Landslide forecasting and warning at slope scale

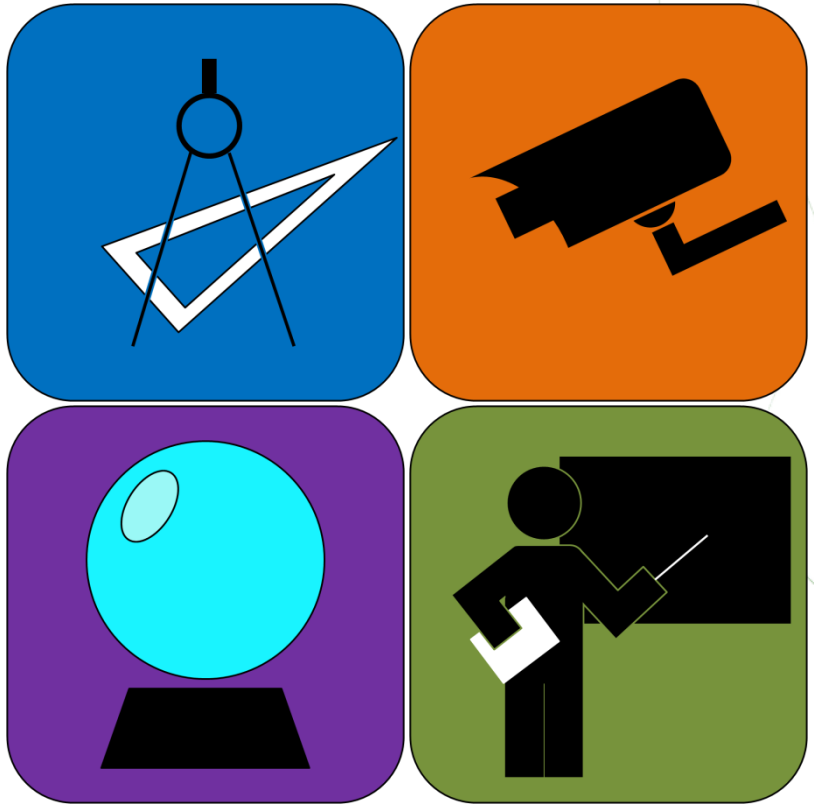
Advanced technologies for monitoring and prediction of ground instabilities
Firenze, 27-30 January 2025

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani

Early Warning Systems

1. Design:
- Geological knowledge
- Risk scenarios
- Design criteria
- Choice of geo-indicators



2. Monitoring:
- Instruments installation
- Data collecting
- Data transmission
- Data elaboration

3. Forecasting:
- Data interpretation
- Comparison with thresholds
- Forecasting methods
- Warning

4. Education:
- Risk perception
- Safe behaviours
- Response to warning
- Population involvement

Intrieri et al. (2013)

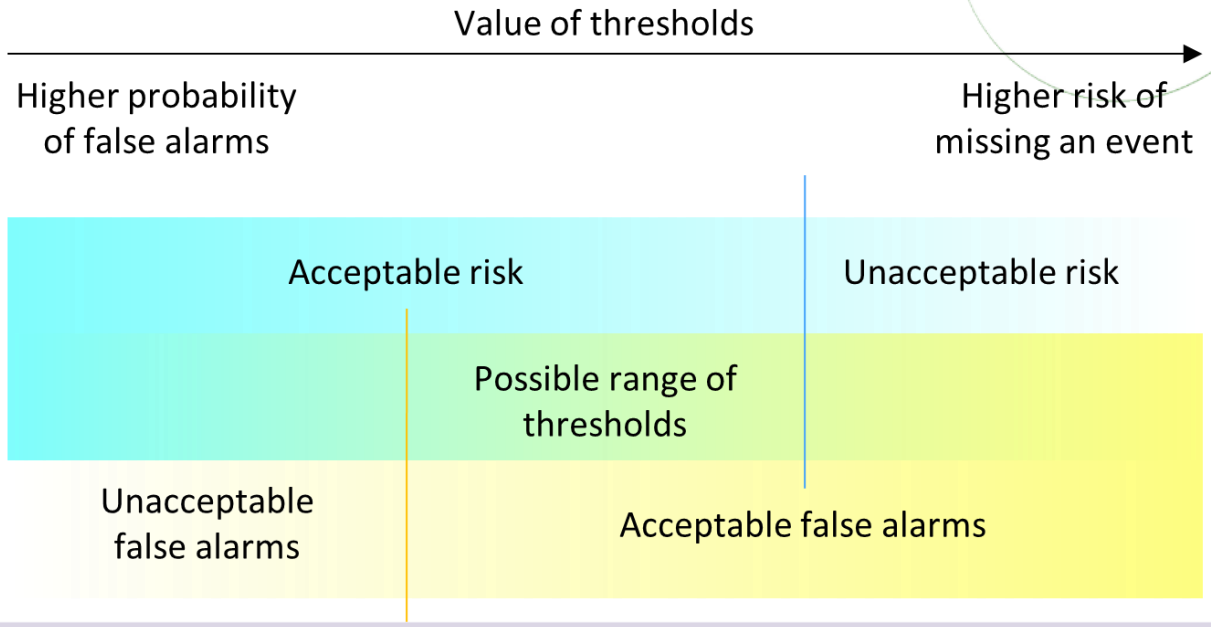
Forecast

Determination of the time, place and magnitude of the single most significant movement episode of the object of monitoring

Structural interventions

EWS Principles

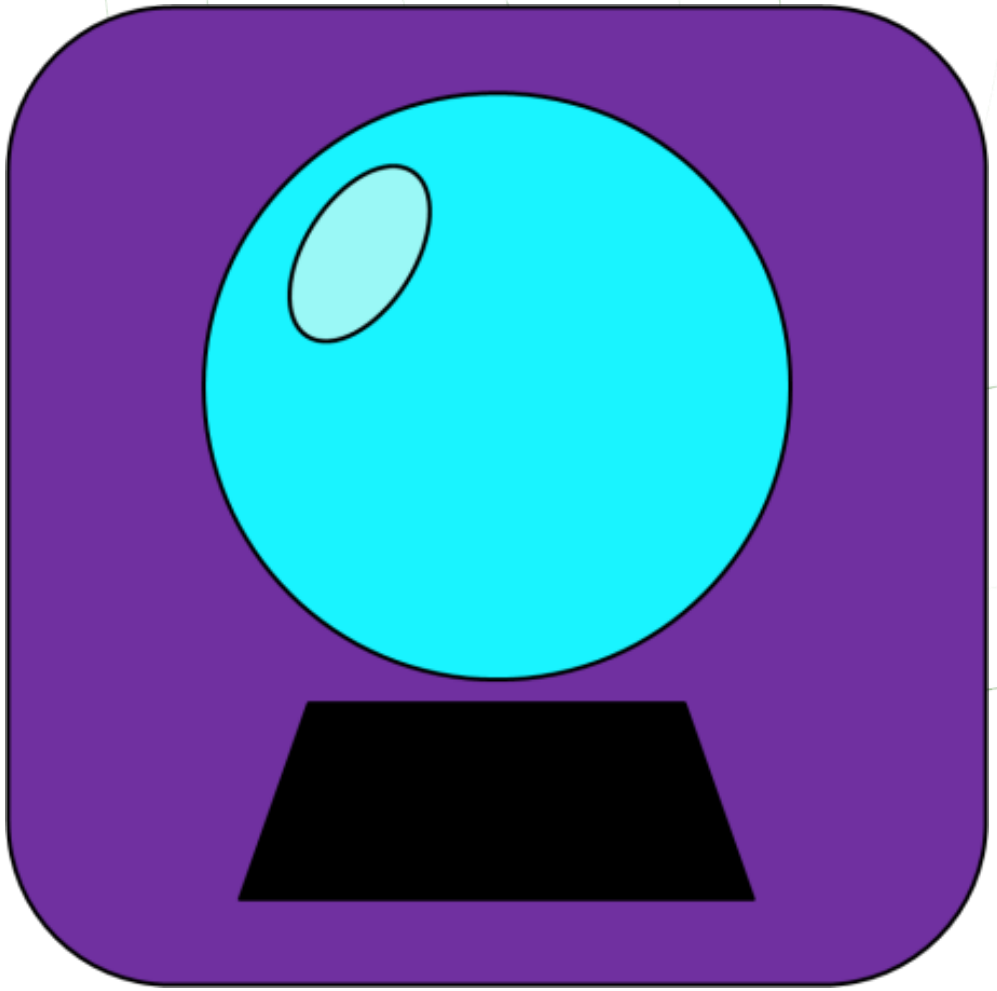
- Site-specific: There is no such thing as a universal EWS
- Simplicity: avoid confusion, time loss and too many warning levels
- Earliness: it is relative to the landslide behavior
- Redundancy: some events are critical for the slope and the instruments
- Risk acceptability: depends on risk scenarios and culture



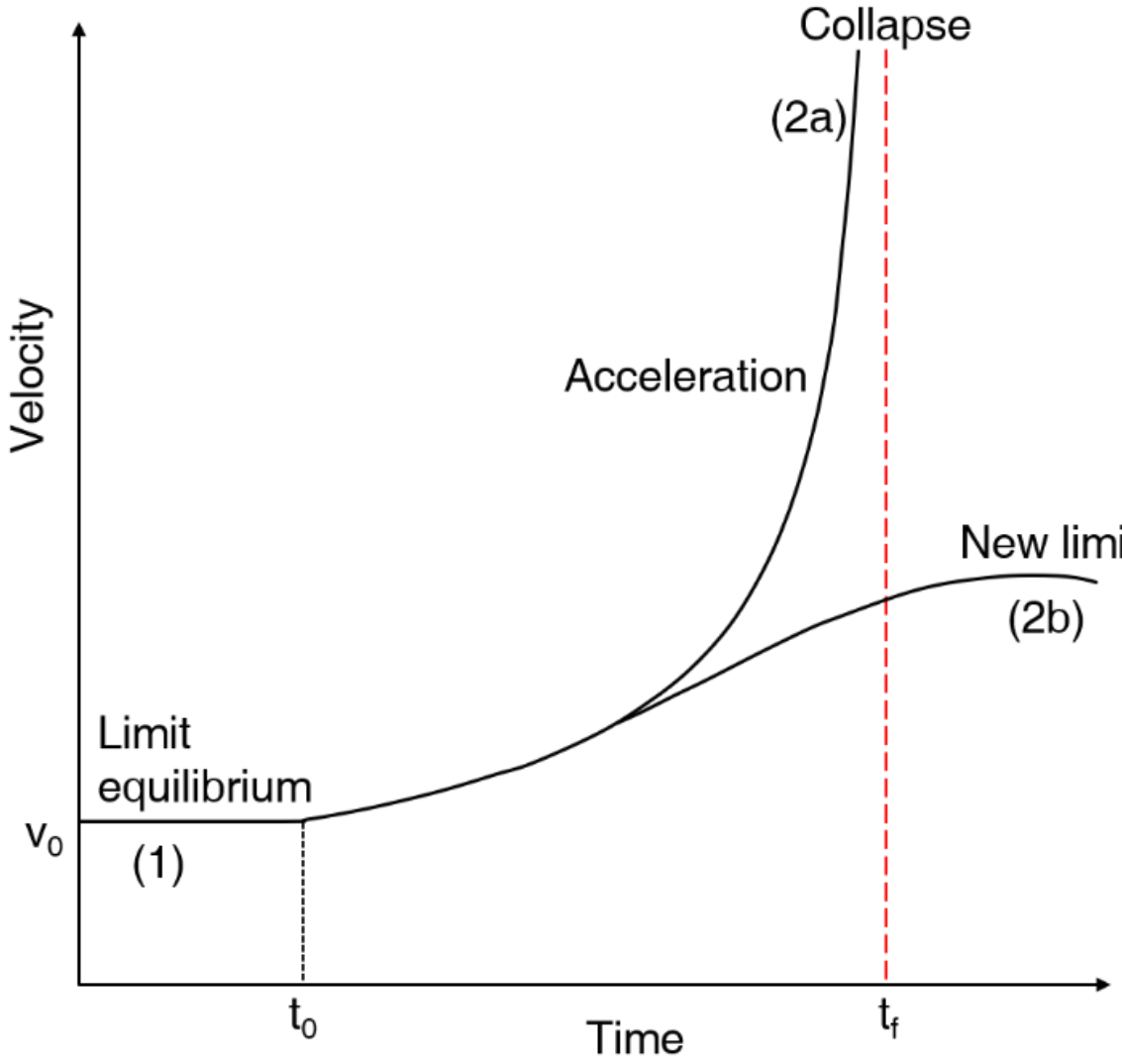
Nadim & Intrieri (2011)

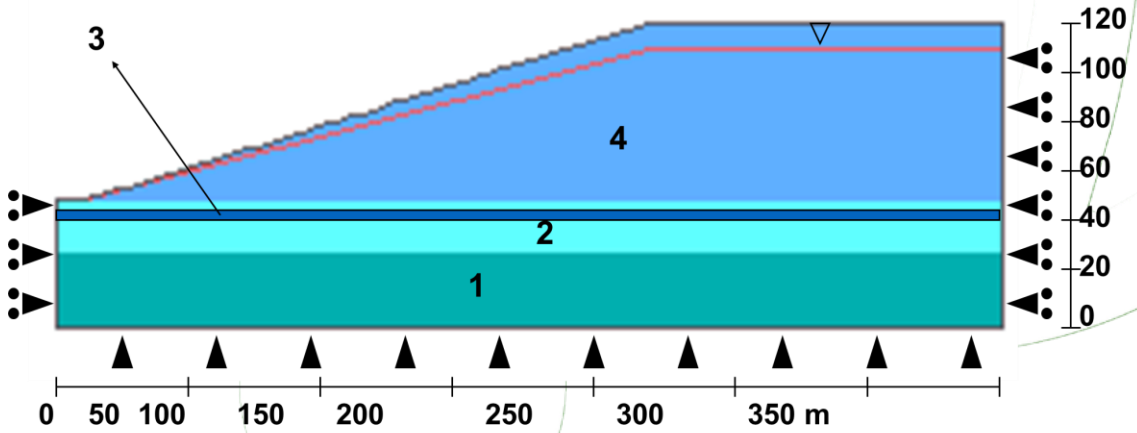
Forecasting methods

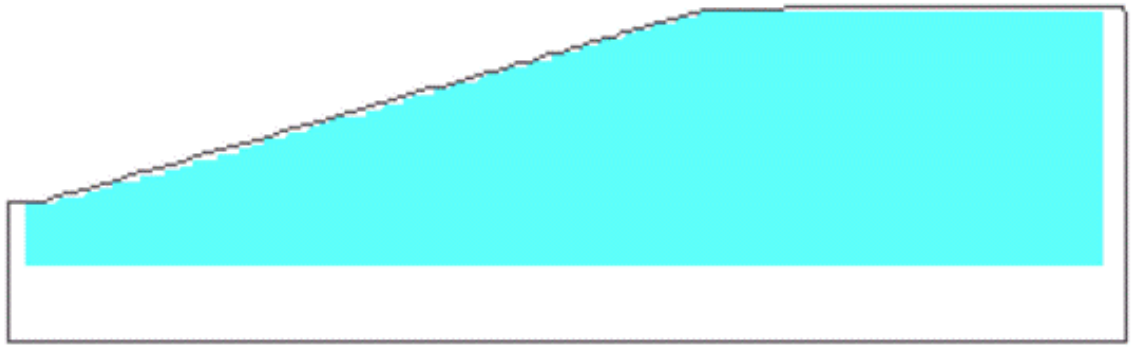
- Rainfall based
- Porewater pressure
- Acoustic emissions
- Rockfall frequency
- **Kinematic based (monitoring)**



Pre-paroxistic acceleration





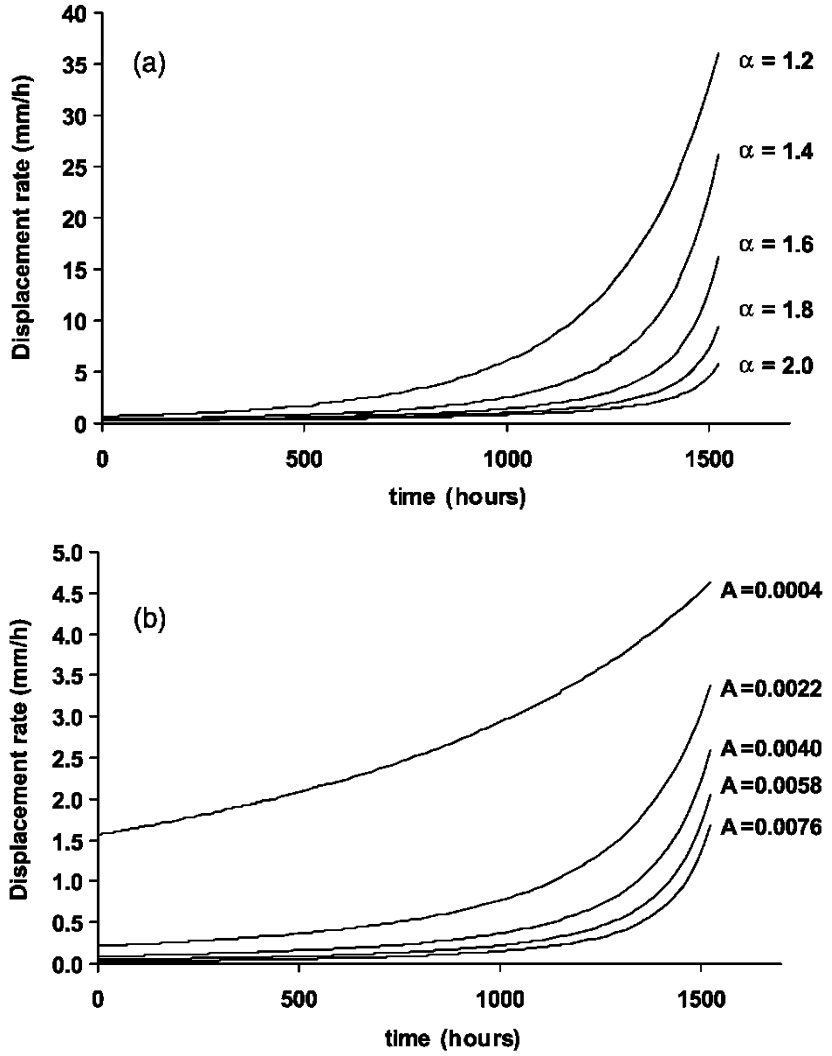


Fukuzono (1985)

Power law relationship between **acceleration** and **velocity** before failure, tested on laboratory physical models

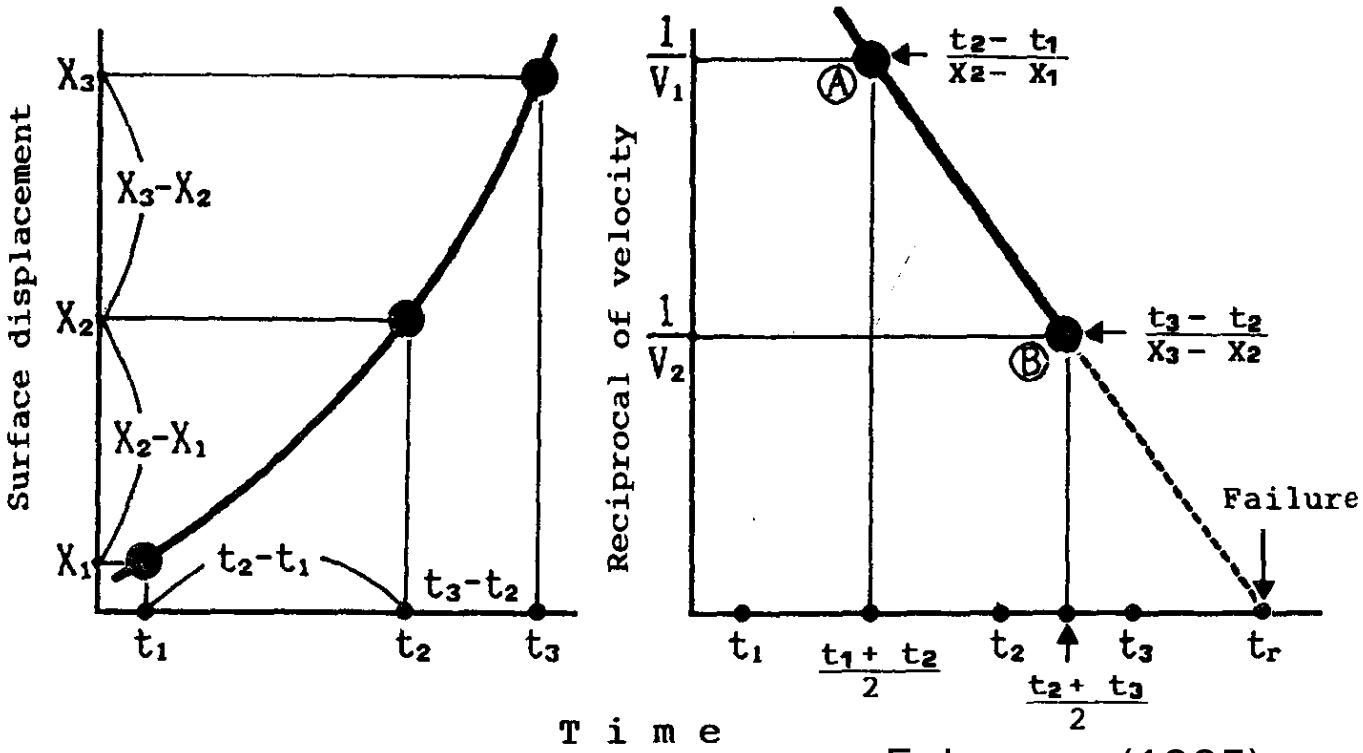
$$\frac{d^2x}{dt^2} = A\left(\frac{dx}{dt}\right)^{\alpha}$$

for $\alpha > 1$: $$\left(t_f - t_i\right) = \frac{\left(v_f\right)^{1-\alpha} - \left(v_i\right)^{1-\alpha}}{A(1-\alpha)}$$

