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STRATEGIE RESILIENTI DI CONTRASTO AL DISSESTO IDROGEOLOGICO
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Bari, 24 Gennaio 2020

# PHENOMENOLOGICAL ANALYSIS OF THE LANDSLIDE PROCESSES FOR THE LANDSLIDE HAZARD ASSESSMENT


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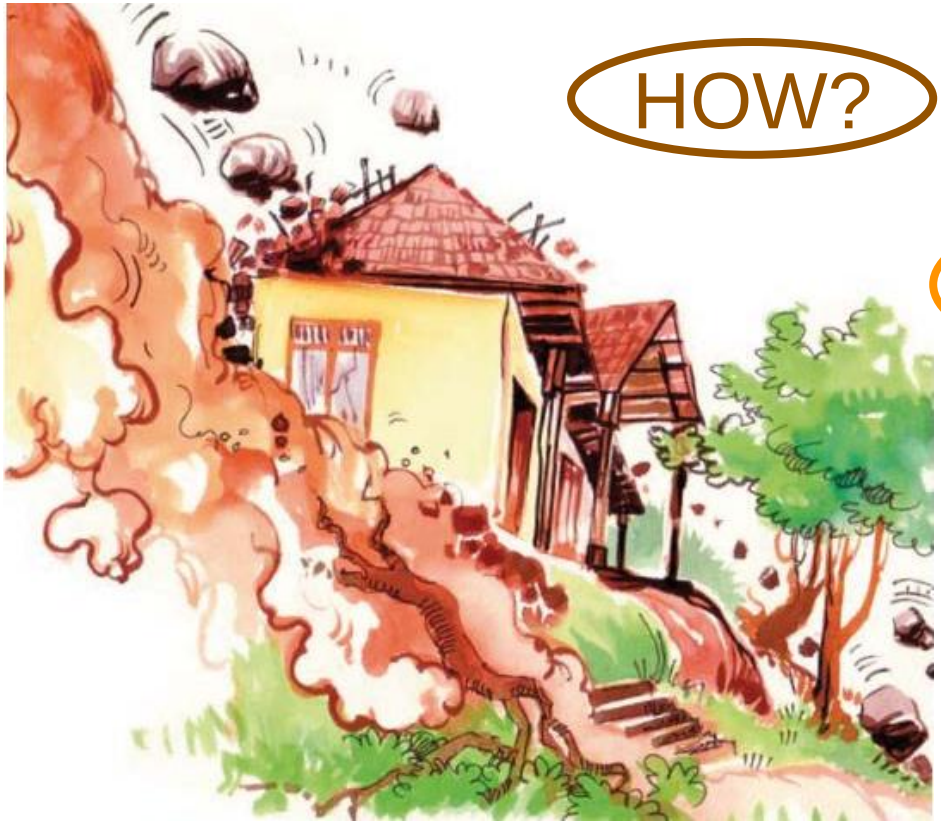
# LANDSLIDE HAZARD ASSESSMENT

**LANDSLIDE HAZARD** is the **PROBABILITY OF OCCURRENCE**

- of a landslide of **A GIVEN MAGNITUDE – HOW LARGE?**
- within a **GIVEN AREA – WHERE?**
- in a **SPECIFIED PERIOD – WHEN or HOW FREQUENTLY?**



HOW?

WHERE?

WHEN?

# LANDSLIDE HAZARD ASSESSMENT









# LANDSLIDE HAZARD ASSESSMENT

The **LANDSLIDE HAZARD ASSESSMENT** should be resulted from the comprehension of the geo-hydro-mechanical processes which predispose and trigger the landslides

**DIAGNOSIS OF THE LANDSLIDE MECHANISM**

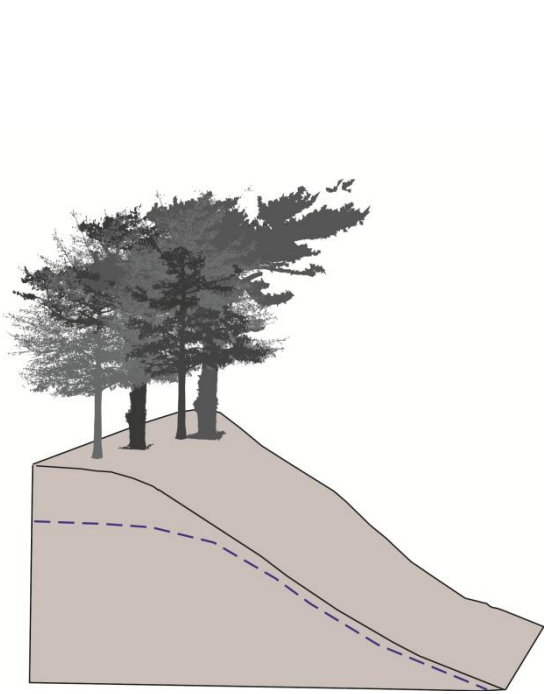
# INDEX

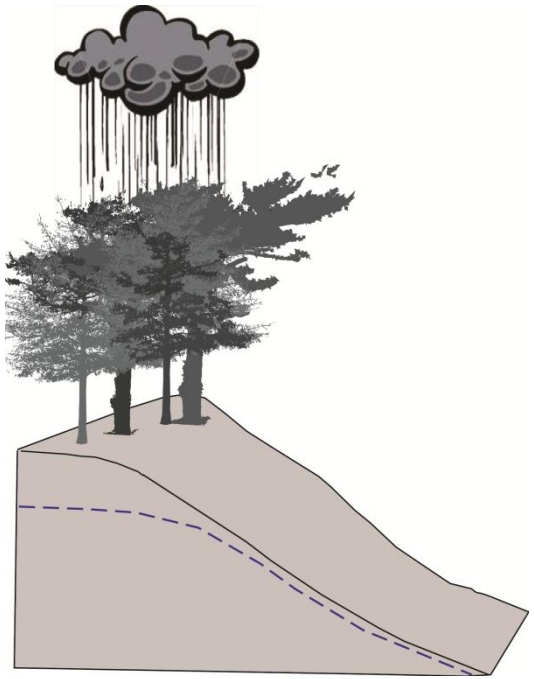
- The landslide mechanism and the slope factors
- Phenomenological analysis for the diagnosis of the landslide mechanism based on the stage-wise methodology :
  - working steps
  - application to the Daunia Apennines slopes
- Conclusion

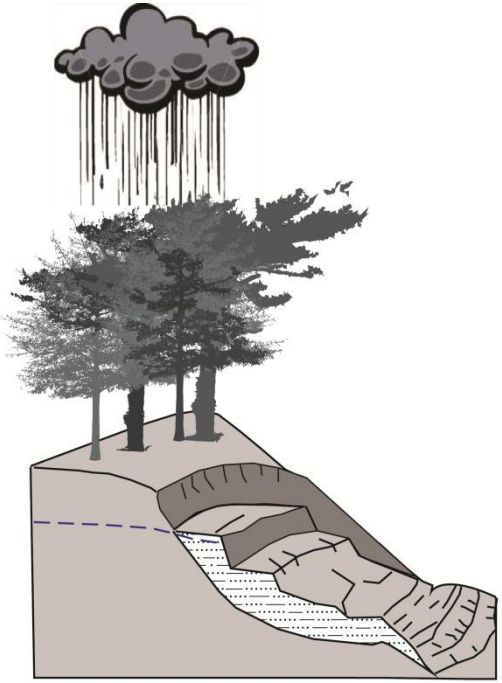
# THE LANDSLIDE MECHANISM

The occurence of a LANDSLIDE is due to a change of the slope equilibrium

Initial slope STABLE in EQUILIBRIUM → DESTABILISING EXTERNAL FORCES: the slope equilibrium is changed → LANDSLIDE

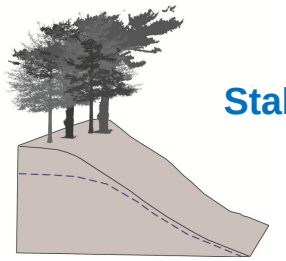




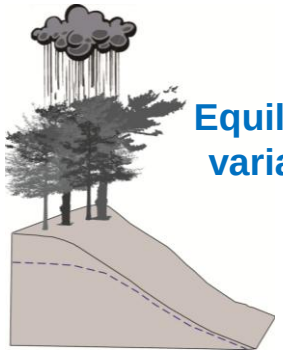


(Terzaghi, 1950; Crozier, 2004; Corominas et al., 2014; Cotecchia et al., 2016)

# THE LANDSLIDE MECHANISM: MAIN SLOPE FACTORS



Stable

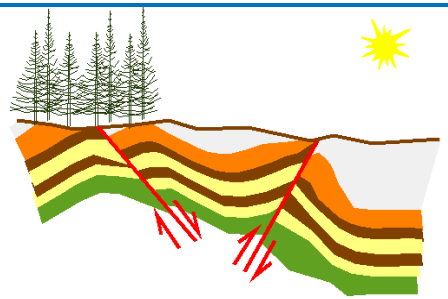


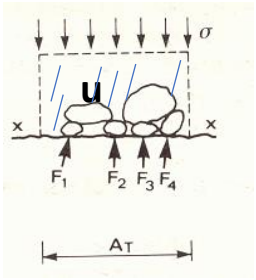
Equilibrium variations

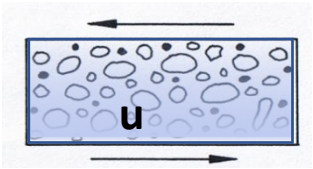
Collapse

## INTERNAL FACTORS

- **Geological setup**
  *(lithology, morphology, tectonic structures etc.)*
- **Mechanical behaviour of the geomaterial**
  *(strength, stiffness, constitutive law)*
- **Hydraulic regime of the slope**
  *(hydraulic conductivity function, water retention curve)*





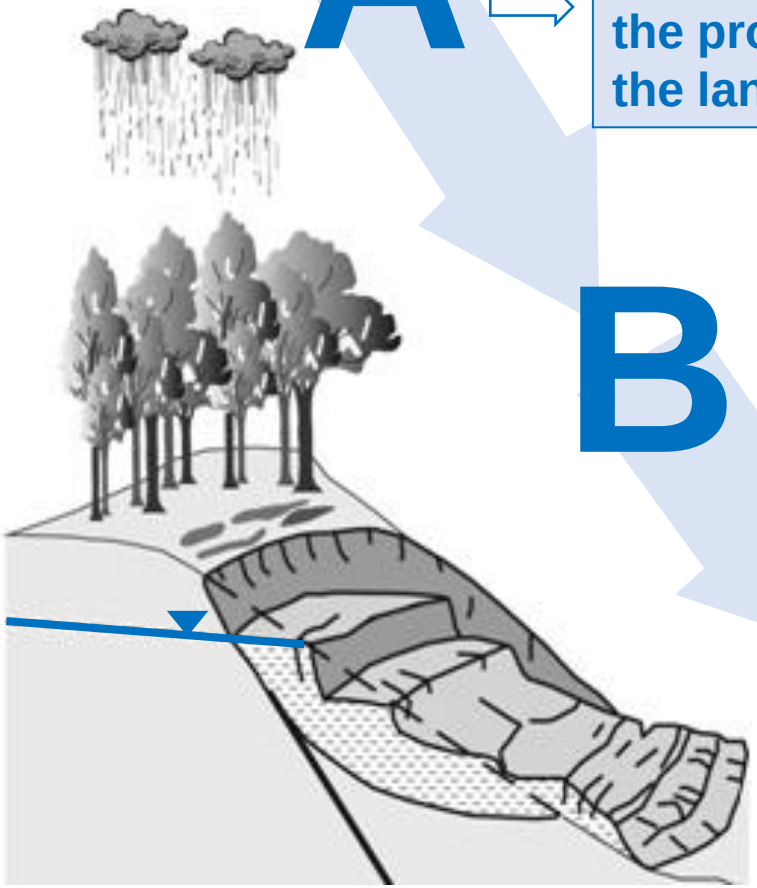




## EXTERNAL FACTORS

- **Climatic agents**
  (*rainfall, temperature, radiation, relative humidity, cloudiness, wind)*
- **Anthropic agents**
  *(loading, unloading, changes of the hydraulic boundary conditions)*
- **Seismic actions**
  *(loading/unloading cycles at high frequencies)*
- **Natural geomorphological evolution**
  (*loading, unloading, weathering)*

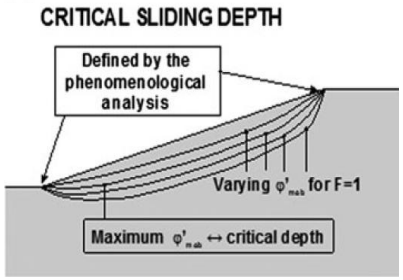
(Terzaghi, 1950)

# DIAGNOSIS OF LANDSLIDE MECHANISM: STAGE-WISE METHODOLOGY

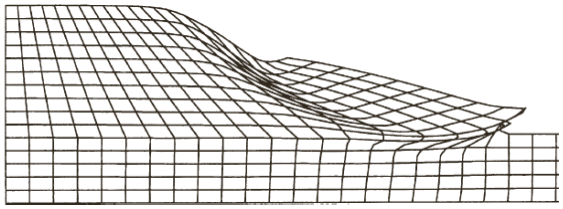


**A** ⇨ **PHENOMENOLOGICAL ANALYSIS of both the slope factors and the landslide mechanisms, including so the probable predisposing and triggering factors of the landslides**

