Ingegneria al servizio del monitoraggio conservativo

nei Campi Flegrei

Castello di Baia, 21 febbraio 2025

Il monitoraggio satellitare per la prevenzione dei geo-rischi: il caso dei Campi Flegrei

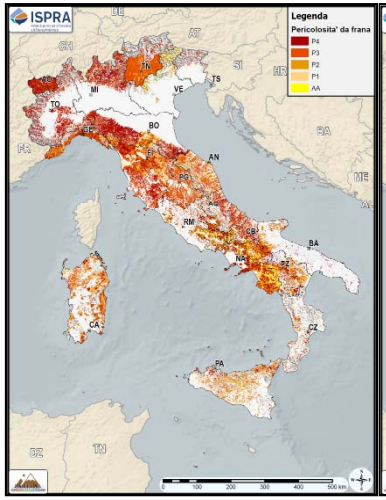
Federica Ferrigno, Gabriele Leoni, Francesco Menniti, **Daniele Spizzichino***

ISPRA – ISTITUTO SUPERIORE PER LA PROTEZIONE E RICERCA AMBIENTALE

In collaborazione con

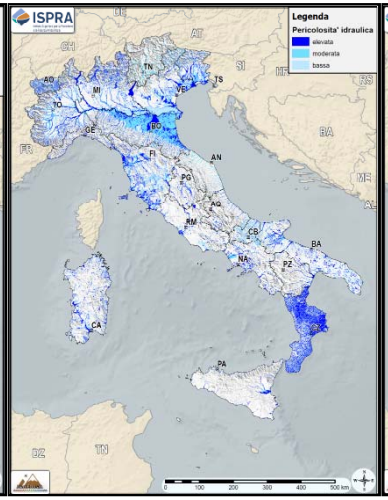
Pericolosità naturale in Italia

FRANE



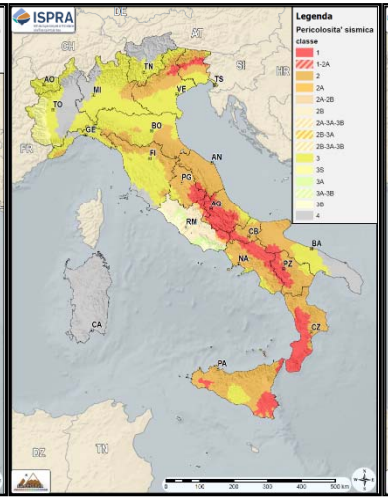
Mosaicatura PAI della pericolosità da frana
Rapporto ISPRA su Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio - Edizione 2021

ALLUVIONI



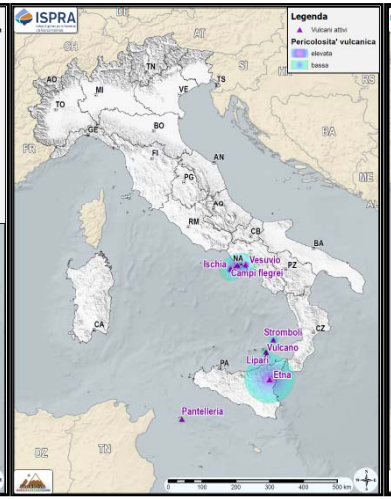
Mosaicatura PAI della pericolosità da alluvioni
Rapporto ISPRA su Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio - Edizione 2021

TERREMOTI



Classificazione sismica su base comunale
Fonte dati : Dipartimento Protezione Civile - INGV; elaborazione grafica ISPRA
Riferimento Annuario Dati Ambientali , ISPRA 2020

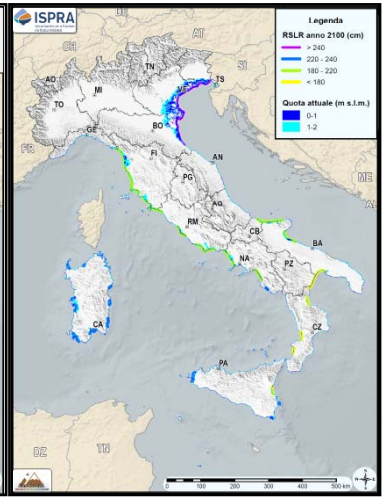
VULCANI



Pericolosità da vulcani attivi

Fonte dati : Dipartimento Protezione Civile - INGV; elaborazione grafica ISPRA.
Aggiornamento 2016.

COSTIERA



Pericolosità da sollevamento del livello del mare

Fonte dati: Università di Bari; elaborazione grafica ISPRA.
Aggiornamento 2019.

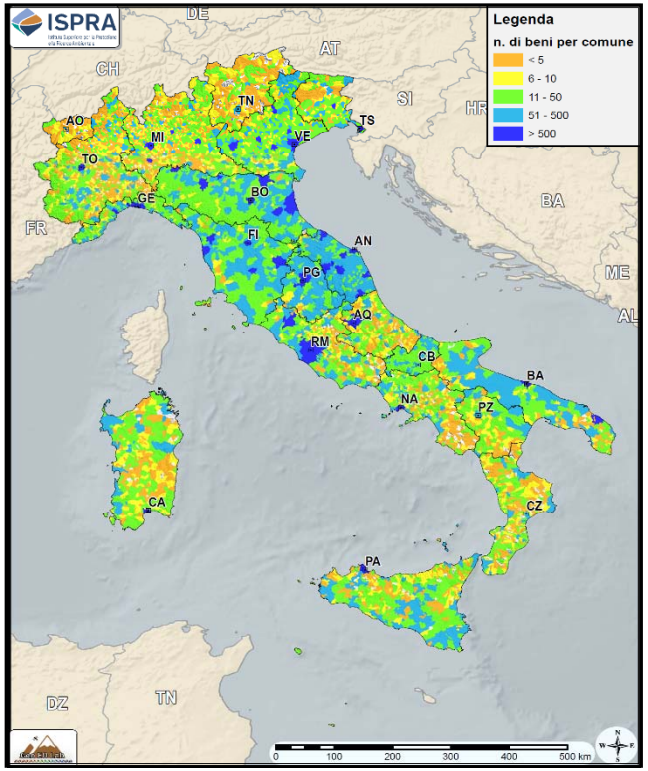
In collaborazione con

BB.CC. in Italia

Beni Culturali dei Comuni italiani
Tot. 229530

Fonte dati:
banca dati VIR e CdR,
elaborazione ISPRA

Archeologici	15026
Architettonici	213618
Parchi e giardini	886

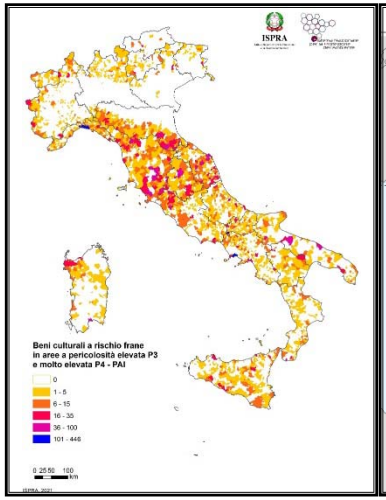


VINCOLI in rete

In collaborazione con

Beni culturali e rischi naturali in Italia

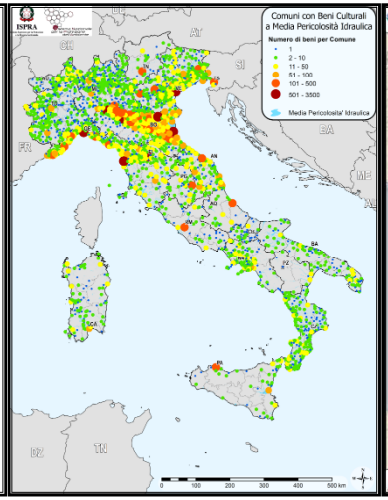
FRANE



BbCc a rischio frana su base comunale

Rapporto ISPRA su Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio - Edizione 2021

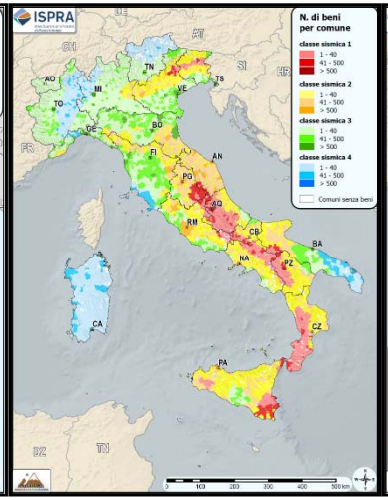
ALLUVIONI



BbCc a rischio alluvione su base comunale

Rapporto ISPRA su Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio - Edizione 2021

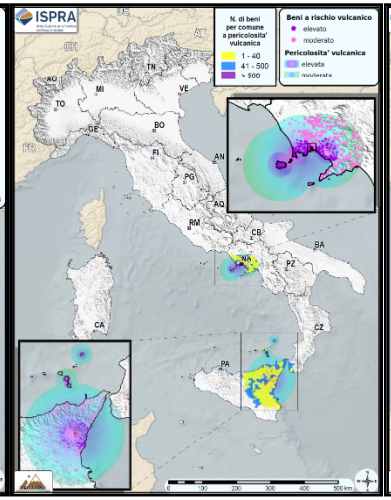
TERREMOTI



BbCc a rischio terremoti su base comunale

Source:
Annuario Dati Ambientali – ISPRA

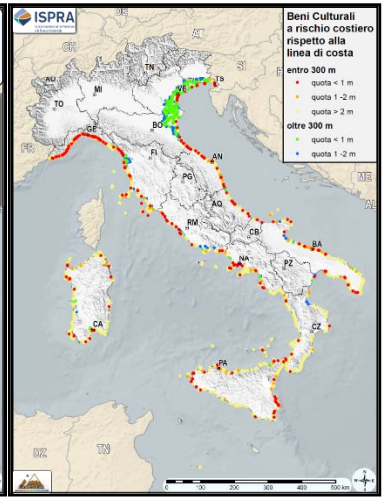
VULCANI ATTIVI



BbCc a rischio vulcanico su base comunale

Source:
Annuario Dati Ambientali – ISPRA

COSTIERA

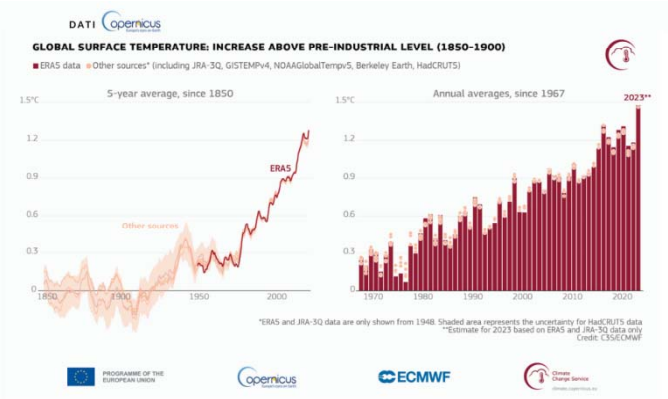


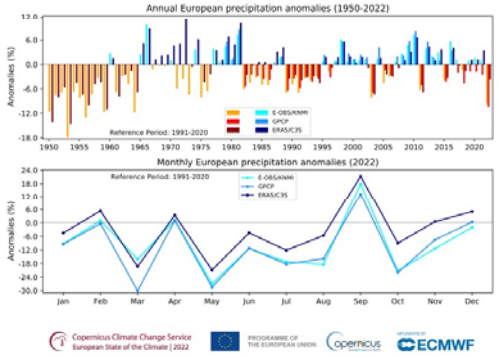
BbCc a rischio costiero

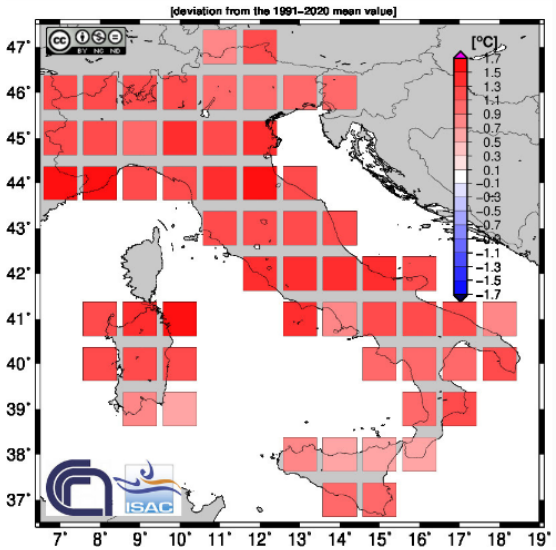
Elaborazione ISPRA.

