Landslide forecasting and warning at slope scale using displacement monitoring

- Emanuele Intrieri

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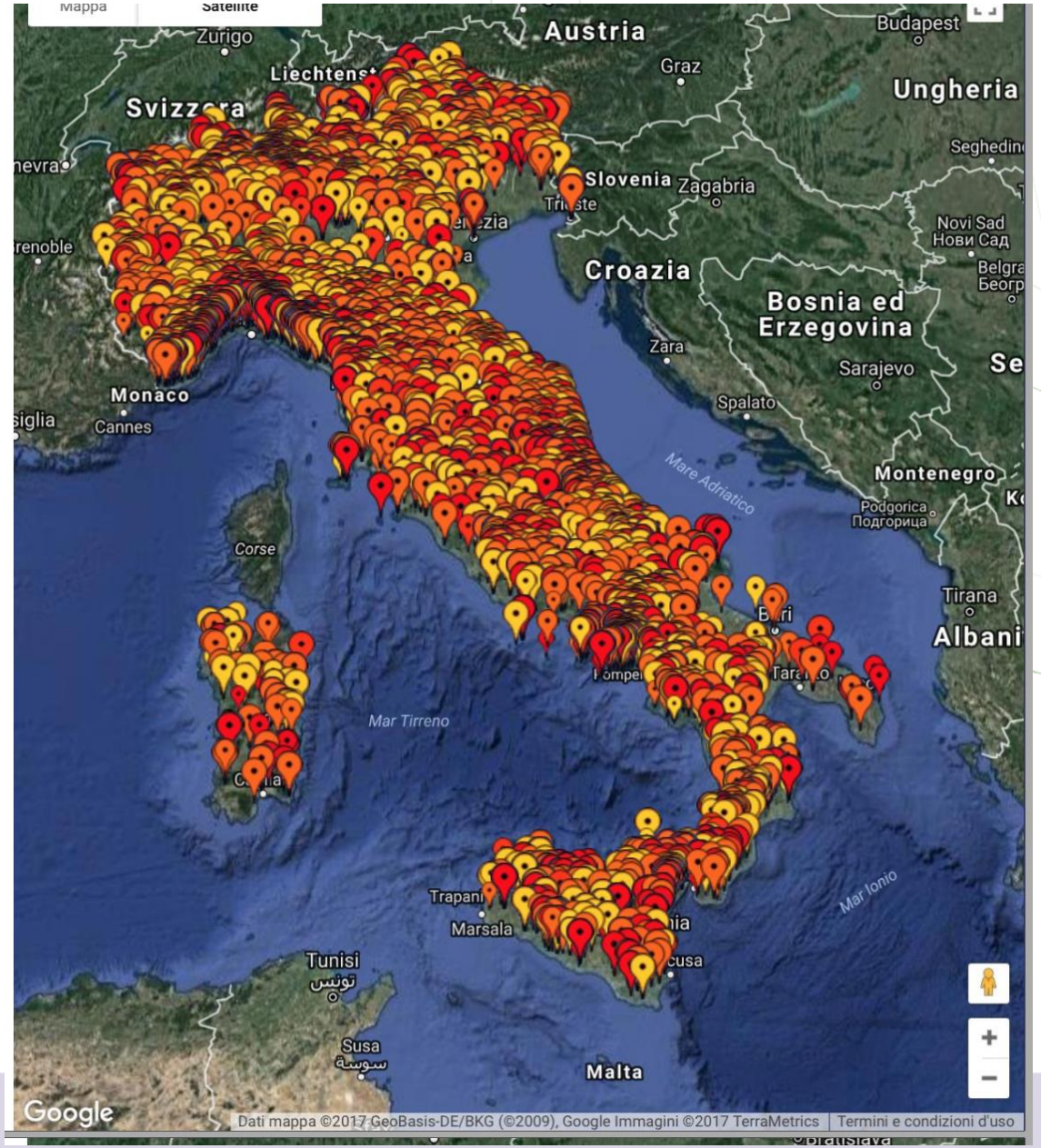
Ministero dell'Università e della Ricerca
Italiadomani

Landslide risk in Italy

11.900+ landslides (2011-2017)

1.700+ per year

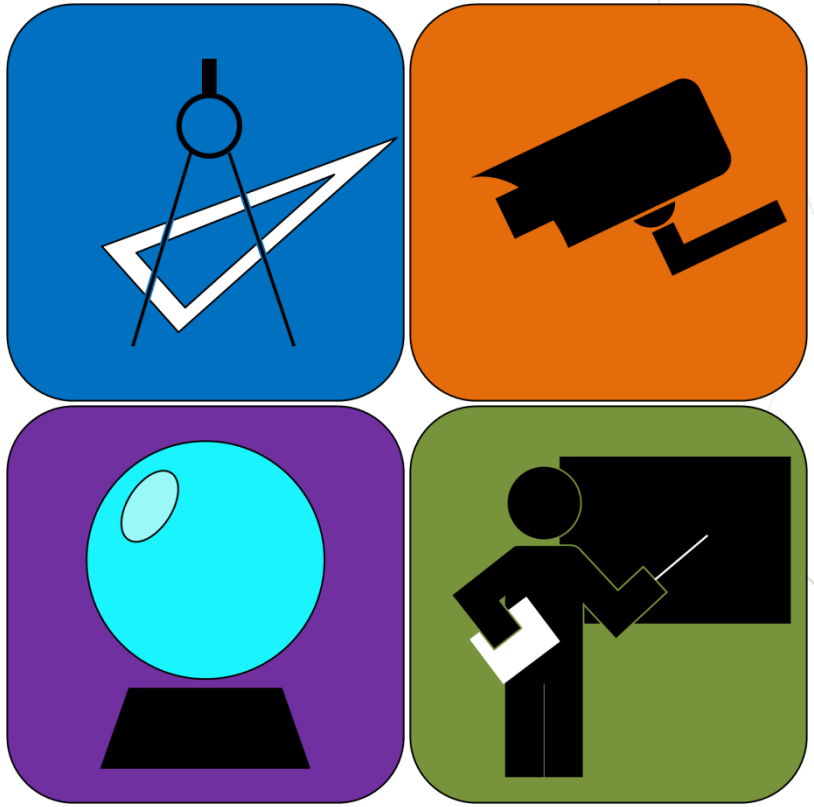
5 per day



Structural interventions

Early Warning System

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

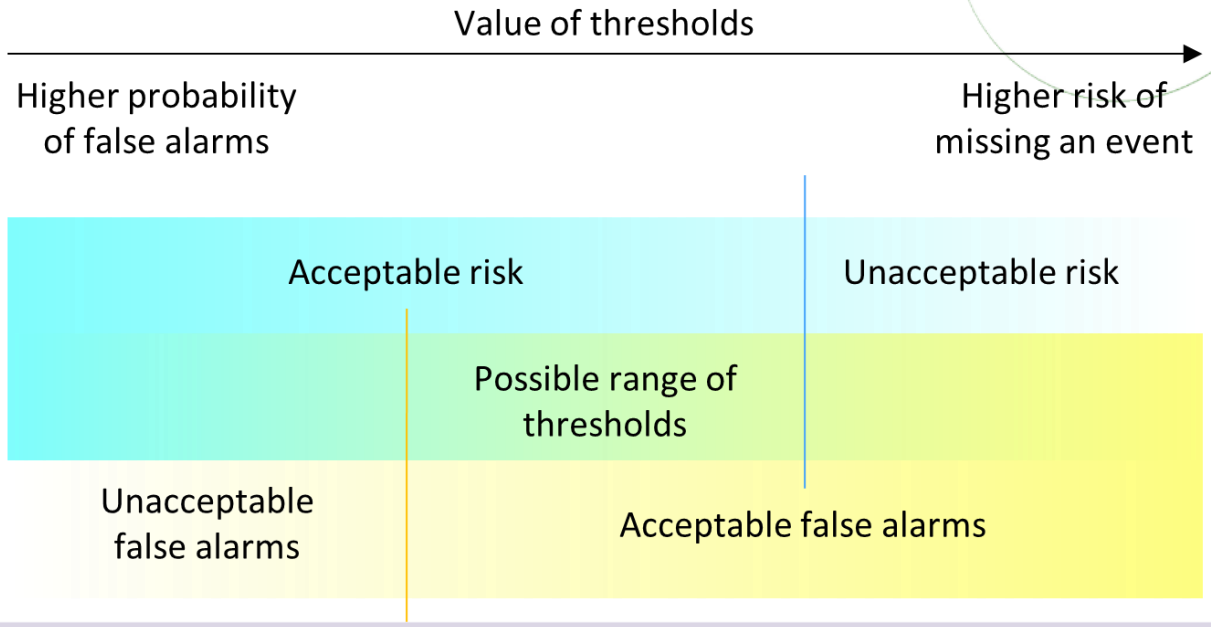
Intrieri et al. (2013)

Forecast

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

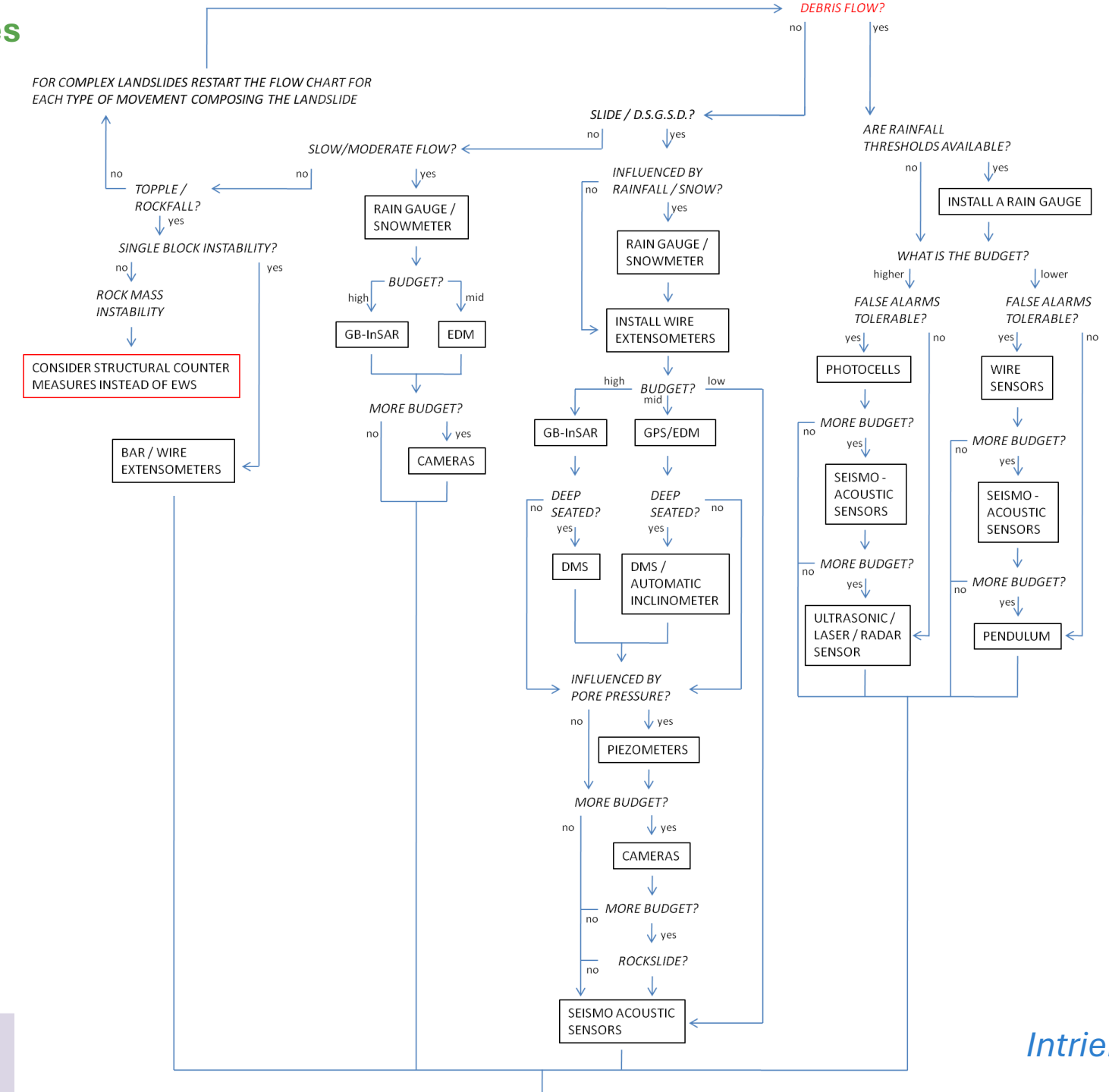
Principles

- 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 (social pact



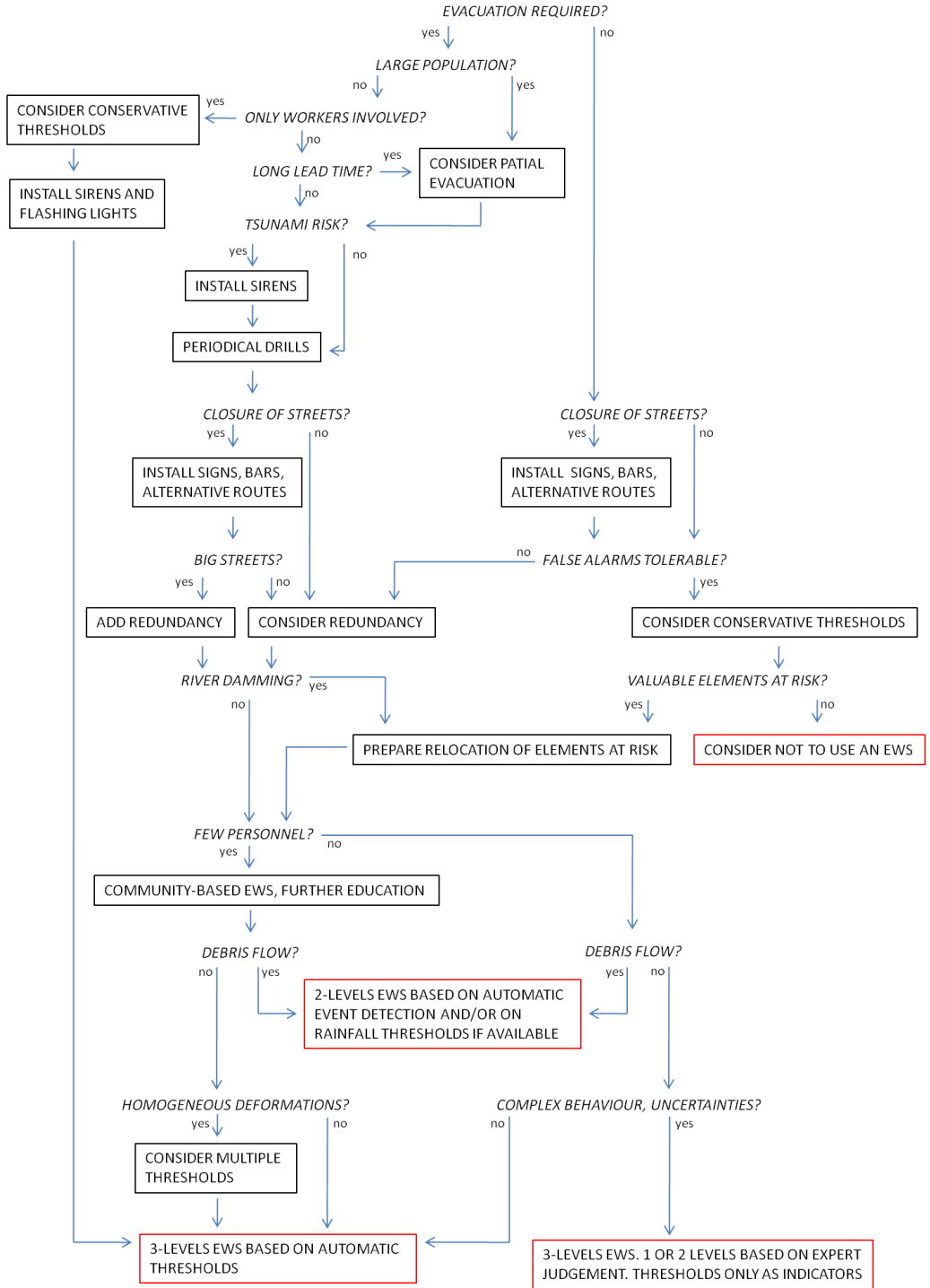
Nadim & Intrieri (2011)

Instrumention choices



Intrieri et al. (2013)

Organization choices

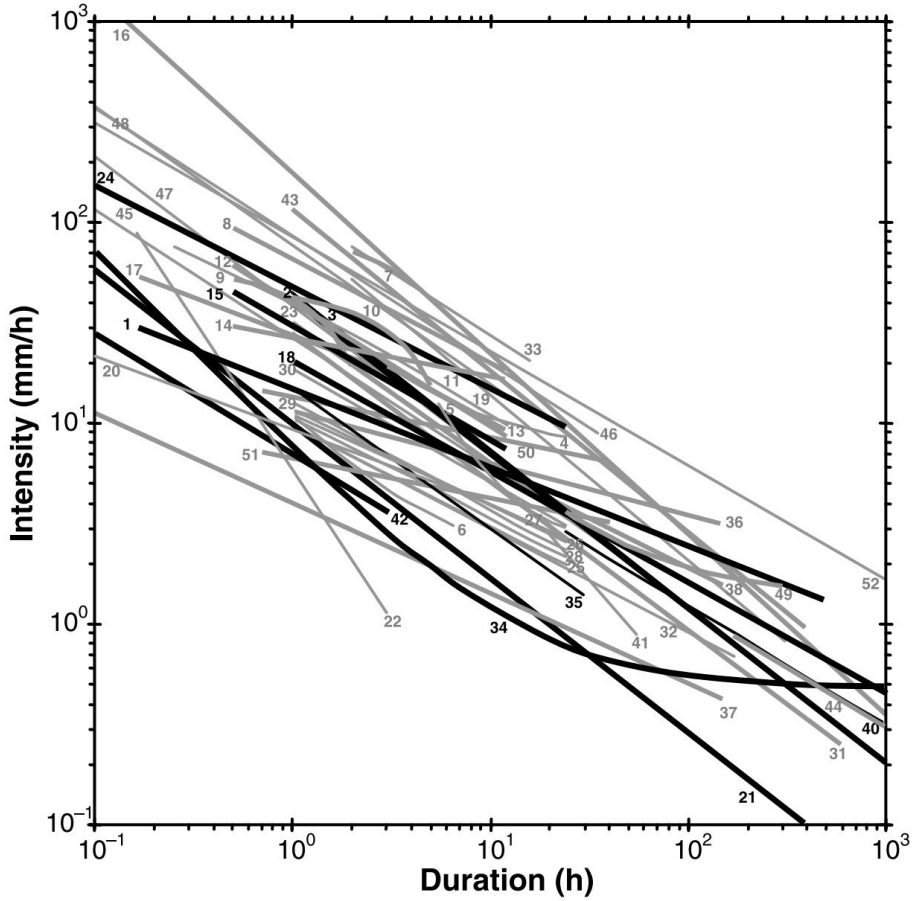


Intrieri et al. (2013)

Forecasting methods

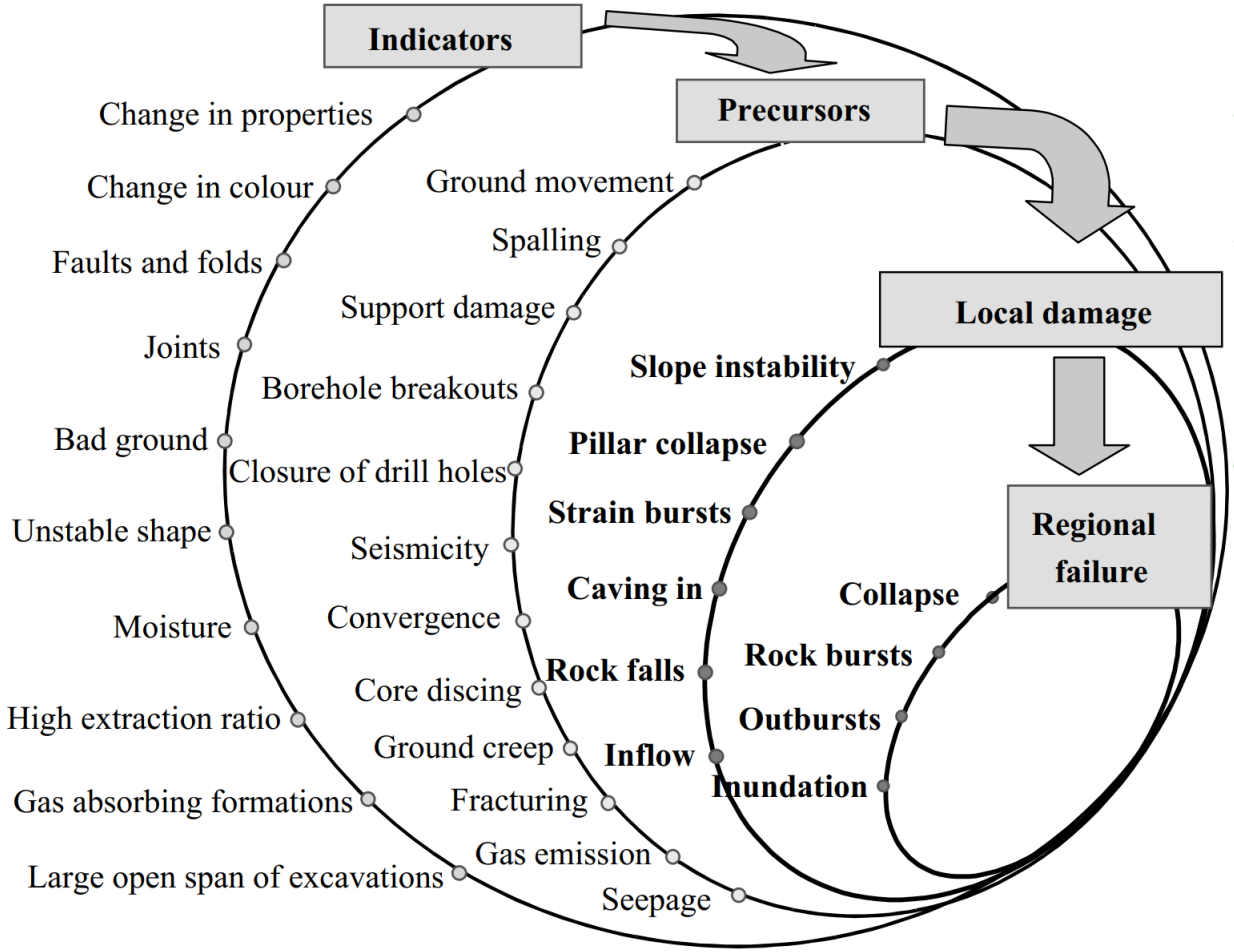
Forecasting methods based on rainfall

- Based on an empirical a posteriori approach.
- Typically applied at basin or regional scale.
- Likely false and missed alarms.



Guzzetti et al. (2007)

Other forecasting methods (acoustic emissions, rockfall frequency, porewater pressure)



Szwedzicki, 2003

Forecasting methods based kinematic parameters

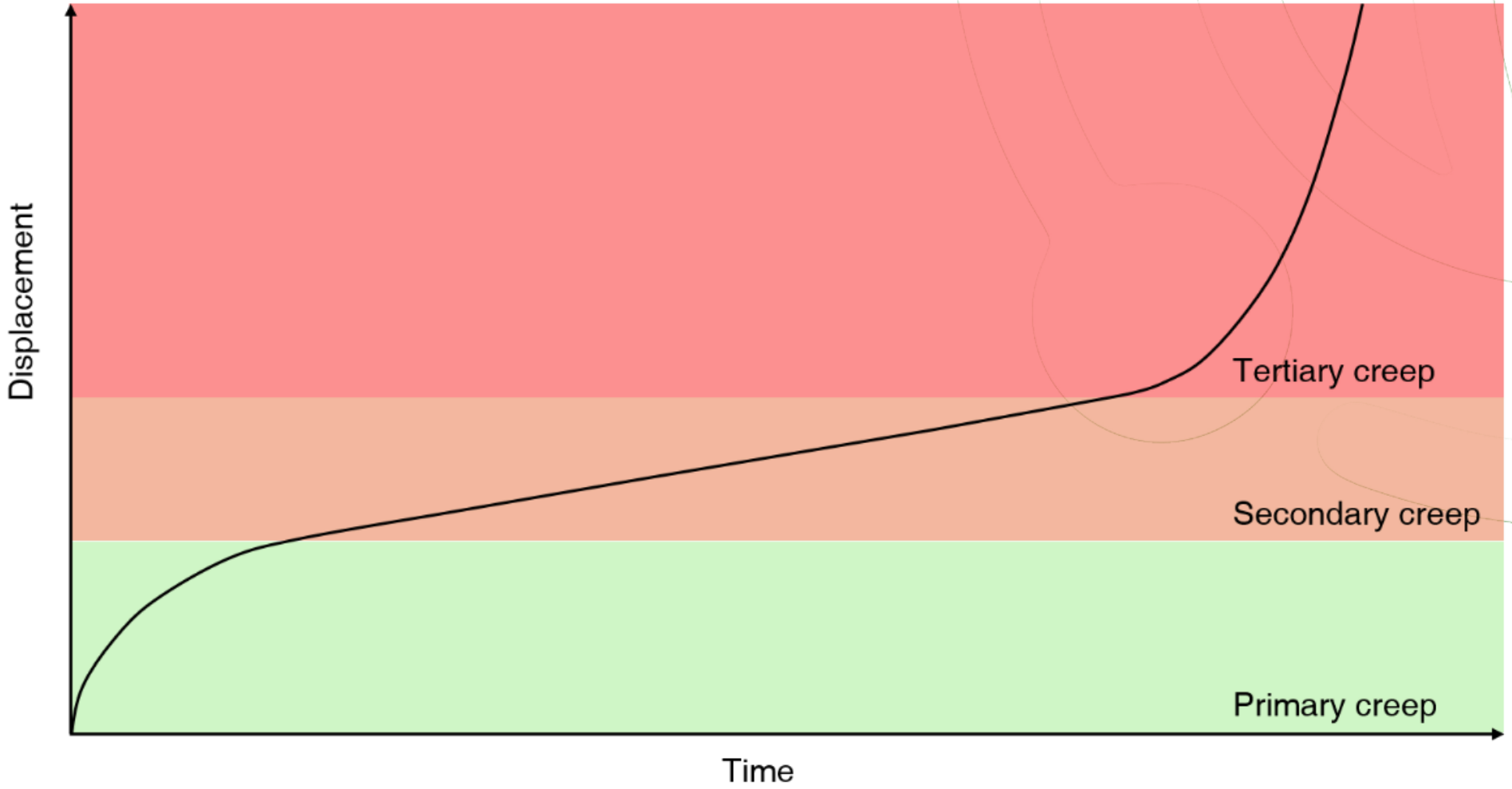
- Empirical methods
- Semi-empirical methods

Other methods are often associated with landslide prediction:

- Numerical methods
- Methods for the definition of thresholds

Empirical methods

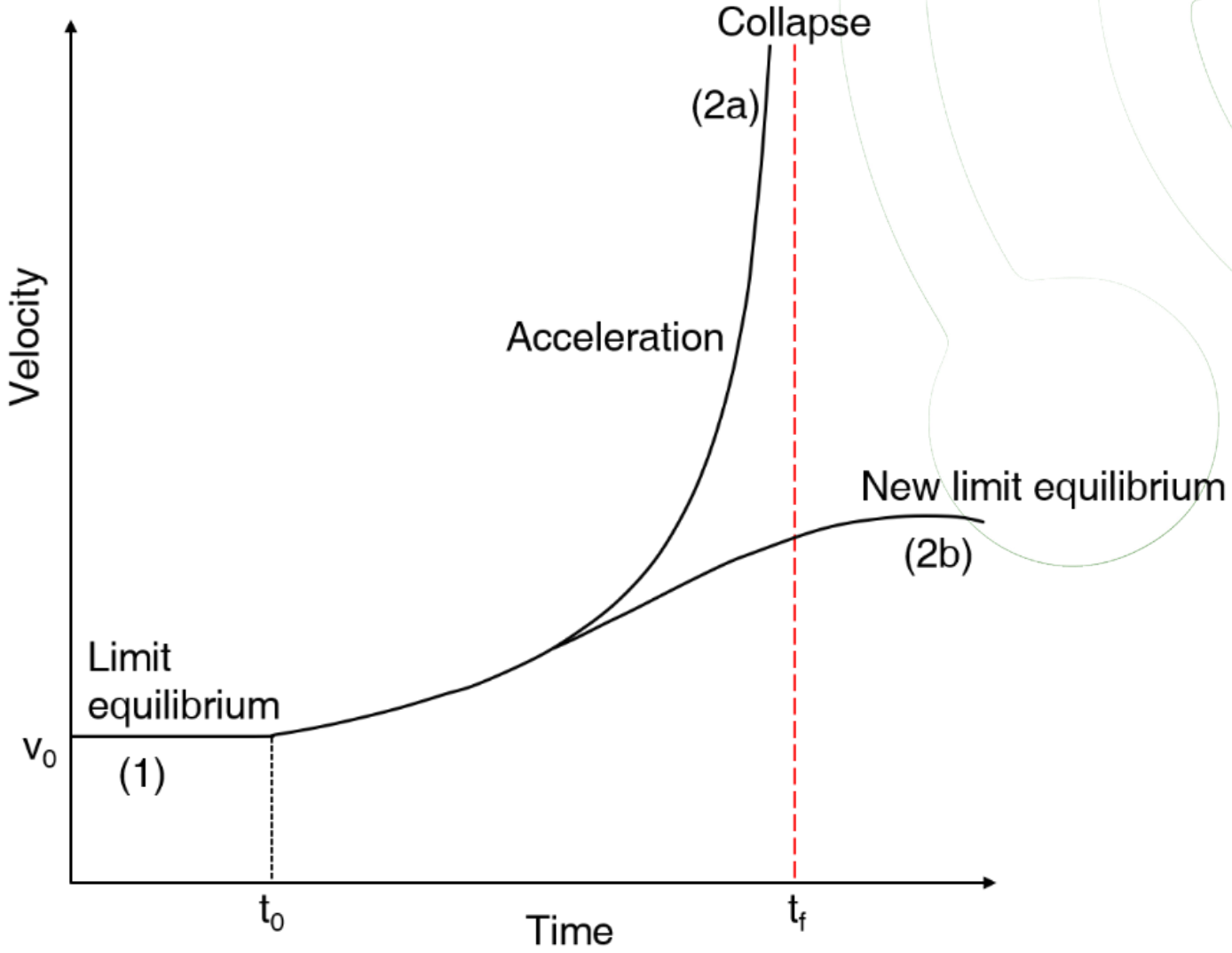
Creep


Displacement
Time
Tertiary creep
Secondary creep
Primary creep

The failure process

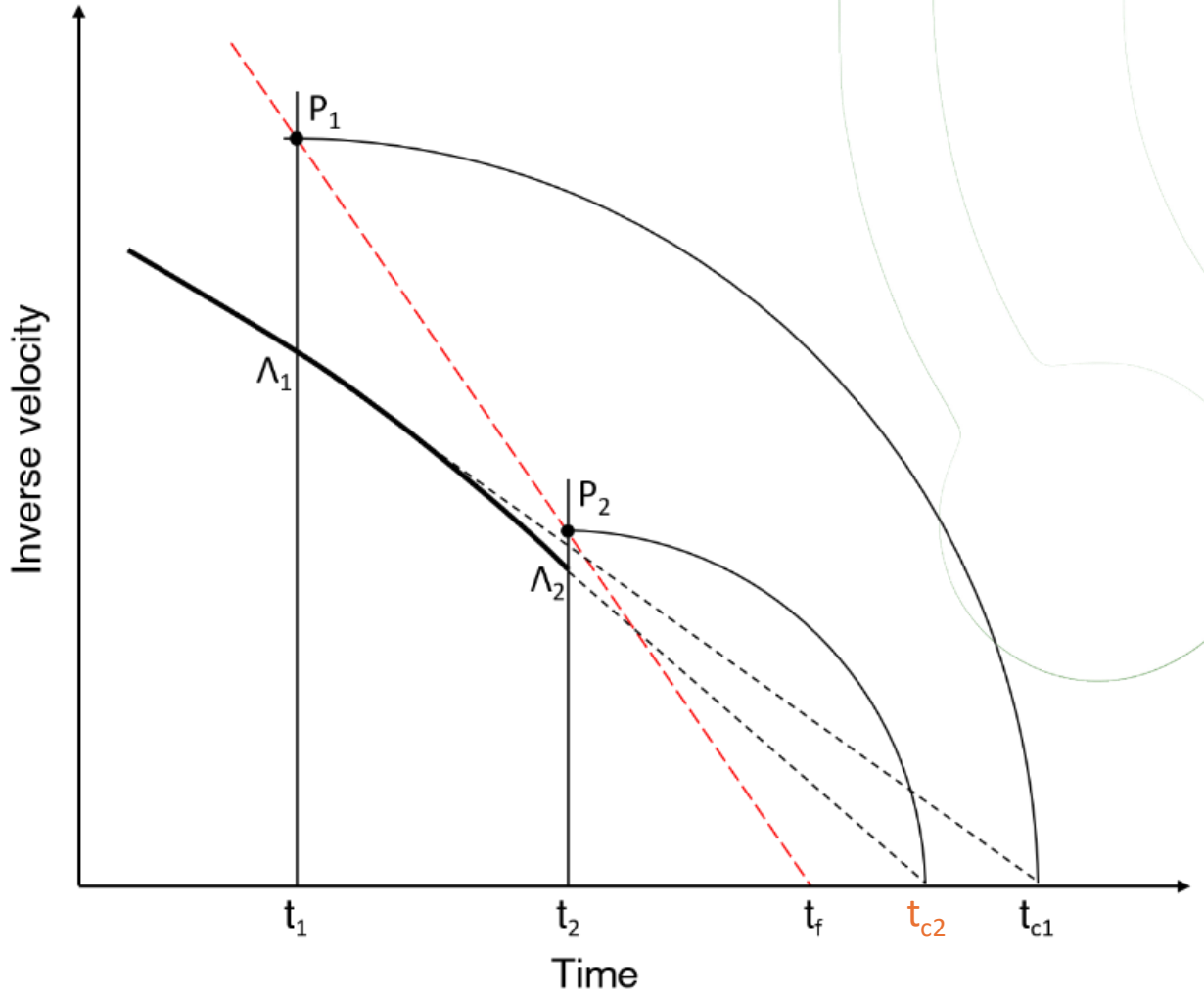
- Models and experiments on rock specimens that display brittle creep behavior have revealed the existence of power-law relationships between the time of failure and the applied stress, where a number of constants that depend on the rock properties; ambient conditions also play a role, including the strength of the rock, temperature, water saturation and chemical-corrosion processes.
- When scaling up to a more complex system (such as a landslide), tertiary creep still typically assumes the shape of a power law.
- The increasing length of the propagating cracks increases the stress intensity at the tip of the crack itself and, therefore, the velocity of further crack propagation. Such a self-feeding process creates the striking non-linearity of tertiary creep.