**B** ⇨ **LIMIT EQUILIBRIUM ANALYSIS**

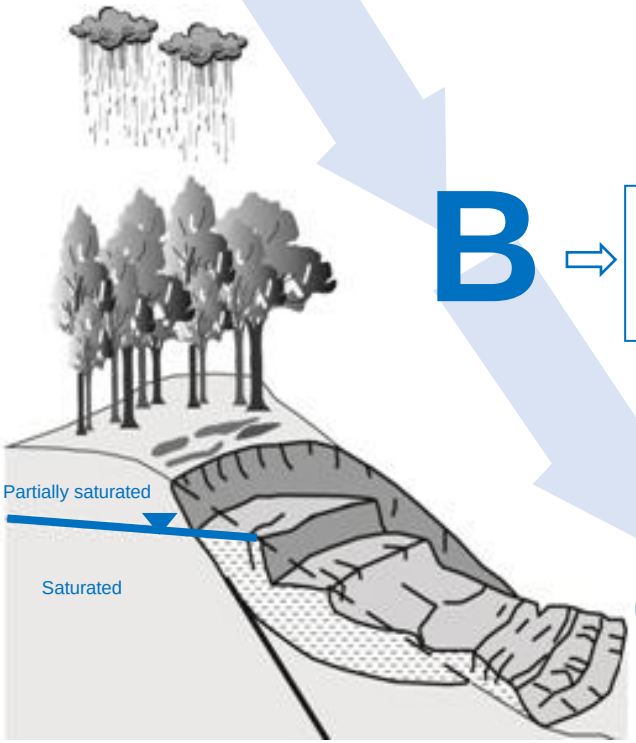



**C** ⇨ **NUMERICAL MODELLING implementing the most relevant factors and processes**



(Cotecchia et al., 2014, e 2016, GAR2019)

# THE LANDSLIDE MECHANISM: STAGE-WISE METHODOLOGY




**A** ⇨ **PHENOMENOLOGICAL INTERPRETATION**

**B** ⇨ **LIMIT EQUILIBRIUM ANALYSIS**

**C** ⇨ **NUMERICAL MODELLING**

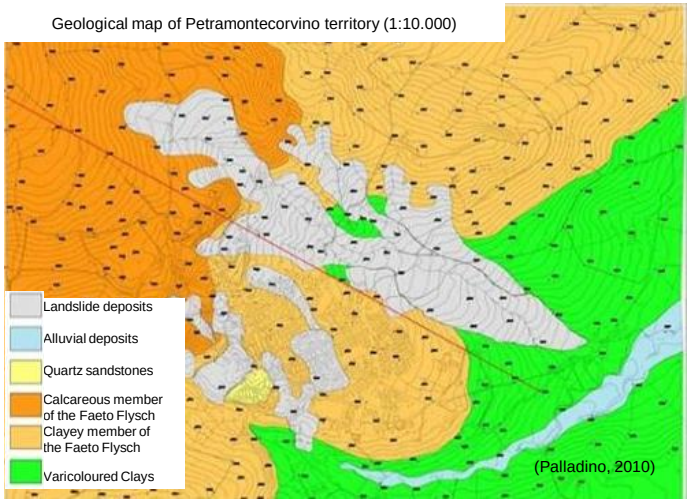
LANDSLIDE DIAGNOSIS FOR LANDSLIDE HAZARD ASSESSMENT

(Cotecchia et al., 2014, e 2016, GAR2019)

# PHENOMENOLOGICAL ANALYSIS: WORKING STEPS

- Field surveys (litological and structural setting of the slope)
- Analysis of historical data (archives and aerial photos analysis) for temporal slope evolution

## Field Surveys



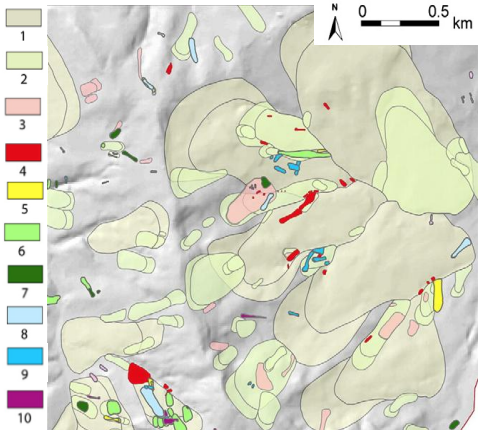

## Historical and bibliographical archives

## Stereoscopic Aerial Photographs

Analogue stereoscope

Digital stereoscope


## Multi-temporal landslide map



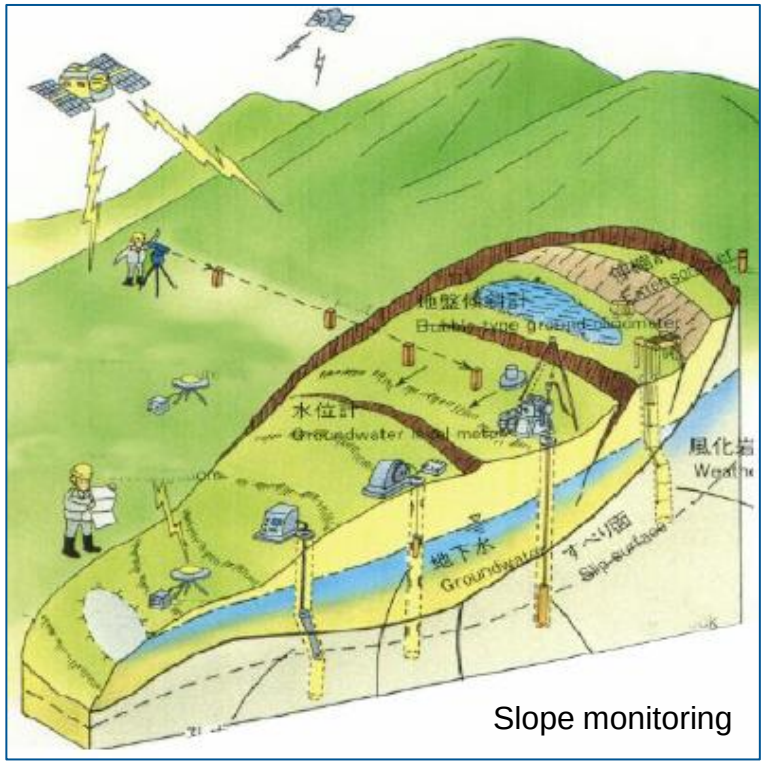

Landslides: (1) relict, (2) very old, (3) older than 1941, (4) active in 1941, (5) active in 1954, (6) period 1955–1976, (7) active in 1977, (8) 1978–1984, (9) active in 1985, (10), mapped in winter 2010

(Santaloia, 2012 Cotecchia et al., 2014, e 2016, GAR2019)

# PHENOMENOLOGICAL ANALYSIS: WORKING STEPS

- Field surveys
- Analysis of historical data
- Field investigation
- Laboratory testing
- Slope monitoring

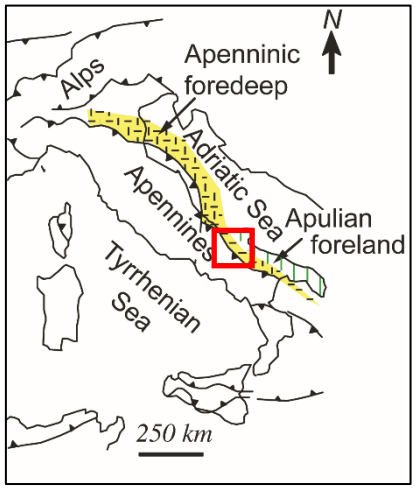
Field investigation



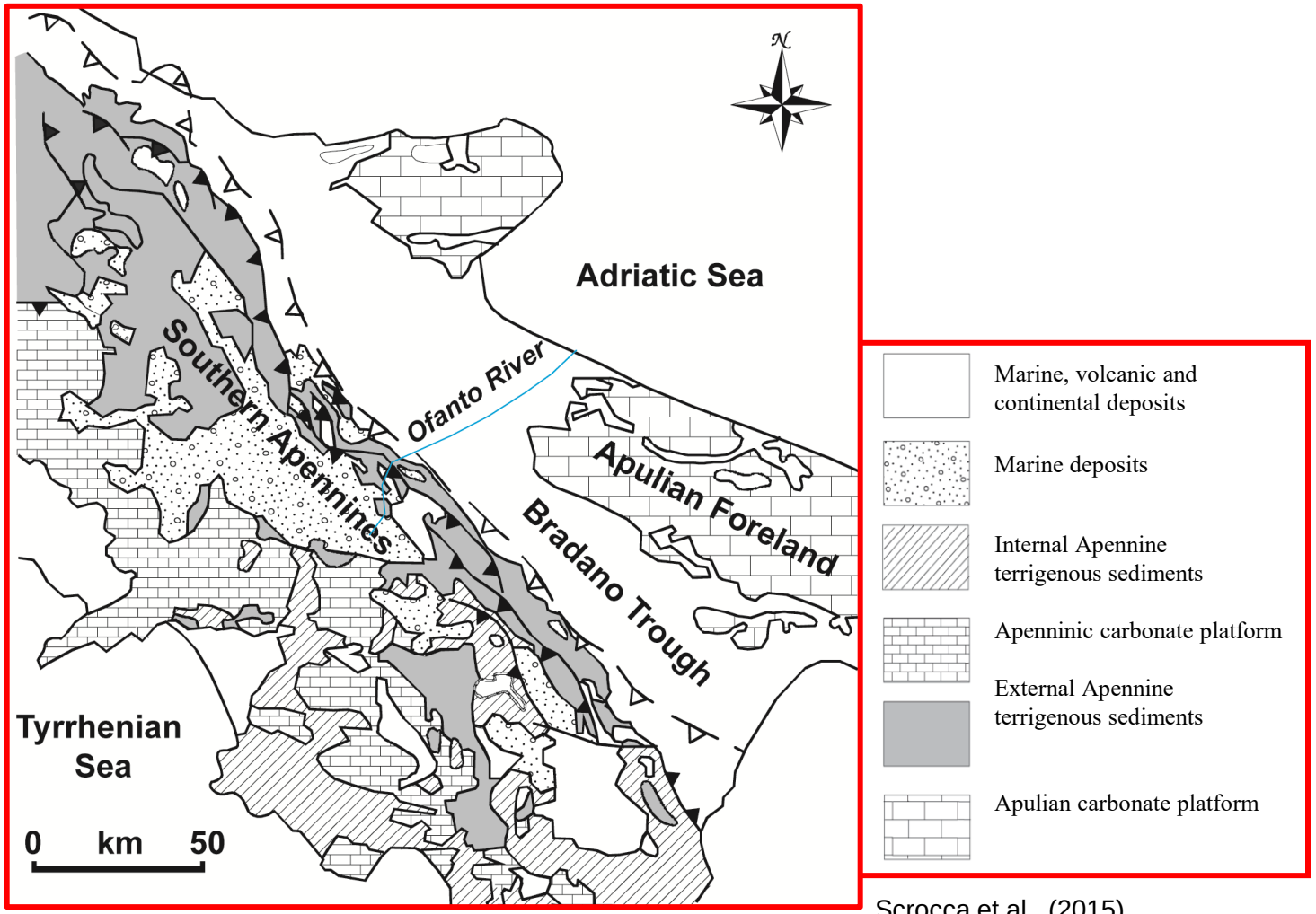

Slope monitoring

Laboratory testing

# PHENOMENOLOGICAL ANALYSIS: DAUNIA APENNINES

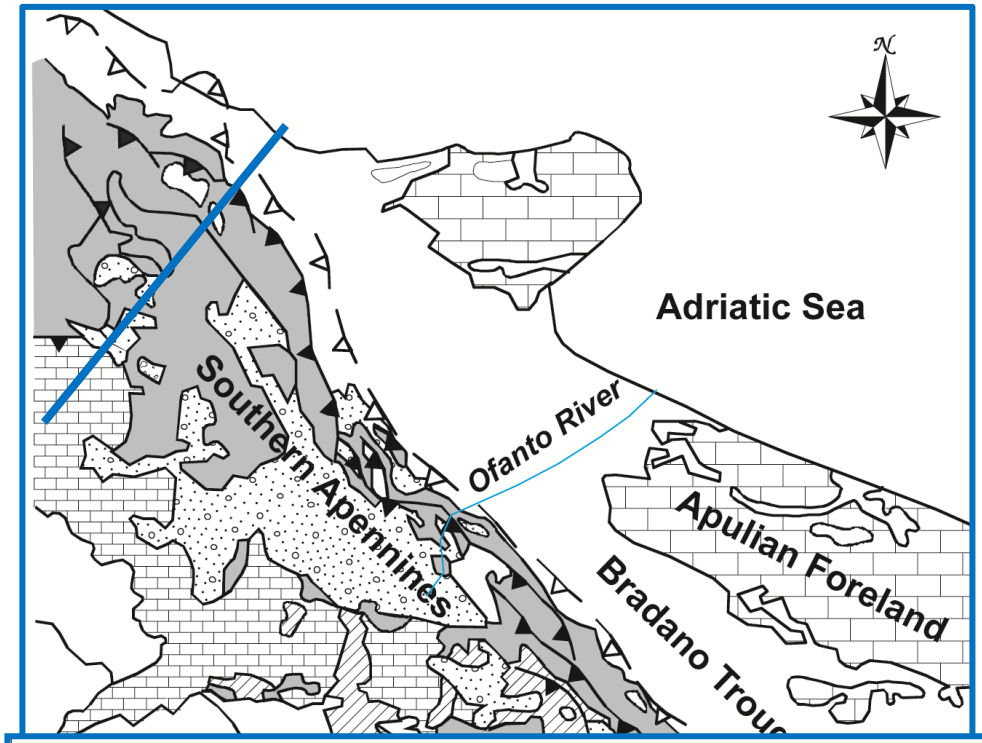



Outer sector of the Southern Apennines located



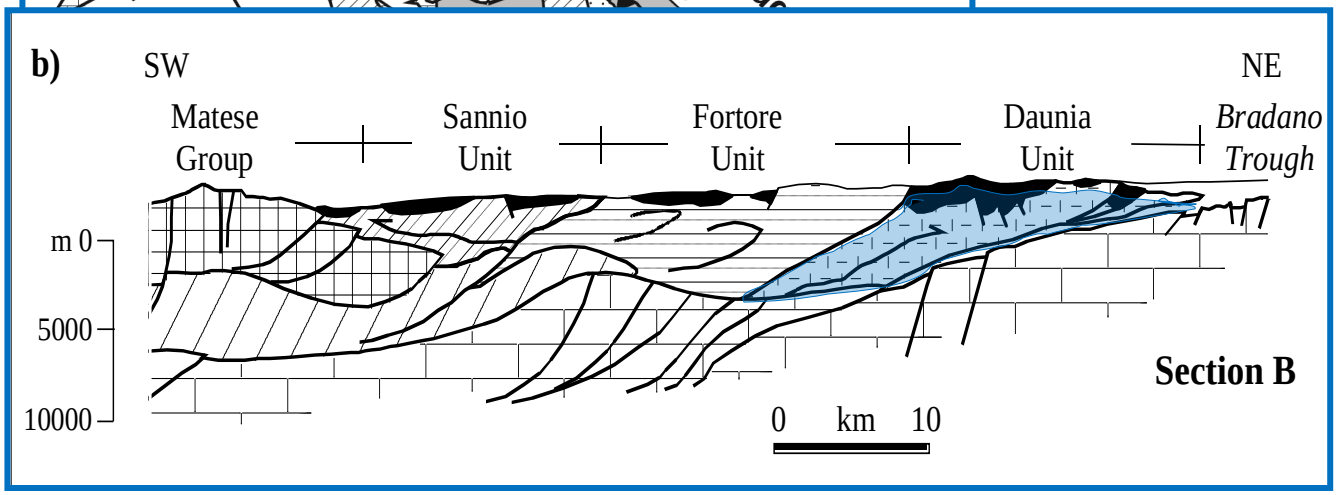

Scrocca et al., (2015)