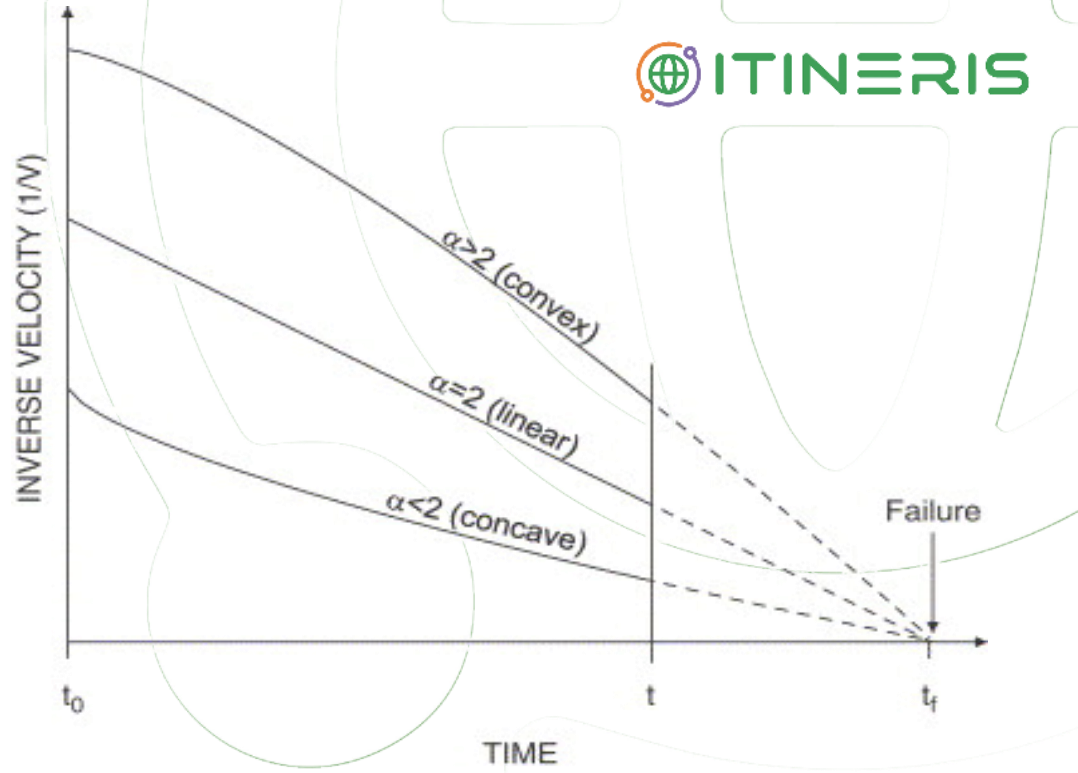


Inverse velocity method

$$v_f = \infty \Rightarrow \frac{1}{v_i} = [A(\alpha - 1)]^{\frac{1}{\alpha - 1}} (t_f - t)^{\frac{1}{\alpha - 1}}$$



Fukuzono (1985)

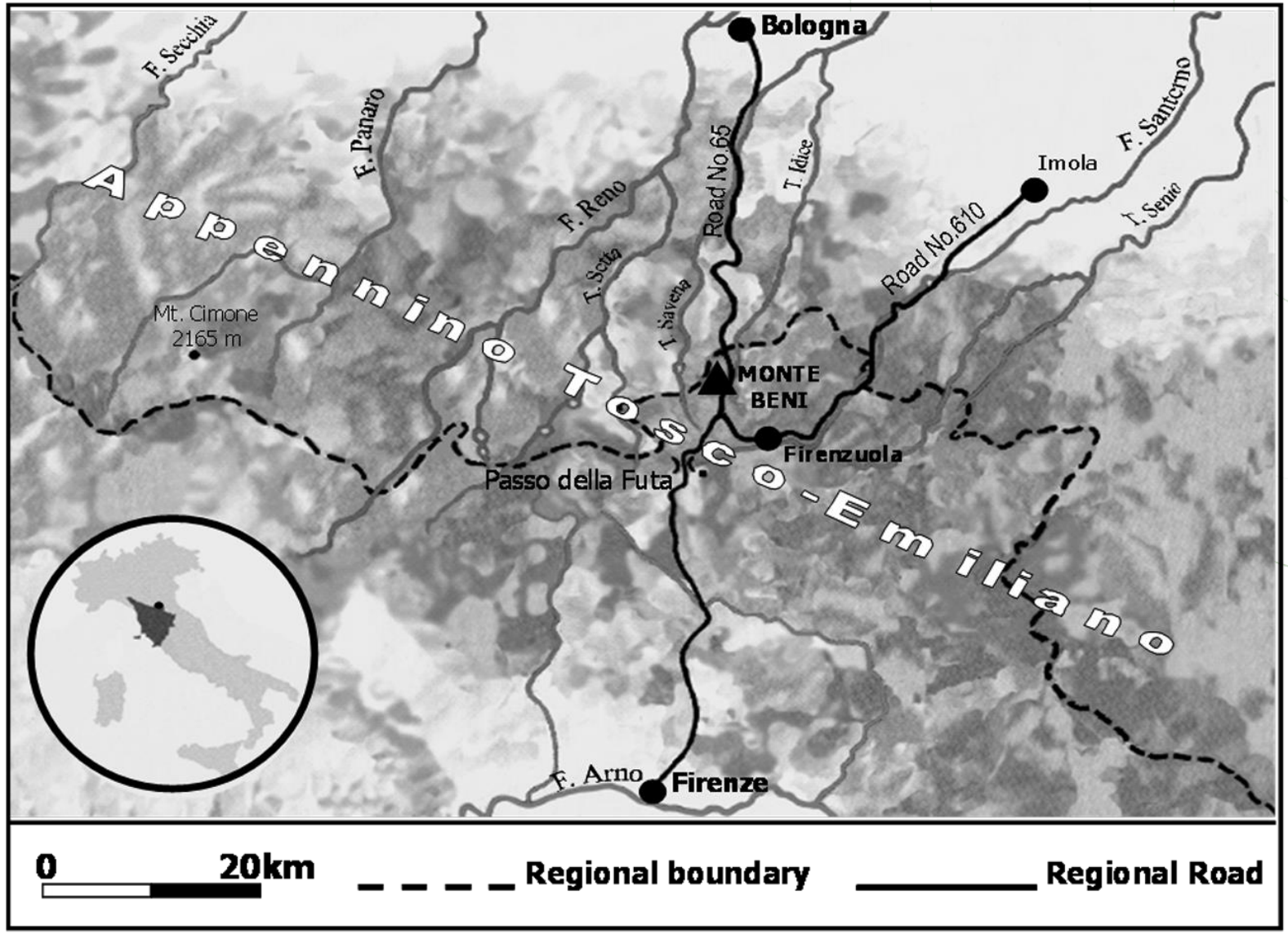


If $\alpha = 2$:

$V^{-1} = A(t_f - t)$

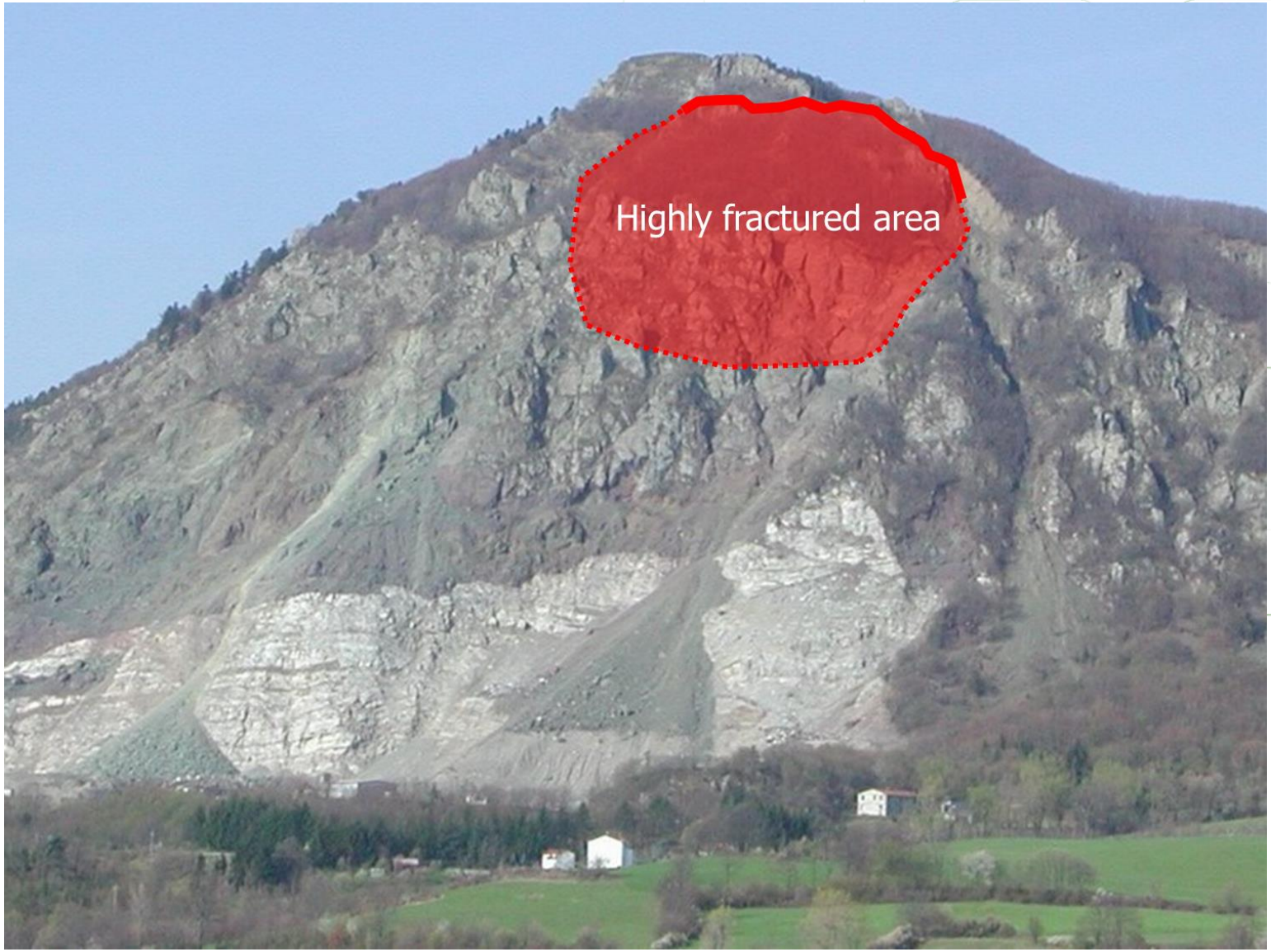
HYPERBOLA

Case study: the Montebeni landslide

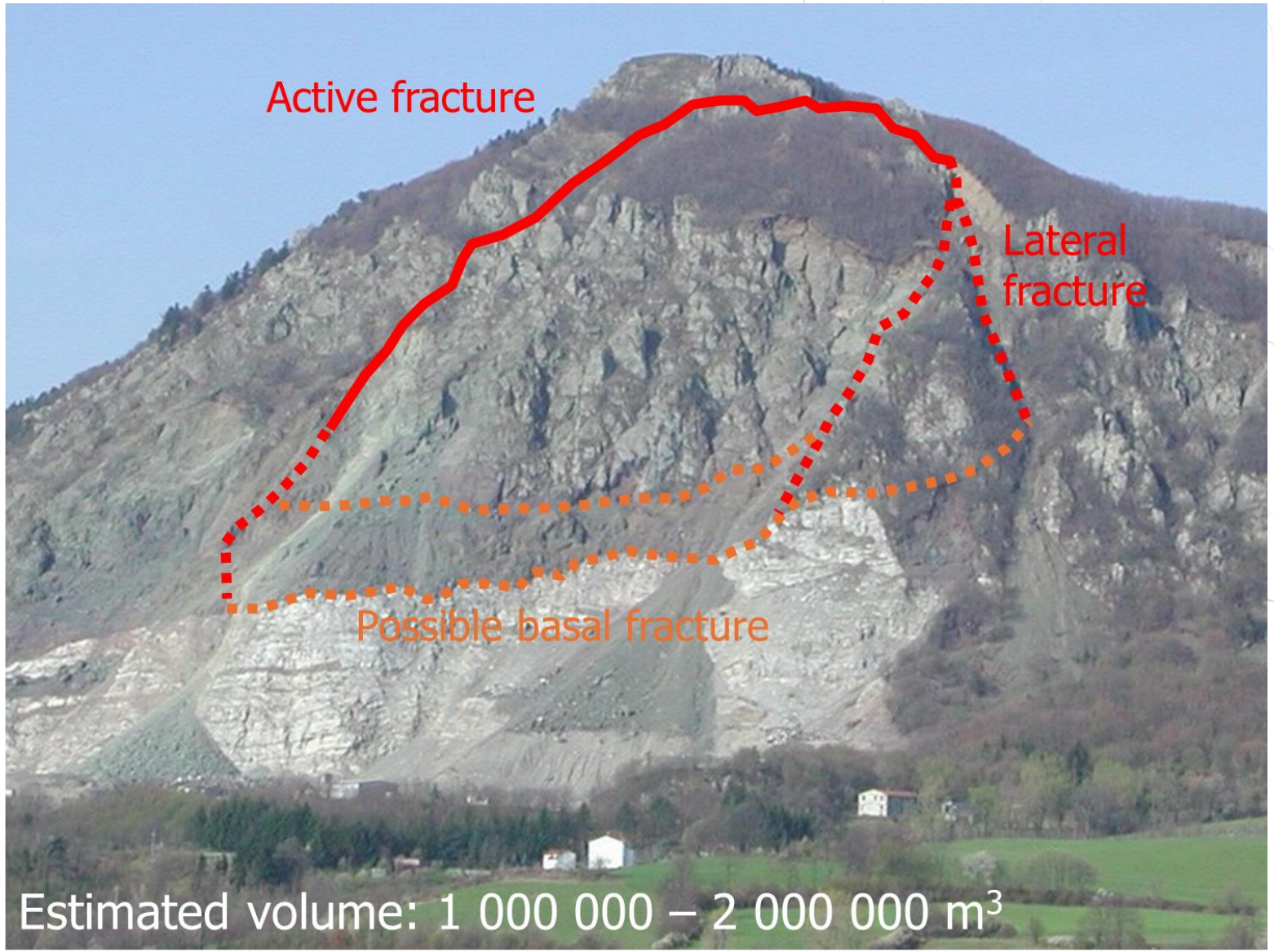


August, 2000

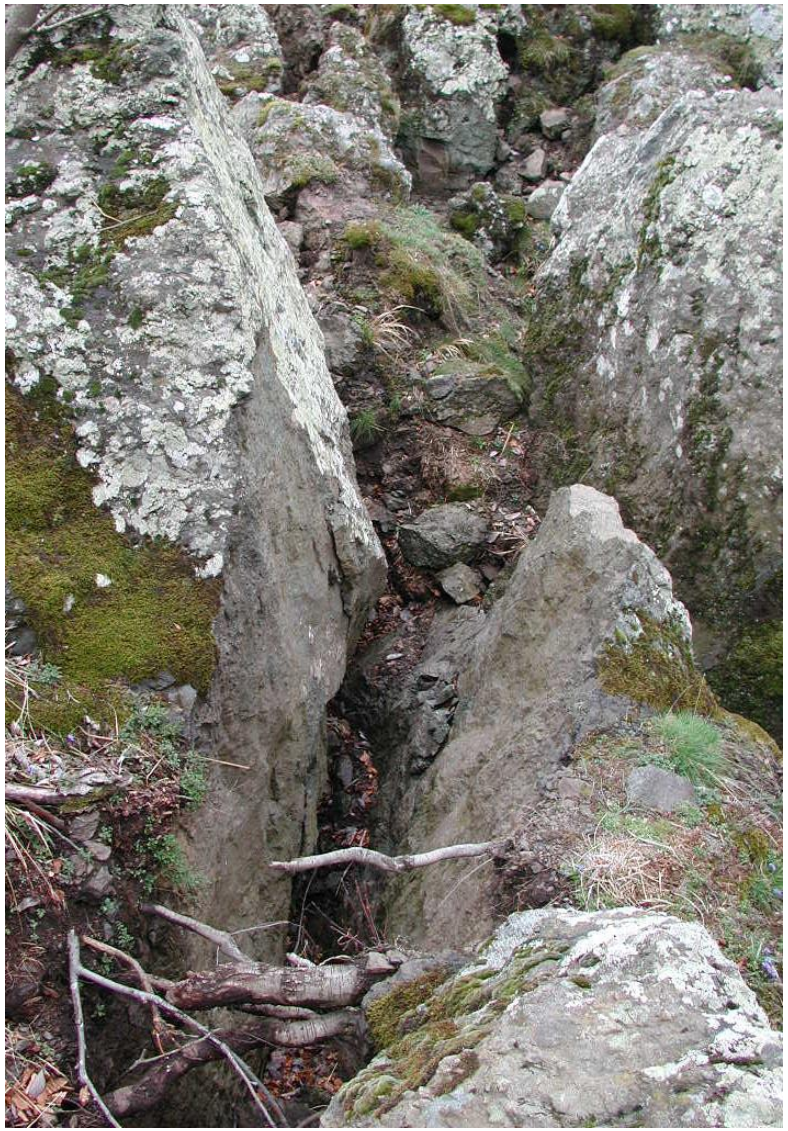
- Kinematic Analysis
- Rockfall simulations



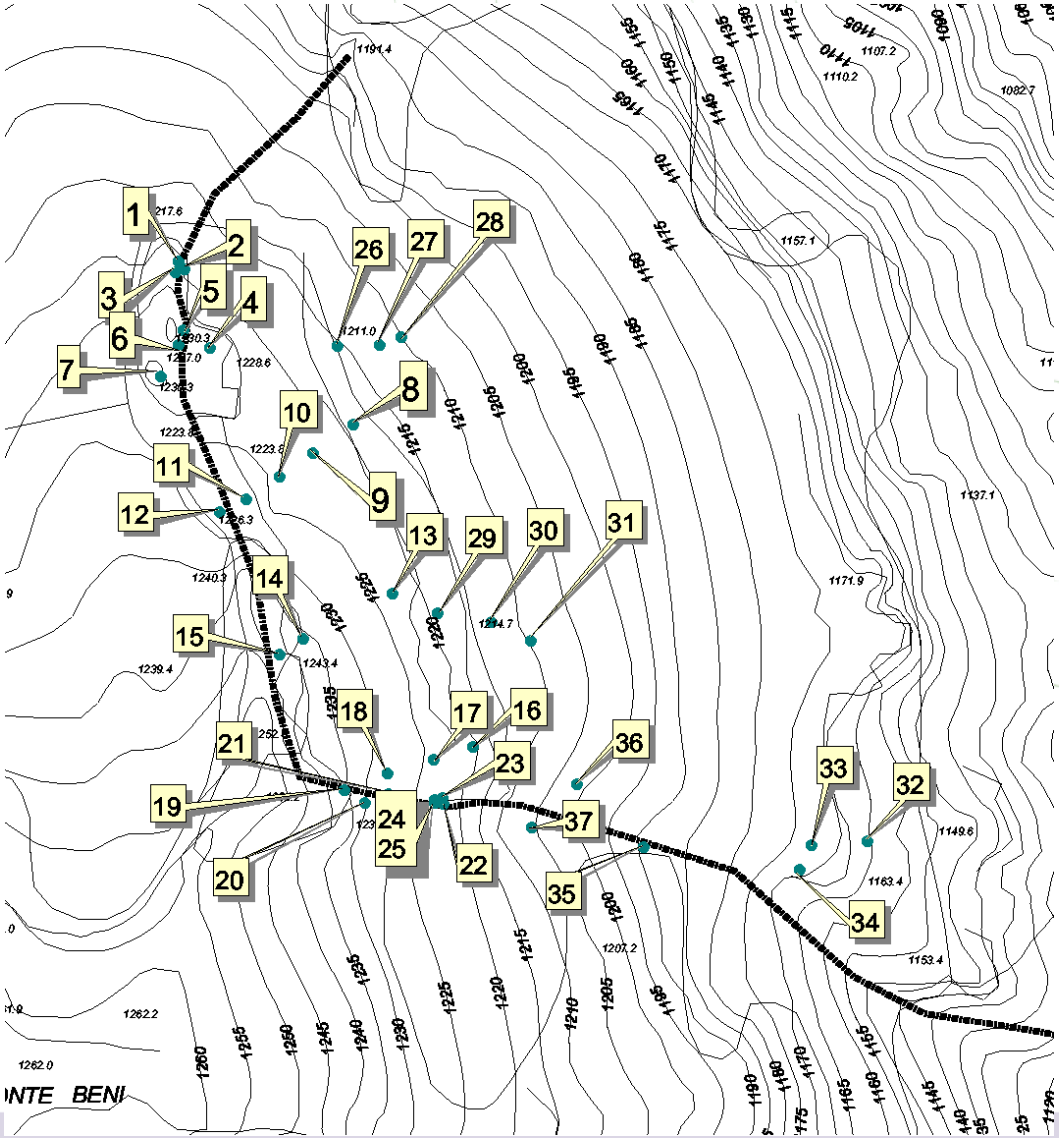
April, 2002


Active fracture
Lateral fracture
Possible basal fracture
Estimated volume: 1 000 000 – 2 000 000 m³