In collaborazione con

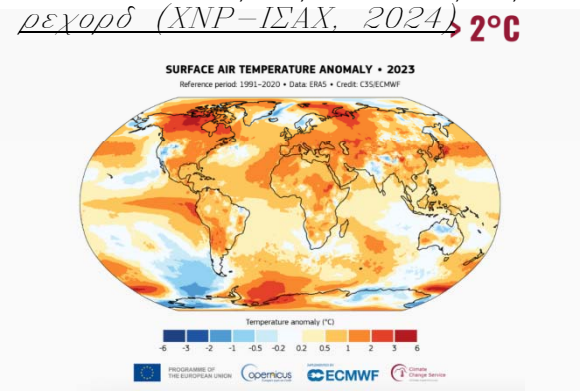
Rationale #2 Climate change in the mediterranean area and Italy



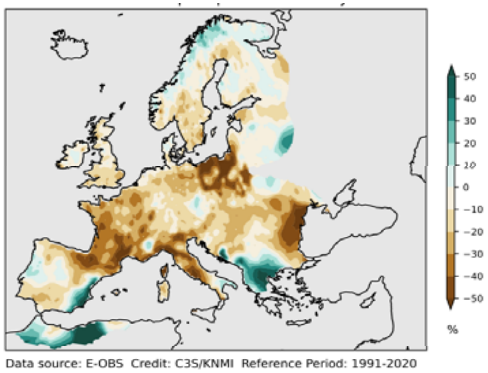




2023 ωασ τηε ηοττεστ ψεαρ ον ρεχορδ (ΧΝΡ–ΙΣΑΧ, 2024)

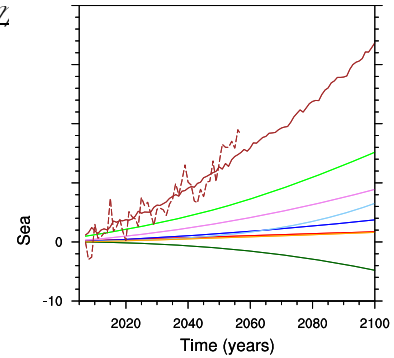


Ωιτη τηε ηοττεστ μοντη ρεχορδεδ ατ γλοβαλ λεΕελ (ΧΝΡ–ΙΣΑΧ, 2024)



πρεχιπιτατιον ανομαλιεσ ατ Μεδιτερρανεαν σχαλε ανδ νατιοναλ σχαλε (ωιτη 21% λεσσ σιυχε 1961)

Ιφ ωε χονσιδερ τηε 10 ωαρμεστ ψεαρσ φορ ουρ χουντρ[illegible]



In collaborazione con

Hegra – Thermal stress, erosion and geomorphological instability in KSA© Spizzichino

Blackening -Vittoriano (Roma)

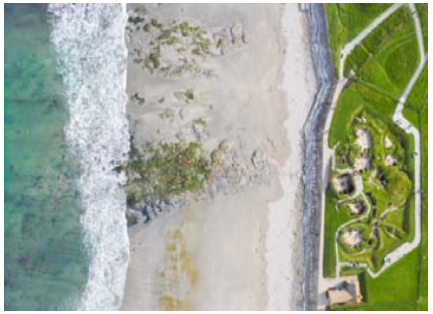
Sea level rise - Venice

Surface recession S. Filippo church (Torino)

Vegetation Terme di Baia (Naples) © Spizzichino

Rock facade collapse in Petra (Jordan) and in David Gareja Mocomplex (Georgia) © Spizzichino

Erosion in Akapana pyramid (Bolivia) © Spizzichino

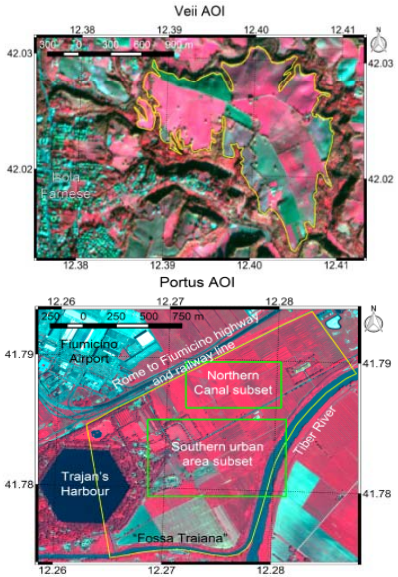


Coastal Erosion Skara Brae © Hist. Env. Scotland

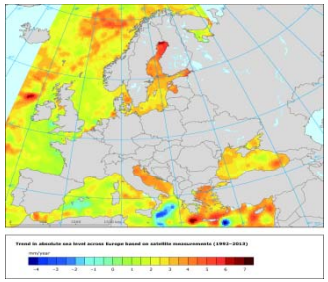
In collaborazione con

OPTICAL images, from data to downstream services

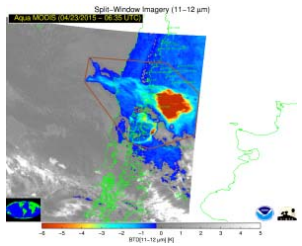
(e.g. multispectral and Hyper spectral analysis)



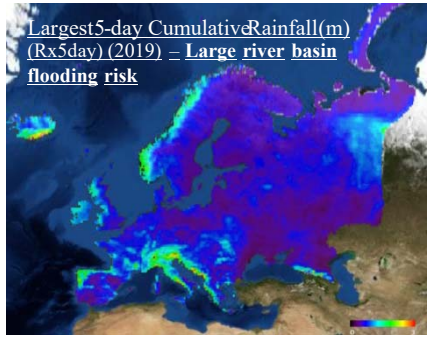
Land use, change detection and buried sites © ESA



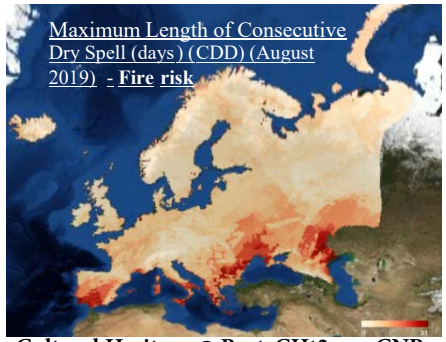
sea level rise © EEA



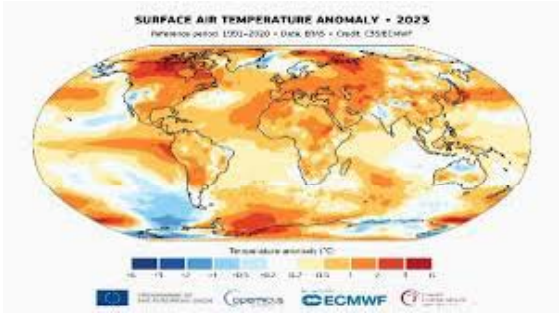
Volcanic Cloud Monitoring website.



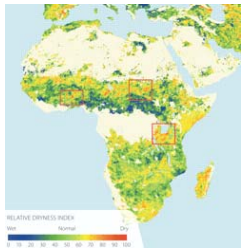
Largest5-day CumulativeRainfall(m) (Rx5day) (2019) – **Large river basin flooding risk**

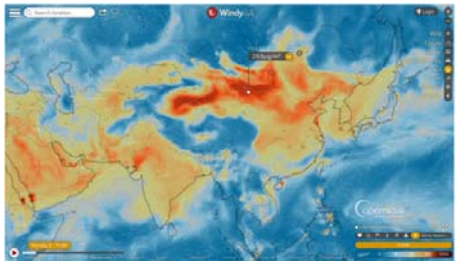


Maximum Length of Consecutive Dry Spell (days) (CDD) (August 2019) - **Fire risk**

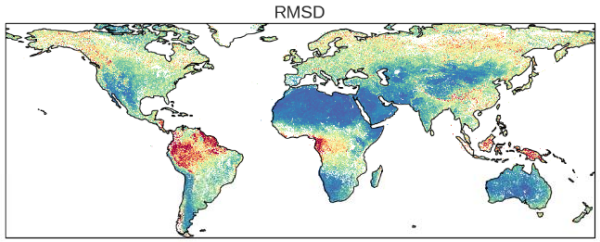


Climate variables and extreme events impact on Cultural Heritage @ ProteCHt2save CNR –ISAC Bonazza et al.

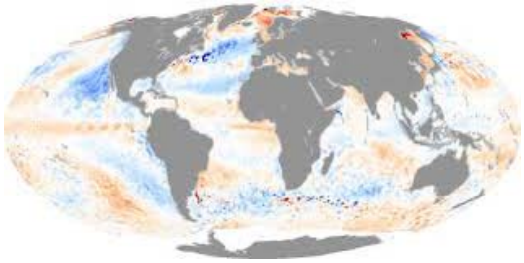




Pollutant concentration © Windy.com



NDVI normalized Vegetation index © Copernicus



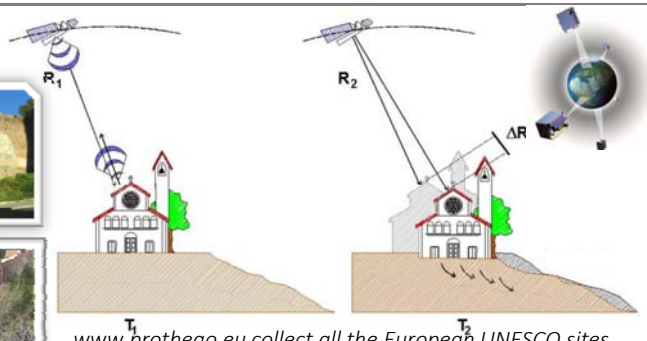
Sea Surface Temperature anomaly © NASA

In collaborazione con

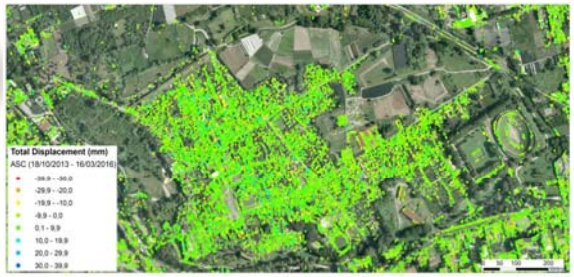
RADAR images, data and products

Differential SAR Interferometry (InSAR or DInSAR)

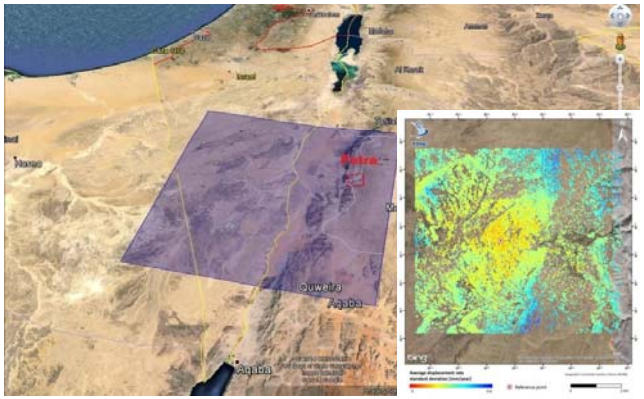
Rome Walls deformation satellite monitoring © Spizzichino

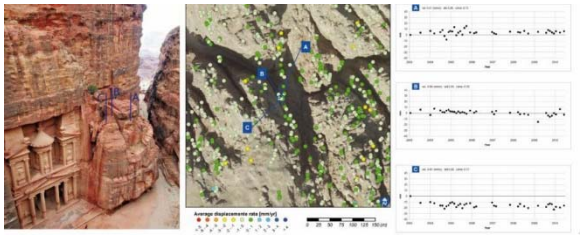


www.prothego.eu collect all the European UNESCO sites where GEO-Hazards and satellite data are already available