# PHENOMENOLOGICAL ANALYSIS: DAUNIA APENNINES

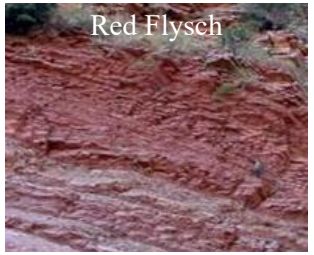



Turbiditic successions, pelagic and slope deposits, delta river sediments, platform deposits and piggyback basin deposits

**DAUNIA UNIT**





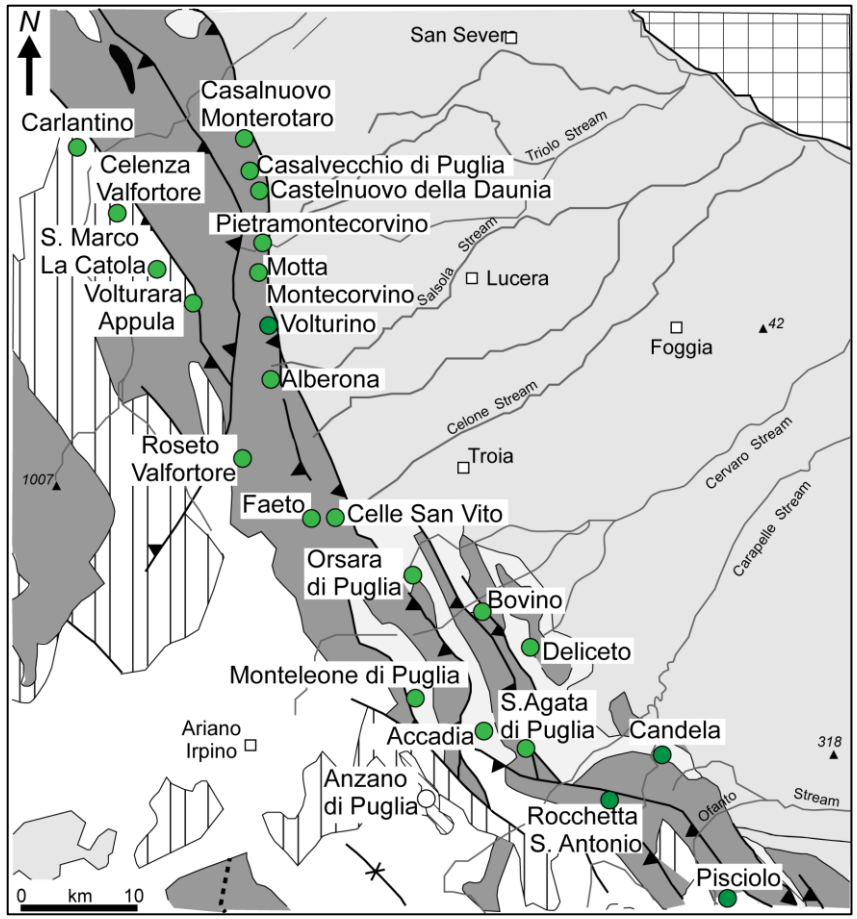
# PHENOMENOLOGICAL ANALYSIS: DAUNIA APENNINES

Test area:
urban territories of the Daunia Apennines and some chain slopes interacting with important infrastructures









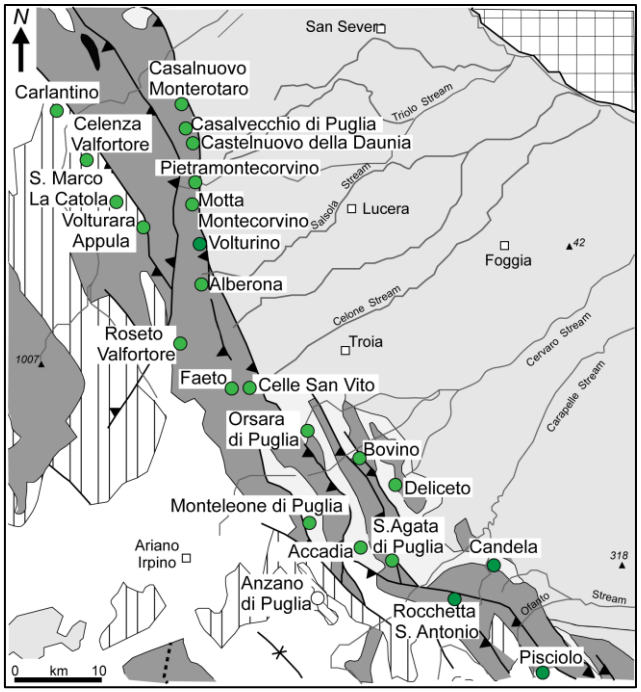

Patacca & Scandone (2007)


# PHENOMENOLOGICAL ANALYSIS: DAUNIA APENNINES

For each territory:

1) Gathering and analysis of the slope factors derived from private and public documents
2) Data implementation in tables and GIS-platforms
3) Geological field surveys

Most of the slopes are constituted by sedimentary successions with lithological heterogeneities and different structural setting but with similar geomechanical behaviour at the slope scale



# DAUNIA APENNINES: GEO-MECHANICAL UNITS

For each territory:

1) Gathering and analysis of the slope factors derived from private and public documents
2) Data implementation in tables and GIS-platforms
3) Geological field surveys

Most of the slopes are constituted by sedimentary successions with lithological heterogeneities and different structural setting but with similar geomechanical behaviour at the slope scale

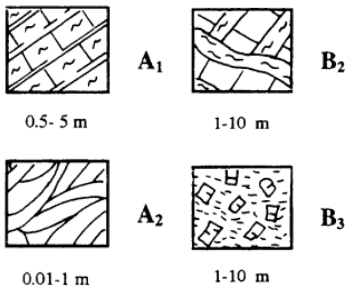
Three main geo-mechanical units have been defined
Each geological formations could include one or more of these units

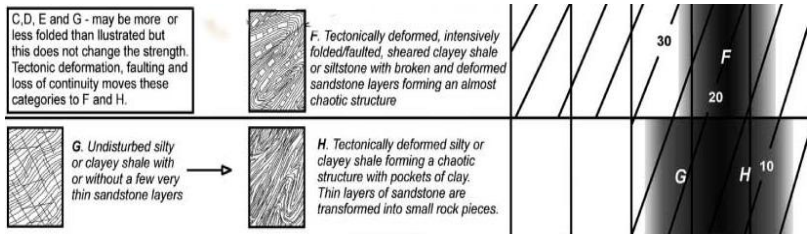


# DAUNIA APENNINES: GEO-MECHANICAL UNITS

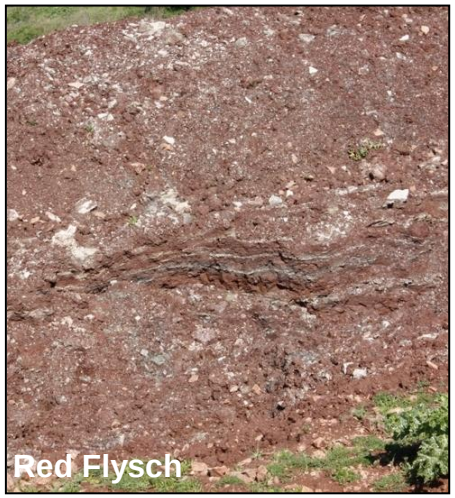
A **SOIL UNIT** consists mainly in clay, silty clay or clayey silt; at the slope scale the mechanical behaviour of this unit is controlled by the clay fraction.

- Structural complexity by Esu (1979): A1-A2 (B2-B3)
- Geological Strength Index by Hoek et al. (1998): GSI< 30
- Fissuring intensity by Vitone et al. (2005): I3-I6 (from low to very high)




| | |
|---|---|
| I3 | Low: 10-30 $m^2/m^3$ 0.001-0.027 $m^3$ |
| I4 | Medium*: 30-100 $m^2/m^3$ 27-1000 $cm^3$ |
| I5 | High**: 100-300 $m^2/m^3$ 1-27 $cm^3$ |
| I6 | Very high*/**: >300$m^2/m^3$ - <1$cm^3$ |



(Santaloia et al., 2012)

# DAUNIA APENNINES: GEO-MECHANICAL UNITS

The mechanical parameters of the **SOIL UNITS**

**Soil unit of Faeto Flysch**
Locally fissured clays
CF ≅ 65-75%
$w_L$ ≅ 100%
PI ≅ 60-70%
A ≅ 0.75-1
$c_p'$=0-25 kPa, $\varphi_p'$= 18-22°
$\varphi_r'$= 8.7°

**Red Flysch**
Scaly clays
CF ≅ 55-70%
$w_L$ ≅ 60-140%
PI ≅ 40-100%
A ≅ 0.75-1.4
$c_p'$=0-20 kPa, $\varphi_p'$= 15-25°
$\varphi_r'$= 5-9°

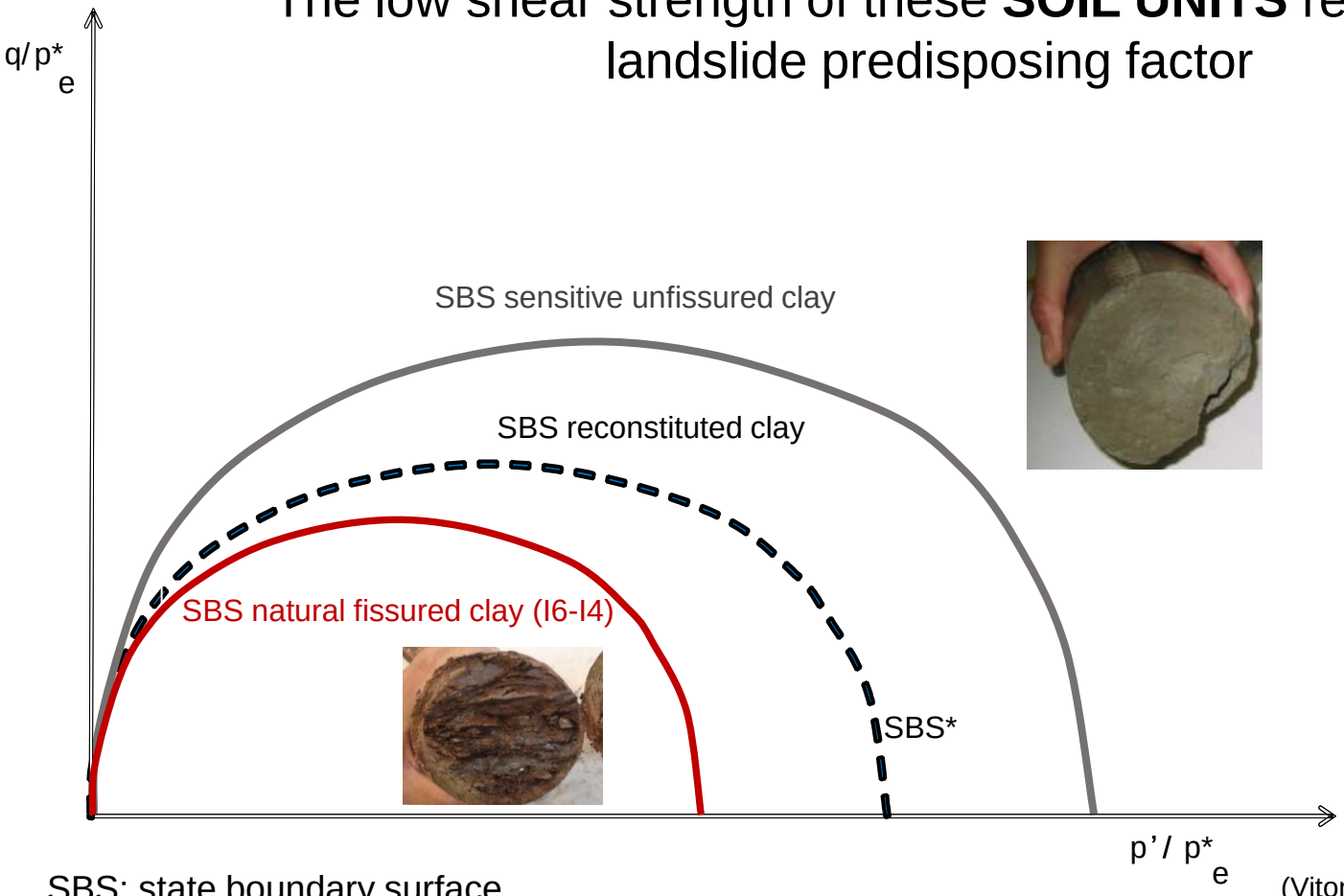
**Toppo Capuana Marls**
Medium fissured
CF ≅ 50-60%
$w_L$ ≅ 30-75%
PI ≅ 30-40%
A ≅ 0.5-07
$c_p'$=0-50 kPa, $\varphi_p'$= 18-20°
$\varphi_r'$= 9.6°