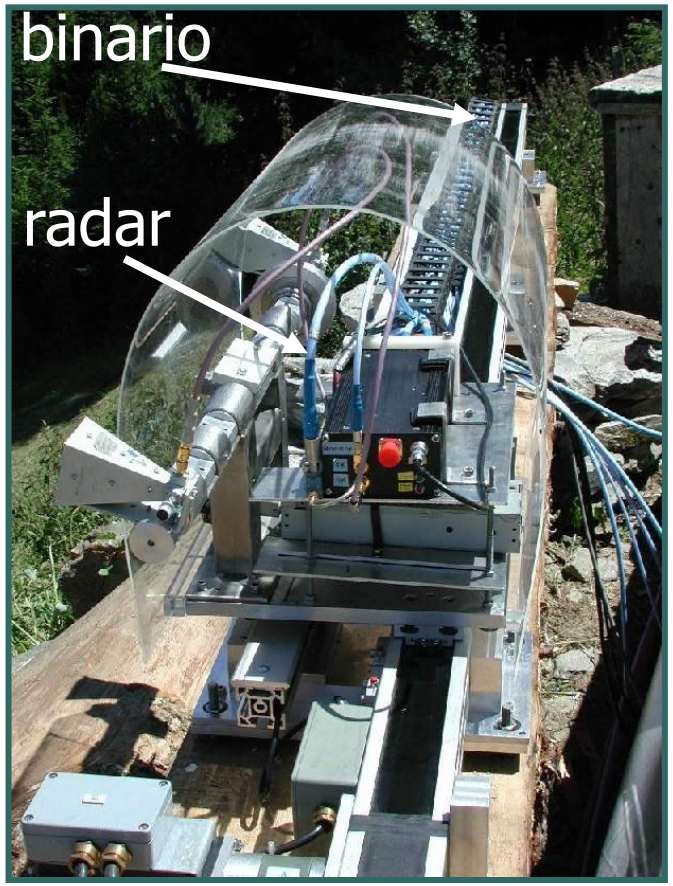
Upper fracture

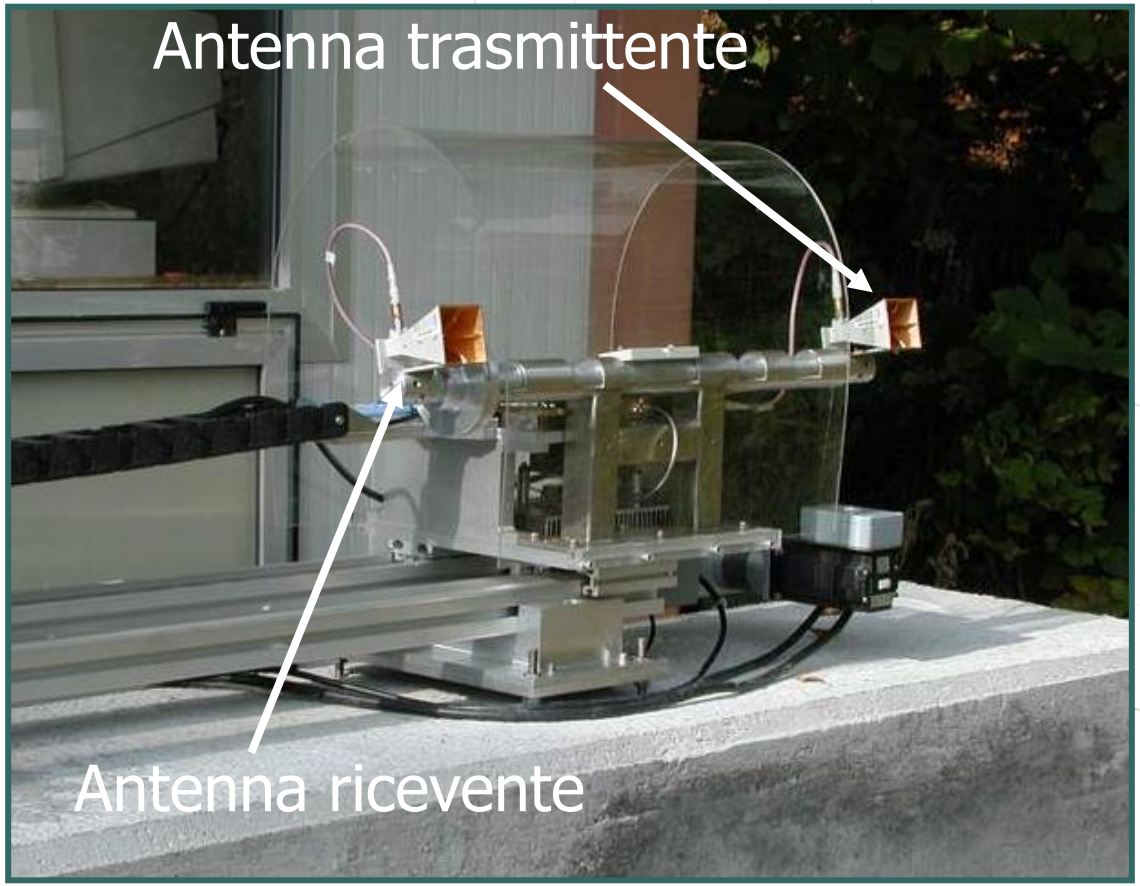


Distometric monitoring



GB-InSAR monitoring

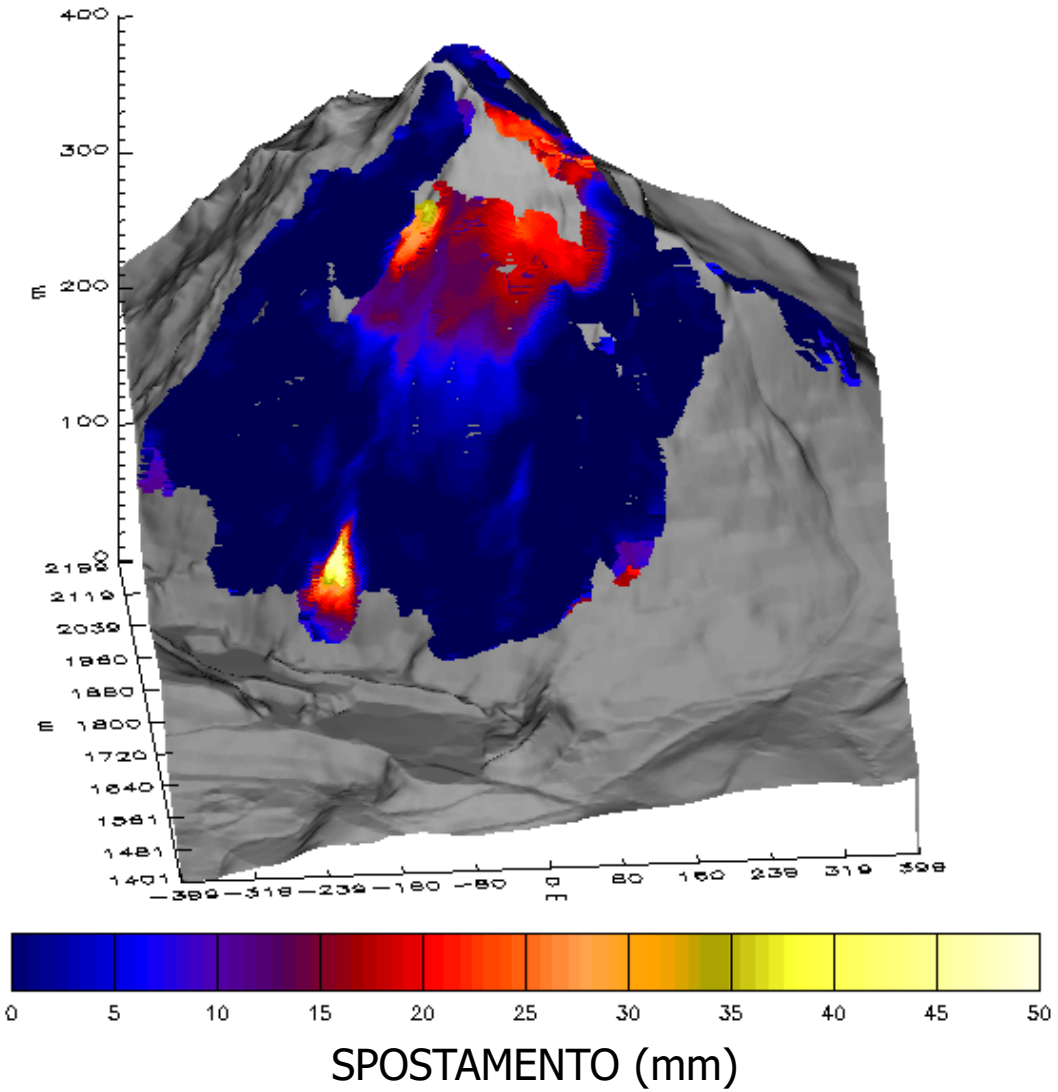




Commissione Europea
Centro Comune di Ricerca – Ispra
Istituto per la Sicurezza del Cittadino

