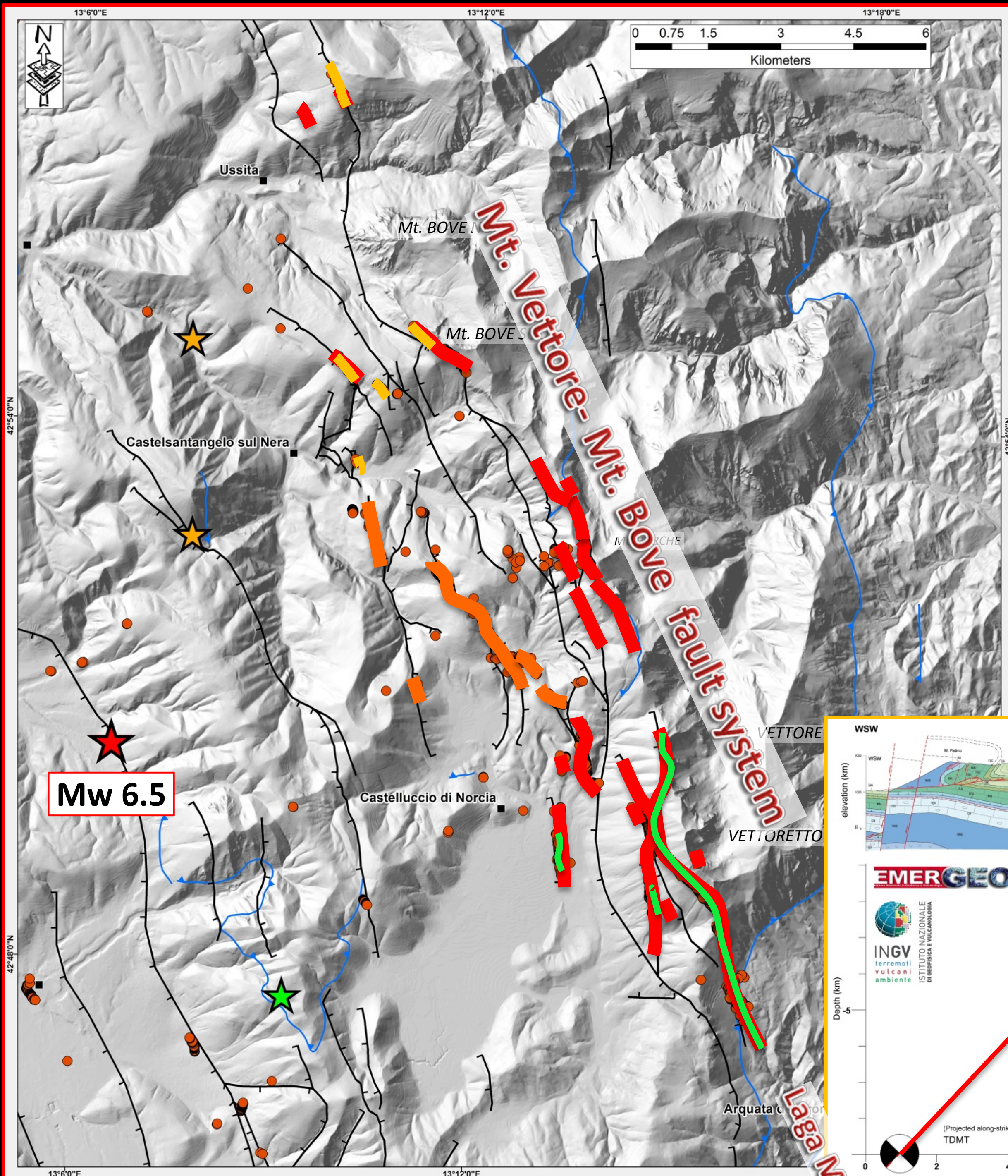
The M_w6.5 main shock ruptured a normal fault striking ≅150° and dipping ≈47° to the SW

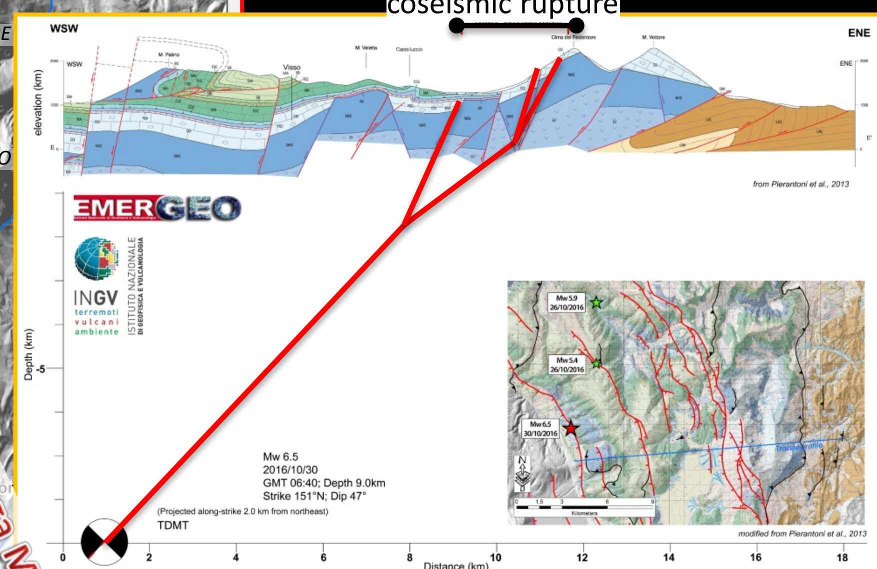


Courtesy of Chiaraluce et al.