Fukuzono (1985)



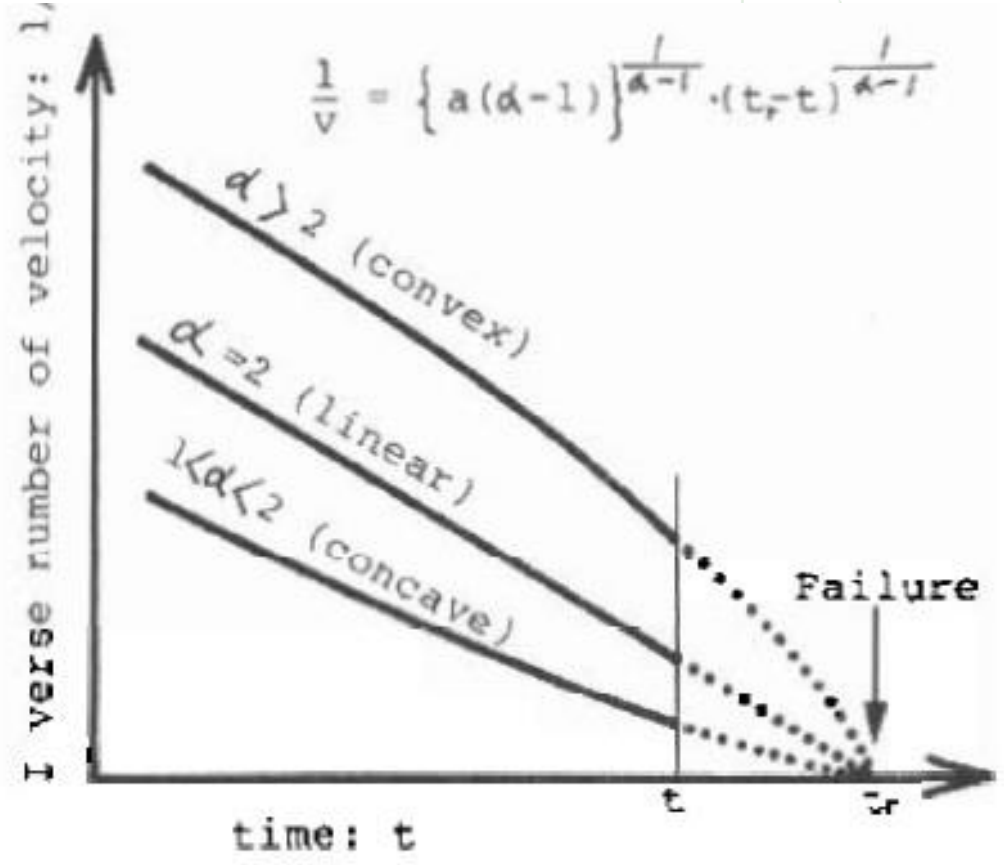
Fukuzono (1985)

$1/v = \Lambda$



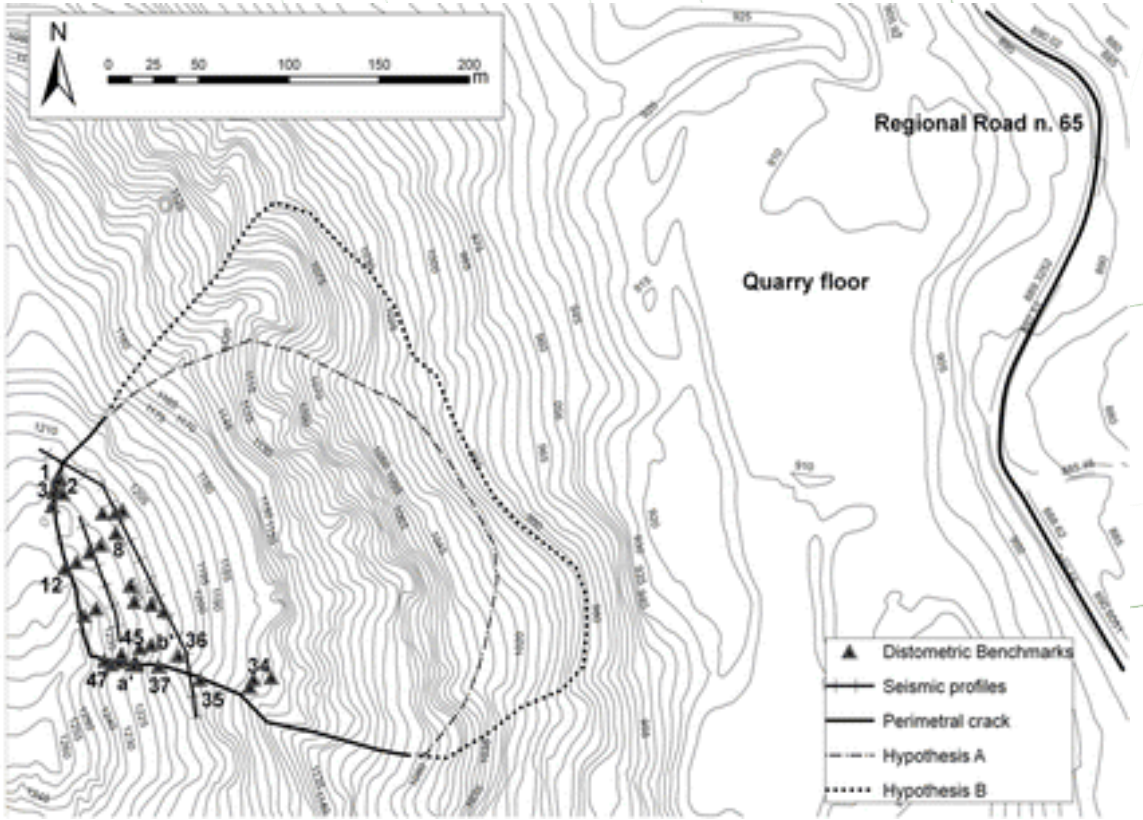
$$t_f = \frac{t_2\,(\Lambda_1) - t_1\,(\Lambda_2)}{\Lambda_1 - \Lambda_2}$$

Fukuzono (1985)



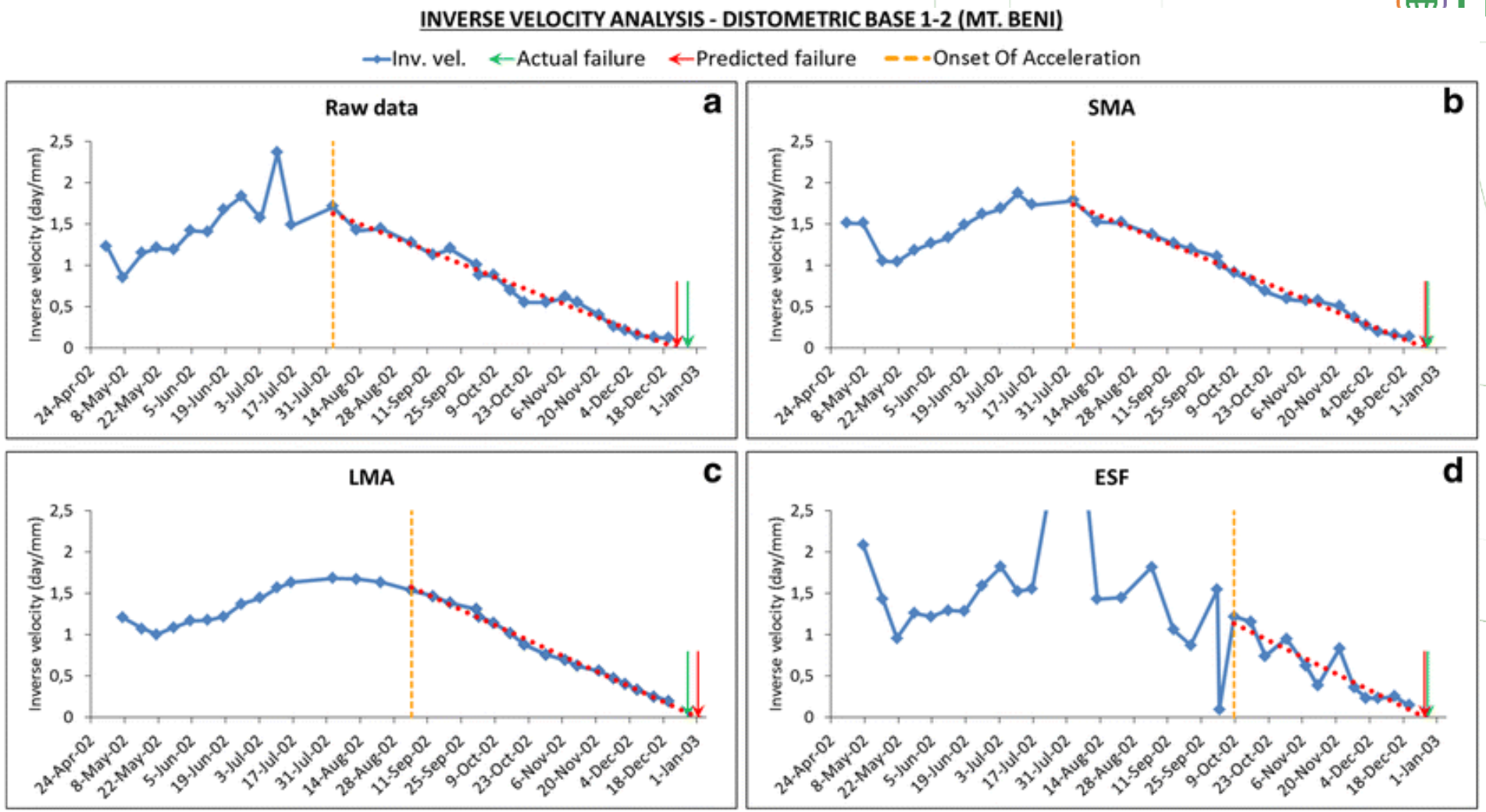
$$\Lambda \equiv 1/v = [A\,(\alpha - 1)]^{1/(\alpha-1)}\,(t_f - t)^{1/(\alpha-1)}$$

Mt. Beni



Gigli et al., 2010

Mt. Beni



Carlà et al., 2017

LMA and SMA

$$\bar{v}_t = \frac{v_t + v_{t-1} + \cdots + v_{t-(n-1)}}{n}$$

ESF

$$\bar{v}_t = \beta \cdot v_t + (1 - \beta) \cdot \bar{v}_{t-1}$$

Mt. Toc (Vajont)

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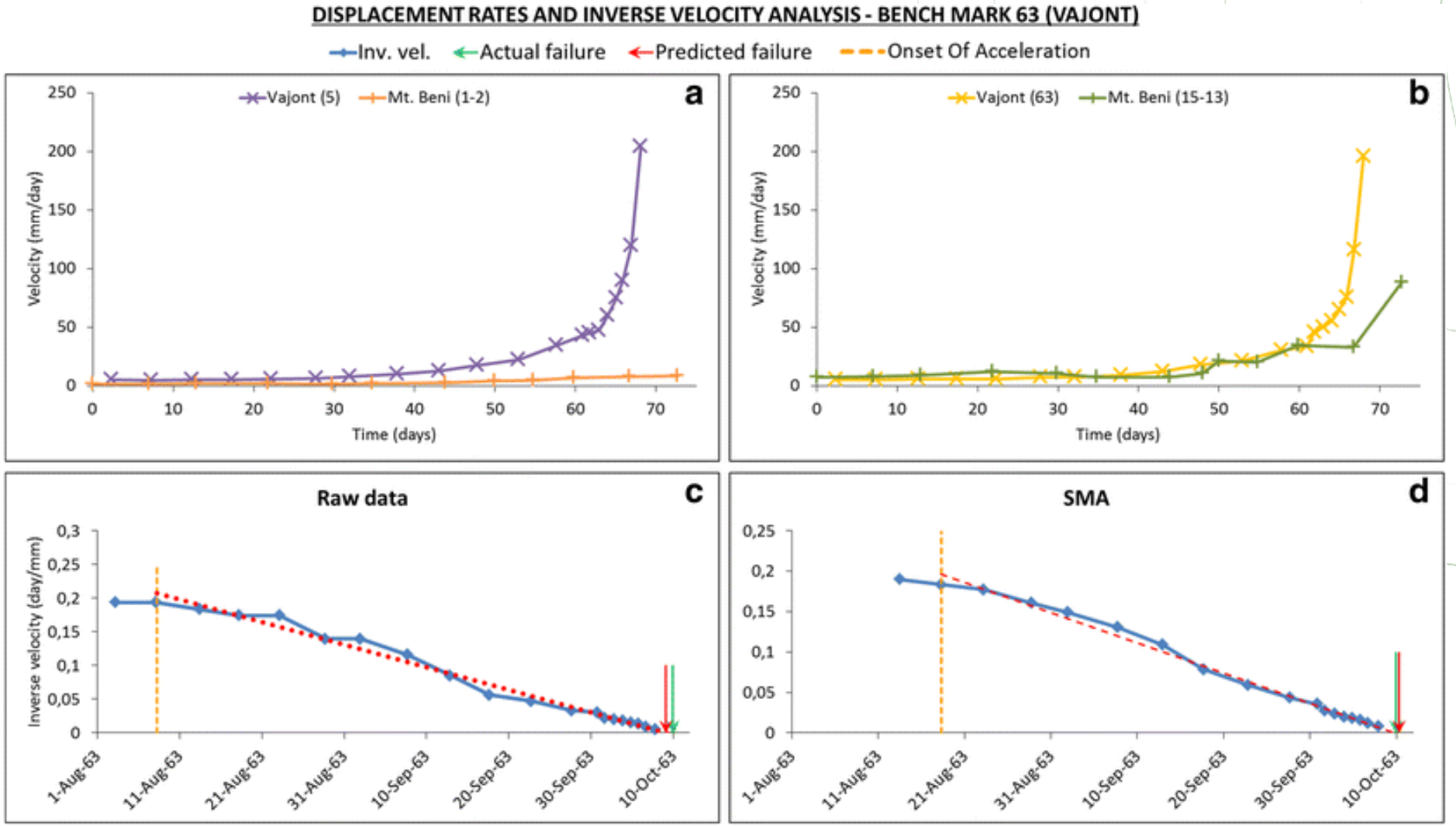
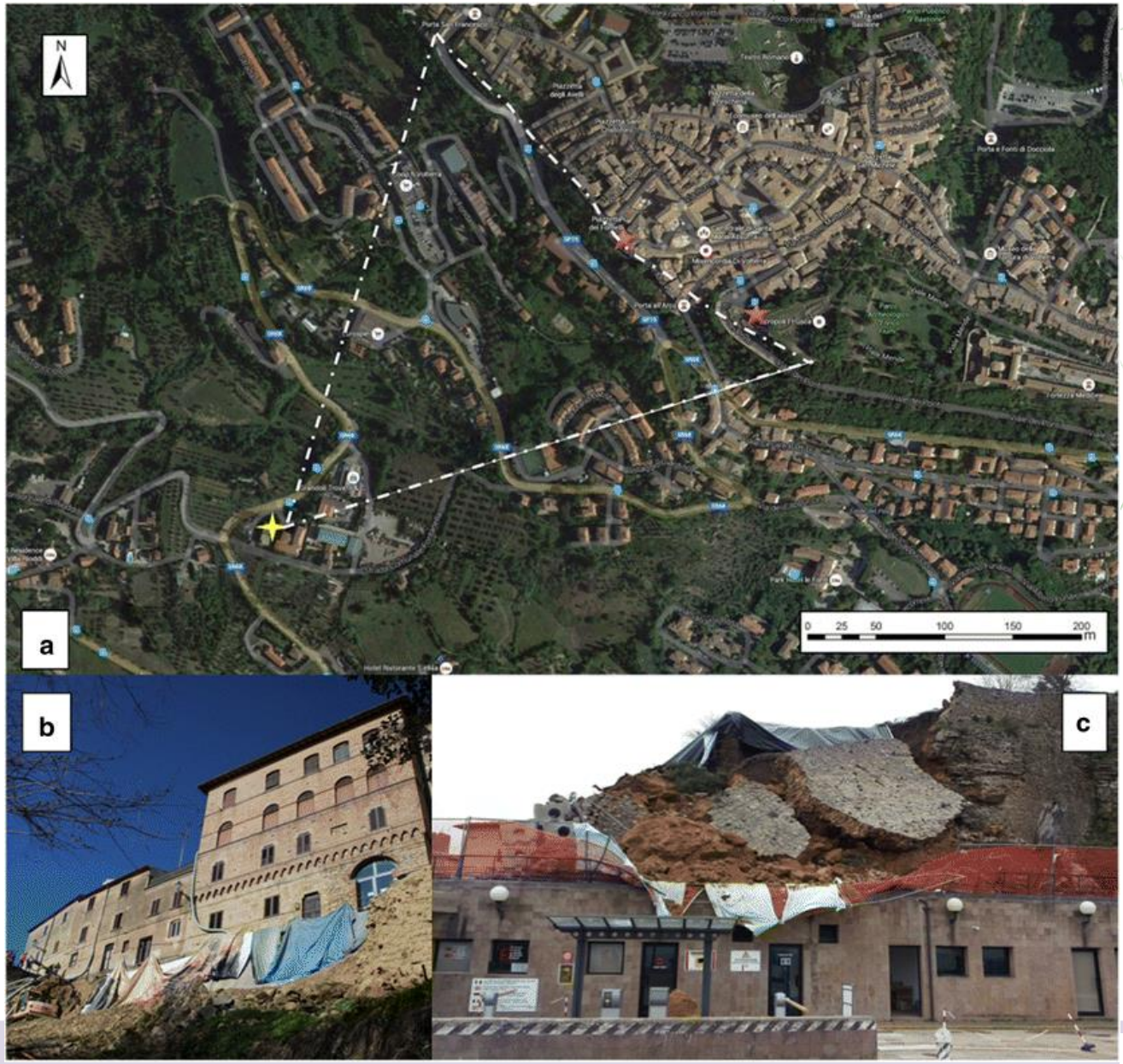


Carlà et al., 2017

Volterra medieval city wall



Carlà et al., 2017

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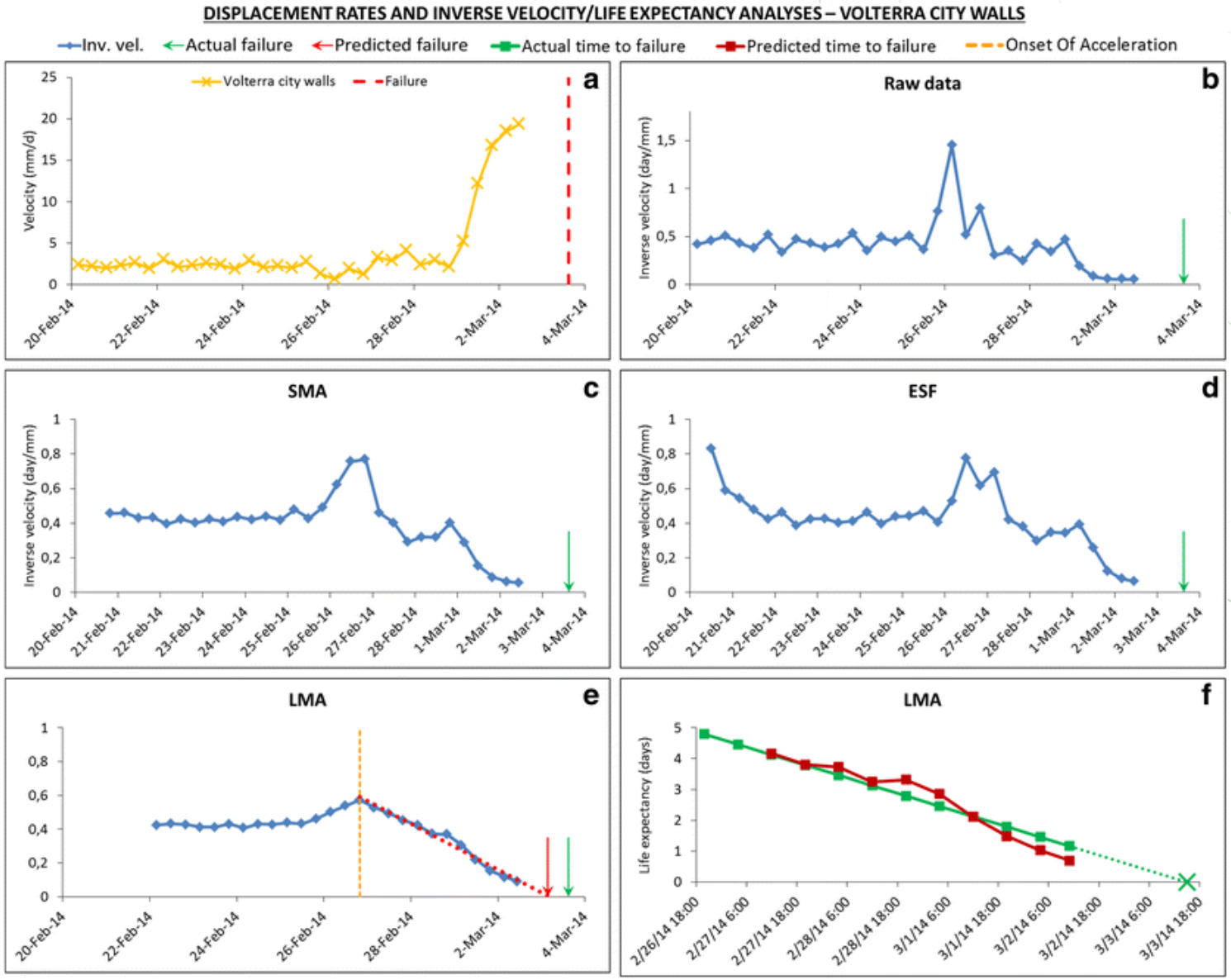
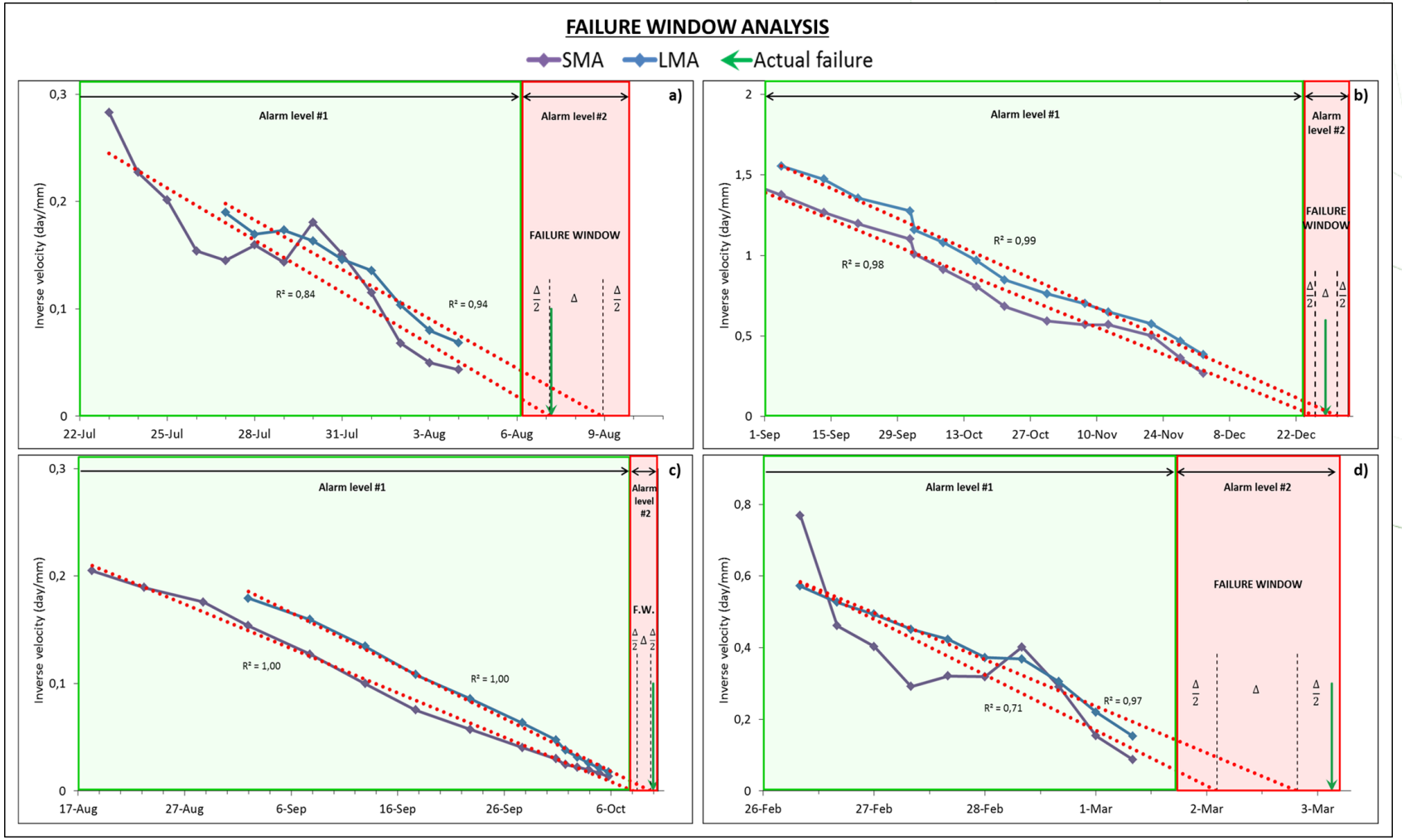
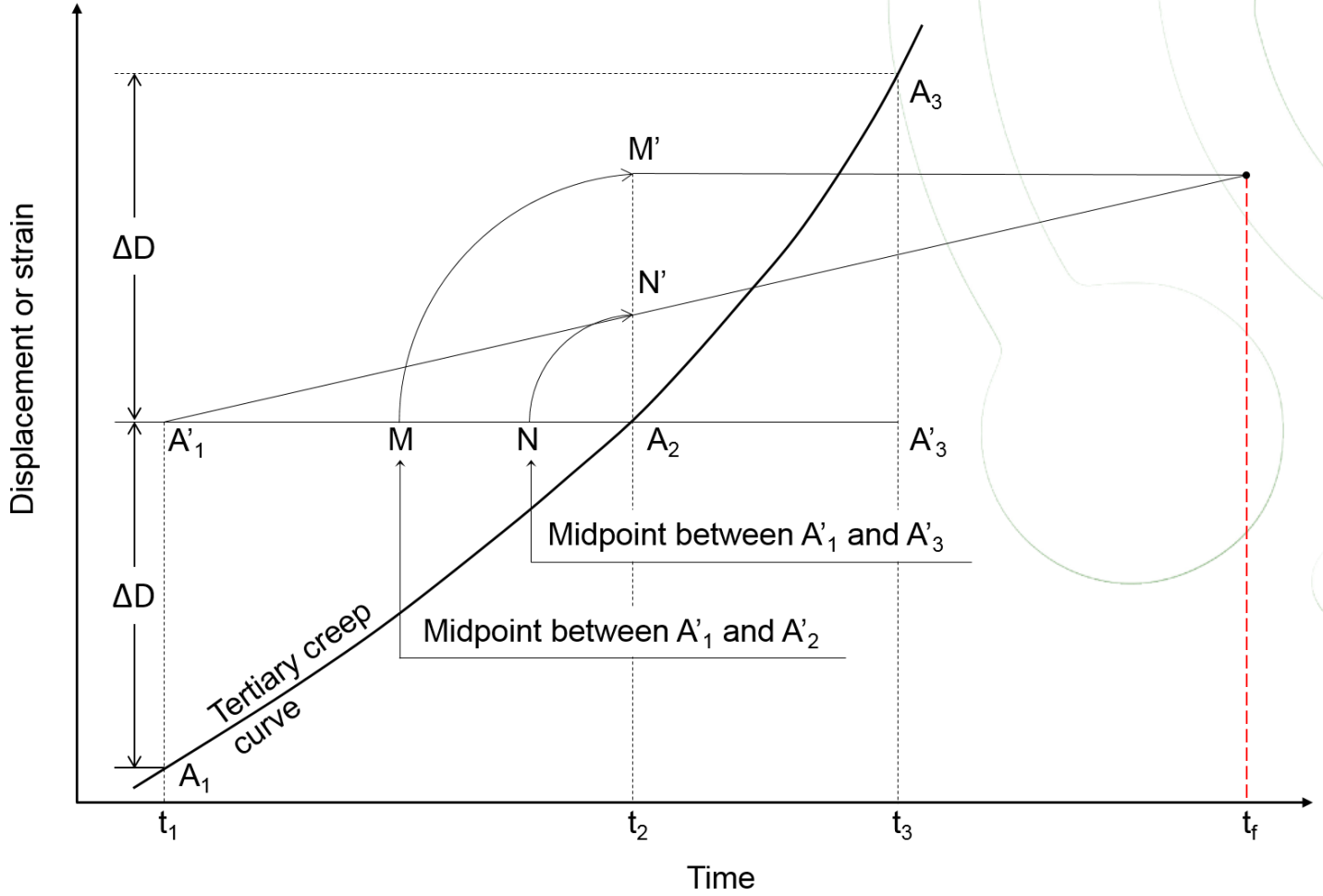


Carlà et al., 2017

Failure window analysis
Carlà et al. (2017)



Saito (1969)



$$t_f = \frac{t_2^2 - t_1 \cdot t_3}{2t_2 - (t_1 + t_3)}$$

Semi-empirical methods

Barry Voight

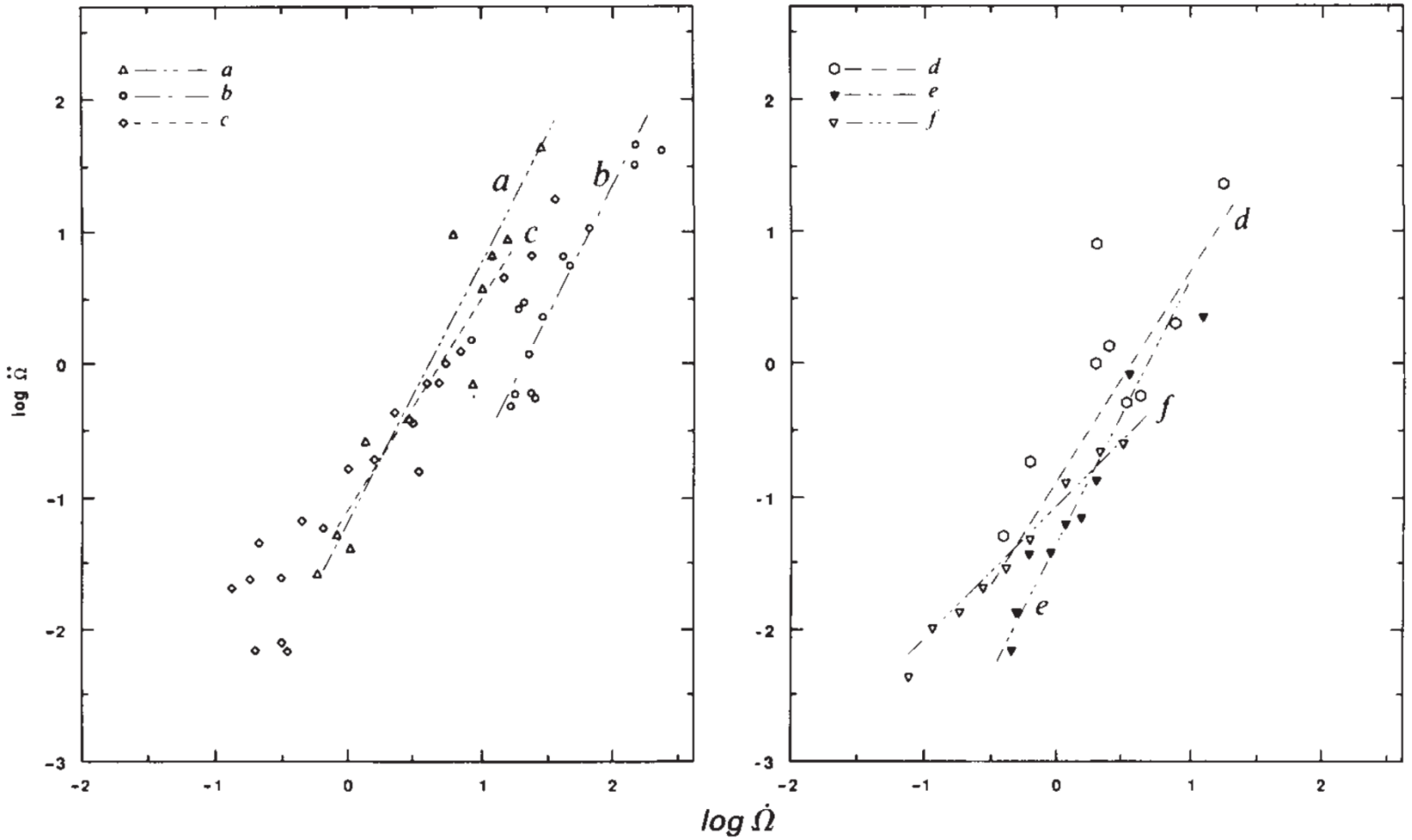
Barry Voight: generalization of Fukuzono (1985)

- A method for prediction of volcano eruptions Nature (1988)
- A relation to describe rate-dependent material failure Science (1989)

May 1980, Mt. St. Helens volcano

July 1995, Montserrat's Soufriere Hills volcano

Voight (1988)

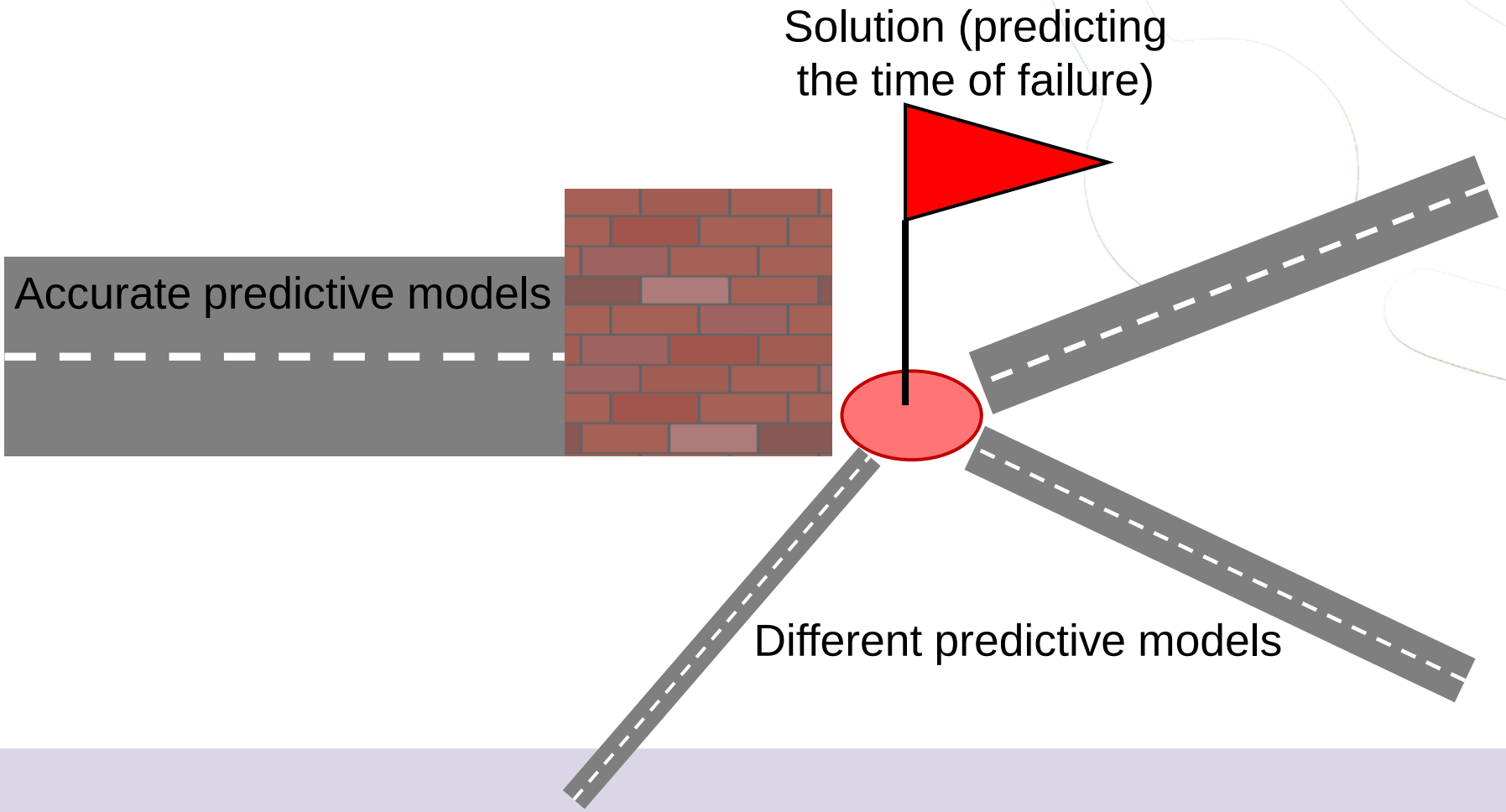


$$\ddot{\Omega} = A\,\dot{\Omega}^{\alpha}$$ α: 0.6÷2.6 A: 10^{-3}÷10^{2}

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

Diversity prediction theorem (Page, 2007)

"In predictive tasks, diversity in predictive models reduces collective error. It's a mathematical fact that diversity matters just as much as highly accurate models when making collective predictions."



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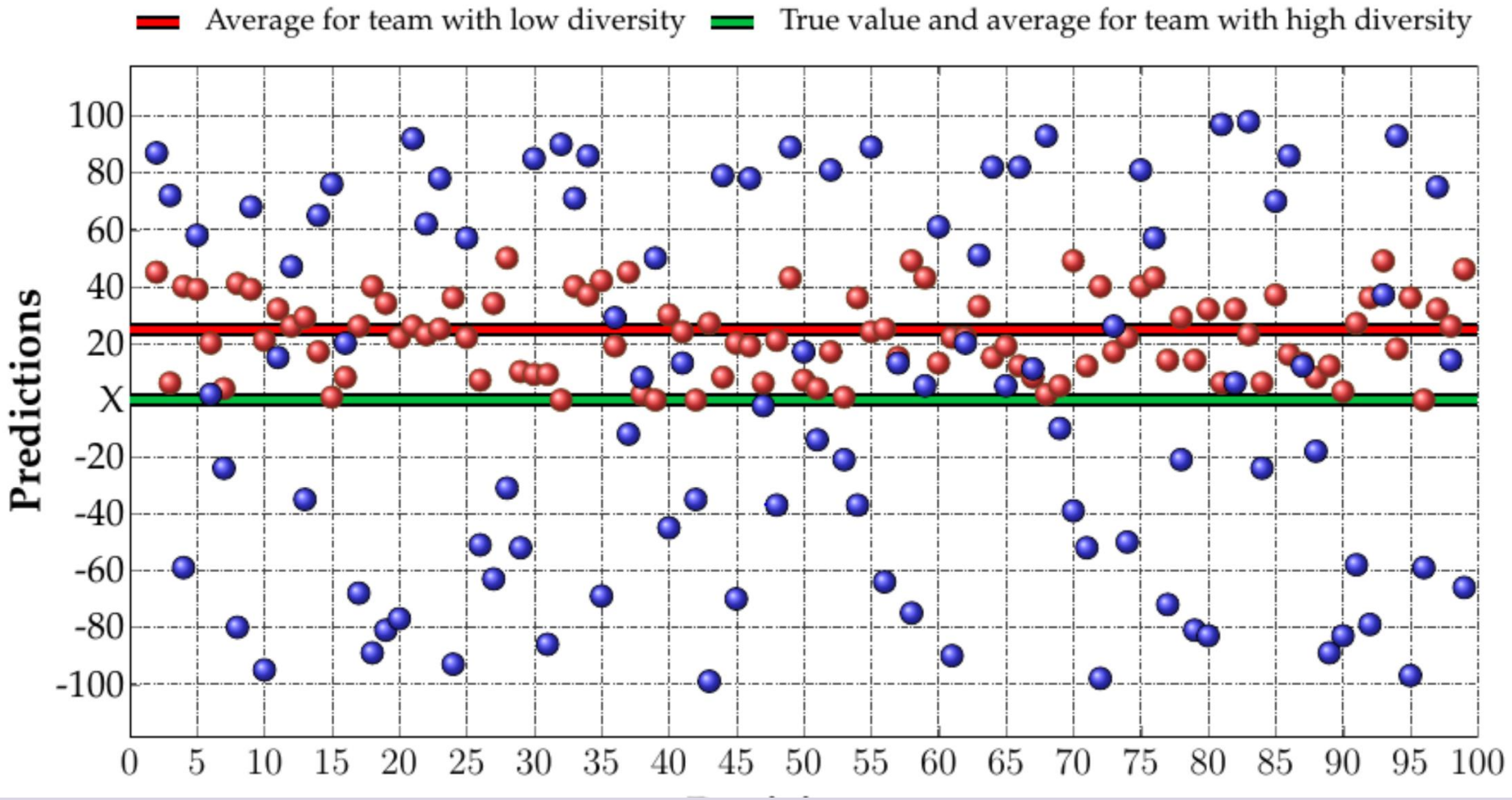
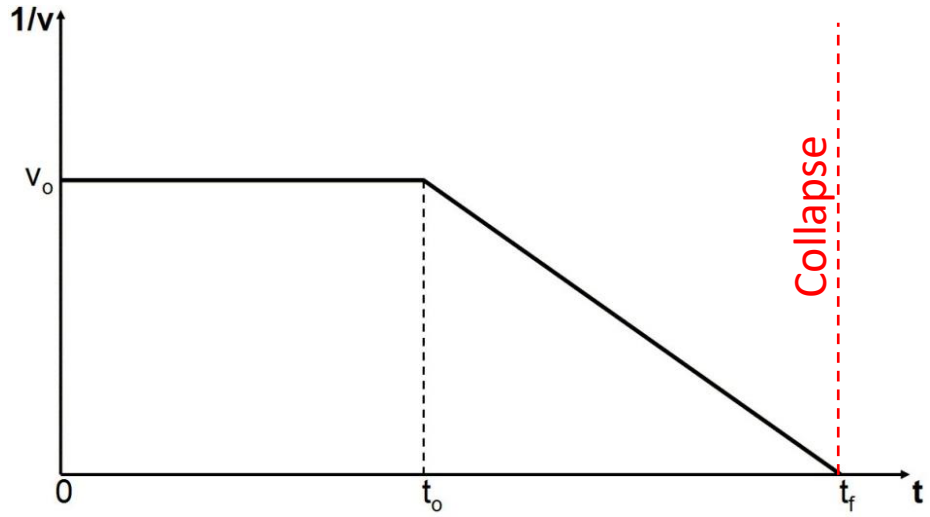


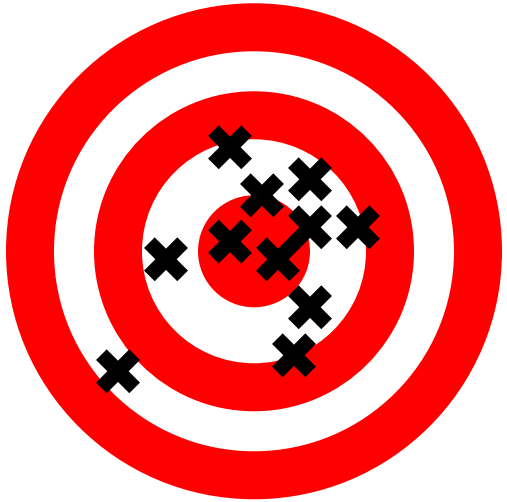
Probabilistic approach (Intrieri and Gigli, 2016)



