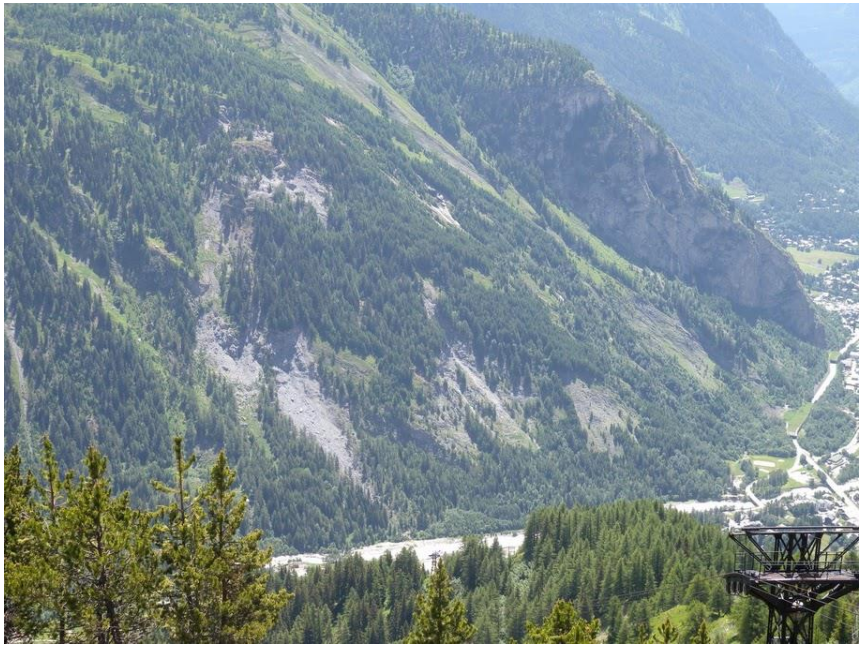
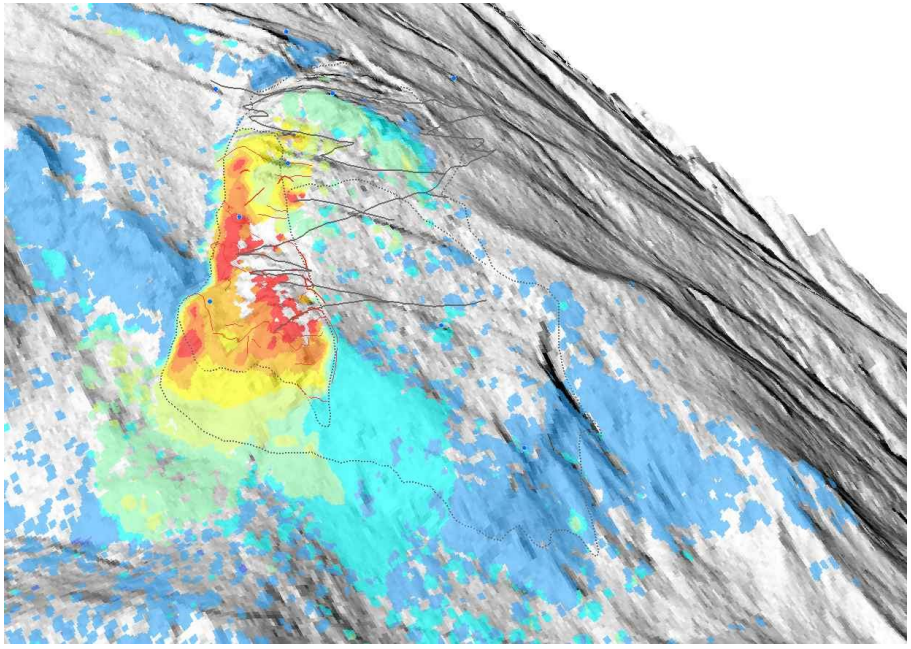




Investigation and monitoring of the Mt de la Saxe landslide

Crosta, G.B., Castellanza, R., Frattini P., Agliardi, F., Lari, S.
Dept. Earth and Environmental Sciences, Univ. Studi di Milano Bicocca, Milano, ITALY

Cancelli, P., *SCA, ITALY*
Tamburini, A., Alberto, W., *IMAGEO, ITALY*

In collaboration with Valle d'Aosta Region, Geological Survey

Approach under complex conditions

active or reactivated landslide → no data available

2002-2009 → 2009-2013

1 **Improving available knowledge for general understanding:**

- investigations

2 **Definition of Warning Thresholds**

- Preliminary and «Definitive»
- Ground surface
- subsurface

3 **Setting up a Monitoring Network**

- For understanding behaviour
- For estimating geometry, properties
- For EWS
- For calibration of models

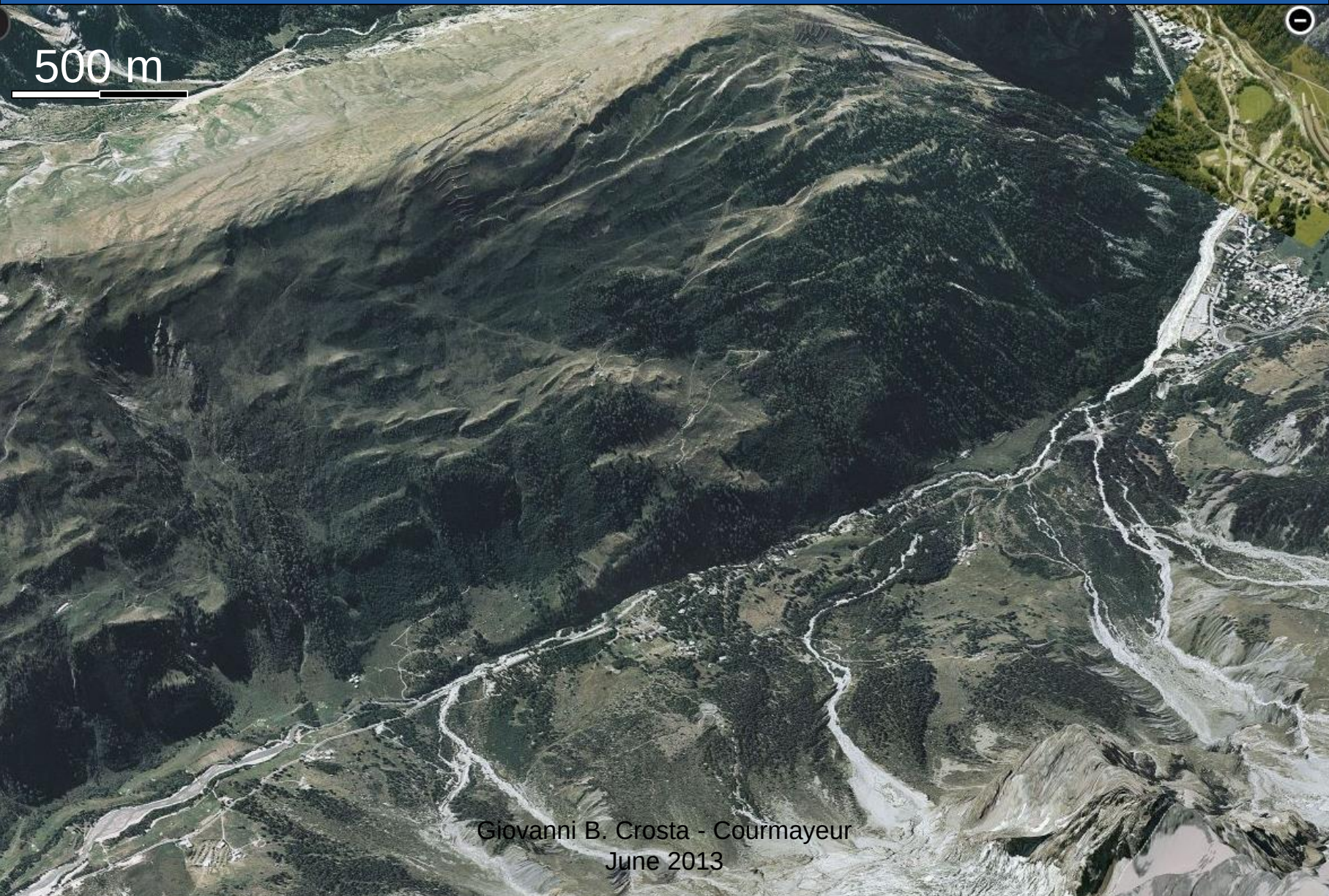
4 **Prediction of behavior:**

- Sensitivity to triggering
- modeling

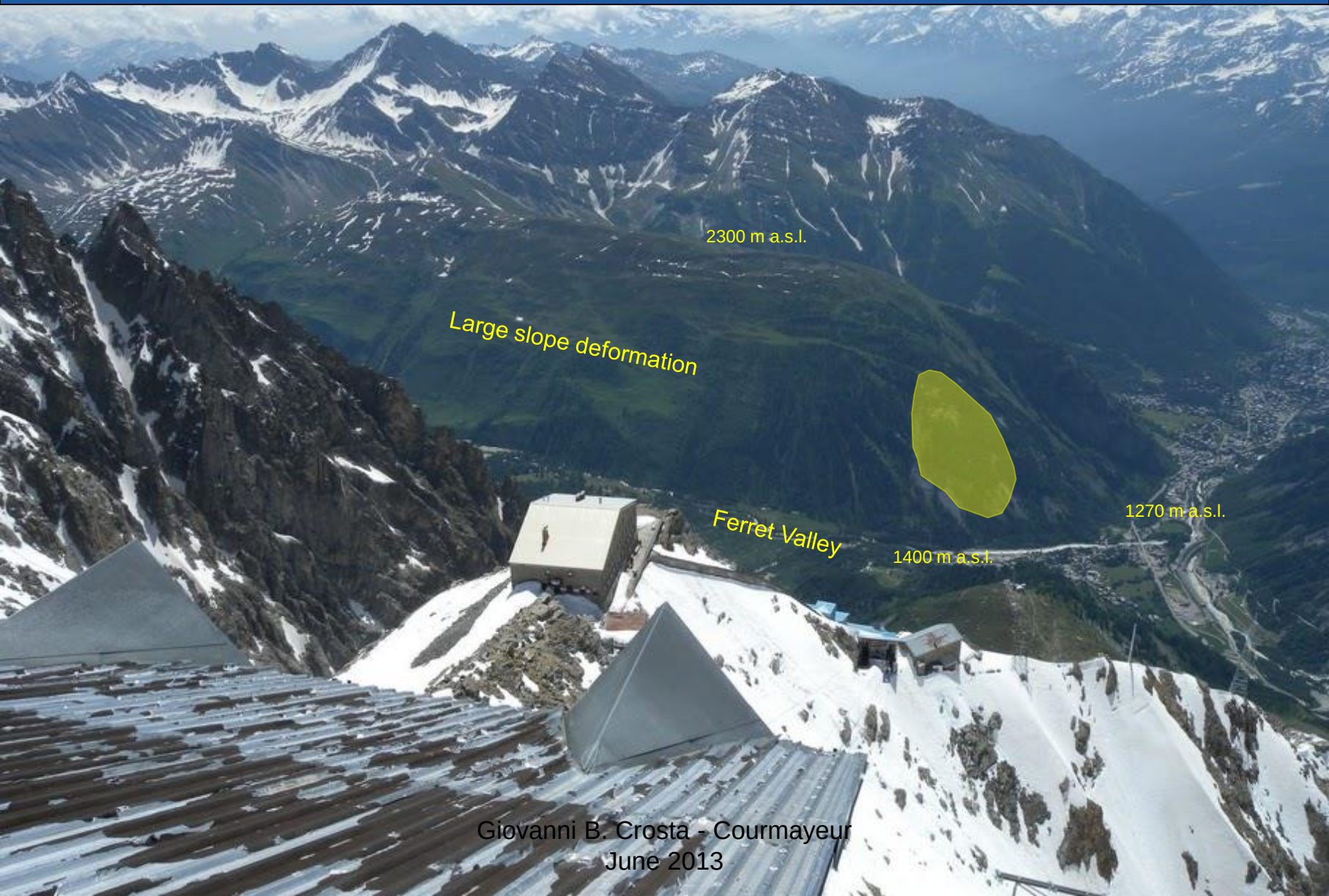
5 **Mitigation countermeasures:**

- EWS
- Passive structural
- Stabilization

Ferret Valley



Settings



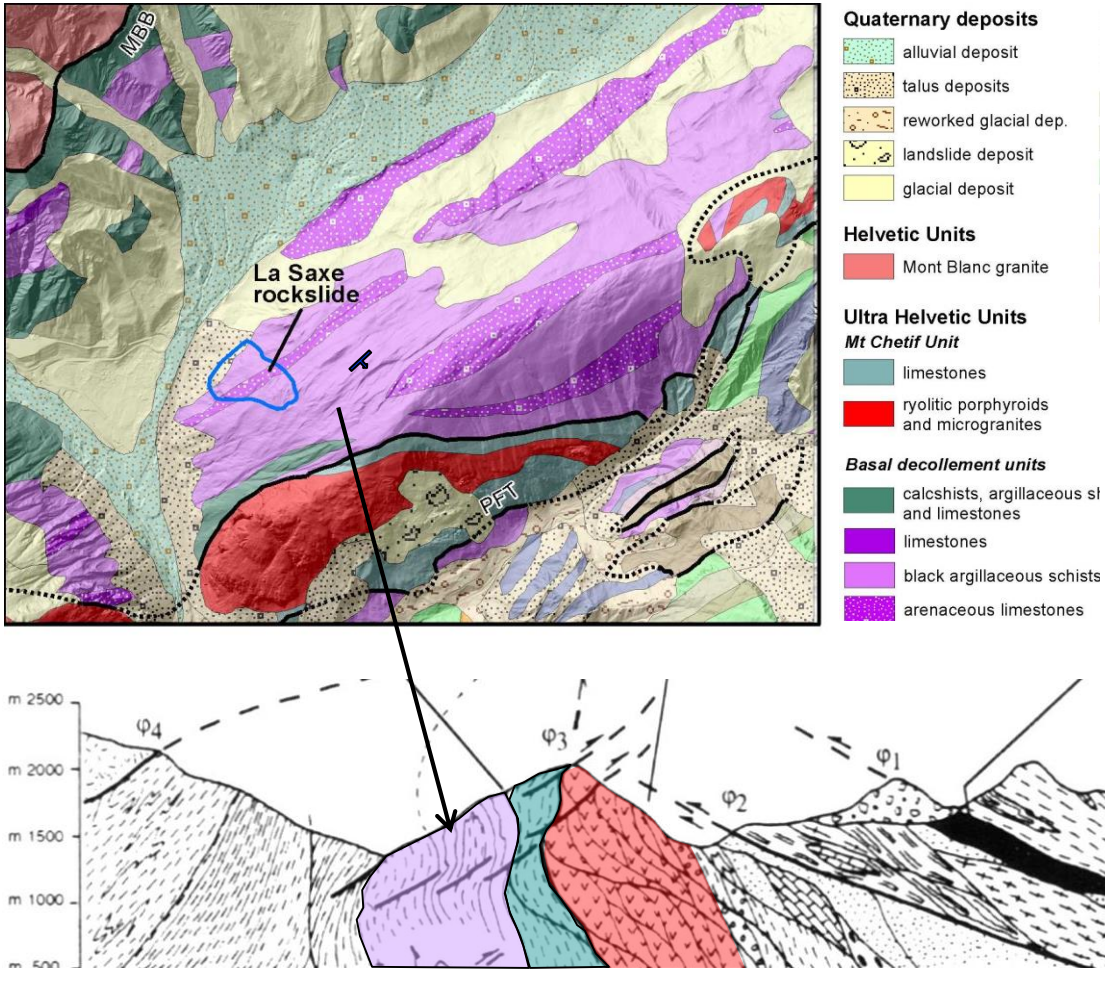
Giovanni B. Crosta - Courmayeur
June 2013

Elements at risk

- **Entréves – La Palud villages** (about 1 Billion euros)
- **National road, SS26dir**
- **Aosta - Mt Blanc Highway**
- **Entrance to Mt Blanc Tunnel** (cost of closure about 1 Billion euros/year)
- **New Mt Blanc Cable Way station**

- **High and long term socio-economic impact on the Courmayeur tourist resort**

Geology



Perello et al., 1999

intensely deformed ***meta-sedimentary rocks*** (Jurassic **limestone-marly limestone, black schist and calcschist**) variable dip (Helvetic - Ultra Helvetic)