(Santaloia et al., 2012; Cotecchia et al., 2016; Cafaro et al., 2016)

# DAUNIA APENNINES: GEO-MECHANICAL UNITS

The shear strength of the fissured clays belonging to some **SOIL UNITS** is lower than that one of the corresponding reconstituted clays

The low shear strength of these **SOIL UNITS** represents a landslide predisposing factor



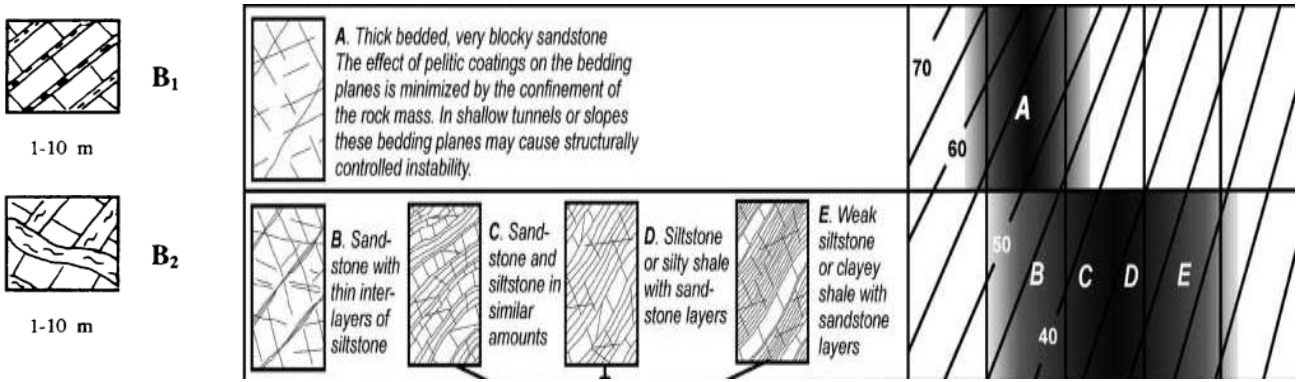

SBS: state boundary surface

(Vitone e Cotecchia F., 2009, 2011)

# DAUNIA APENNINES: GEO-MECHANICAL UNITS

A **ROCK UNIT** consists mainly in sandstone or limestone; at the slope scale the mechanical behaviour of this unit is controlled by the rock fraction.

- Structural complexity by Esu (1979): B1-B2
- Geological Strength Index by Hoek et al. (1998): GSI>20





Numidian Flysch


Limestone member of the Faeto Flysch


Sandstones of the Bovino Synthem

(Santaloia et al., 2012)

# DAUNIA APENNINES: GEO-MECHANICAL UNITS

The **reference scale** of the different geo-mechanical units is the **SLOPE SCALE** (> ten of meters)

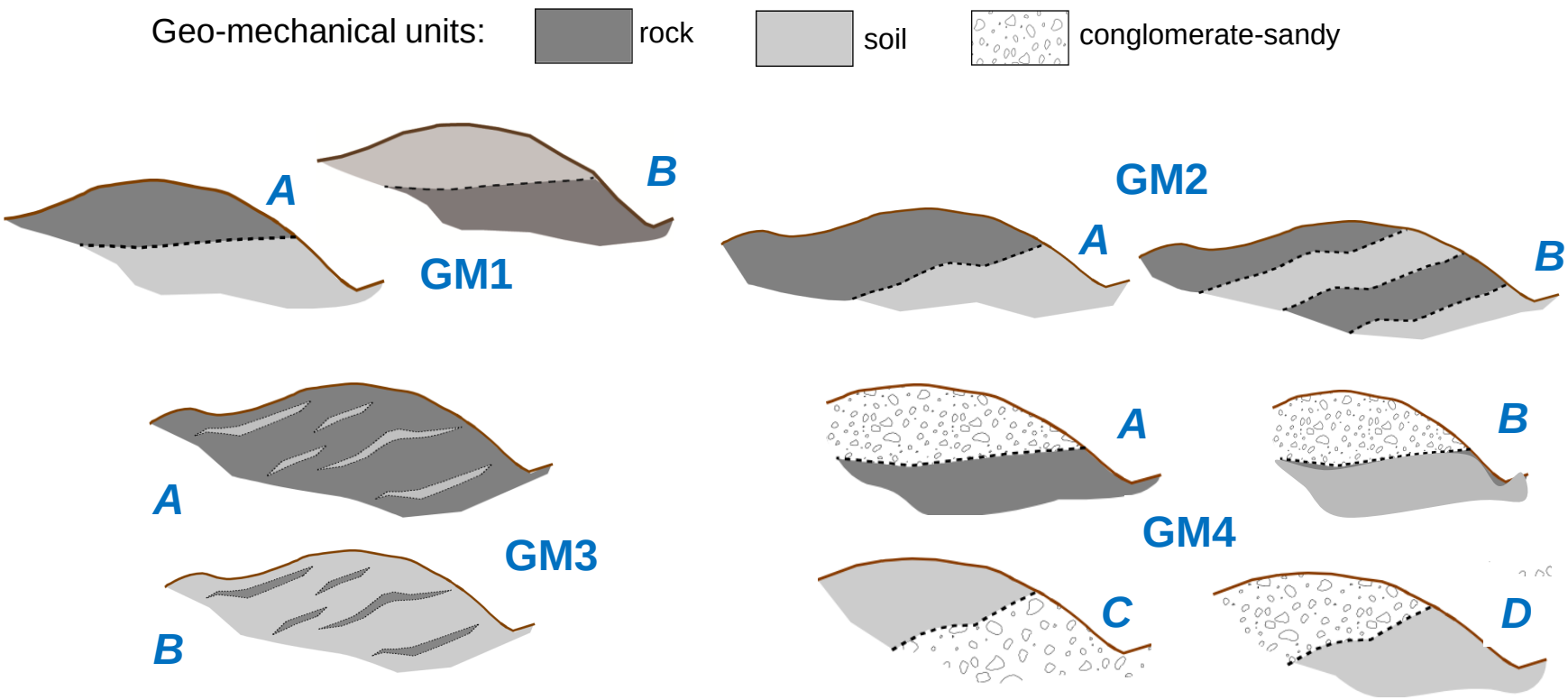





(Santaloia et al., 2012)

# DAUNIA APENNINES: GEO-MECHANICAL SLOPE SETTING

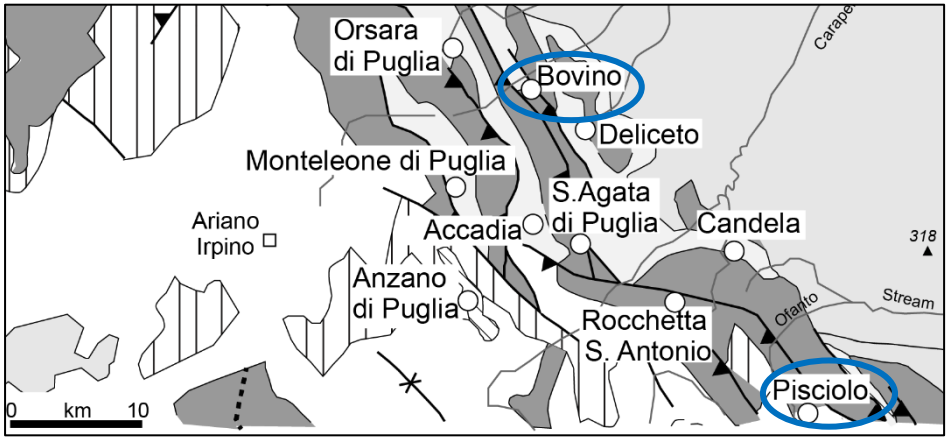
The spatial arrangement of the geo-mechanical units: IDENTIFICATION OF THE GEO-MECHANICAL SLOPE SETTING (GMi)

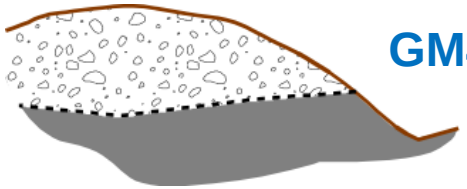



**GM2>>GM3>GM1>> GM4**

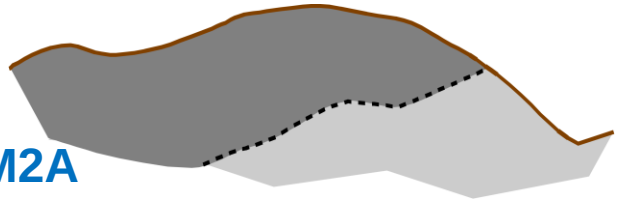
(Santaloia et al., 2012; Cotecchia et al., 2016; Cafaro et al., 2016)

# DAUNIA APENNINES: GEO-MECHANICAL SLOPE SETTING

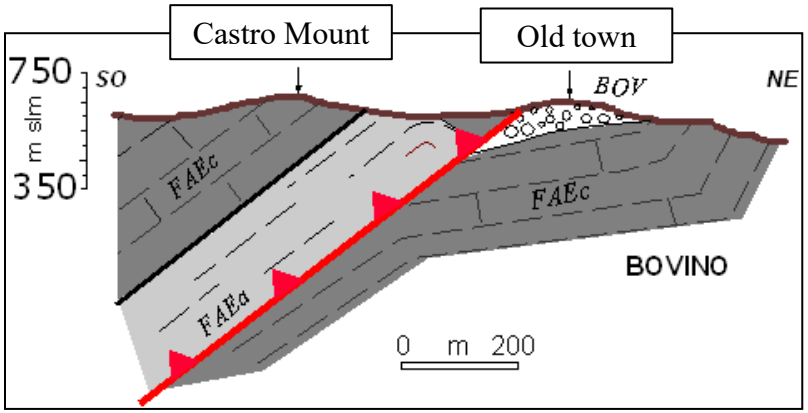


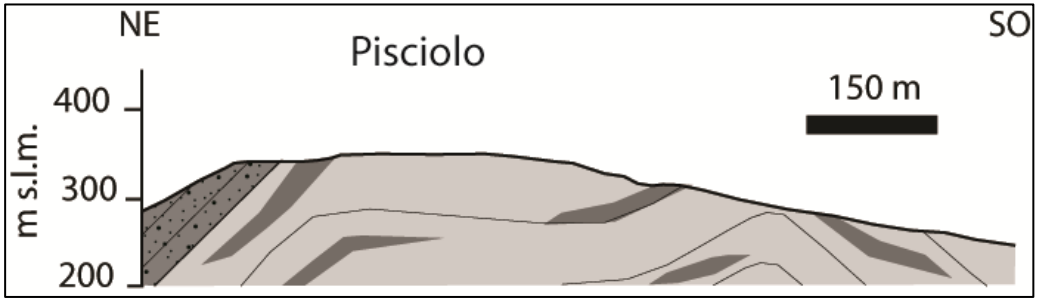



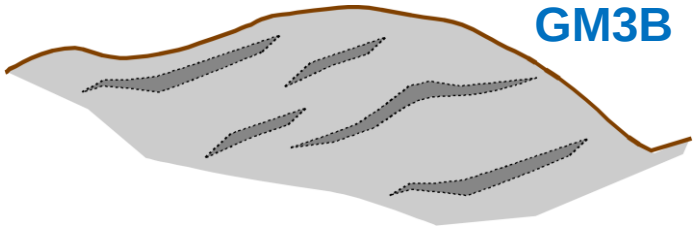
**GM4A**



**GM2A**



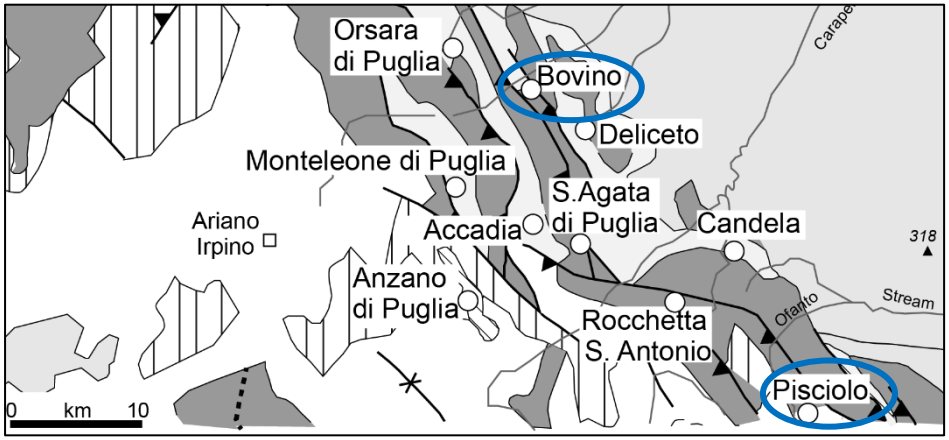



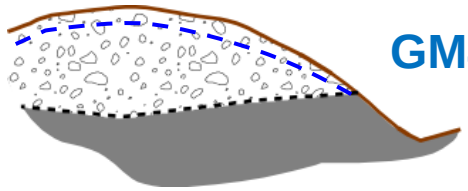



**GM3B**

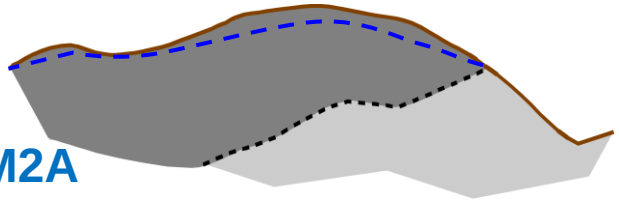
(Santaloia et al., 2012; Cotecchia et al., 2016; Cafaro et al., 2016)