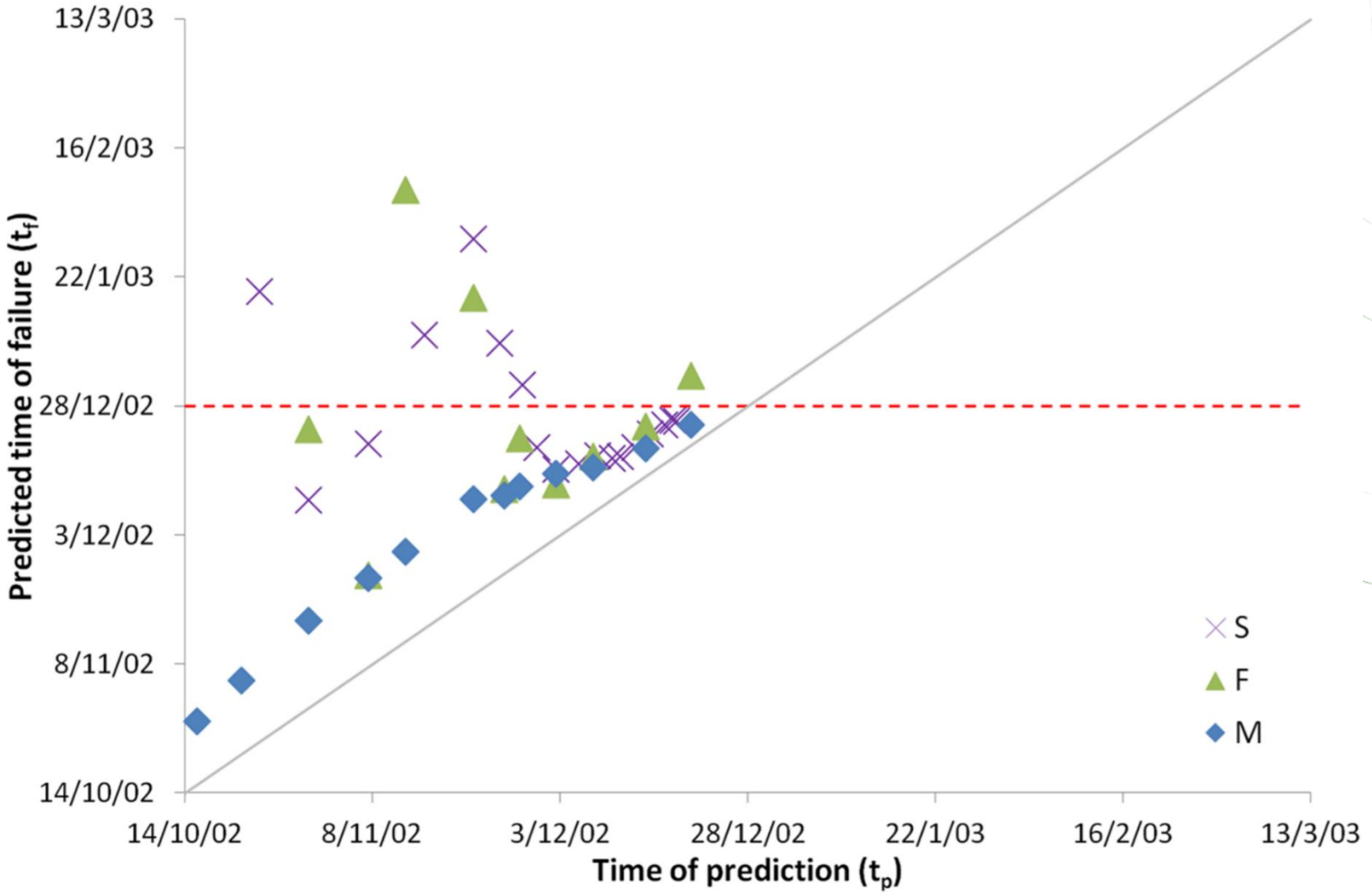
$$t_f = \frac{t_2^2 - t_1 \cdot t_3}{2t_2 - (t_1 + t_3)}$$

$$t_f = \frac{t_2(\Lambda_1) - t_1(\Lambda_2)}{\Lambda_1 - \Lambda_2}$$

$$t \cdot v = t_f \cdot v - b$$



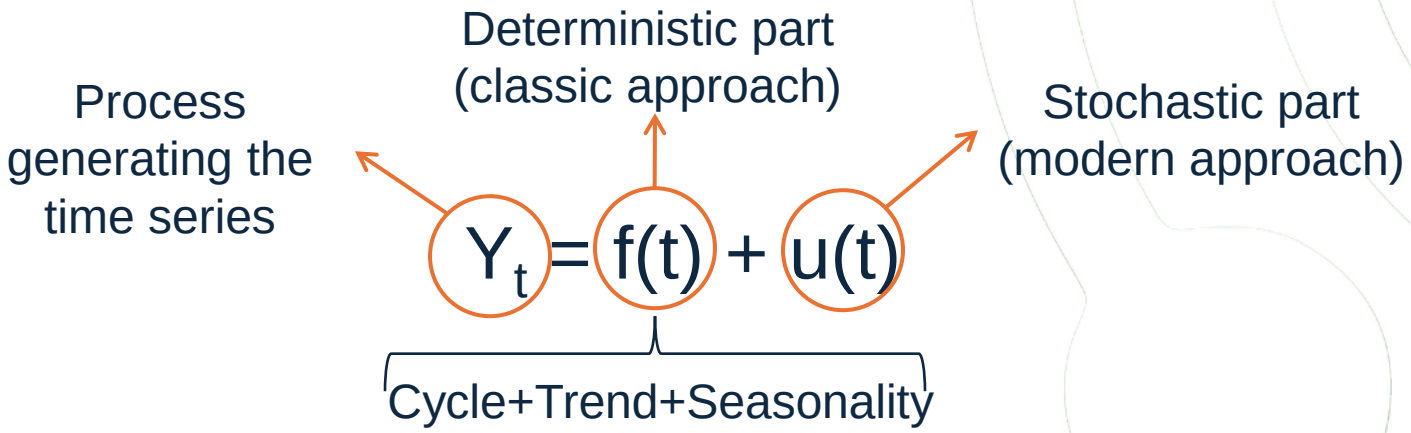
Prediction plot



Intrieri and Gigli, 2016

Numerical methods

Statistical methods of displacement forecasting



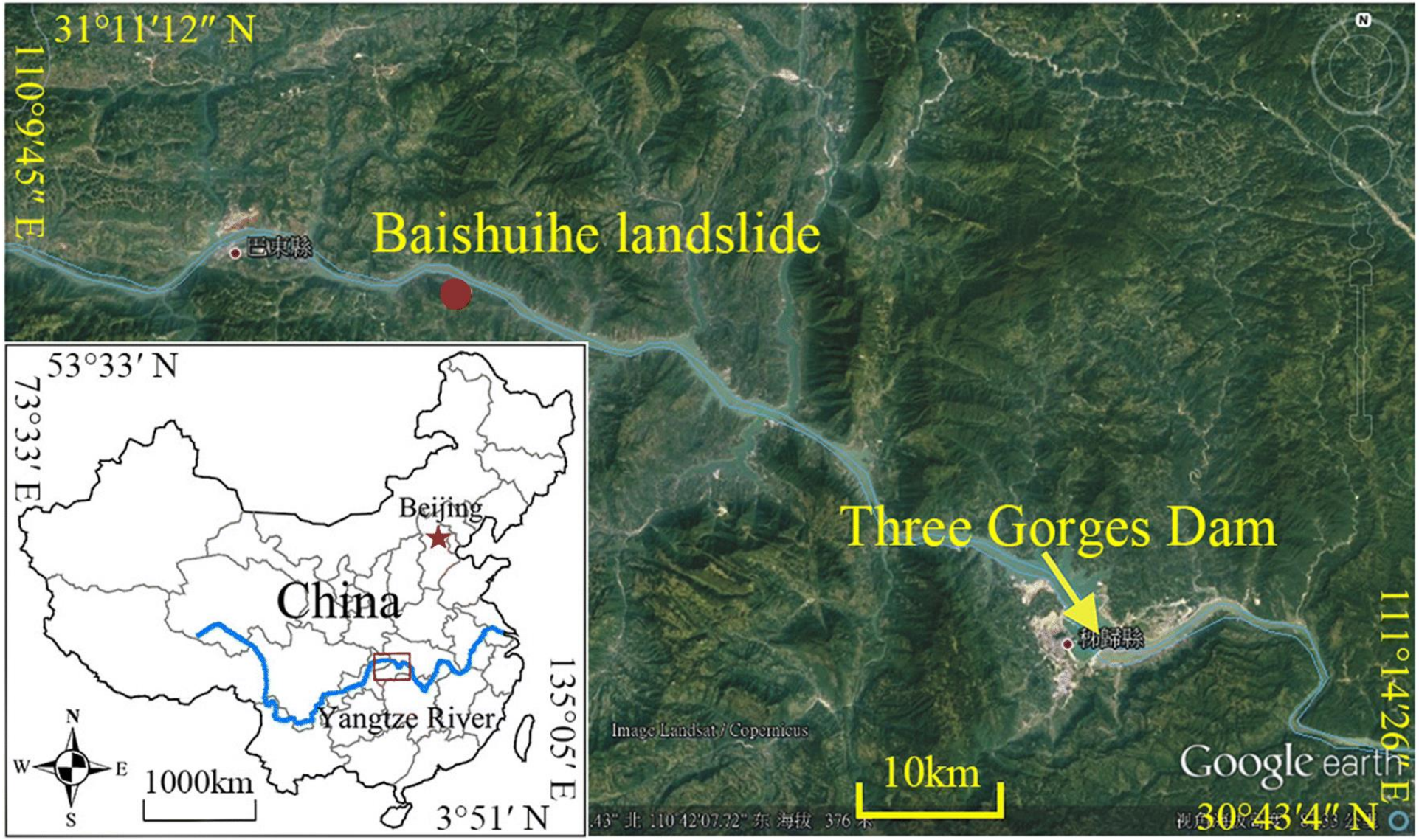
Classic approach: the deterministic part is modelled in all its components: cycle, trend, seasonality, random error.

Modern approach: the process generating the time series is stochastic, that is it only follows probabilistic laws and the time series is the only known realization of such unknown process.

“Study the past to forecast the future”

Confucius, -500 (ca.)

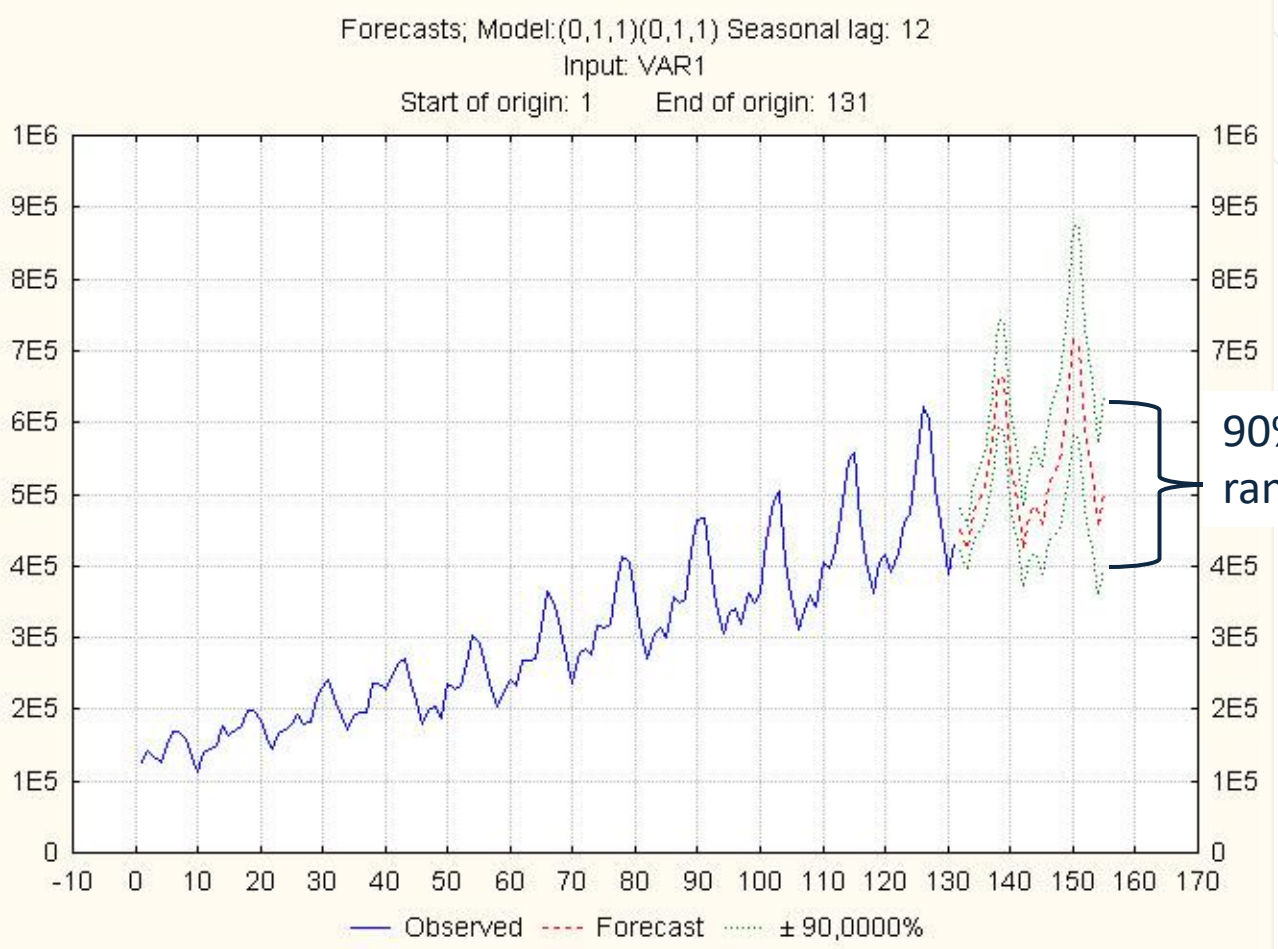
Three Gorges landslides



Zhou et al., 2018

ARIMA models

Airline series

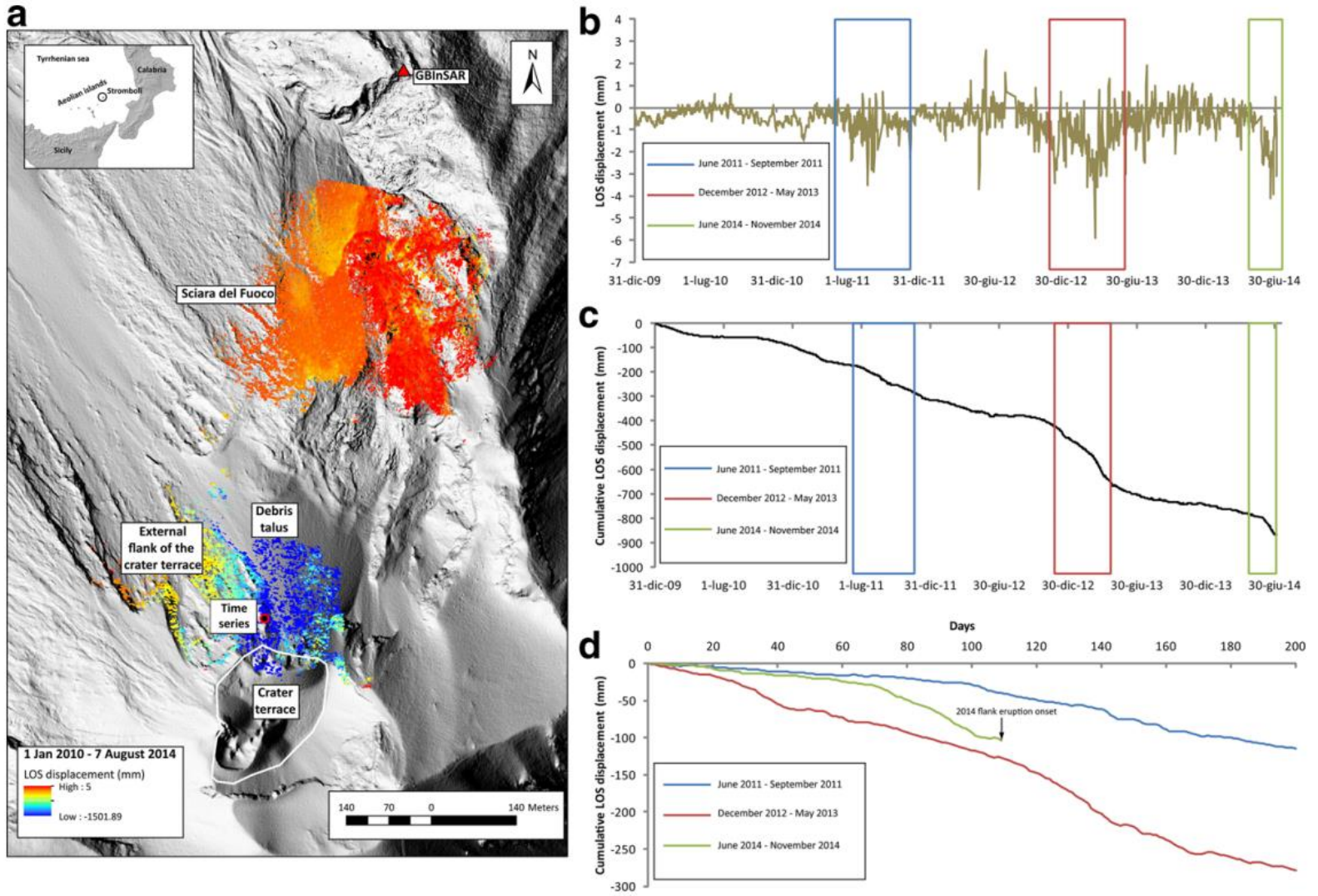


90% confidence range

Box and Jenkins (1976)

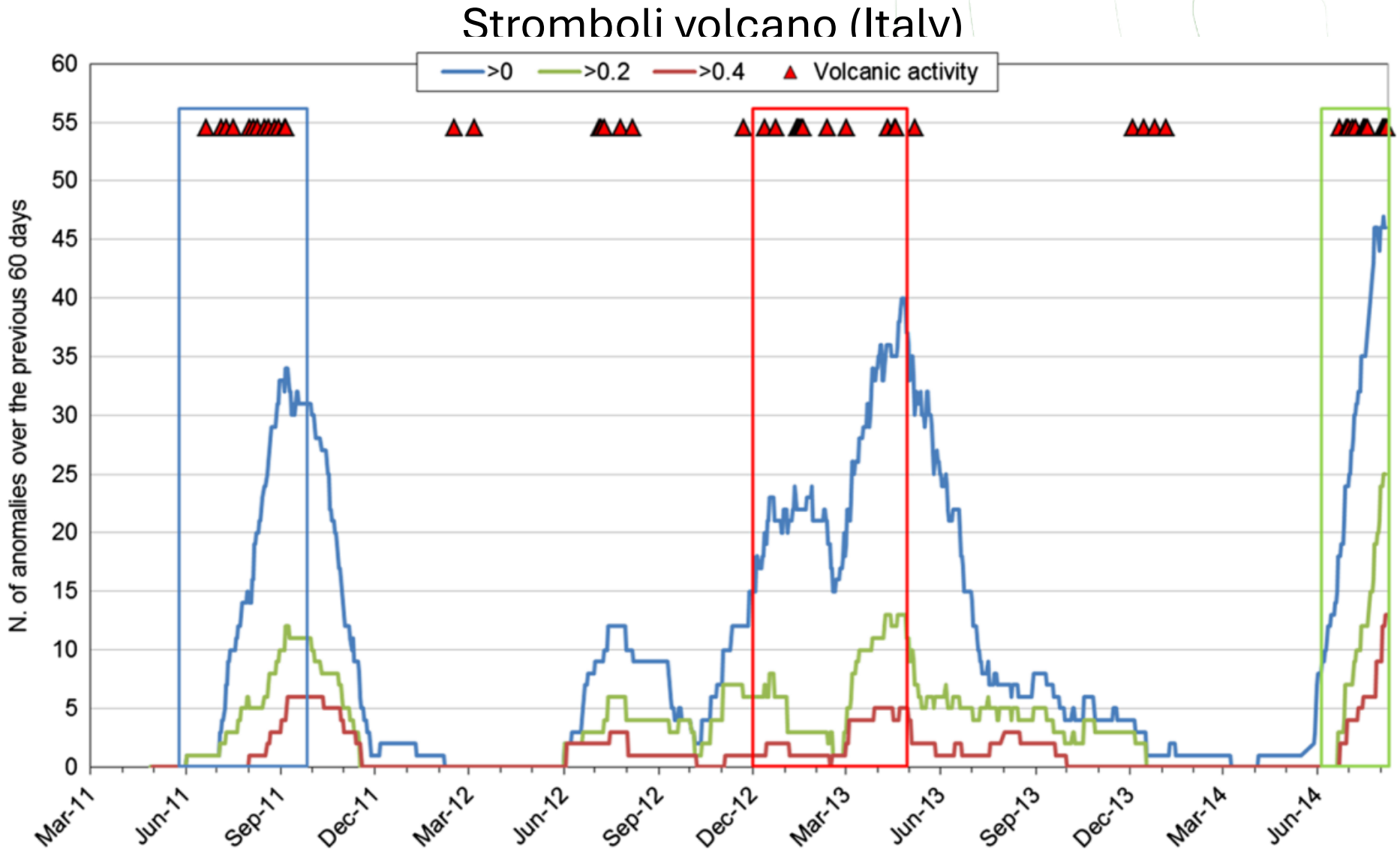
Threshold based on displacement forecast

Stromboli volcano (Italy)



Carlà et al. (2016)

Threshold based on displacement forecast



Carlà et al. (2016)

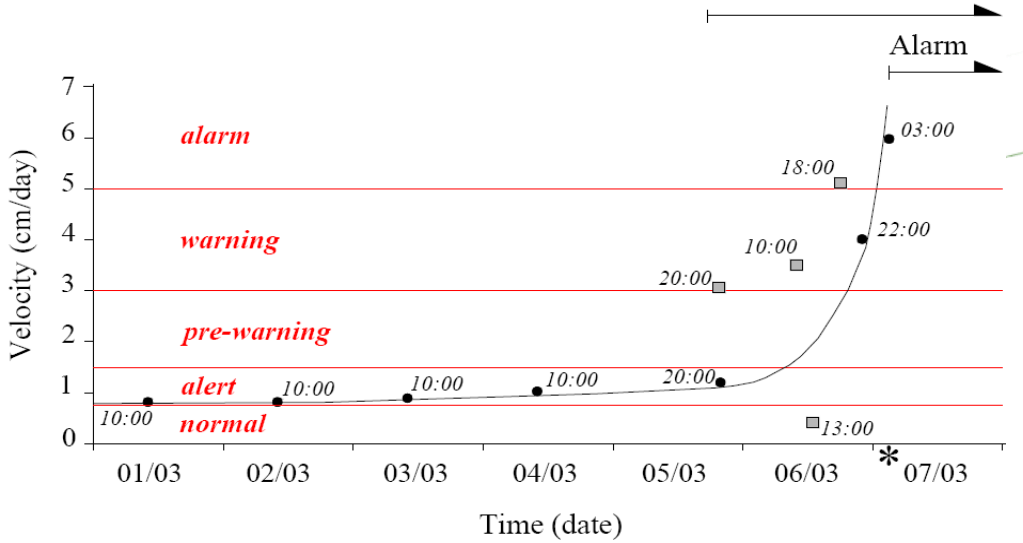
Methods for the definition of thresholds

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

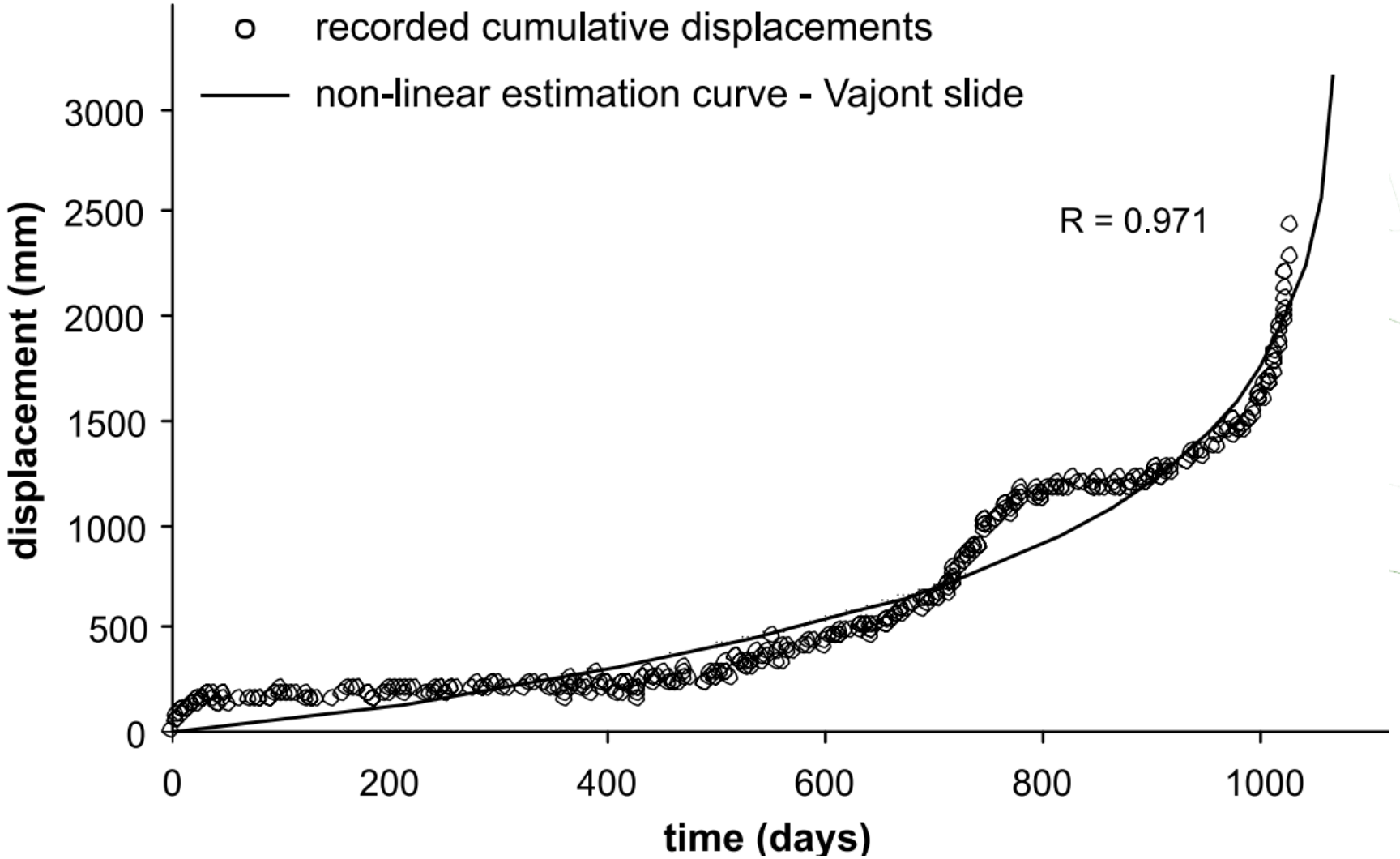
(Oboni, 1988)

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



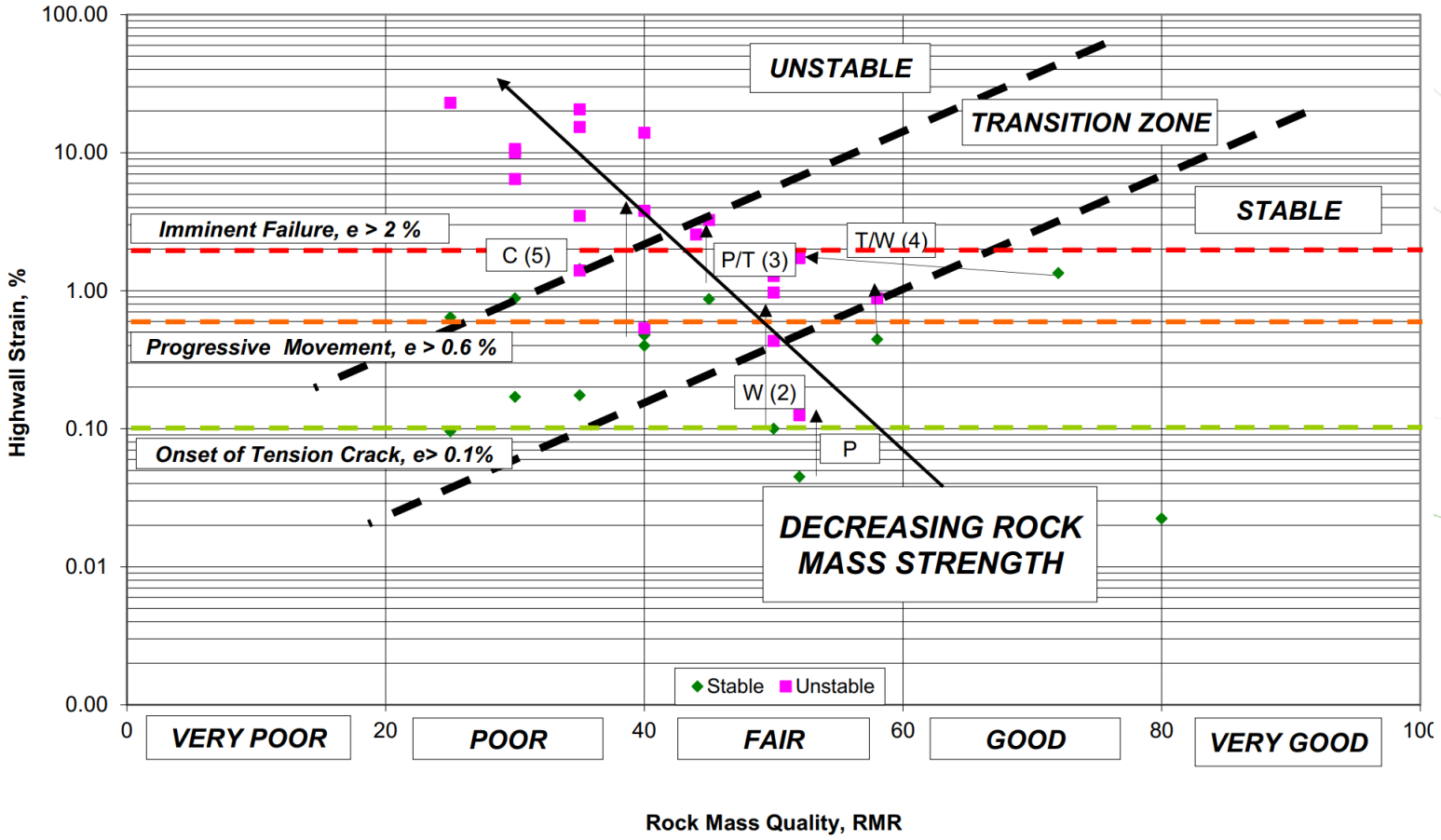
(Iovine et al., 2006)

Crosta and Agliardi (2002)

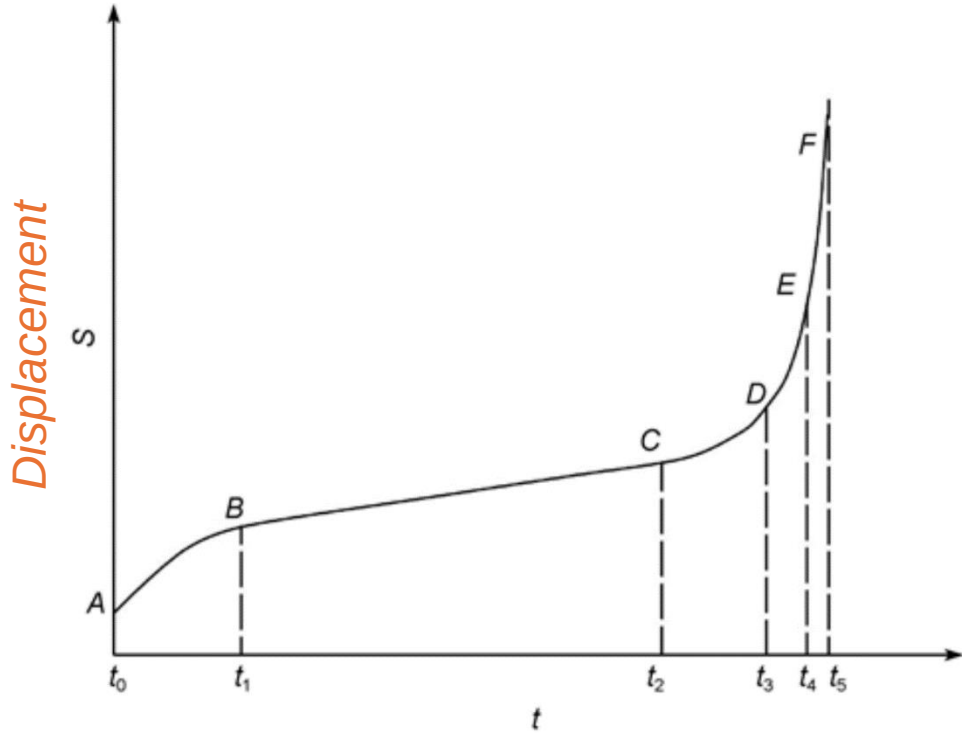


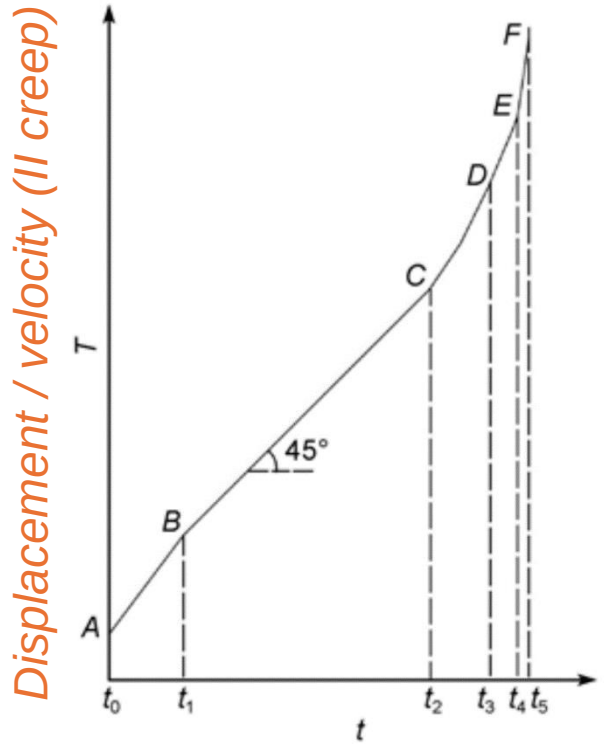
Brox and Newcomen (2003)

Figure 1 – Case History Highwall Strain Data and Empirical Highwall Strain Criteria



Xu et al. (2011)





<45°: primary creep

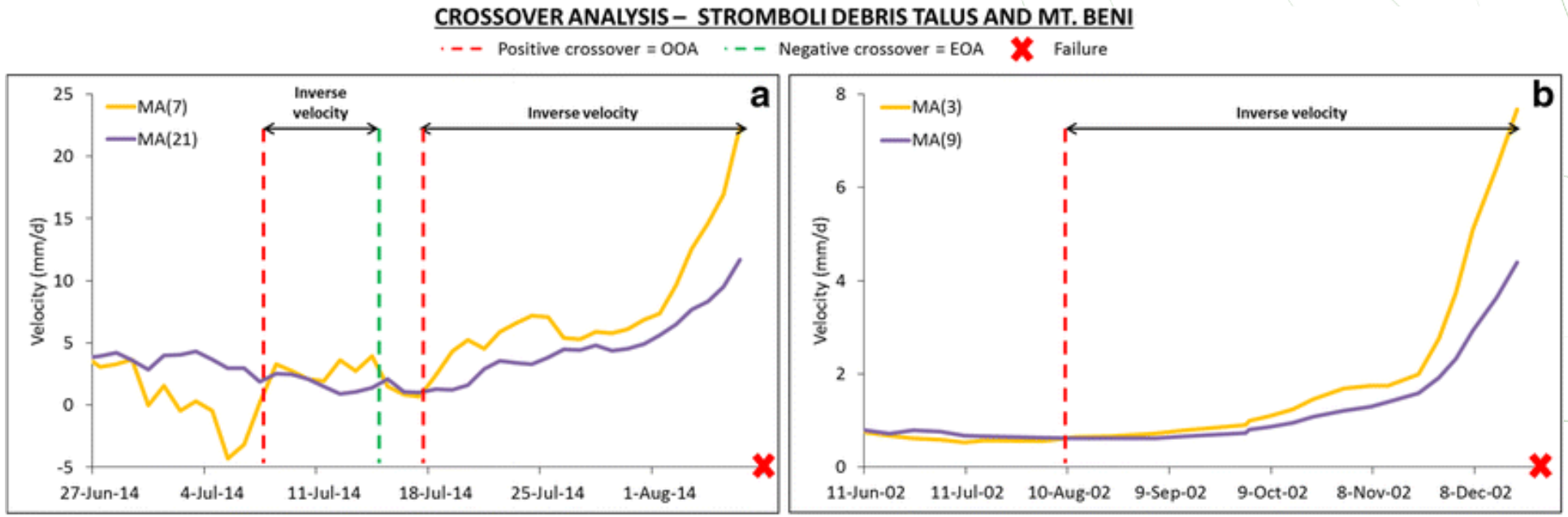
≈45°: secondary creep

45°÷80°: tertiary creep (first warning threshold)

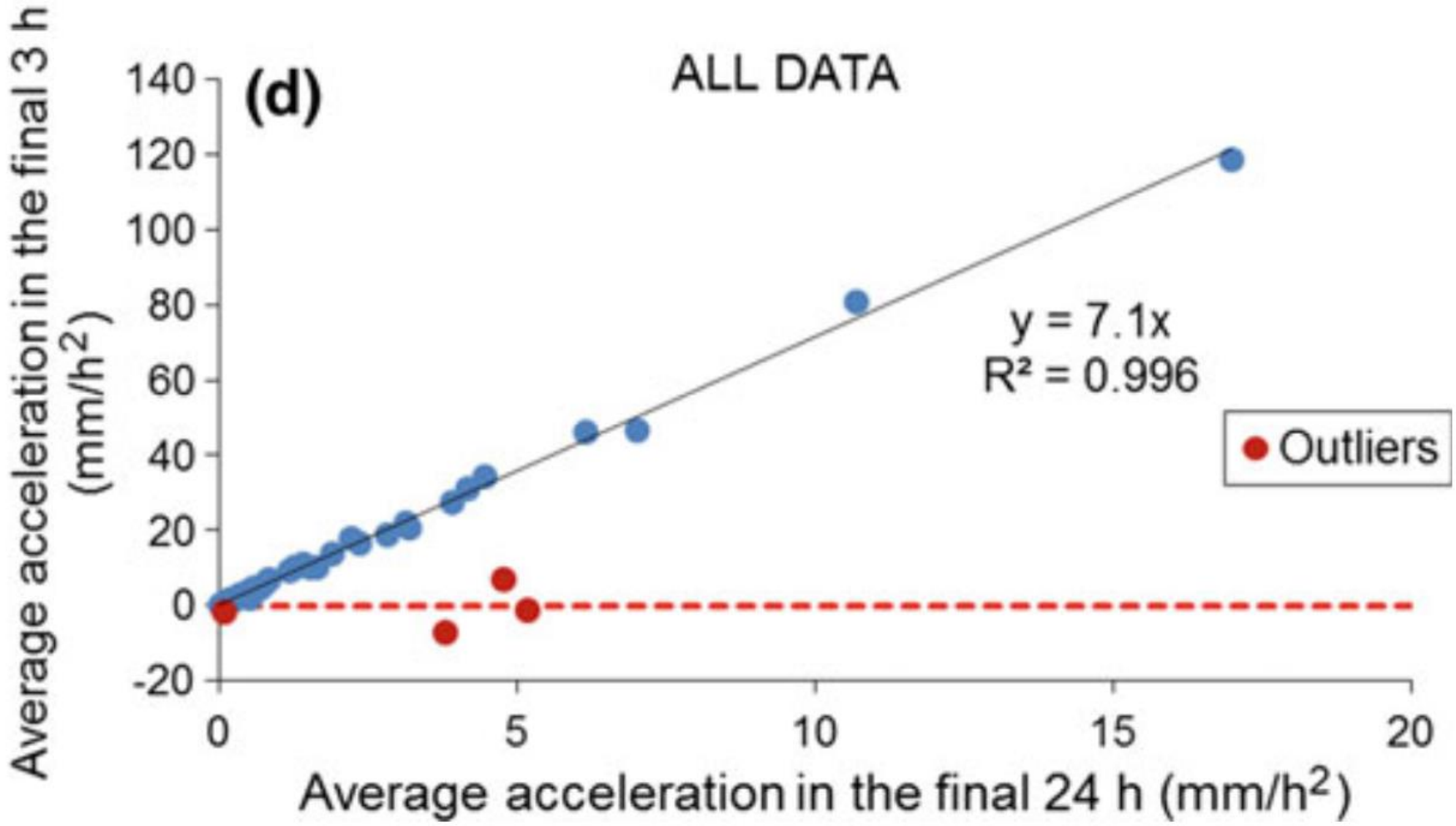
80°-85°: second warning threshold

>85°: close to failure (third warning threshold)

Carlà et al. (2017a)

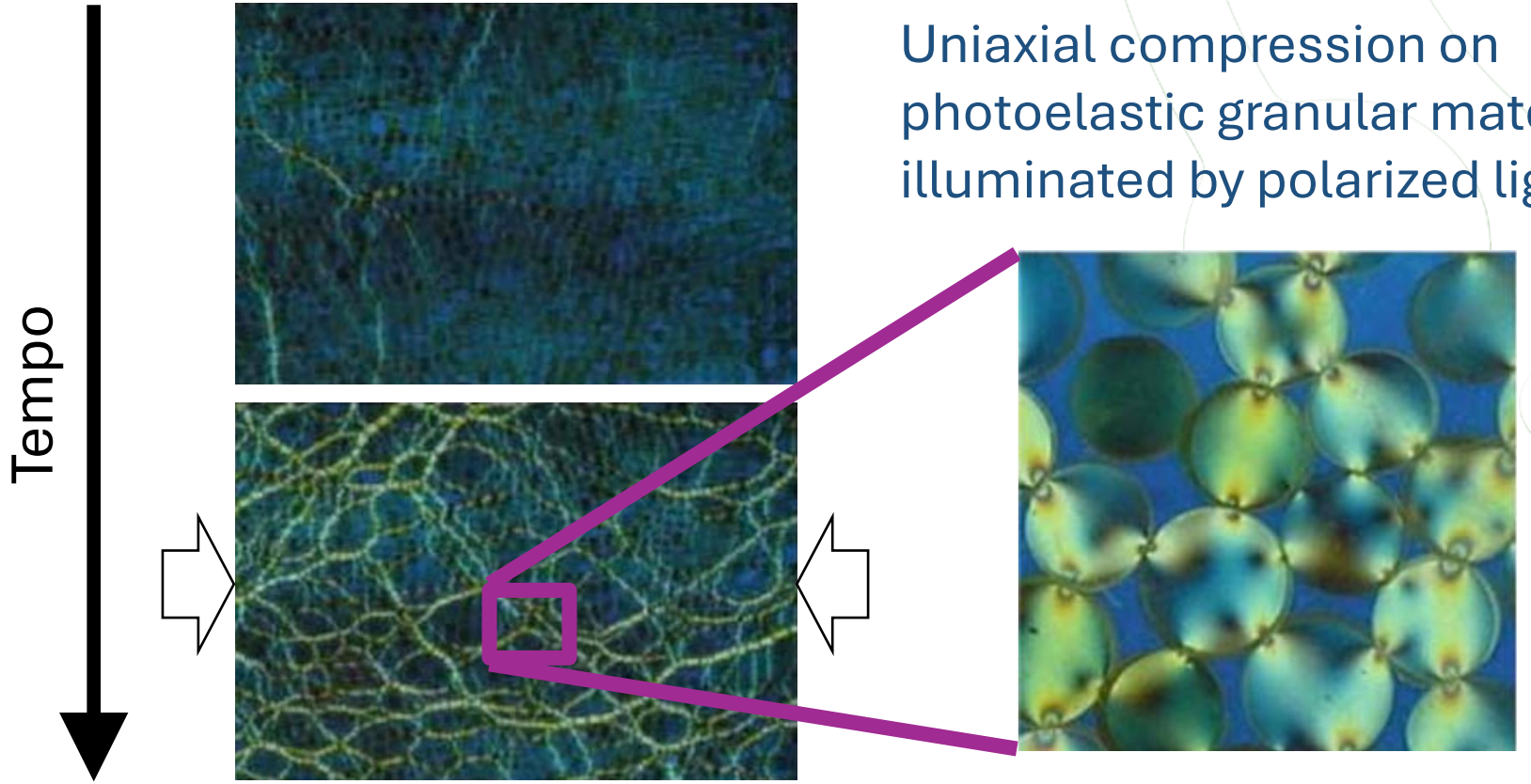


Carlà et al. (2017b)