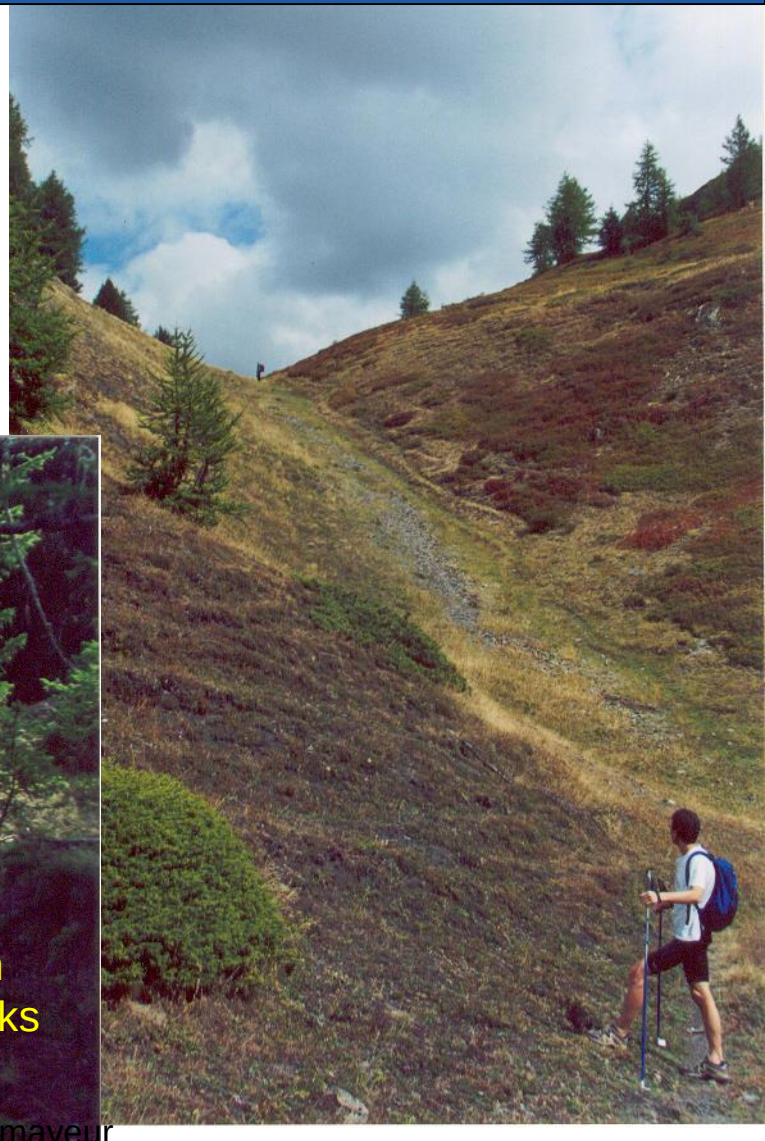
tectonic contact with the Chetif - Mont de La Saxe ***meta-granites and meta-rhyolites***

Penninic Thrust front

Schistosity dip into the slope at medium to high angle

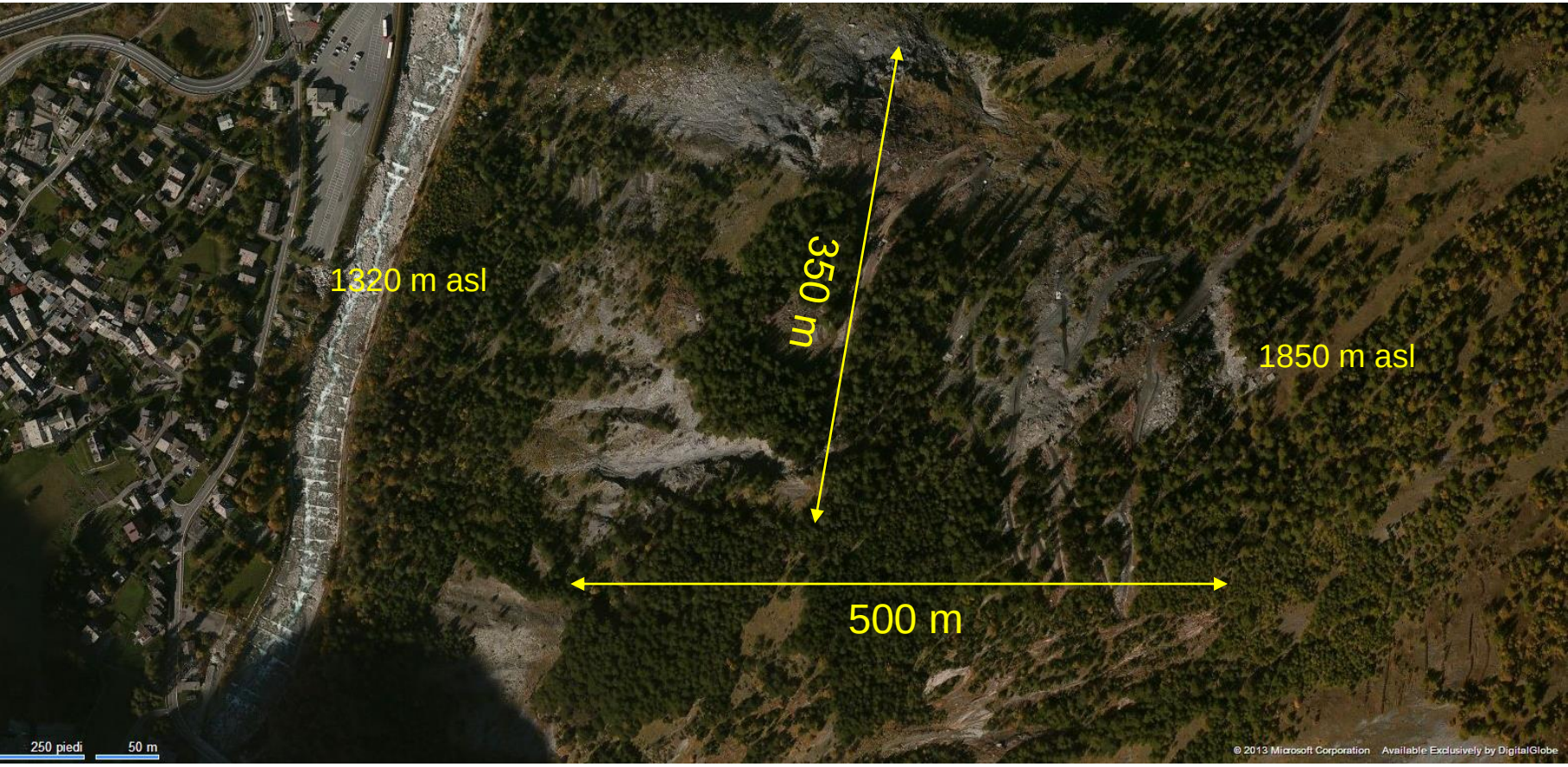
Field evidences of a large instability

Trenches
Counterscarps
Transversal to slope direction
Up to 1 km long



Closed depression
Open tension cracks
Tensioned roots
Tilted trees

Field evidences of a large instability

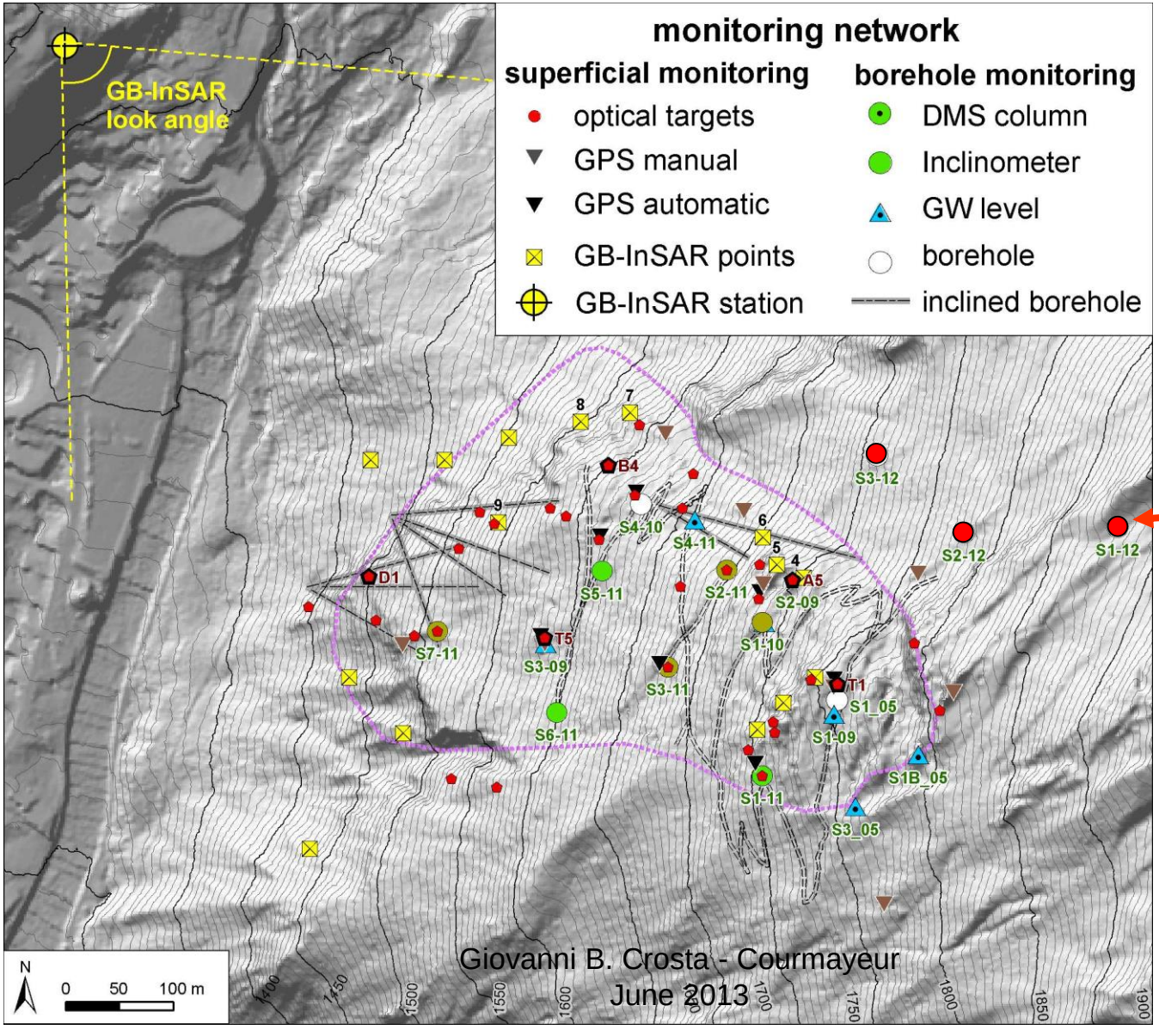


Ave. Slope gradient: 35˚

Giovanni B. Crosta - Courmayeur

June 2013

Boreholes and Monitoring network



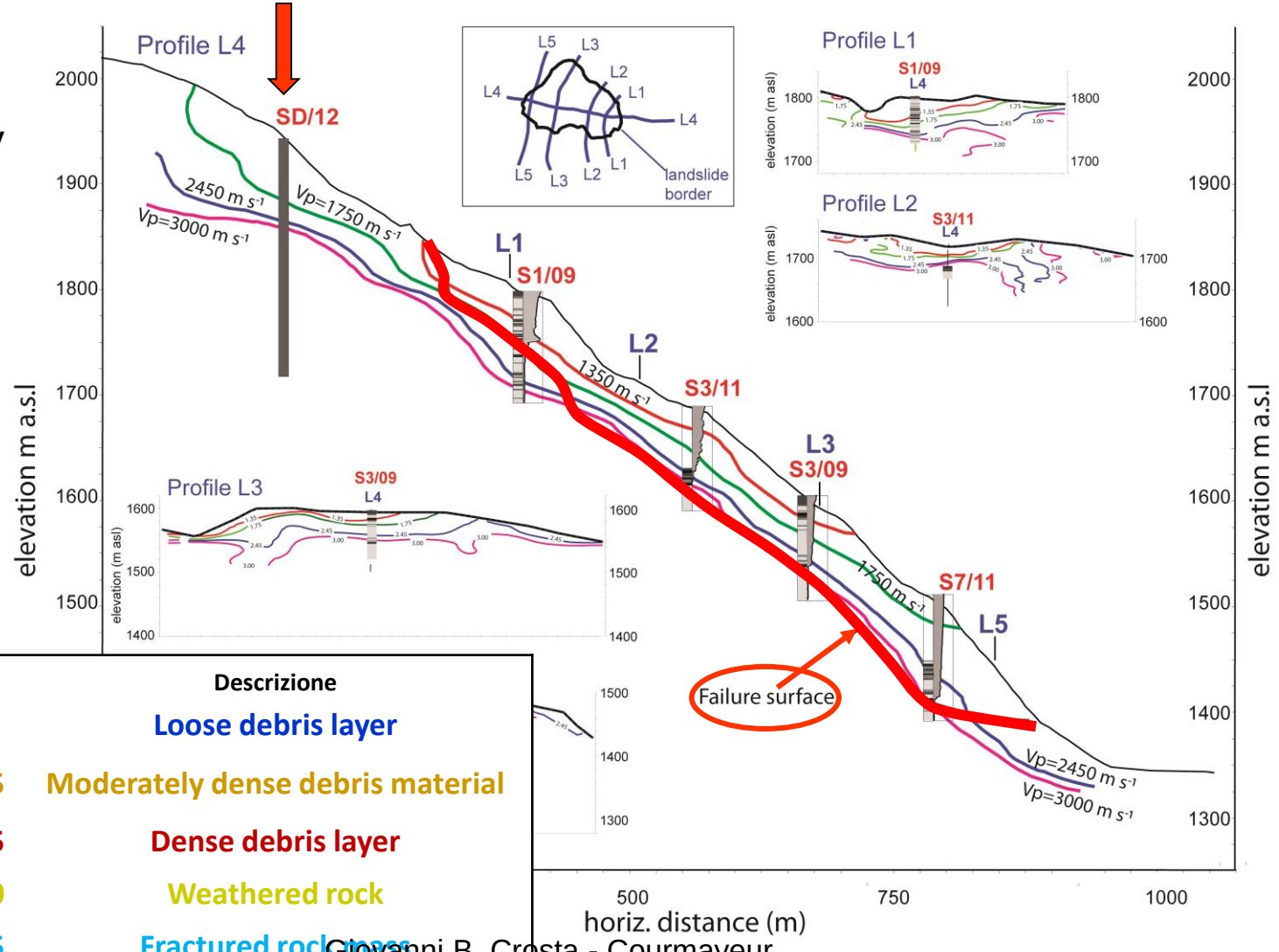
210 m deep borehole

18 boreholes
(2005-2012)

14 inclined
boreholes
(22 – 29˚ ,110 to 180 m)

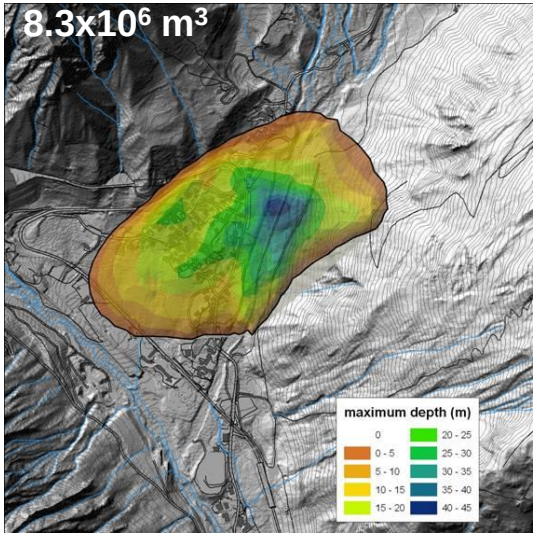
Direct and indirect investigation

Seismic refraction tomography



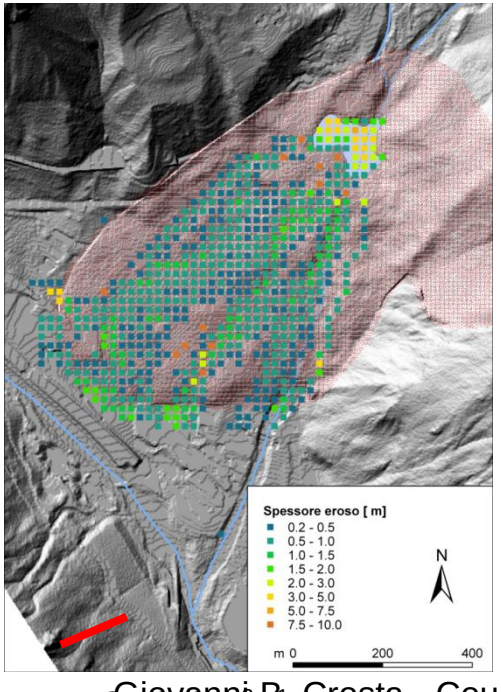
Vp (km s^{-1})	Descrizione
V_p<1.35	Loose debris layer
1.35 < V_p<1.75	Moderately dense debris material
1.75 < V_p<2.45	Dense debris layer
2.45 < V_p<3.00	Weathered rock
3.00 < V_p<5.25	Fractured rock mass
5.25 < V_p	Massive Rock mass