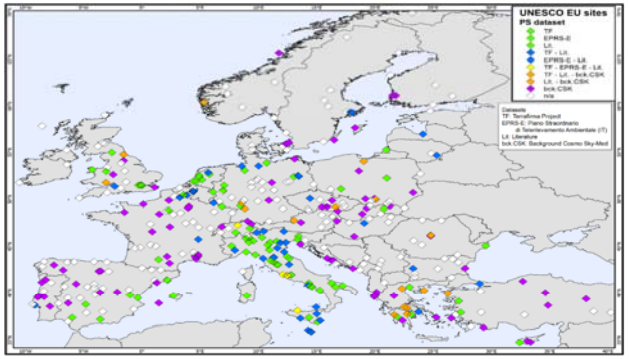


Instability processes and SAR data analysis POMPEI

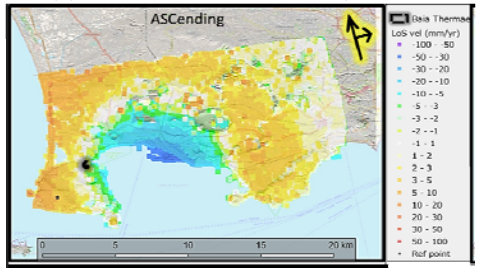


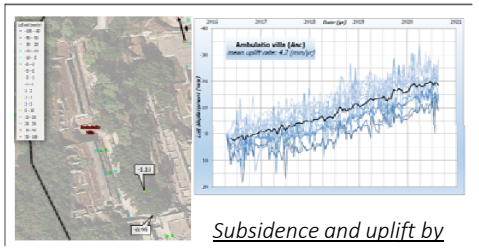


Surface deformation RADAR satellite images Petra © Spizzichino



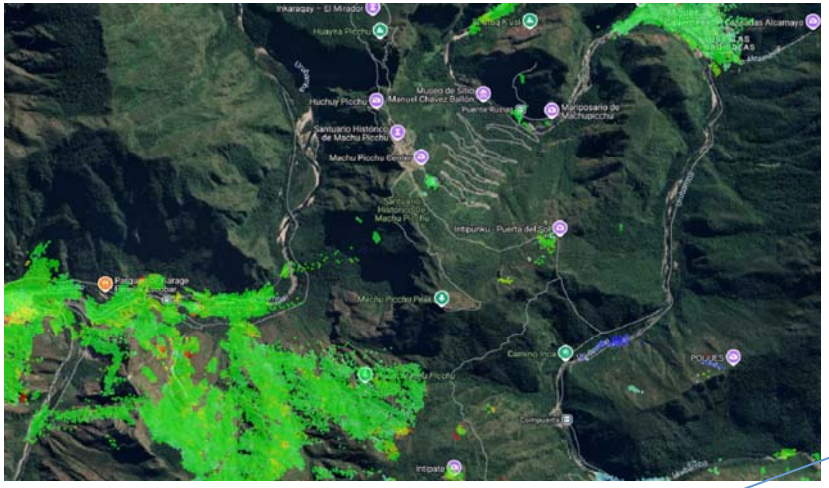
All data after processing, must be calibrated, validate and interpreted by in situ survey in order to be used as support for the mitigation measures



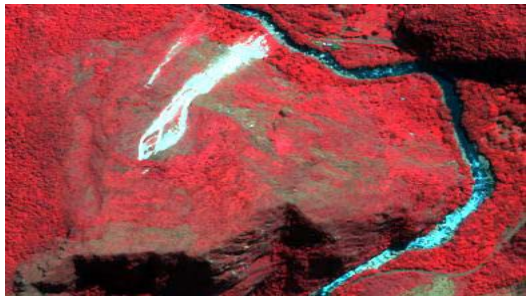


Subsidence and uplift by satellite analysis PACF Park © Spizzichino

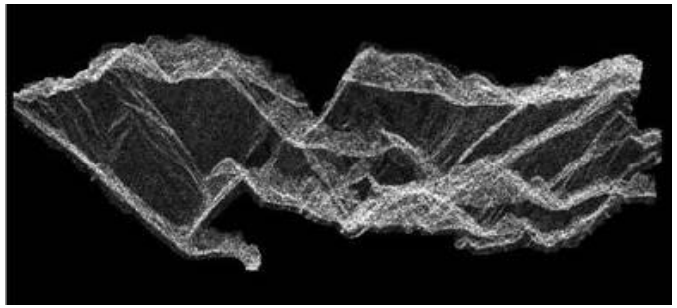
In collaborazione con



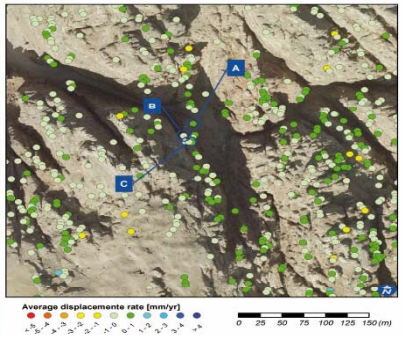
Machu Picchu 2003-2005

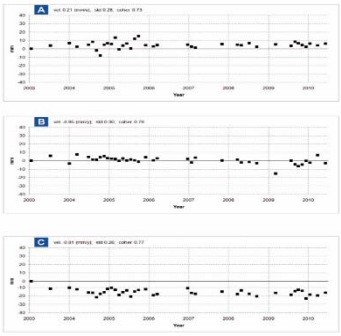


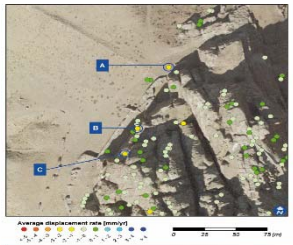
- **Ground based SAR Interferometry**
- **Optical images**
- **GPS**
- **Laser scanner**

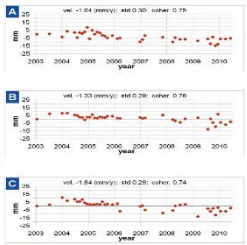


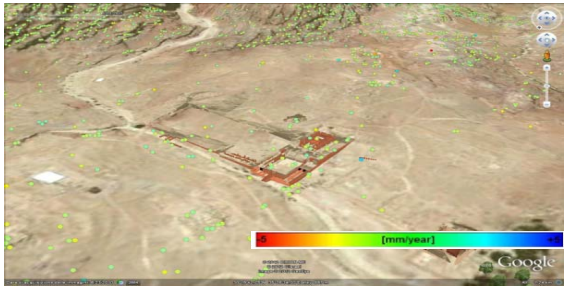
Petra -2011

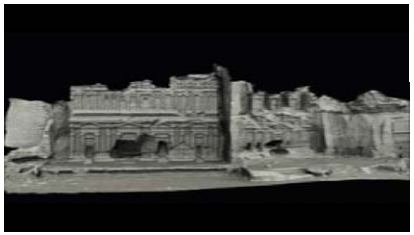






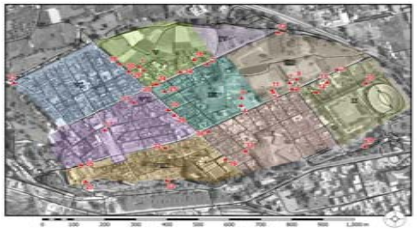


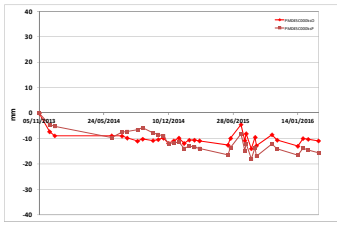




- 51 sq. km,
- 38 images ENVISAT2-V
- from January 2003 to June 2010,
- 61,983 measure points (ca. 1,215 points/sq. km)

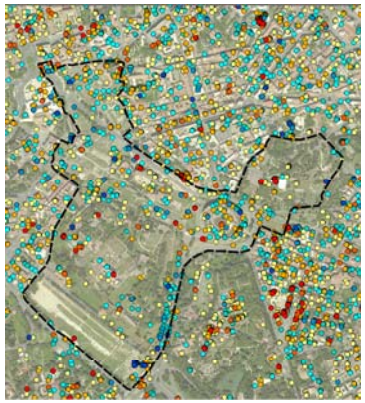
Pompei -2015 - 2017

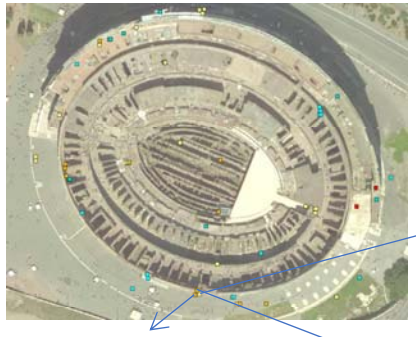




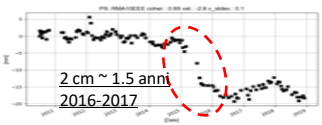
In collaborazione con

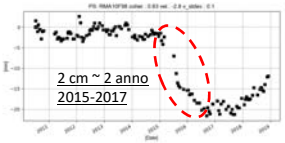
Rome pilot: "Colosseo Park & Aurelian Walls "
Threats: weathering, transportation dynamic interaction, collapses. **SAR Techniques analyses**



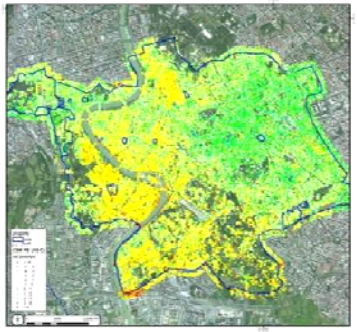


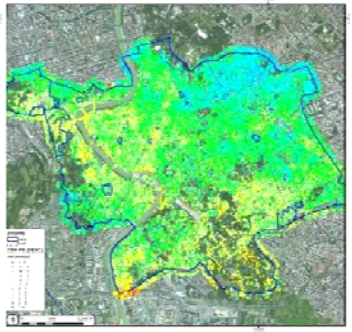
Cosmo Sky-Med, ascending, 2010/11 –

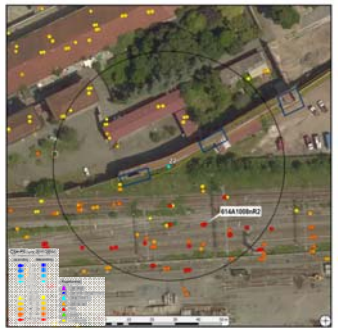


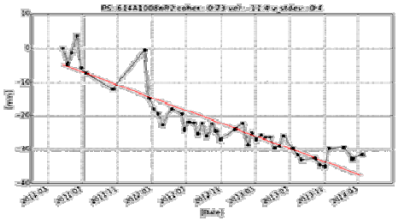


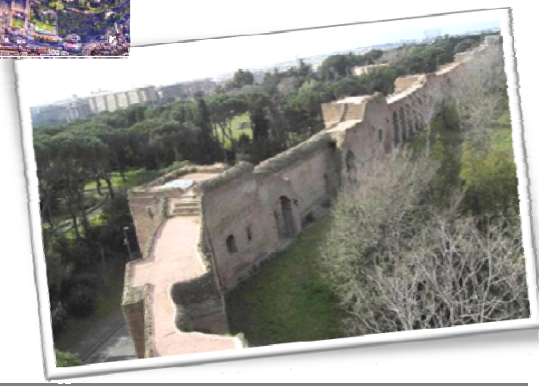
CENTRO storico di Roma











In collaborazione con

Technical Board institution for the national Parks monitoring DM n. 5 del 19/02/2019, still active until 2025

National Protocol among Ministry of Culture and ISPRA (26/05/2021)

Active agreement:
Extraordinary National Plan for the monitoring and conservation of CH (June 2022 – June 2024) – prolonged till end of 2024.

The National Plan for Monitoring and Conservation of Cultural Heritage: INTEGRATED SATELLITE-TERRESTRIAL MONITORING SYSTEM

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Methodological approach

A

CH Background (desk and field study): investigating the origin, typology, construction techniques, restoration history, evolution in time, etc.

FOUR

steps

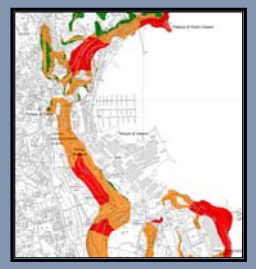
In collaborazione con

A

CH Background (desk and field study):
investigating the origin, typology, construction techniques, restoration history, evolution in time, etc.

B

Geohazard assessment
Hazard and risk map analysis



C

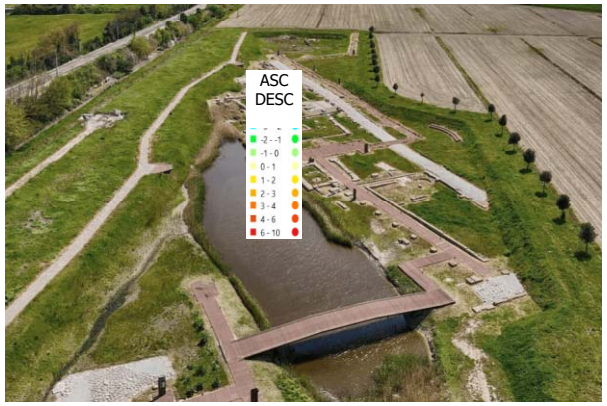
SAR Interferometry
Data integration and services

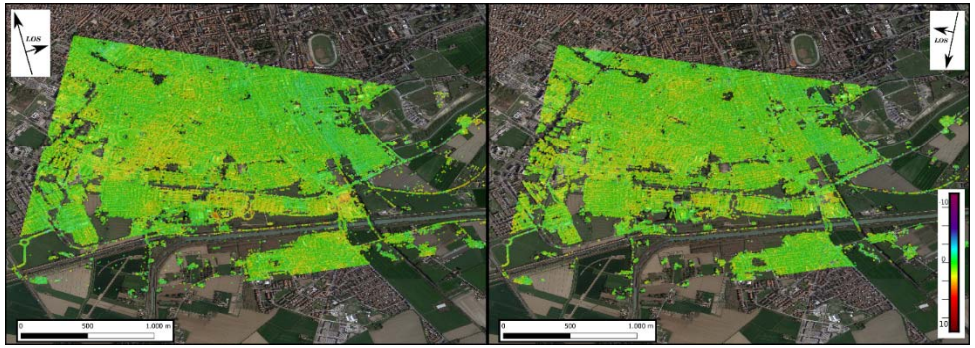
D

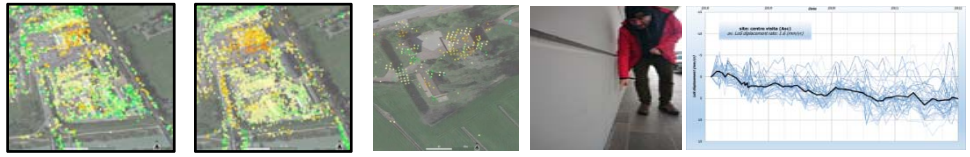
Ground motion monitoring
Field survey and risk mitigation plan