Atmospheric conditions

GB-InSAR cumulated displacement



Start: 8/5/2002 13:59
End: 13/5/2002 18:12

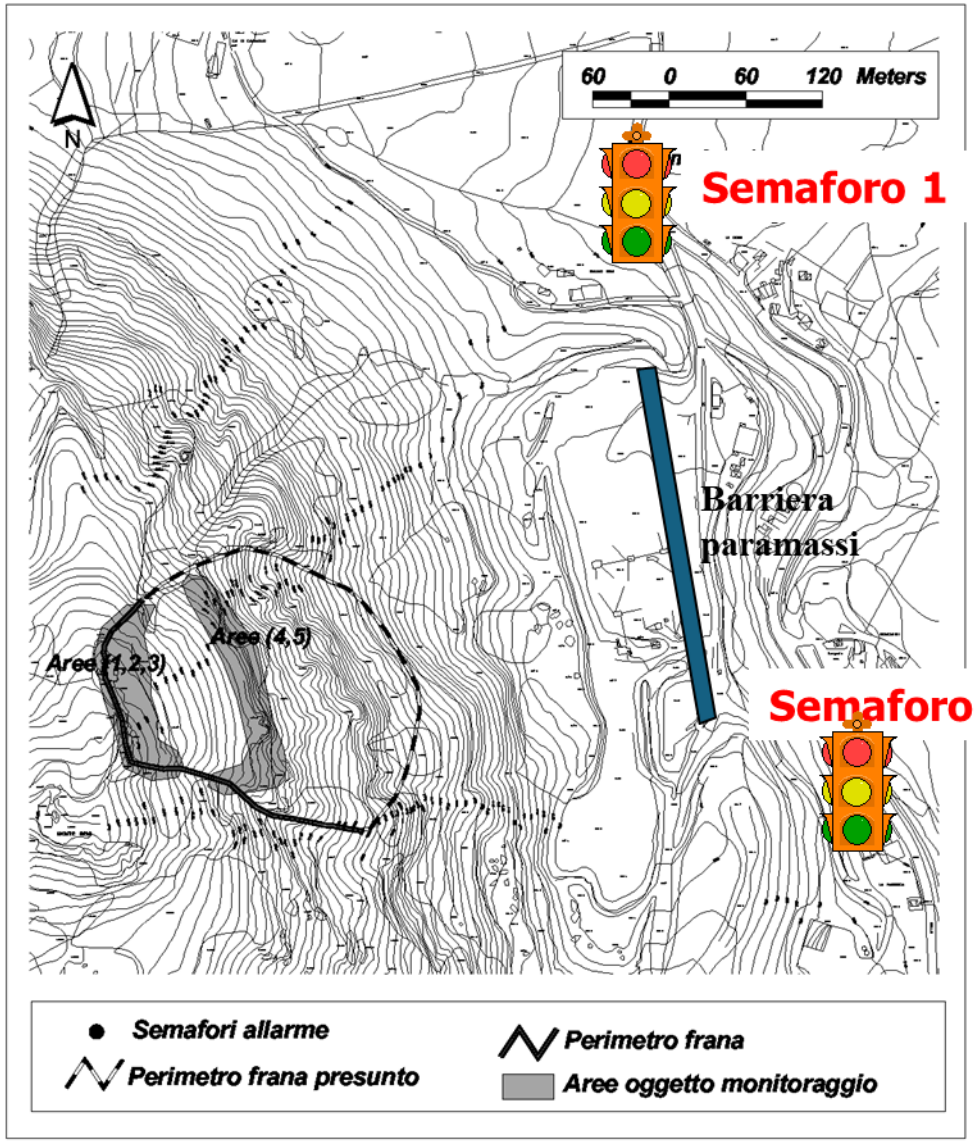
Intervallo di tempo:
124 h

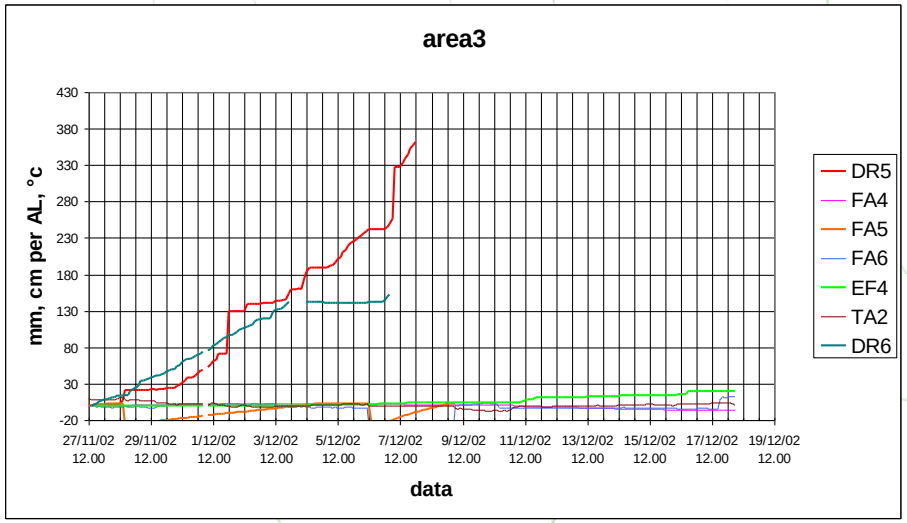
Tempo di acquisizione:
40 min

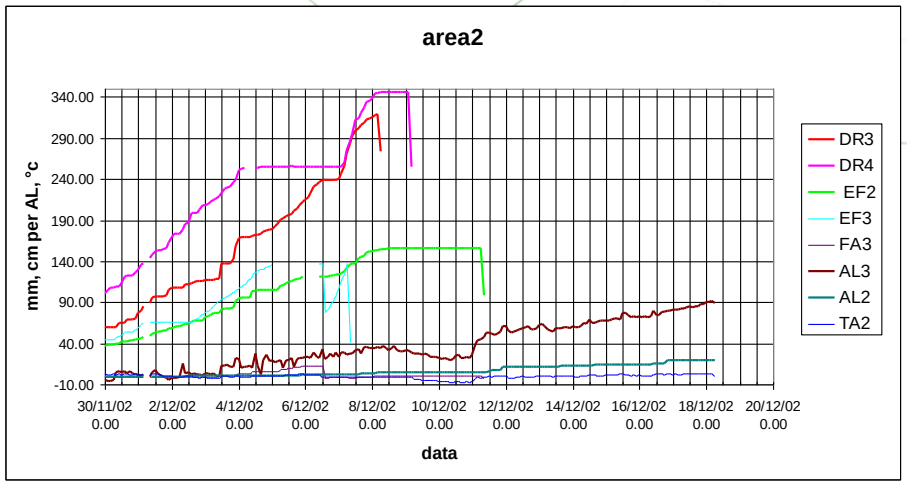
Velocità massima:
0.48 mm/h

Velocità media:
0.16 mm/h

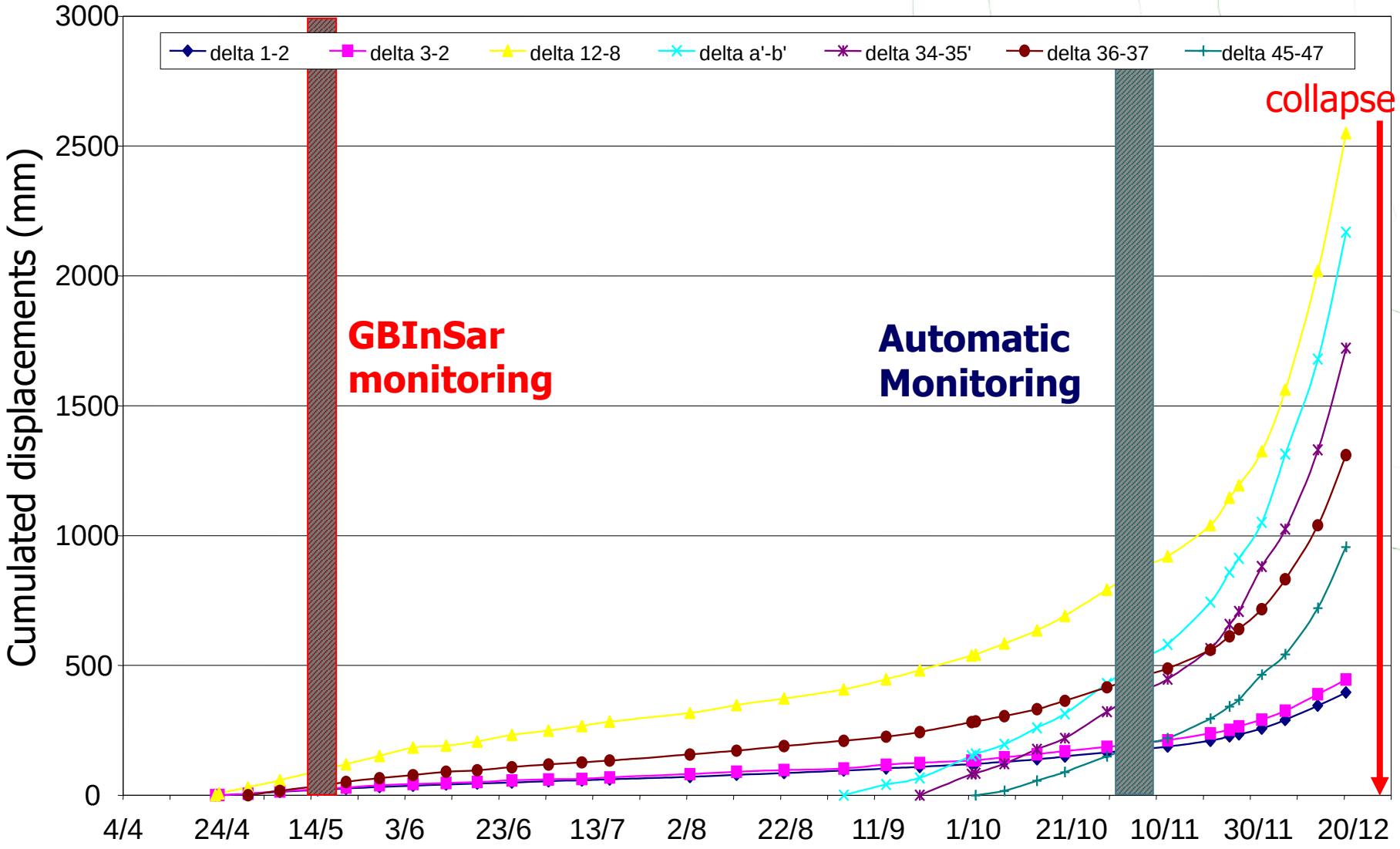
Emergency management



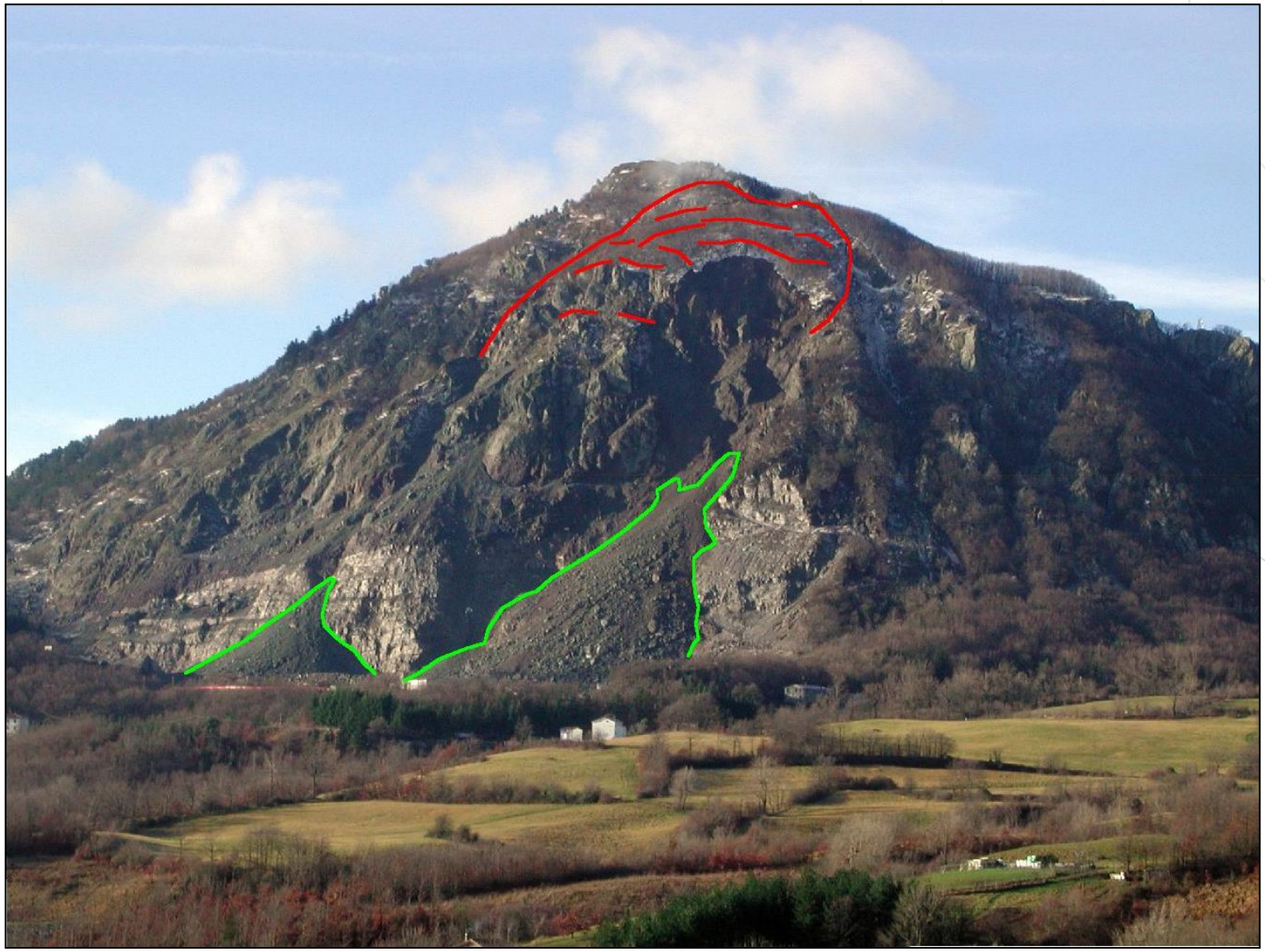




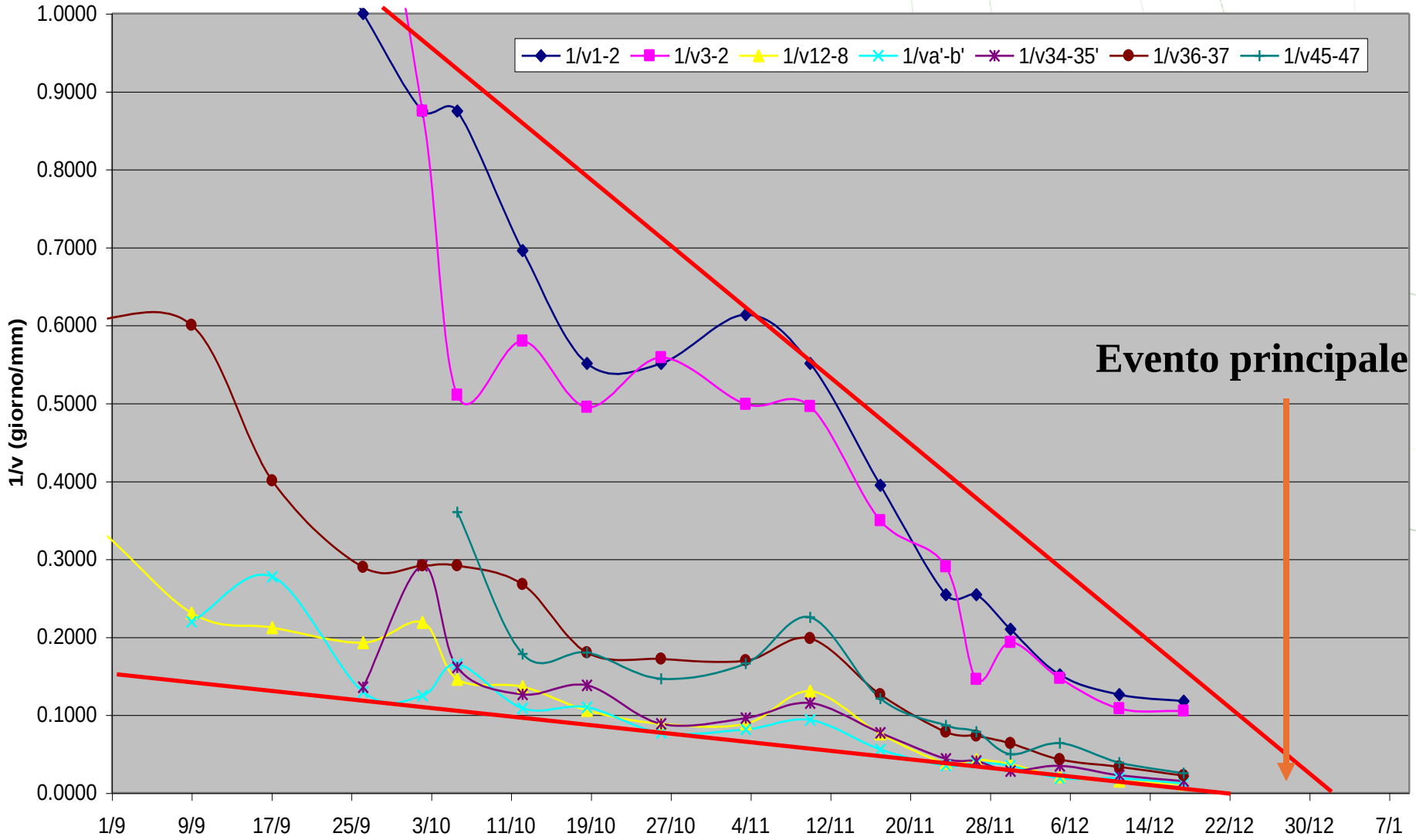
Monitoring - summary



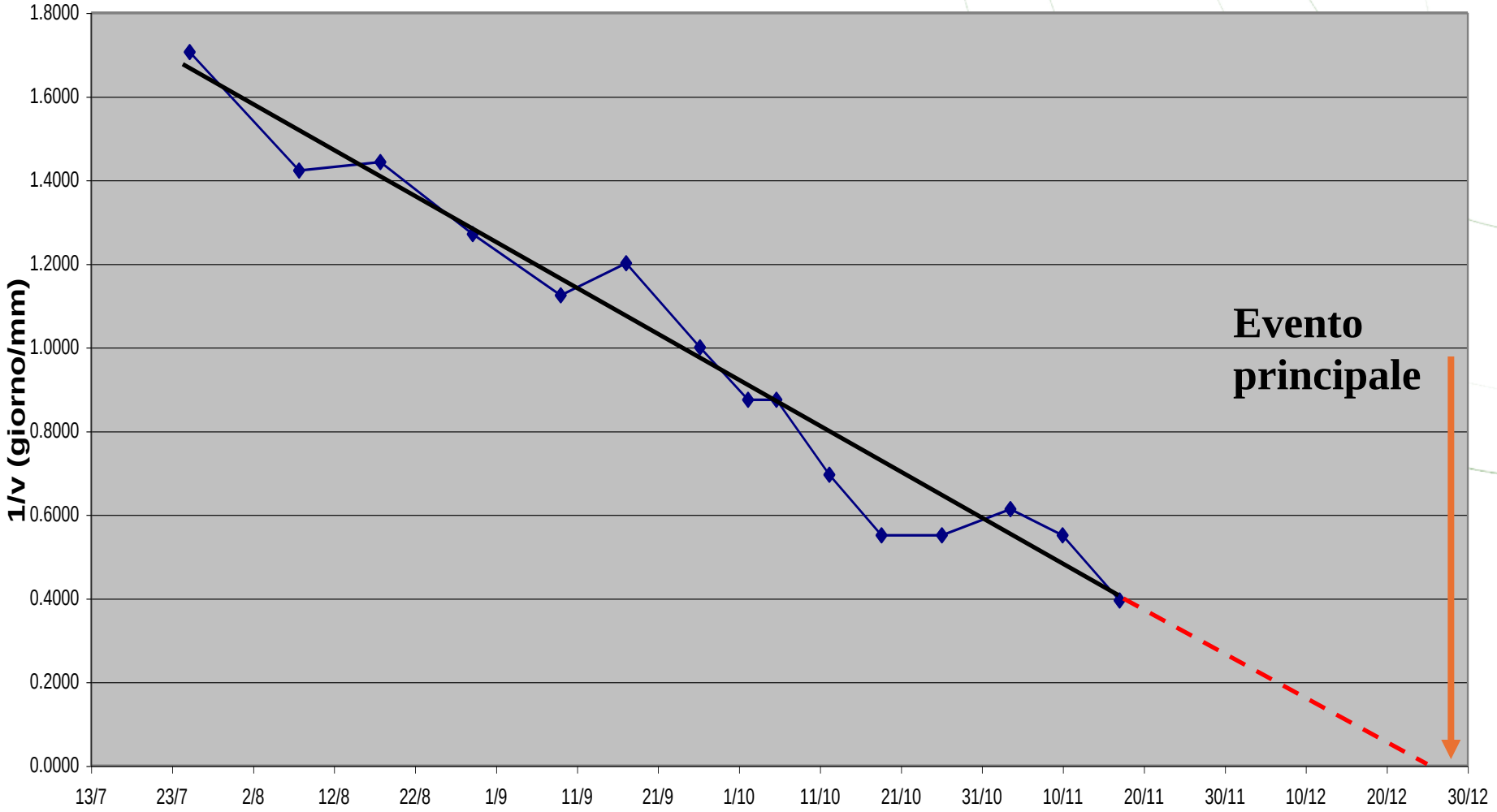
15/12/2002 event



Time of failure forecast



Time of failure forecast – baseline 1-2



Announcements

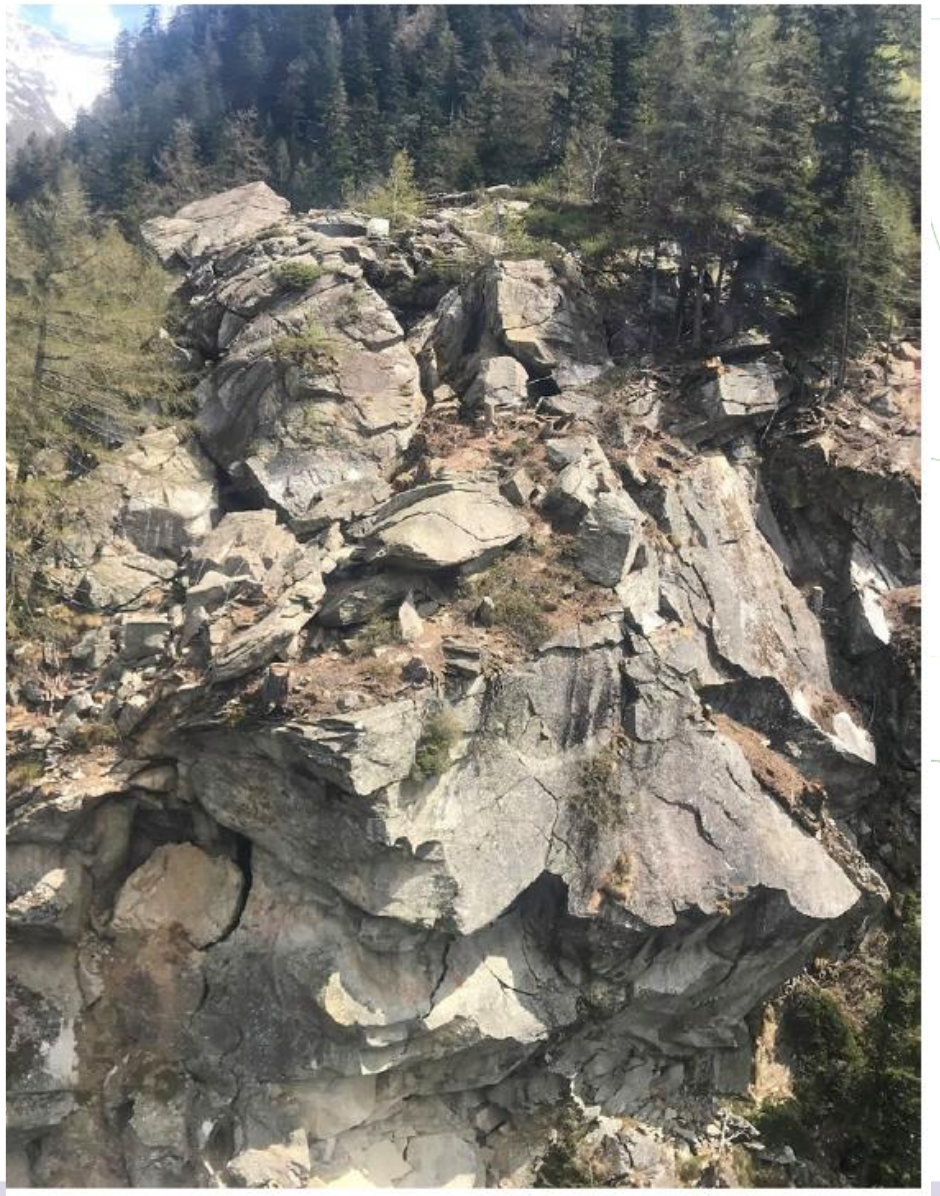
- “… la frana, fino ad oggi sensibile alle precipitazioni meteoriche, sembra avere subito questa accelerazione in modo indipendente dalle precipitazioni…” (lettera del Prof. Canuti al Sindaco di Firenzuola, 26/11/02).

- “… il temuto collasso della “massa grande” è ormai prossimo: porre attenzione che nelle festività natalizie sia rispettata l’ordinanza di evacuazione.” (lettera del Prof. Canuti al Sindaco di Firenzuola, 23/12/02).

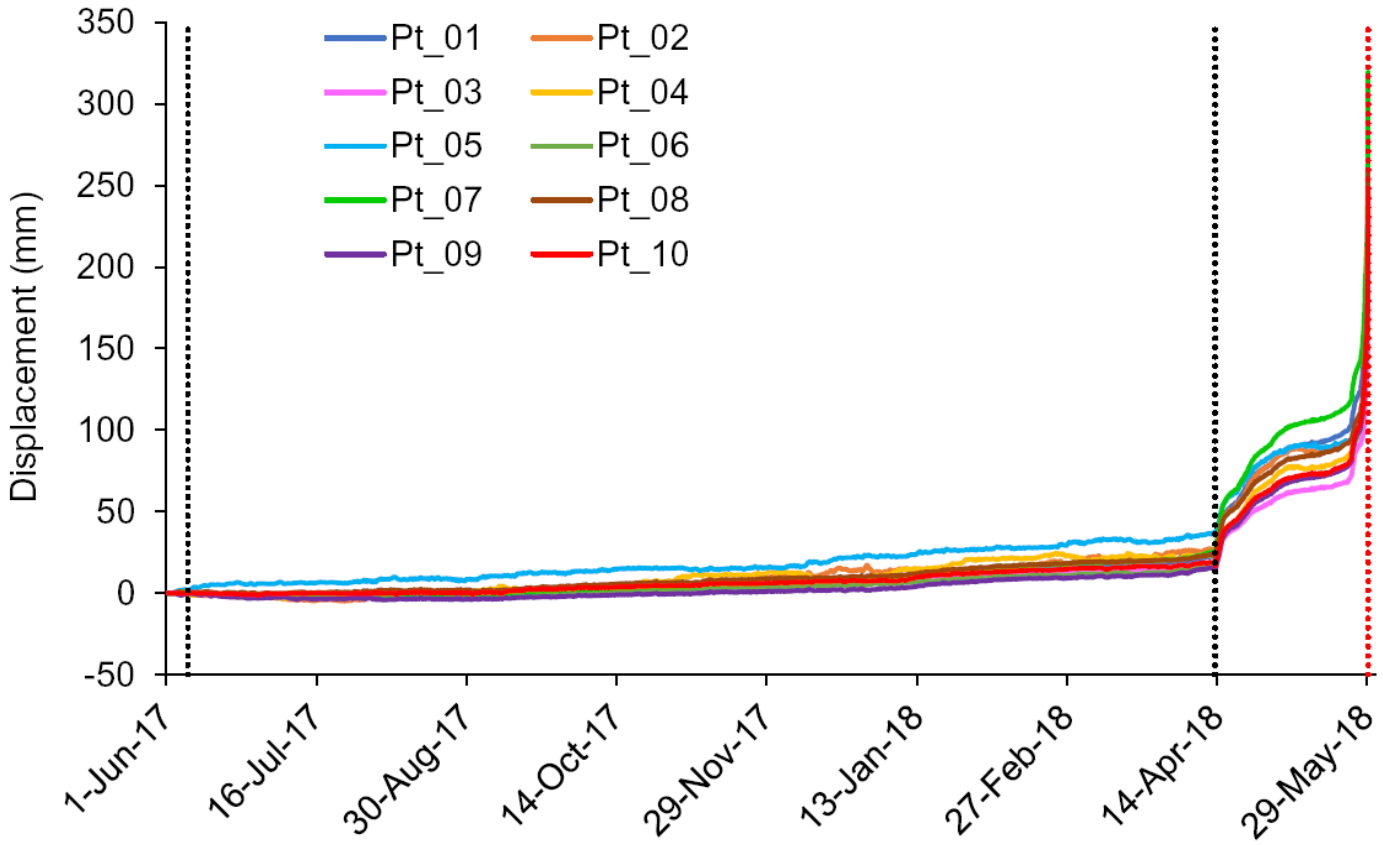
- “… la “massa grande” collasserà entro i primi giorni di gennaio 2003.” (Presentazione del Prof. Canuti alla Commissione Monte Beni del 27/12/02).