Runout, damming and breaching

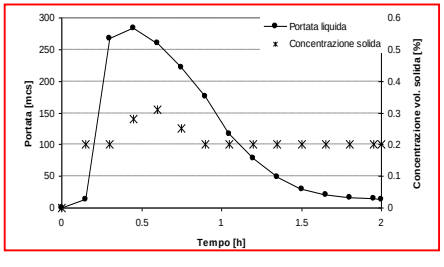


Breaching and erosion of landslide deposit Scenario A

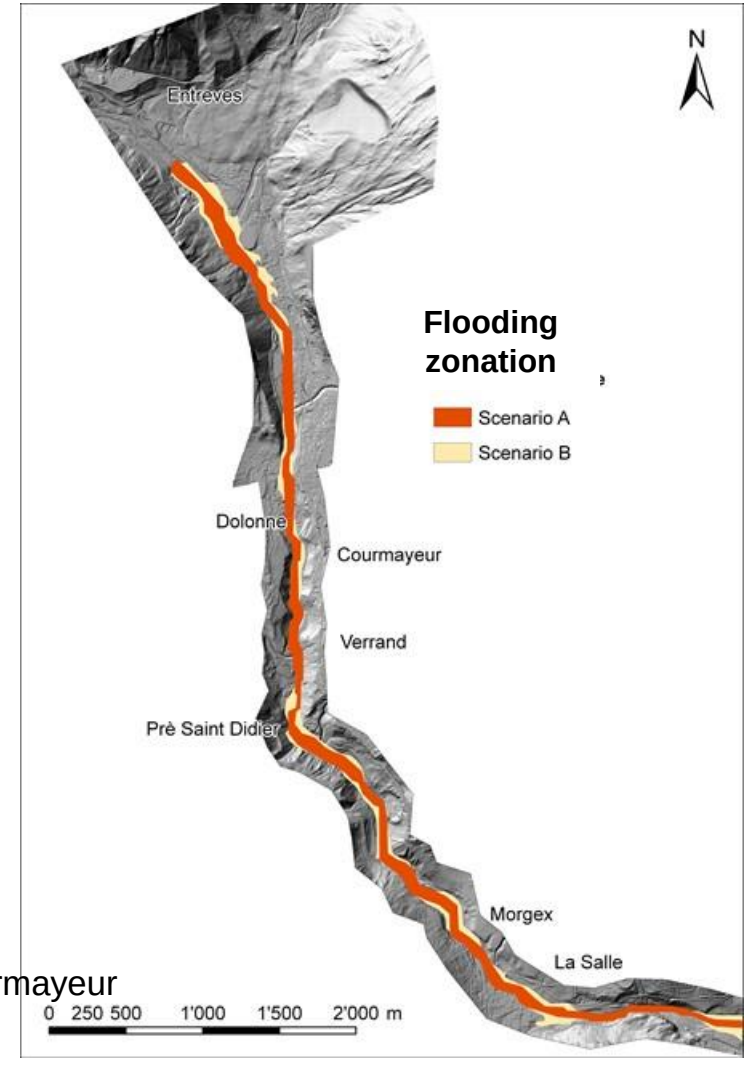
V_{eroded} = 82.000 m³
ave depth = 0,85 m
max = 6-8 m



Breach discharge
Scenario A



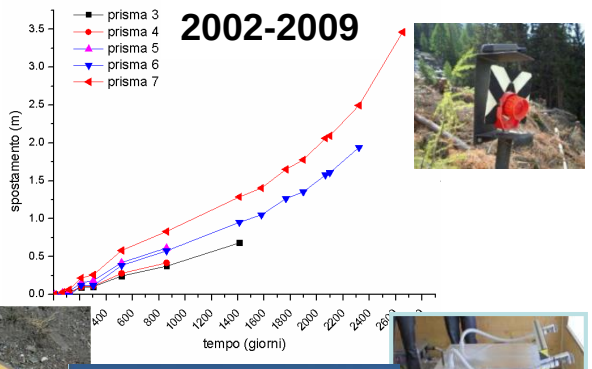
Q= 278 m³ s⁻¹ (water)
Vol. sediment = 116.000 m³

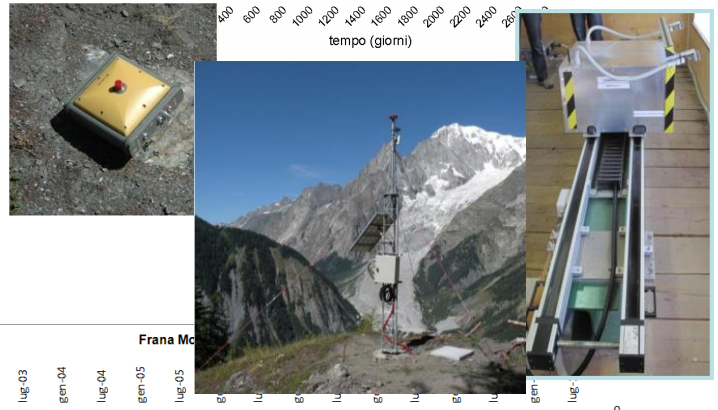


Monitoring network

Ground surface displacements

- **EDM: 8 targets, 2 station points, 15 measurements:** 2002-2009
- **1 GB-InSAR** *(LisaLab system, by Ellegi srl)*
- **9 GPS** for periodic manual measurements
- **5 continuous GPS**
- **1 Total station: ca. 35 optical targets** (1 measure/h)

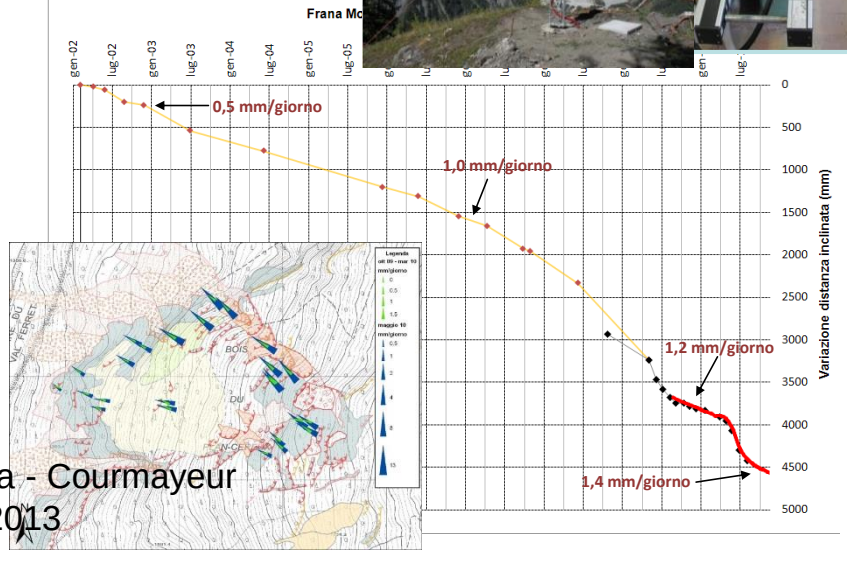




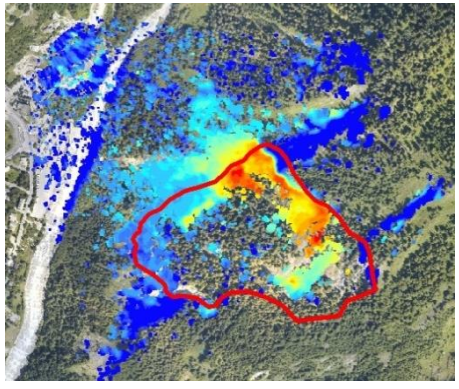
Geotechnical monitoring network

(active at different times)

- **6 Inclinometer casings** for periodic measurements
- **3 borehole wire extensometers**
- **6 open case piezometers**
- **4 DMS multi-parametric probes** (length: 1 DMS 12 m, 2 DMS 80 m, 1 DMS 110 m)



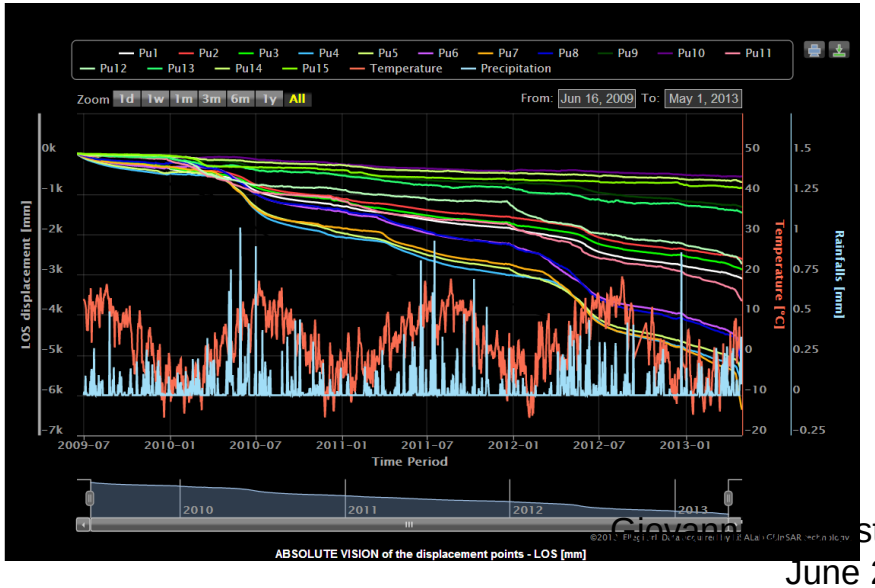
GB-InSAR: ground based radar interferometry

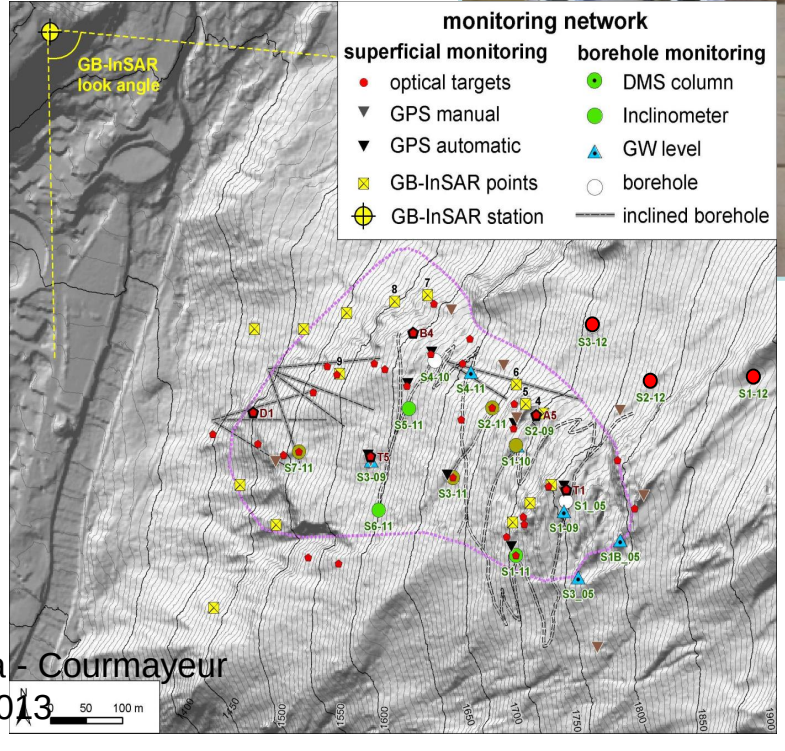


- *Accuracy = ±0.1-0.3 mm*
- *Precision = ±0.3-0.7 mm*
- *Frequency = Ca. 17 GHz*

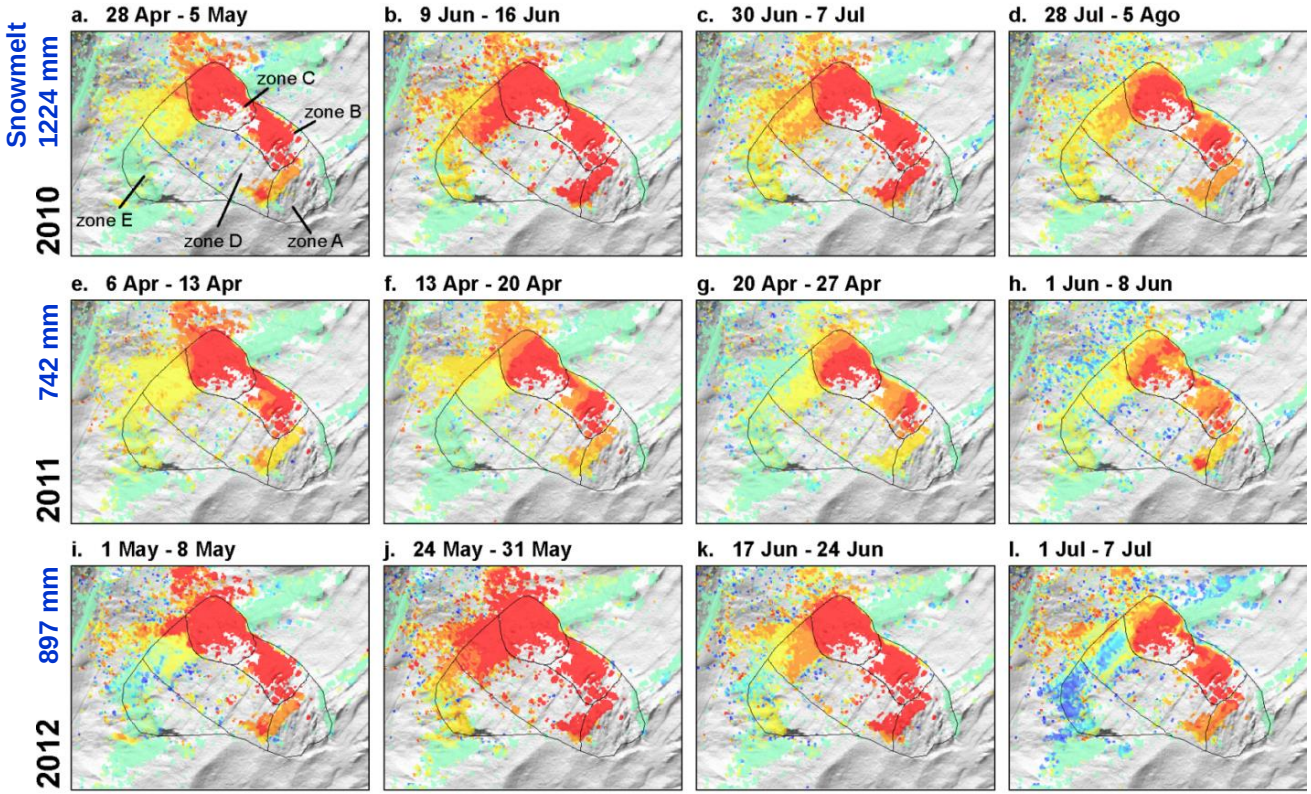
LiSALab - GB-InSAR
Continuous Monitoring

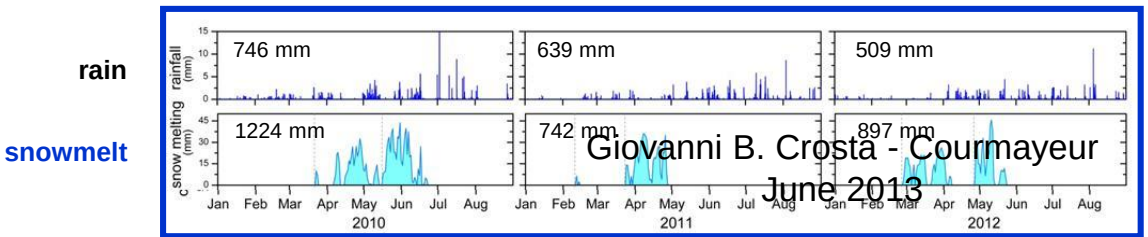
- **Displacement field in the LOS direction**
- **Scan time**: 9 min
- **Ground resolution**:
  0.5 to 4 m → 500 to 2000 m
- **15 streaming points** since june 2009