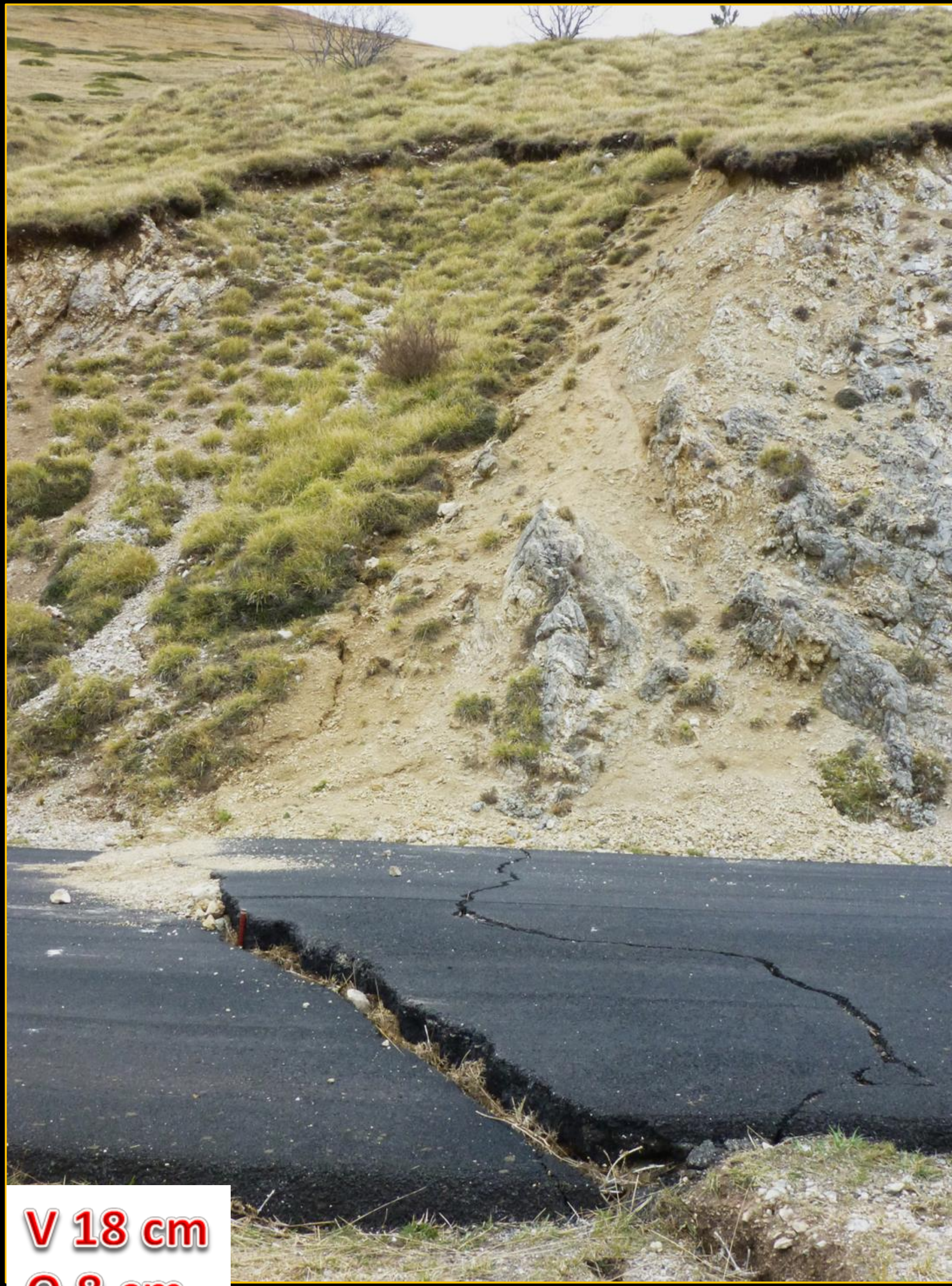
Observations relative to the 30th October 2016 Mw6.5

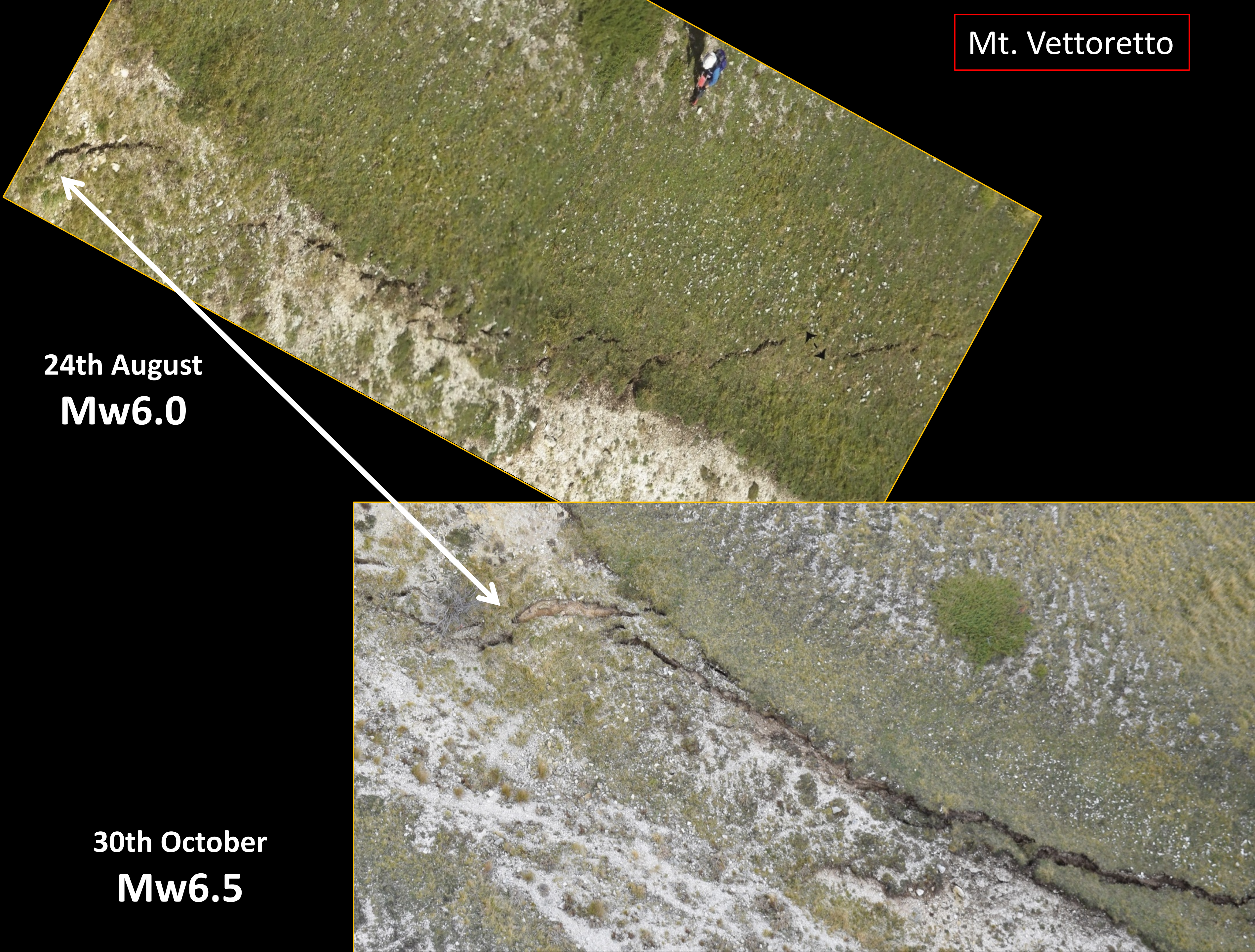
SURFACE FAULTING: continuous alignment of ruptures, total length ~20 km, N150°/155°-striking, SW side down, following different cumulative tectonic fault splays of the Vettore-Bove fault system.