In collaborazione con

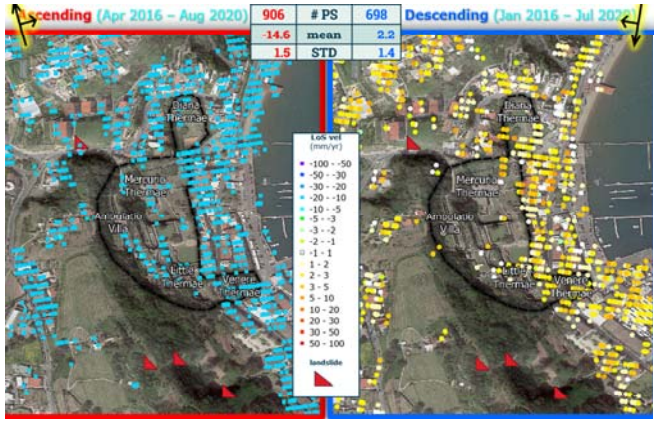
Ravenna pilot: "Archaeological harbor of Classe"
Threats: historical subsidence/differential deformation
SAR Techniques analyses

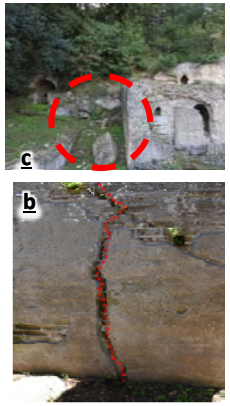


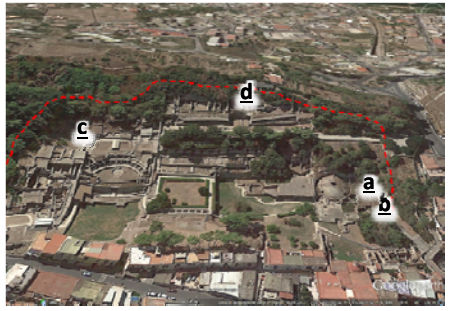


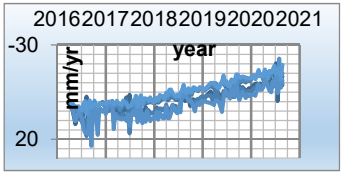


Campi Flegrei pilot: "Archaeological thermae of Baia"
Threats: uplift, rock fall and sea level rise
SAR Techniques analyses



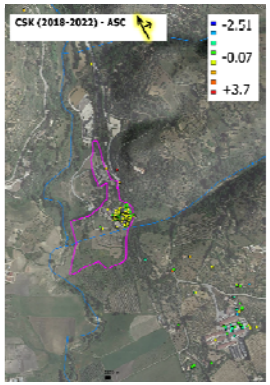


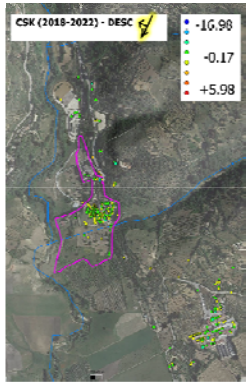


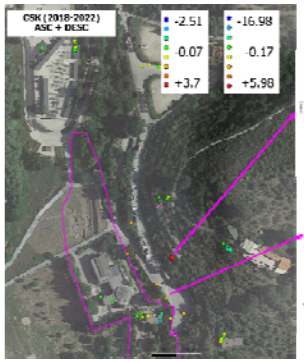


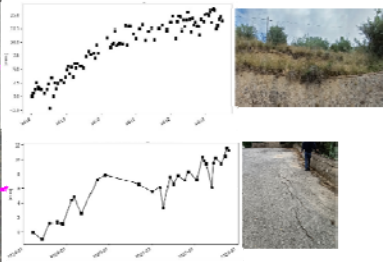
In collaborazione con

Piazza Armerina pilot: "Roman mosaic"
Threats: slow and rapid landslide; water table fluctuation
SAR Techniques analyses

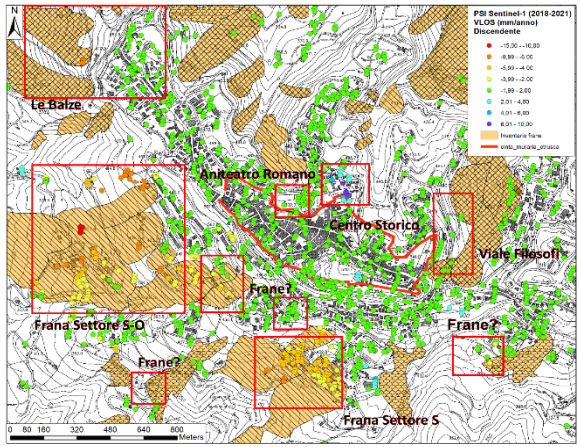








Volterra: "Historical village and medieval walls"
Threats: slow landslide
SAR Techniques analyses



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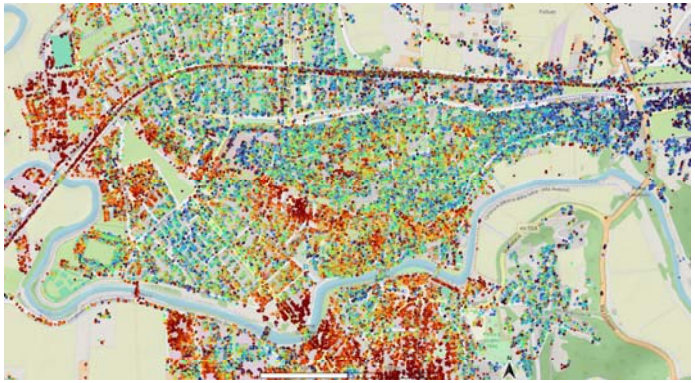
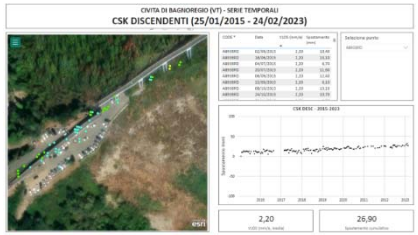
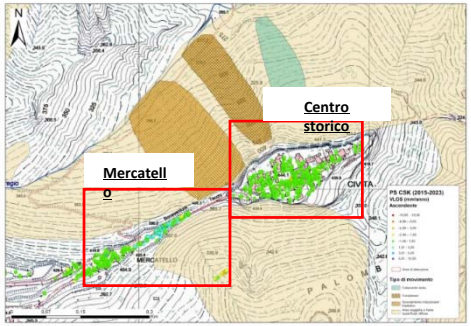
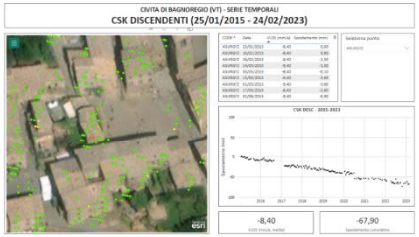
RIETI pilot: "Historical center"
Threats: slow landslide; water table fluctuation
SAR Techniques analyses

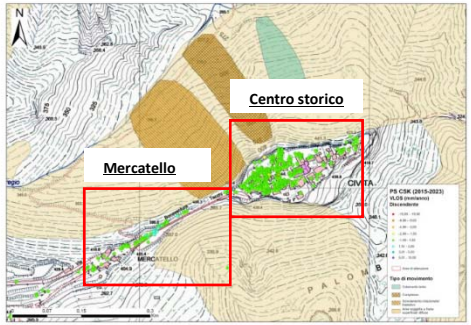


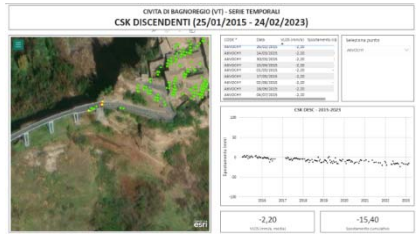
Civita_pilot: "Historical village"
Threats: slow landslide & ground deformations
SAR Techniques analyses







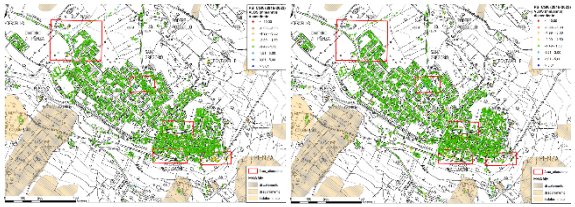




In collaborazione con

Paestum pilot: "Archaeological roman Park"
Threats: water table fluctuation, weathering, SAR Techniques analyses

Pienza pilot: "Historical small town"
Threats: DGPV/regional fault; sructural damage: SAR Techniques analyses



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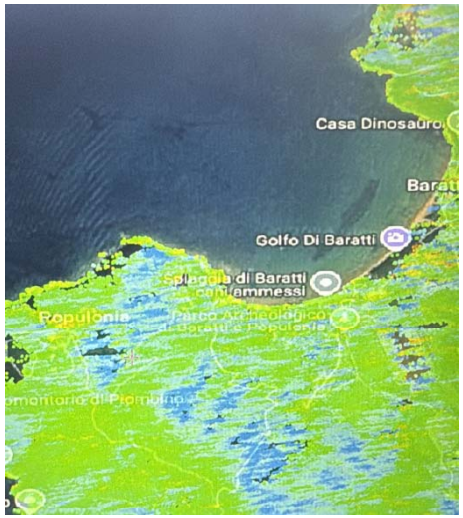
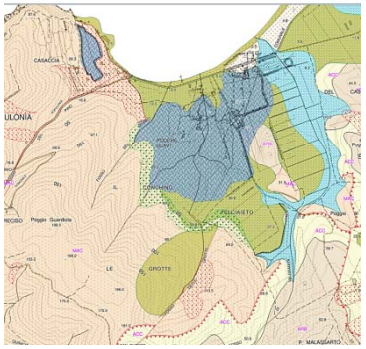
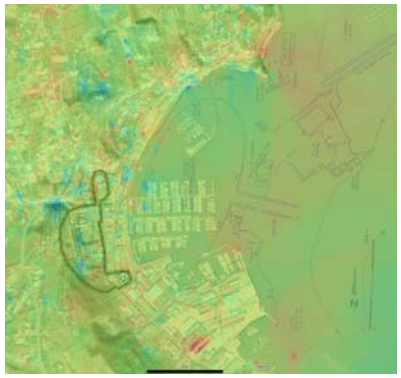
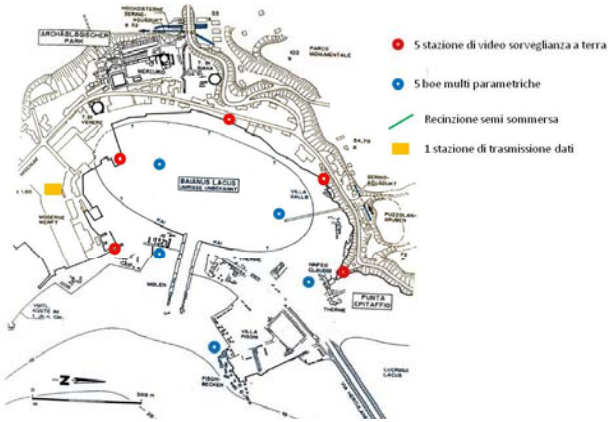
Baratti&Populonia pilot: "Archaeological area"
Threats: subsidence and morphological phenomena
ground motion,
SAR Techniques analyses





Parco sommerso Terme di Baia pilot:
"Archaeological submarine area"
Threats: subsidence and bradism, co-seismic effect
morphological phenomena,
SAR Techniques analyses