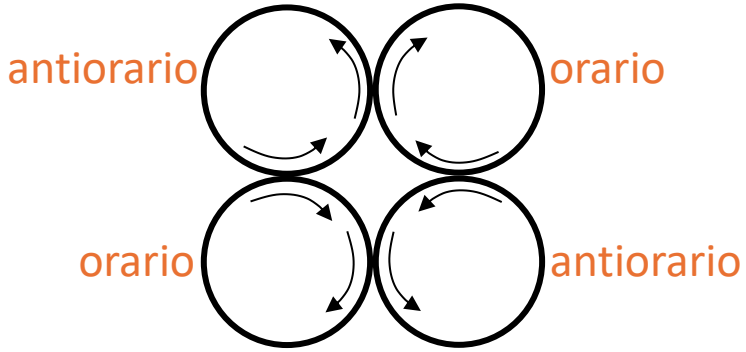


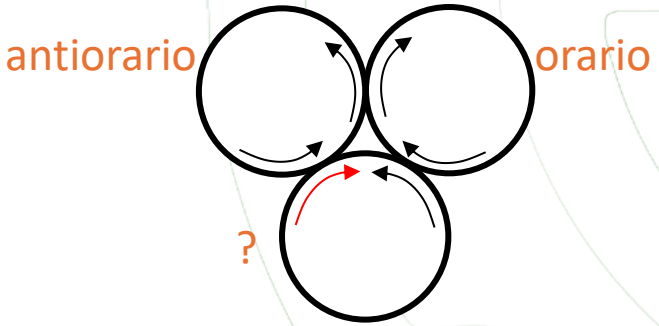
Failure predictability

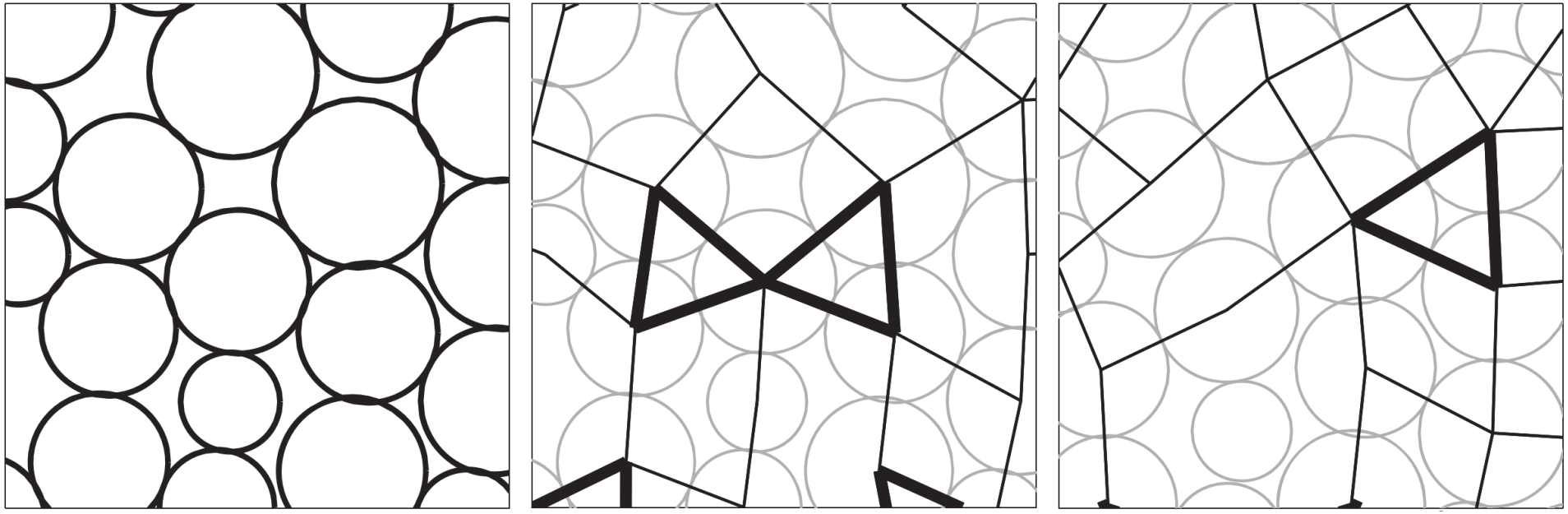
Force chains



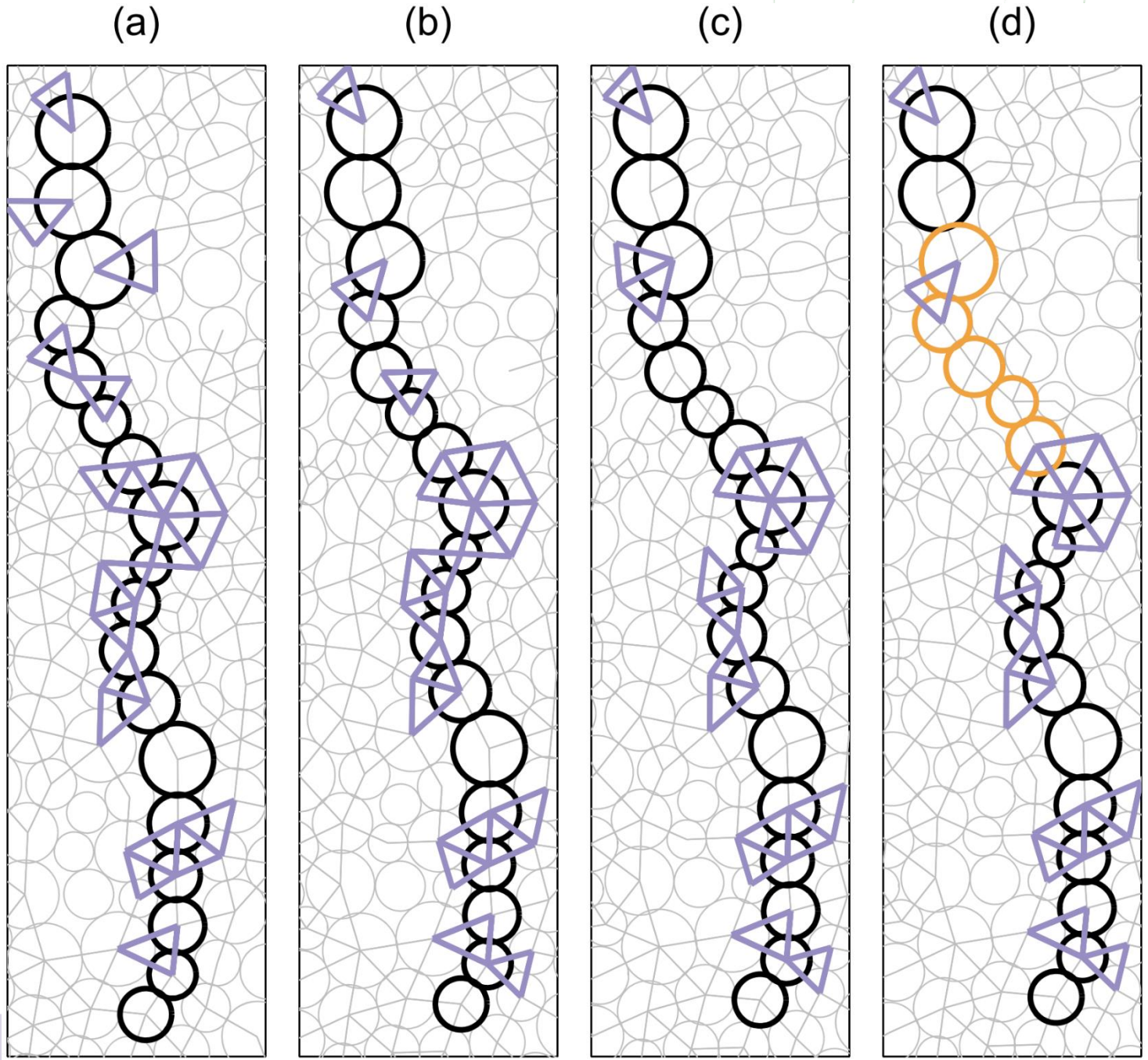
Uniaxial compression on photoelastic granular material illuminated by polarized light

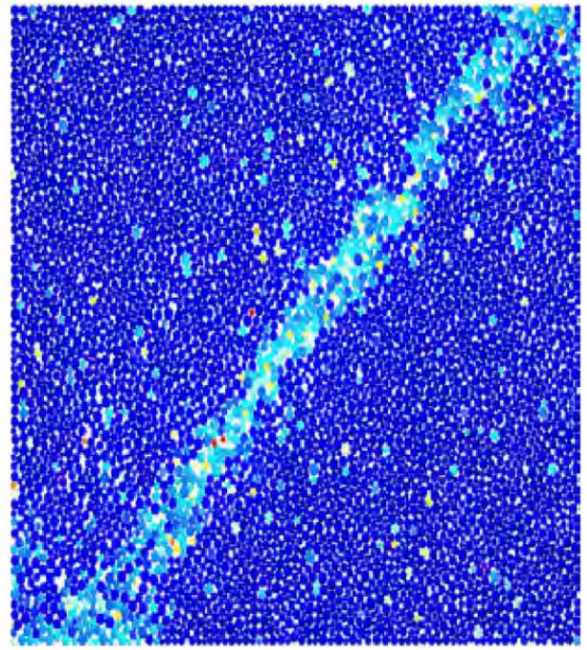


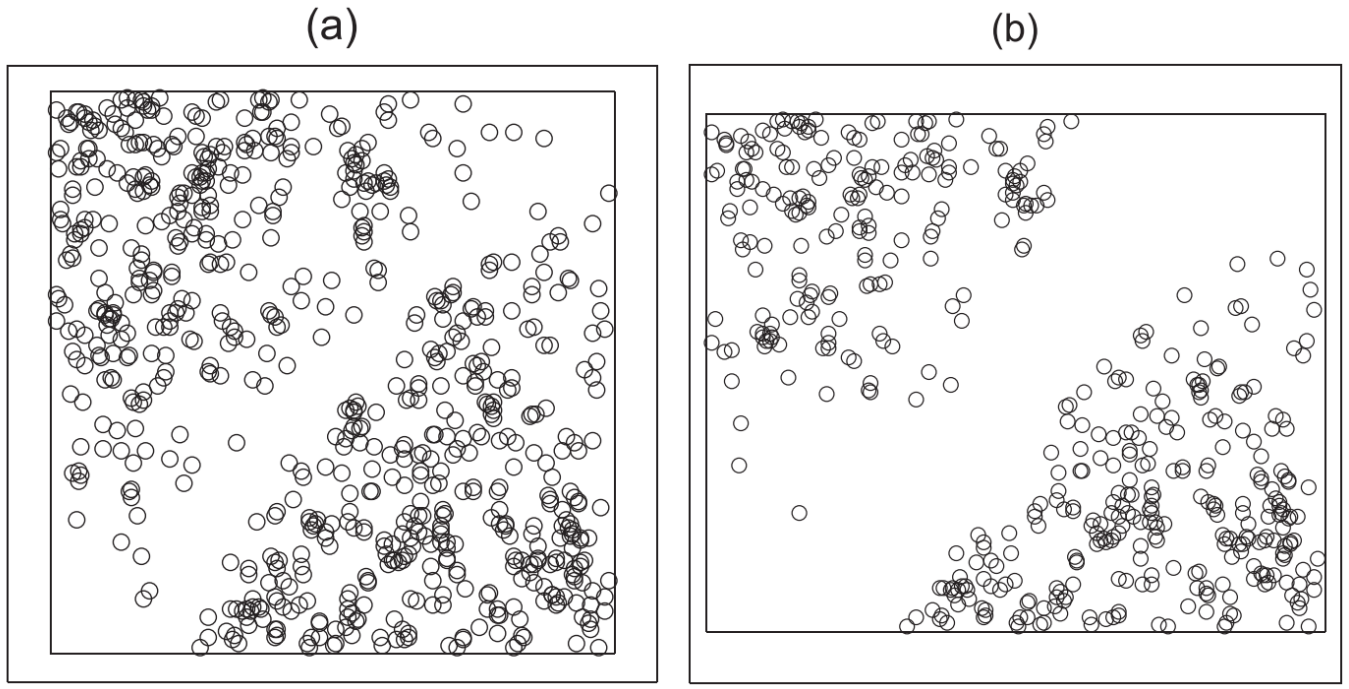


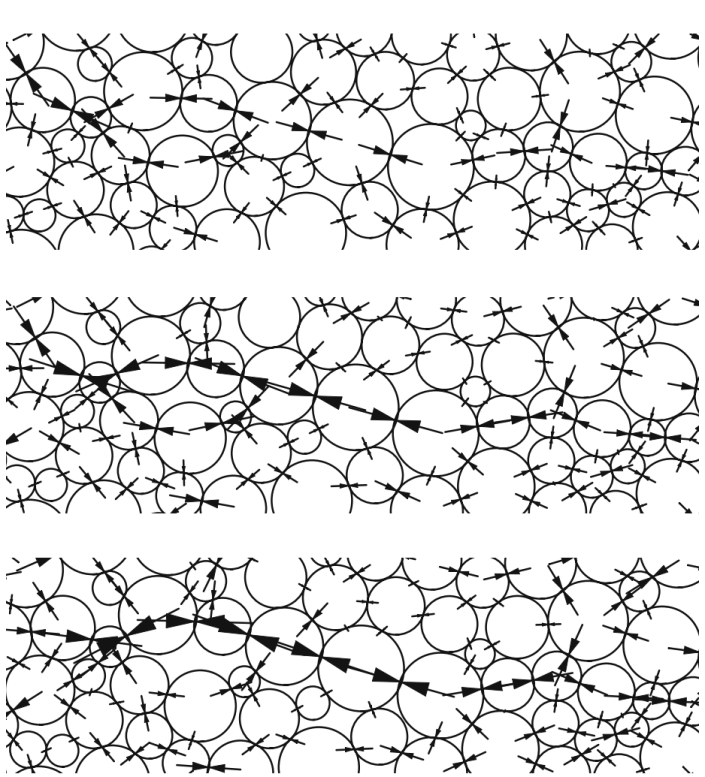


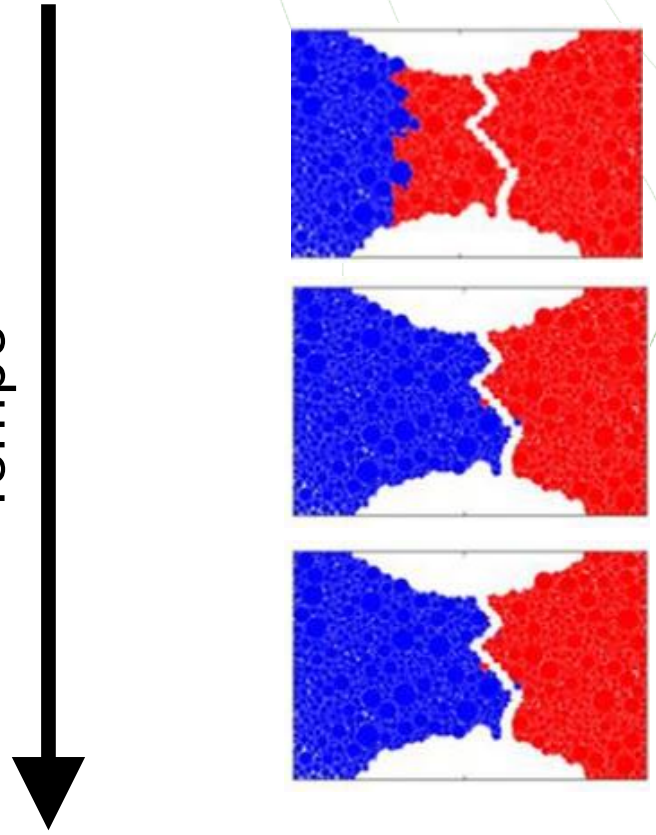
Tordesillas et al. (2014)


(a)
(b)
(c)
(d)




(a)
(b)





Tordesillas et al. (2020)

Hungr vs Petley

Rose & Hungr, 2007

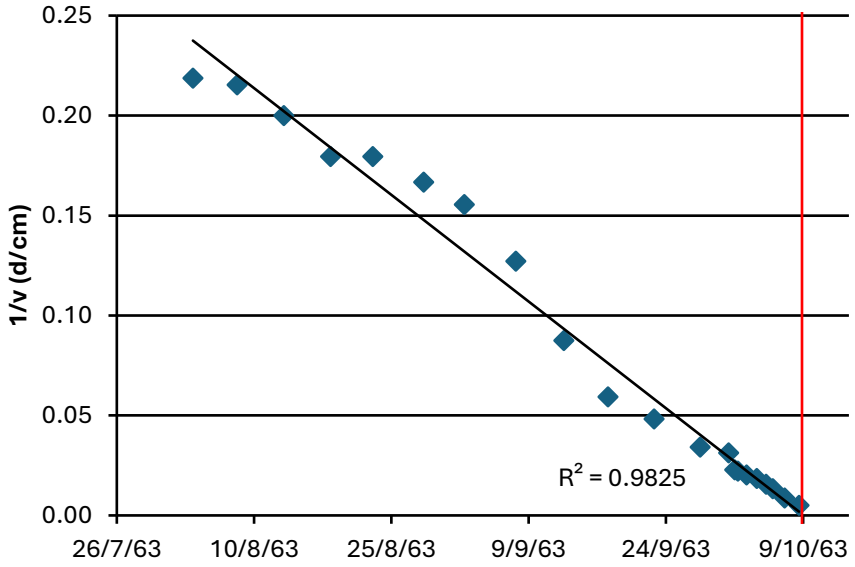
- "Given ductile, accelerating creep occurring under constant effective stress conditions in soil, rock and other materials, the inverse velocity plot would in fact be expected to be linear"
- "The timing of [brittle rock] failure cannot be anticipated by means of displacement monitoring"

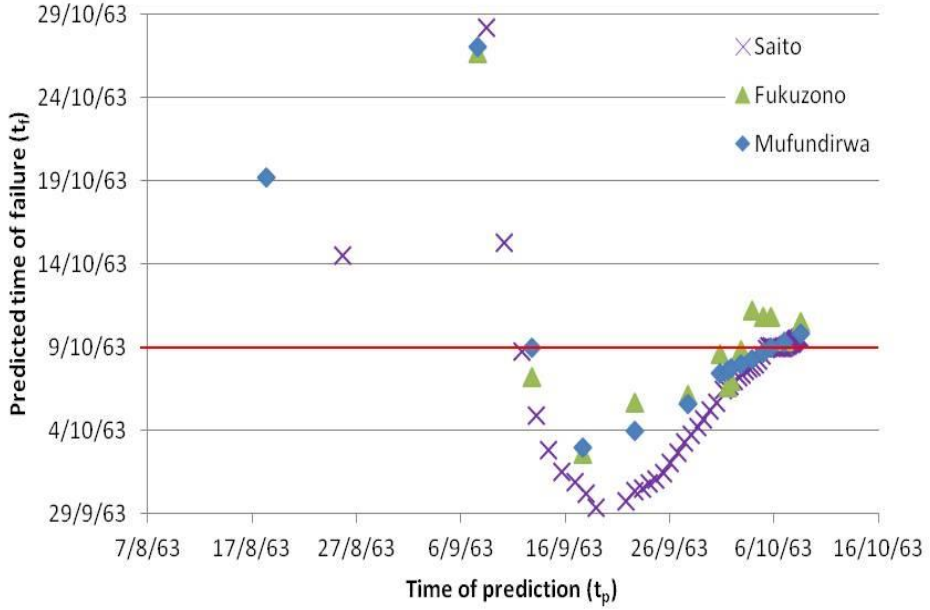
Petley, 2004

- "Saito linearity is the result of brittle deformation processes associated with the formation of the shear surface [(first time rupture)]"
- "Where the process occurring at depth is ductile, or indeed consists of sliding on existing surfaces, [...] an asymptotic trend might be expected [(reactivation)]"
- "It is not possible to use Saito linearity to predict failure in non-brittle materials"

Vajont (Italy)

- Limestone with clay interlayers
- Reactivated landslide
- High brittleness
- $2.7 \cdot 10^8$ m^3
- Collapse 09/10/1963
- Reactivated landslides may present <u>brittle failure</u> and linear trend in <u>particularly complex geological environments</u>.

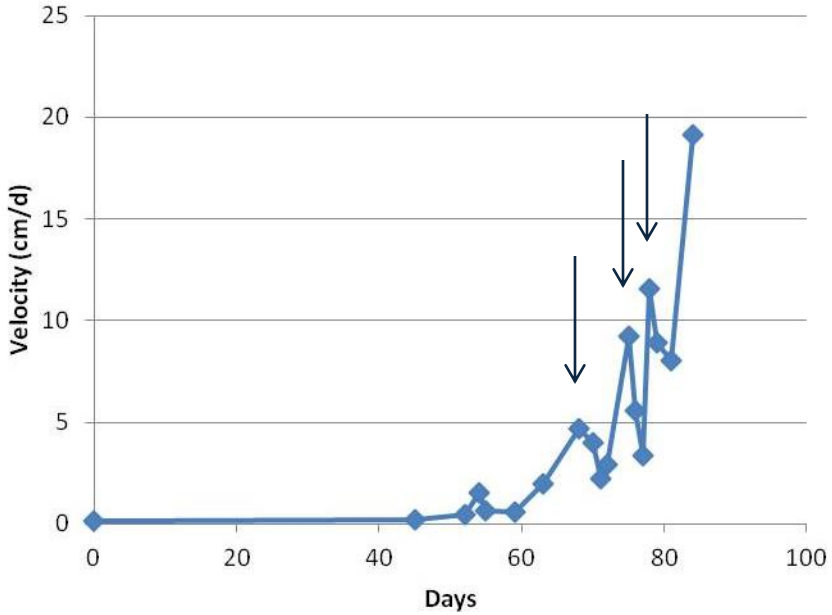


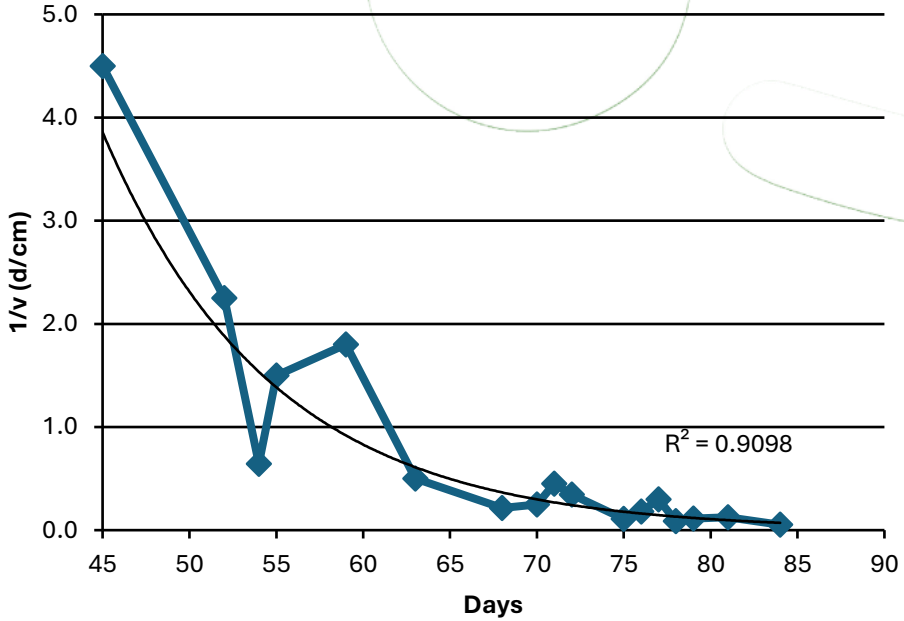


Intrieri and Gigli (2016)

Liberty Pit (USA)

- Weathered quartz monzonite
- First time failure
- Mid-high brittleness
- $6 \cdot 10^6$ m^3
- Asymptotic trend caused by external forces (explosions) that, still, do not prevent from forecasting

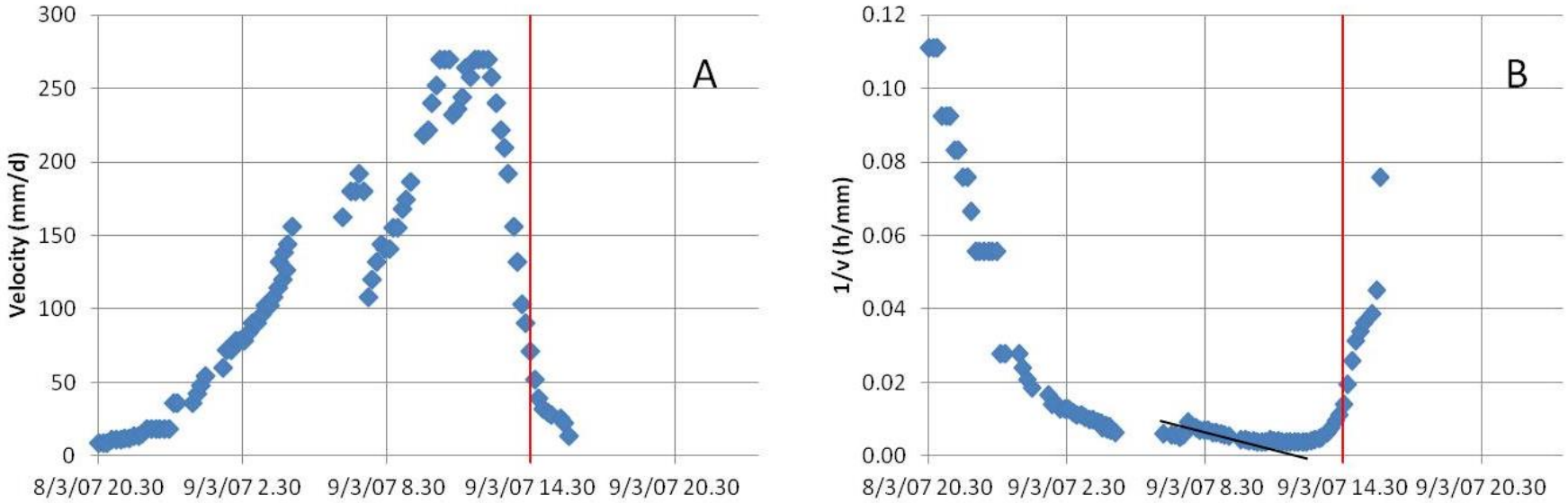




Intrieri and Gigli (2016)

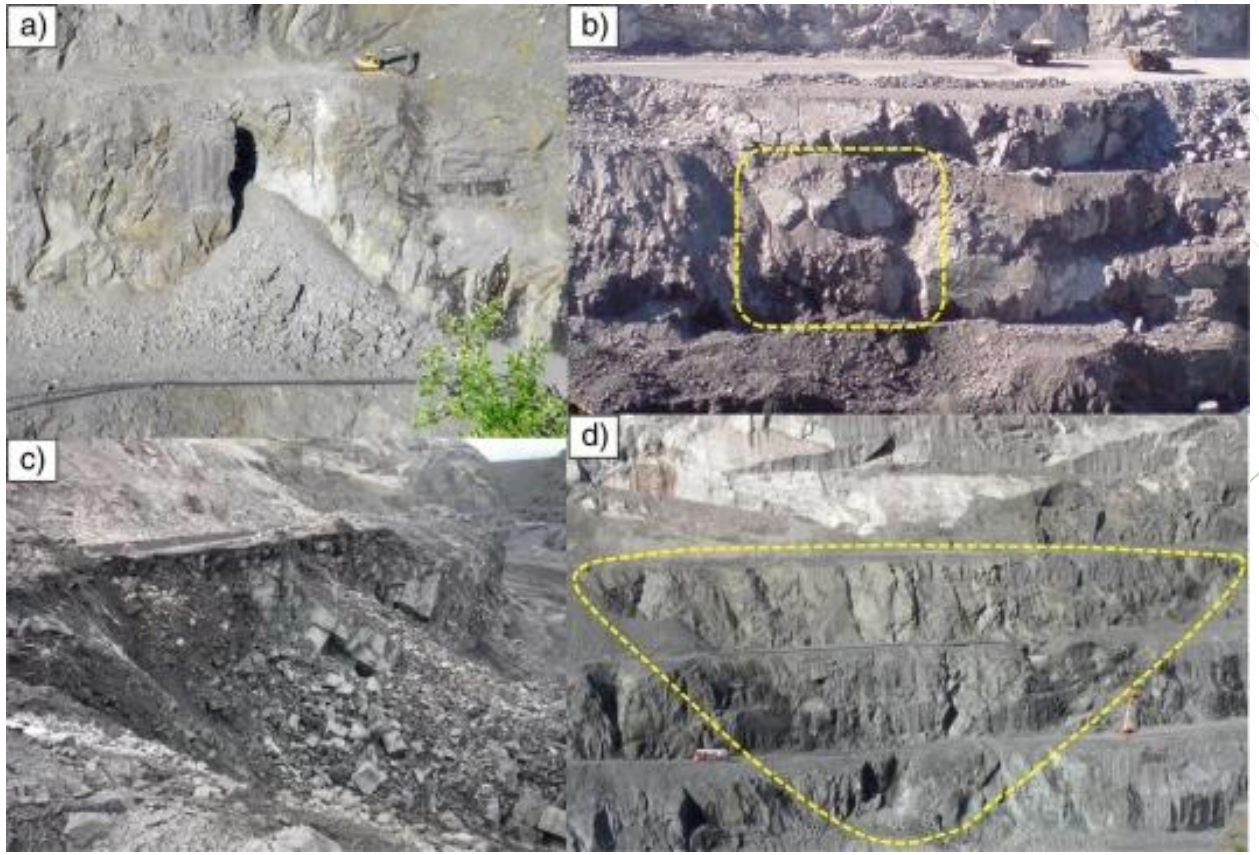
Stromboli

- Alternation of pyroclastic material and lava
- First time failure
- Mid brittleness
- Opening of an effusive vent at 400 m a.s.l.
- Asymptotic trend caused by <u>external forces (magma pressure)</u>



Intrieri and Gigli (2016)

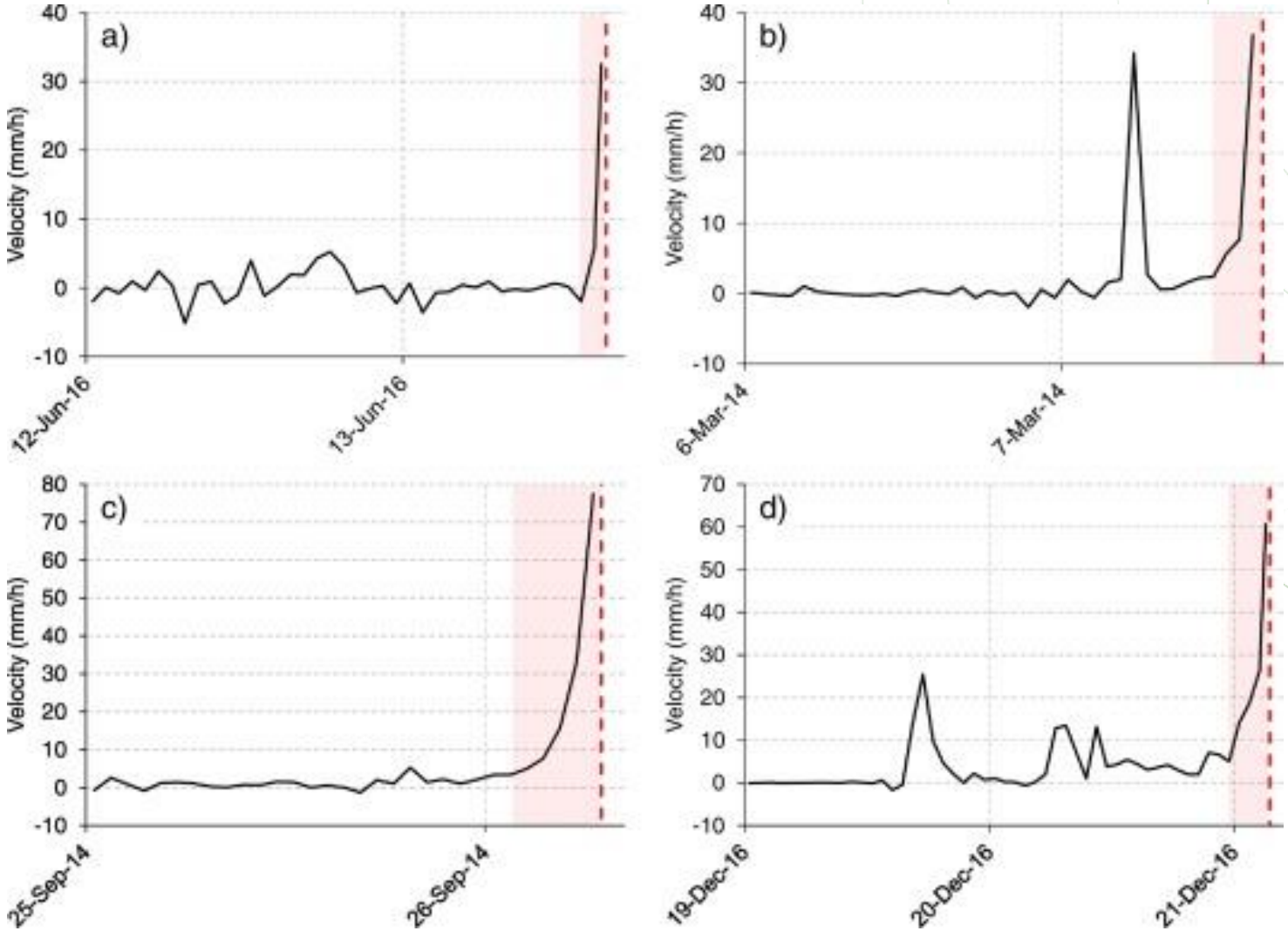
Open-pit mine in hard rock



60 < RMR < 80

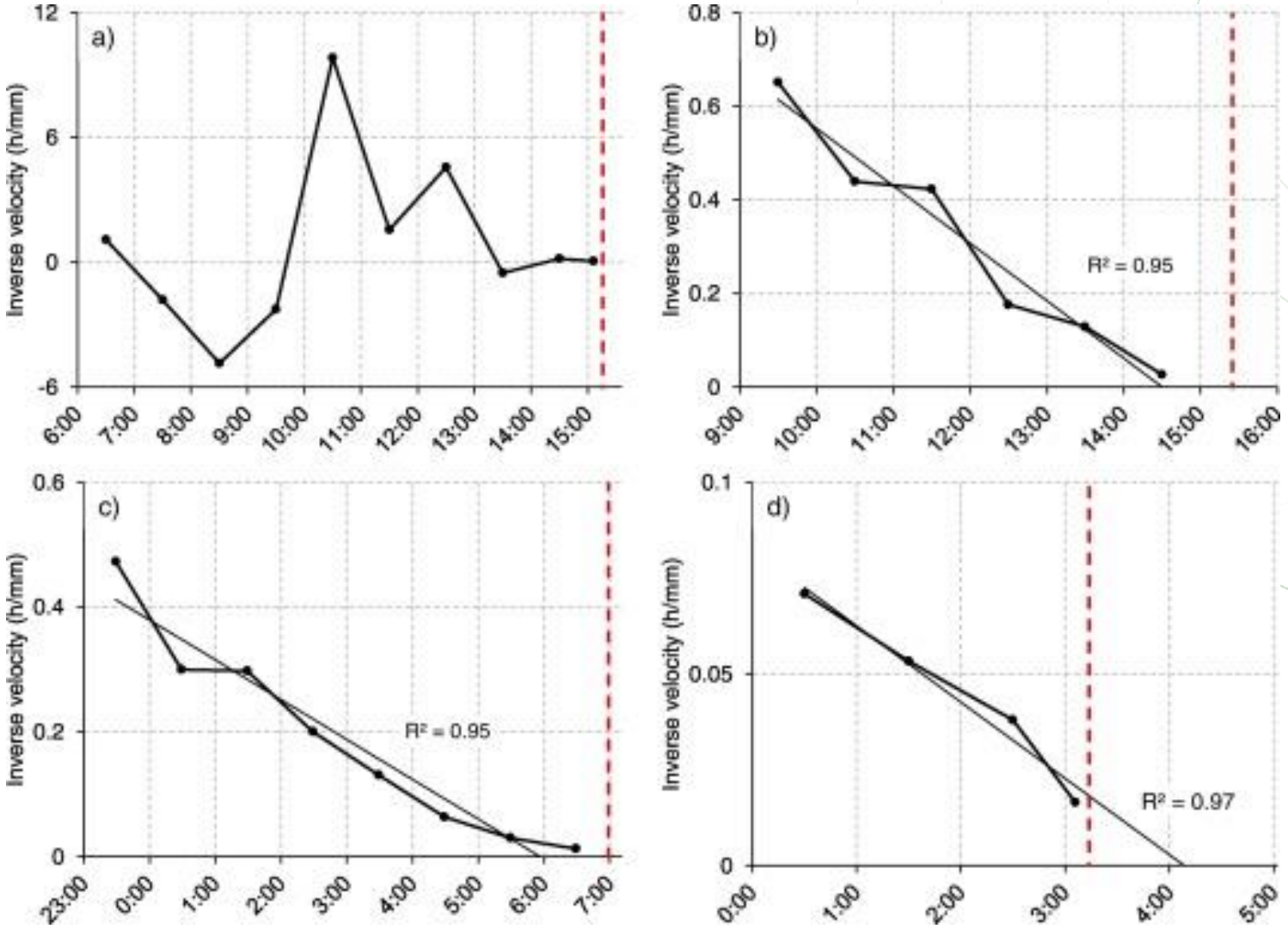
Carlà et al. (2017)

Open-pit mine in hard rock

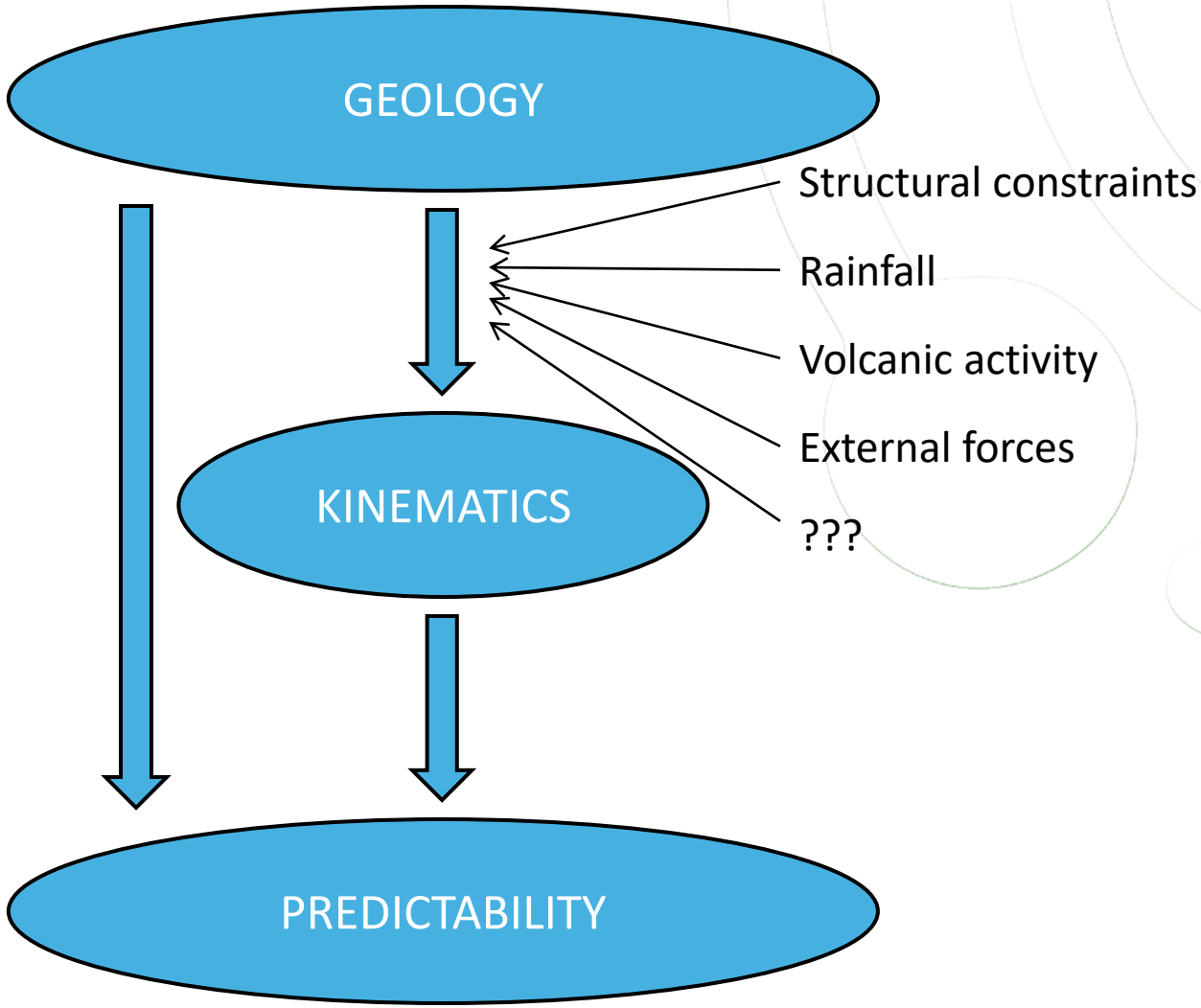


Carlà et al. (2017)

Open-pit mine in hard rock



Carlà et al. (2017)

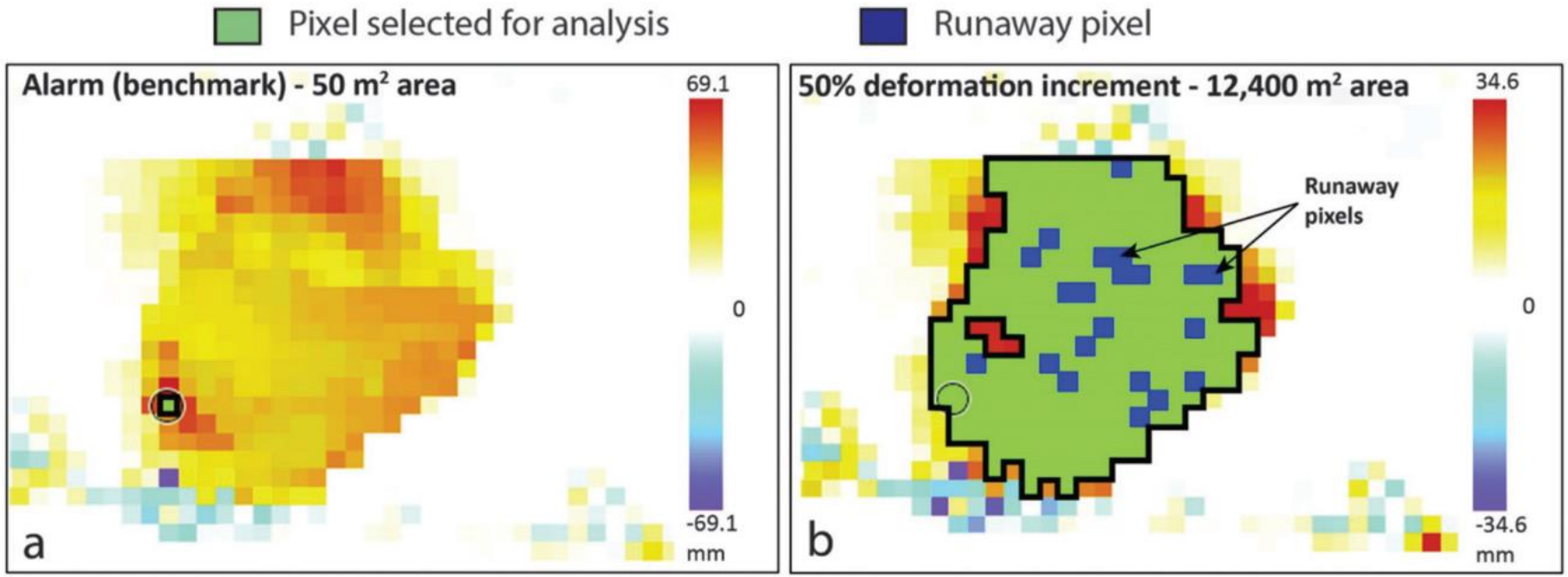

GEOLOGY
KINEMATICS
PREDICTABILITY
Structural constraints
Rainfall
Volcanic activity
External forces
???