Forca di Presta **24th August Mw6.0** **30th October Mw6.5**




Mt. Vettoretto
24th August
Mw6.0
30th October
Mw6.5

Mt. Vettoretto/Mt. Vettore pass

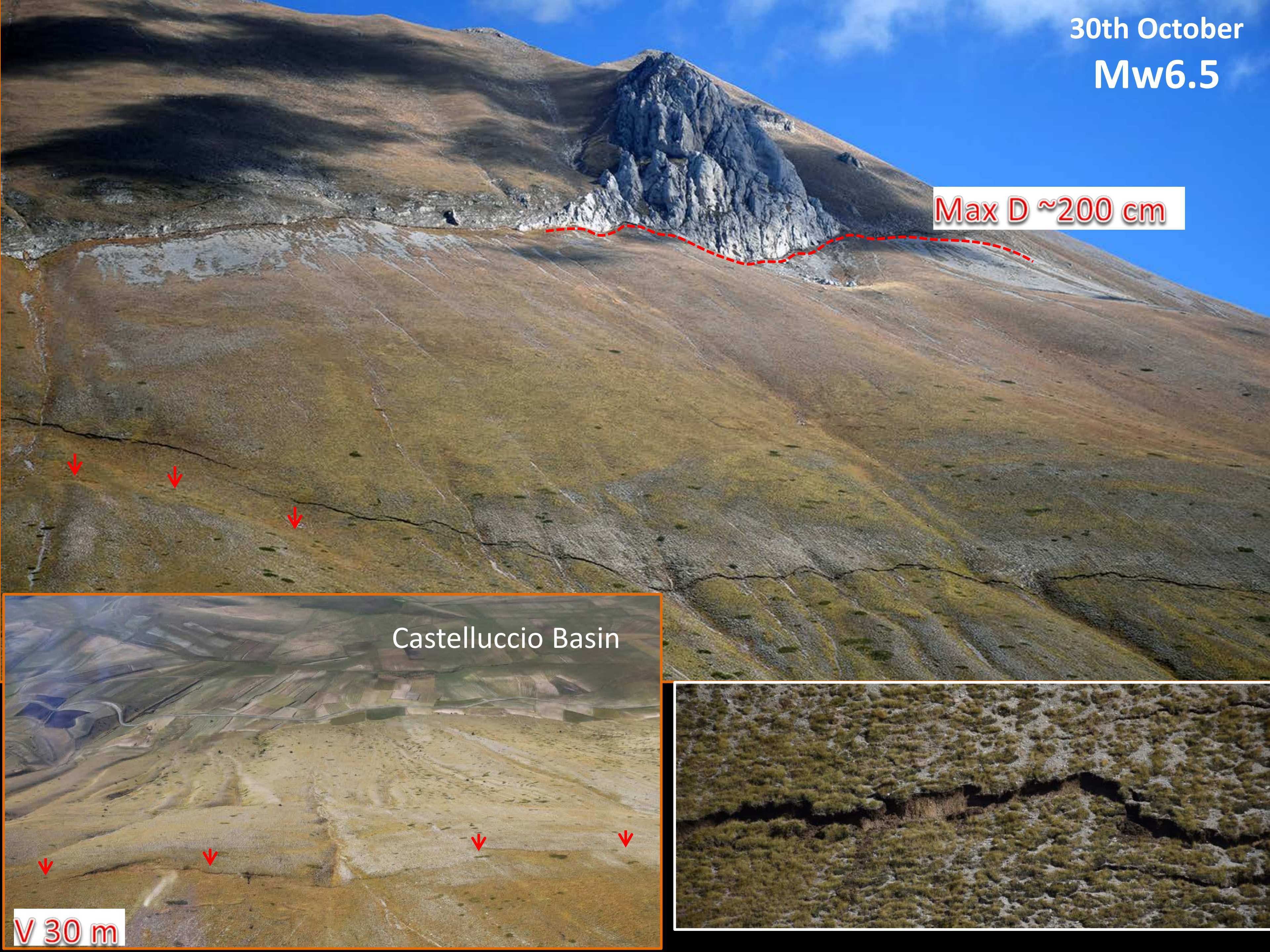
30th October
Mw6.5

24th August
Mw6.0

Mt. Vettore western slope

30th October

Mw6.5


30th October
Mw6.5
Max D ~200 cm
Castelluccio Basin
V 30 m


24th August
Mw6.0
V 25 cm