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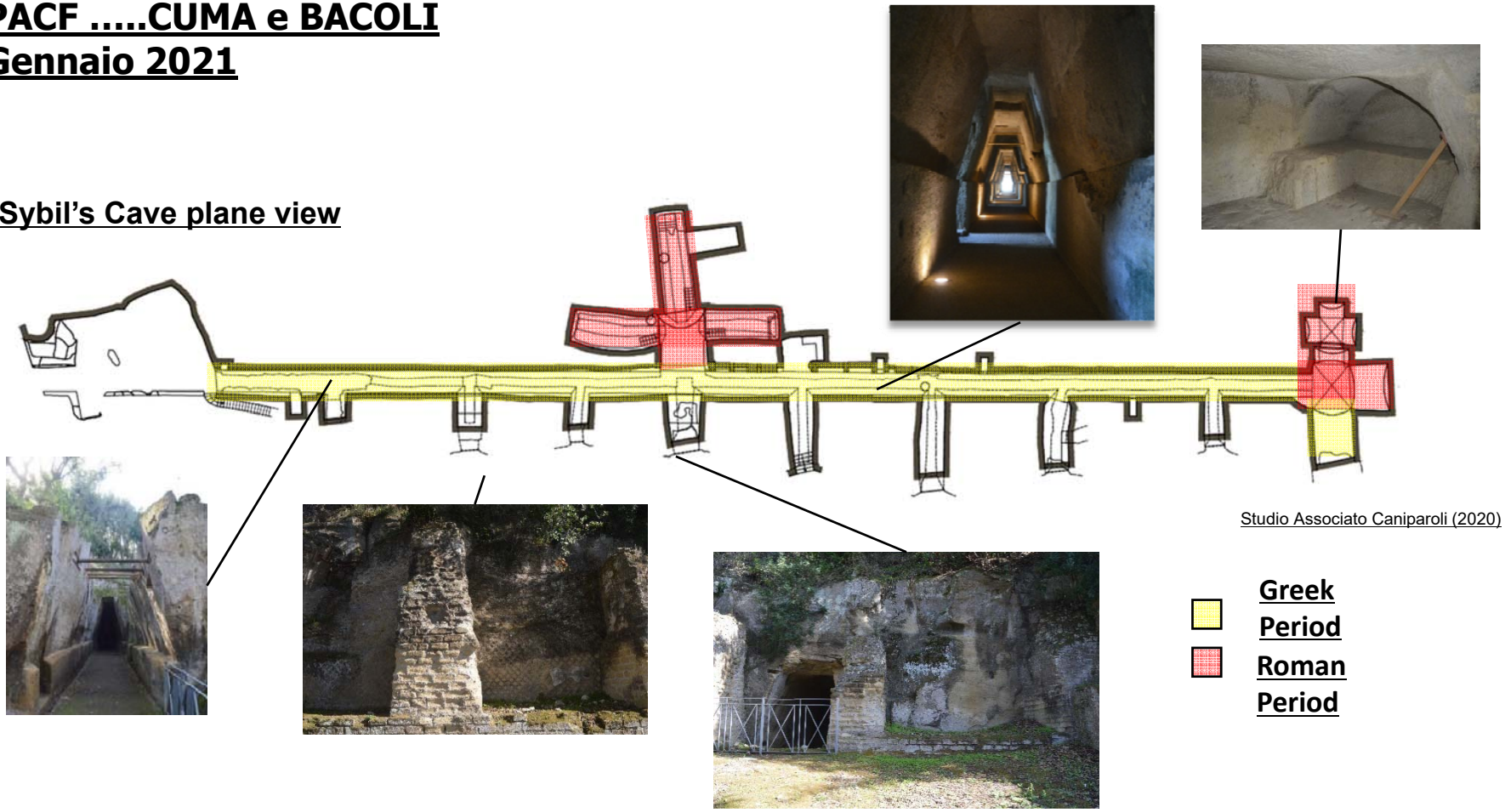
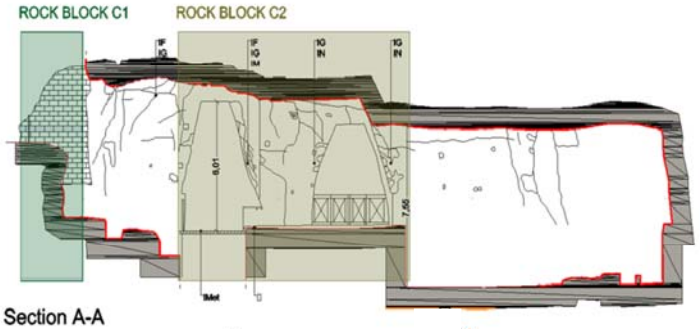
PACF .....CUMA e BACOLI
Gennaio 2021

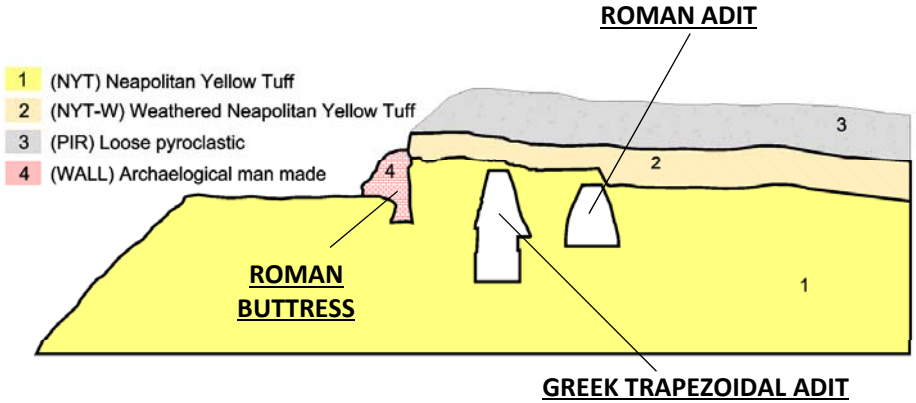
Sybil's Cave plane view

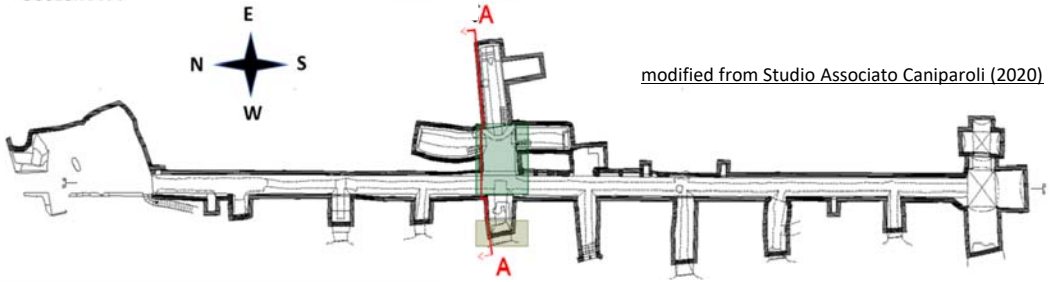


Studio Associato Caniparoli (2020)

In collaborazione con





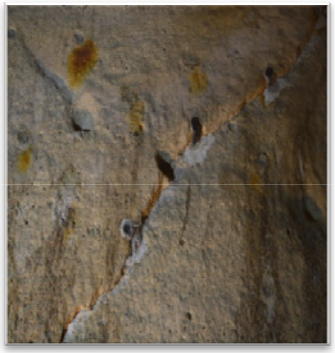


modified from Studio Associato Caniparoli (2020)

Prepared and tested at LARGIN, University of Bologna, Italy

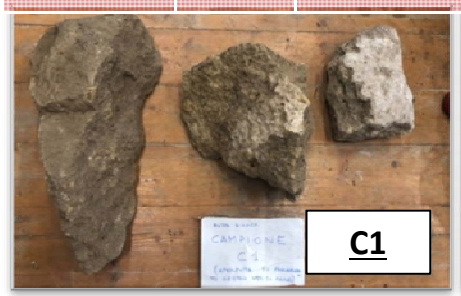
BLOCK C1

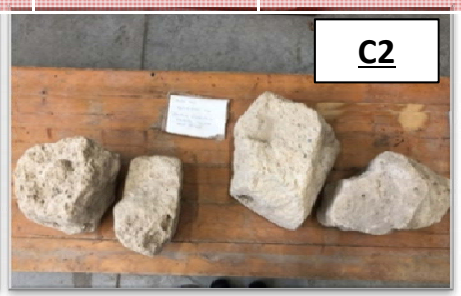
BLOCK C2



In collaborazione con

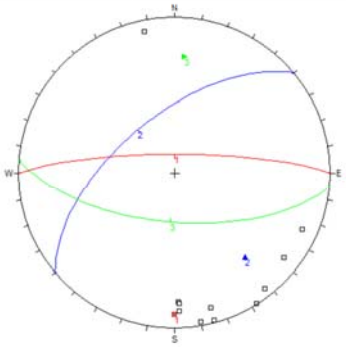
Block #	n [%]	V_P [km/s]	γ_{dry} [kN/m³]	γ_{sat} [kN/m³]	$\sigma_{f,dry}$ [MPa]	$\sigma_{t,dry}$ [MPa]	$\sigma_{f,sat}$ [MPa]	$\sigma_{t,sat}$ [MPa]
C1	50.9	2.13	12.7	17.4	4.87	0.59	4.76	0.60
C2	51.0	2.01	12.5	17.2	4.98	1.68	3.52	0.55
mean	**51.0**	**2.07**	**12.6**	**17.3**	**4.93**	**1.03**	**4.14**	**0.57**





2 blocks

49 specimens



NYT

JRC = 12

JCS = $\sigma_{f,sat}$ - 20% = 3.3 MPa

jset #	dd [°]	dip [°]
K1	360	80
K2	320	60
K3	185	64

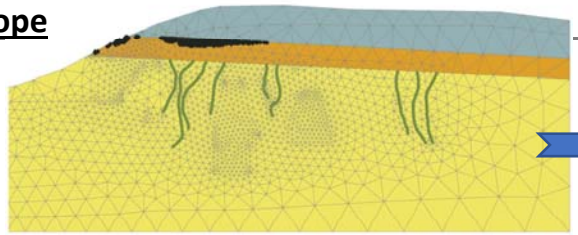
NYT-W

JRC = 12-2 = 10

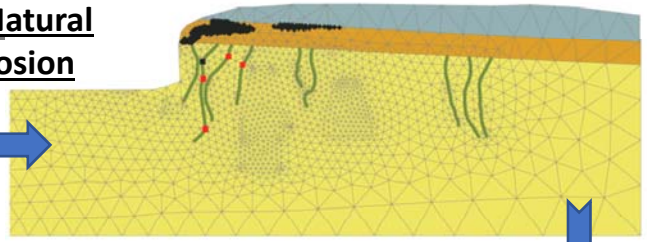
JCS = JCS_{NYT} - 20% = 2.6 MPa

In collaborazione con

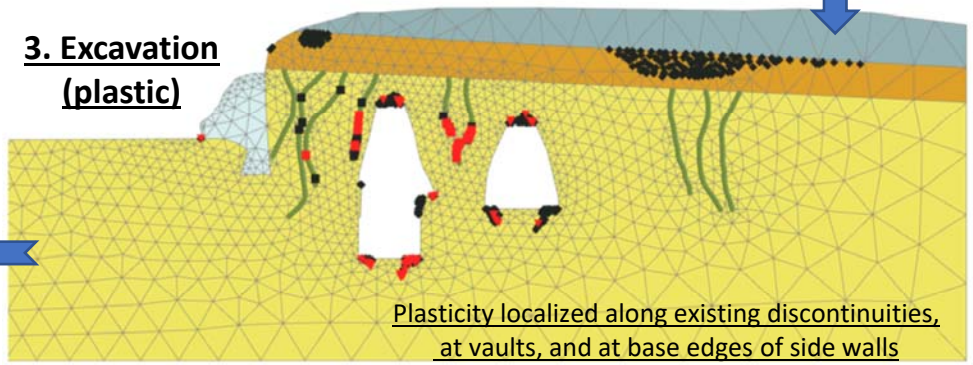
1. Original slope



2. Natural erosion

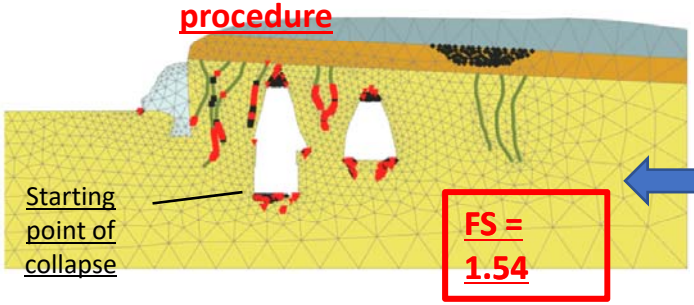


3. Excavation (plastic)

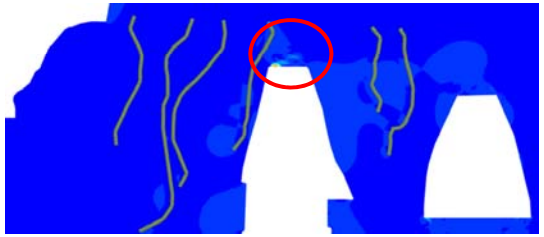


Plasticity localized along existing discontinuities, at vaults, and at base edges of side walls