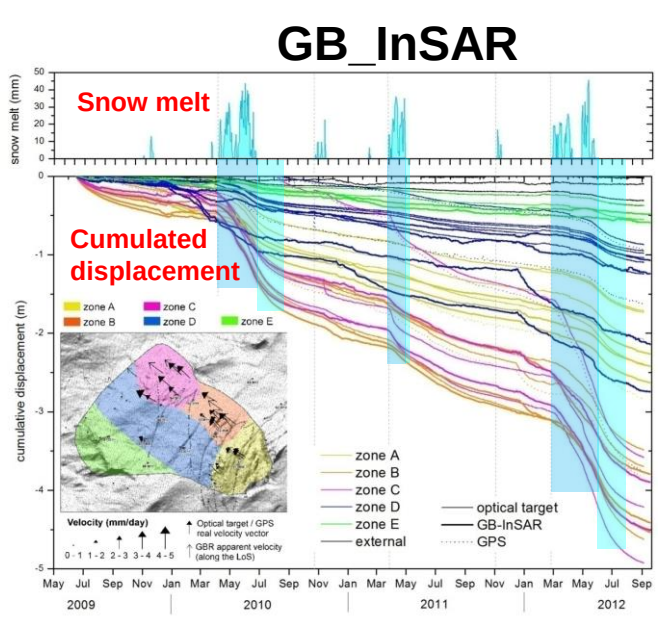
GB-InSAR: displacement field at 3 reactivations



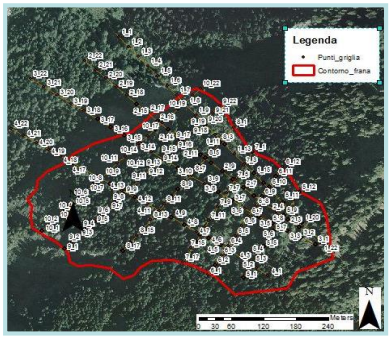


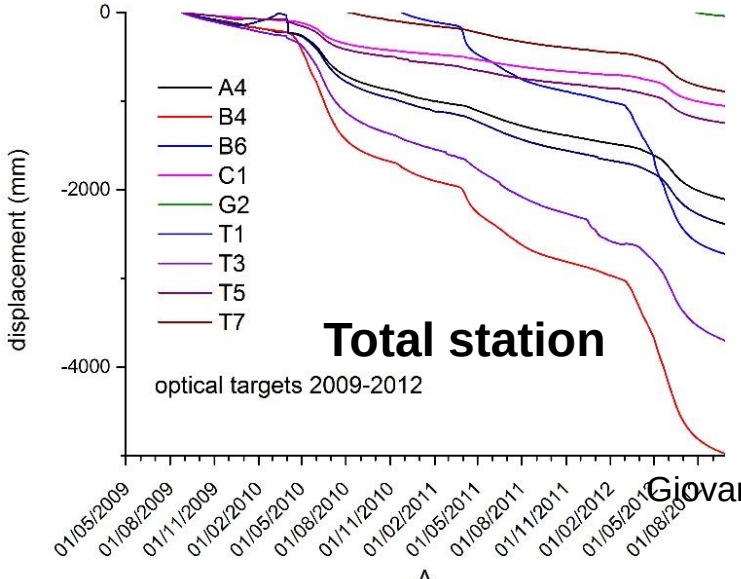
- **Seasonality**: mainly associated to snow melt
- **debris toe slope reactivation** shorter and antecedent with respect to rockslide
- **Daylighting** of failure surface
- sectors **with different sensitivity,** not always reactivated or at different instants

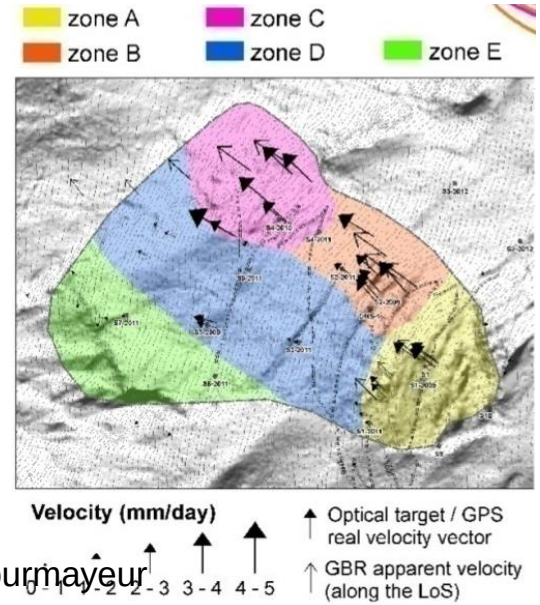
GB-InSAR: rockslide zonation



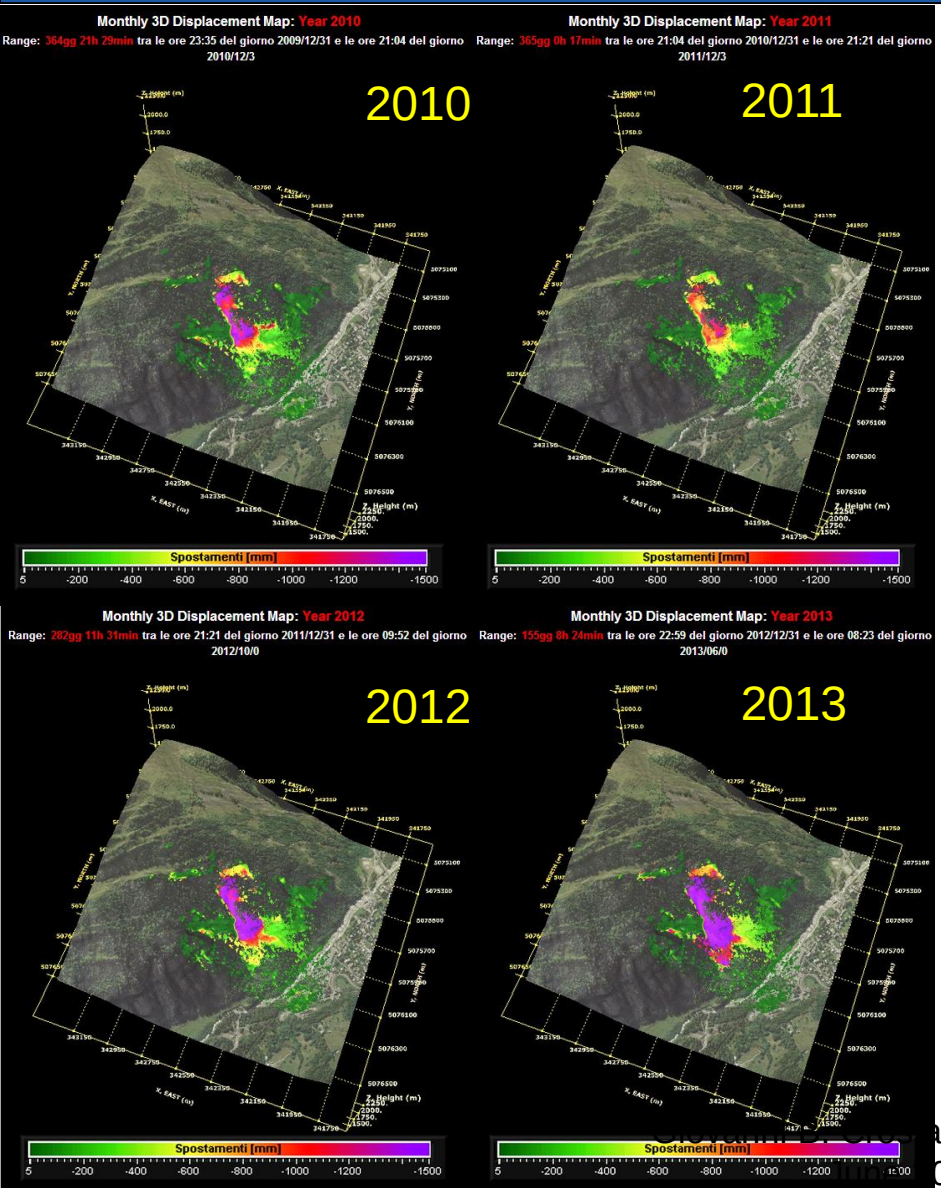
- 190 points
- extraction of the time histories:16-06-009→2013



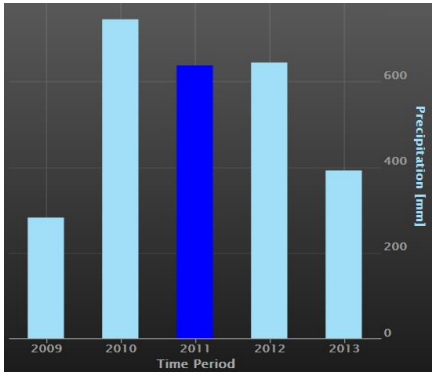




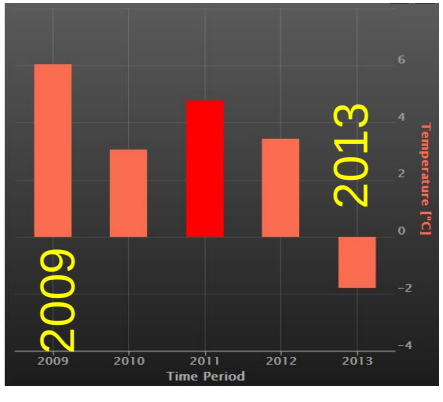
GB-InSAR: yearly comparison



Annual Rainfall

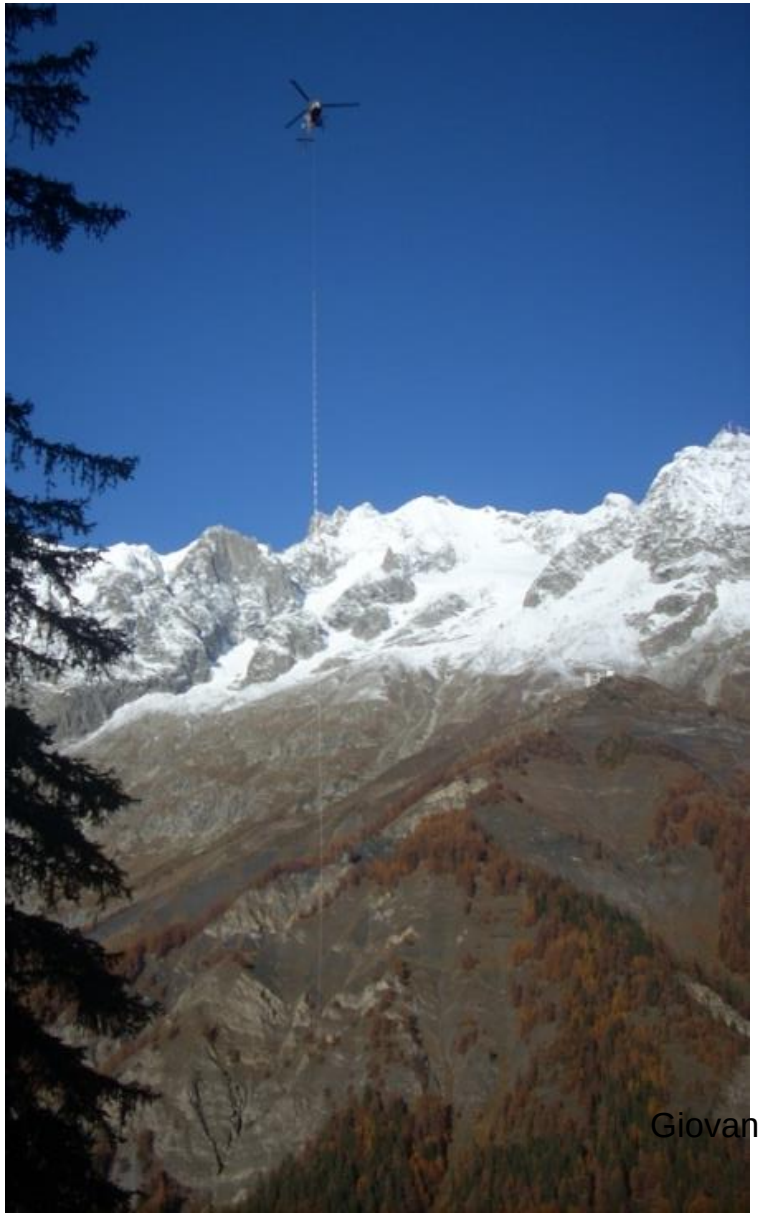


Annual Ave.Temperature



- Courmayeur
- 2013 → Jan to May

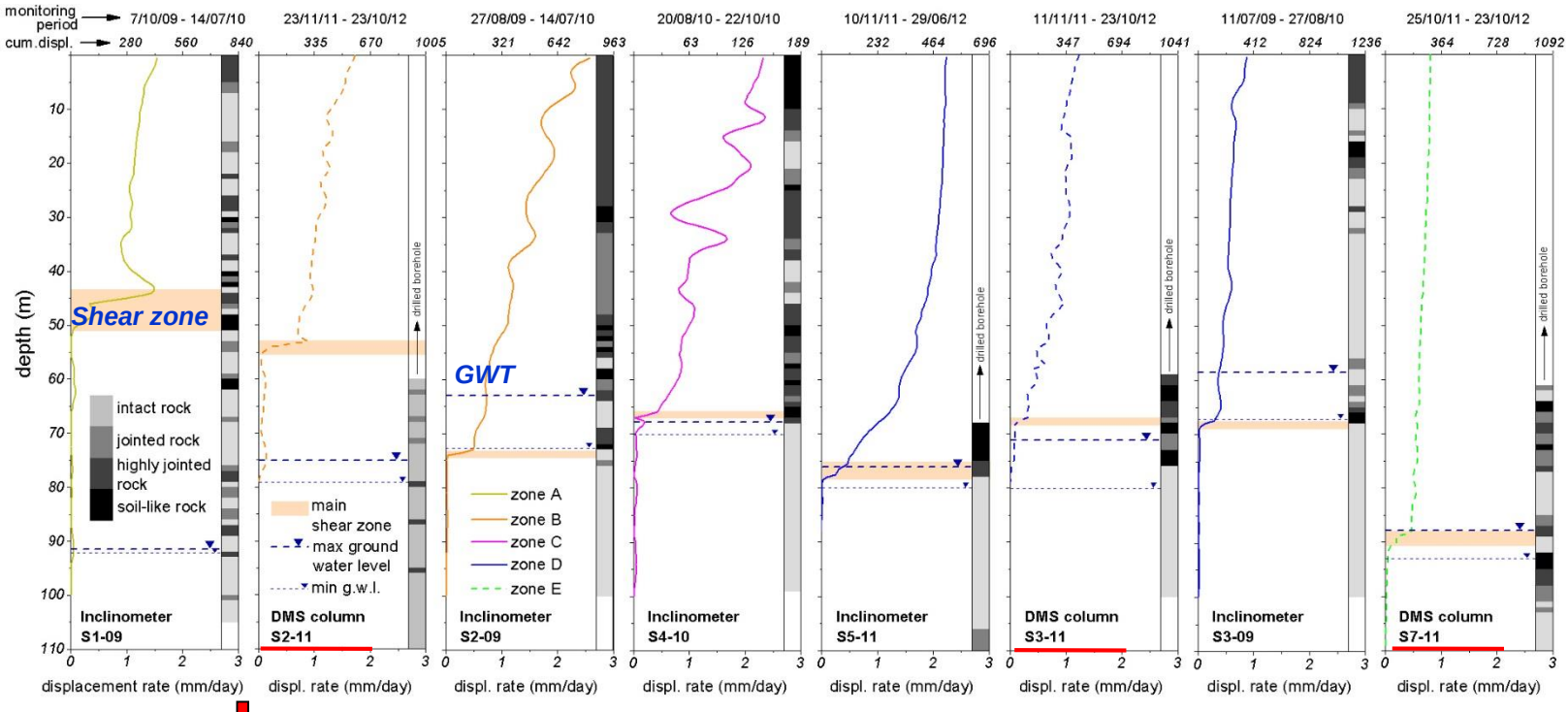
Subsurface monitoring

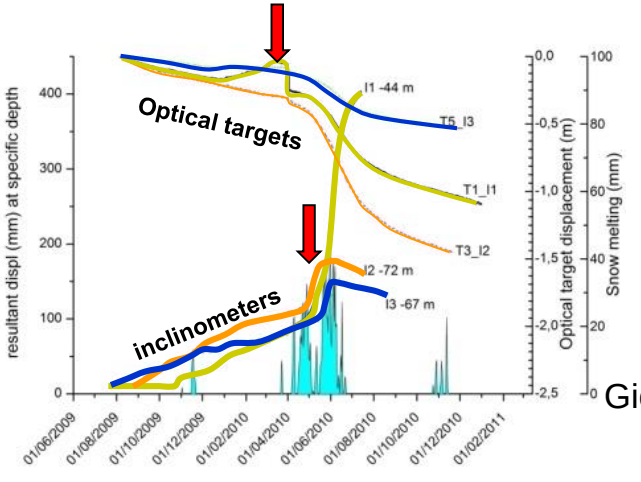


DMS – CSG srl
4 multi-parametric probes

- Installation of the 4 biaxial columns (in 2010 and 2011)
- Up to 100 m columns made of 1 m long measuring probe elements
- Extremely low drift
- Resist large displacements