# DAUNIA APENNINES: GEO-HYDRO-MECHANICAL SLOPE SETTING

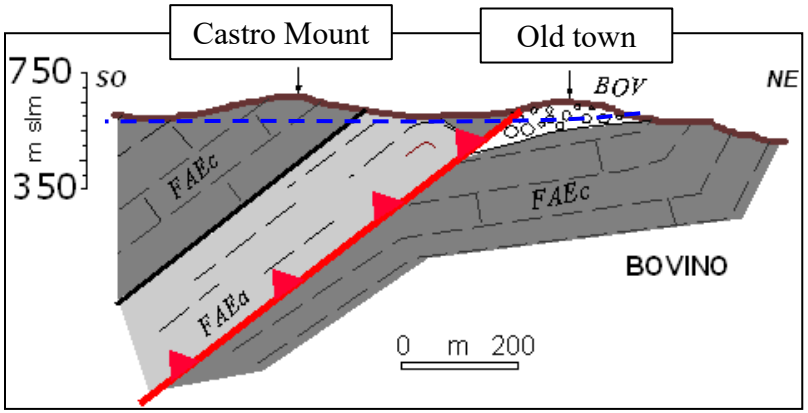


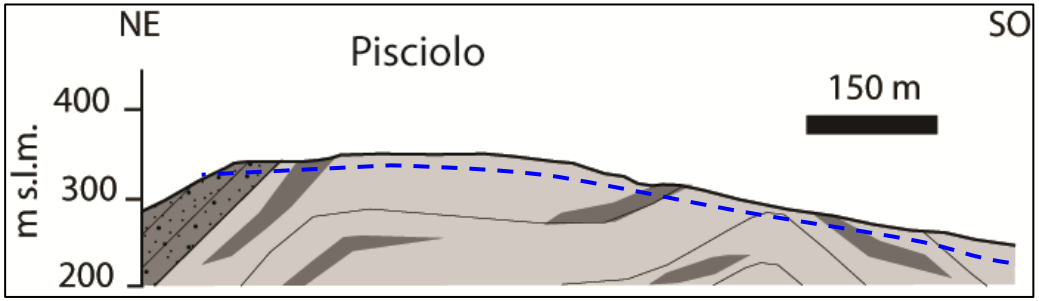



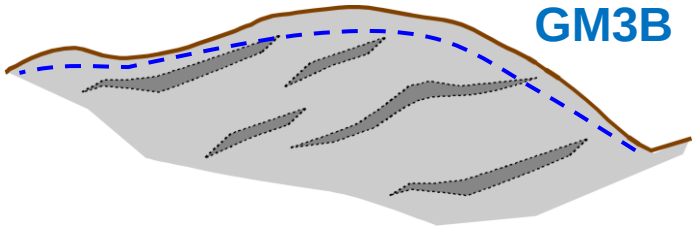
GM4A



GM2A



GM3B

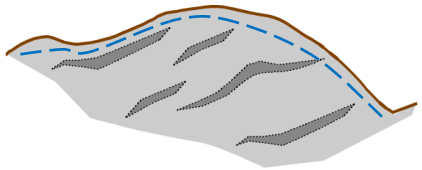
(Santaloia et al., 2012; Cotecchia et al., 2016; Cafaro et al., 2016)

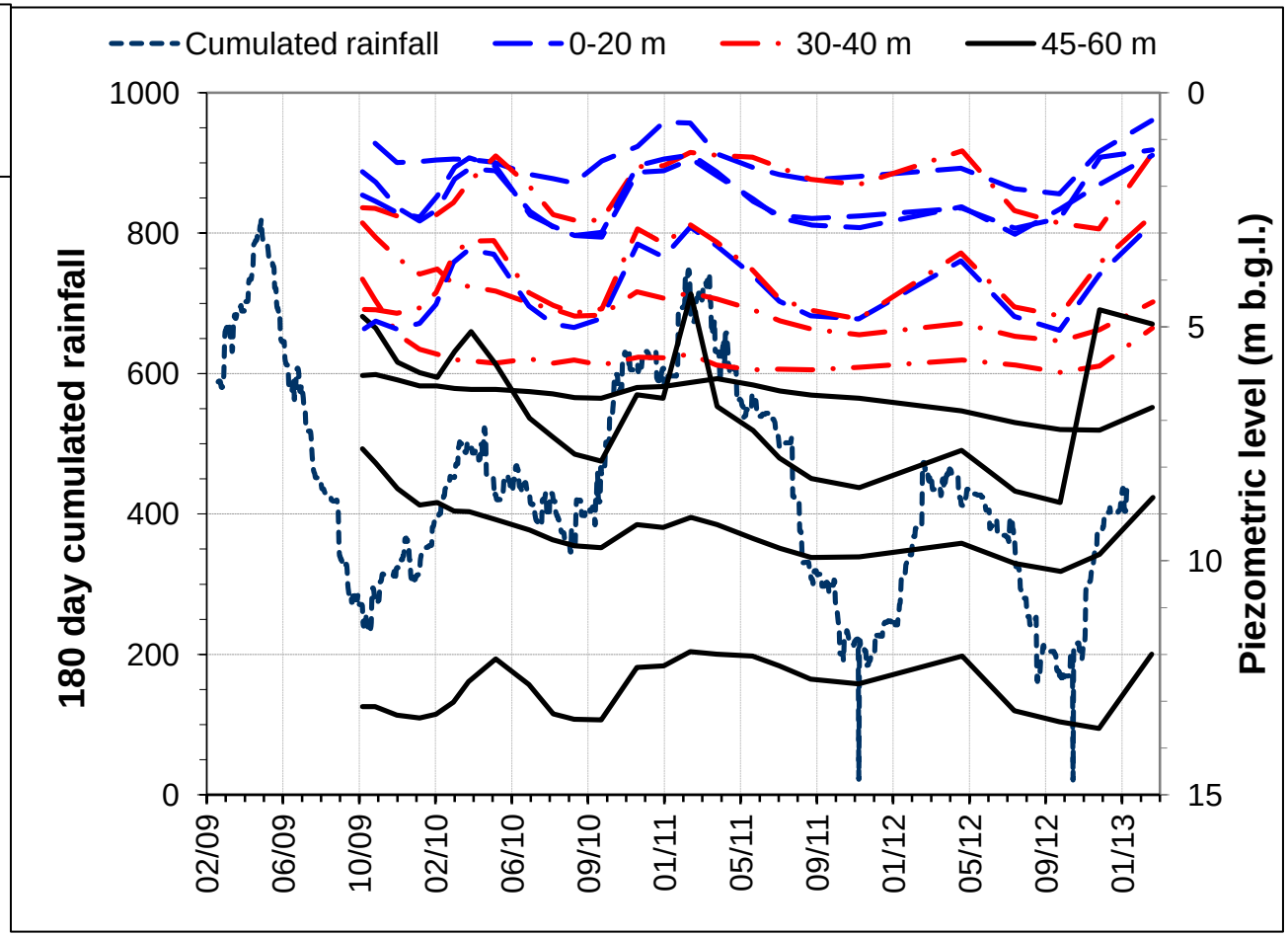
# DAUNIA APENNINES: GEO-HYDRO-MECHANICAL SLOPE SETTING

Very high piezometric heads (w.t. at 3-4 m) subjected to significant seasonal fluctuations down to more 50 m depth fed by cumulated rainfalls

Pisciolo landslide basin

**GM3B**



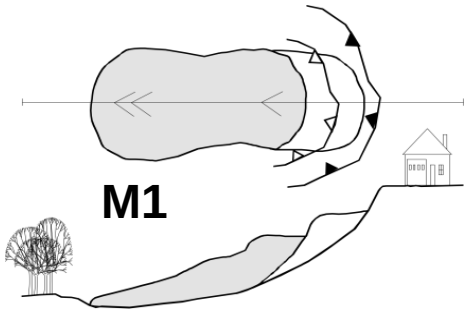



LANDSLIDE PREDISPOSING FACTOR

(Cotecchia et al., 2014, 2016)

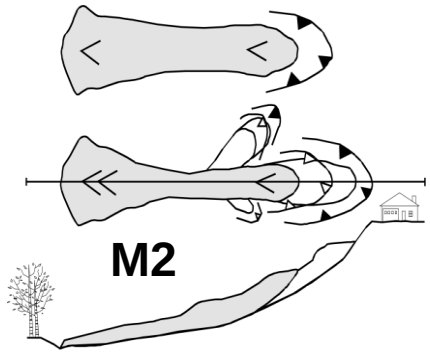
# DAUNIA APENNINES: LANDSLIDE MECHANISM

Analysis of the historical data, field surveys, aerial-photointerpretation ⇒ REPRESENTATIVE LANDSLIDE MECHANISM (Mi)



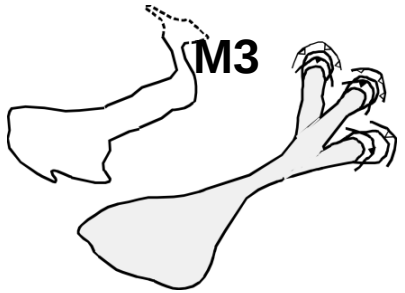

**Roto-translational landslide**

$z_m \geq$ 30-40 m




**Clay slide**

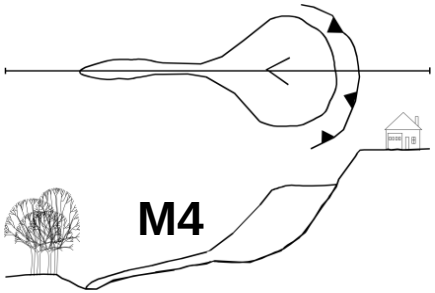
$z_m \geq$ 20 m




**Clay slide-flow/ Earthflow**

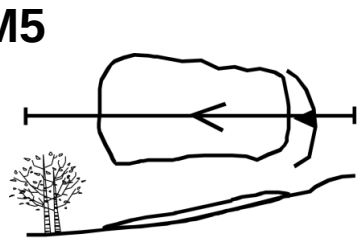
$z_m$ = variable

$z_m$= average depth od the sliding surface




**Slump-earthflow**

slump - $z_m \geq$ 30-40 m




**Soil slips**

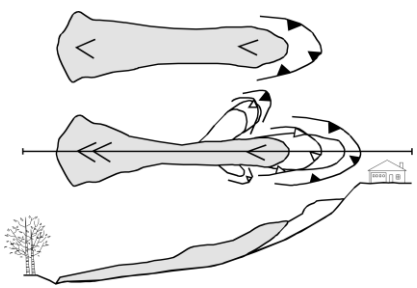
$z_m \leq$ 3-5 m

Secondary landslides:
Rotational slides, fall and toppling

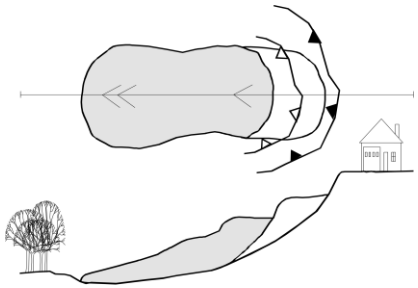
(Santaloia et al., 2012; Cotecchia et al., 2016; Cafaro et al., 2016)

# DAUNIA APENNINES: LANDSLIDE MECHANISM

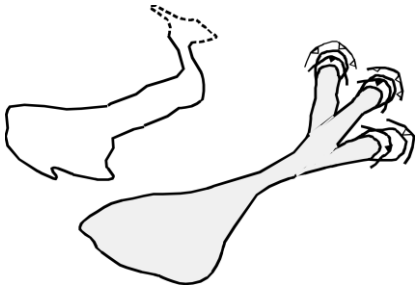
**M2 >>> M1** **M1 >> M3** **M3 > M4**



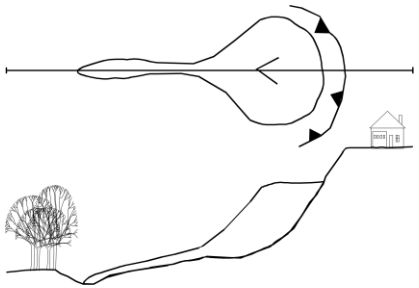
**Clay slide**



**Roto-translational landslide**



**Clay slide-flow Earthflow**



**Slump-earthflow**

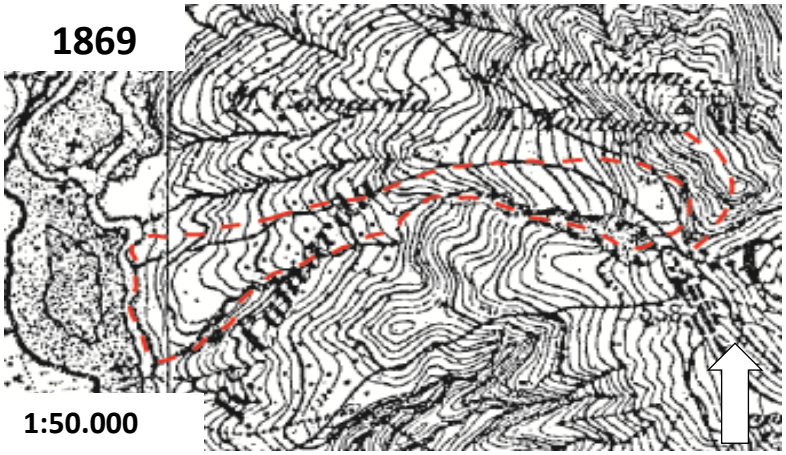
Most of the landslides (M1-M4) are very old mass movement, reactivated several times during the centuries with slow movement rates (v<1.6 m/year)