28/12/2002 landslide

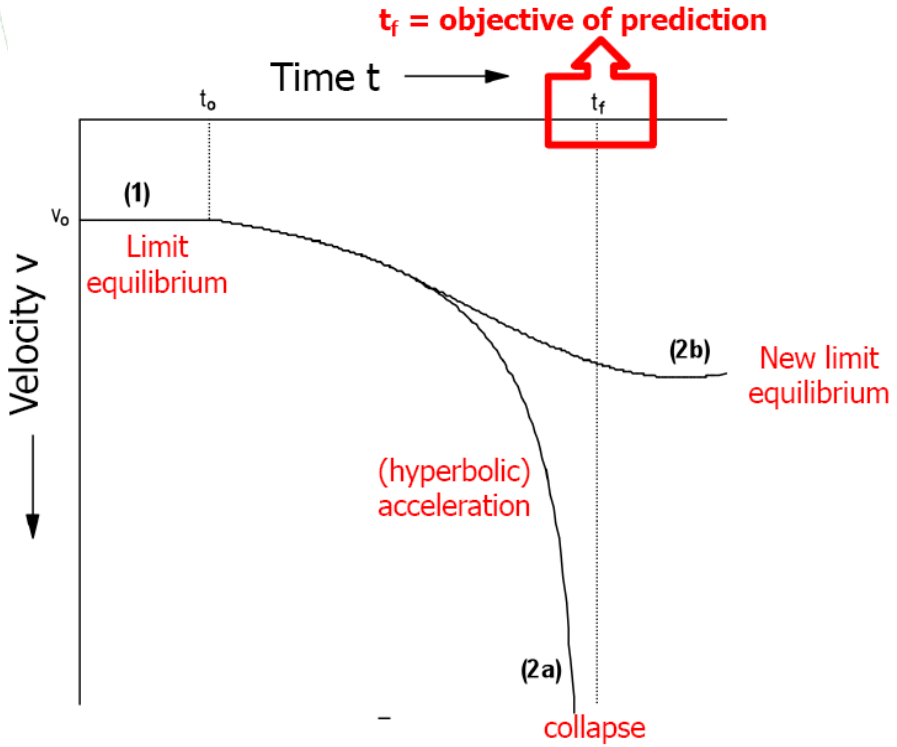
Gallivaggio landslide



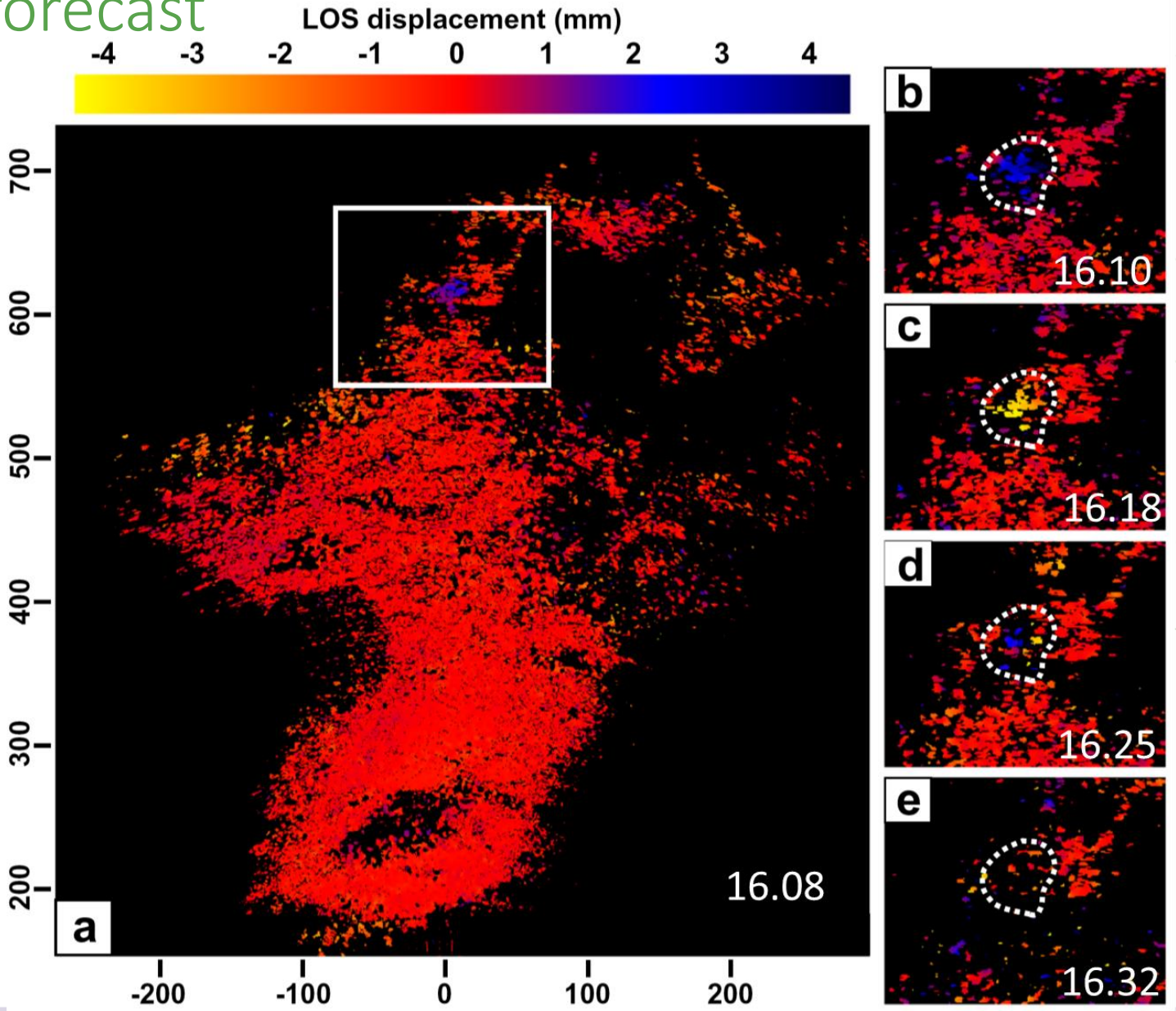
Time of failure forecast



Carlà et al., 2019

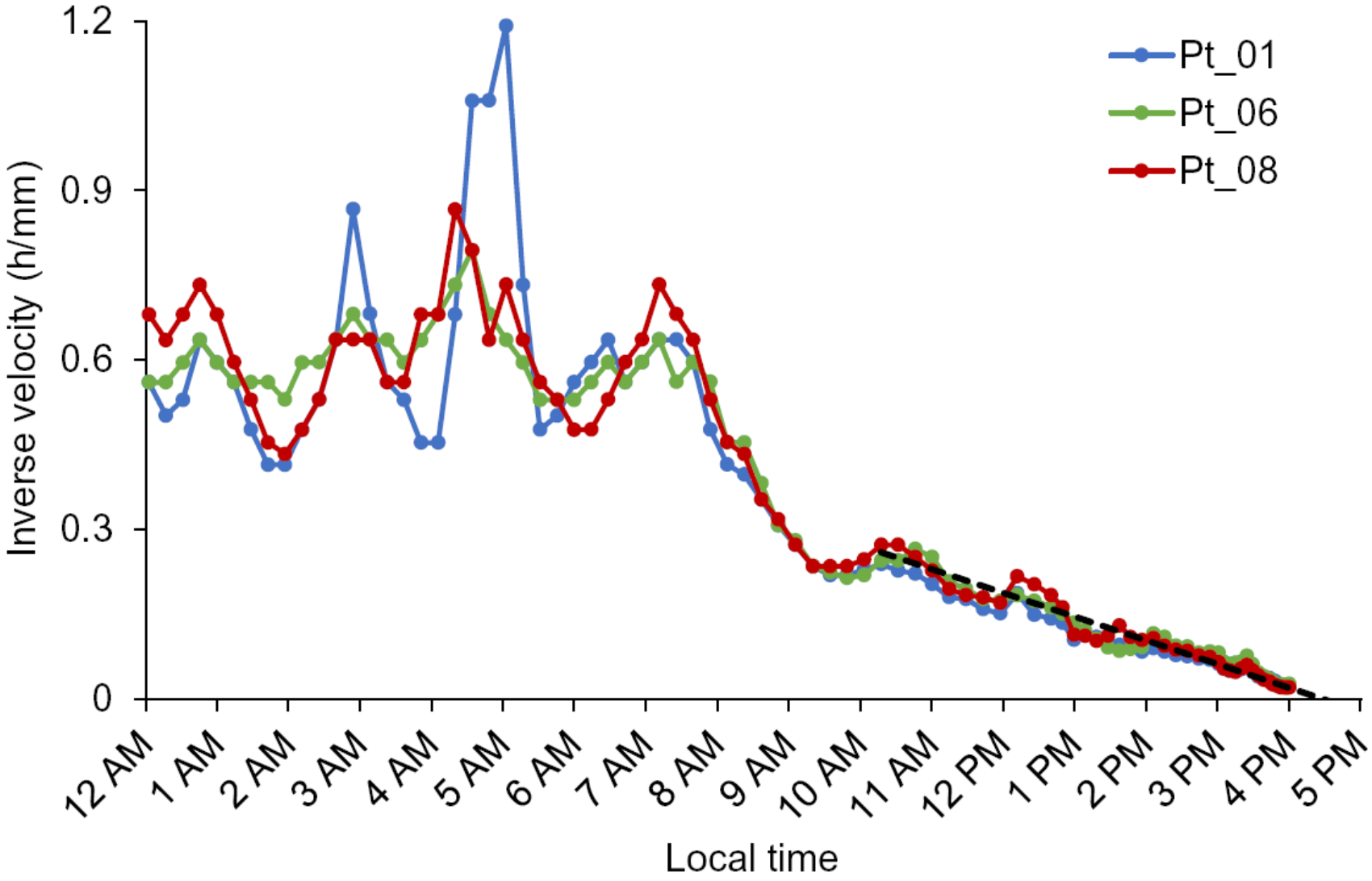


Time of failure forecast



Carlà et al., 2019

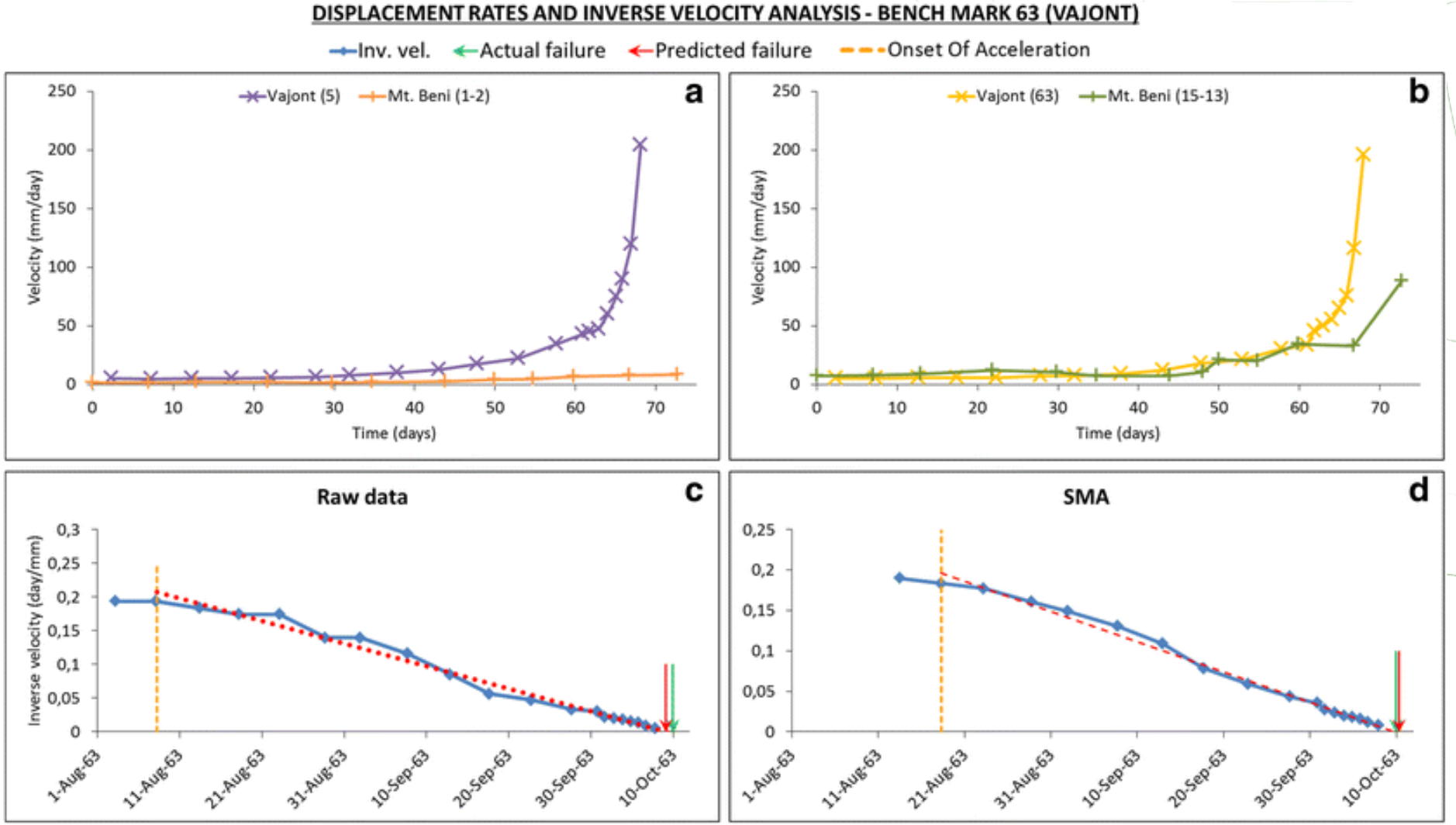
Time of failure forecast



Rock collapse

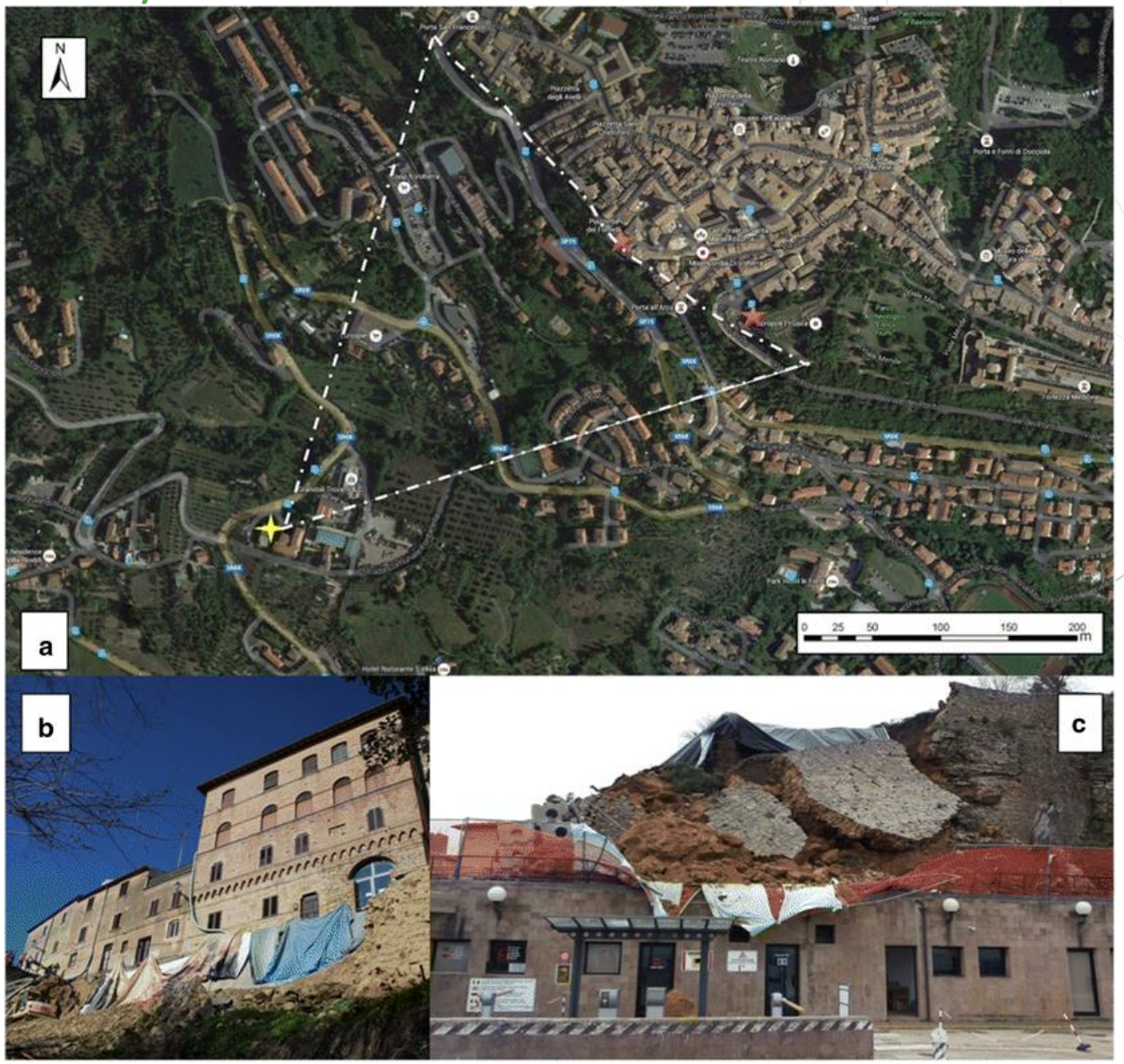
Mt. Toc (Vajont)

Mt. Toc (Vajont)



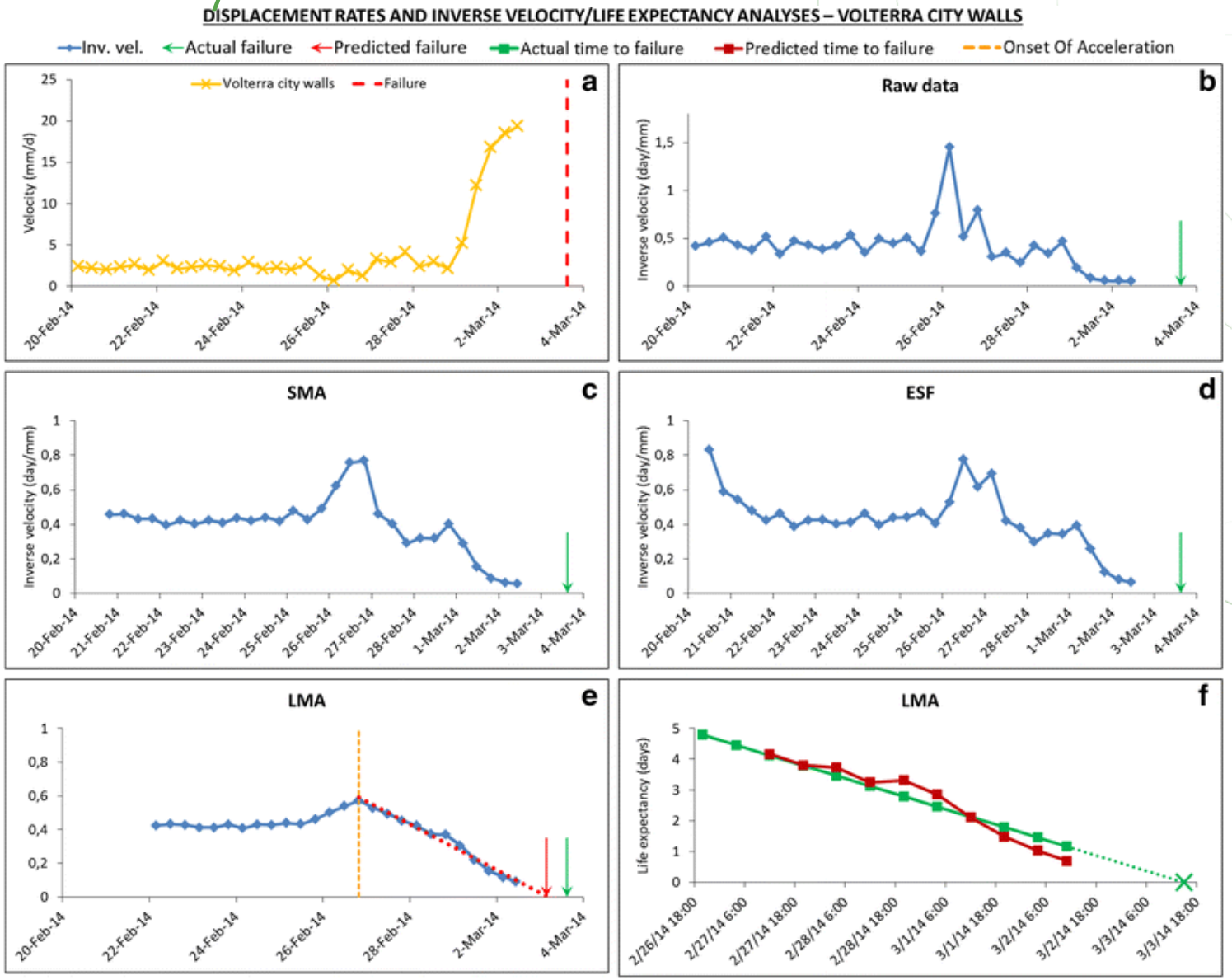
Carlà et al., 2017

Volterra medieval city wall



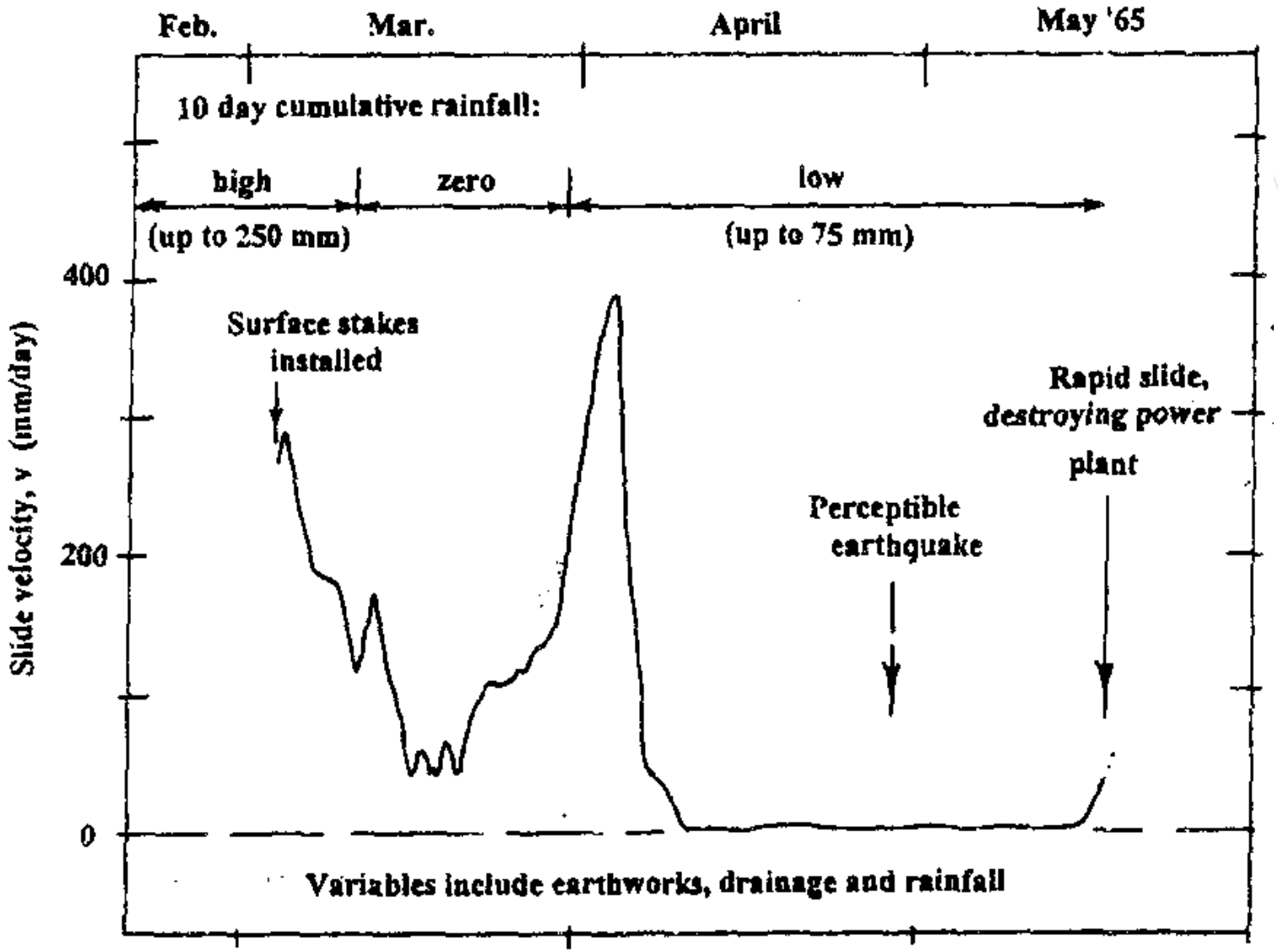
Carlà et al., 2017

Volterra medieval city wall



Carlà et al., 2017

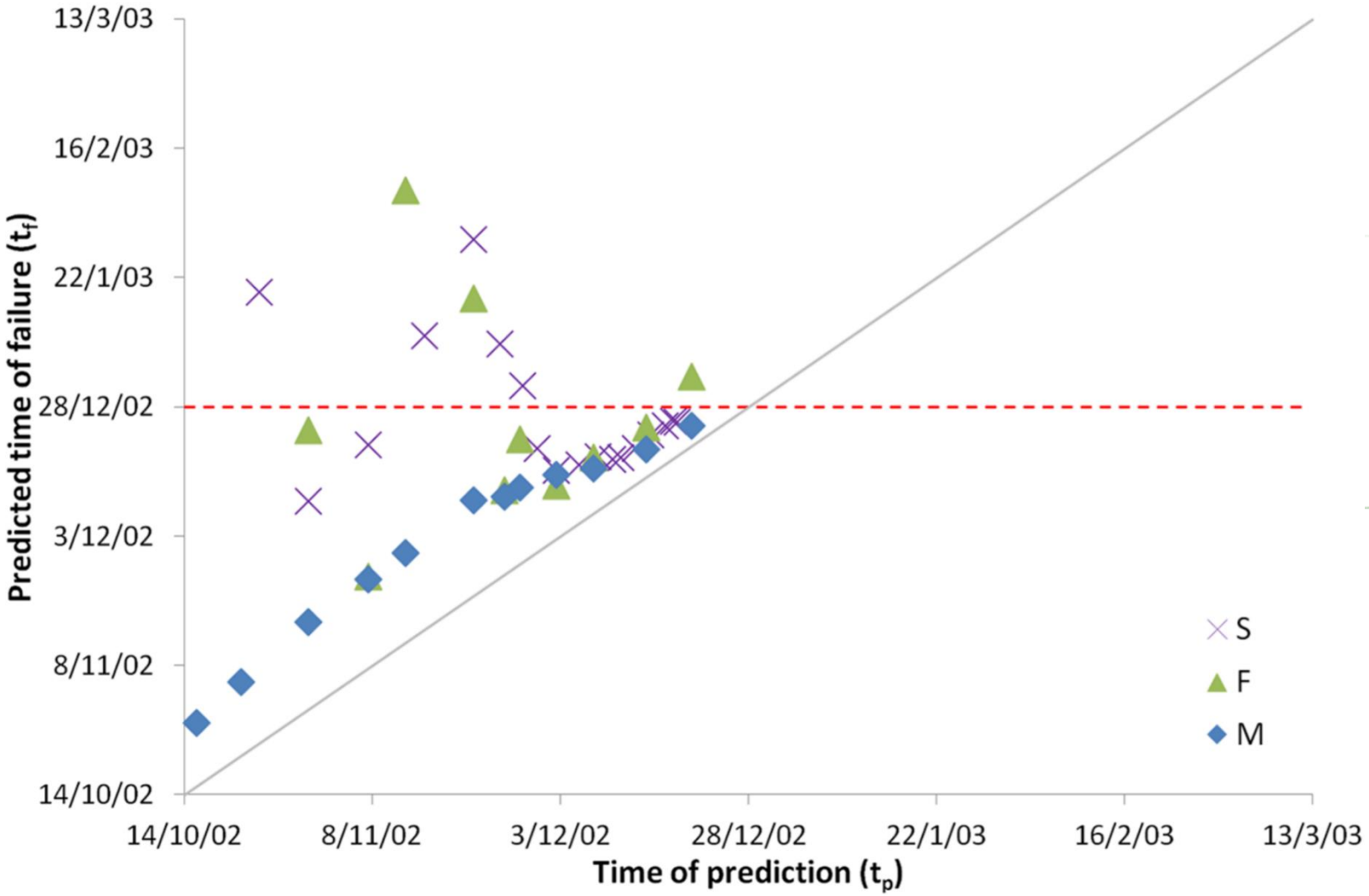
Unexpected failure



- Measurement error
- Random noise
- Local movements
- Anthropic activity
- Earthquakes
- Meteorologic factors
- Structural constraints
- Ductile Behaviour
- Invalid assumptions

Hutchinson (2001)

Probabilistic approach



Intrieri and Gigli, 2016

Thersholds and actions

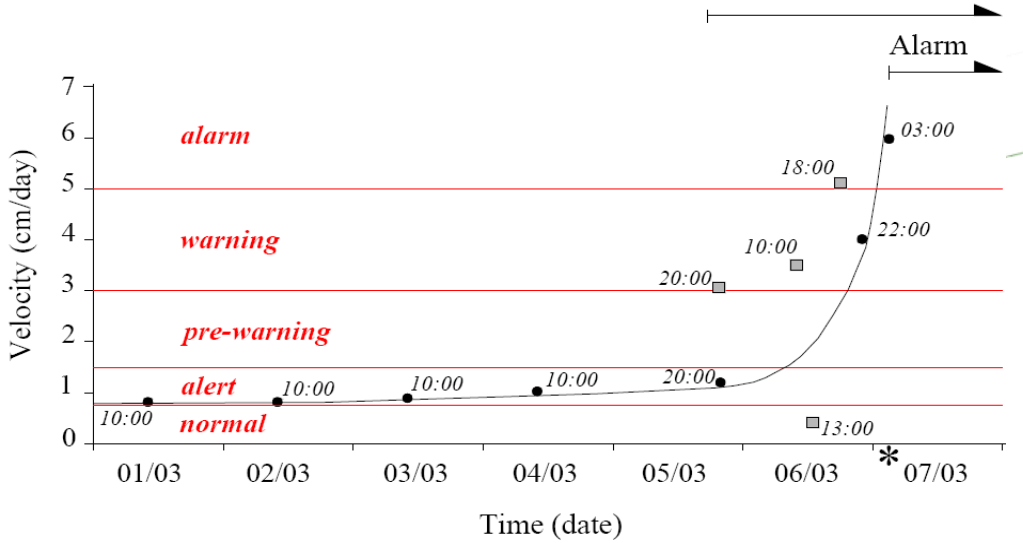
NOTHING SPECIAL	**BE AWARE**	**BE PREPARED**	**TAKE ACTION**
Stable or constant veloci	Start of acceleration	Sustained acceleration	Asymptotic acceleration
Weekly reports	Daily reports	Hourly reports	Continuos reports
			