Subsurface monitoring



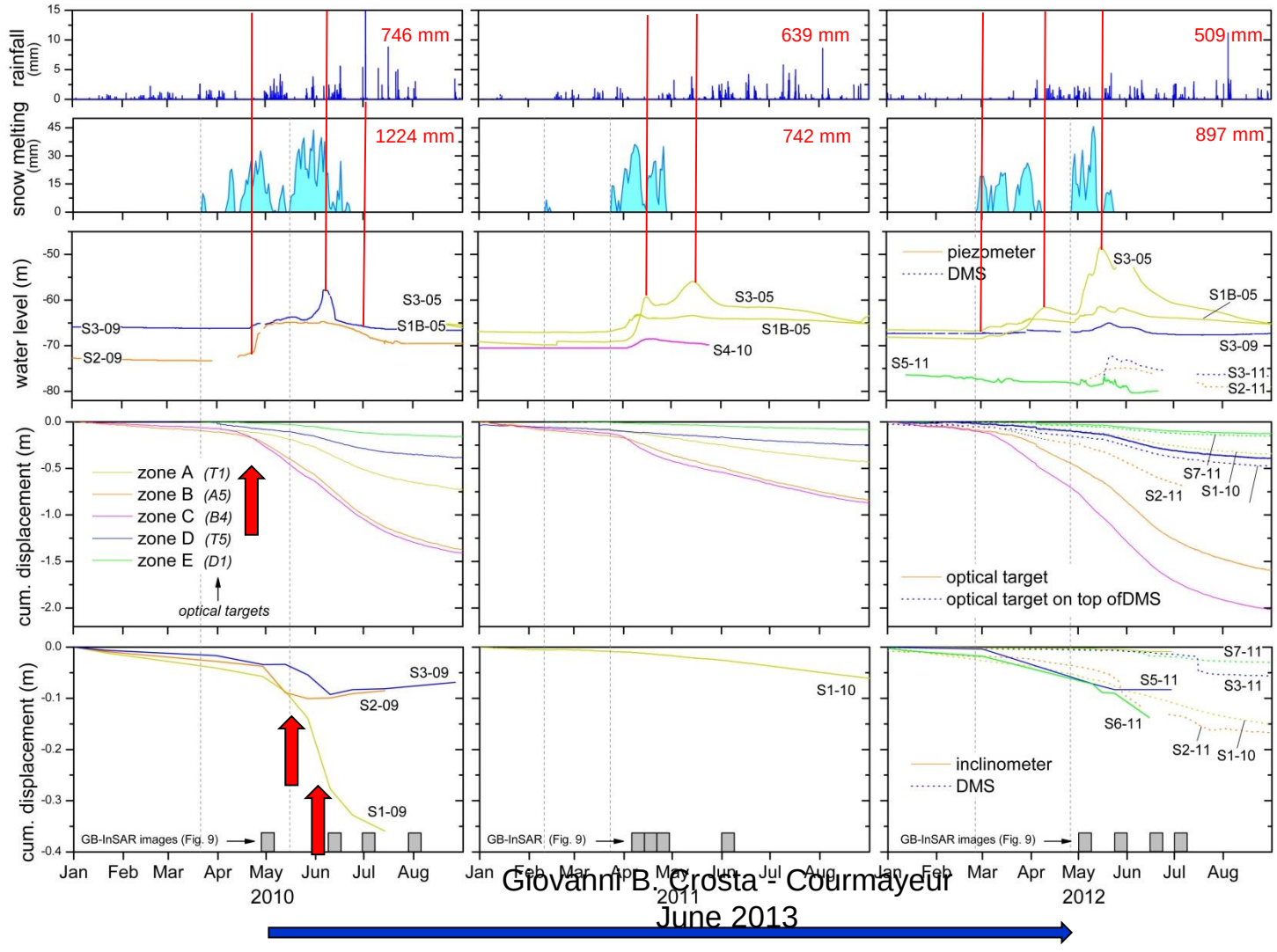


- Relatively "**Sharp" failure surface** (in general)
- Failure surface **not always at deepest** weak layer
- **GWT oscillation** up to 12 – 15 m

- Slightly **stronger sensitivity of deep** vs superficial displacements
- **Sharp reactivation of deep** displacements
- **Superficial displacements** cumulates the effects

Subsurface monitoring

Triggering events vs superficial and deep movements



Rain (Low sensitivity)

snow melt

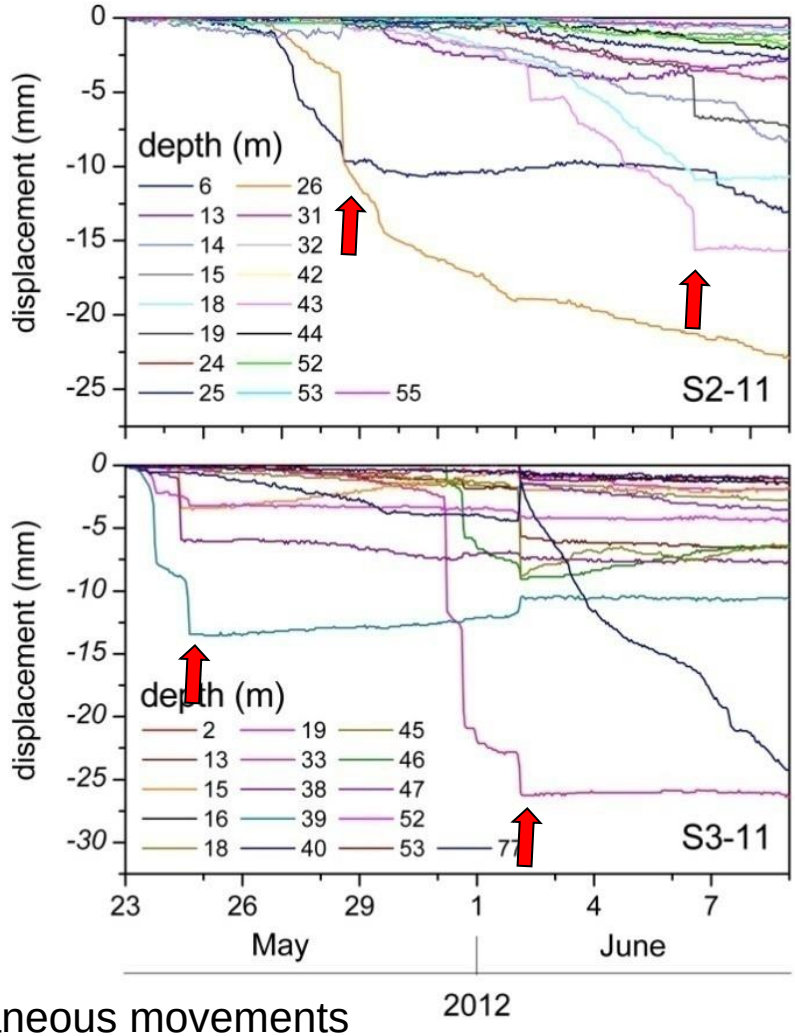
Δh=2-15 m (GWT raises later to snowmelt)

Δx=0.15-2 m

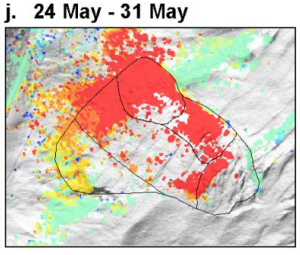
Δx=0.05-0.4 m (DMS sharper increase than OT and inclinometers)

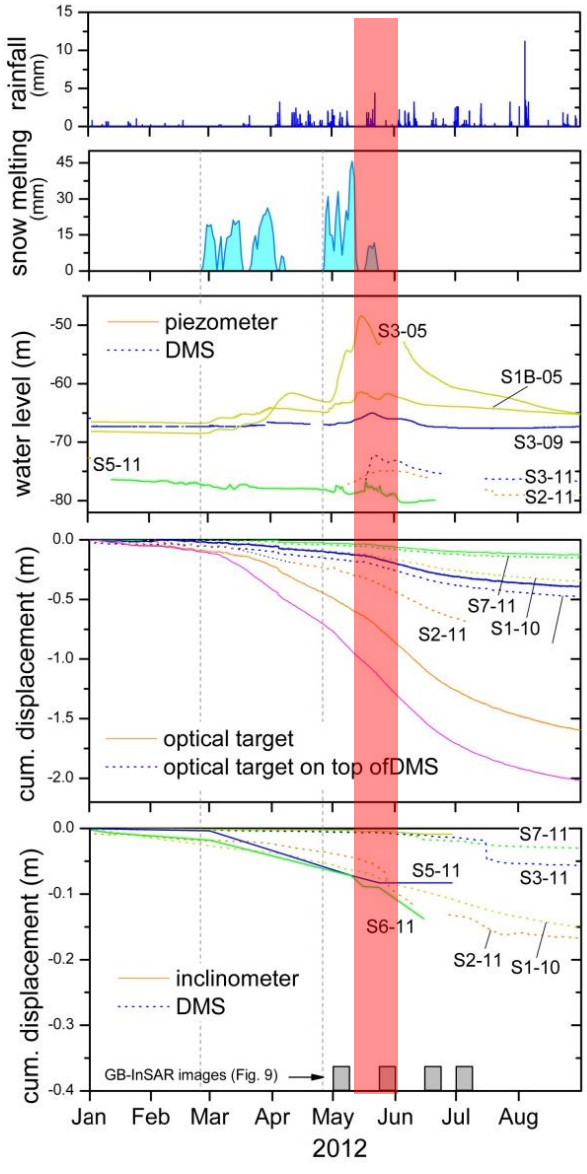
Subsurface monitoring: DMS multiparametric probes

Displacement at different depths along the DMS columns



2012 snow melt

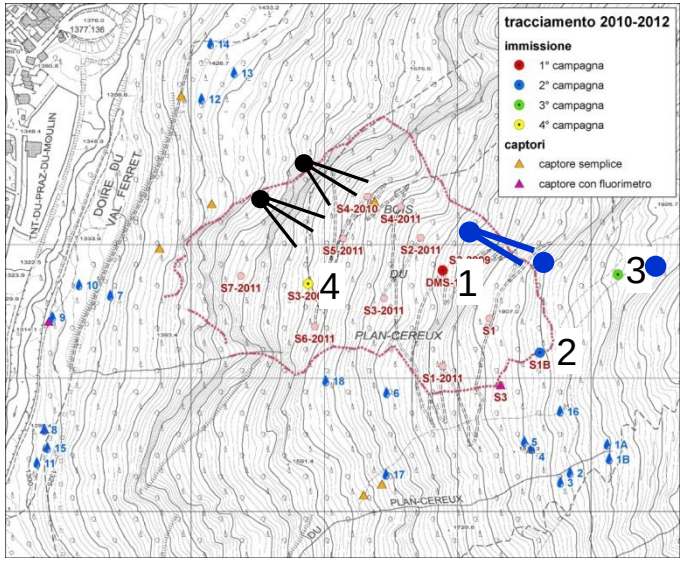


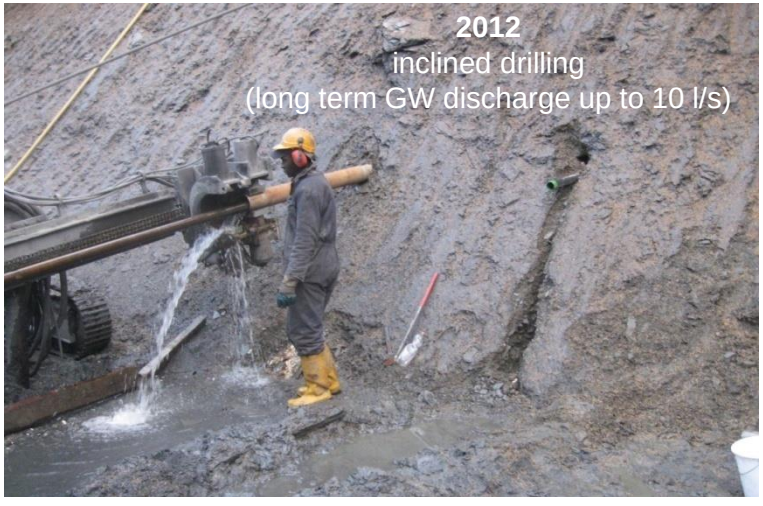


- almost instantaneous movements
  - **Stick slip**
  - **Over-pressuring and successive relaxation**

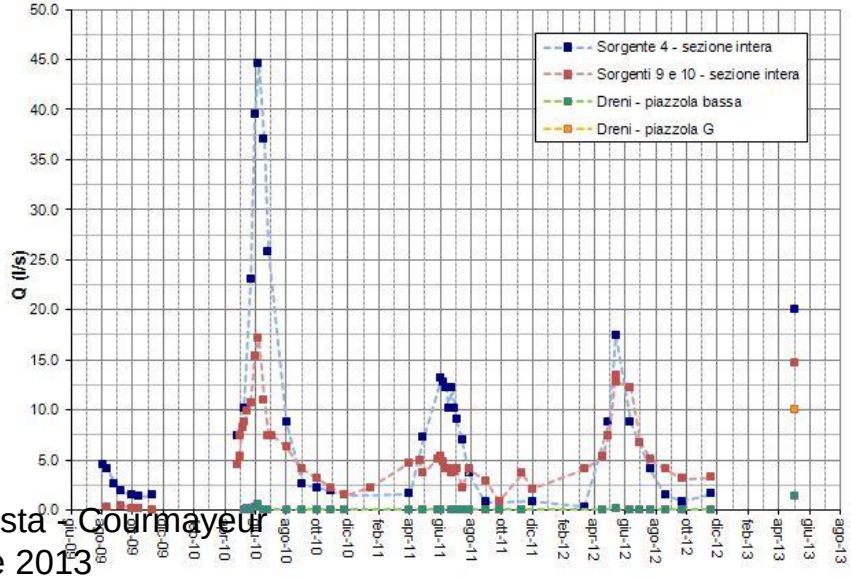
Groundwater flow: Subhorizontal drilling

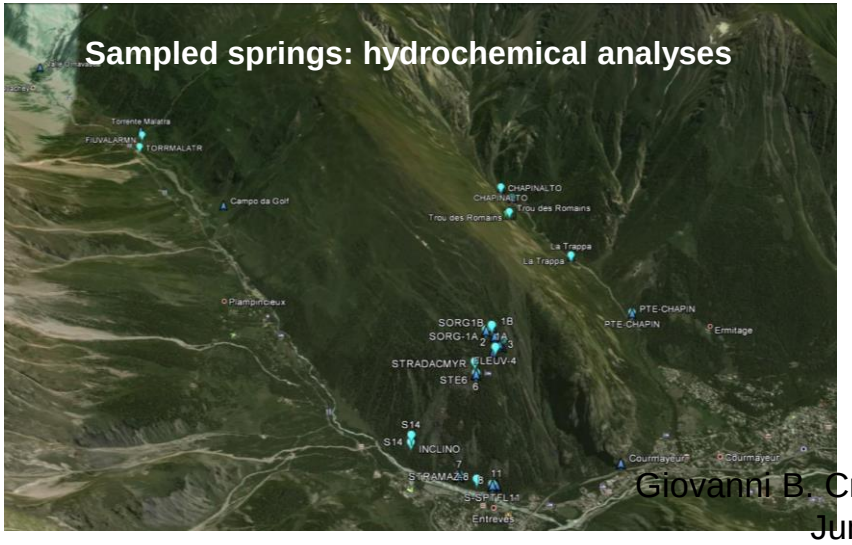
Springs, inclined drillings, tracer injection points