Fukuzono linearity

- The linear model applies to the most part of slope failures (both first time and reactivations) in a "simple" geological environment (i.e. with a single main driving factor of instability)
- Non-linear (asympthotic) behaviour has been observed in first time failures during volcano eruptions
- In many cases reactivated failures exhibit a brittle behavior (related to the linear model). Key reference: HUTCHINSON J.N. (1987) - *Mechanisms producing large displacements in landslides on pre-existing shears. 1st Sino-British Geol. Conf., Tapei, Memoir of the Geological Survey of China, 9, 175-200.*

Future perspectives, opportunities and challenges

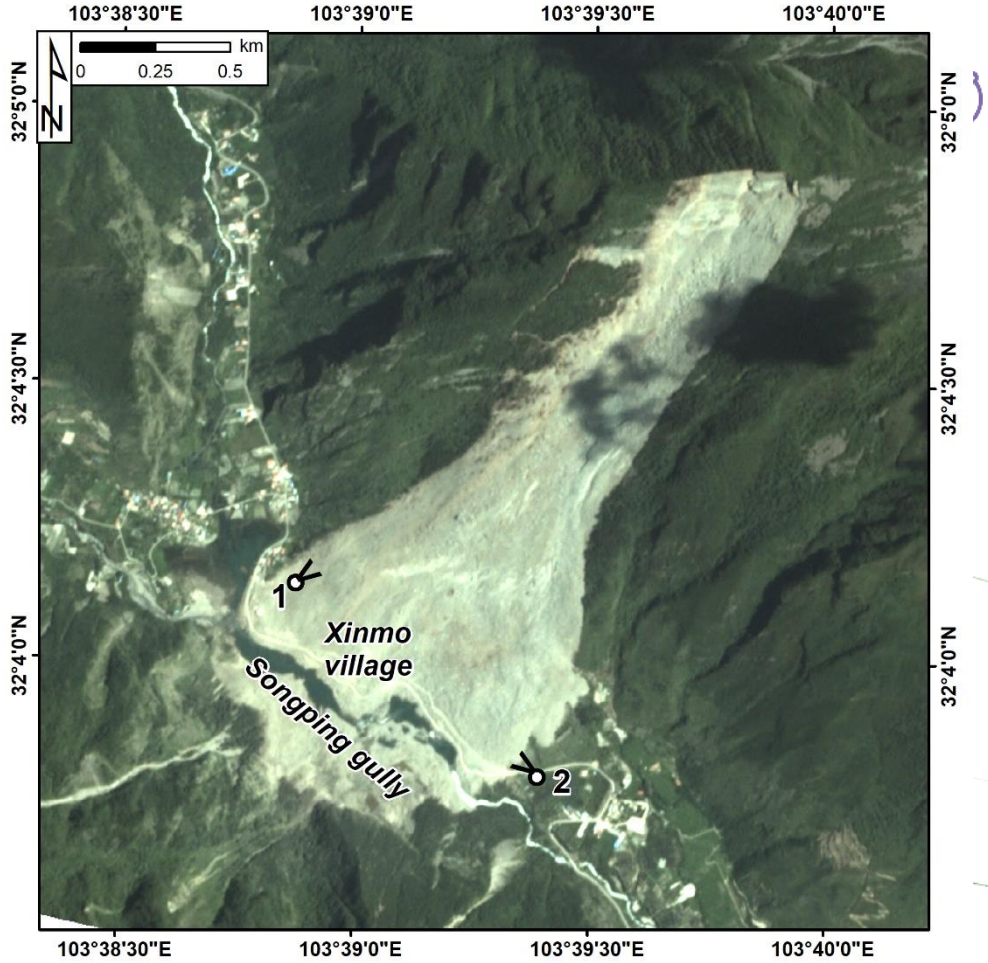
Exploiting GB-InSAR spatial analysis



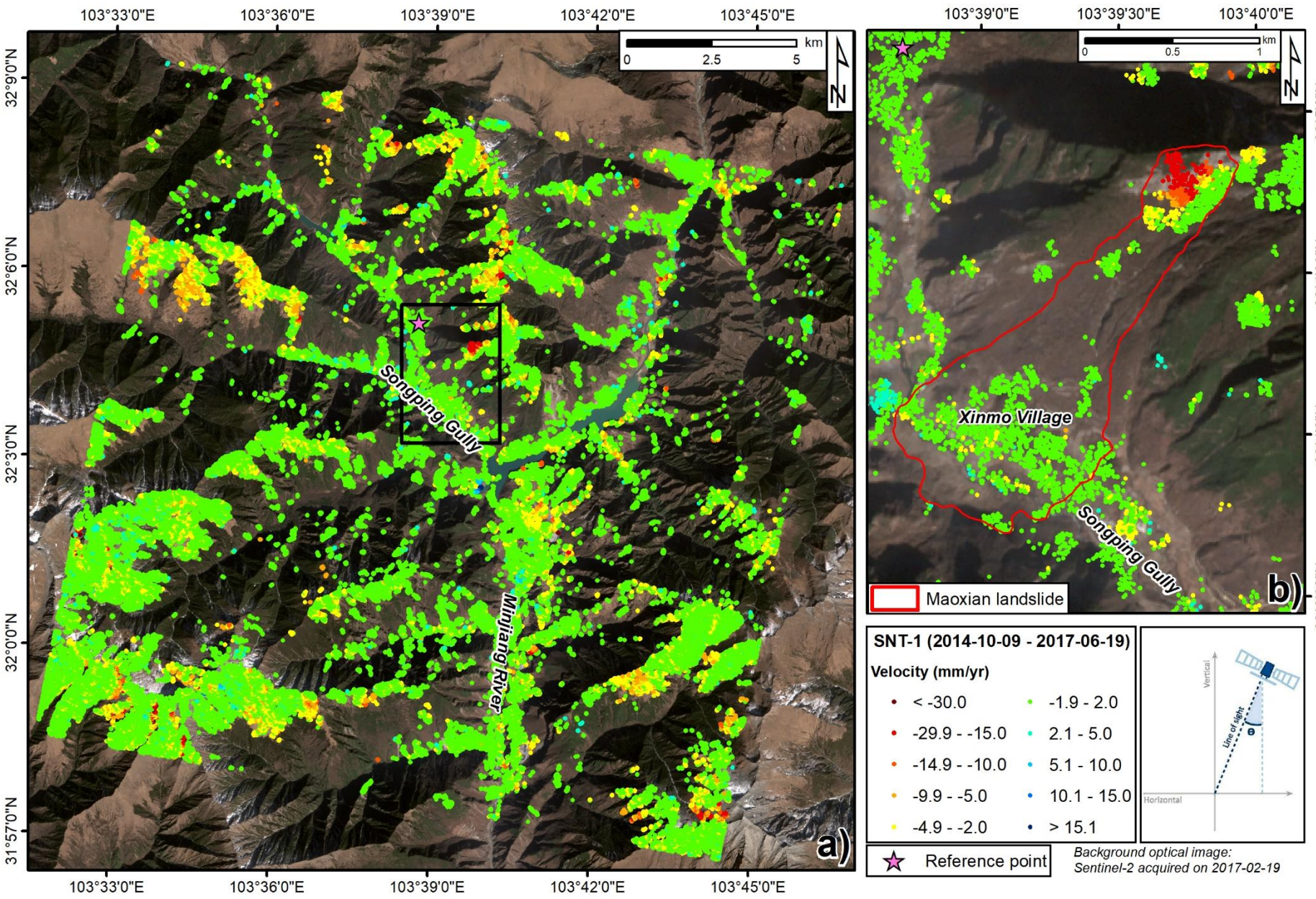
Dick et al. (2015)

Xinmo (Maoxian, China)

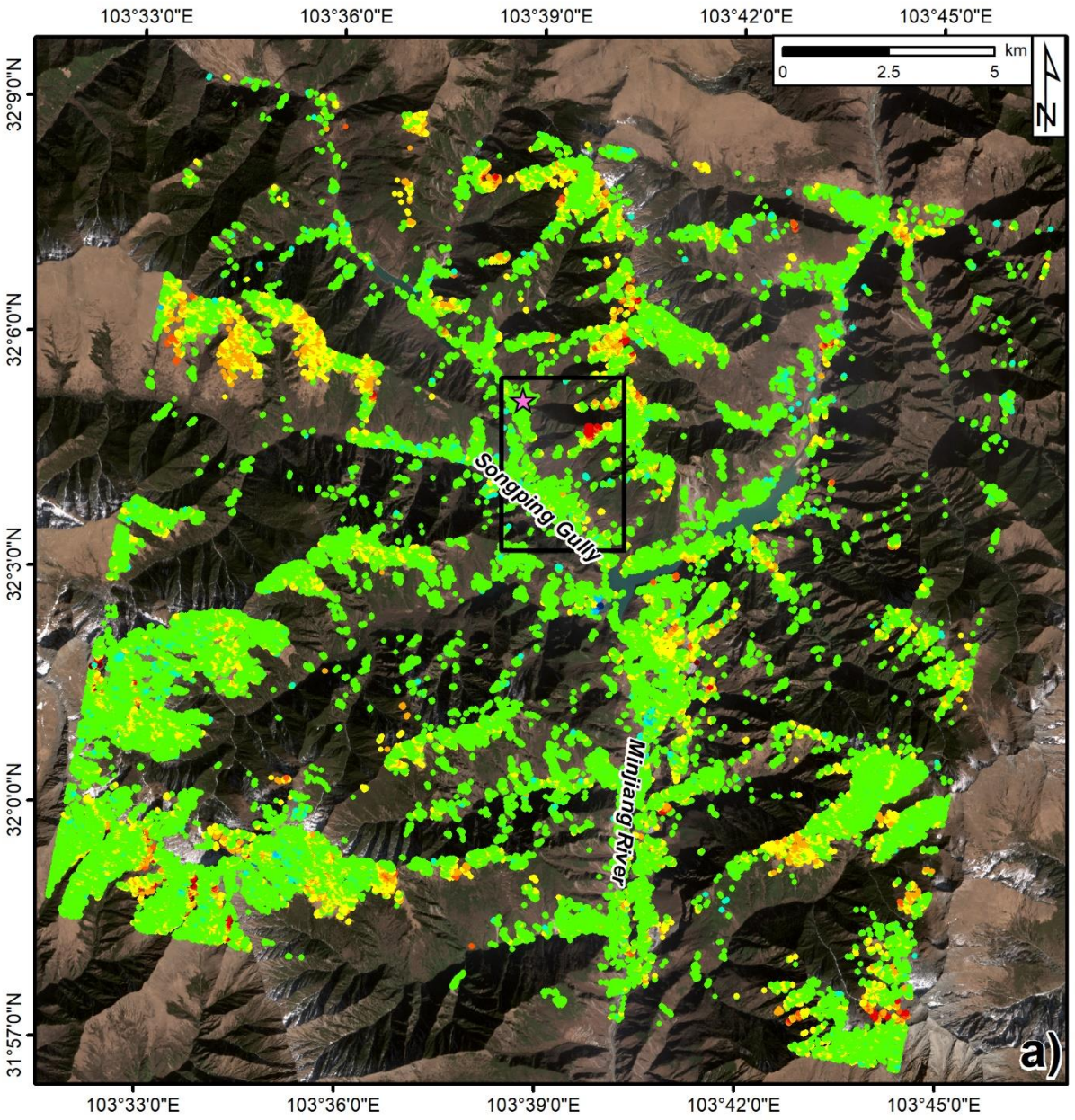
- 24 June 2017
- 18 million m^3
- More than 100 people killed
- Highly seismic area (earthquakes reaching M=8.0 in the last century)



Intrieri et al. (2018)

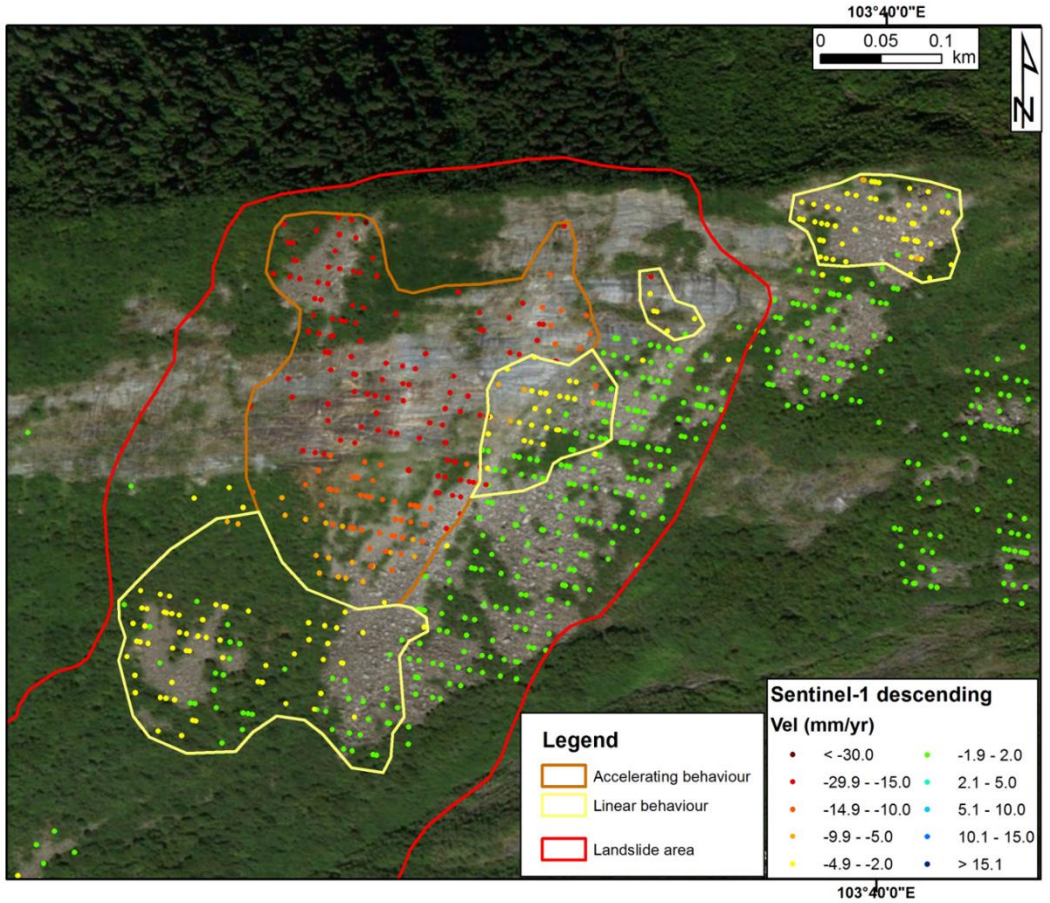


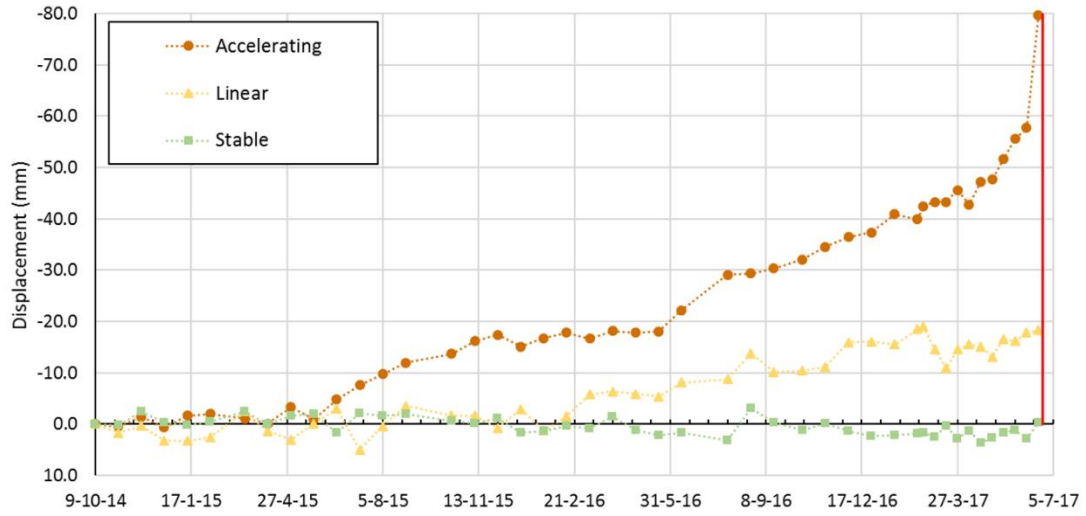
Intrieri et al. (2018)



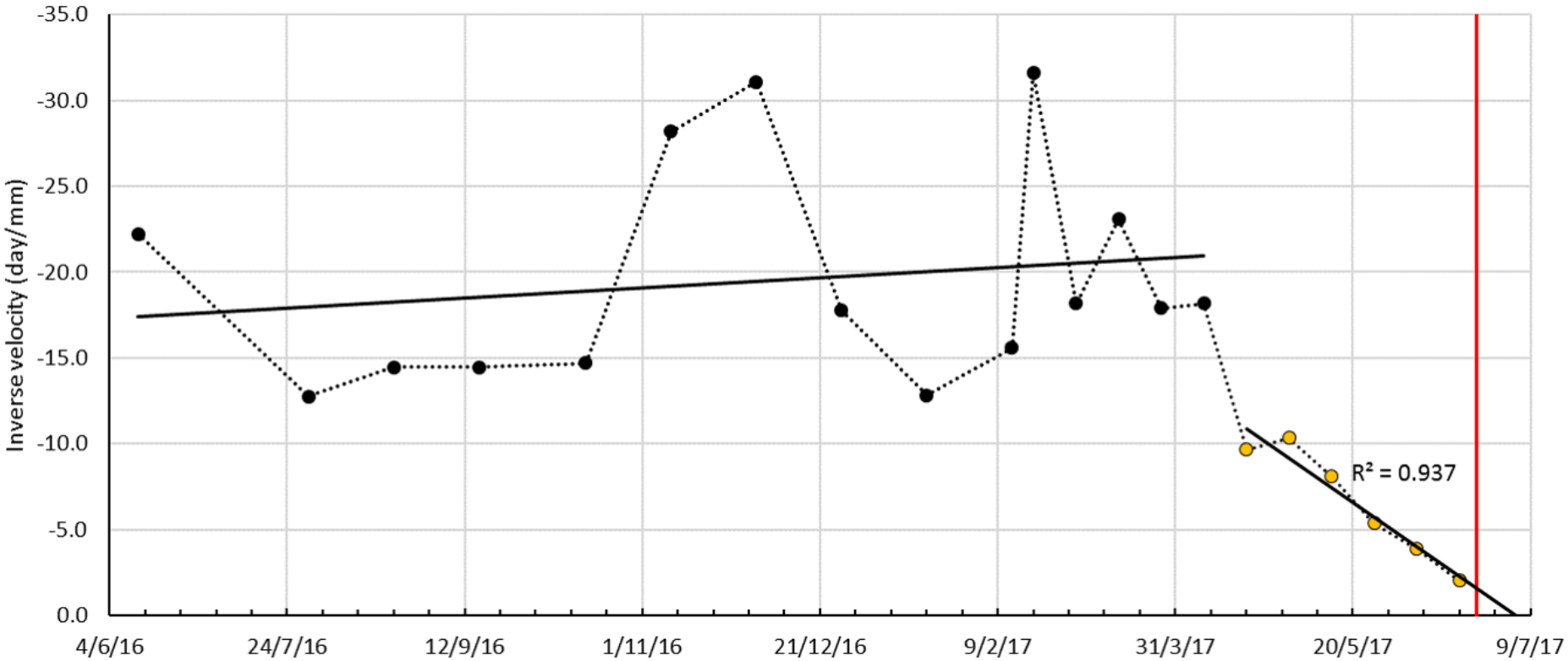
- Sentinel-1 multi-interferogram analysis
- C-band (5.6-cm wavelength)
- Interferometric Wide swath mode (250 km swath)
- 5 m x 14 m spatial resolution
- 45 images spanning from 9 October 2014 to 19 June 2017
- 130.000 measurement points (SqueeSAR technique)

Intrieri et al. (2018)



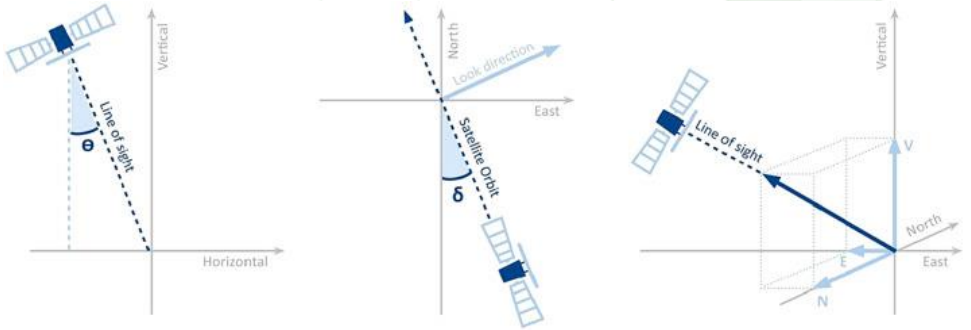


Intrieri et al. (2018)



Intrieri et al. (2018)

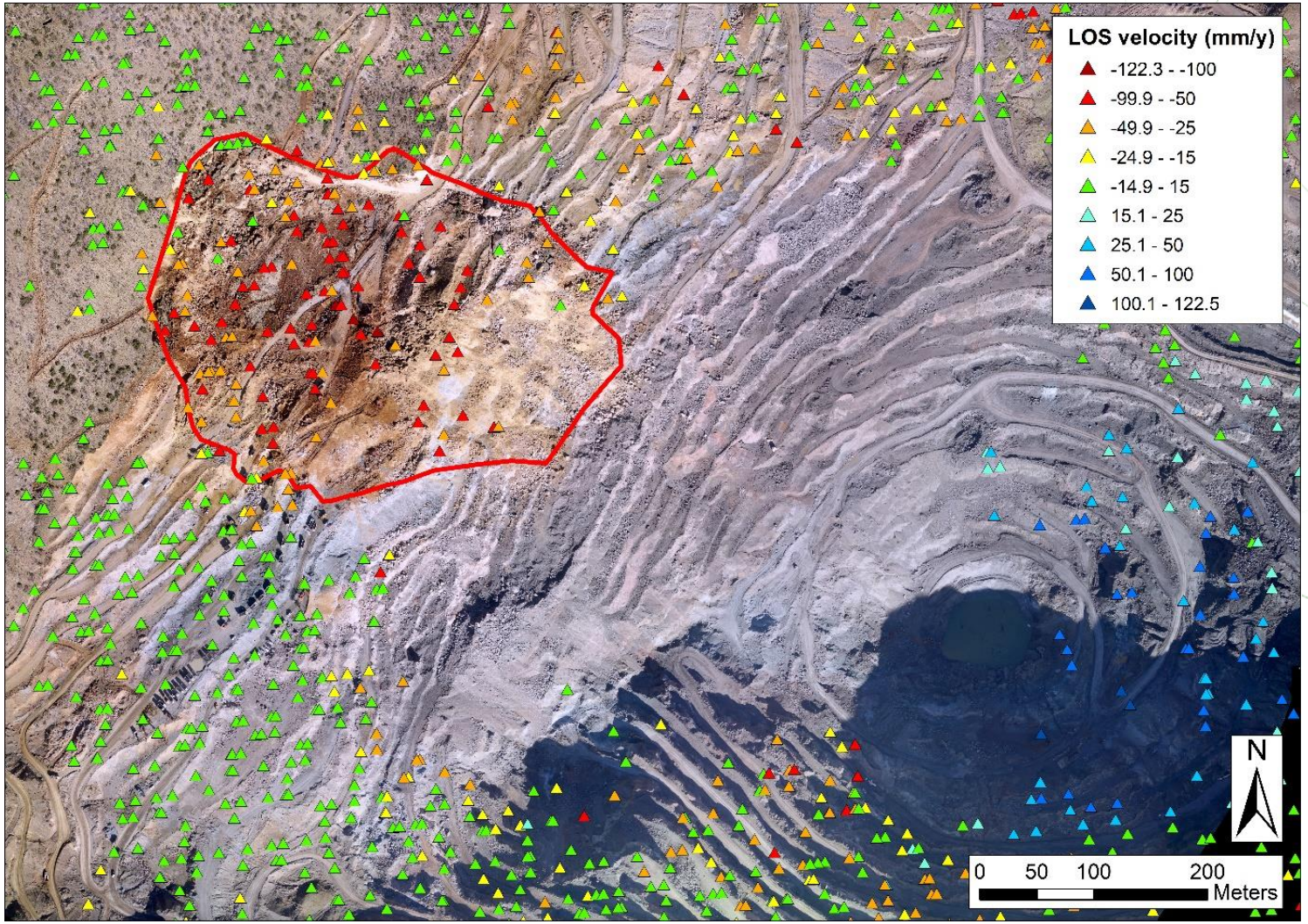
Copper open-pit mine



Sentinel-1
Ascending orbit
$\theta = 39.22°$; $\delta = 8.31°$

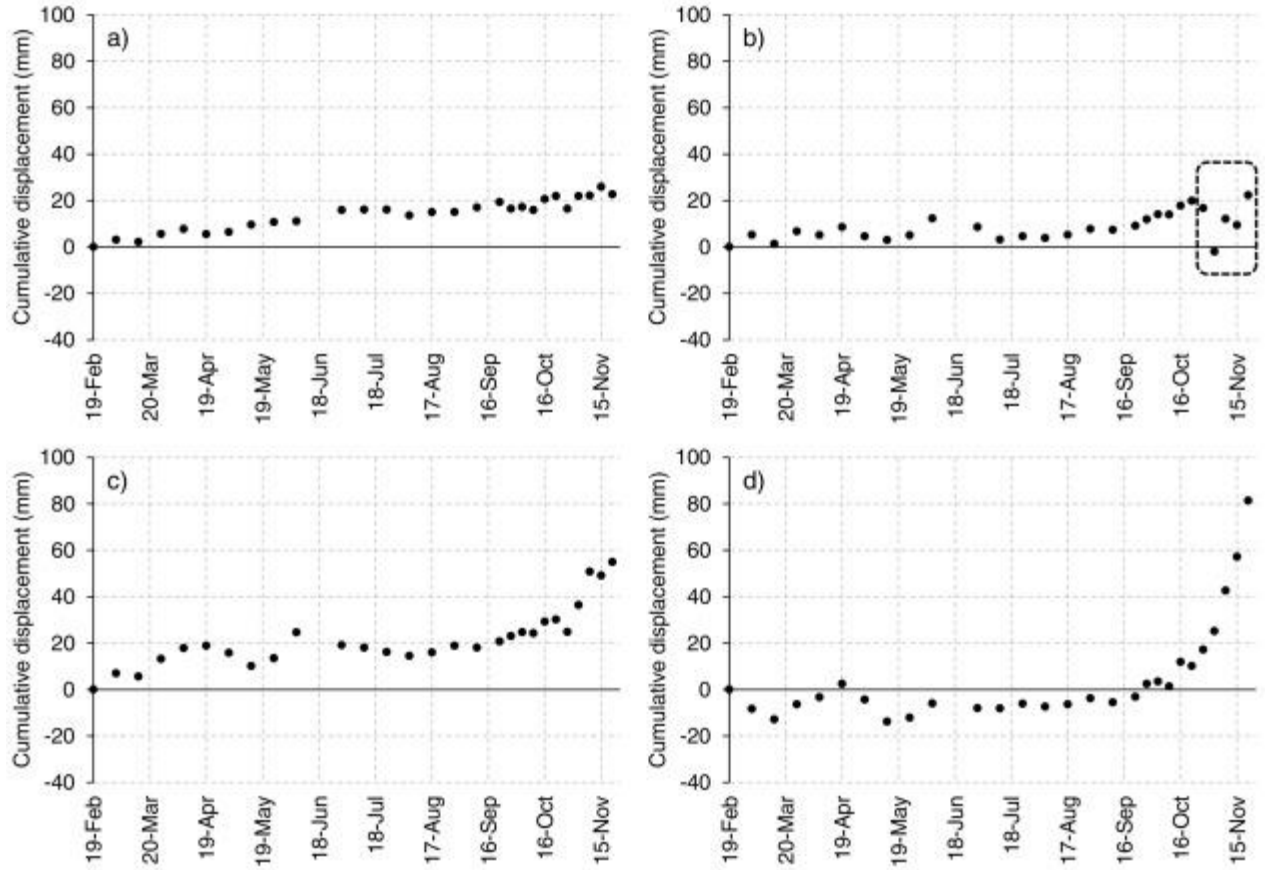
Carlà et al. (2018)

Copper open-pit mine



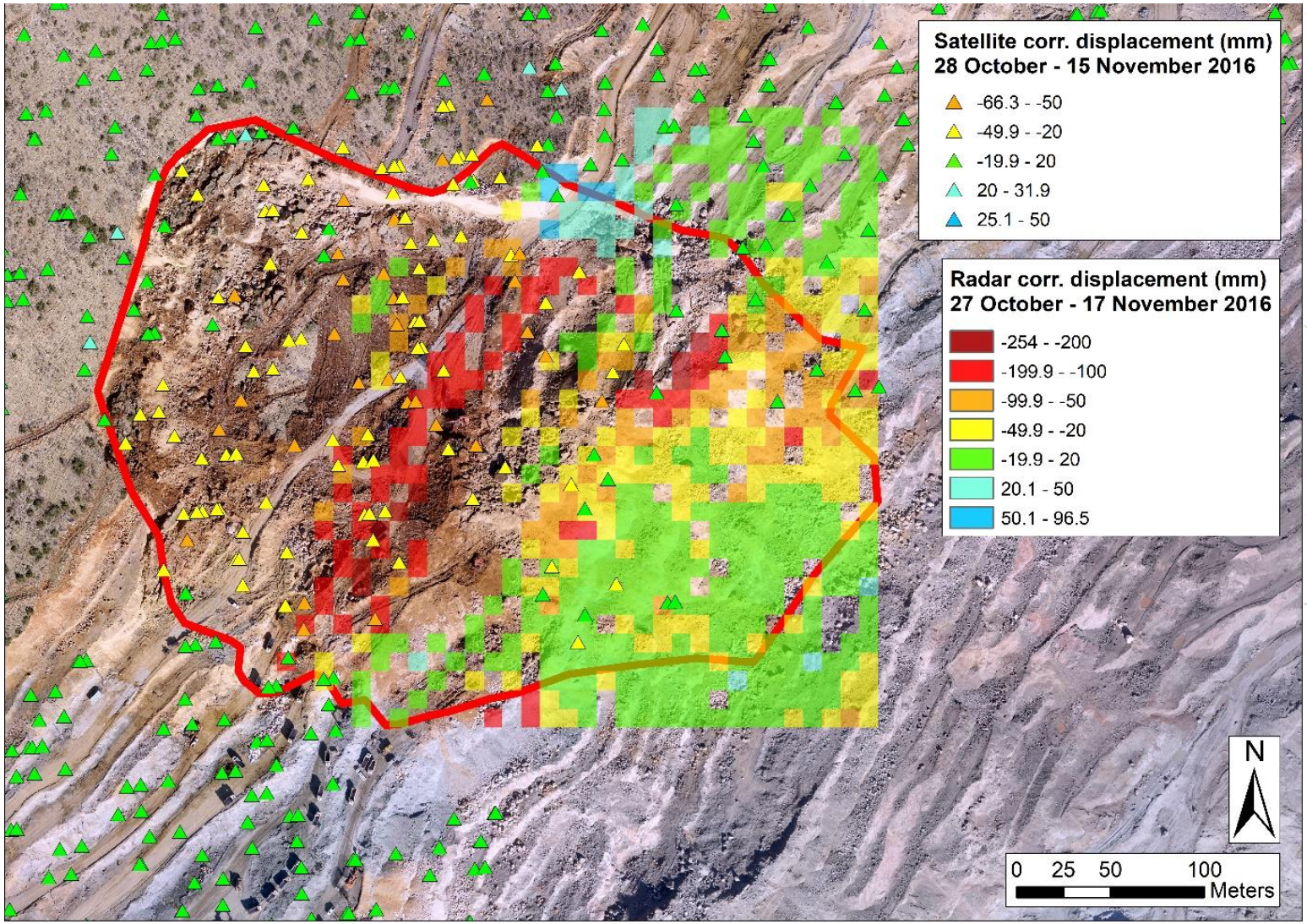
Carlà et al. (2018)

Copper open-pit mine



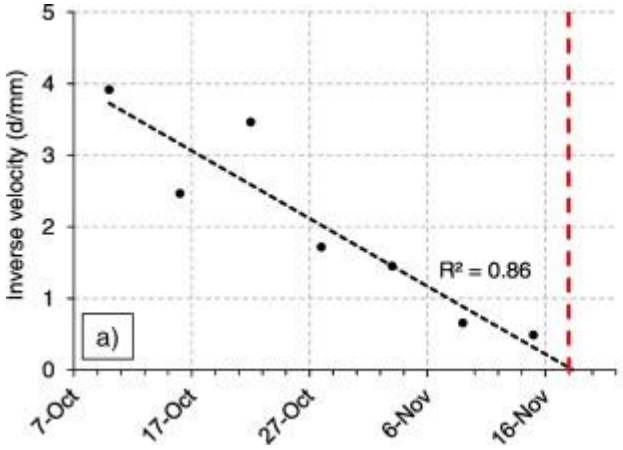
Carlà et al. (2018)

Copper open-pit mine

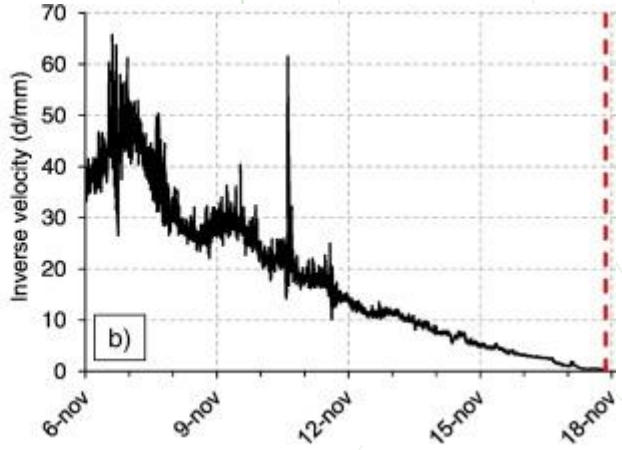


Carlà et al. (2018)

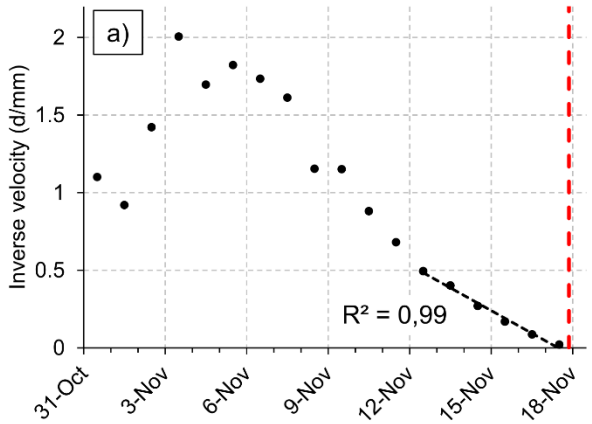
Copper open-pit mine



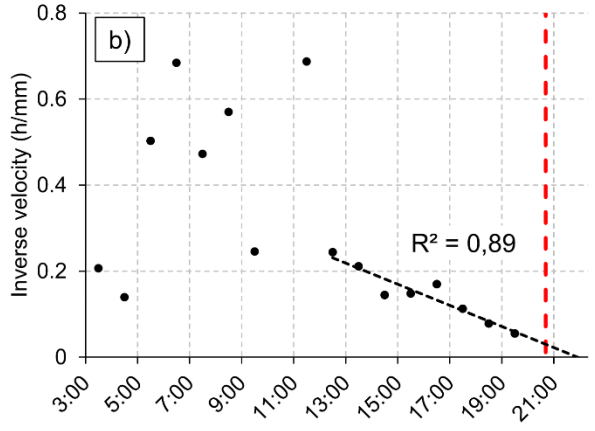
Sentinel-1



GB-InSAR



GB-InSAR
(daily average)



GB-InSAR
(hourly average)