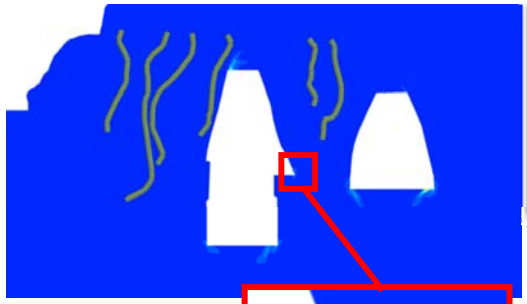
4. Phi-c reduction procedure



▼ ■ Failure point ◆ ■ Tension cut-off point



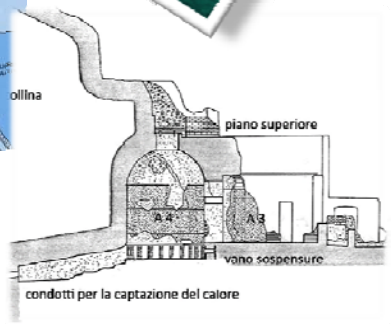
Incremental volumetric strains
Stage 3 Step 368 (last)



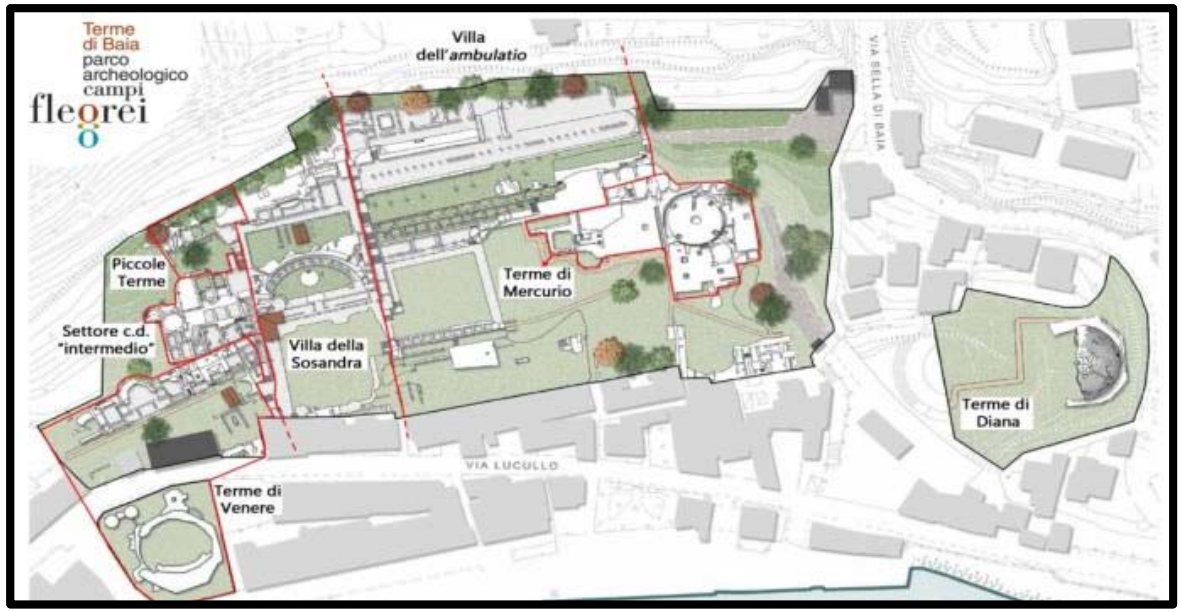
Total deviatoric strains
Stage 3 Step 368 (last)

In

Parco Archeologico dei Campi Flegrei: Terme Romane di Baia



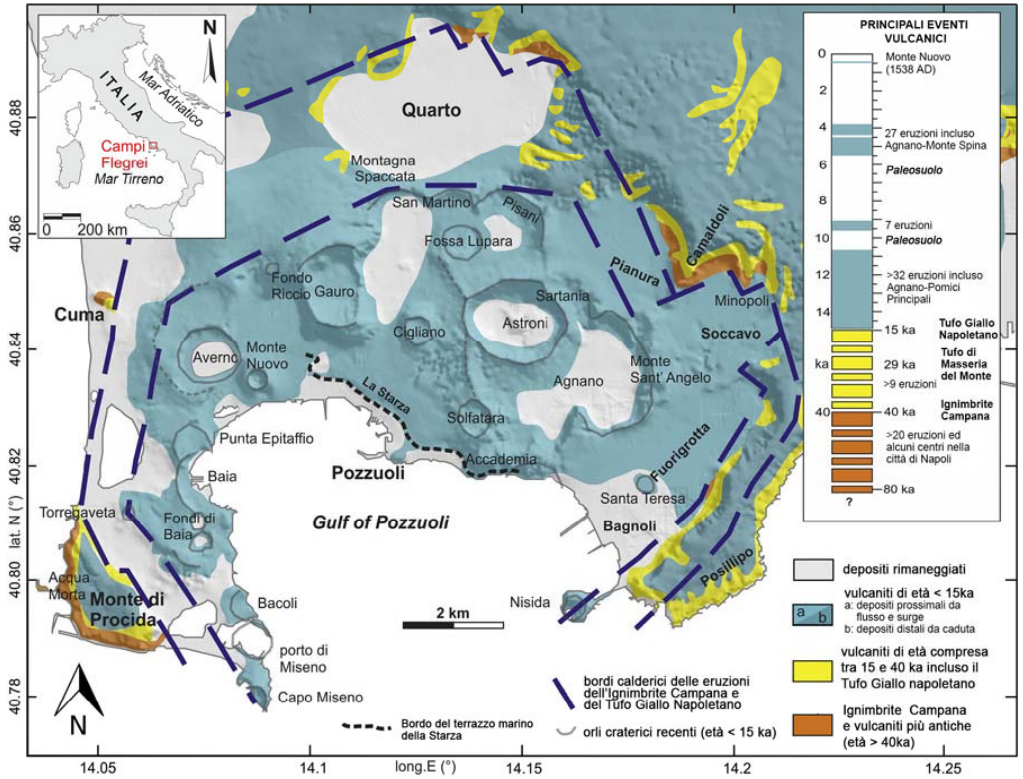
In collaborazione con



In collaborazione con

Inquadramento geologico

- abbassamento correlato ai vulcani con cicli caratterizzati da un intenso sollevamento e abbassamento del suolo