2009-2013 Spring and drainage discharge (l s^{-1})



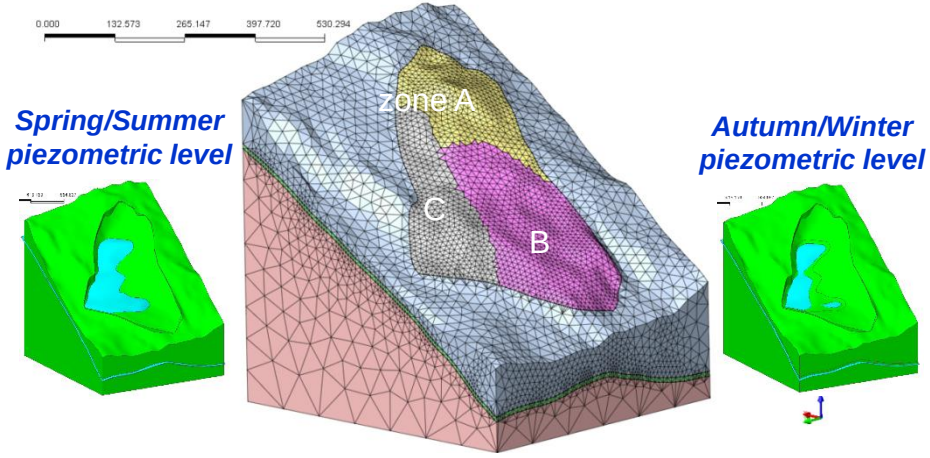


2D-3D FEM: SSR – shear strength reduction

Problem: active-unstable rock slide

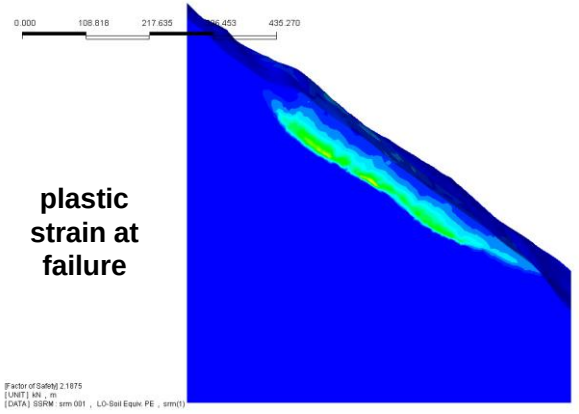
To study: Efficiency of stabilization works

Ave. Material properties

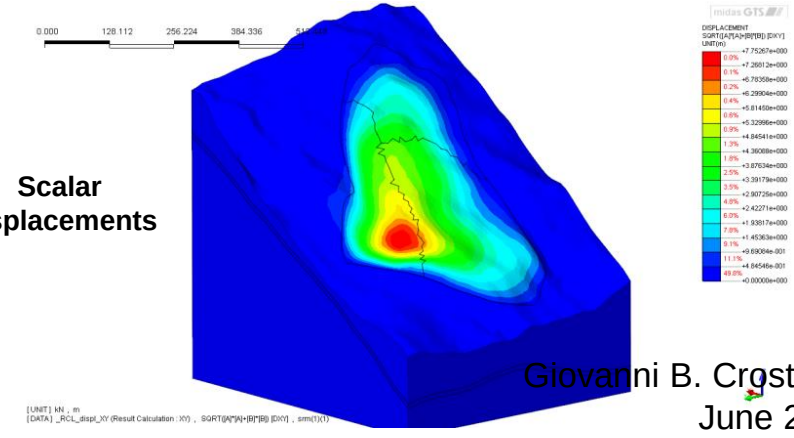


Spring/Summer piezometric level

Autumn/Winter piezometric level



plastic strain at failure



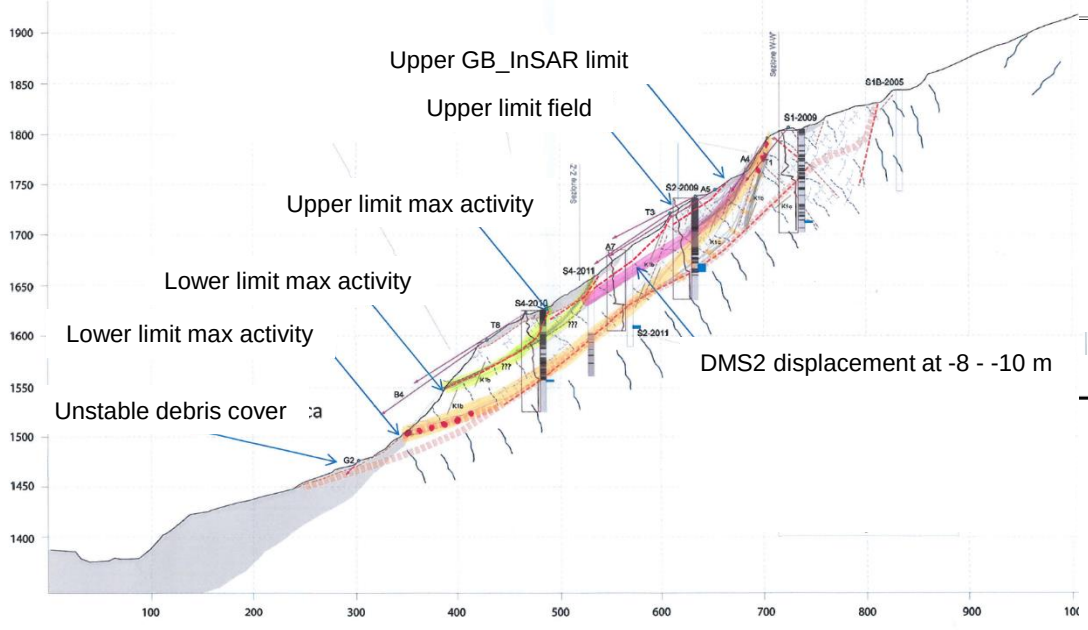
Scalar displacements

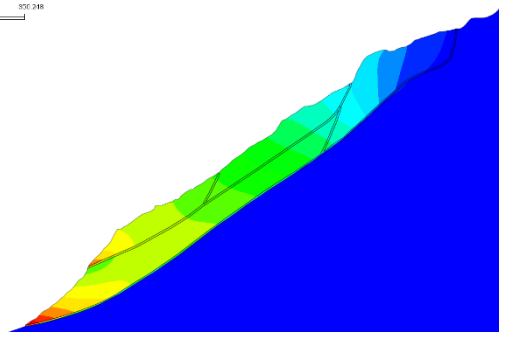
SSR (slope stability)

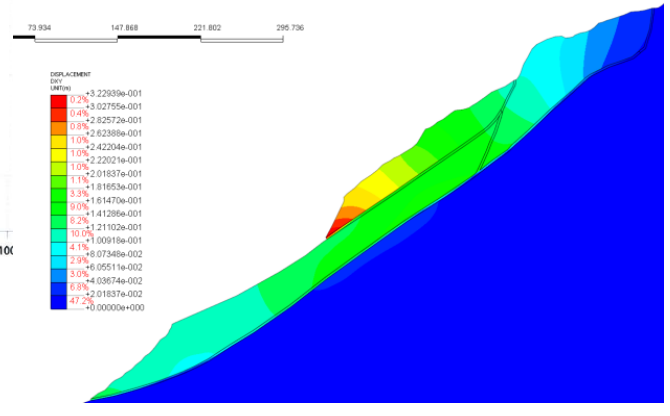
Spring/Summer: FS = 1.0

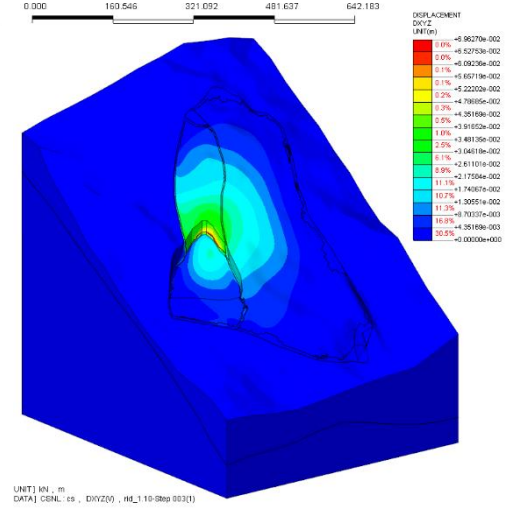
Autumn/Winter: ΔFS = +0.12

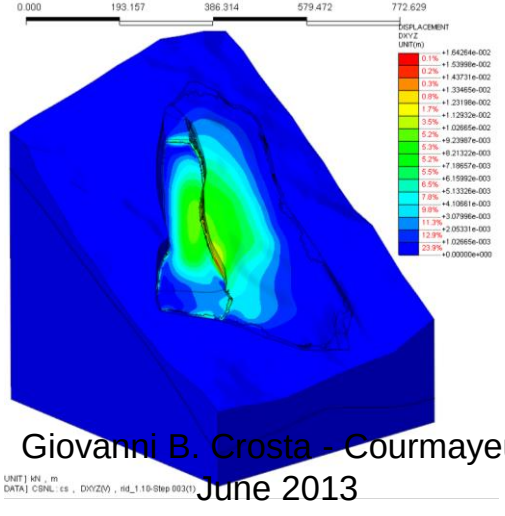
Analysis of multiple sequential failures

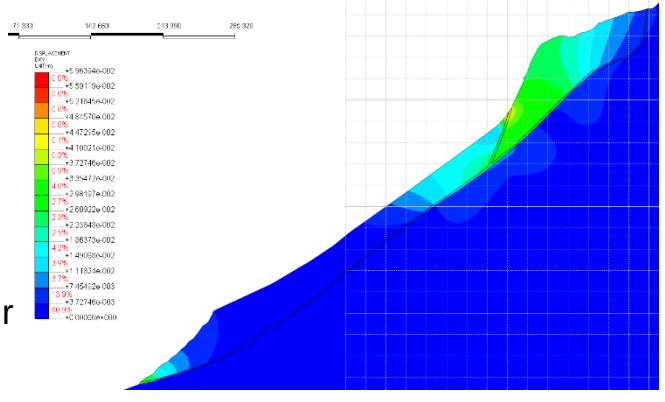








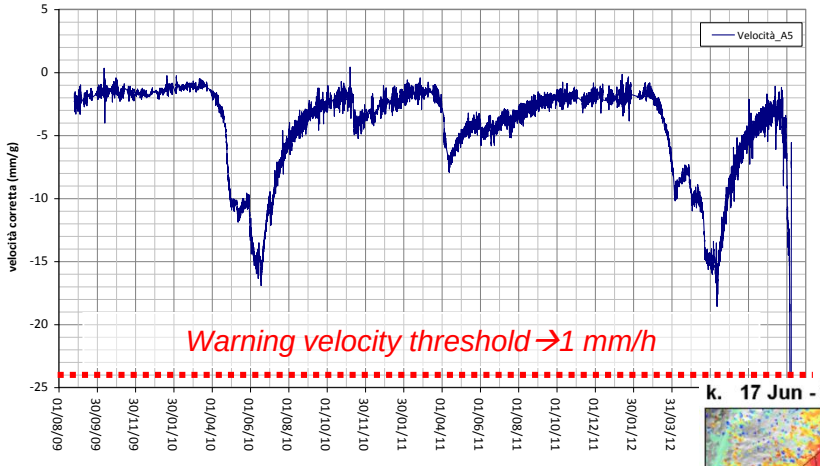




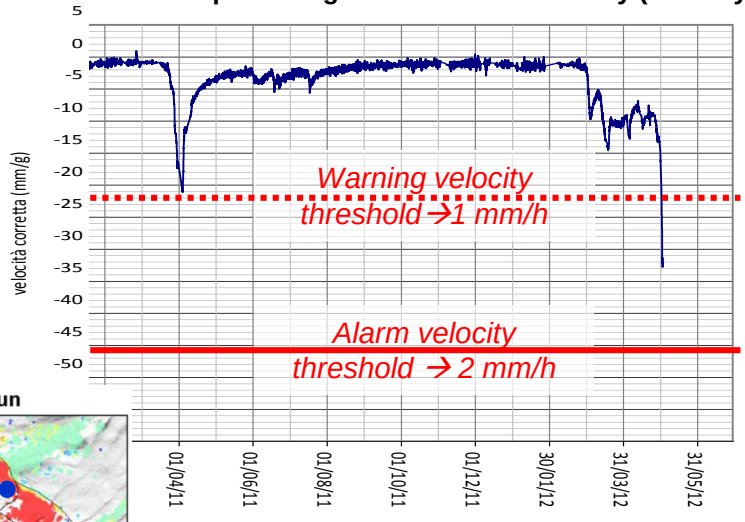
Displacement rate thresholds

Empirically based; performed well during relatively small events

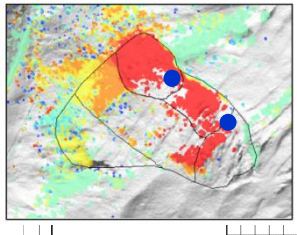
A5 optical target velocity (mm/d)



B5-B6 optical targets: 3D correct velocity (mm/day)

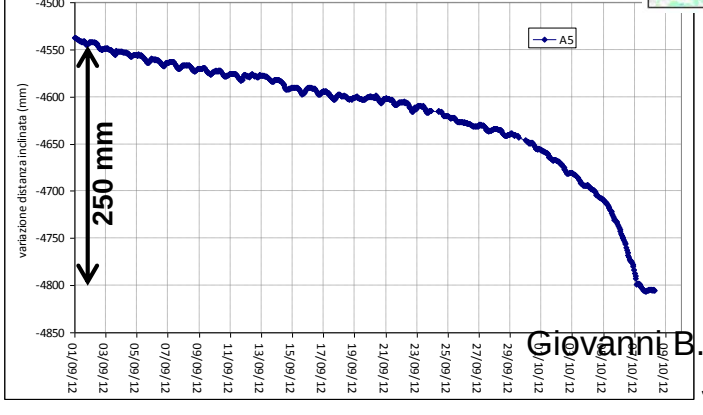


k. 17 Jun - 24 Jun



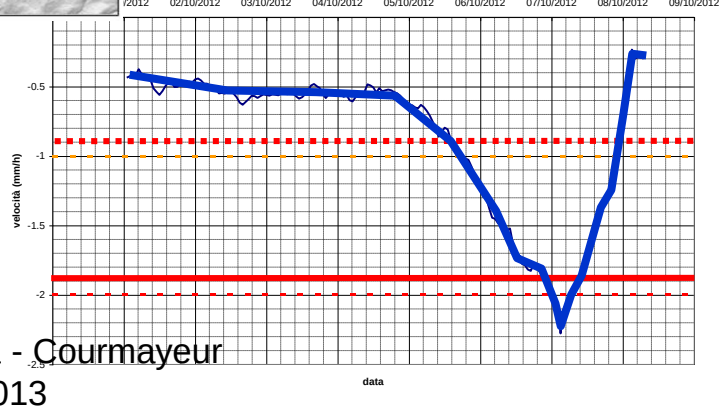
October 2012 event

A5 optical target cumulative displacement (mm



October 2012 event

A5 optical target velocity (mm/h)