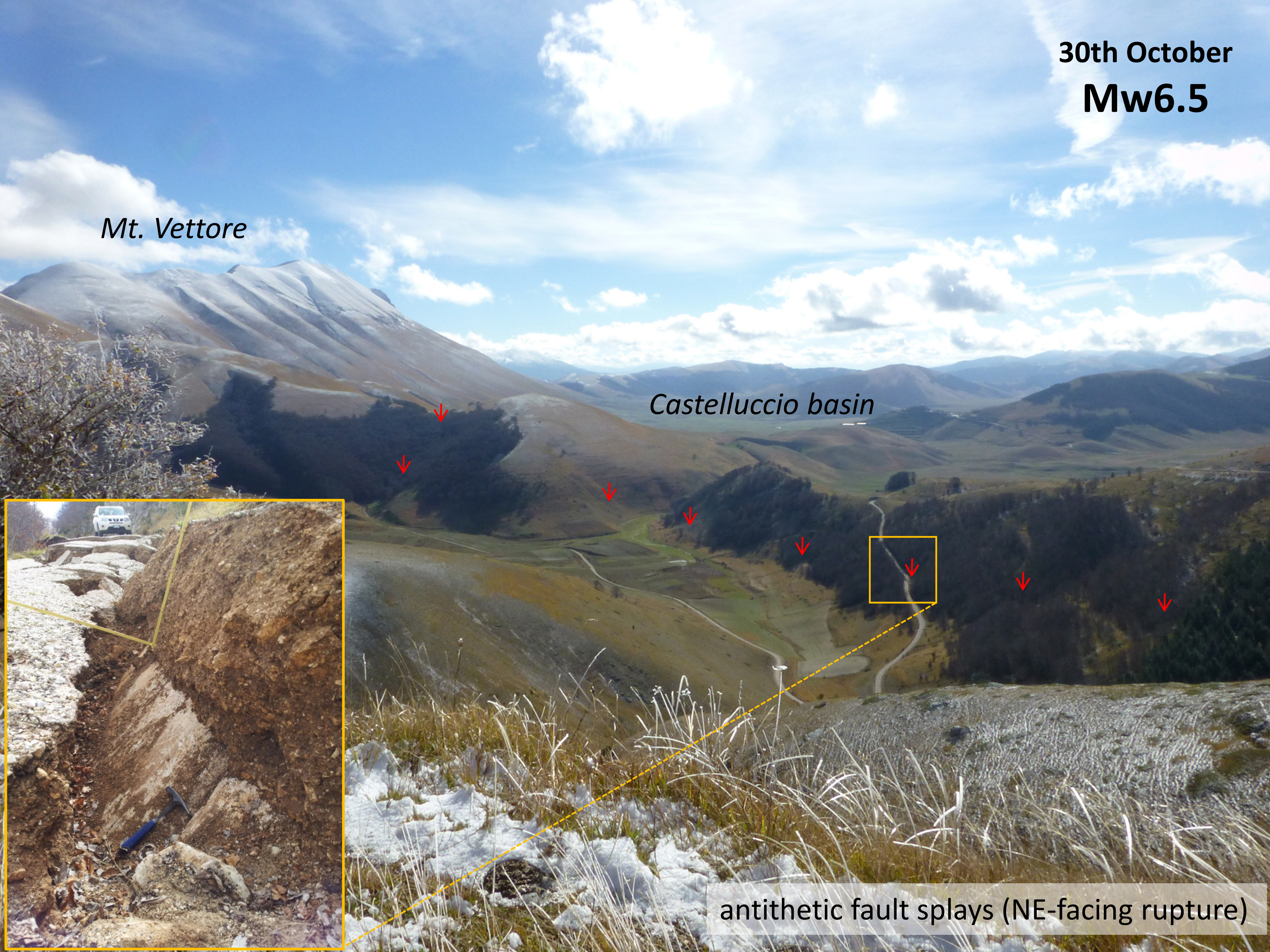
V 230 cm


30th October
Mw6.5
before Mw6.0
after Mw6.0
after Mw6.5

Castelluccio basin


Colli Alti
24th August
Mw6.0
SIRIUS
V 75 cm

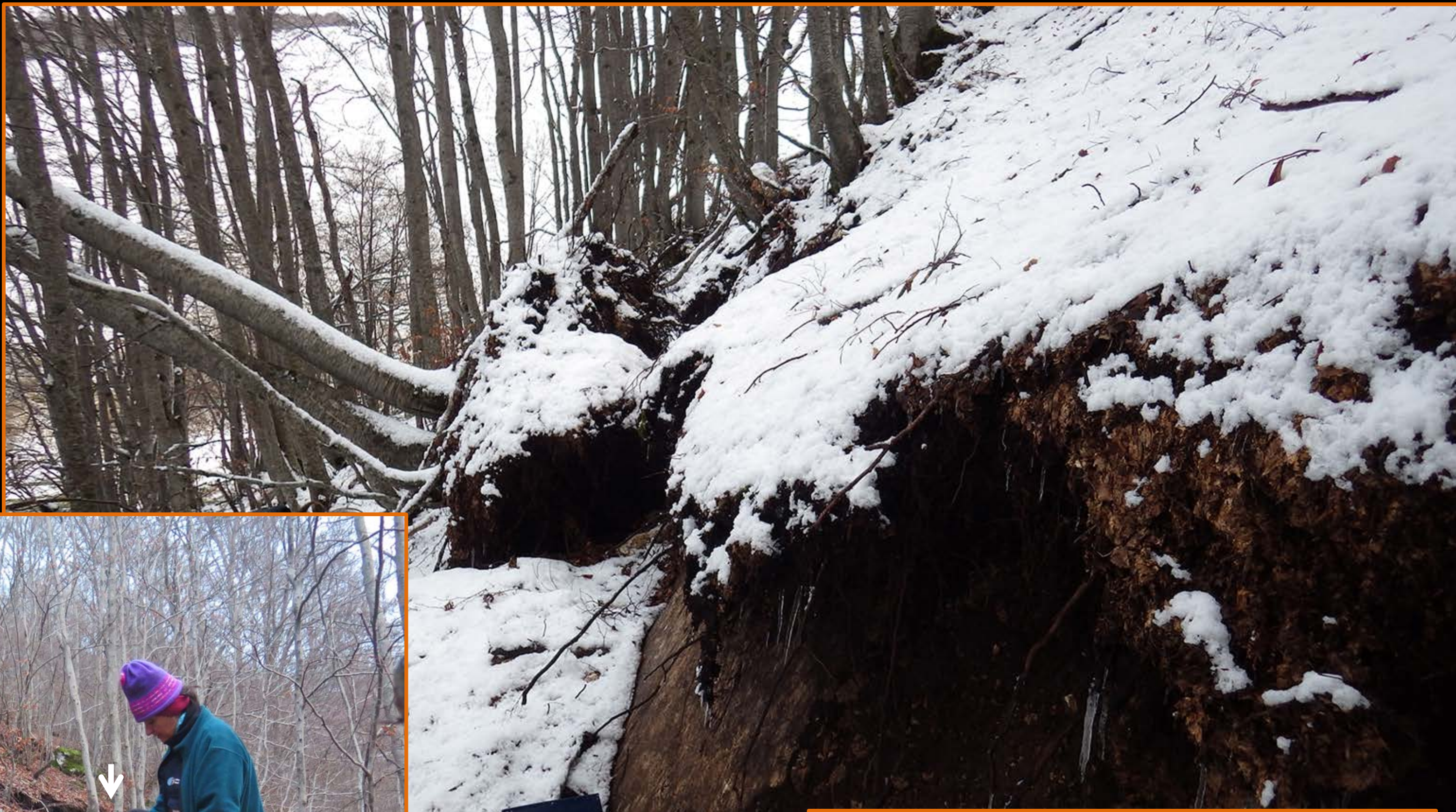

Colli Alti
30th October
Mw6.5
V 75 cm

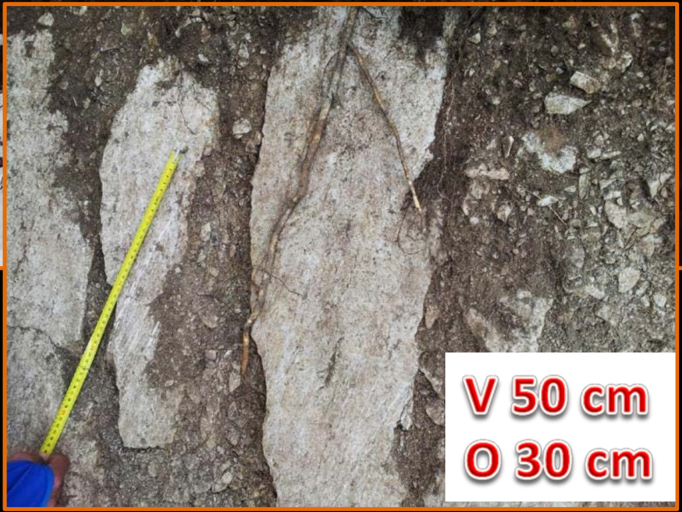

30th October
Mw6.5
Mt. Vettore
Castelluccio basin
antithetic fault splays (NE-facing rupture)