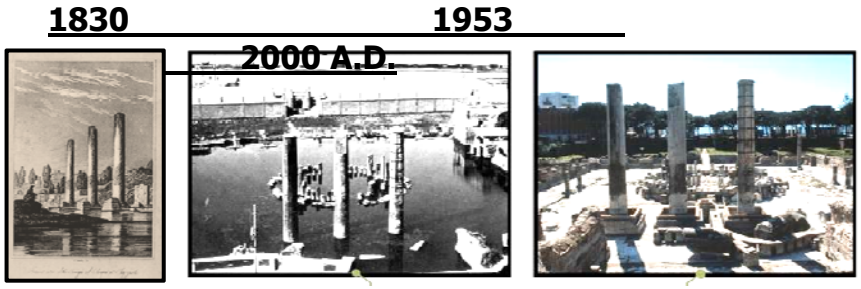
Surge deposists

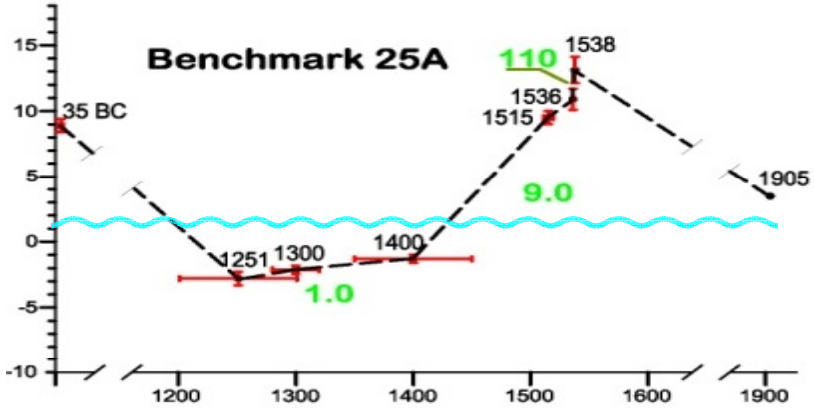
Depositi piroclastici

Breccia Vulcanica

In collaborazione con

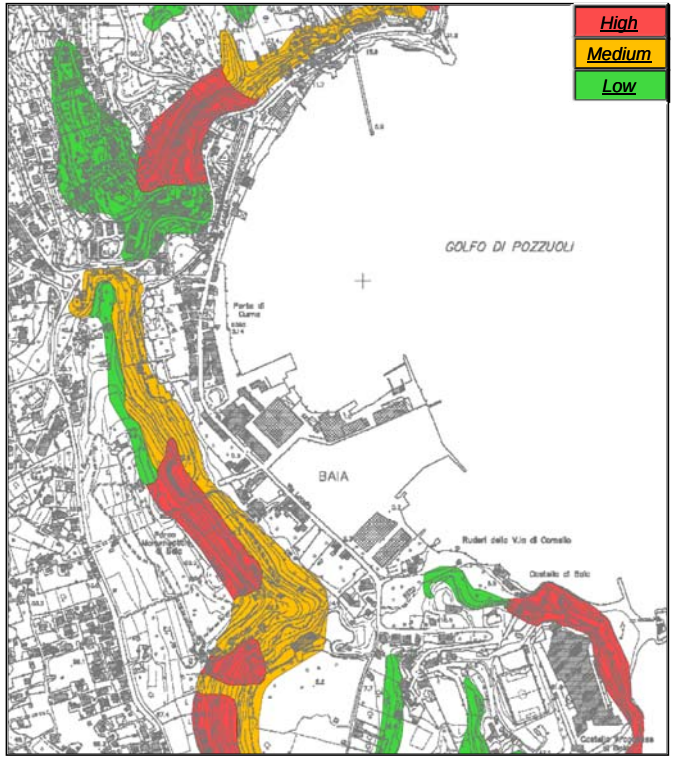
Inquadramento storico

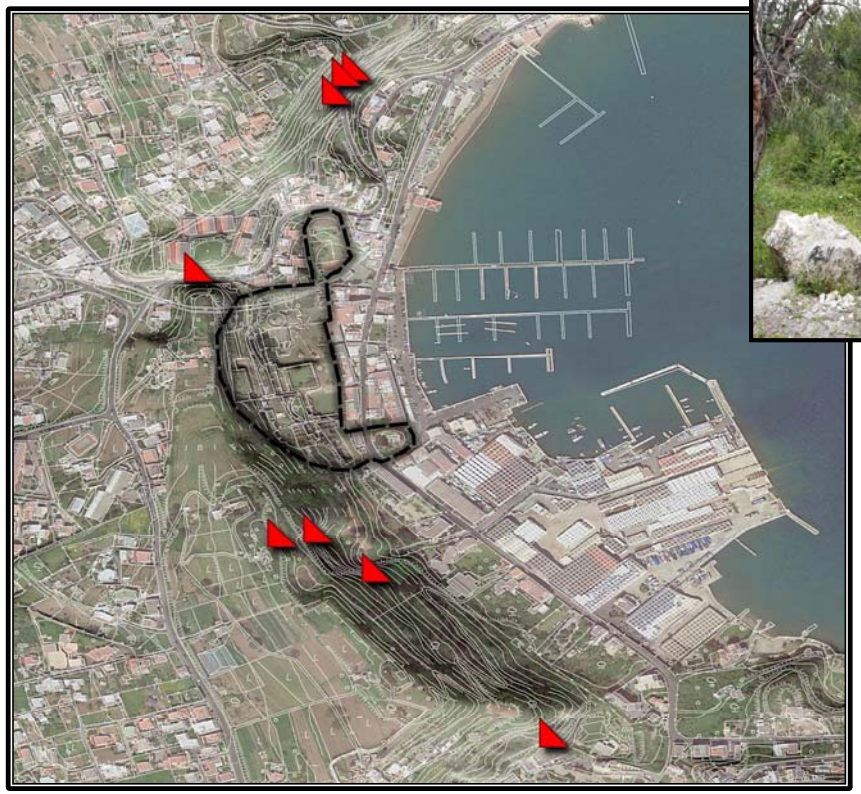




In collaborazione con

Inquadramento geomorfologico: fenomeni di instabilità

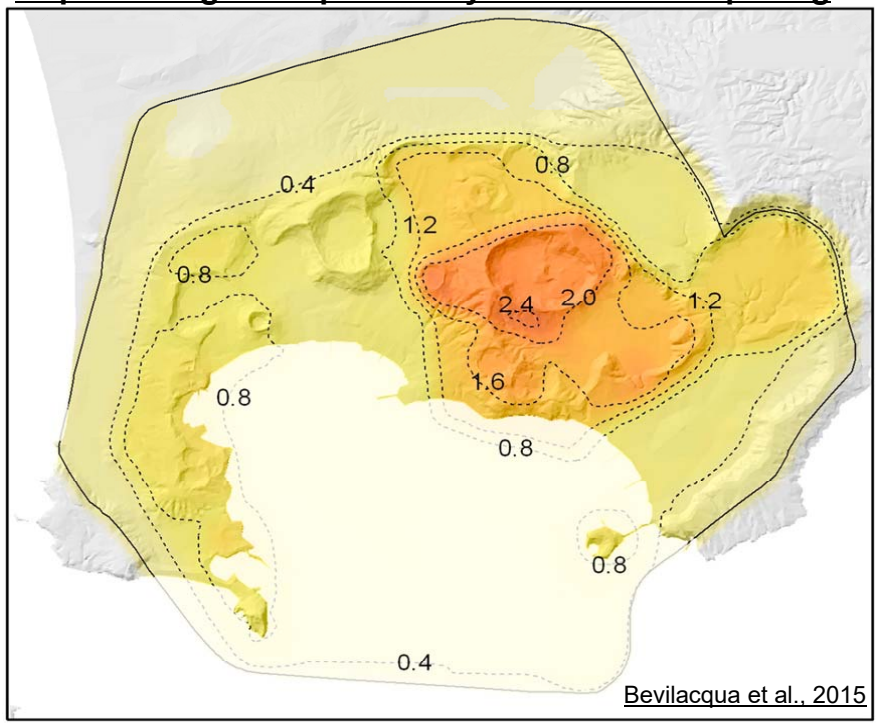




In collaborazione con

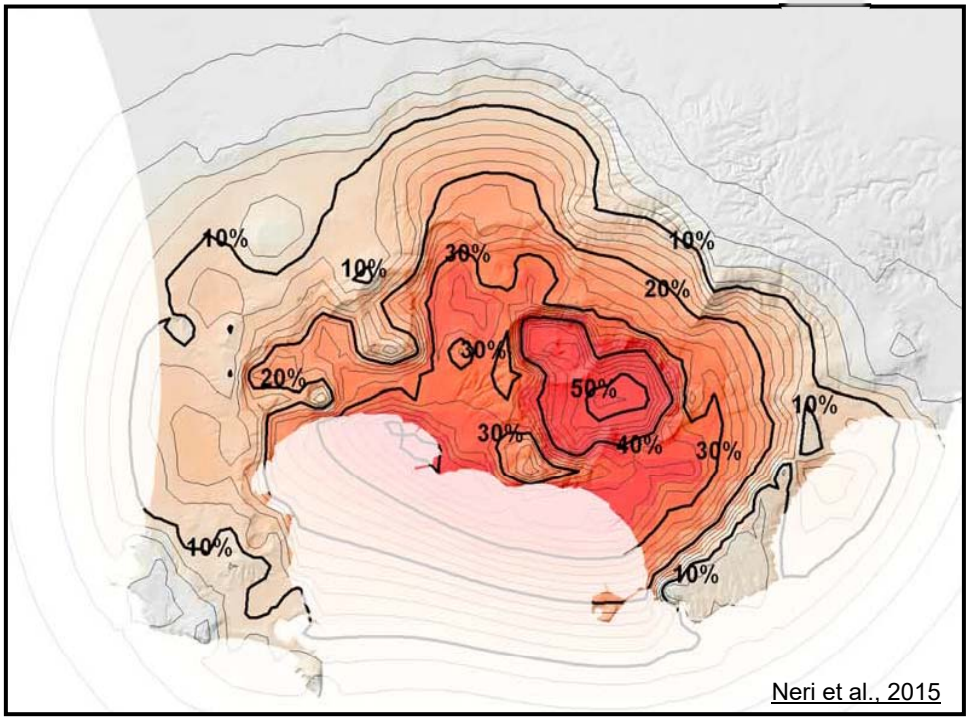
Pericolosità vulcanica

Map of background probability of future vent opening



Bevilacqua et al., 2015

Pyroclastic Density Currents (PDC) invasion probability maps

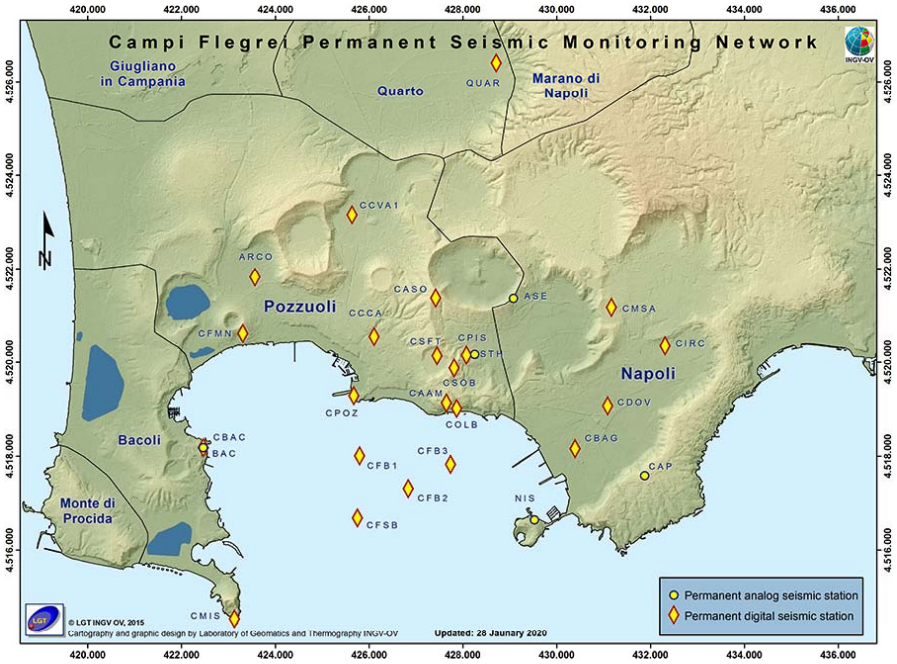


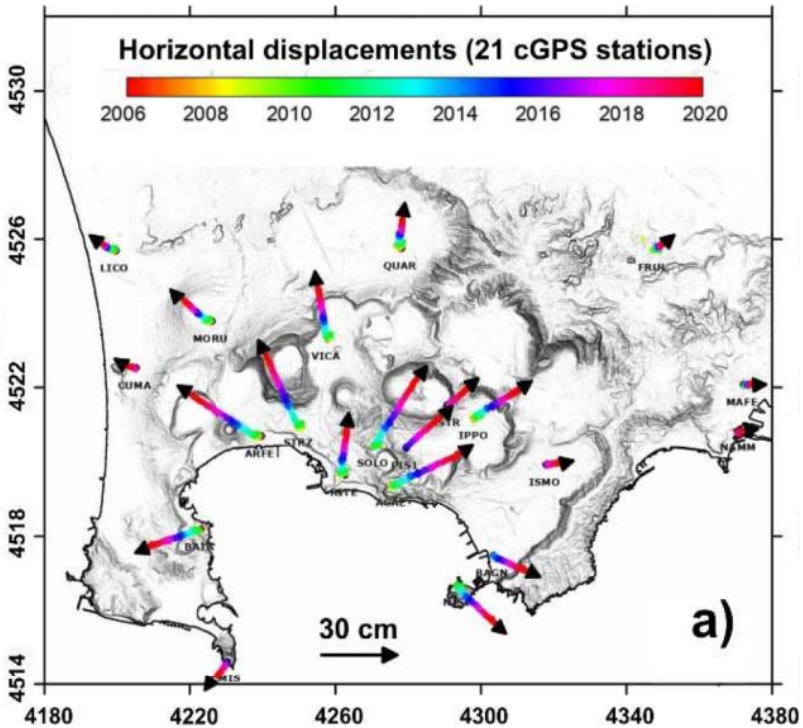
Neri et al., 2015

In collaborazione con

Rete monitoraggio sismico

Permanent Seismic Monitoring Network

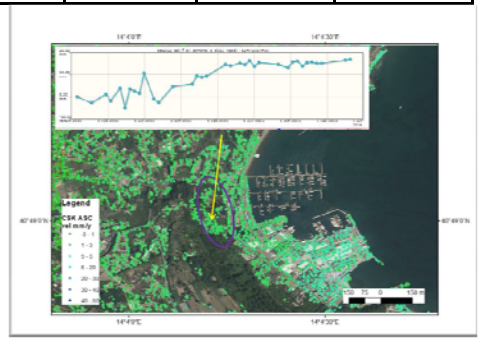


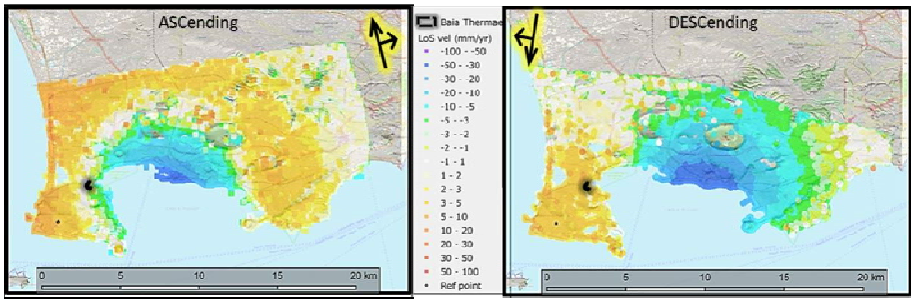


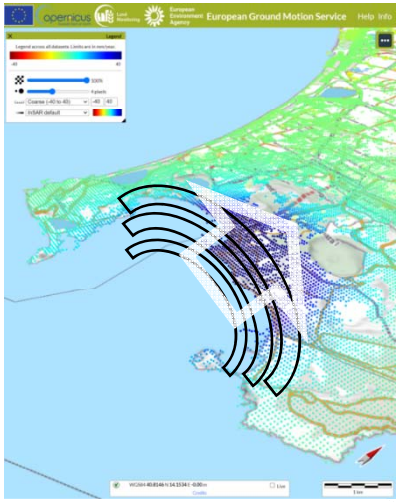
In collaborazione con

Ground Motion: interpretazione dati PS InSAR di sito

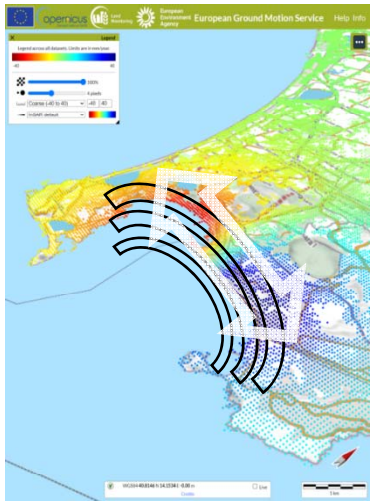
Satellite	Periodi di riferimento	Tempo di rivisita	Banda	Risoluzione	Processing
ERS - PST	1993 - 2001	35	C	15 x 4	PSInSAR™
Cosmo Sky-Med (CSK) PST	2003 - 2009	35	X	3 X 3	PSInSAR™
SENTINEL-1	2016 - 2020	12	C	15 X 4	PSI
Cosmo-SkyMed (CSK)	2017 - 2022	16	X	3 X 3	PSI
EGMS (SENTINEL-1)	2015 - 2021	12	C	15 X 4	Ortho Level







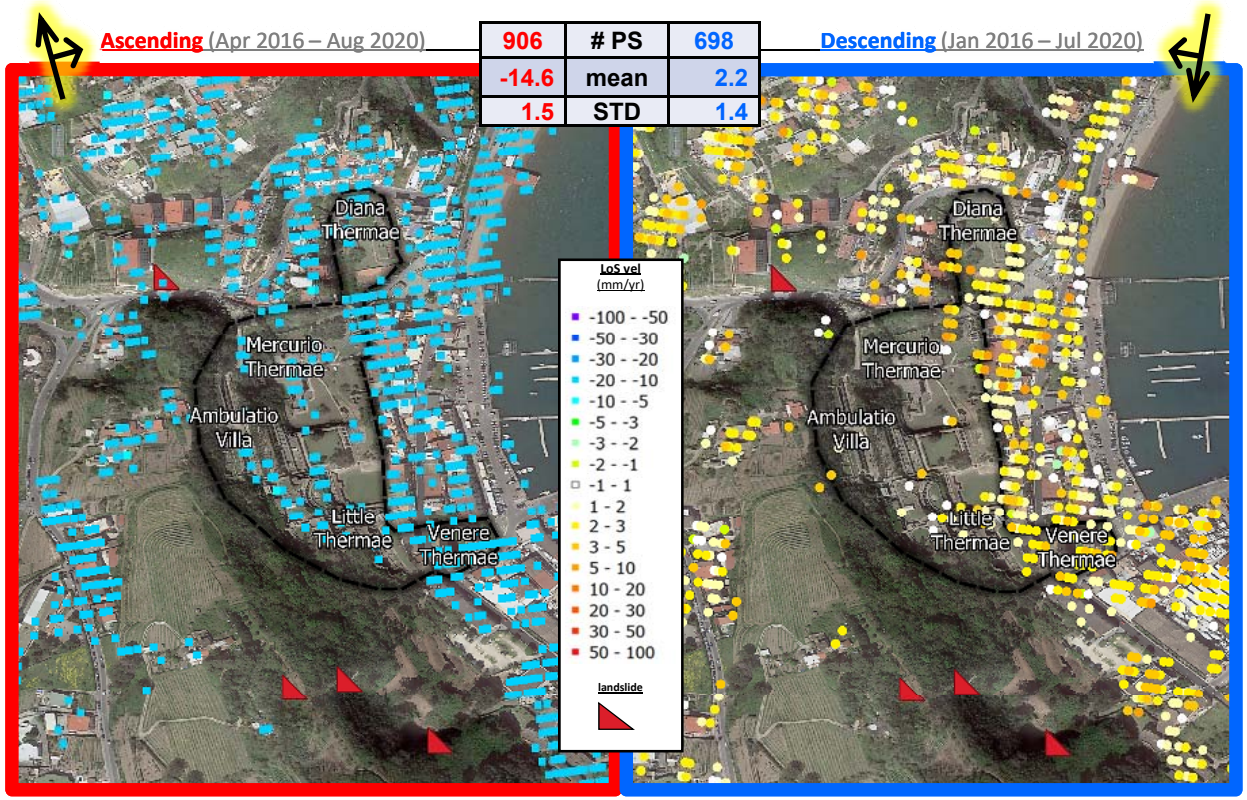
vertical (UP) +8.1 mm/year



horizontal (E-W) -19.2 mm/year

In collaborazione con

Ground Motion: interpretazione dati PS InSAR di sito



L'interpretazione dei dati PS InSAR a scala di sito richiede la massima risoluzione disponibile.