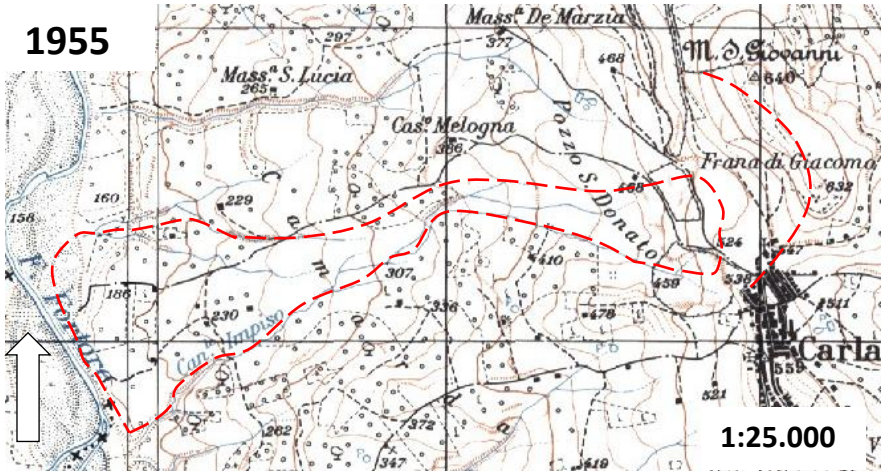
(Santaloia et al., 2012; Cotecchia et al., 2016; Cafaro et al., 2016)

# DAUNIA APENNINES: LANDSLIDE MECHANISM

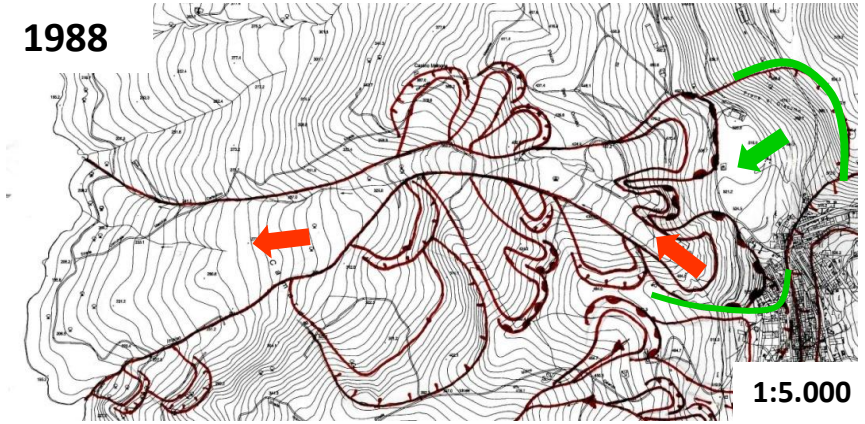
**PALEOLANDSLIDE** or **ANCIENT LANDSLIDES**

FIRST LANDSLIDE EVENT occurred before the end of the XIX during PREHISTORICAL or HISTORICAL times



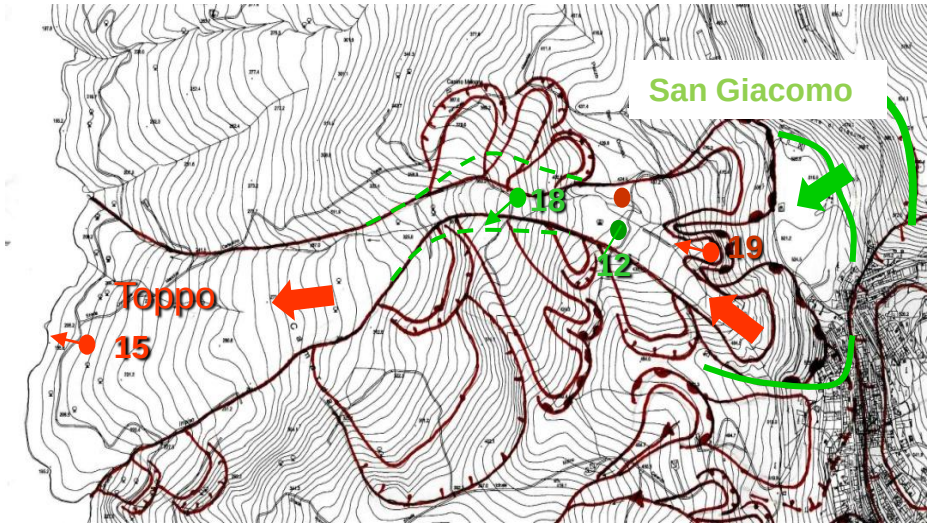



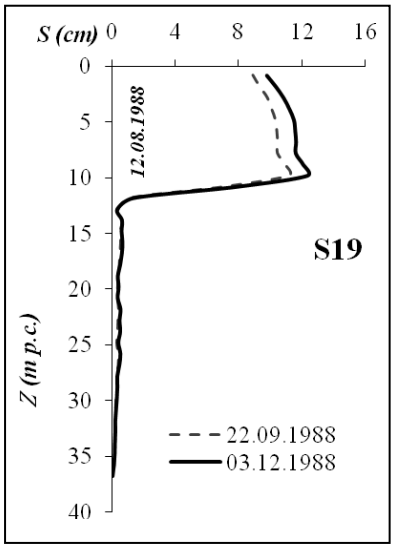

TOPPO LANDSLIDE
M3

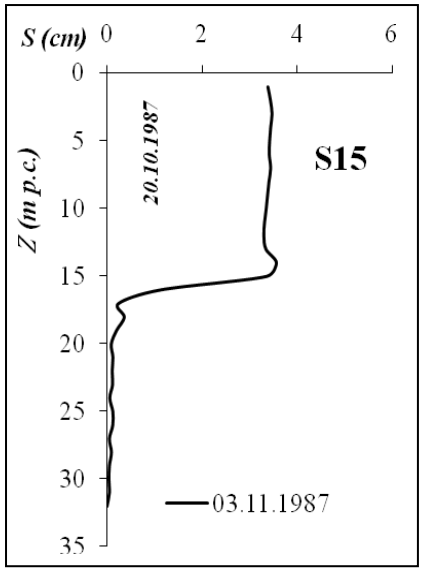


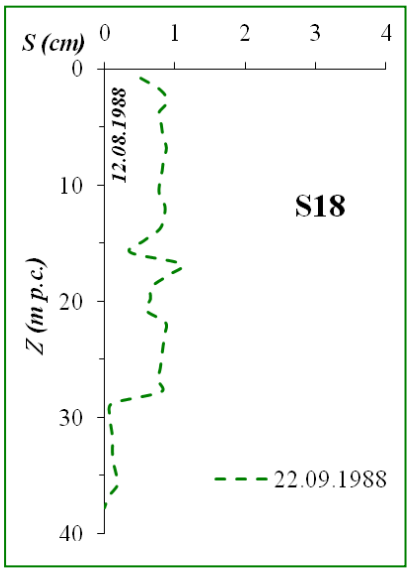
# DAUNIA APENNINES: LANDSLIDE MECHANISM

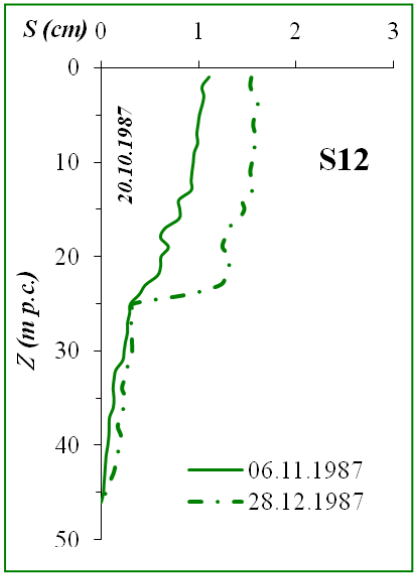
The recent activity of Toppo landslide is deeply connected to the upslope sliding body (San Giacomo landslide)



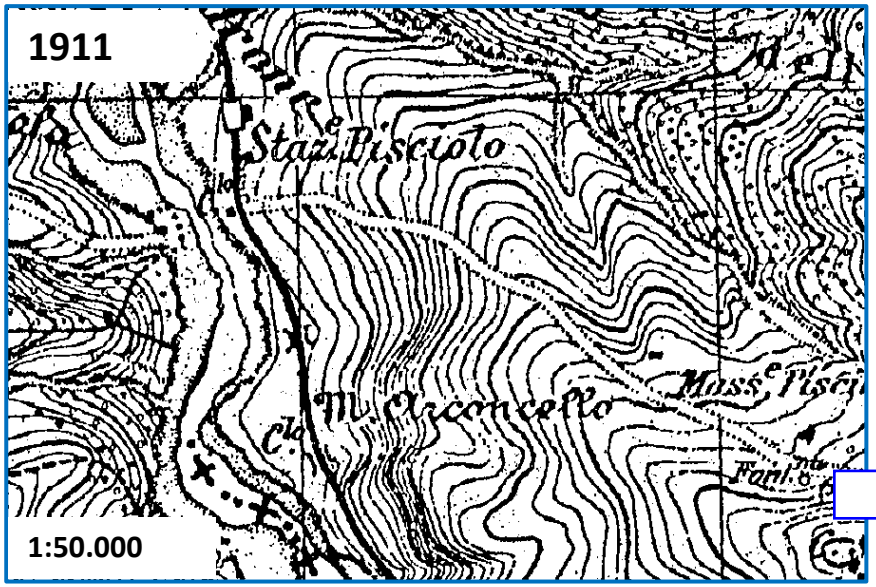

(De Marco, 2008)

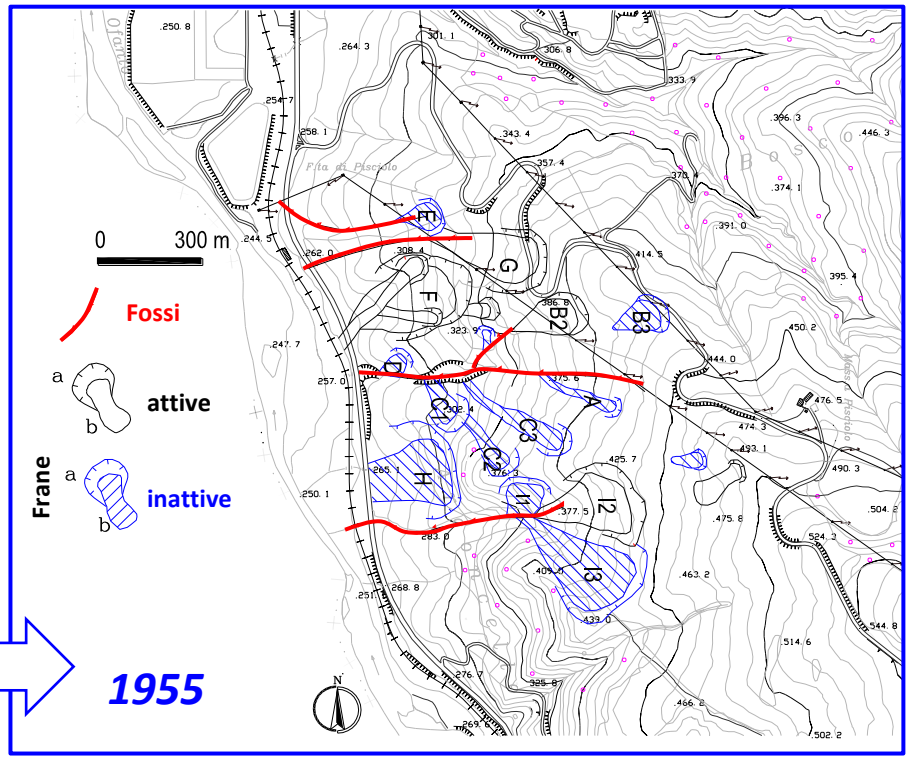
# DAUNIA APENNINES: LANDSLIDE MECHANISM

## **HISTORICAL** or **RECENT LANDSLIDES**

FIRST LANDSLIDE EVENT occurred between the beginning of the XX and the fifties

PISCIOLO LANDSLIDE BASIN (M2-M1)