30th October

Mw6.5

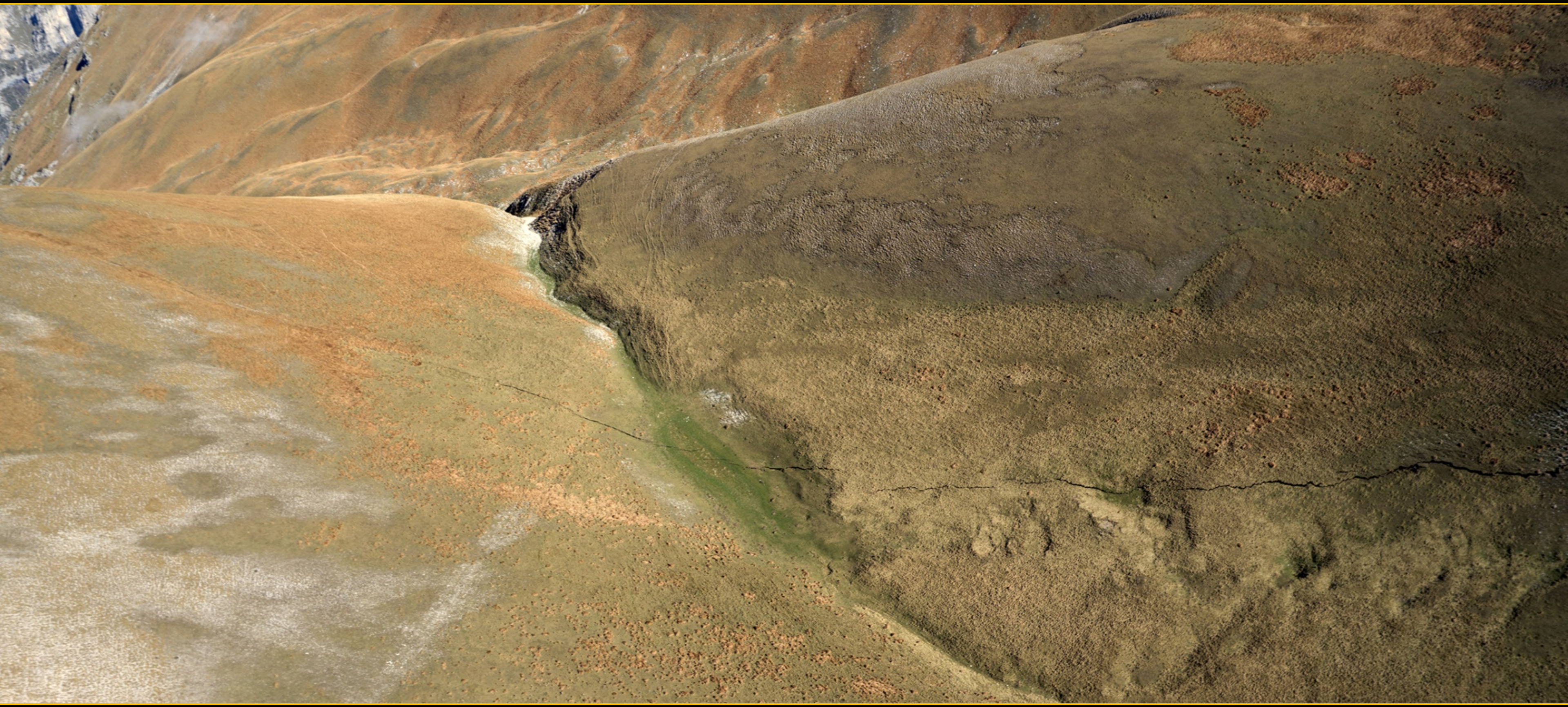
40°-50° dip
of the bedrock
fault plane





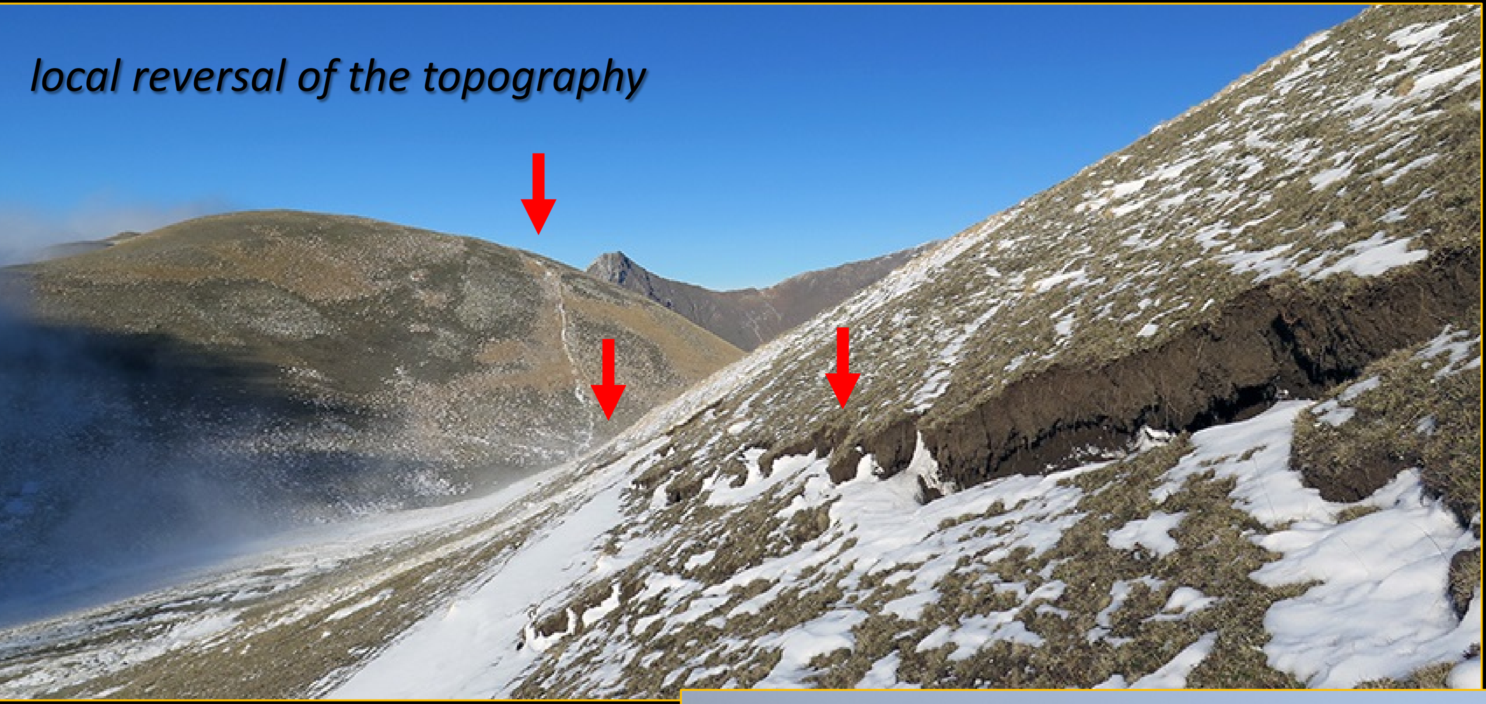
V 60 cm
O 30 cm

V 60 cm
O 30 cm



30th October

Mw6.5


local reversal of the topography

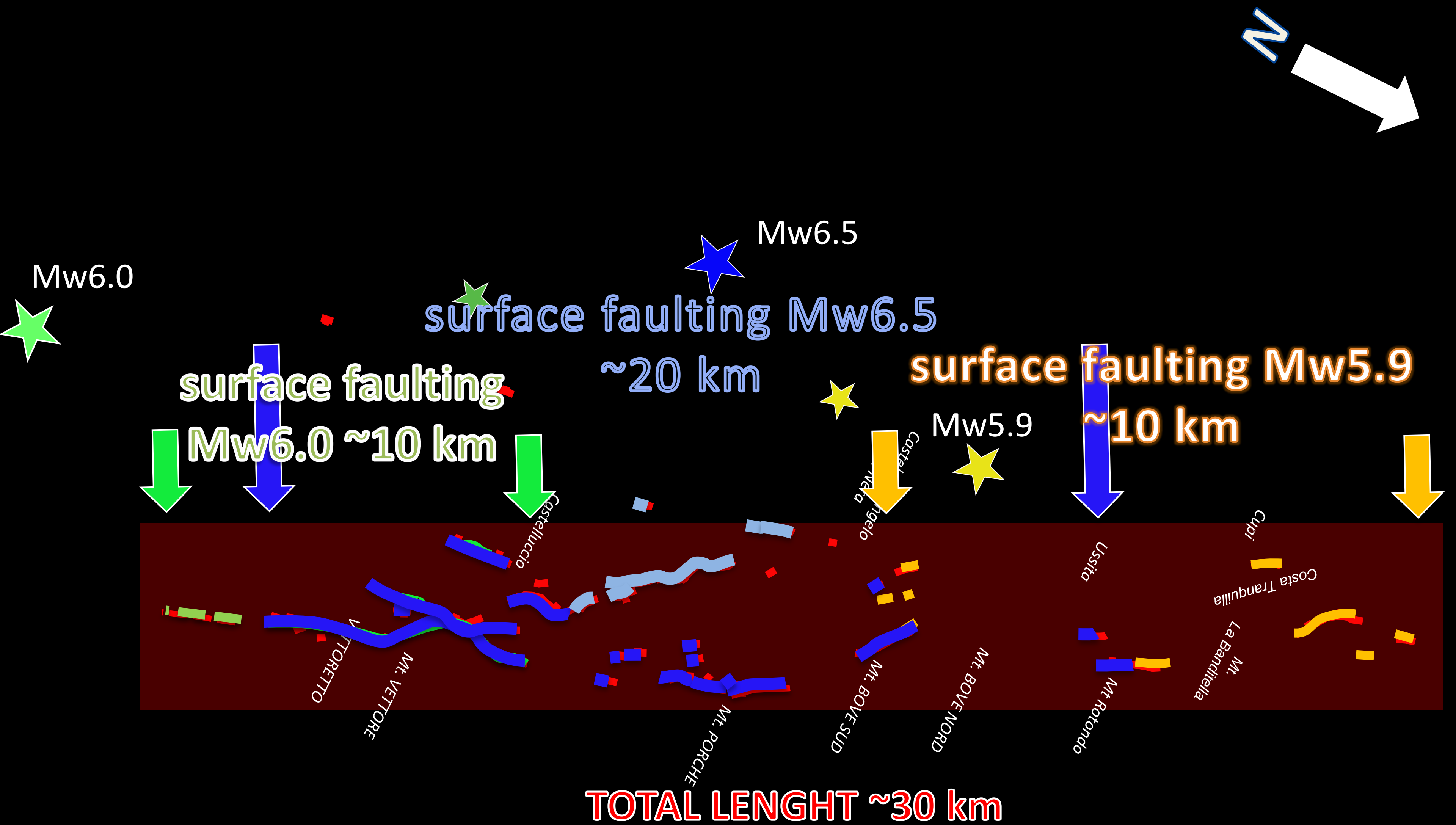

TOP

30th October

Mw6.5

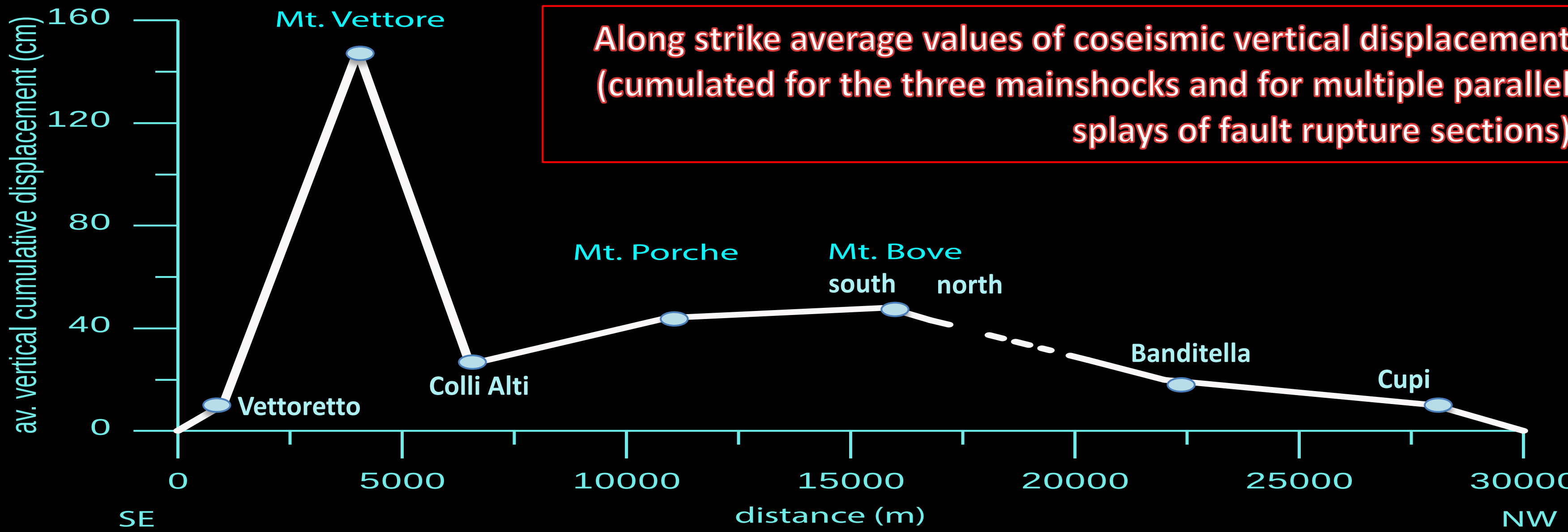
Mt. Bove

V 80 cm
O 30 cm

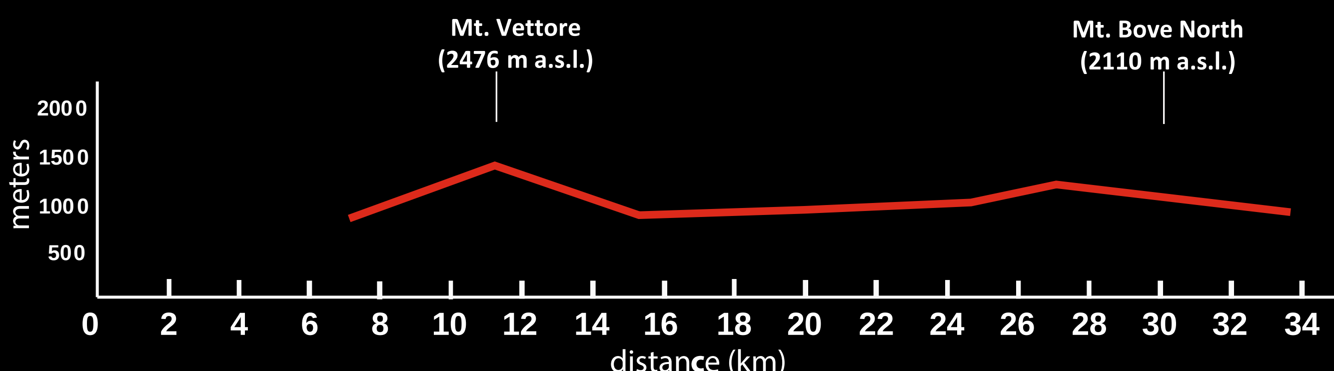


N
Mw6.0
Mw6.5
Mw5.9
surface faulting Mw6.5 ~20 km