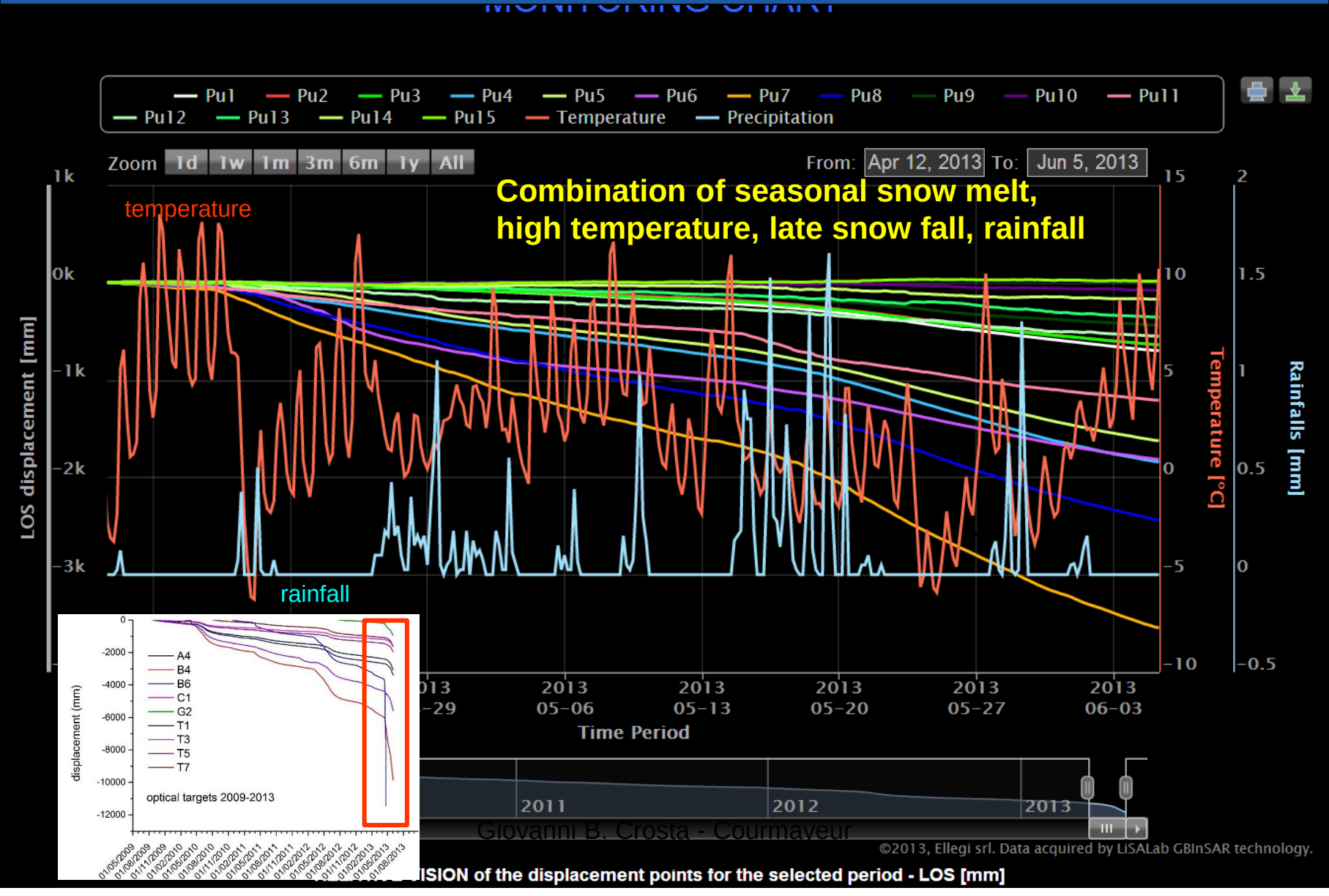


April-May 2013 Reactivation

14/04/2012

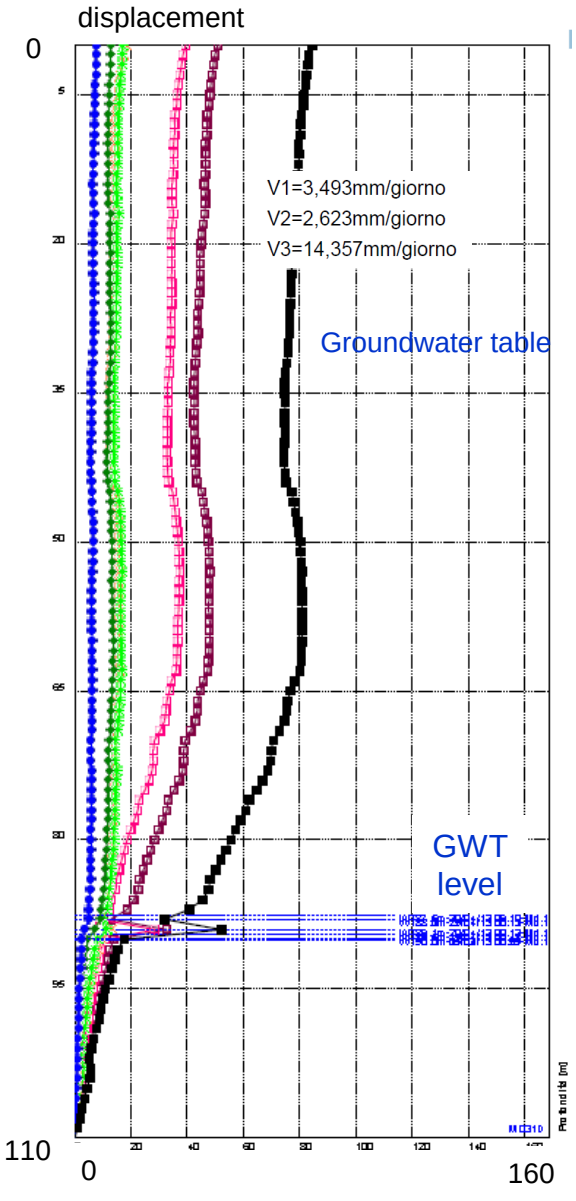
30/03/2013

April-May 2013 Reactivation



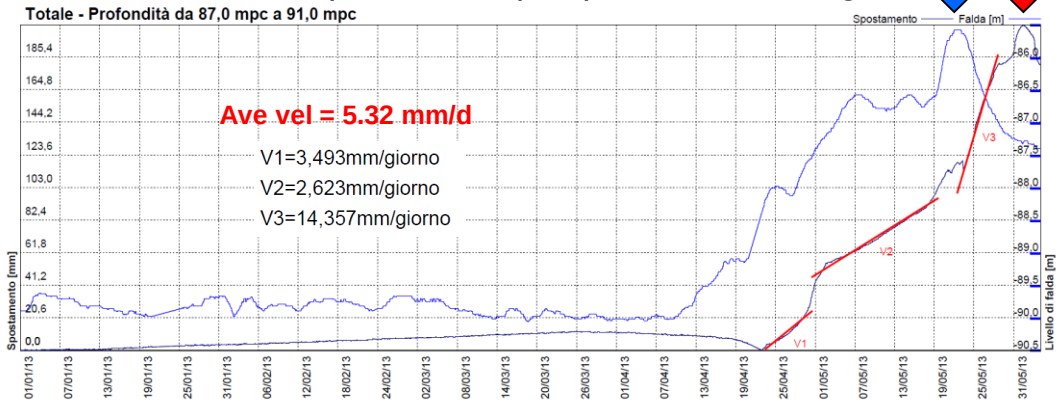
ISION of the displacement points for the selected period - LOS [mm]

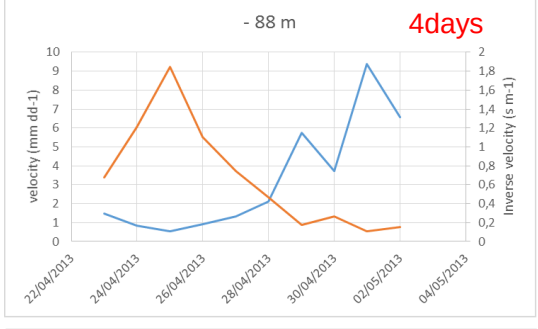
April_May 2013 Reactivation



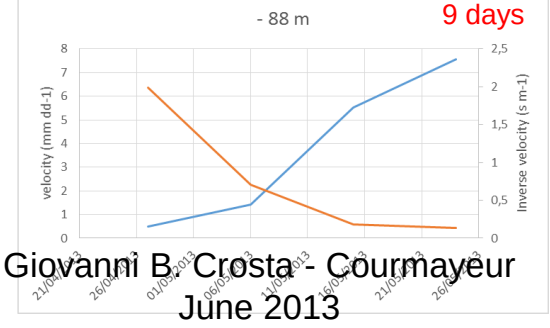
Total cumulative displacement (mm) -87 to -91 m bgl

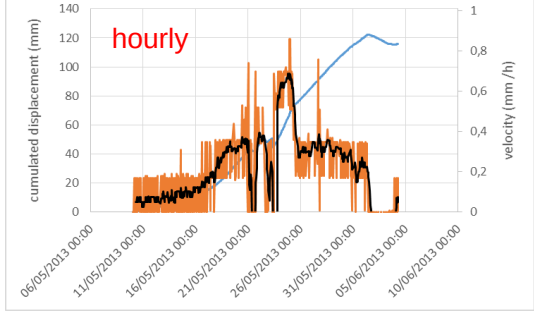
15 days





1/5/2013 — 1 month — 31/5/2013





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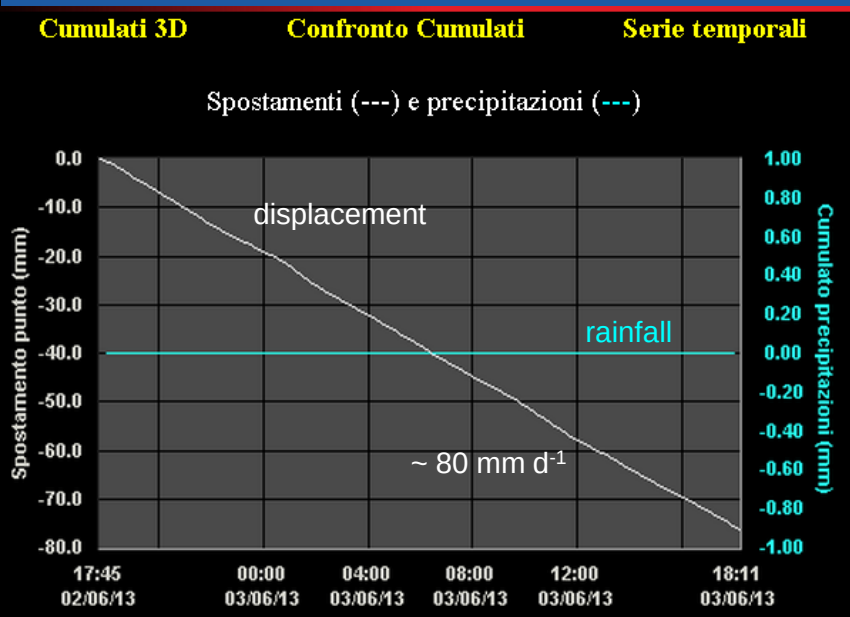
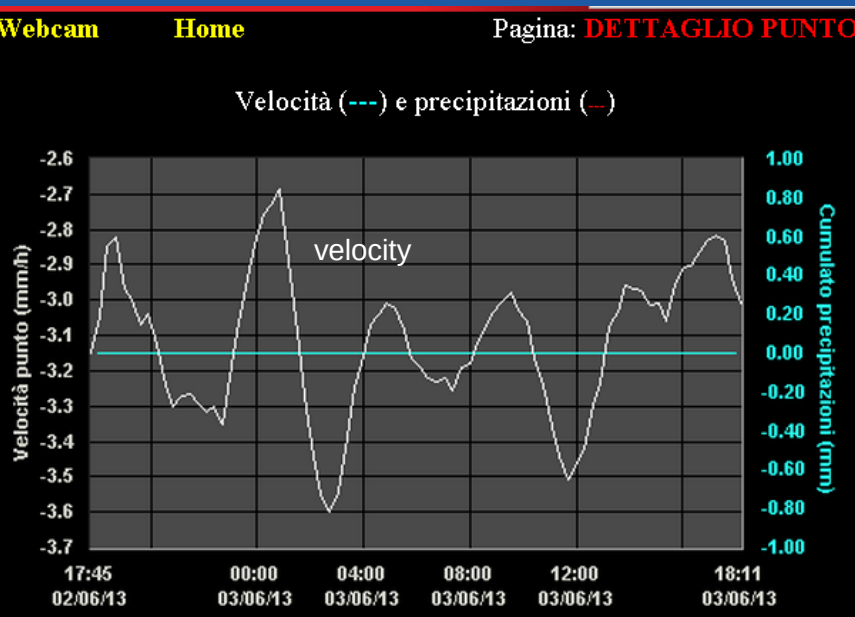
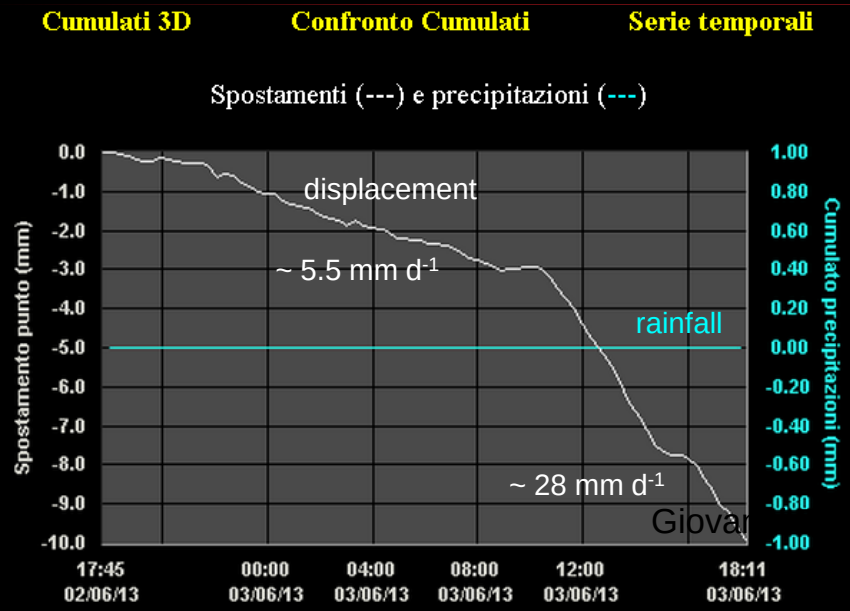
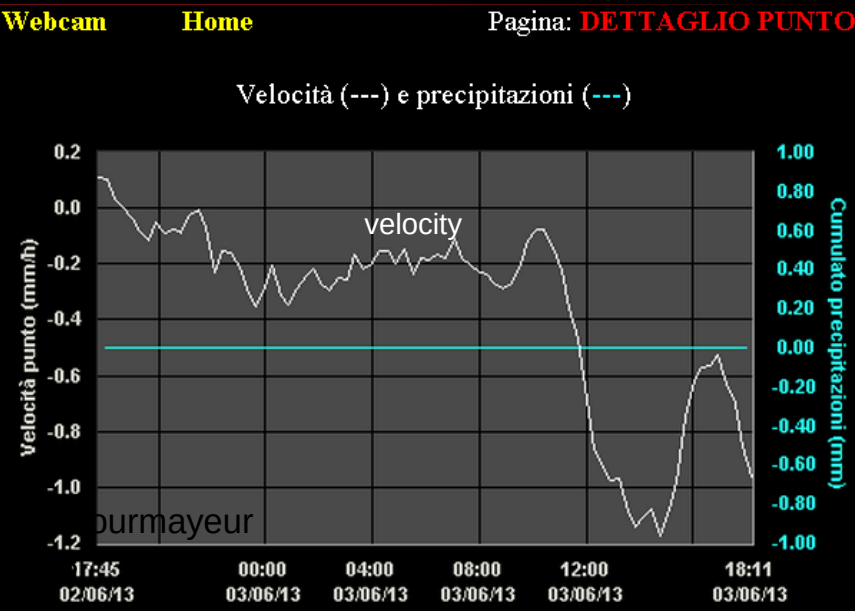
Displacement rates and thresholds









Warning thresholds

Table 7. Alert velocity threshold values (mm/day) obtained by the analysis of literature data.