Site-specific empirical thresholds

Alert level	Velocity (cm/day)	Status	Monitoring
0	v<0.2	Normal	1/month
0	0.2<v<0.4	Normal	1/10days
0	0.5<v<1.5	Normal	1/day
1	0.5-1<v<1.5-3	Alert	1/day
2	1-2.5<v<3-5	Pre-warning	1/day
3		Warning	1/day

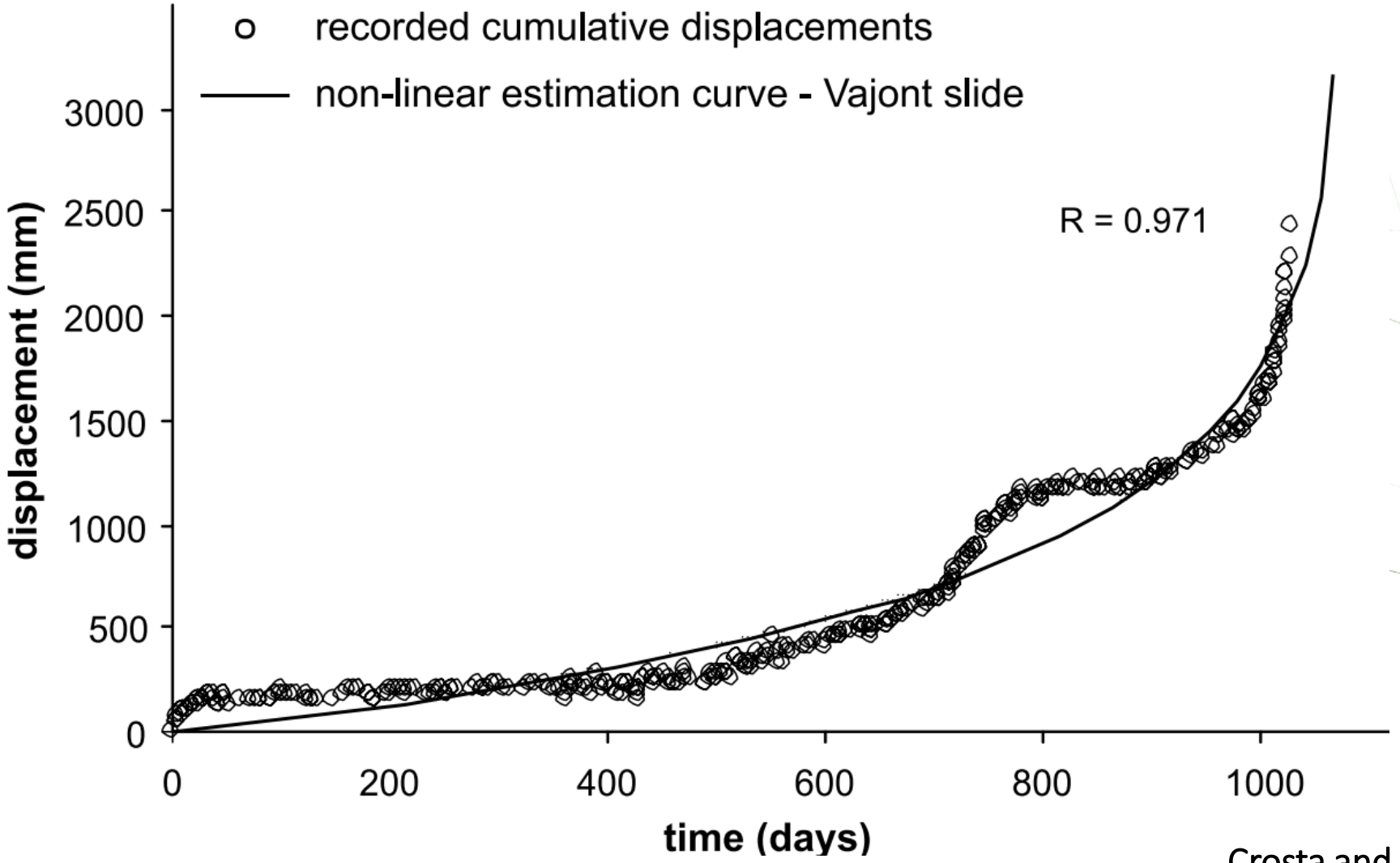
(Oboni, 1988)

Status	Maximum punctual velocity (cm/day)
Normal	v<0.75
Alert	0.75≤v<1.5
Pre-warning	1.5≤v<3.0
Warning	3.0≤v<5.0
Alarm	5.0≤v



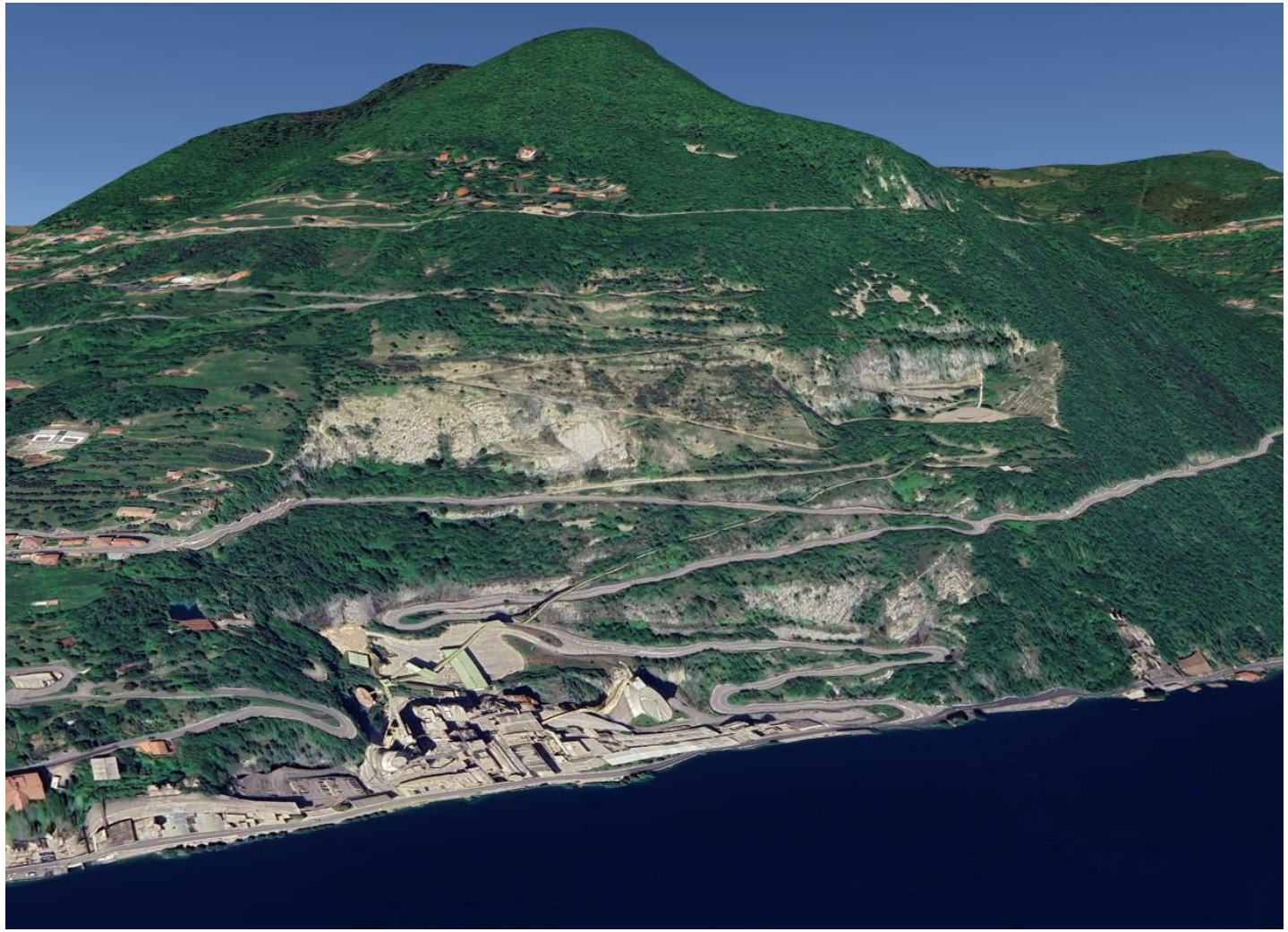
(Iovine et al., 2006)

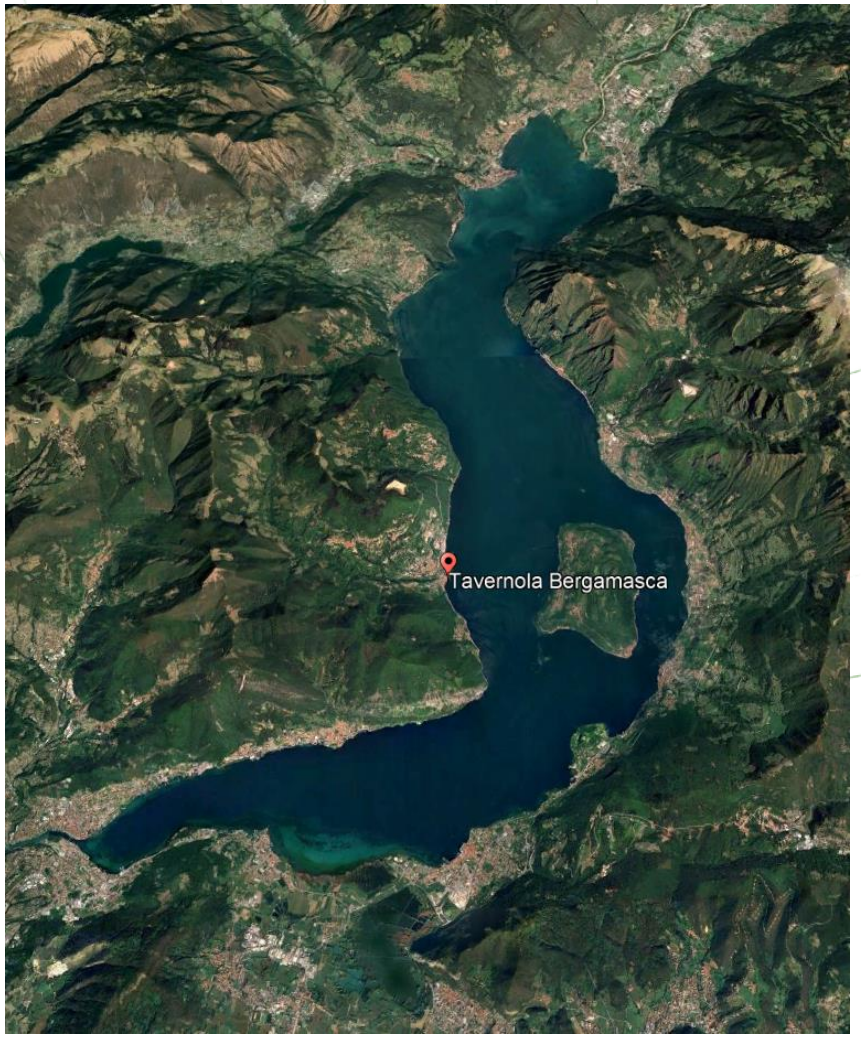
Thresholds definition



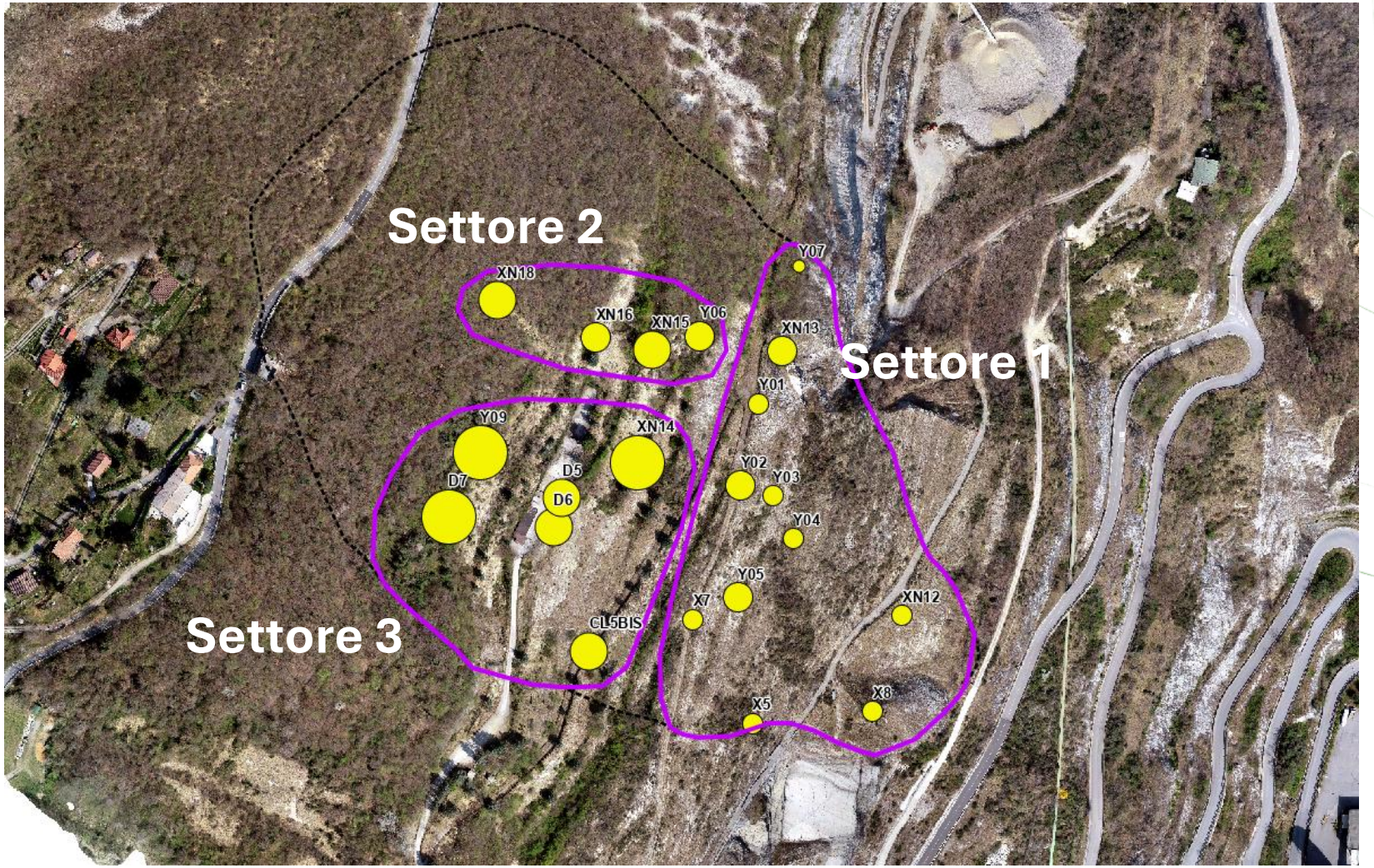
Crosta and Agliardi (2002)

Tavernola Landslide



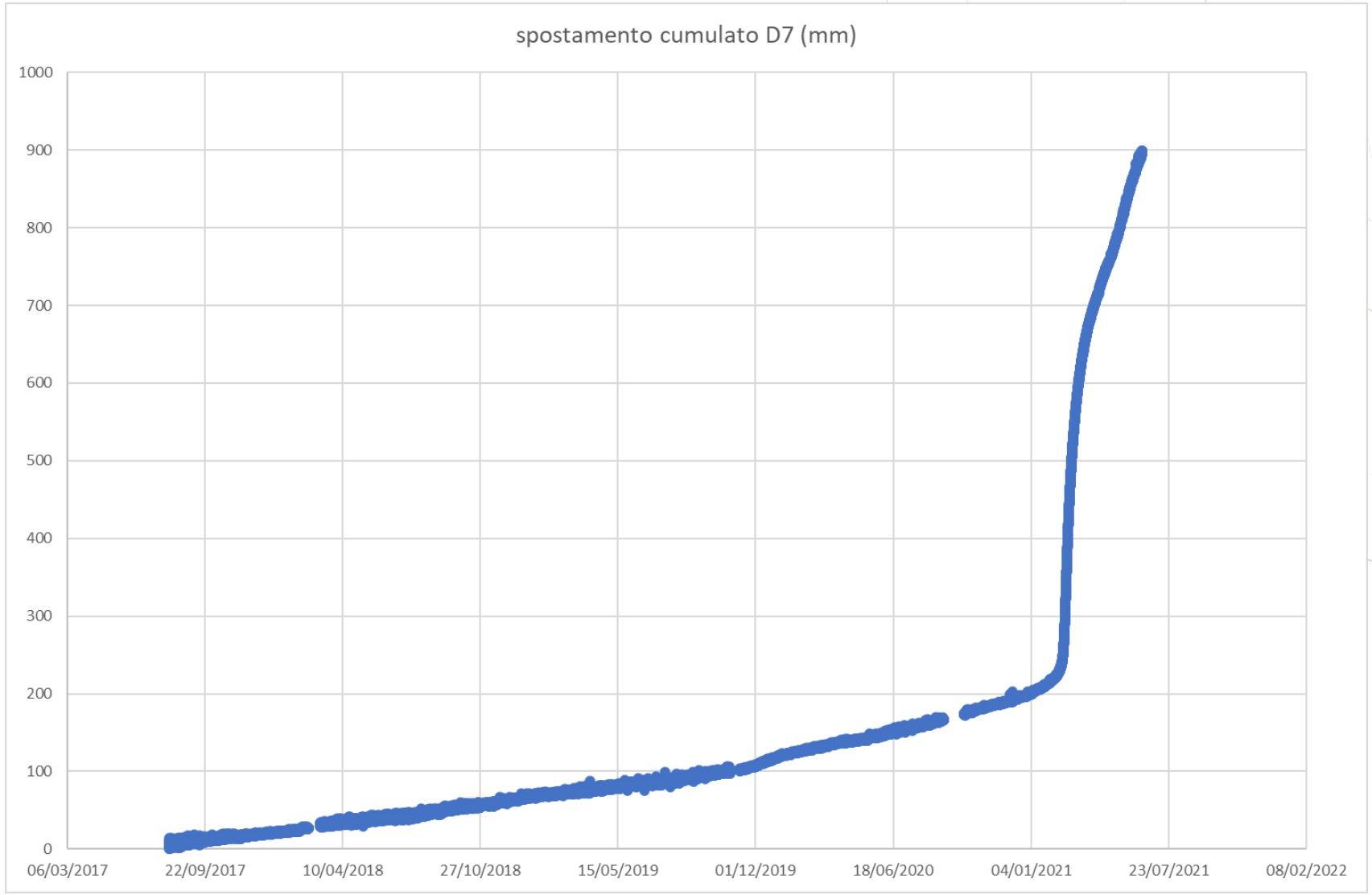


RTS monitoring

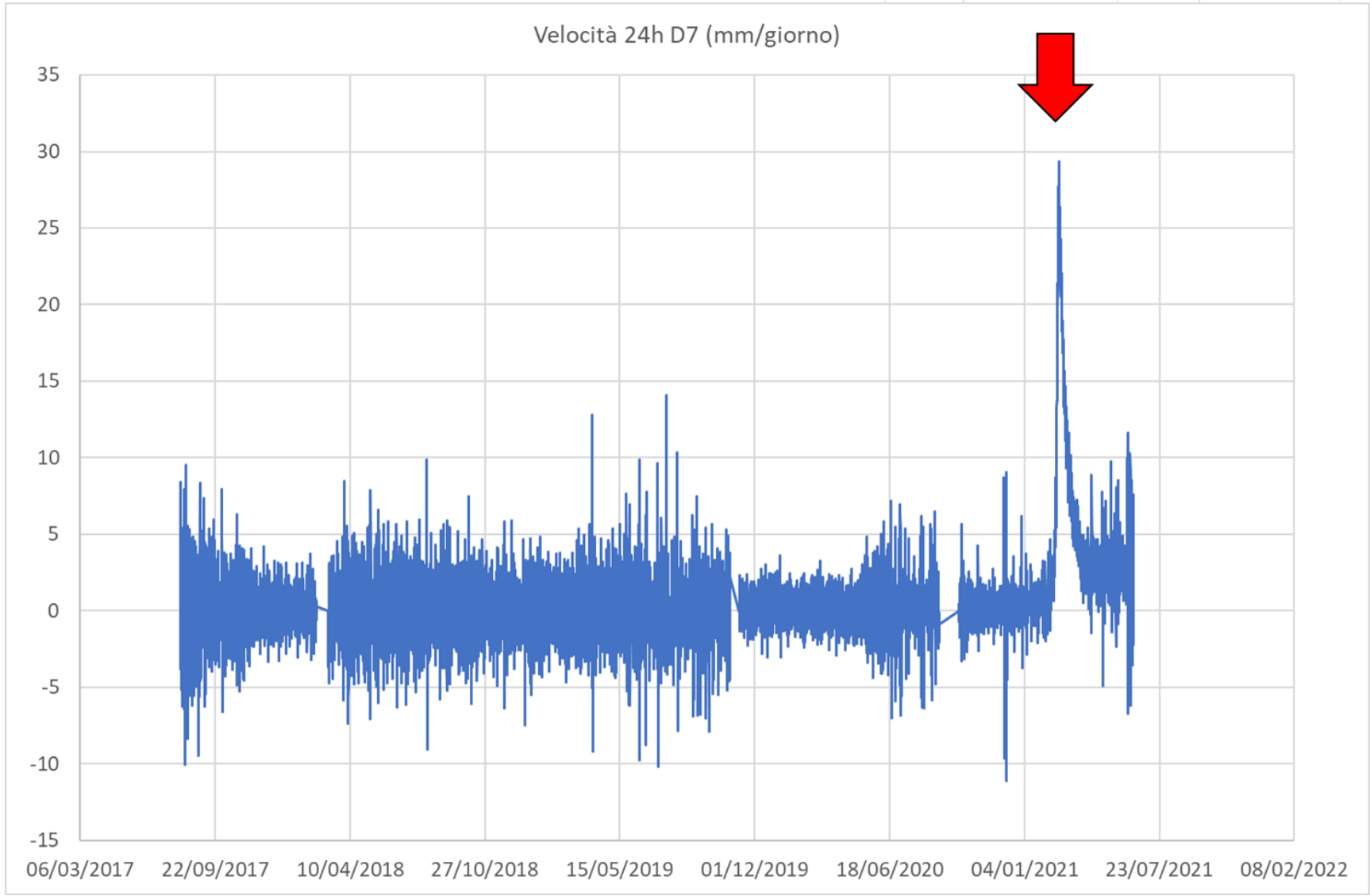


Nota: la distribuzione dei prismi si riferisce alla situazione del mese di febbraio 2021