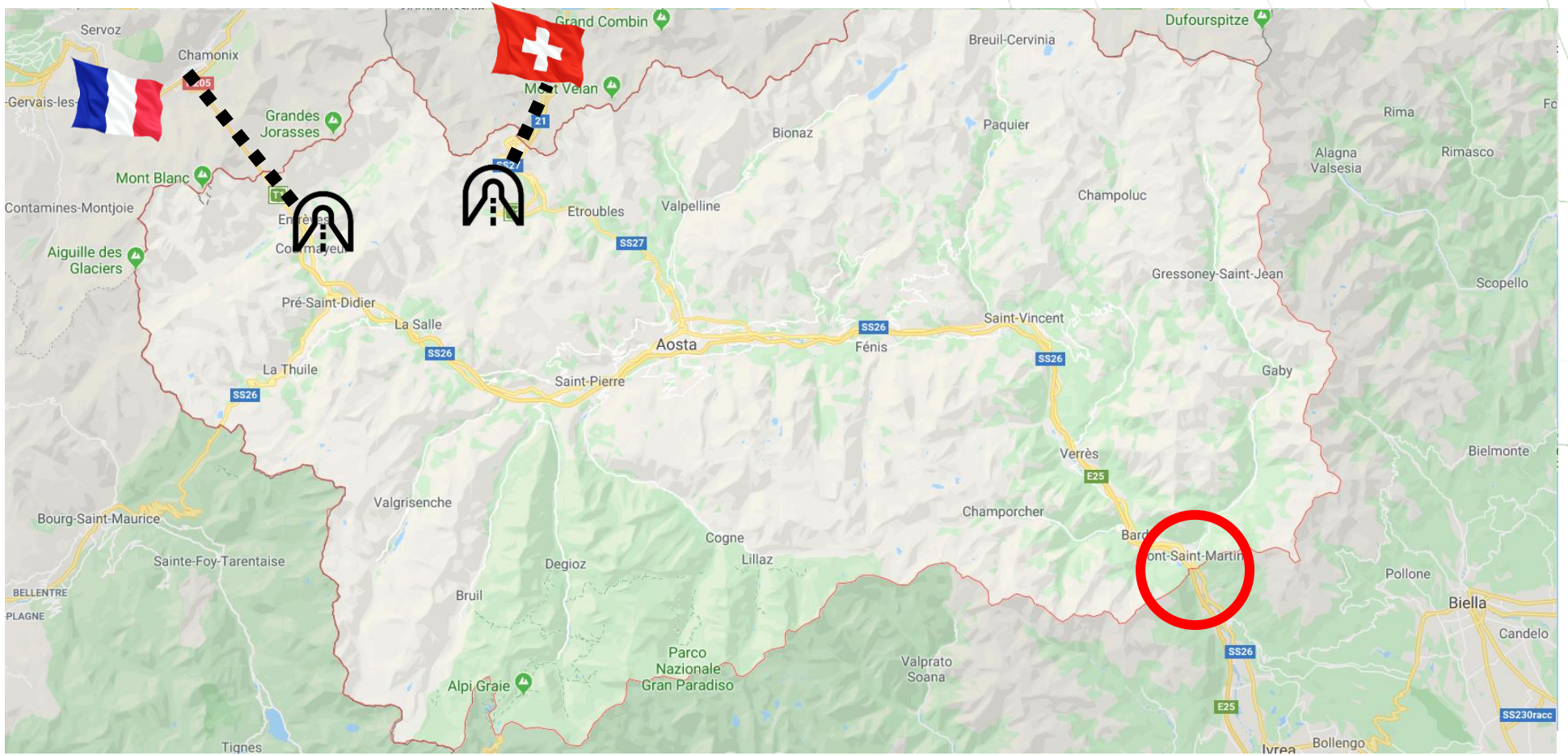
Carlà et al. (2018)

Simulation

Location


Bern
SWITZERLAND
Vaduz
LIECHTENSTEIN
AUSTRIA
HUNGARY
Rhine
Lake Geneva
Inn
Drava
Mur
Balaton
Danube
Bolzano
TRENTINO-ALTO ADIGE
Tarviso
FRUILI-VENEZIA GIULIA
SLOVENIA
Ljubljana
Zagreb
Sava
Drava
SERBIA AND MONT.
Sondrio
Lecco
Trento
Belluno
Pordenone
Udine
Varese
Como
Bergamo
Brescia
VENETO
Treviso
Trieste
FRANCE
Milan
Vicenza
Gulf of Venice
CROATIA
Novara
LOMBARDY
Verona
Padova
Venice
Pavia
Lodi
Cremona
Adige
Mantova
Rovigo
Piacenza
Parma
Ferrara
Alessandria
Reggio Nell'Emilia
Modena
Bologna
Cuneo
Savona
Genoa
EMILIA-ROMAGNA
Ravenna
La Spezia
Massa
Forlì
Rimini
Imperia
MONACO
Pistoia
Prato
Pesaro
SAN MARINO
Lucca
Pisa
Florence
Ligurian Sea
Livorno
Ancona
Macerata
Adriatic Sea
Siena
Arezzo
Perugia
MARCHE
TUSCANY
UMBRIA
Ascoli Piceno
Grosseto
Elba
Terni
Teramo
Pescara
Viterbo
Rieti
L'Aquila
Chieti
LAZIO
ABRUZZO
Corsica (FR.)
VATICAN CITY
Rome
Isernia
MOLISE
Frosinone
Campobasso
Foggia
Strait of Bonifacio
Latina
CAMPANIA
Barletta
Caserta
Benevento
Bari
Olbia
Avellino
PUGLIA
Brindisi
Tempio Pausania
Naples
Salerno
Potenza
Matera
Taranto
Sassari
BASILICATA
Strait of Otranto
Nuoro
Tyrrhenian Sea
Lecce
Golfo di Taranto
SARDEGNA
Otranto
Oristano
Lanusel
Sanluri
Cagliari
Sardinia
Carbonia
Cosenza
CALABRIA
Crotone
Catanzaro
ISOLE EOLIE
Vibo Valentia
Mediterranean Sea
Messina
Palermo
Ionian Sea
Trapani
Reggio di Calabria
SICILIA
Stretto di Messina
Caltanissetta
Enna
Catania
Strait of Sicily
Agrigento
Sicily
Siracusa
Gela
Ragusa
Tunis
Pantelleria

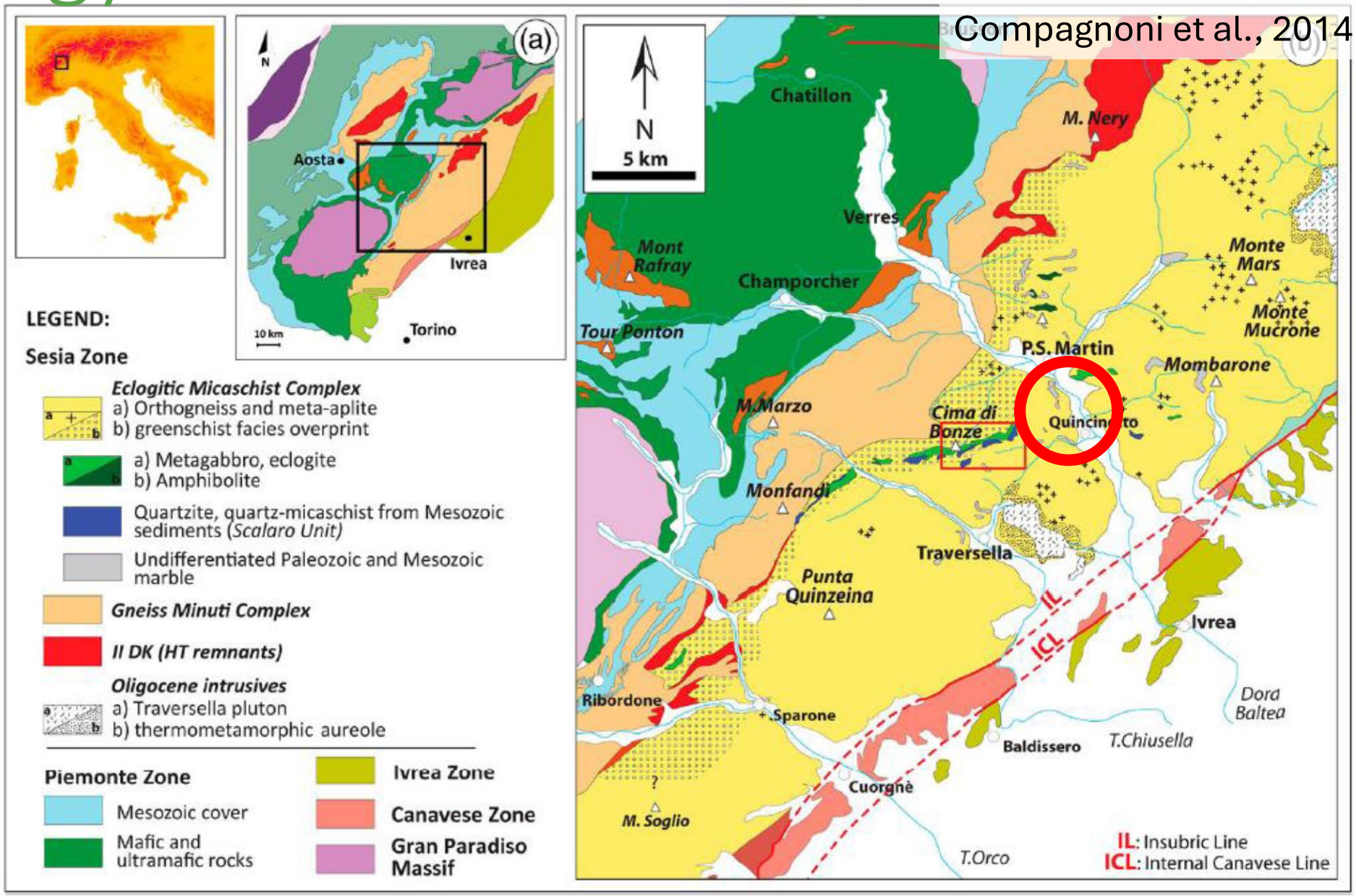
Motorway A5 Torino-Aosta



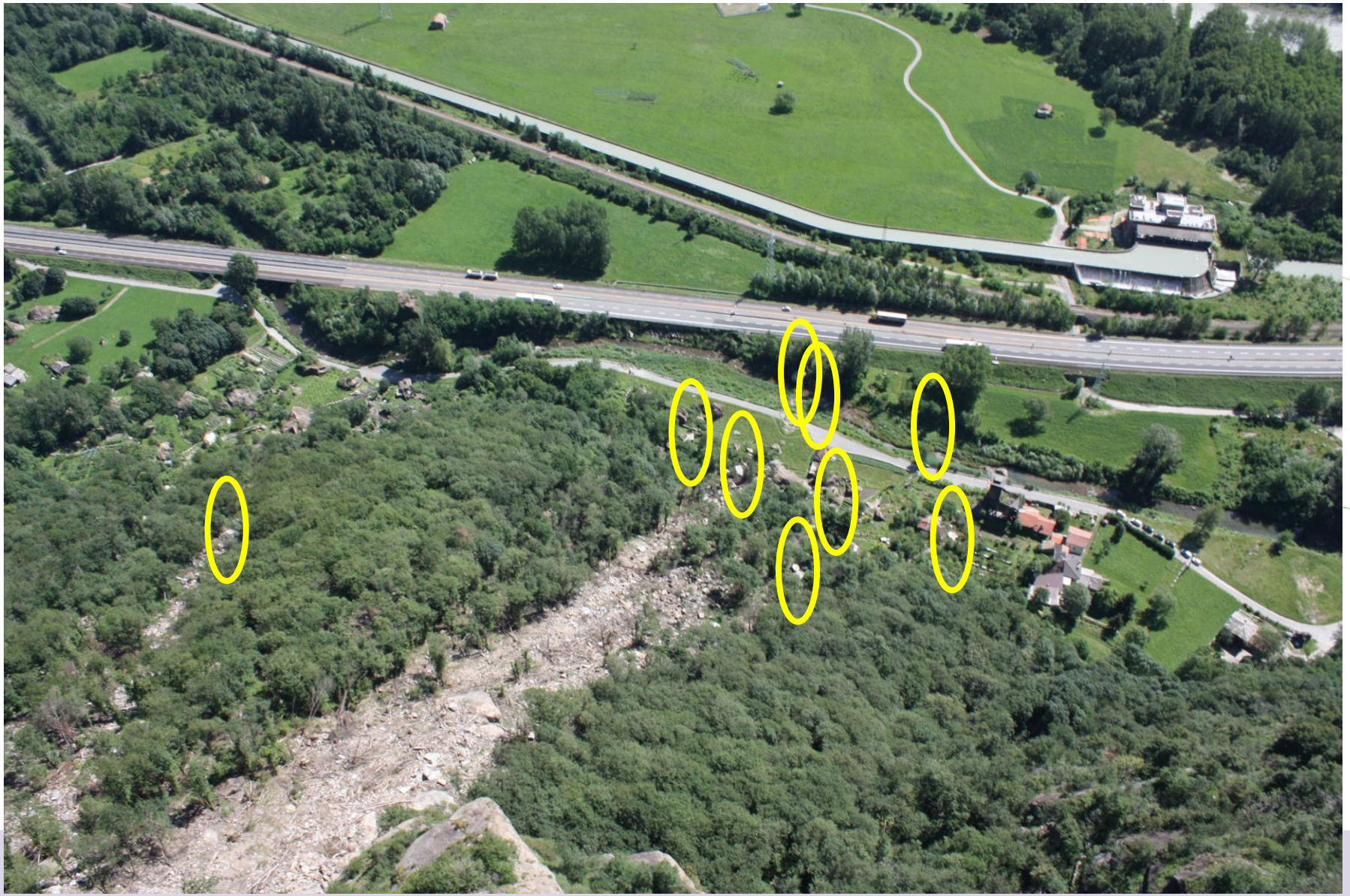
Dora Baltea Valley

The slope

Geology


Compagnoni et al., 2014
(a)
N
Aosta
Ivrea
Torino
10 km
(b)
N
5 km
Chatillon
M. Nery
Verres
Mont Rafray
Champorcher
Monte Mars
Monte Mucrone
Tour Ponton
P.S. Martin
Mombarone
M.Marzo
Cima di Bonze
Quincinetto
Monfandi
Traversella
Punta Quinzeina
IL
ICL
Ivrea
Ribordone
Sparone
Dora Baltea
Baldissero
T.Chiusella
Cuorgnè
M. Soglio
T.Orco
IL: Insubric Line
ICL: Internal Canavese Line
LEGEND:
Sesia Zone
Eclogitic Micaschist Complex
a) Orthogneiss and meta-aplite
b) greenschist facies overprint
a) Metagabbro, eclogite
b) Amphibolite
Quartzite, quartz-micaschist from Mesozoic sediments (Scalaro Unit)
Undifferentiated Paleozoic and Mesozoic marble
Gneiss Minuti Complex
II DK (HT remnants)
Oligocene intrusives
a) Traversella pluton
b) thermometamorphic aureole
Piemonte Zone
Mesozoic cover
Mafic and ultramafic rocks
Ivrea Zone
Canavese Zone
Gran Paradiso Massif