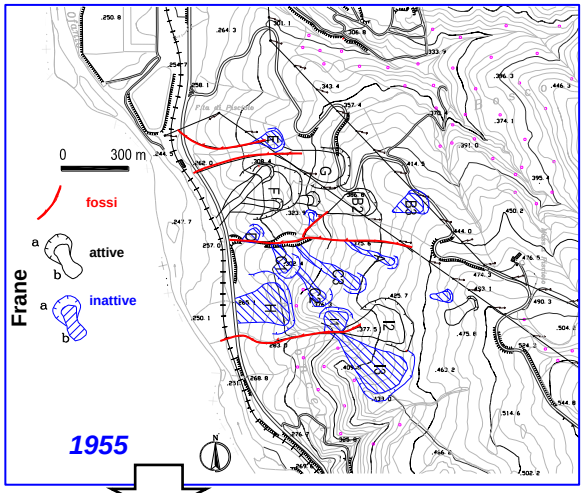



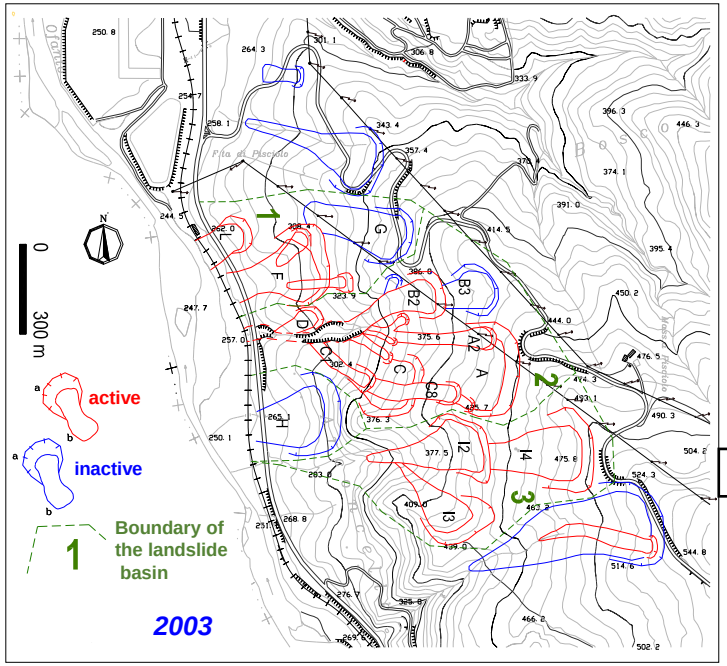

(Cotecchia et al., 2014)

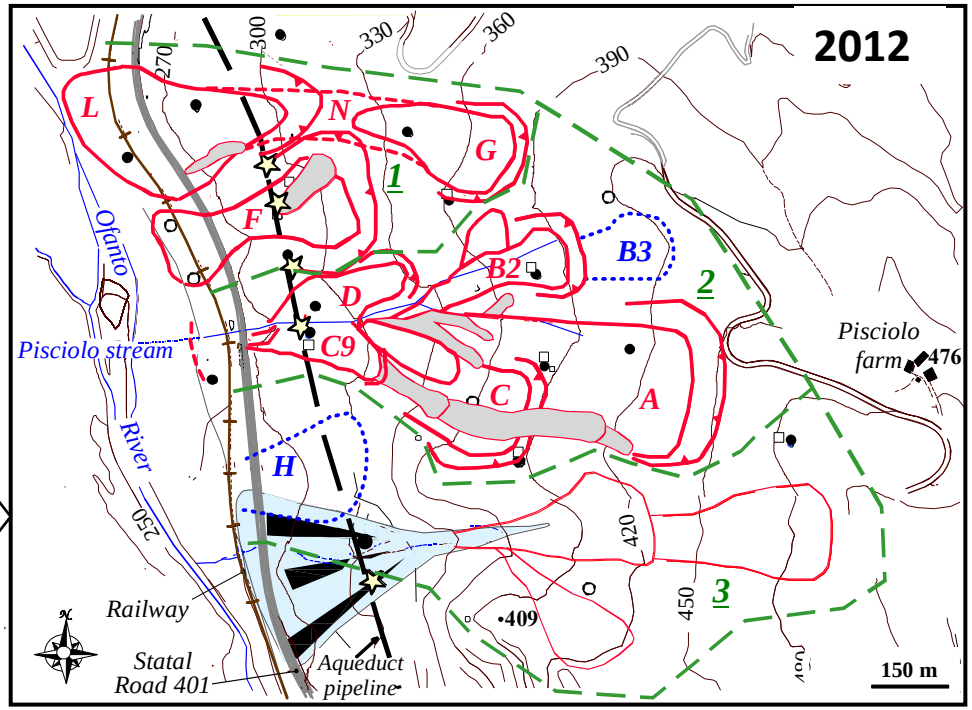
# DAUNIA APENNINES: LANDSLIDE MECHANISM

## PISCIOLO LANDSLIDE BASIN (M2-M1)

Recent landslide activity:
Retrogressive and advancing evolution
of the landslides bodies



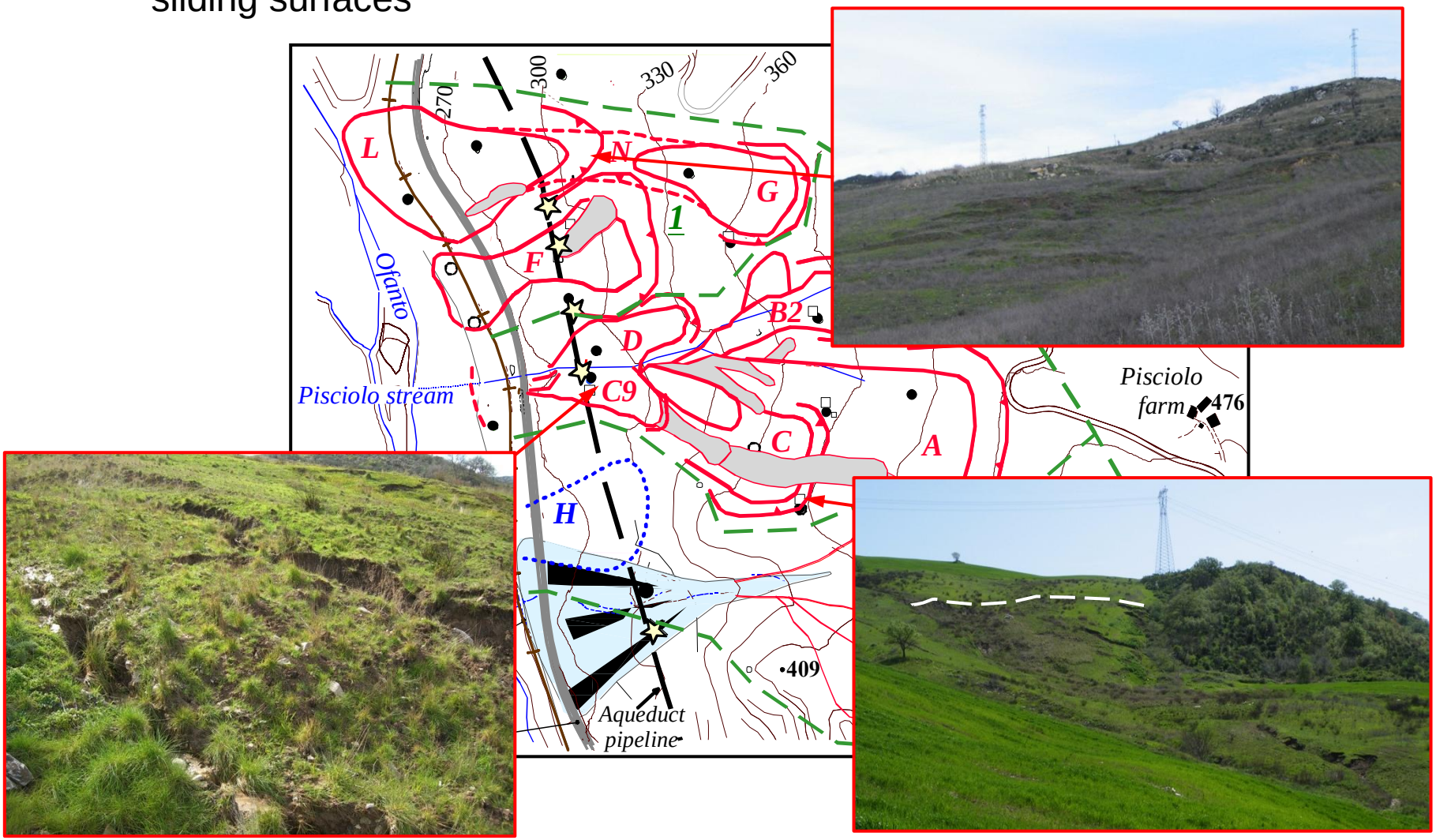




(Cotecchia et al., 2014)

# DAUNIA APENNINES: LANDSLIDE MECHANISM

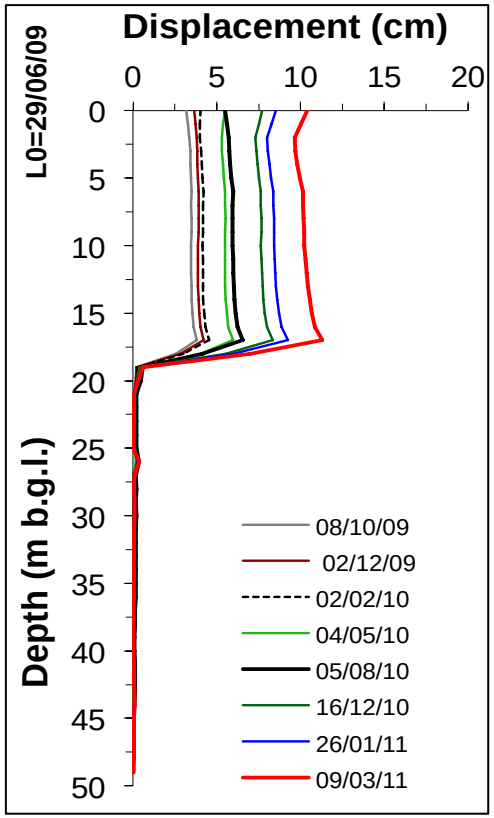
Geomorphological features of the landslides: intermediate to deep sliding surfaces

PISCIOLO LANDSLIDE BASIN (M2-M1)

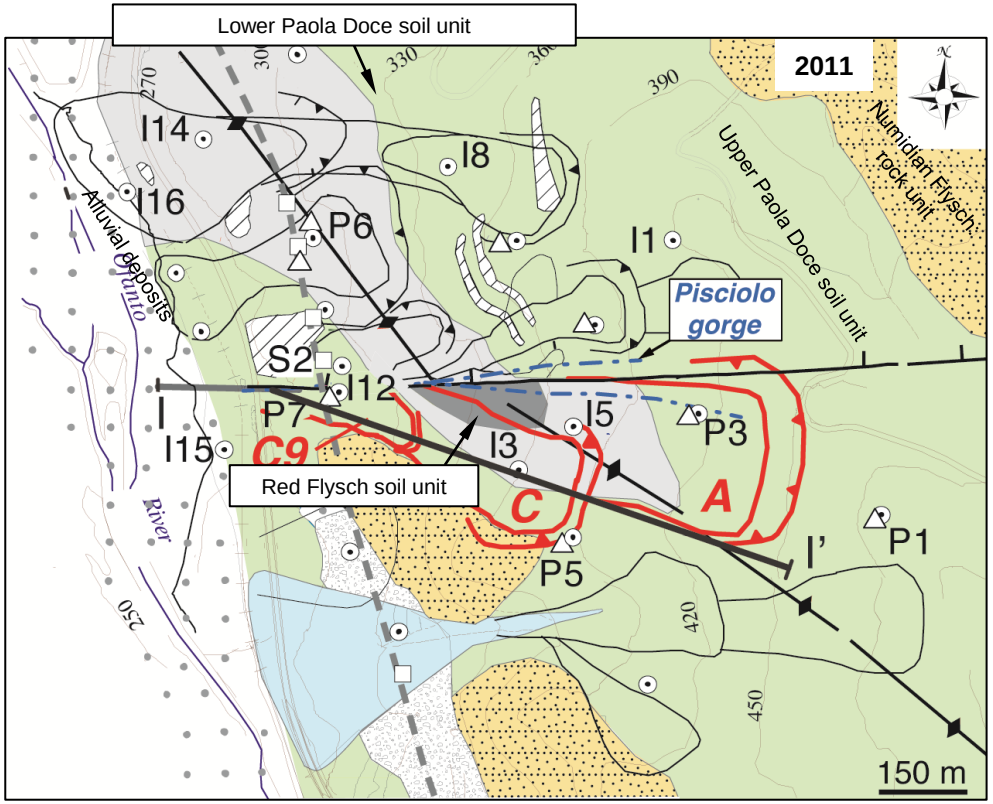


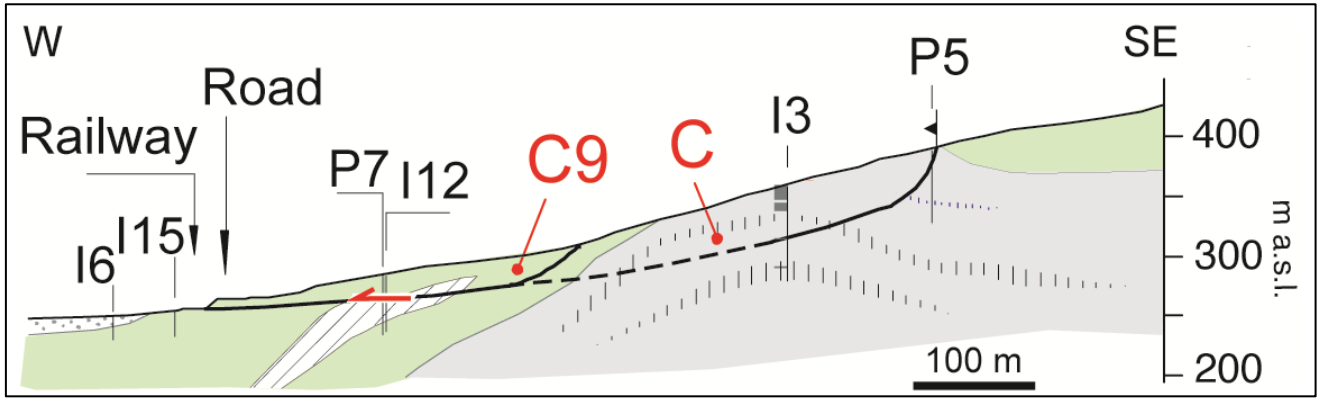
# DAUNIA APENNINES: LANDSLIDE MECHANISM

Active landslides
Average dislacement rate 6 cm/year



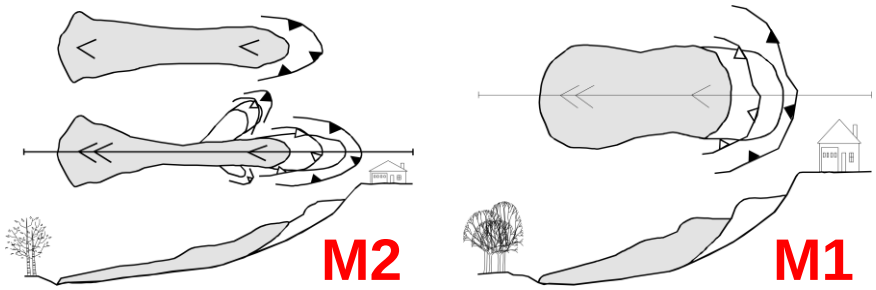

**Failed in April 2011**



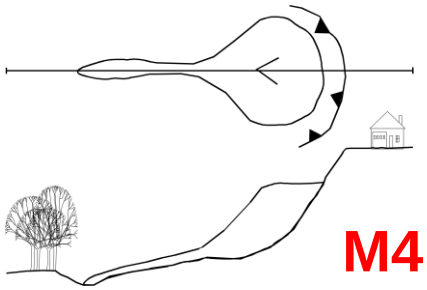

(Rapporto AQP, 2011; Cotecchia et al. 2014, 2015)