	Emergency (7 days)	Alert (15 days)	Pre-alert (30 days)
Val Pola (E2)	9	3	1
Val Pola (ES2)	2	1	0.5
Val Pola (D32)	12	3	1
Braced-Up Cliff	10	6	3
Chuquicamata (5)	207	66	18
Chuquicamata (6)	358	112	27
Chuquicamata (7)	923	227	42
Chuquicamata (9)	482	115	24
Hogarth (J2)	86	44	23
Hogarth (J4)	33	20	11
West Culebra	5	2	1
Takabayama	31	16	7
Vajont (55)	74	40	20
Vajont (76)	77	45	21

Since 2009
Decision to use empirical displacement rate thresholds

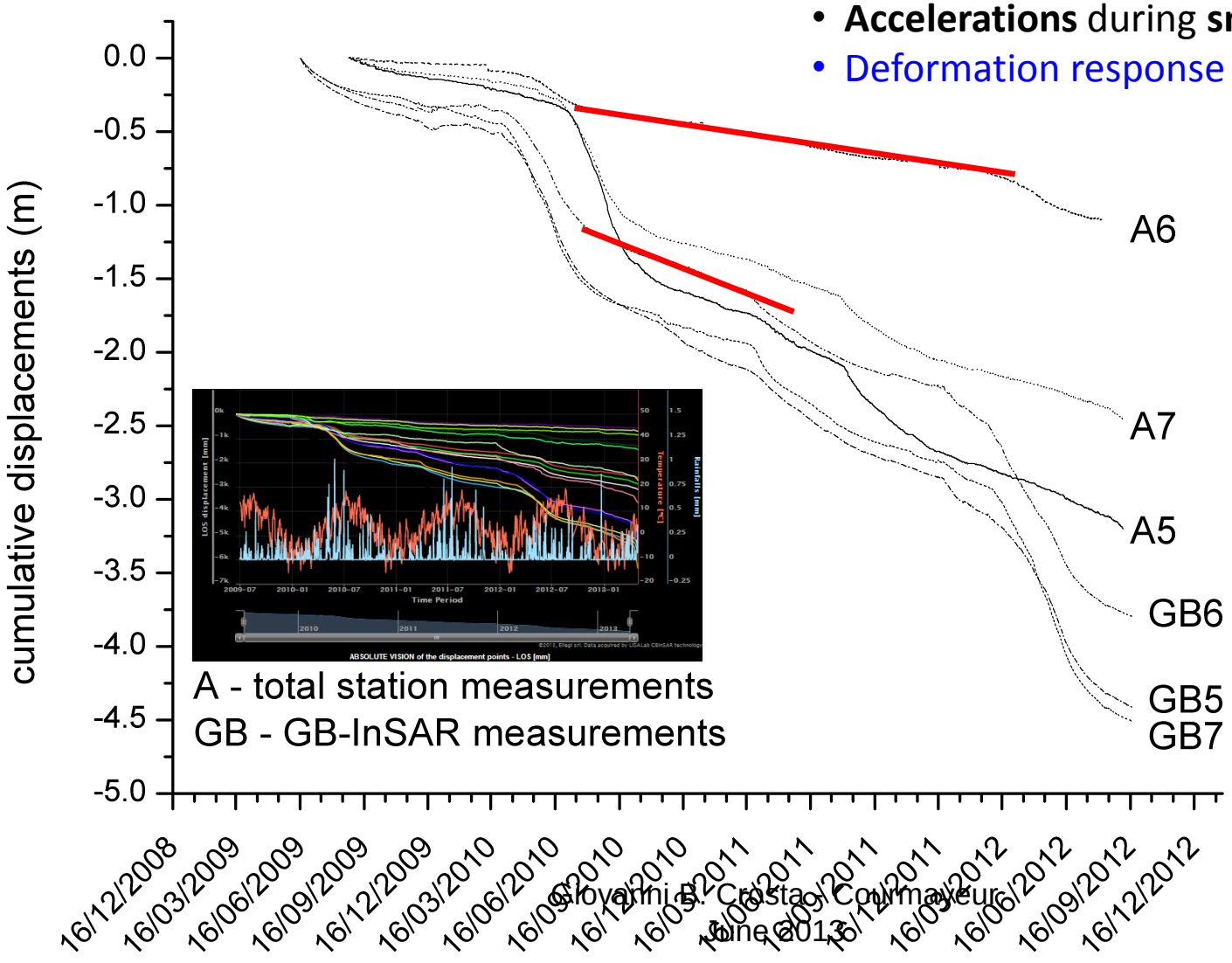
Warning velocity threshold → ***1 mm/h***

Alarm velocity threshold → ***2 mm/h***

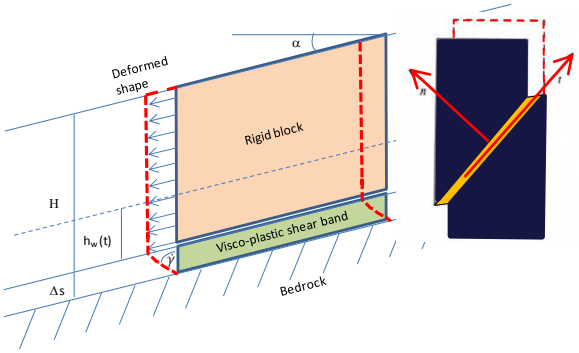
Displacement rate 10-80 mm/day

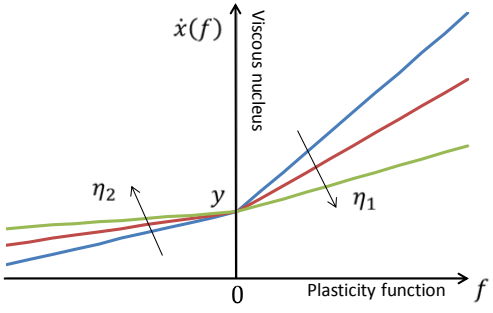
Displacement prediction

- Slow **winter creeping phases**
- **Accelerations** during **snow melt**
- Deformation response **delayed in time**



Displacement prediction: 1D visco plastic model





- Average **constant thickness** in large sectors
- Prevalent **translational displacement**
- **Sliding surface** at fixed position, localized shear band with constant thickness

- Large displacements, close to or at **residual/critical state**

- Considering **inertial dynamic and viscous effects**: a pseudo-dynamic **Newmark-type** of approach is adopted coupled to a **visco-plastic model** **(Perzyna's type): delayed-plastic constitutive approach** (standard plastic flow rule is modified and the consistency condition removed; *di Prisco et al., 2003; Zambelli et al., 2004*)

Time evolution of visco plastic strain

$$d\varepsilon_{ij}^{vp} = \gamma\phi(f)\frac{\partial g}{\partial \sigma'_{ij}}dt$$

plastic potential

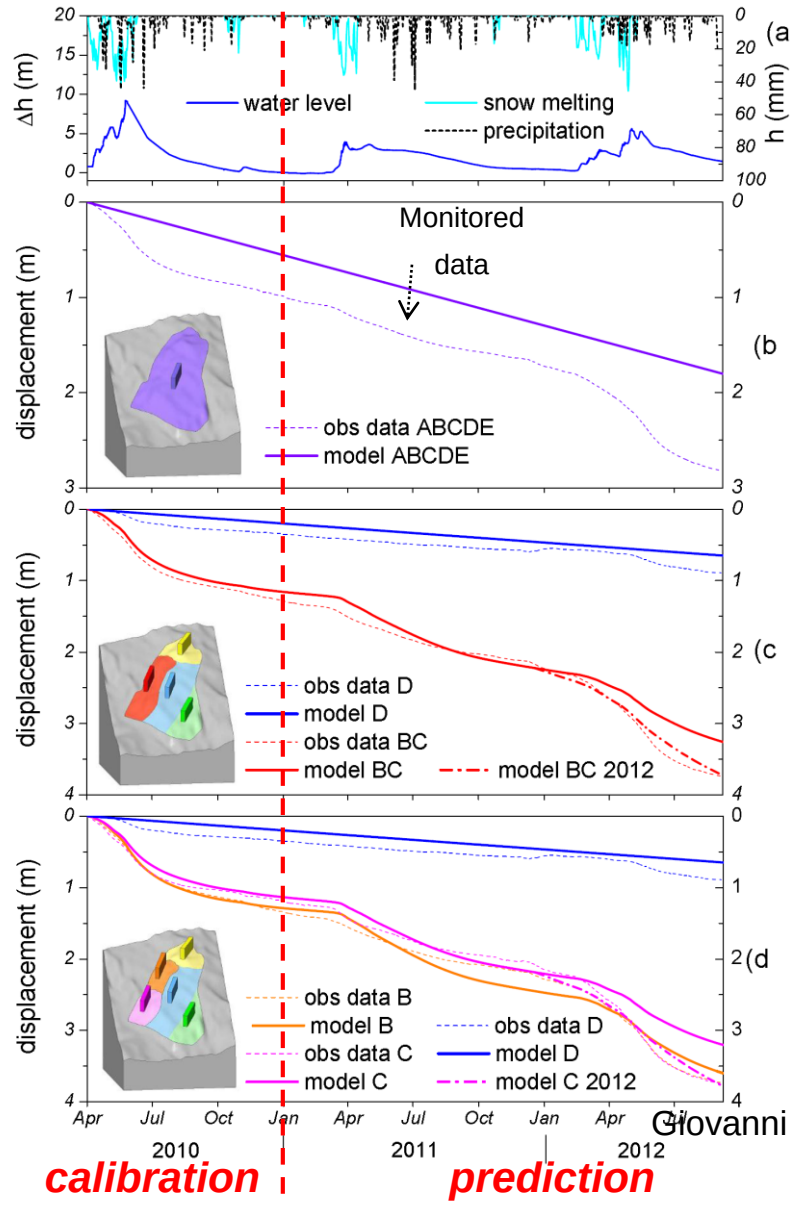
constitutive parameter

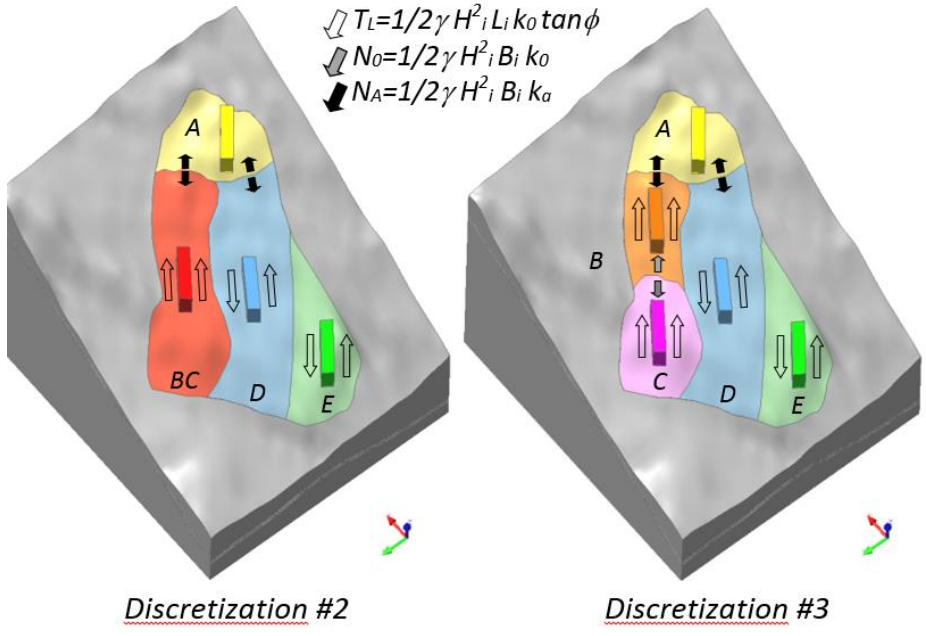
Viscous nucleus

effective stress

- **Includes**: weight, seepage force, hydrostatic force, active/passive force
- **Main Forcing**: piezometric level oscillations: cyclic dynamic perturbations

1D visco plastic model: independent blocks

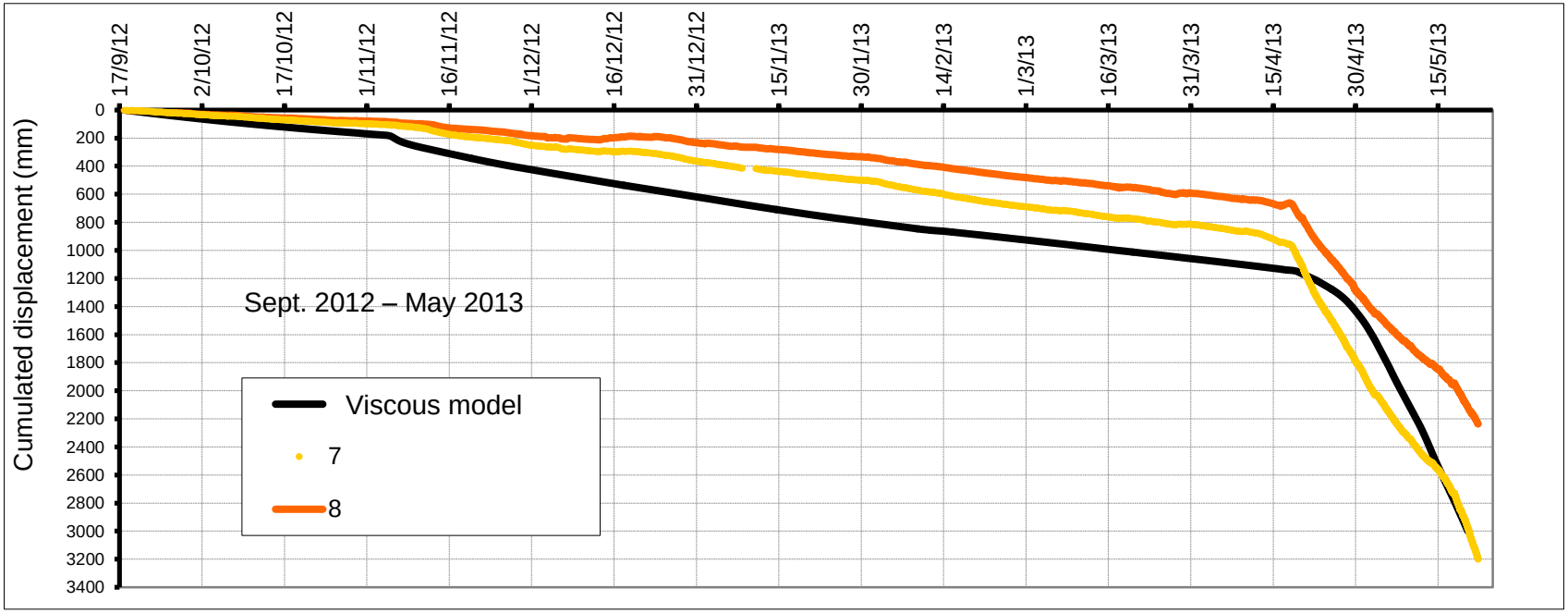


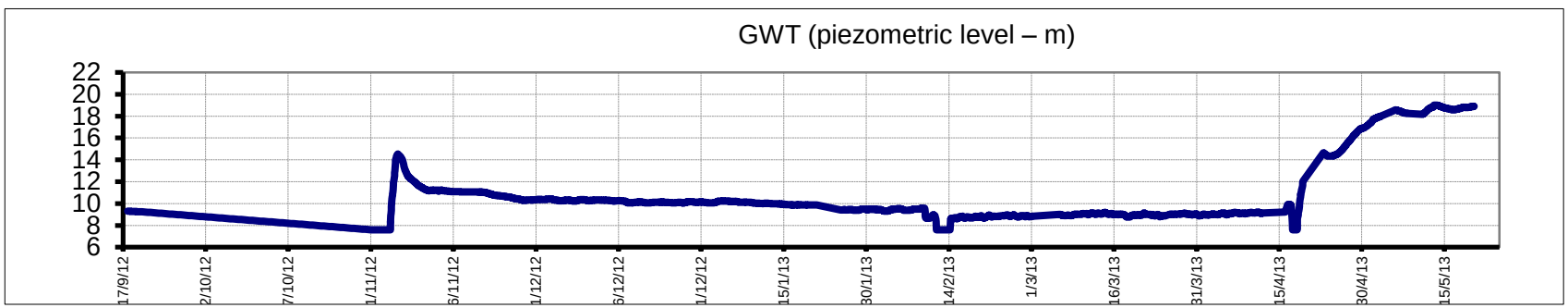


Considering interaction forces in terms of lateral frictional resistence or dragging and of front- and back-thrust

Model calibration: 2009-2010
Model prediction: 2011-2013

Forward prediction-forecasting





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CONCLUSIONS

- Need for a long term monitoring dataset
- Subsurface displacements:
  - Problem short life of boreholes and borehole instrumentation
- Change in slope behaviour with time and successive events

  → 1D visco plastic model
- Complete data interpretation:
  - Relationships DMS displacements with rainfall & PWP
  - thresholding
- Modelling:
  - 2D & 3D groundwater flow model
  - FEM, FDM, DEM: large displacement/deformation
  - 1D→2D multi-block visco-plastic model

CONCLUSIONS

- Modelling:
  - 2D & 3D groundwater flow model
  - FEM, FDM, DEM: large displacement/deformation
  - 1D→2D multi-block visco-plastic model

- Mitigation:
  - Stabilization
  - Need for new data

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