Recent events



Recent events

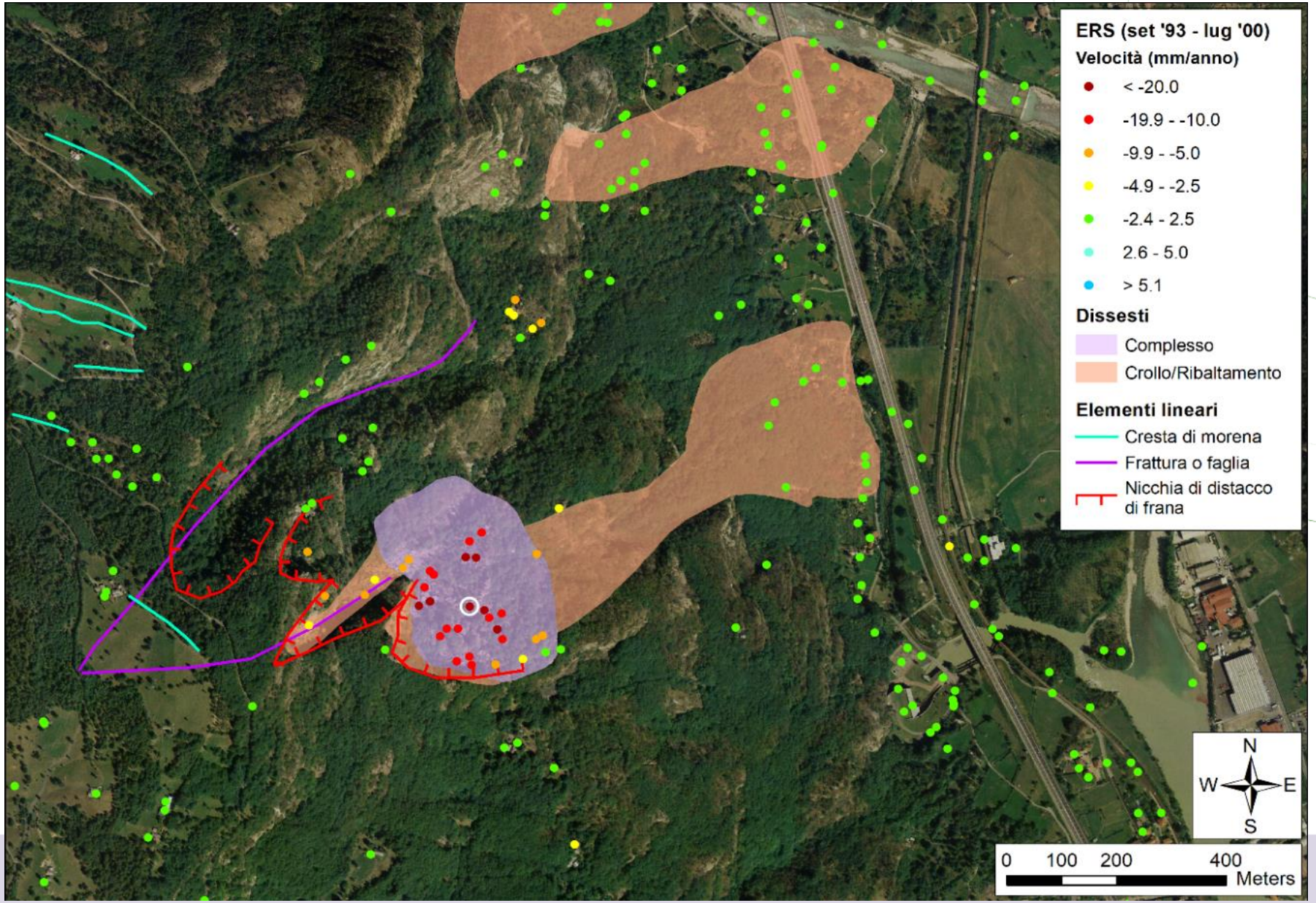
Recent events

Upper slope conditions

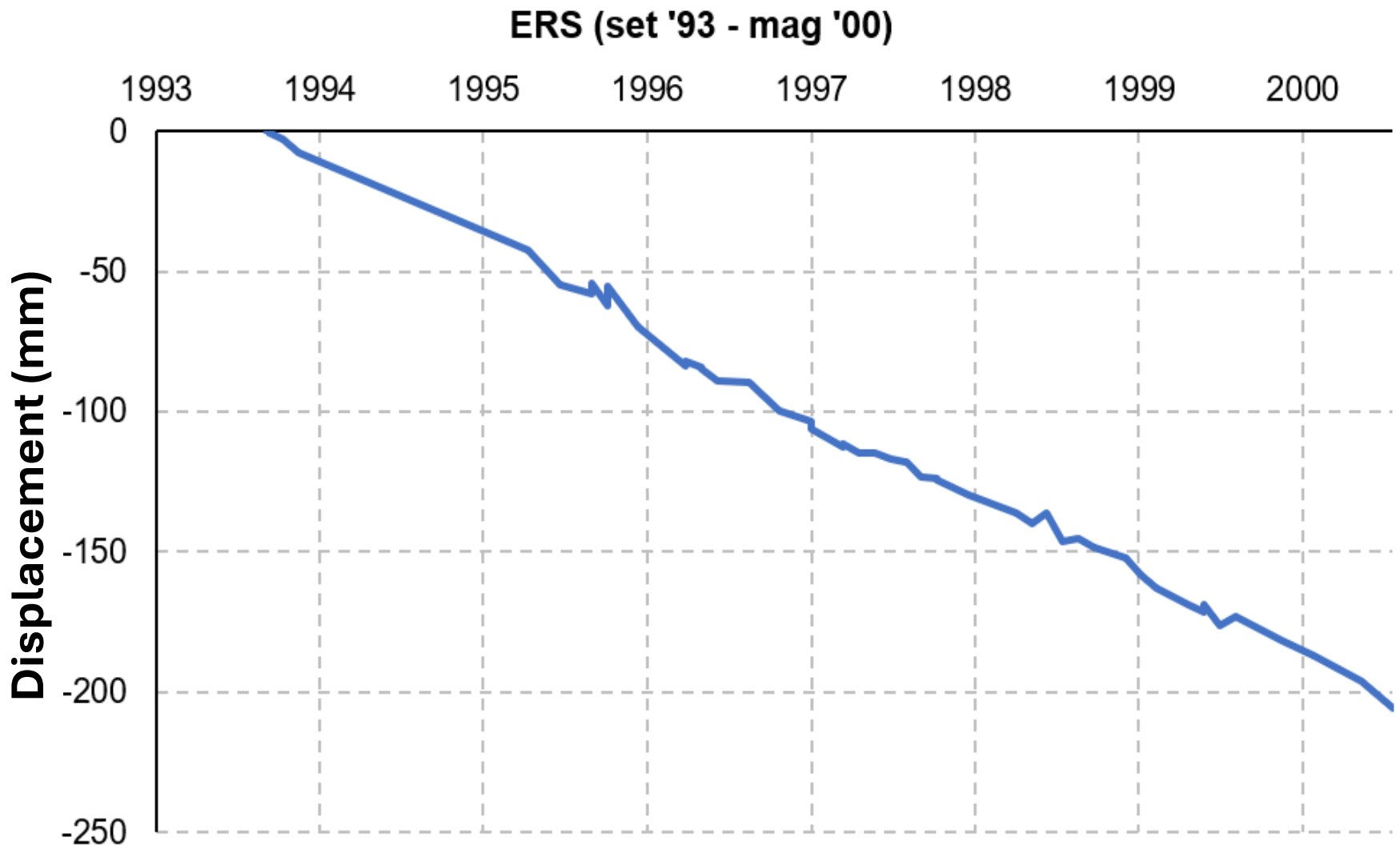
Upper slope conditions

Scenario definition

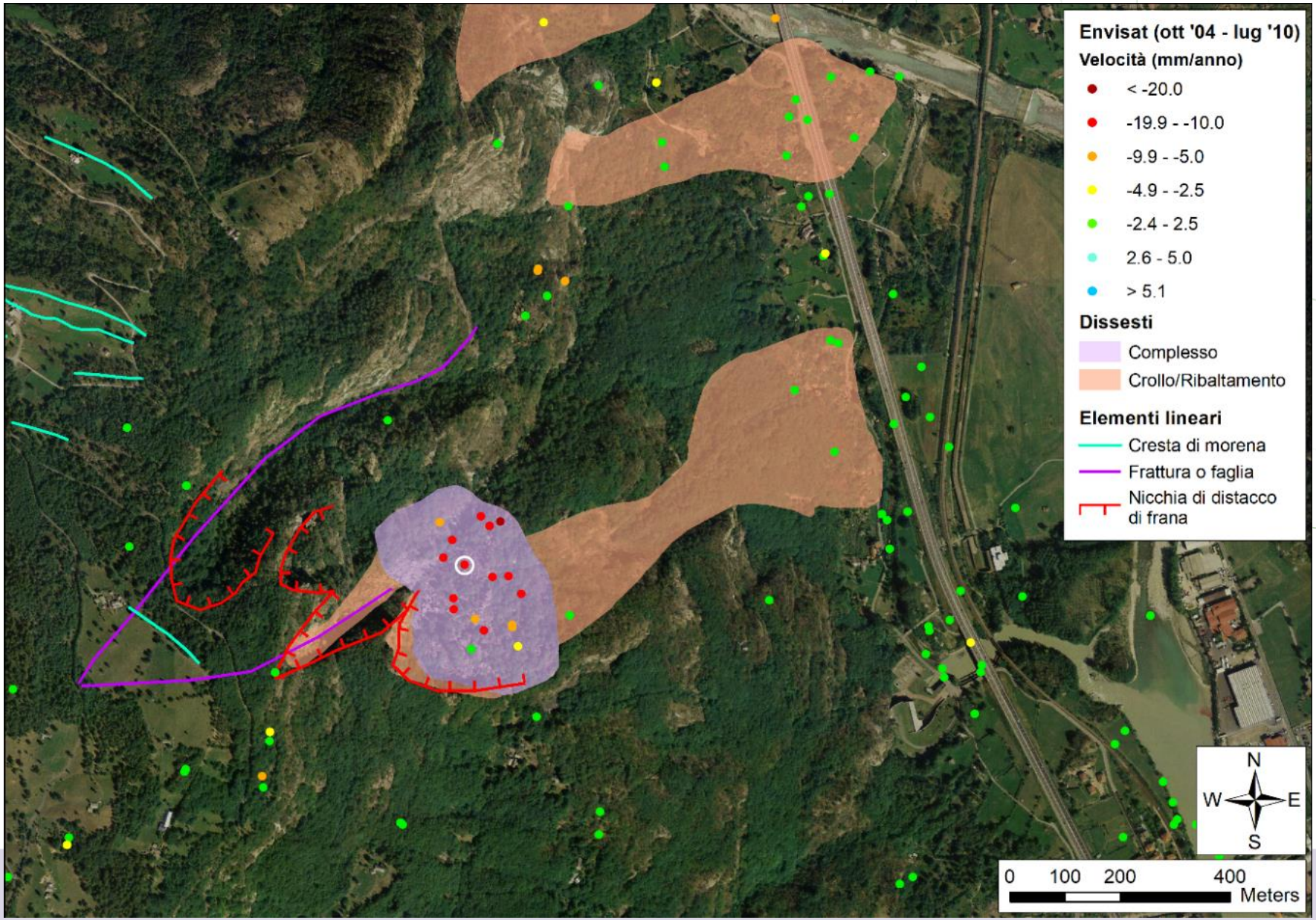
Satellite InSAR monitoring



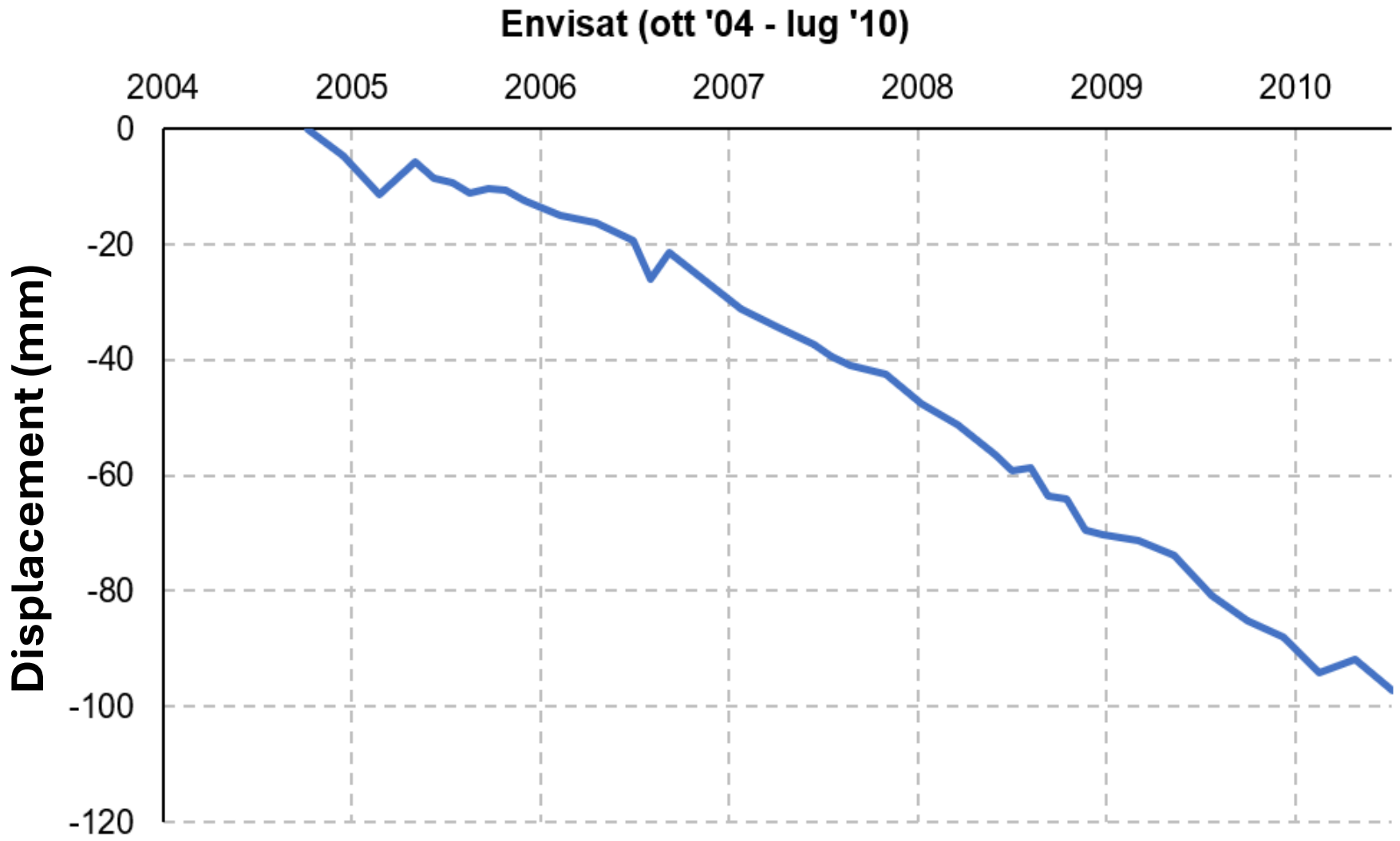
Satellite InSAR monitoring



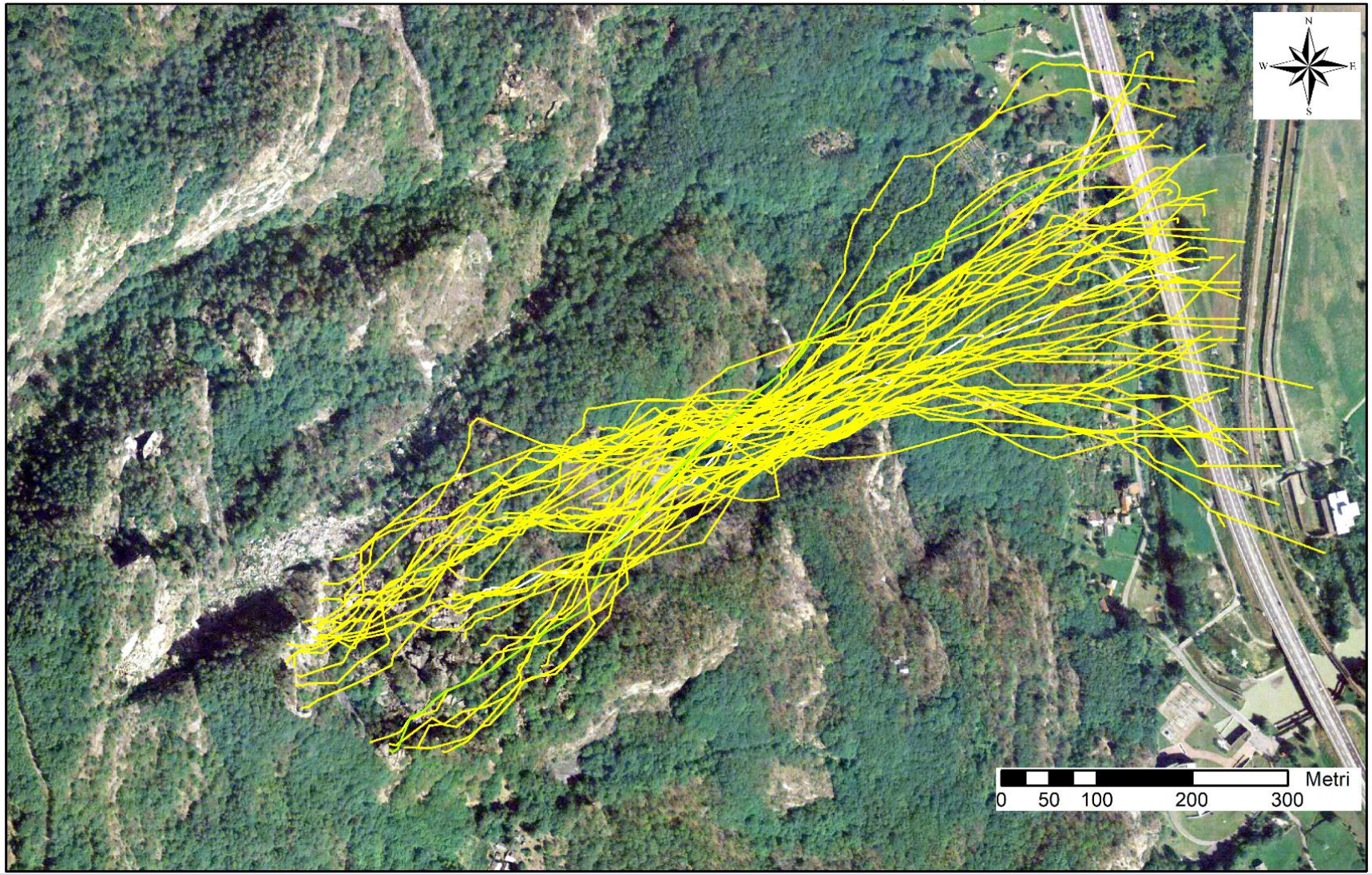
Satellite InSAR monitoring



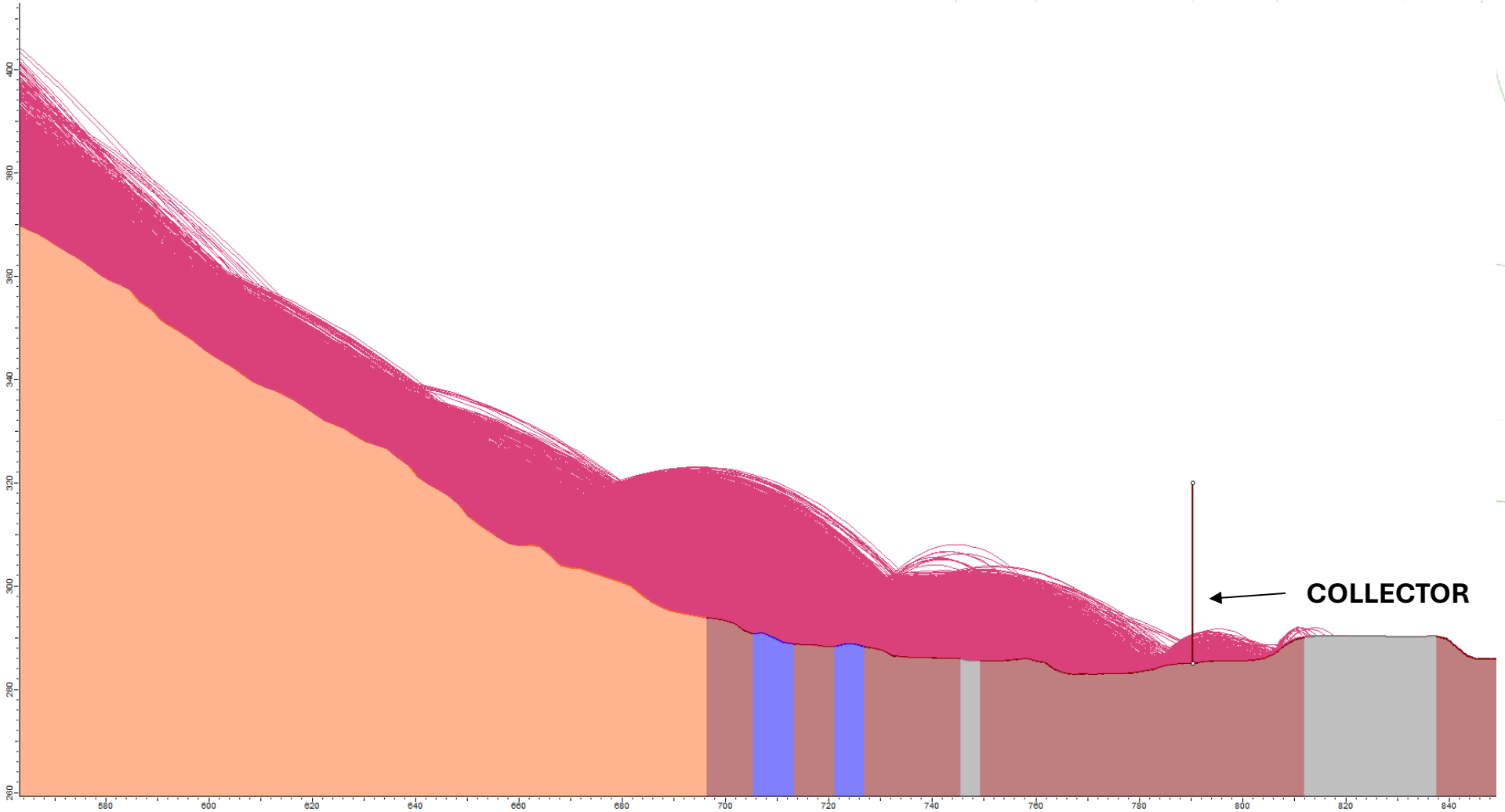
Satellite InSAR monitoring



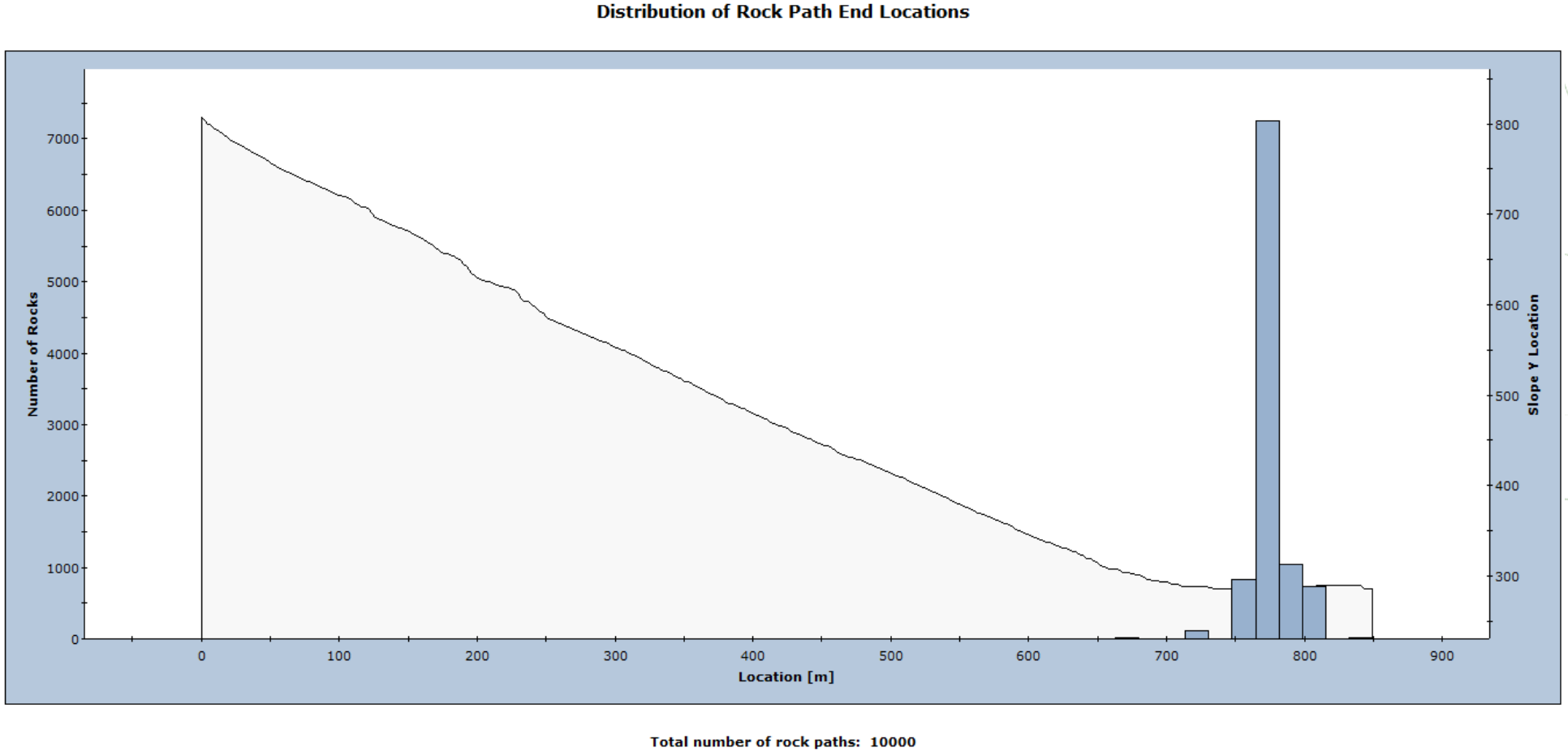
Runout simulations



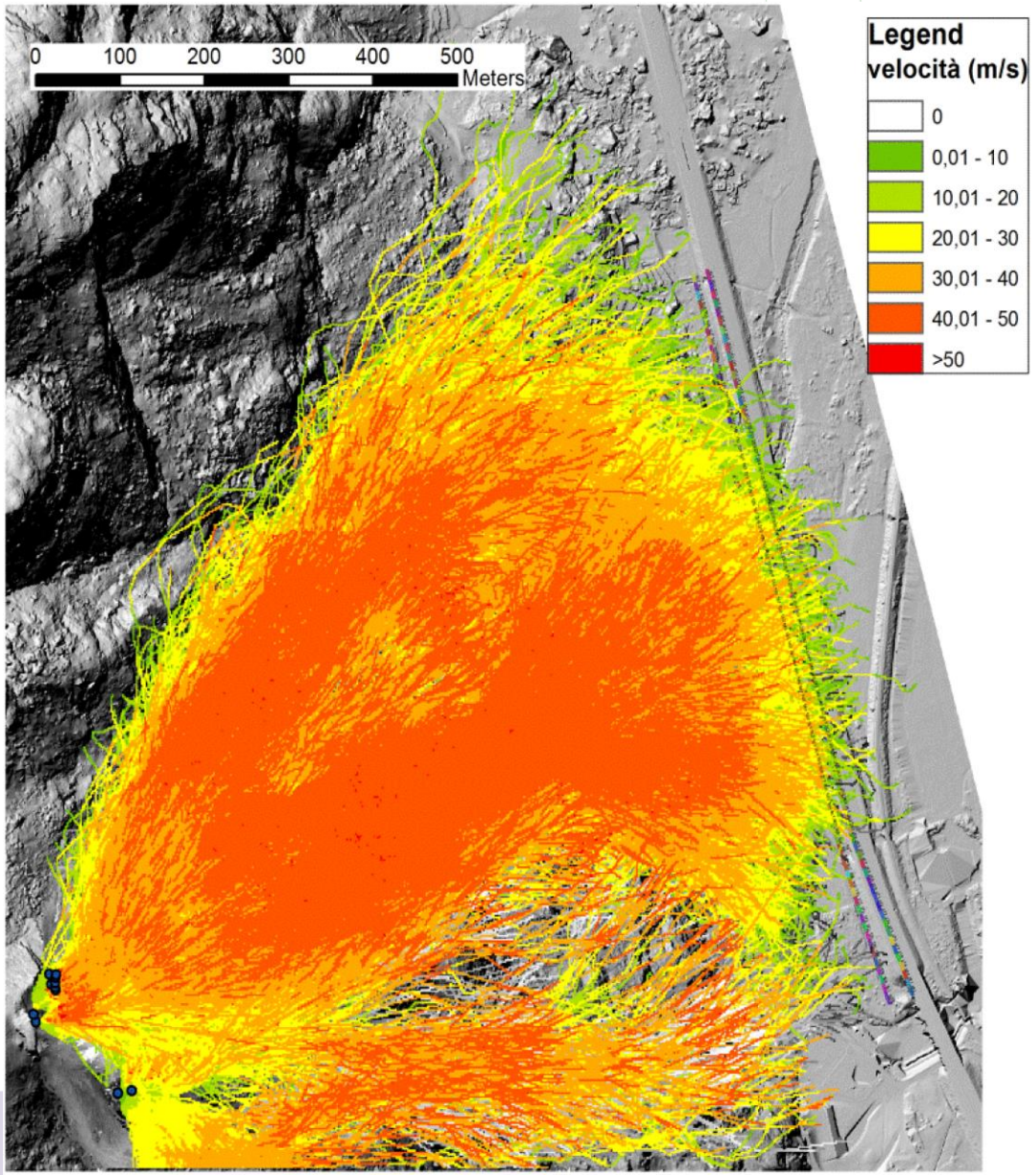
2D runout simulations



2D runout simulations



3D runout simulations

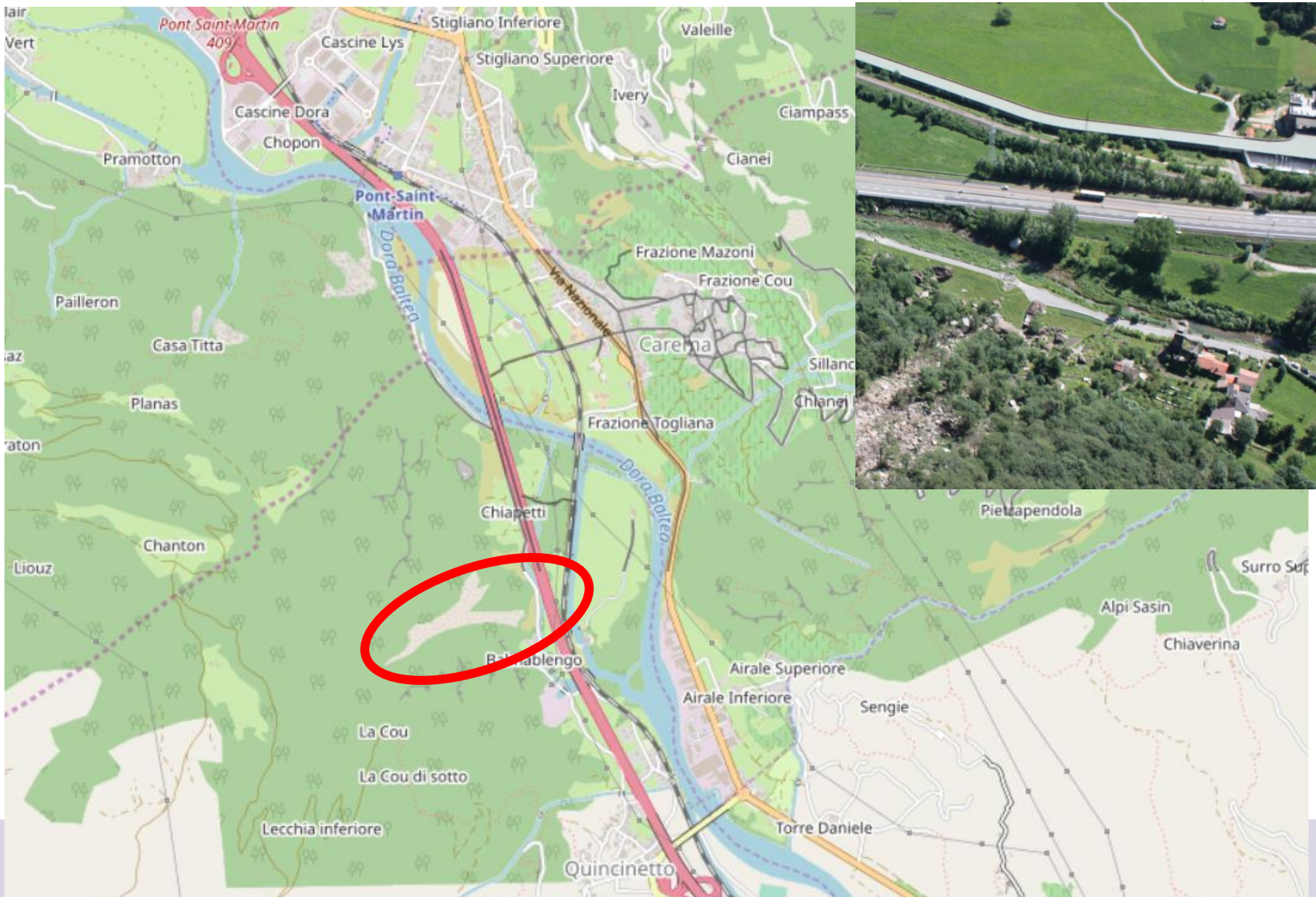


(SGI, 2017)

Runout simulations

Profile ID	Volume (m^3)	Number of blocks at collector	E_{max} (kJ)	H_{max} (m)
1	50	4097	115019	23.5
2	50	2262	123295	24.9
3	299.7	1574	473328	13.1
4	74.6	9346	176847	27.8
5	50	826	47361	8.1
6	50	1831	32772	7.1
7	50	7485	92174	16.5
8	108.3	2657	1037220	28.5
9	…	…	…	…

Elements at risk



Scenario summary

1. Most probable Scenario: rockfall

High probability of occurrence
Blocks up to 10 000 m^3
Short-term precursors
Probability of motorway involvement: High
Probability of railway involvement: Low

2. Most credible Scenario: rock avalanche

Low probability of occurrence
Volume up to 500 000 m^3
Long-term precursors
Probability of motorway involvement: Very high
Probability of railway involvement: High

Risk management activities

Involved institutions

ITINERIS

UNIVERSITÀ DEGLI STUDI FIRENZE

PROTEZIONE CIVILE

Prefettura di Torino

Ufficio Territoriale del Governo

REGIONE PIEMONTE

Regione Autonoma Valle d'Aosta

TORINO METROPOLI

Città metropolitana di Torino

ATIVA

Autostrada
Torino
Ivrea
Valle d'Aosta

SAV

Comune di Quincinetto

RFI

VIGILI DEL FUOCO CORPO NAZIONALE

Center of Competence

Centers of Competence provide the National Civil Protection Department with services, information, data, processing and technical-scientific contributions in specific fields.

The Center for Civil Protection of the University of Florence is a Center of Competence for monitoring and national surveillance aimed at geo-hydrological risk reduction.

Motorway and railway operators

Autostrada
Torino
Ivrea
Valle d'Aosta

The National Government grants concessions for motorways and railways allowing a private company to request a toll in exchange for investments and maintenance on the roads.

The motorway and railway operators provide signaling, maintenance and guarantee the safety on the communication lines.

Regions

REGIONE PIEMONTE

Regione Autonoma Valle d'Aosta

Regions are members of the National Service of Civil Protection and are in charge of civil protection activities.

They are responsible for the regional civil protection plan.

They manage the organization of civil protection systems within the Region and the Regional Operation Room.

Municipalities

Comune di Quincinetto

AND OTHERS

Mayors are the local civil protection authorities.

The Municipalities are responsible for the Municipal Civil Protection Plans.

They manages the Municipal Operational Center (C.O.C.) for prevention and emergency management

Prefecture

Prefettura di Torino

The Prefecture (territorial government office) is a peripheral body of the Ministry of the Interior which represents the National Government at local level.

Prefects ensure the exchange of information among the Department of Civil Protection, the Regions, the Municipalities, the firefighters and the police bodies.

The Prefect is responsible for urgent logistic and technical services at local level during major emergencies.

Police & Firefighters

Firefighters and police bodies are operational structures of the National Service of Civil Protection.

Their main task is to guarantee the safety of citizens and to maintain public order.

Volunteering organizations

Volunteering organizations provide support to the Operating Structures, particularly for surveillance and assistance activities.

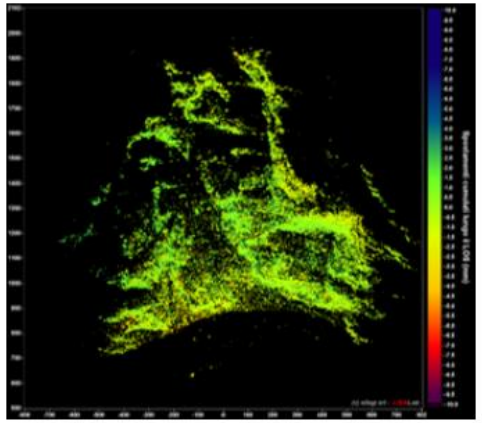
They represent an important link with the population.

Integrated monitoring system

UNIVERSITÀ DEGLI STUDI FIRENZE

PROTEZIONE CIVILE

Satellite InSAR

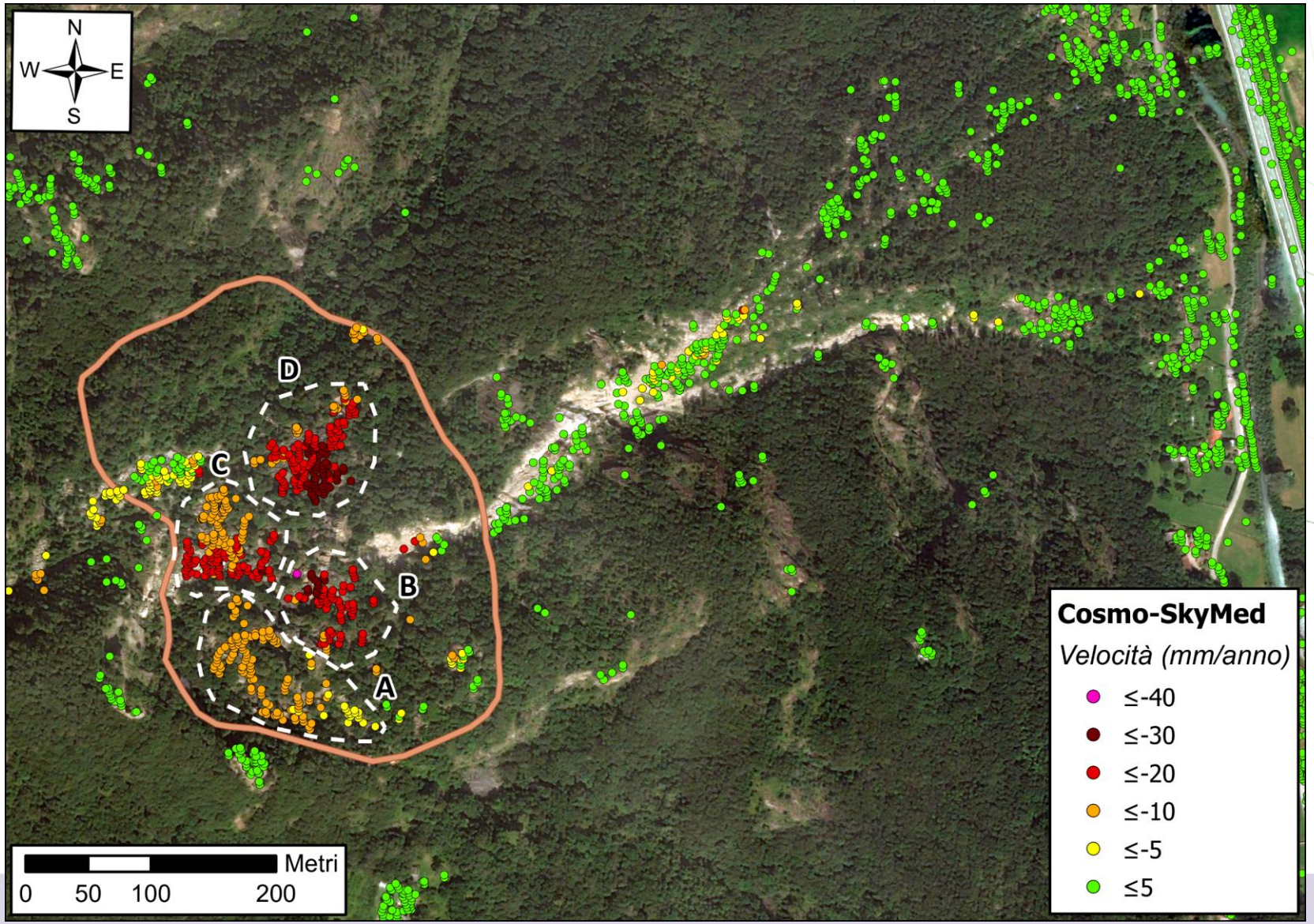


GB-InSAR

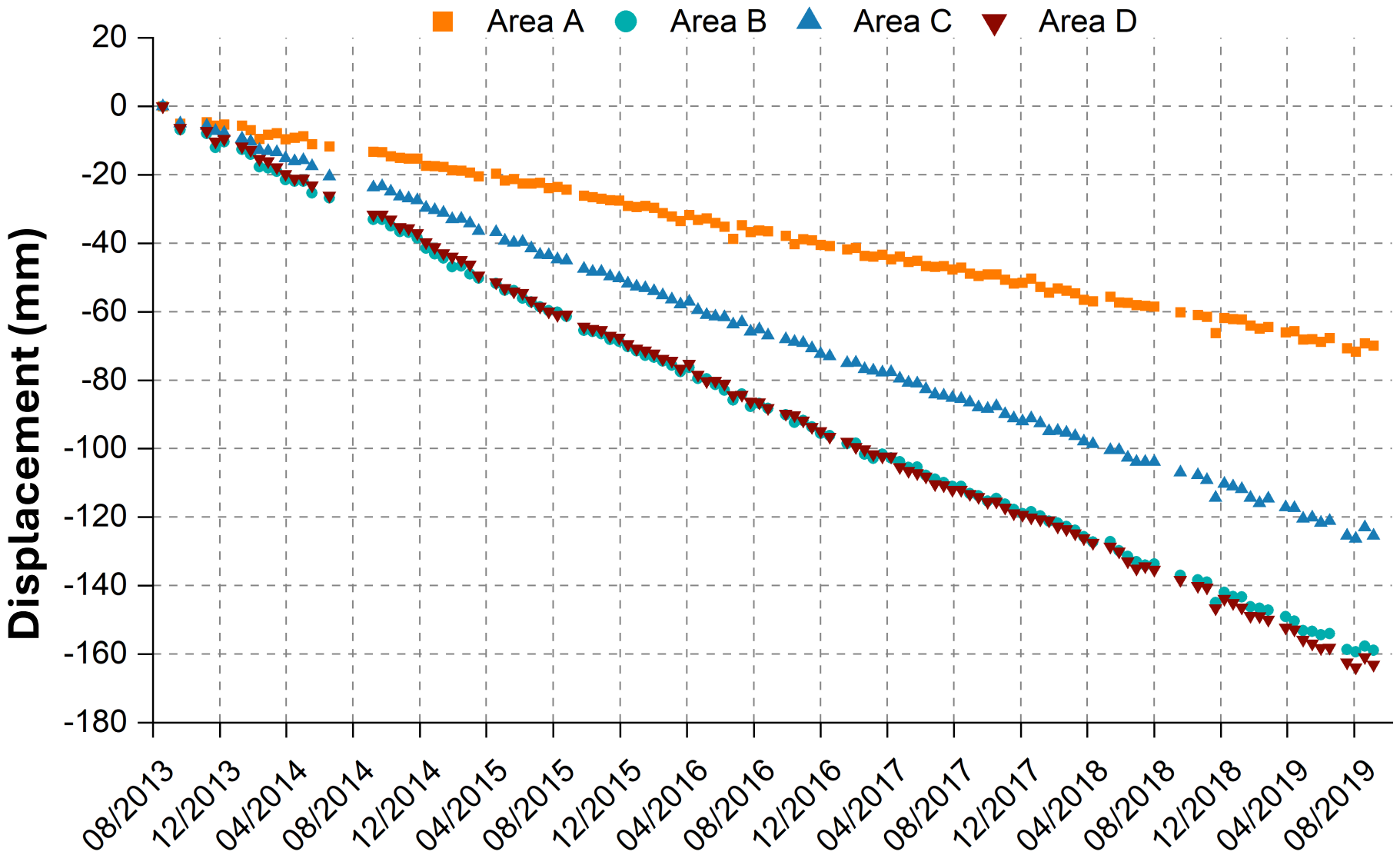
WSN

Total station

Satellite InSAR - CSK

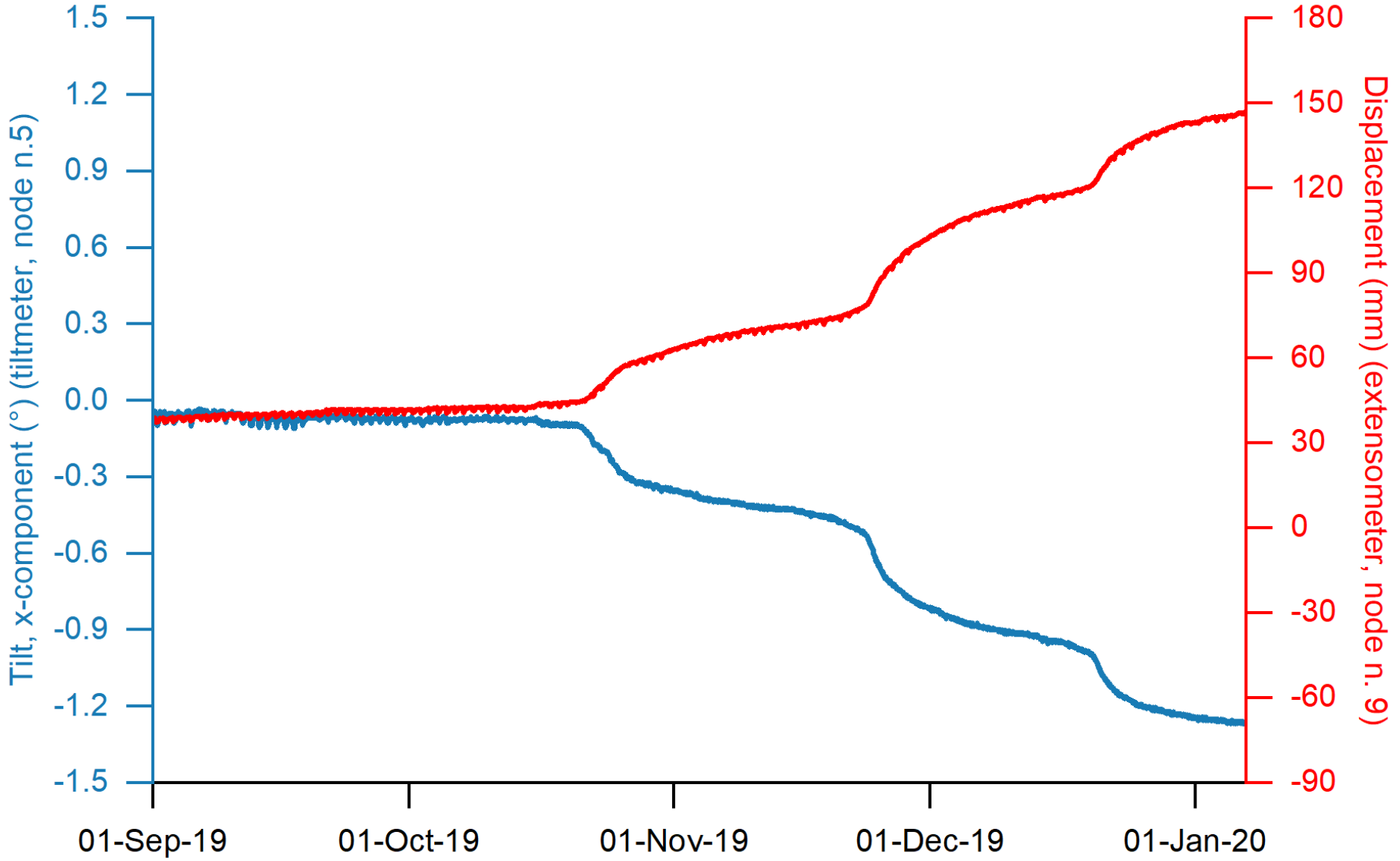


Satellite InSAR - CSK



Wireless sensor network

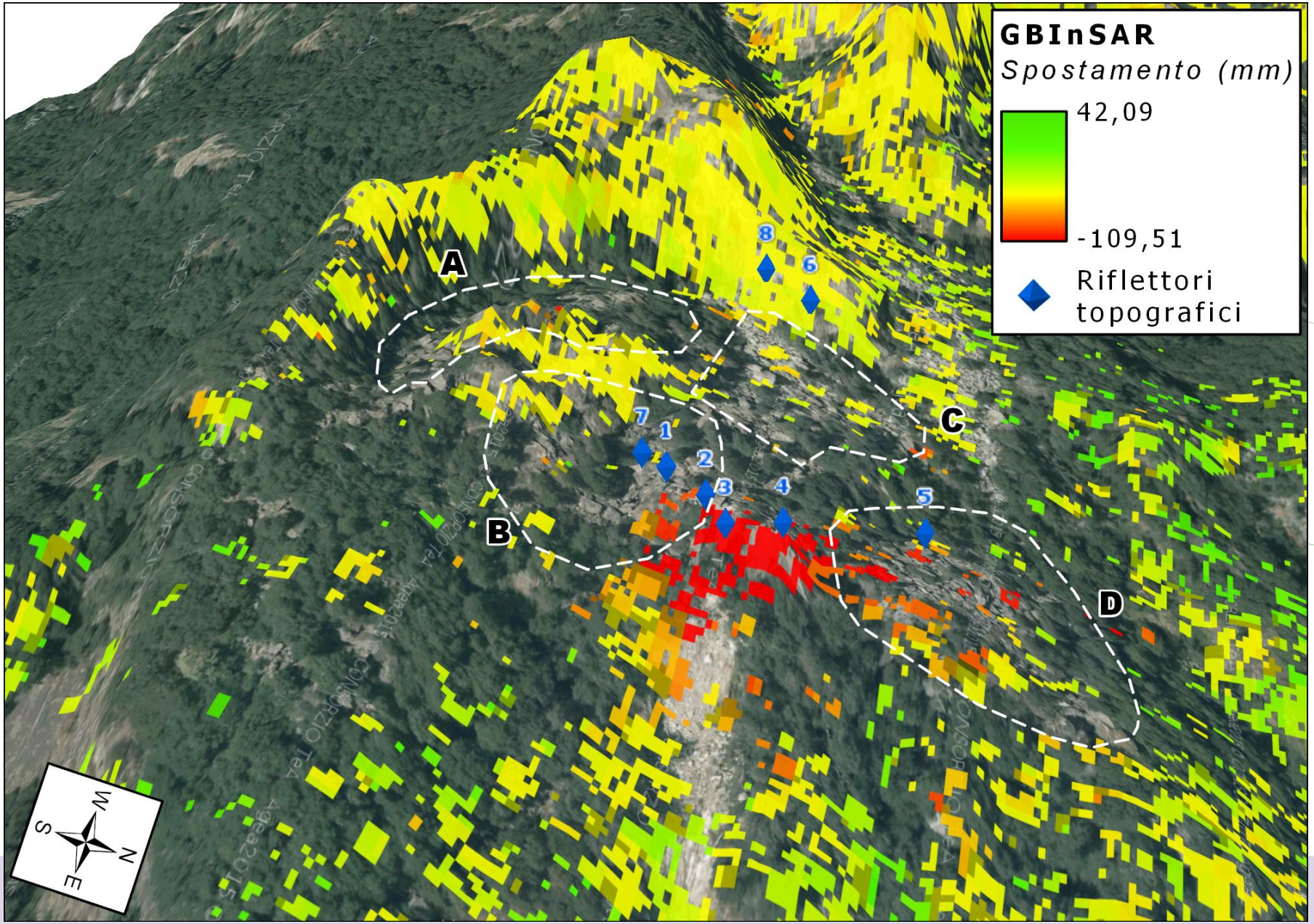
Clinometer 5 vs. Extensometer 9



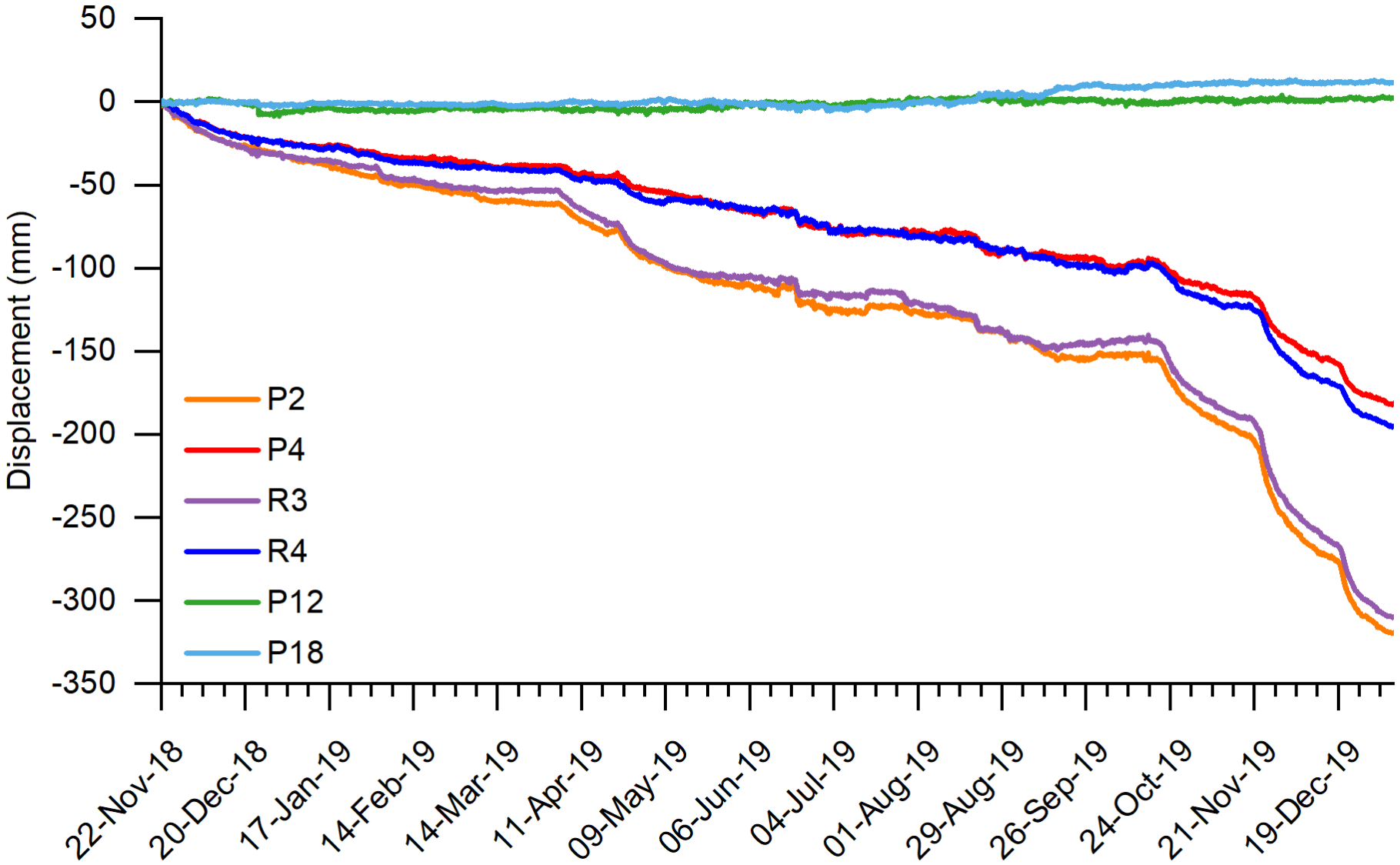
GB-InSAR


P27
P30
P26
R6
P31
P25
P24
P3
P32
P23
P8
P18
P15
P10
P7
P11
P19
P16
P13
P12
P17
P20
P33
P14

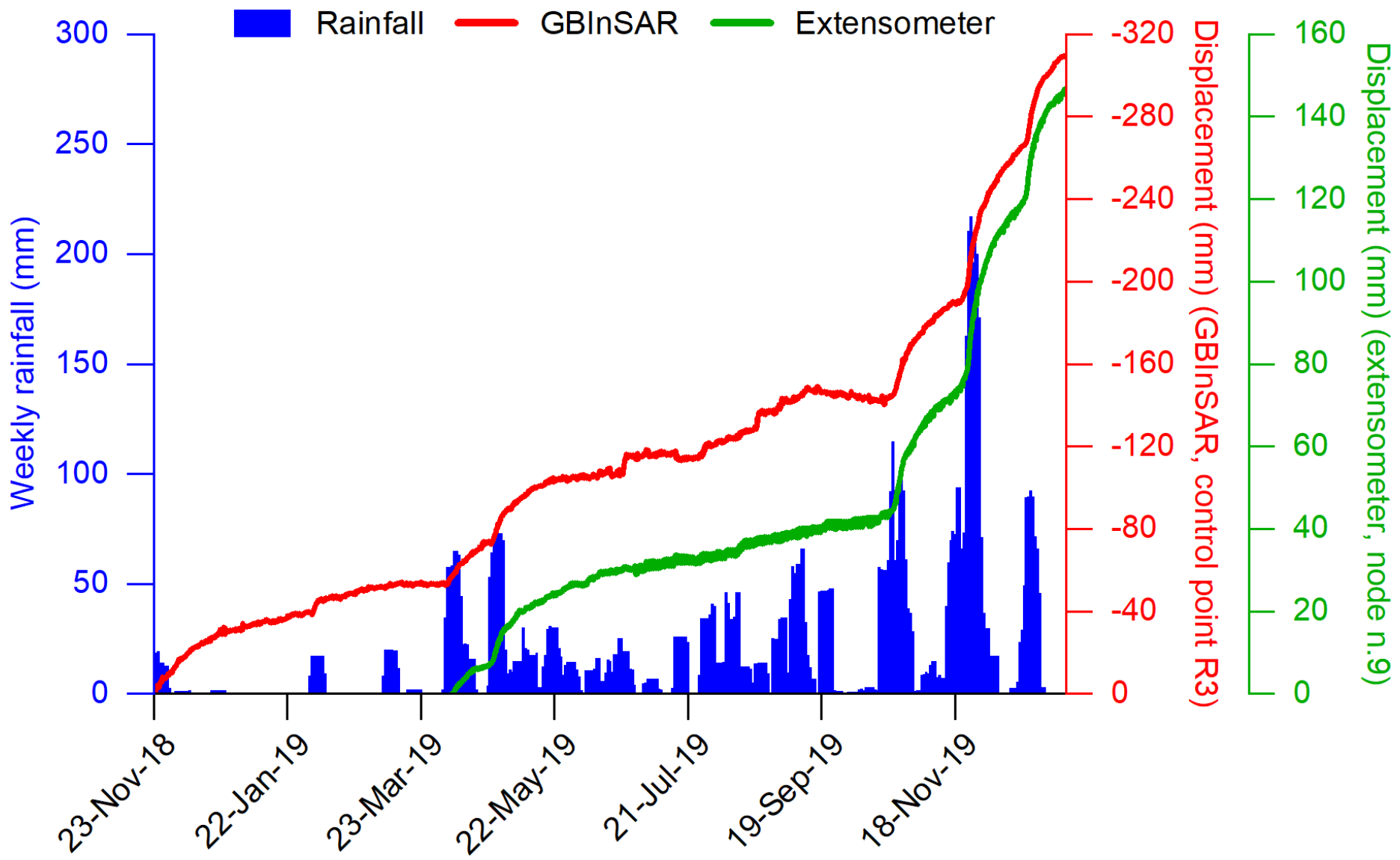
GB-InSAR


GBInSAR
Spostamento (mm)
42,09
-109,51
Riflettori topografici
A
B
C
D
1
2
3
4
5
6
7
8
N
E
S
W

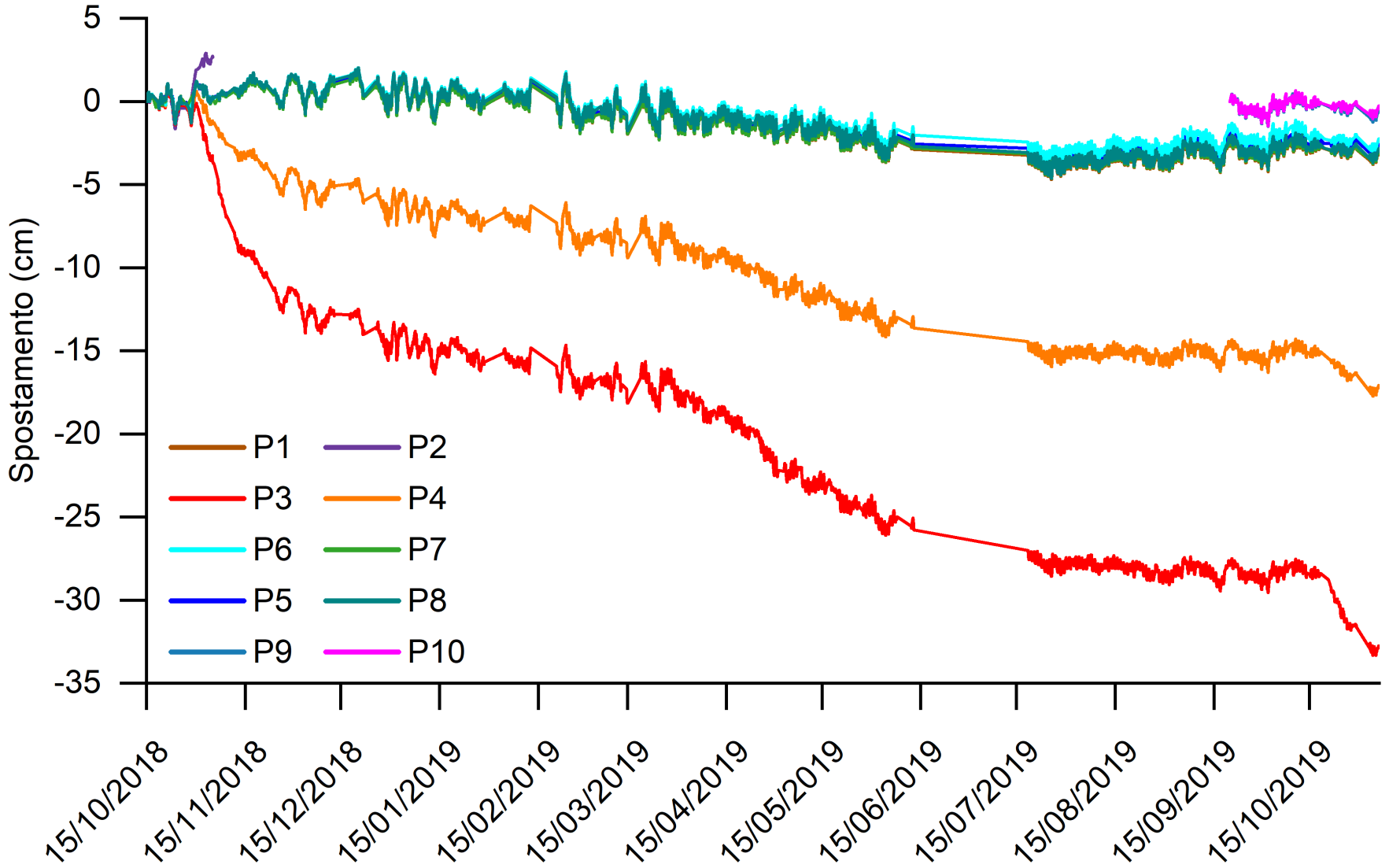
GB-InSAR


50
0
-50
-100
-150
-200
-250
-300
-350
Displacement (mm)
P2
P4
R3
R4
P12
P18
22-Nov-18
20-Dec-18
17-Jan-19
14-Feb-19
14-Mar-19
11-Apr-19
09-May-19
06-Jun-19
04-Jul-19
01-Aug-19
29-Aug-19
26-Sep-19
24-Oct-19
21-Nov-19
19-Dec-19