## CURRENT EVOLUTION OF THE LANDSLIDE PROCESS

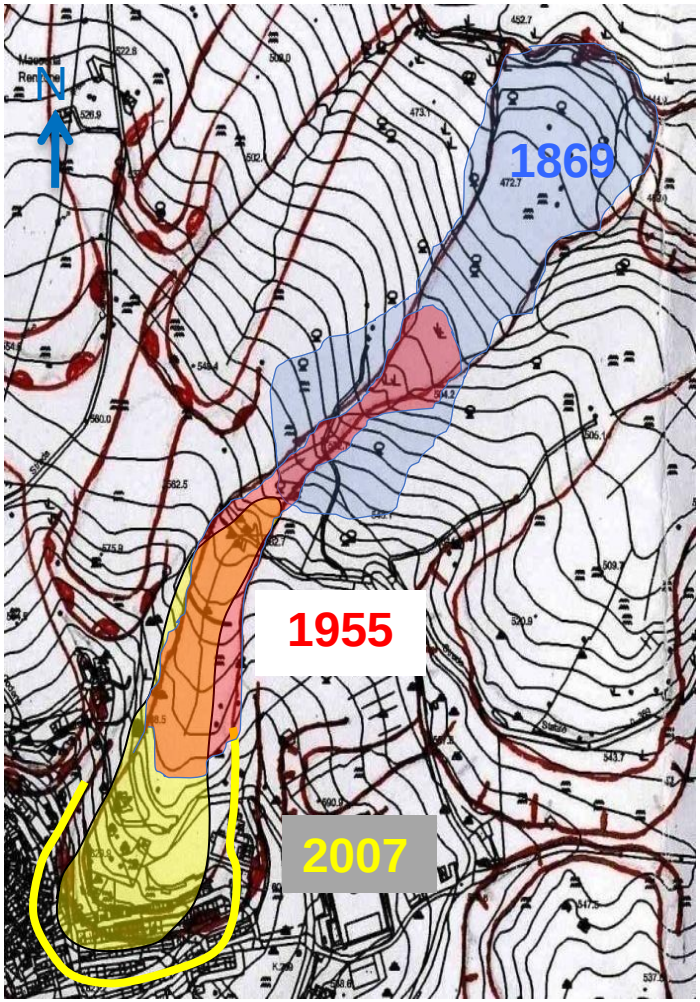



SLOPE FAILURE FROM BOTTOM TO THE TOP OF THE SLOPE

SLOPE FAILURE FROM THE TOP TO THE BOTTOM OF THE SLOPE




Serrone Landslide

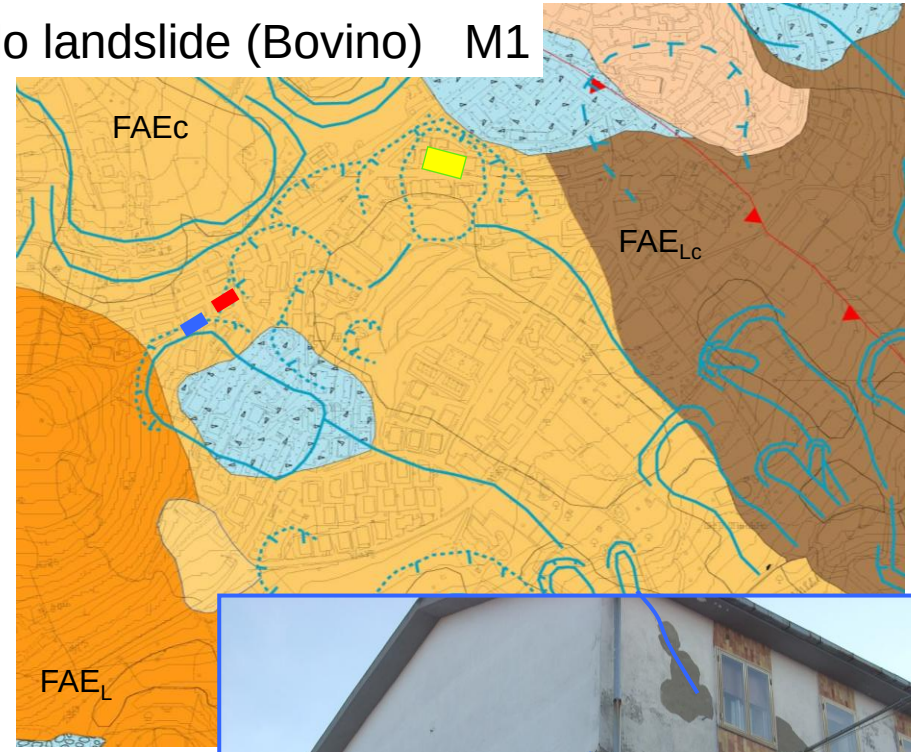


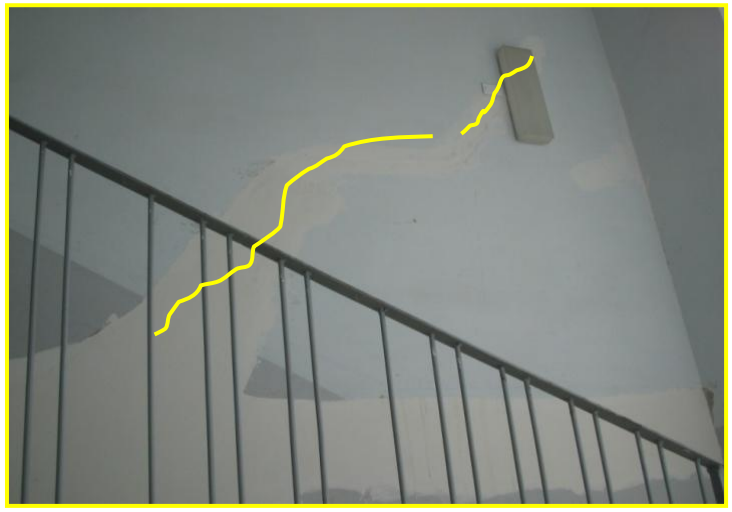

(Palladino, 2009)

# DAUNIA APENNINES: LANDSLIDE MECHANISM

## CURRENT ACTIVITY : damages of the building located nearby the depletion area

Pianello landslide (Bovino) M1



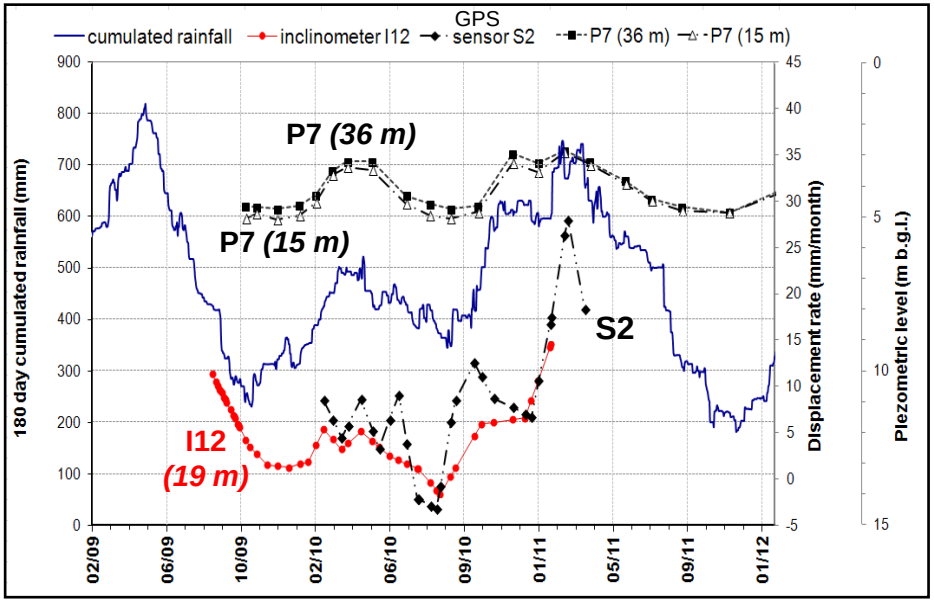
FAE= Faeto Flysch
FAE$_L$ = rock unit (limestone)
FAE$_{Lc}$ = rock unit (limestone with few clay strata)
FAEc= soil unit (clay)

(Palmisano, 2011; Cotecchia et al., 2016)

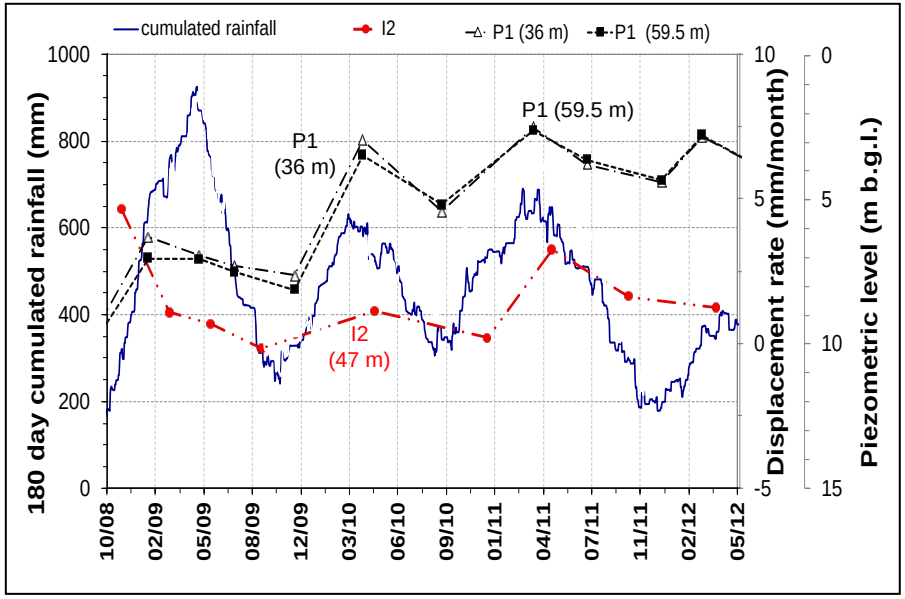
# DAUNIA APENNINES: LANDSLIDE MECHANISM

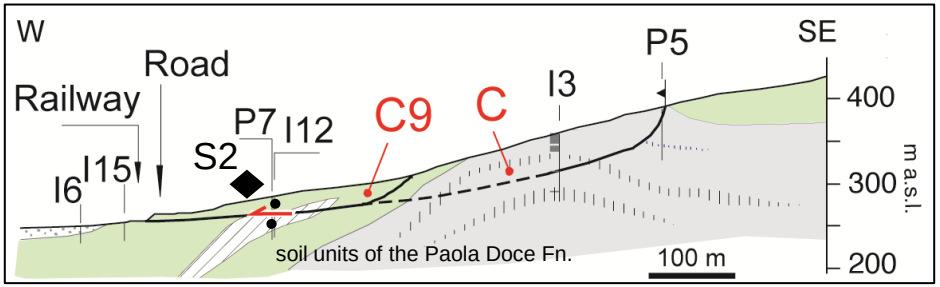
The current activity of many deep landslides is triggered by seasonal rainfall fluctuations

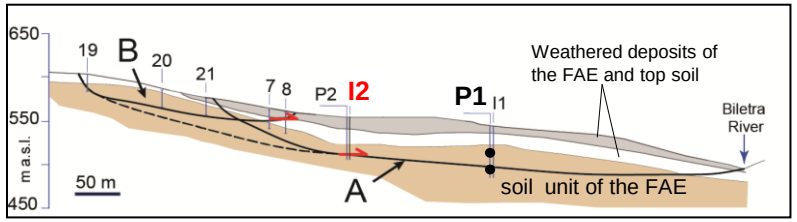
Pisciolo landslide M2




Pianello landslide M1




Drainage system for slope stabilisation

(Cotecchia et al., 2014, 2016)

# CONCLUSION

Based on phenomenological analyses, most of the landslide processes in Daunia are mainly represented by:

- Intermediate to deep sliding processes,
- old landslides (from prehistorical to recent landslides) reactivated with slow-rate of movement ,
- predisposed by soil weakness and high piezometric heads.

Most of the current landslide reactivations are triggered by seasonal fluctuation of the piezometric heads induced by cumulated winter-spring rainfall infiltration

This phenomenological diagnosis of many landslide processes in Daunia region is validated by analytical and numerical modelling

LANDSLIDE HAZARD ASSESSMENT