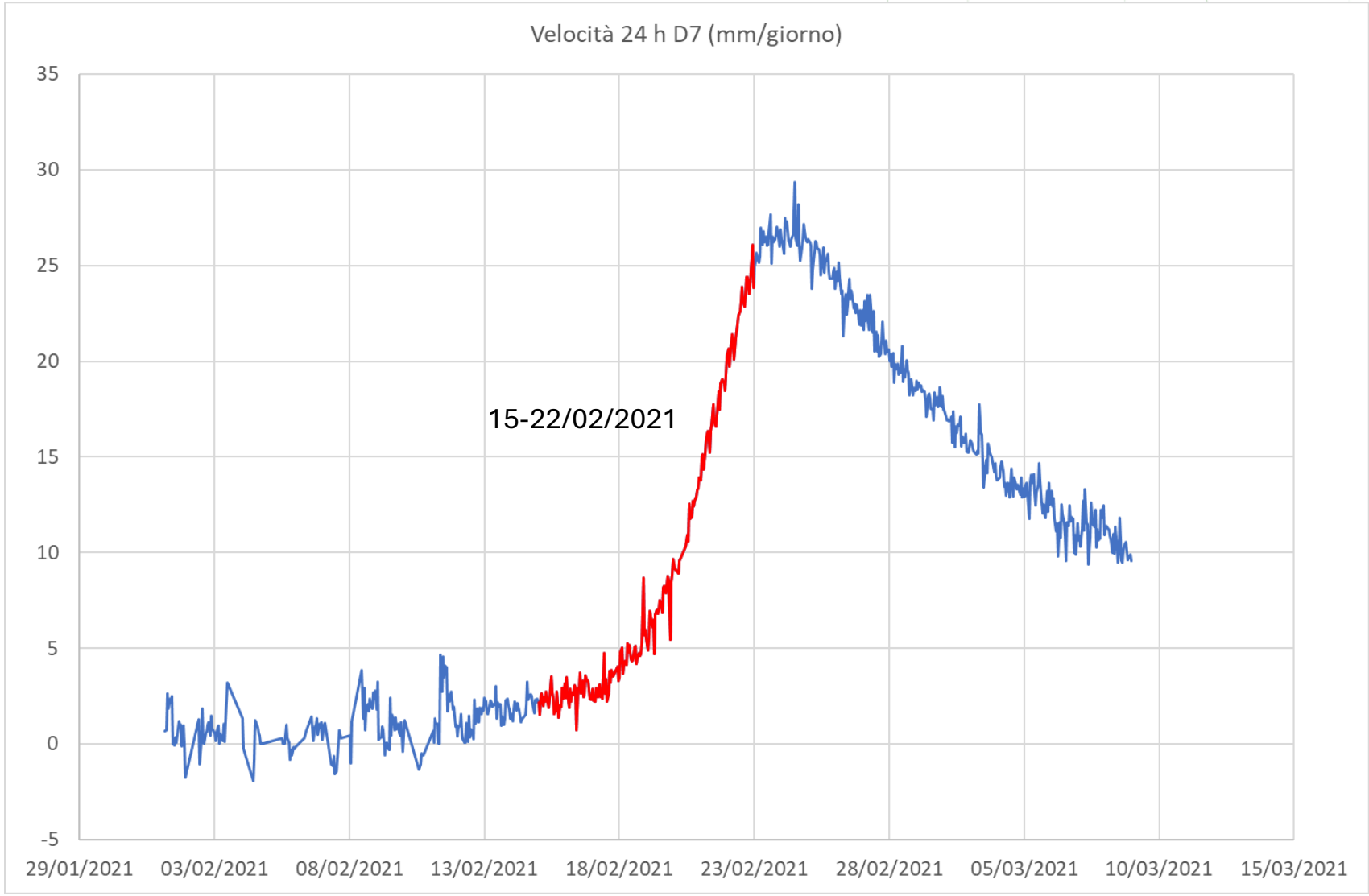
Cumulated displacement at D7



24h Velocity at D7



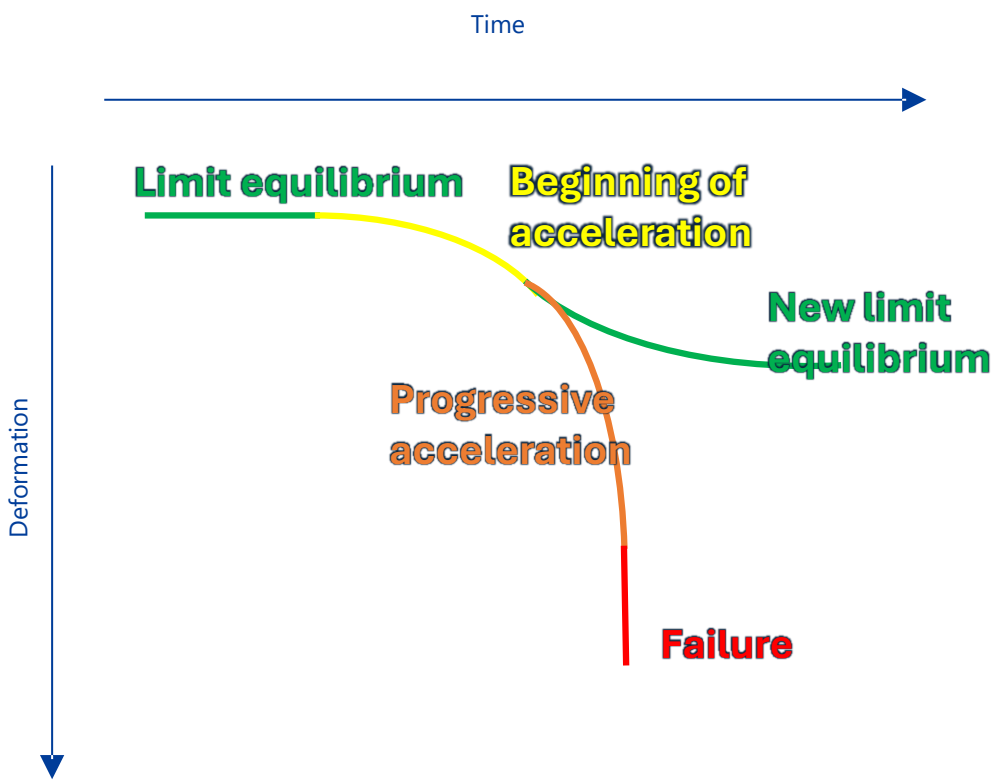
Selected time span

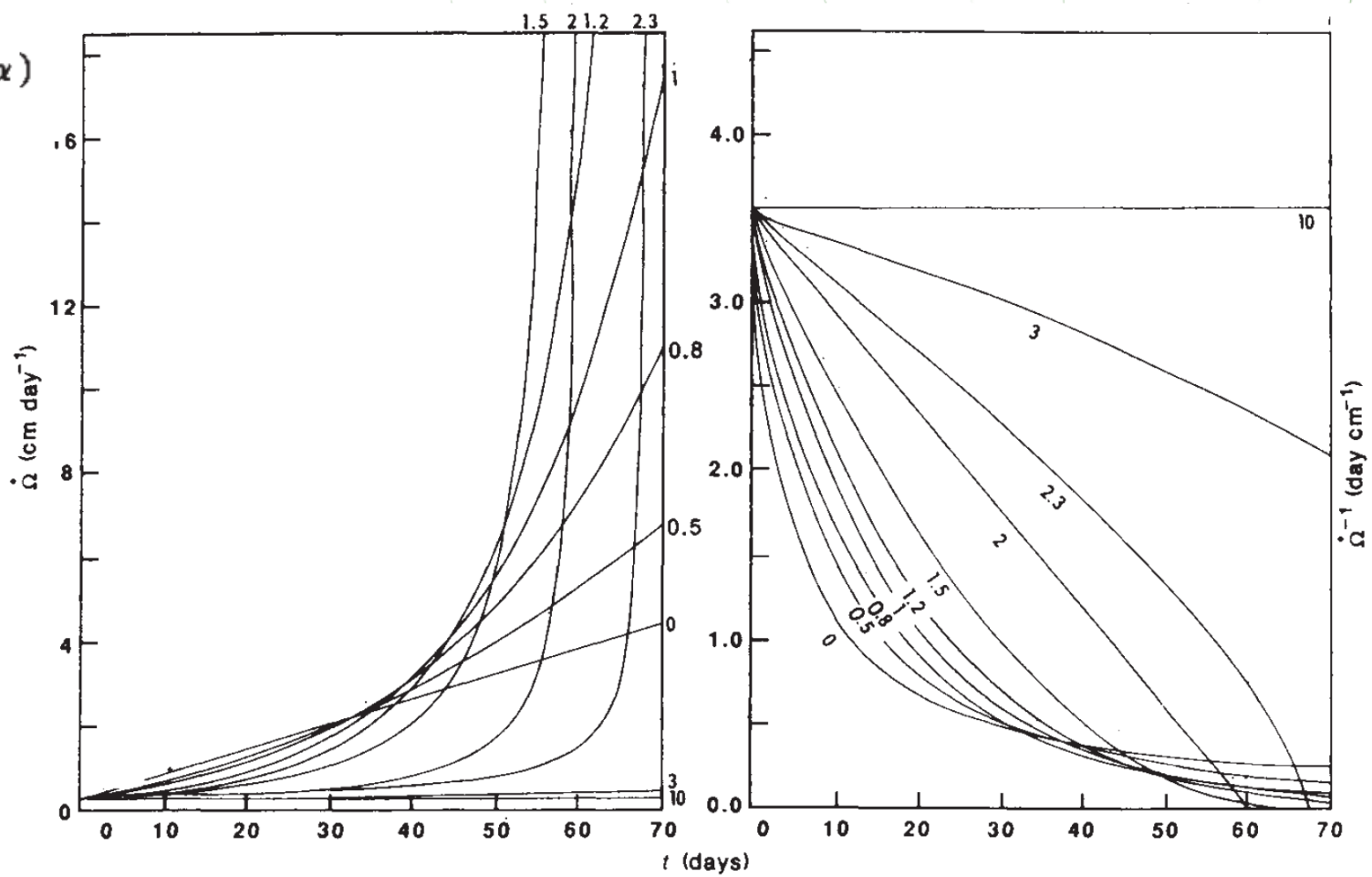


Non linear fitting

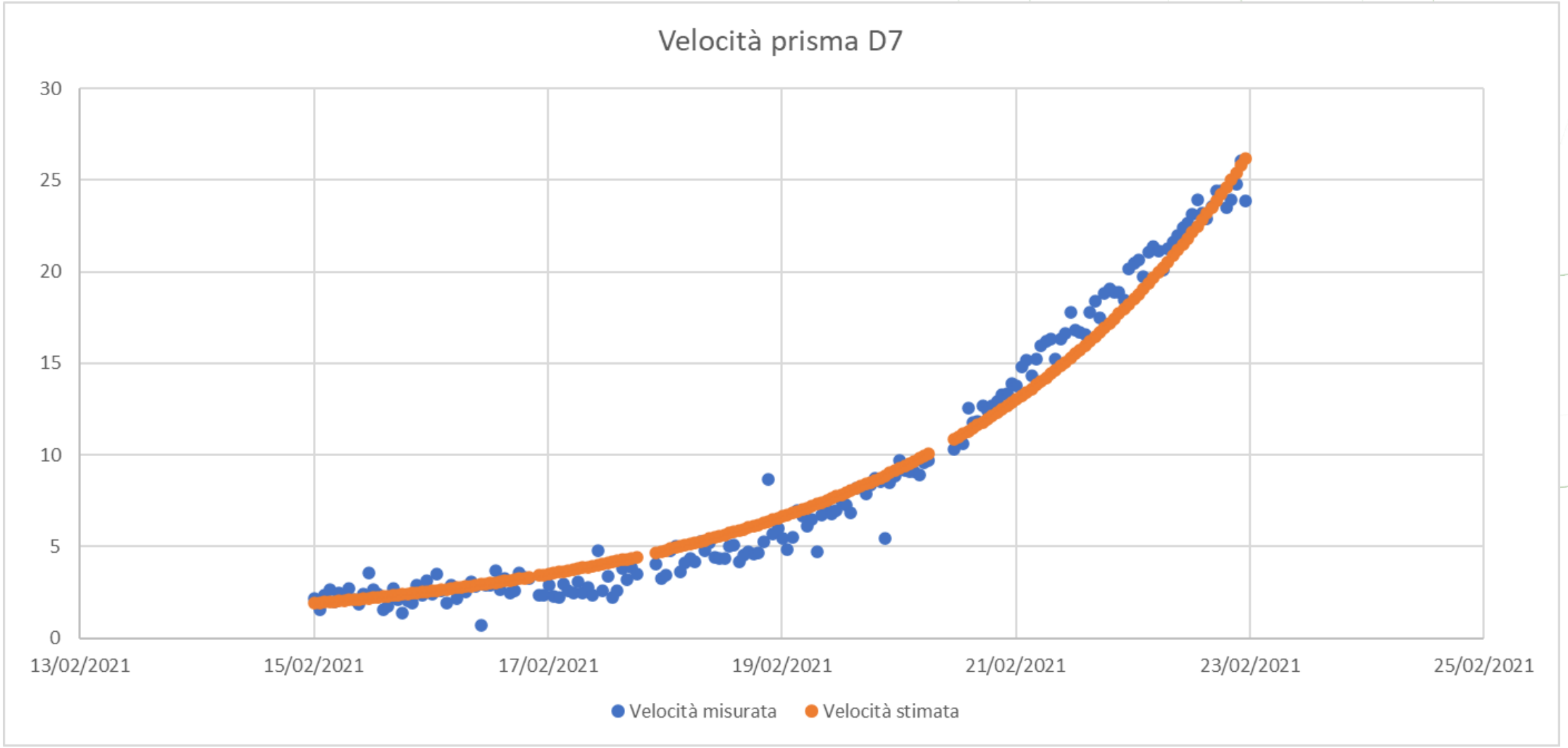
$$\dot{\Omega}^{-\alpha}\ddot{\Omega} - A = 0$$

$$\dot{\Omega} = [A(\alpha - 1)(t_f - t) + \dot{\Omega}_f^{1-\alpha}]^{1/(1-\alpha)}$$

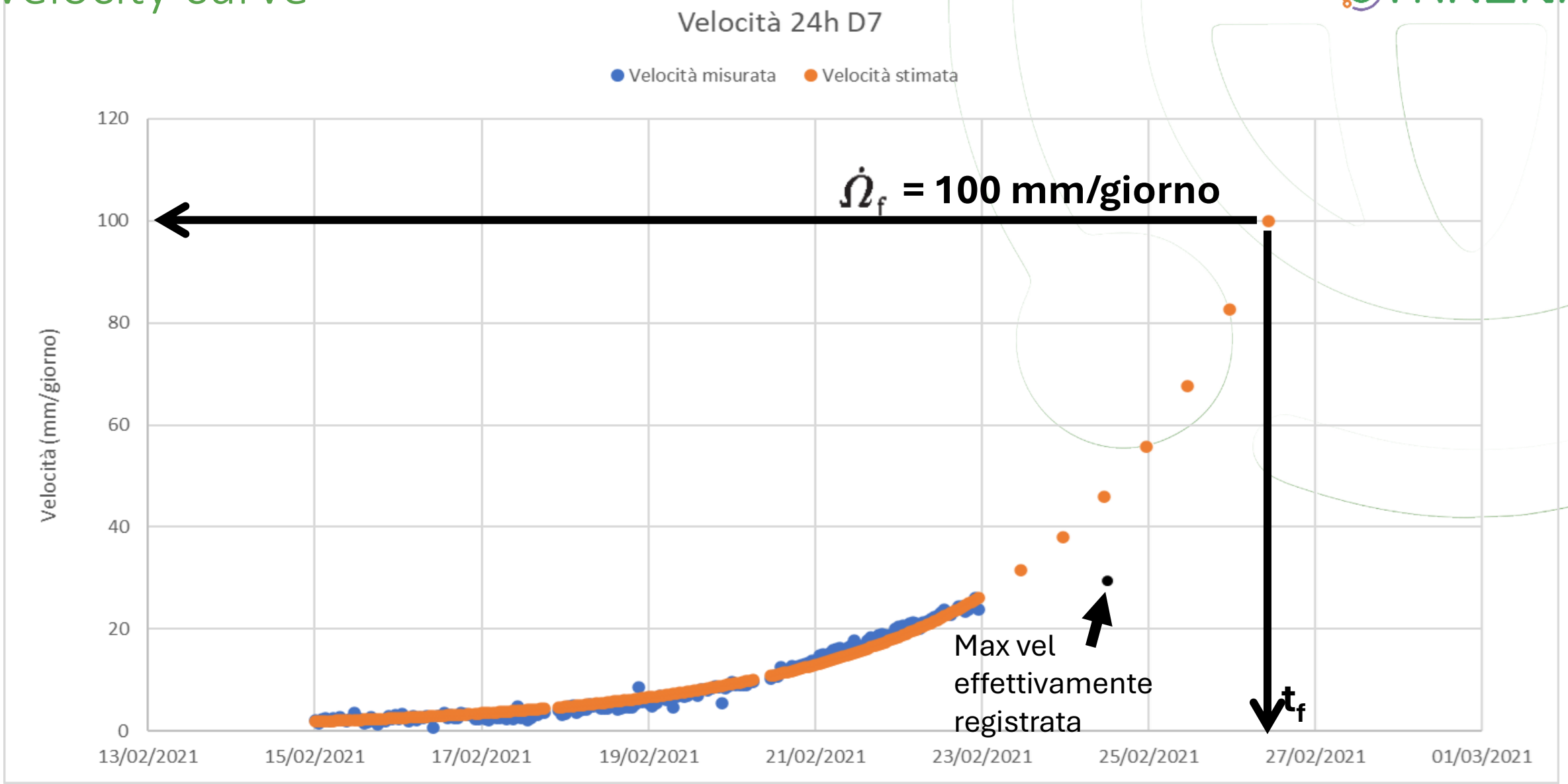




Non linear fitting



Velocity curve



Forecasting overview

Criterio per selezione soglia rossa ↓ **Criterio per selezione soglia arancione** ↓

	settore	Ore a failure da previsione in data 22/02	Vel +12h	Vel +24h	Vel +36h	Vel +48h	Vel +60h	Vel +72h	vel max effetivamente registrata	data vel max effettivamente registrata
'X5.csv'	1	106	18.1	22.1	27.1	33.4	41.4	51.5	17.4	24/2/21 20.13
'X7.csv'	1	104	20.9	25.3	30.7	37.4	45.8	56.2	18.3	24/2/21 12.18
'X8.csv'	1	106	19.6	23.8	25.9	35.4	43.4	53.6	15.9	24/2/21 12.23
'XN12.csv'	1	104	19.9	24.2	29.5	36.1	44.5	54.9	17.7	24/2/21 10.27
'XN13.csv'	1	105	20.8	25.1	30.4	37	45.2	55.5	18.9	23/2/21 14.26
'Y01.csv'	1	104	20.1	24.4	29.7	36.4	44.7	55.1	16.6	24/2/21 4.22
'Y02.csv'	1	102	21.4	26	31.6	38.6	47.2	58.1	18.9	23/2/21 15.21
'Y03.csv'	1	99	22.2	27	32.9	40.3	49.5	61.1	17.7	23/2/21 20.21
'Y04.csv'	1	100	20.7	25.3	31	38.3	47.4	57.9	17.8	24/2/21 12.24
'Y05.csv'	1	103	20.9	25.4	30.9	37.8	46.3	57	19.1	24/2/21 12.20
MEDIA SETTORE1		**103.30**	**20.46**	**24.86**	**29.97**	**37.07**	**45.54**	**56.09**	**17.84**	
'XN15.csv'	2	96	23.2	28.2	34.4	42.2	51.9	64	21.65	24/2/21 12.23
'XN16.csv'	2	94	24	29.3	35.8	43.8	53.9	66.5	20.95	24/2/21 12.23
'XN18.csv'	2	97	25.5	30.6	36.9	44.6	54.1	65.8	22.94	23/2/21 18.15
'Y06.csv'	2	103	23	27.6	33.2	40.2	48.6	59.1	20.48	24/2/21 10.26
MEDIA SETTORE2		**97.50**	**23.93**	**28.93**	**35.08**	**42.70**	**52.13**	**63.85**	**21.51**	
'CL5BIS.csv'	3	106	22.6	27.1	33.1	39.2	47.3	57.2	22.55	24/2/21 12.11
'D5.csv'	3	97	24.1	29.1	35.7	43	52.4	64.3	22.92	24/2/21 20.13
'D6.csv'	3	107	23.5	28.1	34.2	40.2	48.2	57.9	24.65	24/2/21 12.15
'D7.csv'	3	83	31.5	37.9	46.2	55.6	67.7	82.6	29.35	24/2/21 12.12
'XN14.csv'	3	93	26.3	31.7	39.8	46.4	56.4	68.8	25.80	24/2/21 12.20
'Y09.csv'	3	83	32.2	38.8	46.9	56.6	68.5	83.1	27.90	24/2/21 5.12
MEDIA SETTORE3		**94.83**	**26.70**	**32.12**	**39.32**	**46.83**	**56.75**	**68.98**	**25.53**	

Proposed thresholds

Stazione totale			
	settore 1	settore 2	settore 3
Giallo	10	12.5	15
Arancione	18	22	26
Rosso	30	35	40

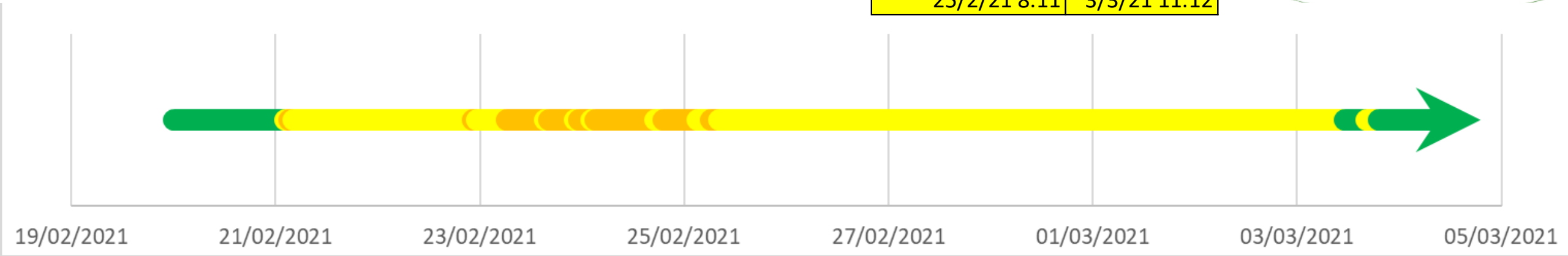
Note:

- ai prismi all'esterno del perimetro di frana si associano le soglie più basse (settore 1)
- le soglie relative al livello giallo sono state calibrate sulla base del rumore della serie di dati

Timeline D7

Stazione totale			
	settore 1	settore 2	settore 3
Giallo	10	12.5	15
Arancione	18	22	26
Rosso	30	35	40

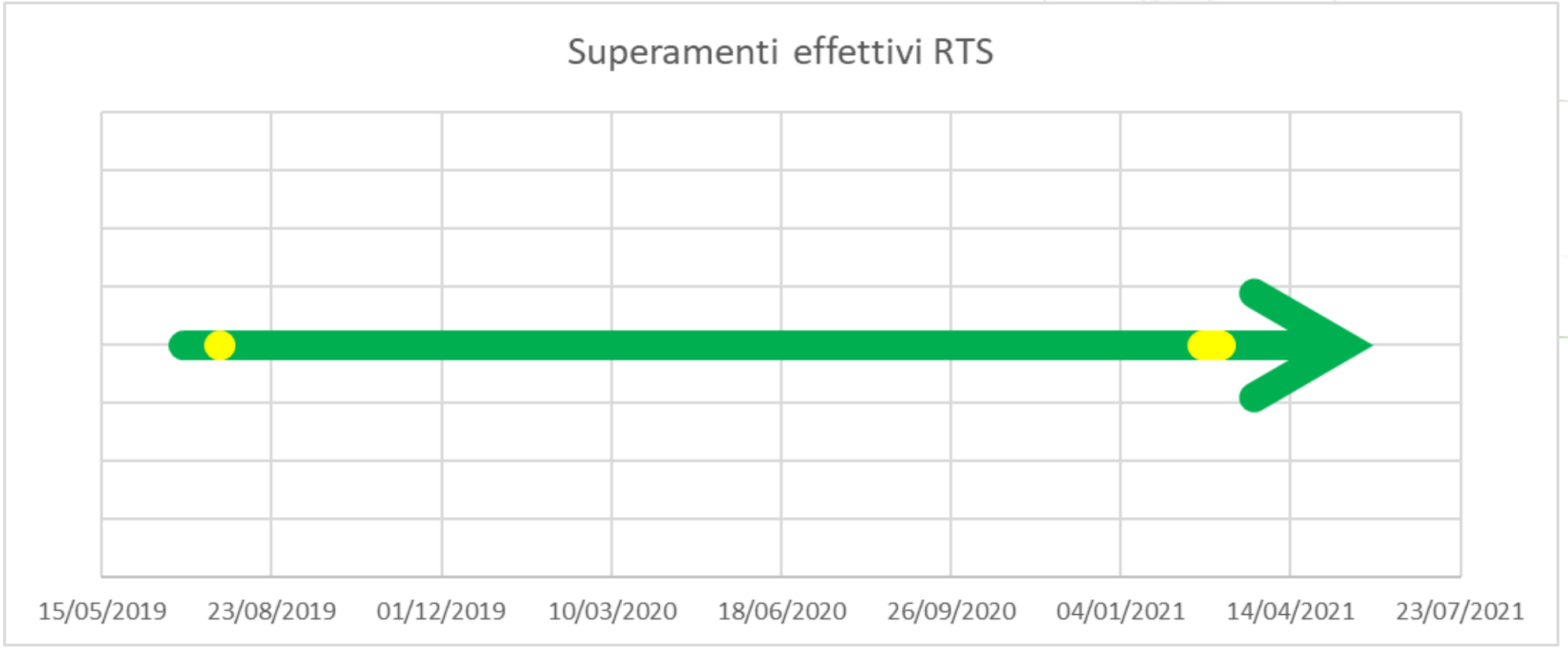
Entrata	Uscita
21/2/21 4.10	22/2/21 22.13
22/2/21 22.13	22/2/21 23.11
22/2/21 23.11	23/2/21 6.10
23/2/21 6.10	23/2/21 15.11
23/2/21 15.11	23/2/21 16.10
23/2/21 16.10	23/2/21 22.10
23/2/21 22.10	23/2/21 23.11
23/2/21 23.11	24/2/21 2.11
24/2/21 2.11	24/2/21 3.10
24/2/21 3.10	24/2/21 17.11
24/2/21 17.11	24/2/21 19.10
24/2/21 19.10	25/2/21 3.10
25/2/21 3.10	25/2/21 6.10
25/2/21 6.10	25/2/21 8.11
25/2/21 8.11	3/3/21 11.12



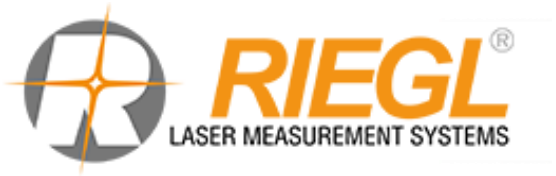
Criticality activation criteria

1) almeno il 50% dei prismi di ciascun settore > soglia
2) almeno 2 settori su 3

Entrata	Uscita
22/7/19 18.24	22/7/19 19.16
21/2/21 9.23	21/2/21 15.14
21/2/21 18.17	2/3/21 1.19
2/3/21 6.17	2/3/21 10.20
2/3/21 14.21	2/3/21 16.23
3/3/21 8.21	3/3/21 15.18

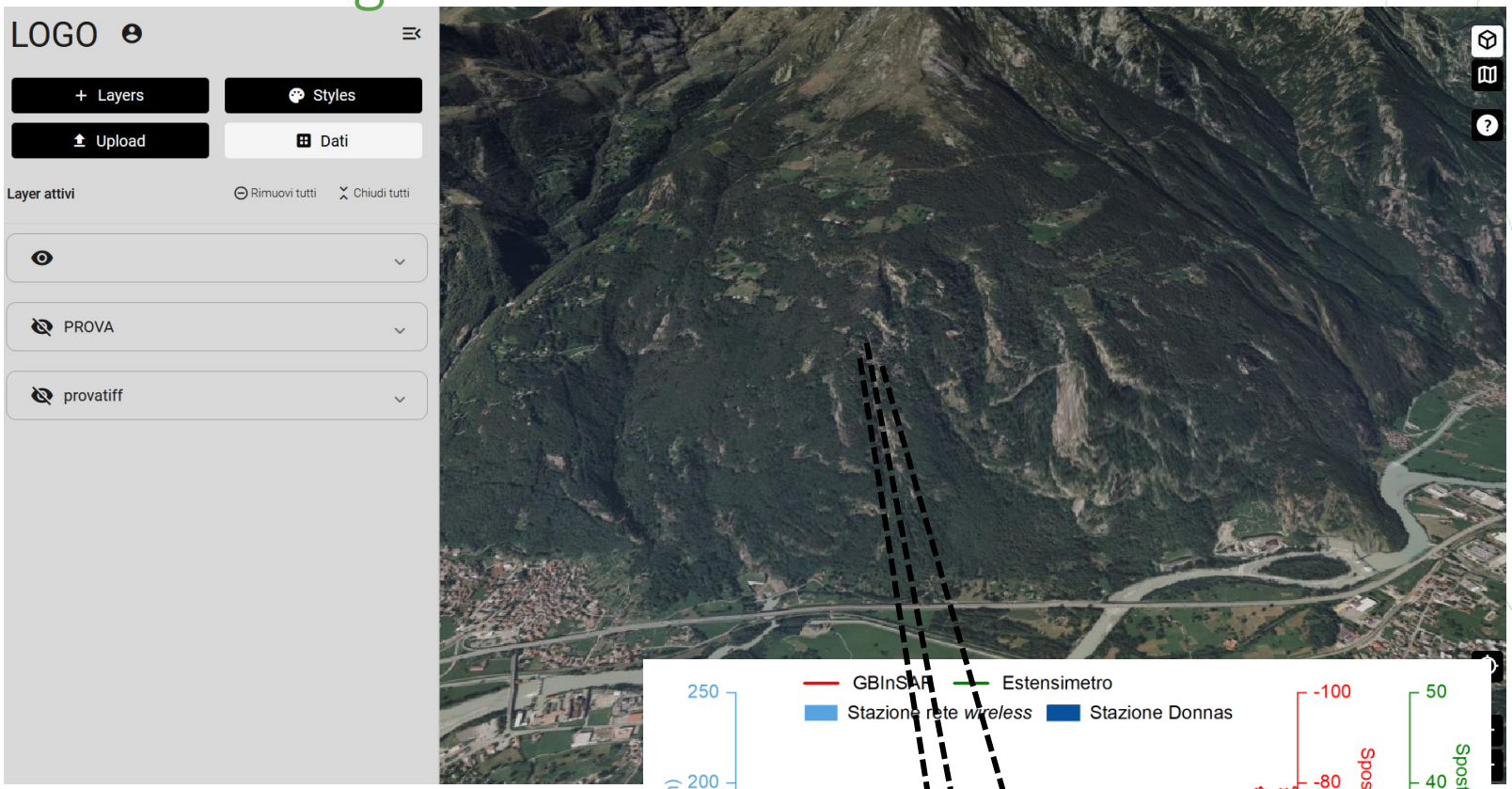


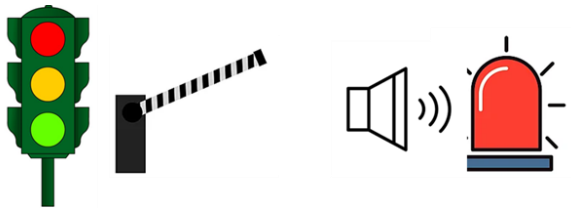
Monitoring and early warning platforms

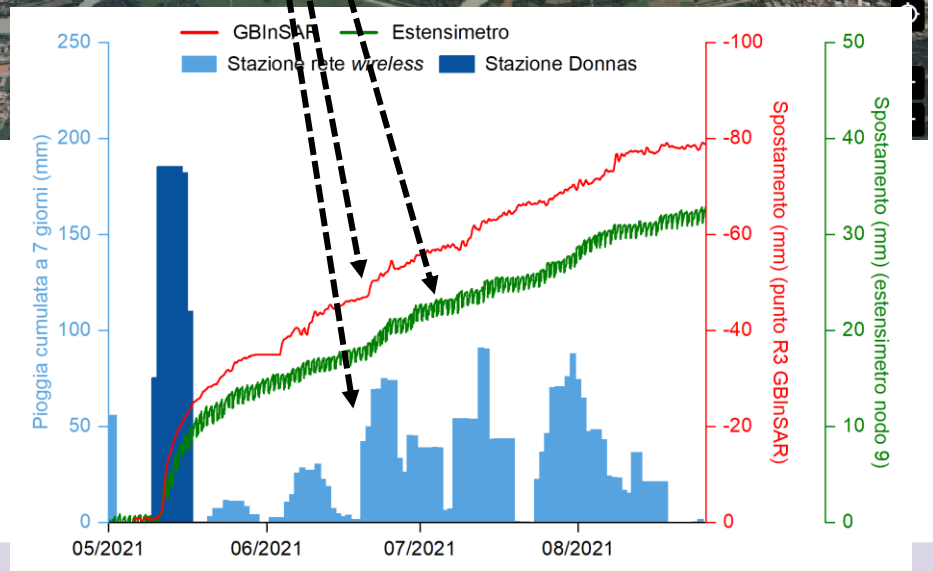


Scientific Instrumentation

Data Sharing and EW Platform

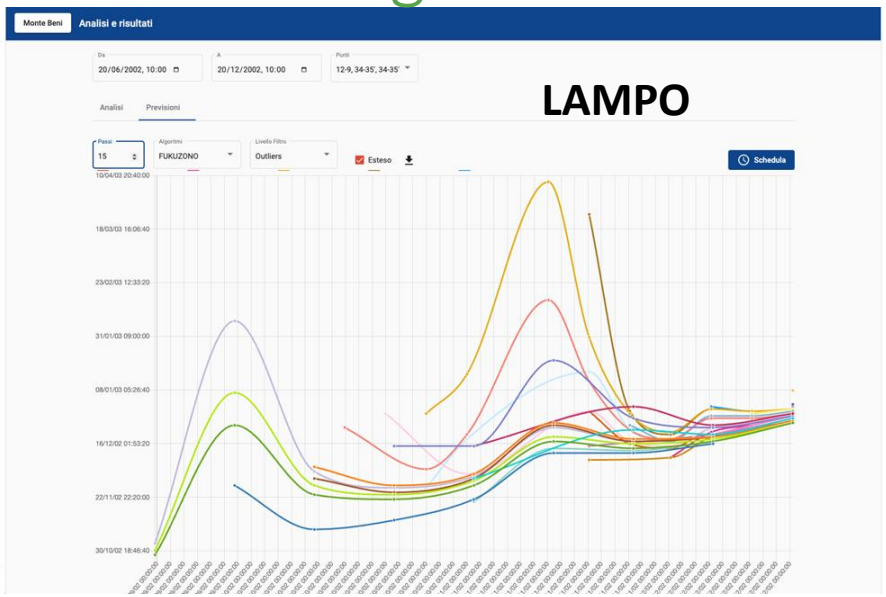






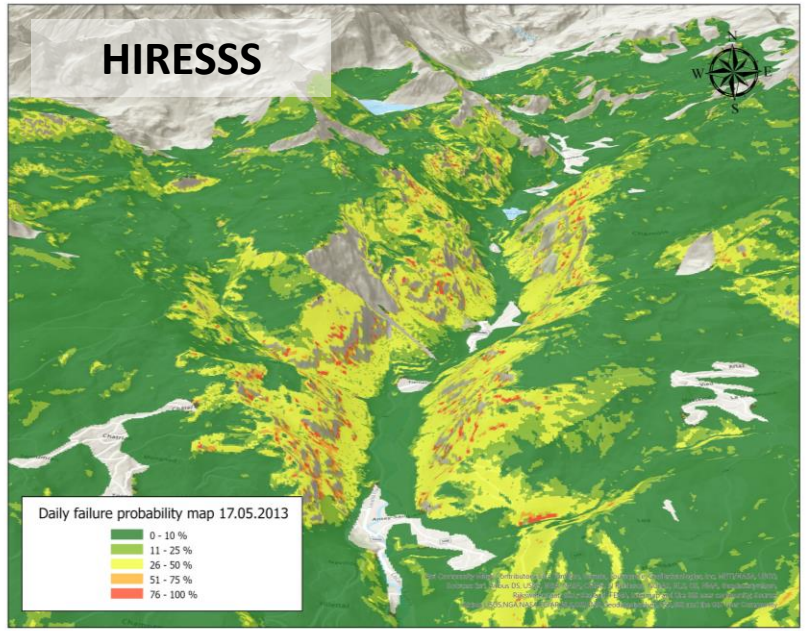
- Display and share planimetric and 3D data
- Real-time monitoring data
- Customised diagrams
- Dashboard for emergency management
- Tools for quickly defining risk scenarios
- Real-time forecasting algorithms
- Definition of alarm thresholds
- Threshold exceeding notifications

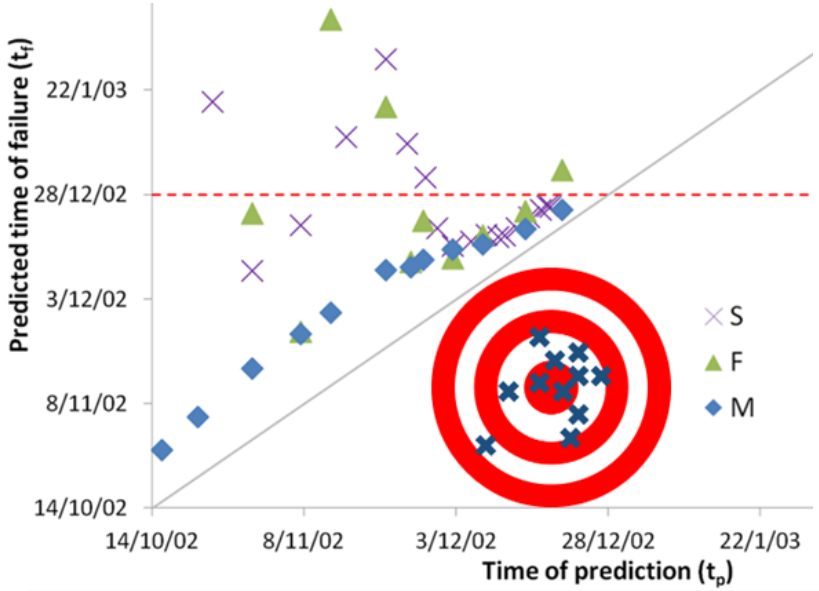
Forecasting Models

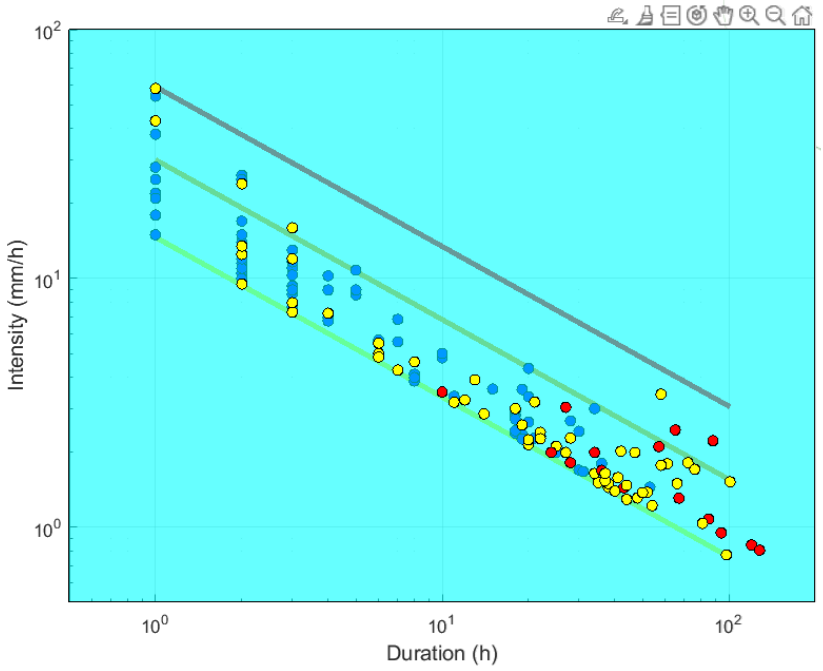


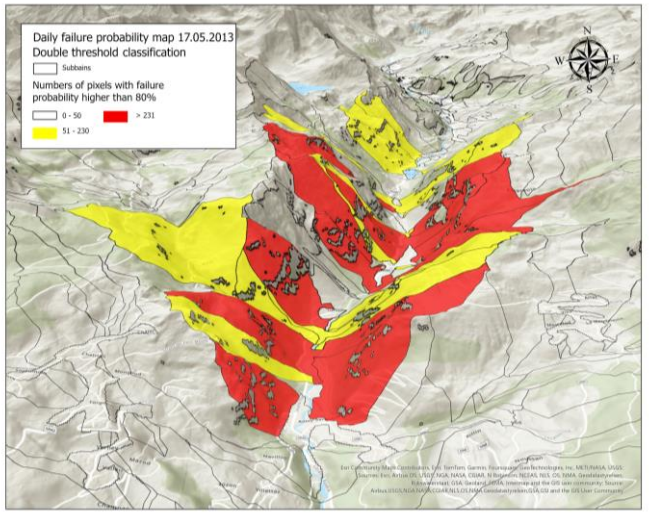
PROTEZIONE CIVILE

MACUMBA

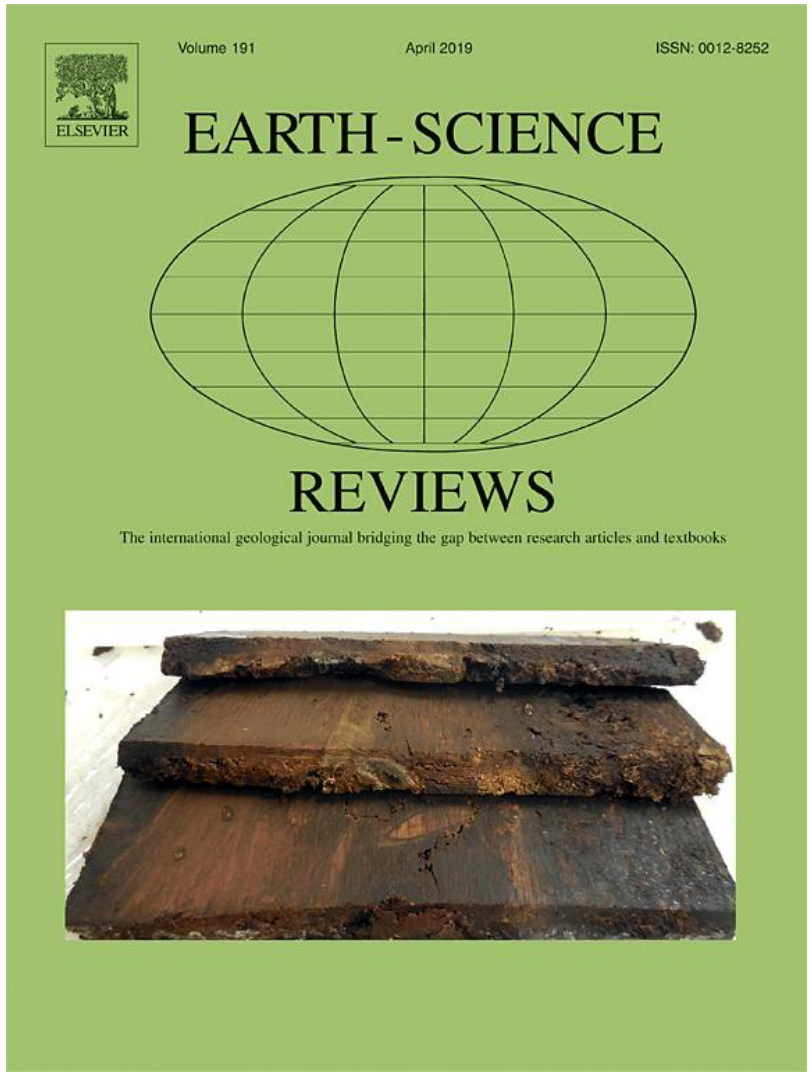








References



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