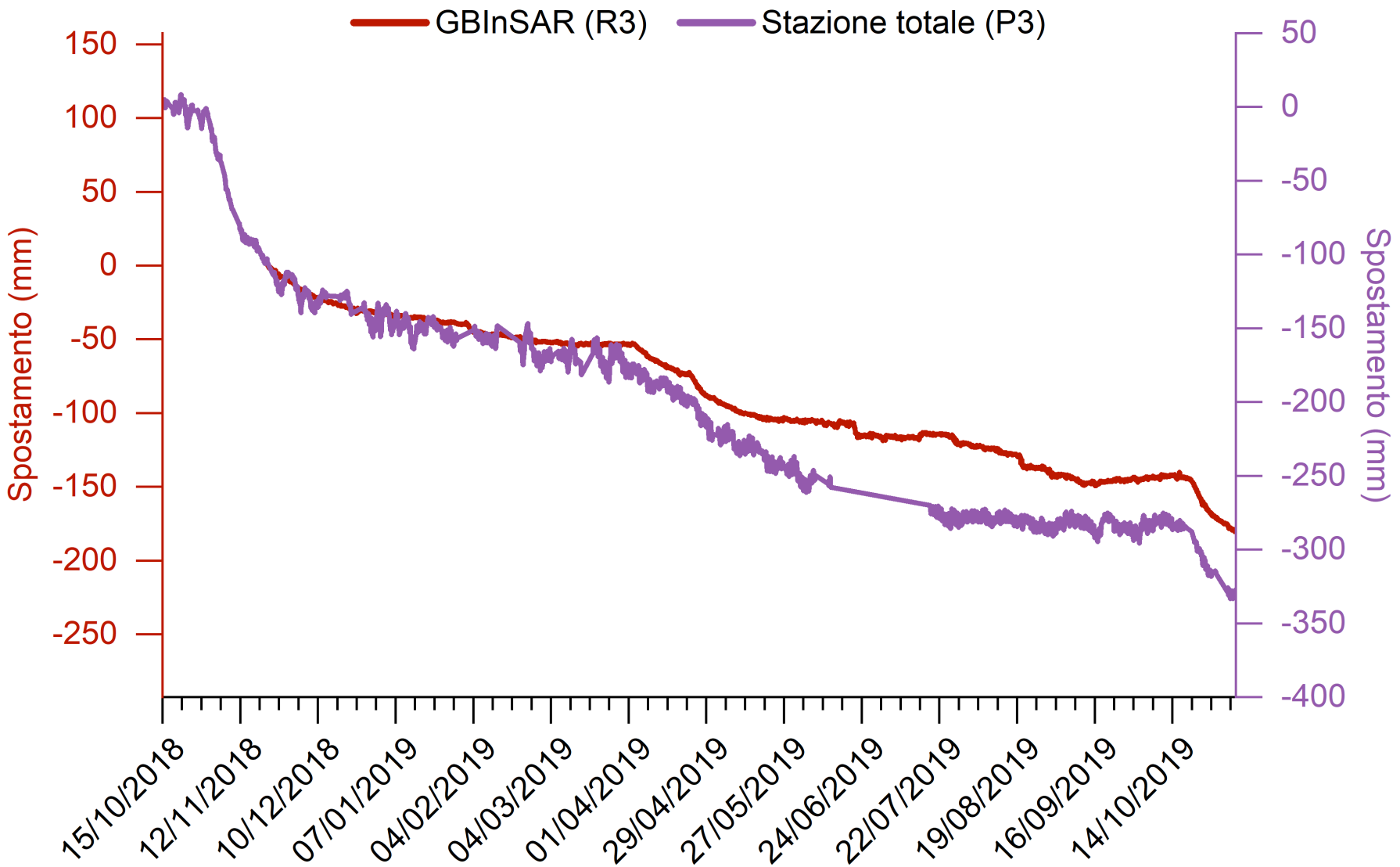
GB-InSAR R3 vs. Extensometer 9



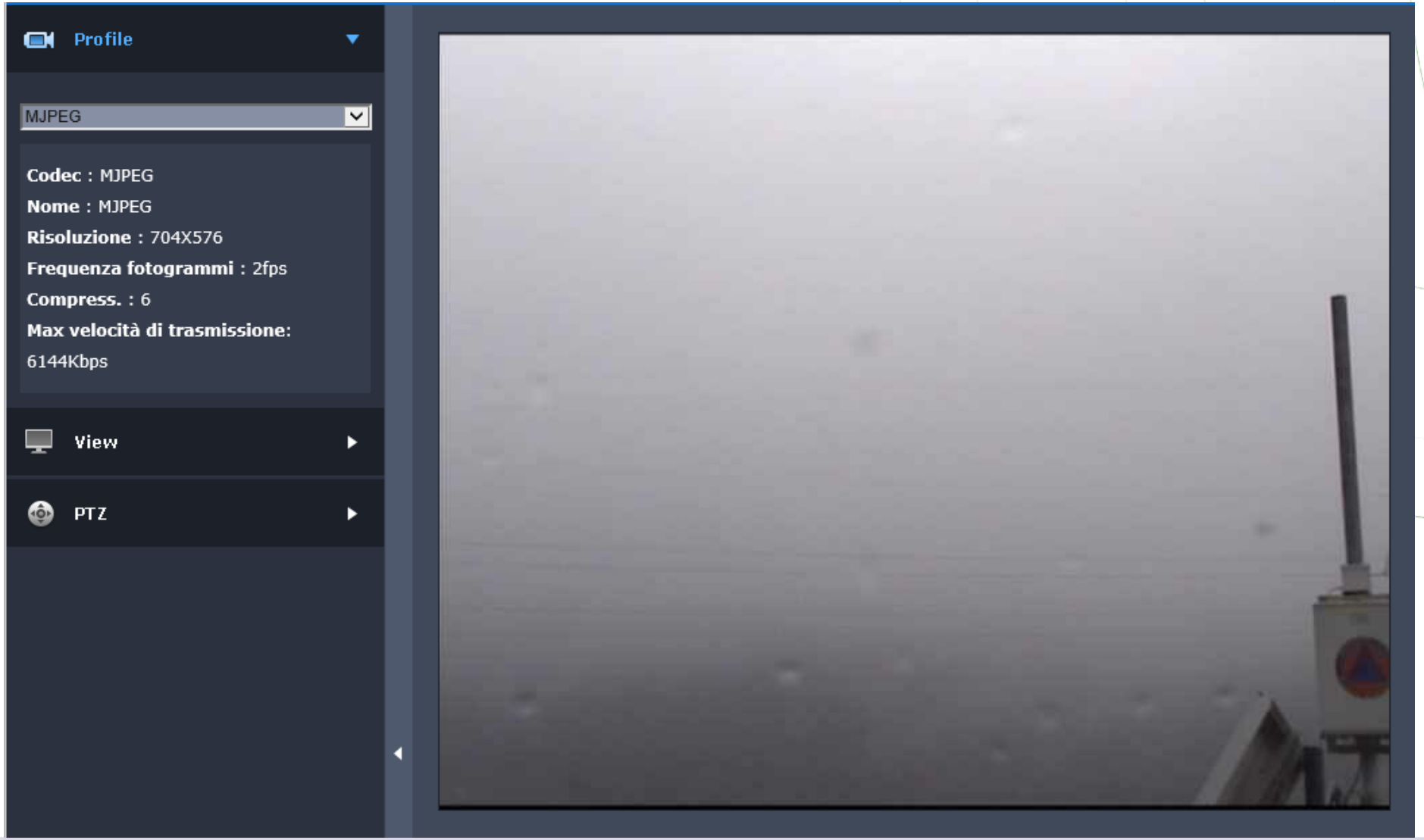
Total station



GB-InSAR vs. total station



November 3, 2019 visibility

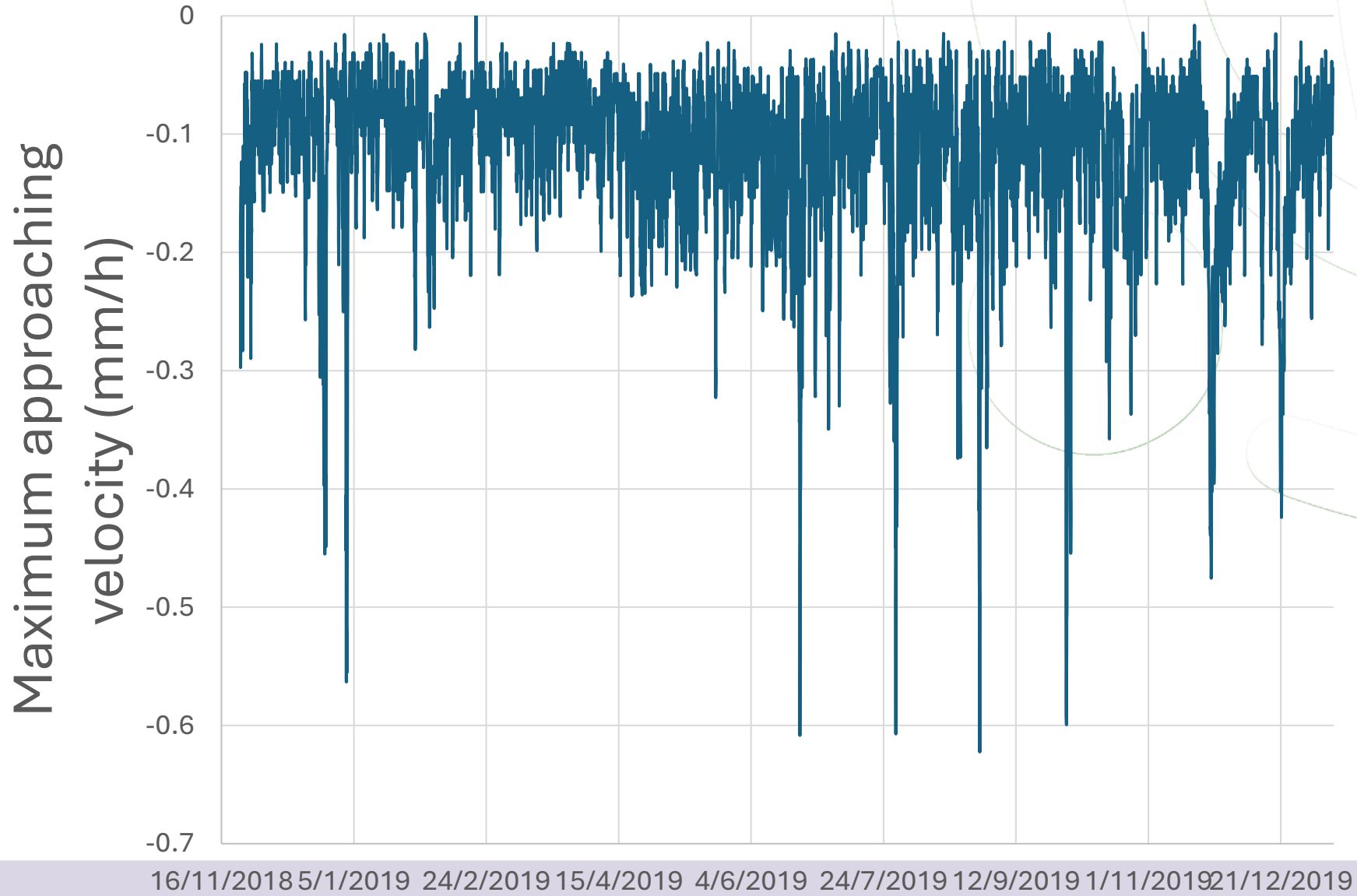


Building the emergency plan

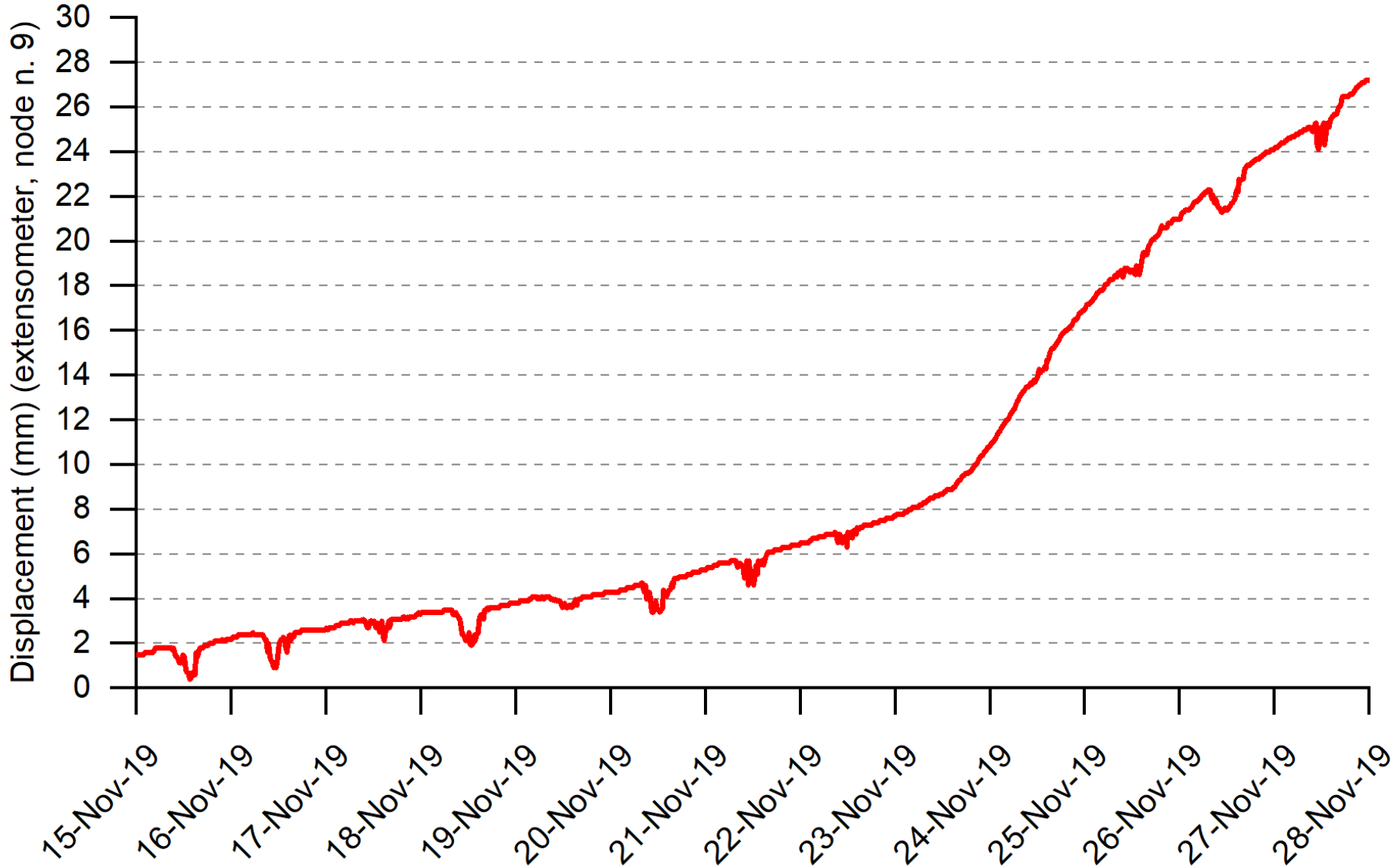
Emergency plan objectives

- To define reliable monitoring thresholds for the different alarm levels
- To integrate the alarm levels with the weather-based warning system of the Piemonte and Valle d'Aosta Regions
- To identify the alternative routes to be used in case of closure of motorway sections
- To organize alert, communication and operational response system, at different levels, in order to respond to the inconvenience to road users and to the whole affected area

GB-InSAR threshold definition



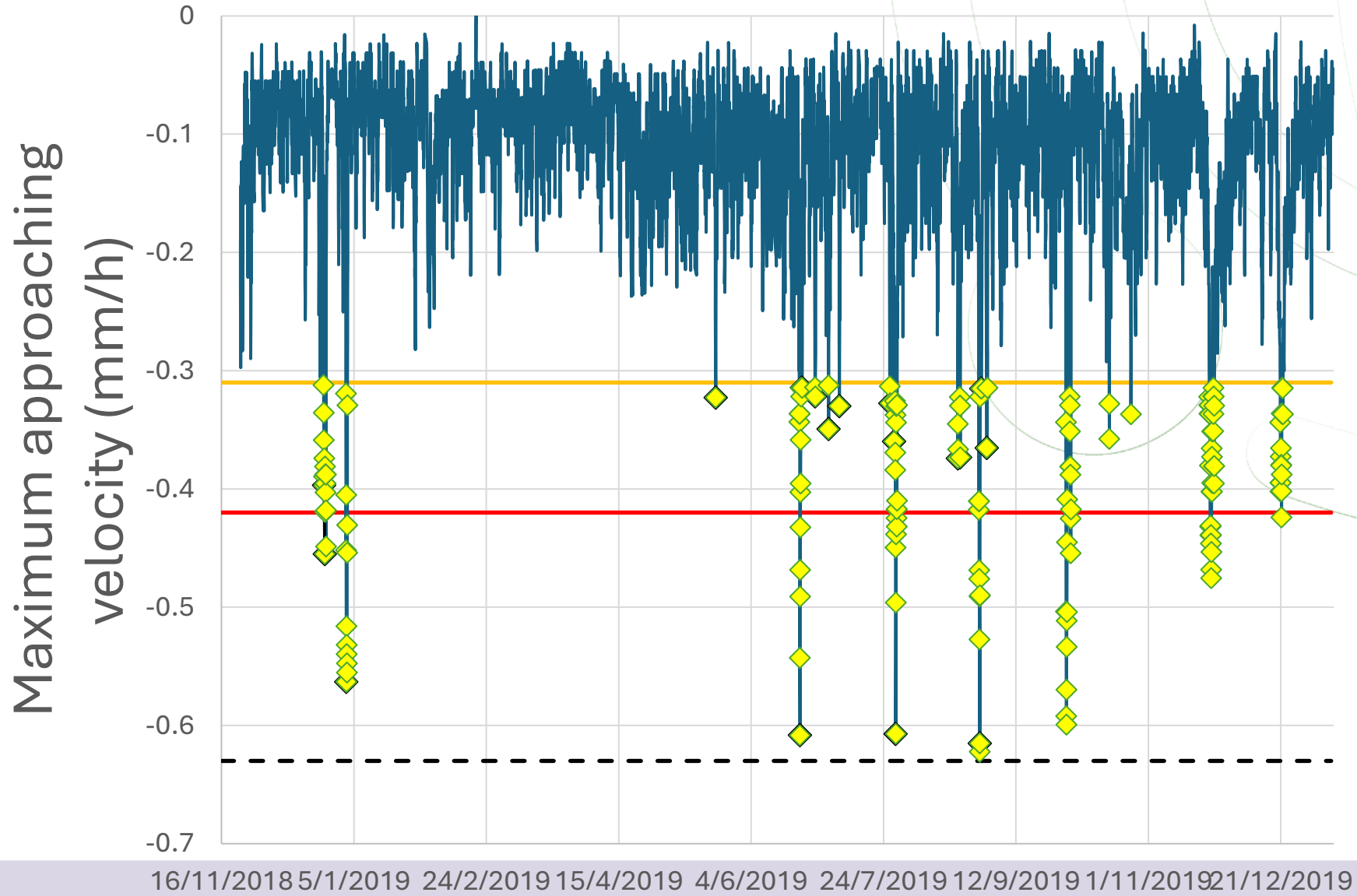
Extensometer threshold definition



Monitoring thresholds

Alarm level	GB-InSAR	Extensometers
NONE	-	-
ATTENTION	V_{LOS} <	V_{EXT} < .....
PRE-ALARM	..... < V_{LOS} <	..... < V_{EXT} < .....
ALARM	V_{LOS} >	V_{EXT} > .....

GB-InSAR threshold definition



Monitoring thresholds

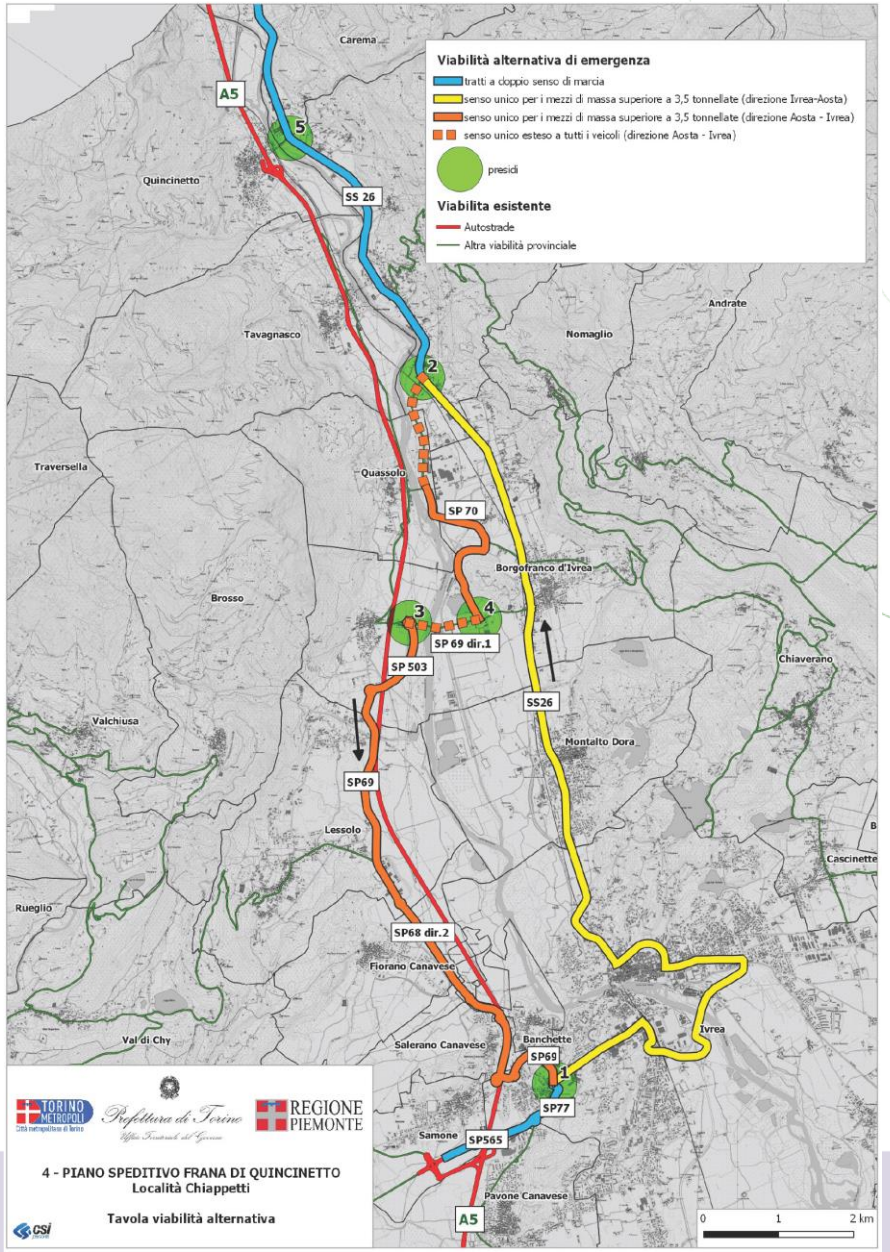
Alarm level	GB-InSAR	Total station	Extensometers	Tiltmeters	Rainfall	Regional Alerts
NONE	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
ATTENTION	V_{LOS} < 0,31 mm/h	V_{RTS} < 0,31 mm/h	V_{EXT} < 0,16 mm/h	V_{ANG} < 0,05 deg/h	1 h < 10 mm 3 h < 20 mm 6 h < 30 mm 12 h < 40 mm 24 h < 60 mm	Yellow
PRE-ALARM	V_{LOS} 0,31–0,42 mm/h	V_{RTS} 0,31–0,42 mm/h	V_{EXT} 0,16–0,21 mm/h	V_{ANG} 0,05–0,07 deg/h	1 h 10–20 mm 3 h 20–30 mm 6 h 30–40 mm 12 h 40–50 mm 24 h 60–70 mm	Orange
ALARM	V_{LOS} > 0,42 mm/h	V_{RTS} > 0,42 mm/h	V_{EXT} > 0,21 mm/h	V_{ANG} > 0,07 deg/h	1 h > 20 mm 3 h > 30 mm 6 h > 40 mm 12 h > 50 mm	Red alert

Finding alternative routes

Finding alternative routes

Quincinetto motorway node

Emergency alternative routes



Operational phase activation

Operational phase	Activation criteria
Attention (Level 1)	Displacements shown by monitoring system or Yellow alert from the regional weather-based warning system
Pre-Alarm (Level 2)	Pre-alarm monitoring thresholds exceded or Orange alert from the regional weather-based warning system
Alarm (Level 3)	Alarm monitoring thresholds exceded or Red alert from the regional weather-based warning system

Center of Competence actions

Operational phase	Action
Attention (Level 1)	• 24 h automatic check of monitoring data
Pre-Alarm (Level 2)	• 24 h automatic check of monitoring data • Expert assessment on demand • Informs through automatic messages the motorway and railway operators, the Prefecture and the Regions • Sends a brief assessment about the ongoing situation • Communicates the return to level 1
Alarm (Level 3)	• 24 h automatic check of monitoring data • Expert assessment on demand • Informs through automatic messages the motorway and railway operators, the Prefecture and the Regions • Sends a brief assessment about the ongoing situation • Communicates the return to level 2

Motorway/railway operator actions

Operational phase	Action
Attention (Level 1)	• Periodical check of motorway/railway lines
Pre-Alarm (Level 2)	• South carriageway closure • Prepare for motorway/railway closure • Activate motorway/railway surveillance from safe position • Give information on digital panels
Alarm (Level 3)	• Motorway/railway closure • Communicate motorway/railway closure • Give information on digital panels

Regions actions

Operational phase	Action
Attention (Level 1)	• Publish the daily meteo-hydrogeological bulletin
Pre-Alarm (Level 2)	• Publish the daily meteo-hydrogeological bulletin • Communicate the reaching of level 2 to the Municipalities • Communicate the return to level 1 to the Municipalities • Warn the volunteering organizations for population assistance at critical points
Alarm (Level 3)	• Publish the daily meteo-hydrogeological bulletin • Communicate the reaching of level 3 to the Municipalities • Activate the volunteering organization for citizen information and assistance at critical points • Co-supervise with the Prefecture the activities of all the institutions • Communicate the return to level 2 to the Municipalities

Municipalities actions

Operational phase	Action
Attention (Level 1)	• Guarantee the efficiency of the secondary road network
Pre-Alarm (Level 2)	• Prepare to activate their Operative Coordination Center (COC) • Give information on digital panels
Alarm (Level 3)	• Activate their Operative Coordination Center (COC) • Communicate the Region the Operative Center activation • Activate local police for traffic management • Give information on digital panels

Prefecture actions

Operational phase	Action
Attention (Level 1)	• None
Pre-Alarm (Level 2)	• Communicates the reaching of level 2 to firefighters and police bodies and coordinates their activity
Alarm (Level 3)	• Communicates the reaching of level 3 to firefighters and police bodies and coordinates their activity • Co-supervise with the Regions the activities of all the institutions

Police & Firefighters actions

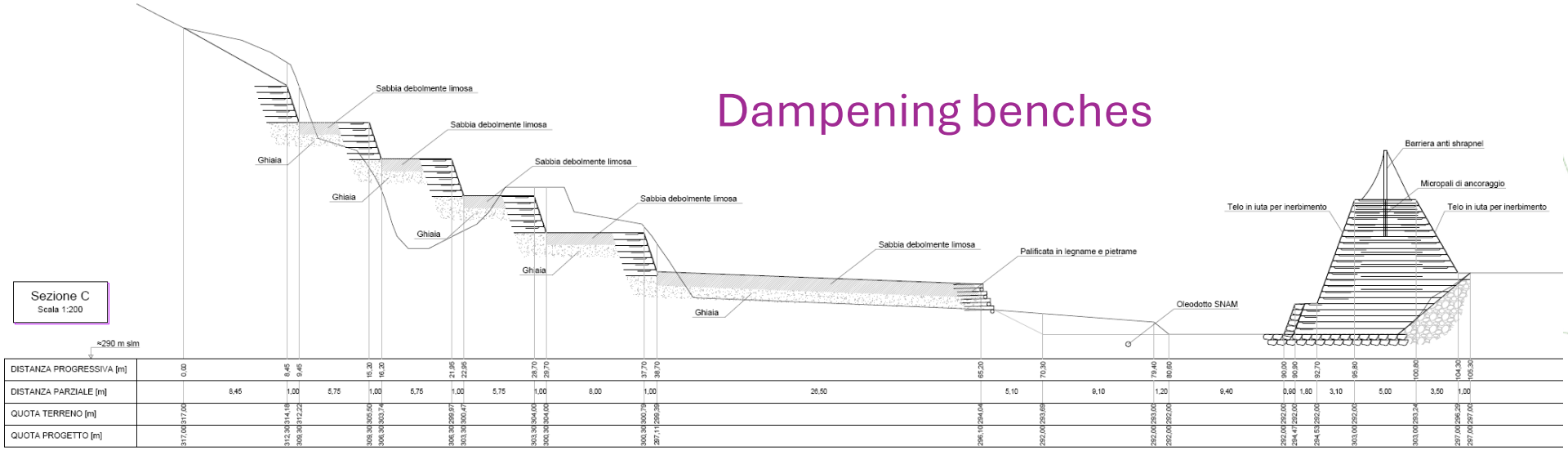
Operational phase	Action
Attention (Level 1)	• None
Pre-Alarm (Level 2)	• Get prepared for level 3
Alarm (Level 3)	• Provide sourveillance and assistance at critical points along the alternative routes

Volunteering organization actions

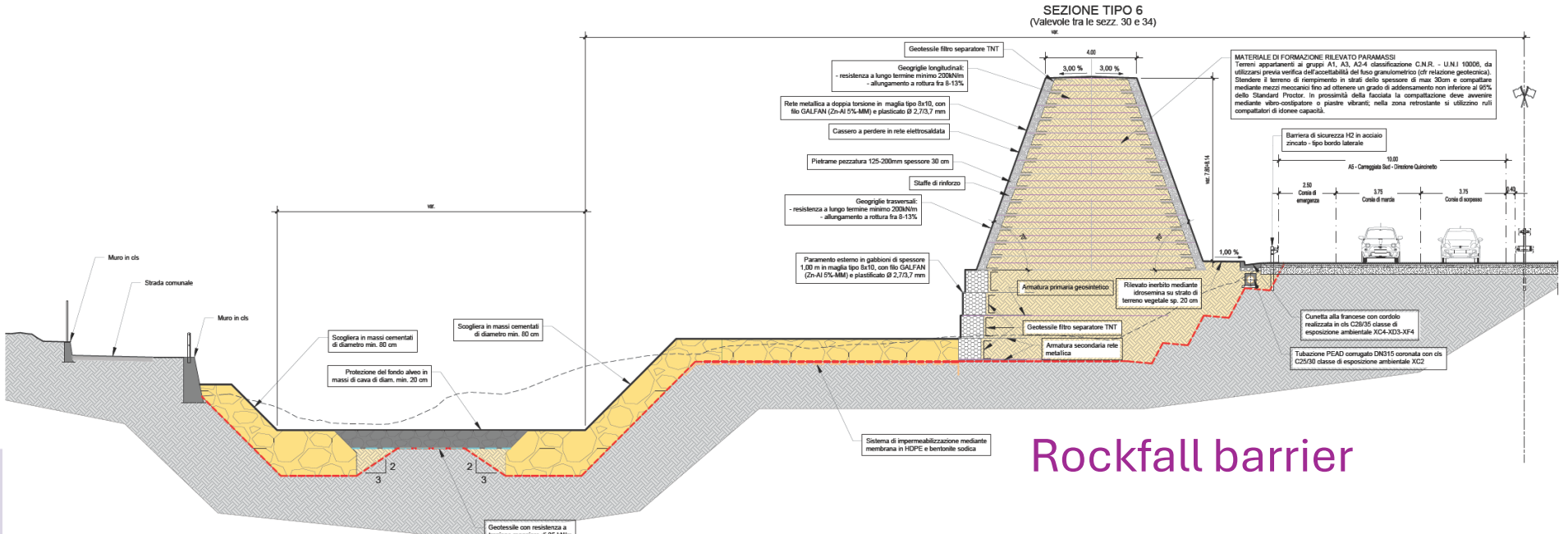
Operational phase	Action
Attention (Level 1)	• None
Pre-Alarm (Level 2)	• Warn their volunteers to be prepared for level 3
Alarm (Level 3)	• Provide support to the firefighters and police bodies at critical points identified along the alternative routes

Risk reduction measures

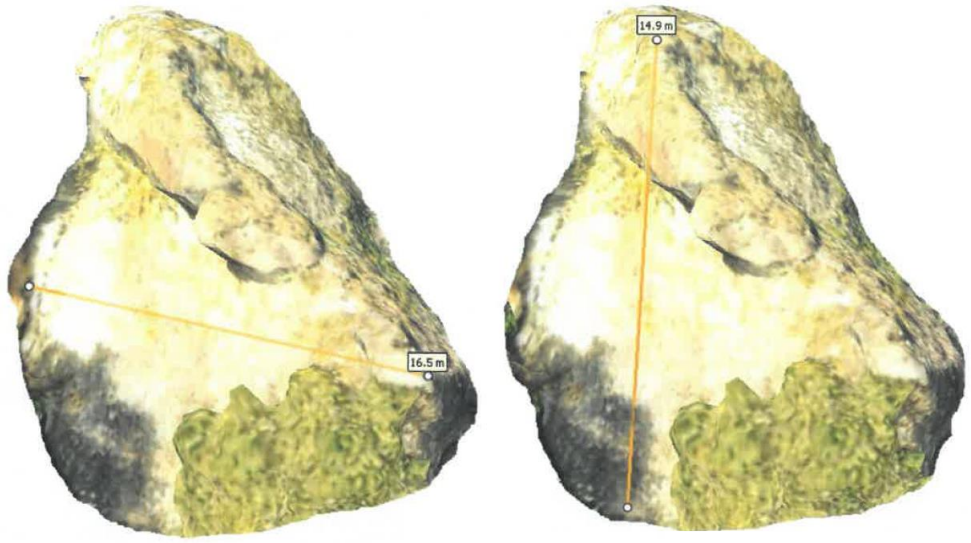
Dampening benches



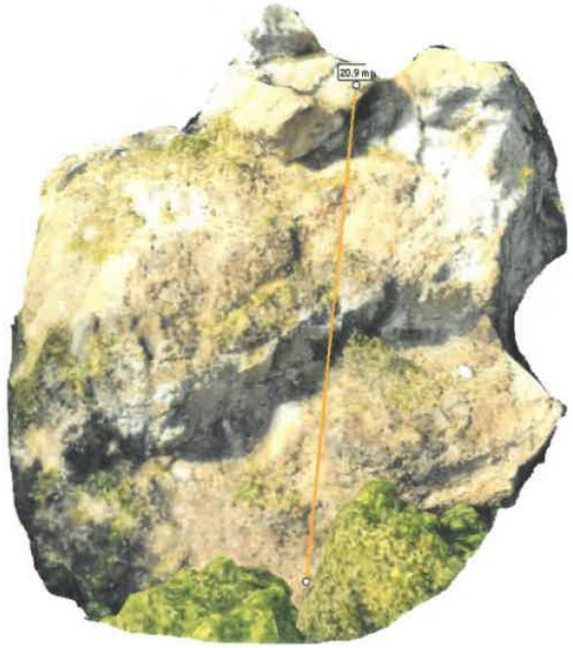
Rockfall barrier

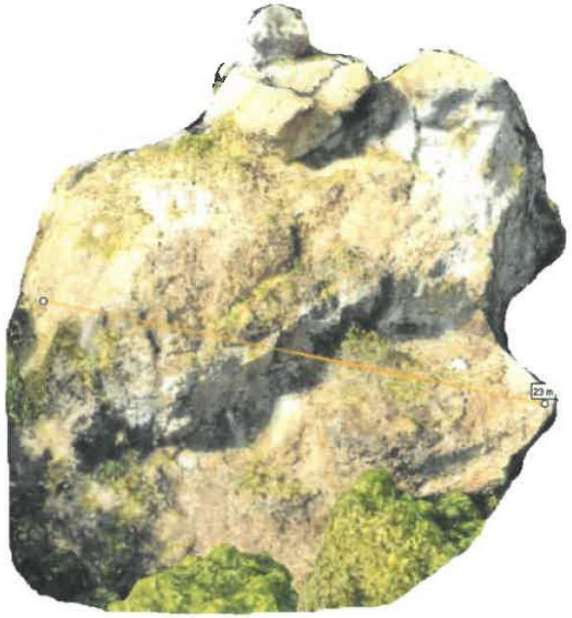


Risk reduction measures



Removal of dangerous blocks



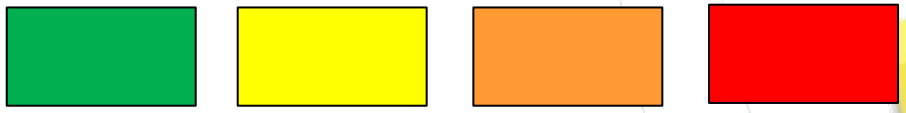


Communication

Peace time communication

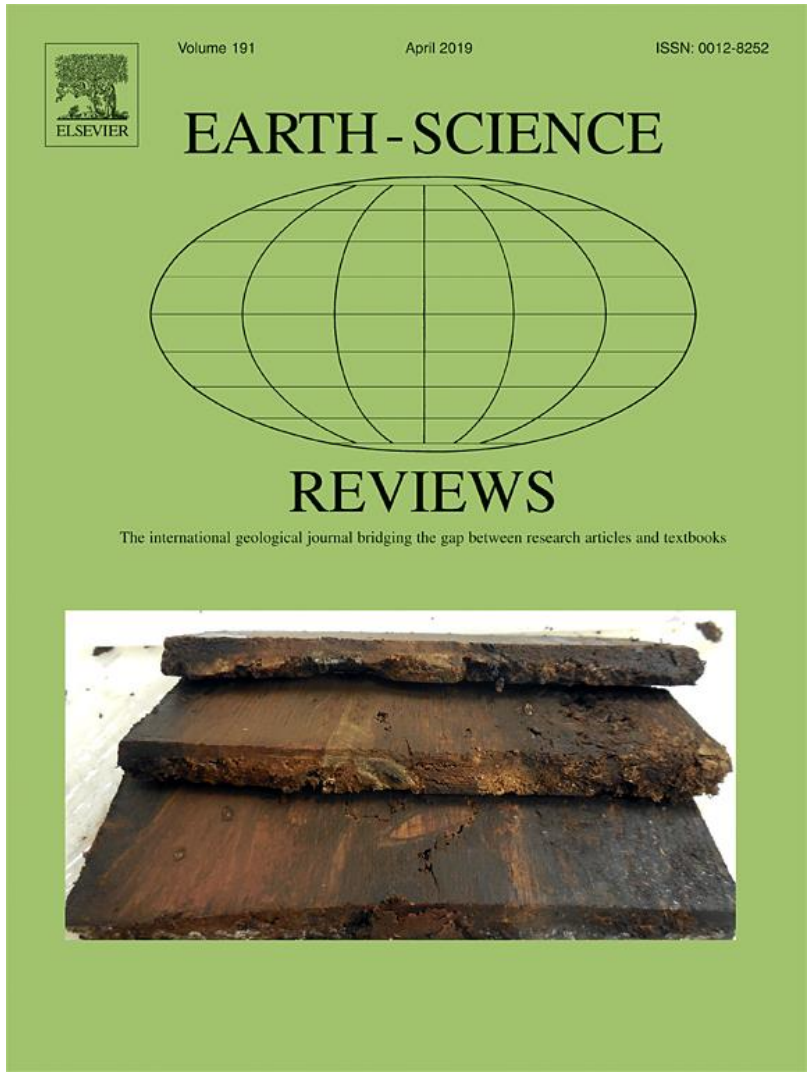
- Risk awareness
- Self-protection rules
- Communication channels
- Warning messages
- Civil protection plan
- Areas at risk
- Waiting areas
- Useful telephone numbers

Emergency communication



- Color-cose
- Type of risk
- Municipality
- Time window of the warning
- Simplified description of the forecasted event
- Updates about the event
- Behavior rules to be followed before, during and after the event

References



Intrieri E., Carlà T., Gigli G., 2019. Forecasting the time of failure of landslides at slope-scale: A literature review. *Earth-Science Reviews*, 193:333-349.

Available at: https://www.sciencedirect.com/science/article/pii/S001282521830518X?fbclid=IwAR1b-DmNKKbr6SCjy-xqPJTsbjjfxLpwiwBg6uicQdI1vpJcNNDlXzCjbC0

References

- Carlà T., Intrieri E., Di Traglia F., Nolesini T., Gigli G., Casagli N., 2017. Guidelines on the use of inverse velocity method as a tool for setting alarm thresholds and forecasting landslides and structure collapses. Landslides, 14:2, 517-534. Available at: http://link.springer.com/article/10.1007/s10346-016-0731-5
- Carlà T., Farina P., Intrieri E., Casagli N., Hakki K., 2018. Integration of ground-based radar and satellite InSAR data for the analysis of an unexpected slope failure in an open-pit mine. Engineering Geology.
- Dick, G. J., Eberhardt, E., Cabrejo-Liévano, A. G., Stead, D., Rose, N.D., 2015. Development of an early-warning time-of-failure analysis methodology for open-pit mine slopes utilizing ground-based slope stability radar monitoring data. Canadian Geotechnical Journal, 52(4), 515-529.
- Fukuzono T., 1985. A method to predict the time of slope failure caused by rainfall using the inverse number of velocity of surface displacement. Journal of Japanese Landslide Society, n. 22, pp. 8-13.
- Guzzetti F., Peruccacci S., Rossi M., Stark C.P., 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorol Atmos Phys 98, 239–267. DOI 10.1007/s00703-007-0262-7
- Intrieri E., Gigli G., 2016. Landslide forecasting and factors influencing predictability. Natural Hazards and Earth Science System, 16(12), 2501-2510. DOI 10.5194/nhess-2016-221. Available at: http://www.nat-hazards-earth-syst-sci.net/16/2501/2016/nhess-16-2501-2016.pdf
- Intrieri E., Gigli G., Casagli N., Nadim F., 2013. Brief communication: Landslide Early Warning System: Toolbox and General Concepts. Natural Hazards and Earth System Science, vol. 13, pp. 85–90, DOI: 10.5194/nhess-13-85-2013. Available at: http://www.nat-hazards-earth-syst-sci.net/13/85/2013/nhess-13-85-2013.pdf
- Intrieri E., Raspini F., Fumagalli A., Lu P., Del Conte S., Farina P., Allievi J., Ferretti A., Casagli N., 2018. The Maoxian landslide as seen from space: detecting precursors of failure with Sentinel-1 data. Landslides, 15(1), pp. 123-133. DOI: 10.1007/s10346-017-0915-7
- Mufundirwa A., Fujii Y., Kodama J., 2010. A new practical method for prediction of geomechanical failure-time. International Journal of Rock Mechanics & Mining Sciences, vol. 47, n. 7, pp. 1079-1090.
- Page S.E., 2007. The difference: how the power of diversity creates better groups, firms, schools, and societies. Princeton Univ. Press, 424 pp.
- Petley D.N., 2004.: The evolution of slope failures: mechanisms of rupture propagation, Nat. Hazards Earth Syst. Sci., 4, 147–152.
- Petley, D.N., Dunning, S. A., Rosser, N. J., 2005. The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities. Landslide risk management. Balkema, Amsterdam, 367-374.
- Rose N.D., Hungr O., 2007. Forecasting potential rock slope failure in open pit mines using the inverse velocity method. International Journal of Rock Mechanics and Mining Science, vol. 44, n. 2, pp. 308-320.
- Saito, M. 1969. Forecasting Time of Slope Failure by Tertiary Creep. Proceedings 7th International Conference on Soil Mechanics and Foundation.

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