surface faulting Mw6.0 ~10 km
surface faulting Mw5.9 ~10 km
Castelluccio
Mt. VETTORE
Mt. PORCHE
Mt. BOVE SUD
Mt. BOVE NORD
Ussita
Mt Rotondo
Cupi
Costa Tranquilla
TOTAL LENGHT ~30 km

Along strike average values of coseismic vertical displacement (cumulated for the three mainshocks and for multiple parallel splays of fault rupture sections)

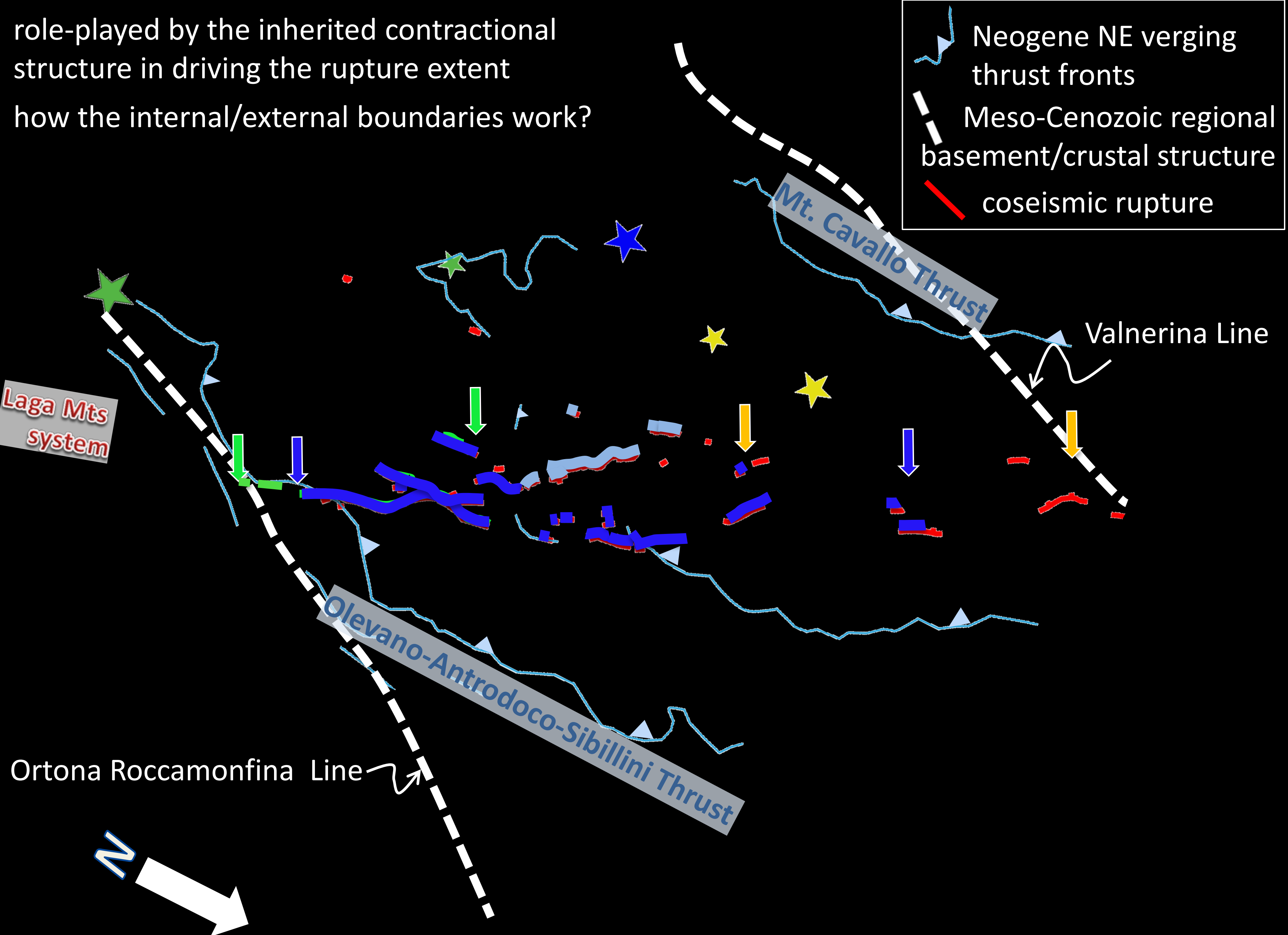


geological downthrow



Pizzi et al., Boll. Soc. Geol. It,, 2002 role-played by the inherited contractional structure in driving the rupture extent

how the internal/external boundaries work?



BASIC ISSUES

- The 2016 earthquake sequence reveals that the moderate (Mw~6.0) normal-faulting earthquakes in the Apennines may rupture the surface
- The 2016 multiple rupture scenario along the Mt. Vettore-Mt. Bove fault system repeated also in the past and left the long-term imprint in the landscape
- Basement-crustal pre-existing oblique lineaments likely controlled the total surface rupture length. While, shallower tectonic structures possibly halt the rupture extent of single segments, but also acted as transfer faults during the M6.5 event
- The 2016 earthquake sequence case has been seldom observed so far and definitively provides new data and insights, also for supporting a worldwide surface faulting database (SURFACE - SURface FAulting Catalogue Earthquakes, INQUA project 2016-2019)

THANKS FOR THE ATTENTION