Questa condizione è rappresentata dalla copertura di PS originale, per singola geometria ascendente e discendente.

Il confronto fra i PS rilevati da due punti di vista opposti mette in evidenza la componente orizzontale degli spostamenti, come avviene per i movimenti di versante.

A Baia la geometria **ascendente** è influenzata maggiormente dallo spostamento verso nordovest dell'area, con valori medi di "sollevamento" di circa 15 mm/anno.

La geometria **discendente** invece, per motivi di geometria di acquisizione, riflette di meno lo spostamento areale, quindi permette di evidenziare meglio gli spostamenti differenziali localizzati.

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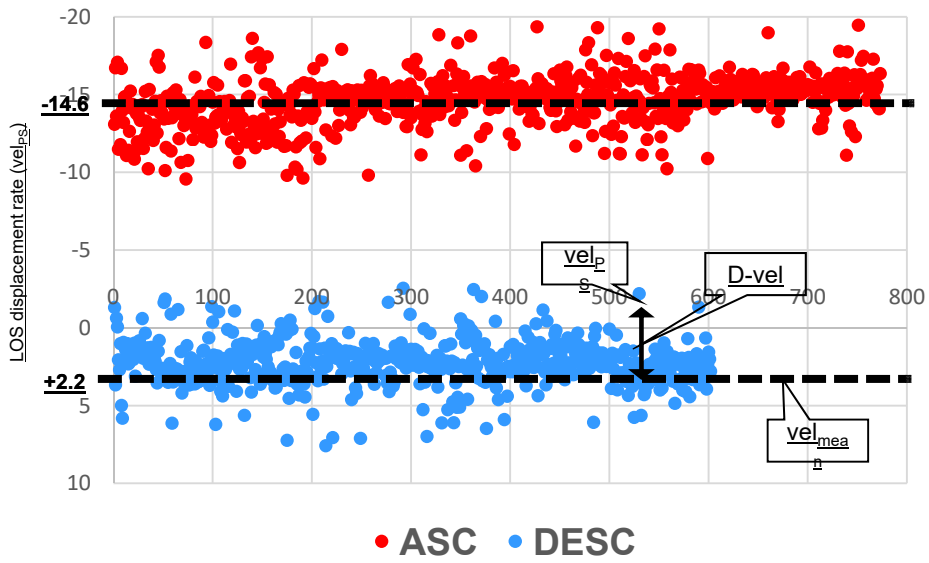
Spostamenti differenziali

L'area è soggetta ad alti tassi di deformazione, particolarmente evidenti in geometria ASCendente.

Quindi, per evidenziare i movimenti del terreno **differenziali** a scala di sito, è stata calcolata la differenza tra la velocità di spostamento di ogni punto di misura (PS) ed il valore medio del sito.

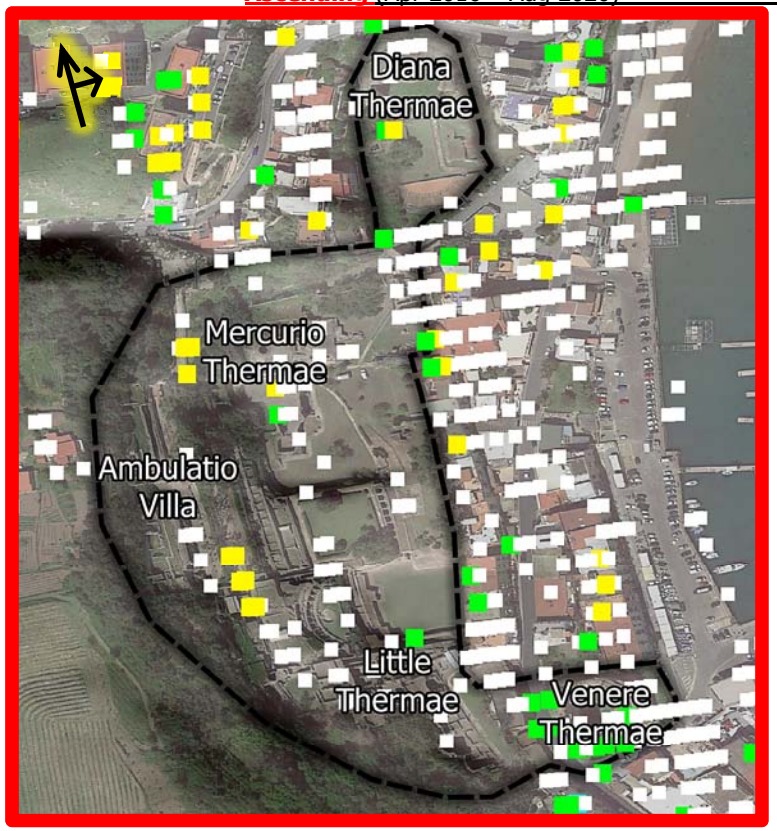
$$\text{D-vel} = vel_{PS} - vel_{mean}$$

ASC	mean D-vel	DESC
-14.6	mm/yr	2.2



Spostamenti differenziali

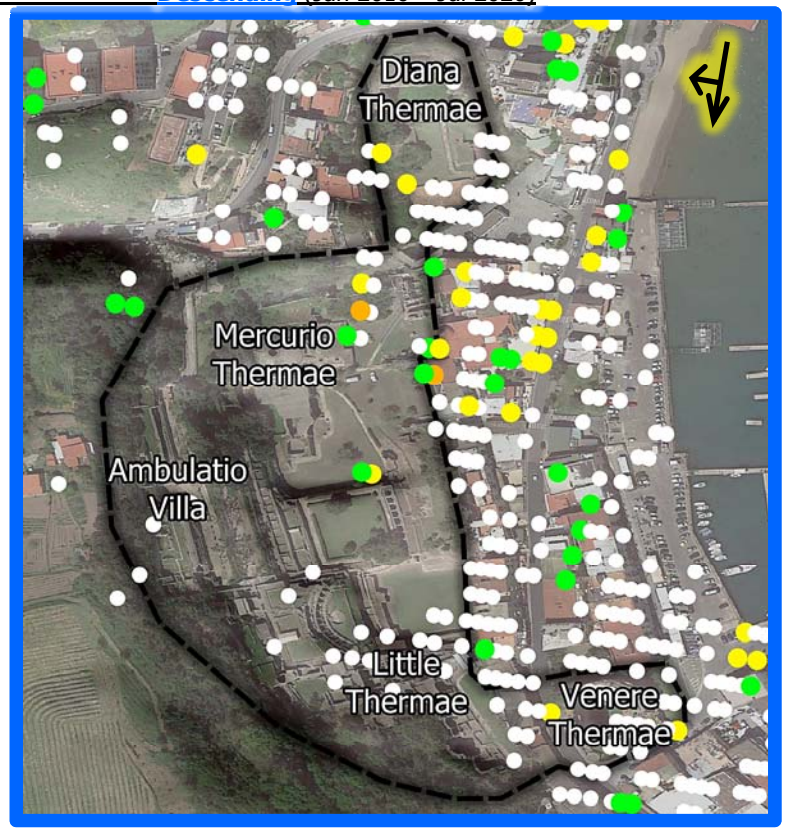
Ascending (Apr 2016 – Aug 2020)



LoS differential displacement velocity, D-vel (mm/yr)

ASC		DESC
	< -10	
	-10 – -5	
	-5 – -2	
	-2 – 2	
	2 – 5	
	5 – 10	
	> 10	

Descending (Jan 2016 – Jul 2020)



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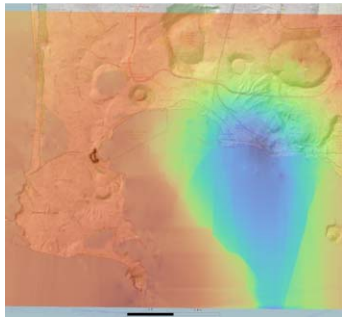
Heatmap analysis

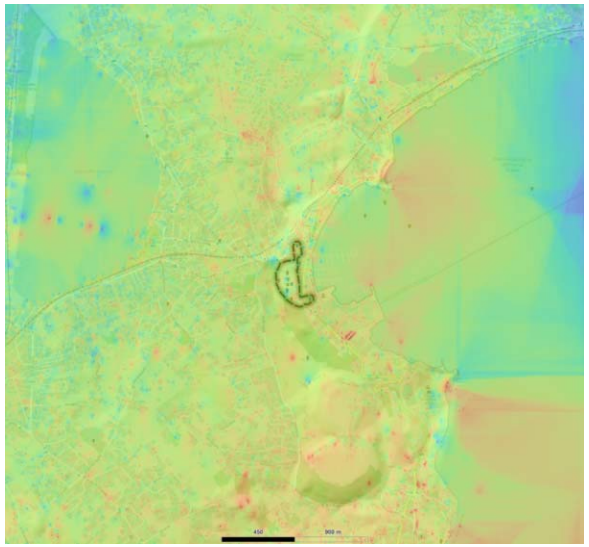
Heatmap interpolation and countoring

DESC LoS displacements (mm/year)

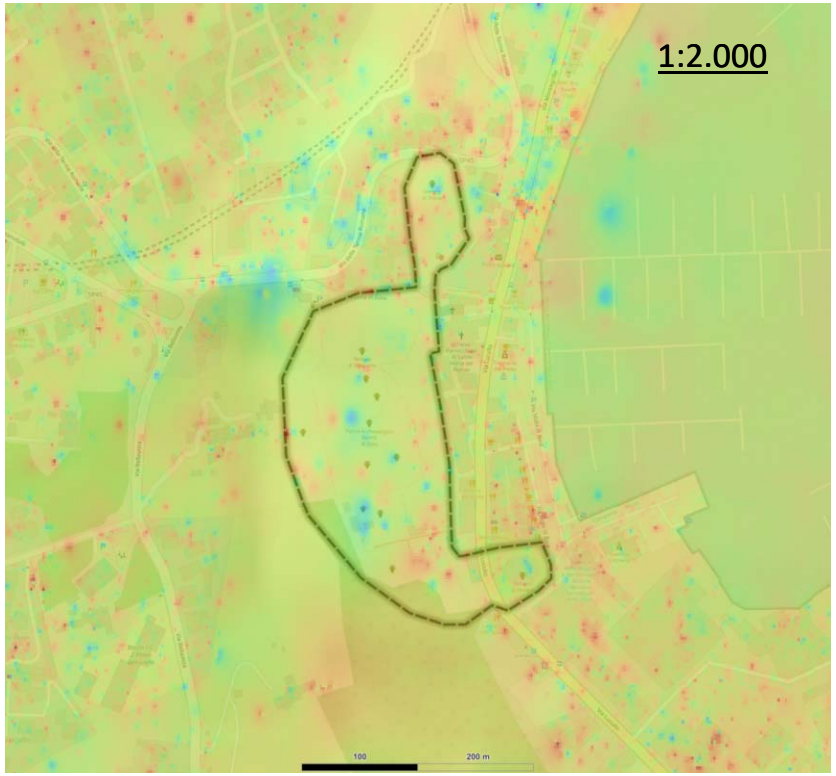
1:25.000



1:10.000



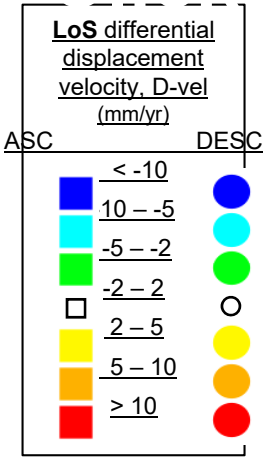
1:2.000

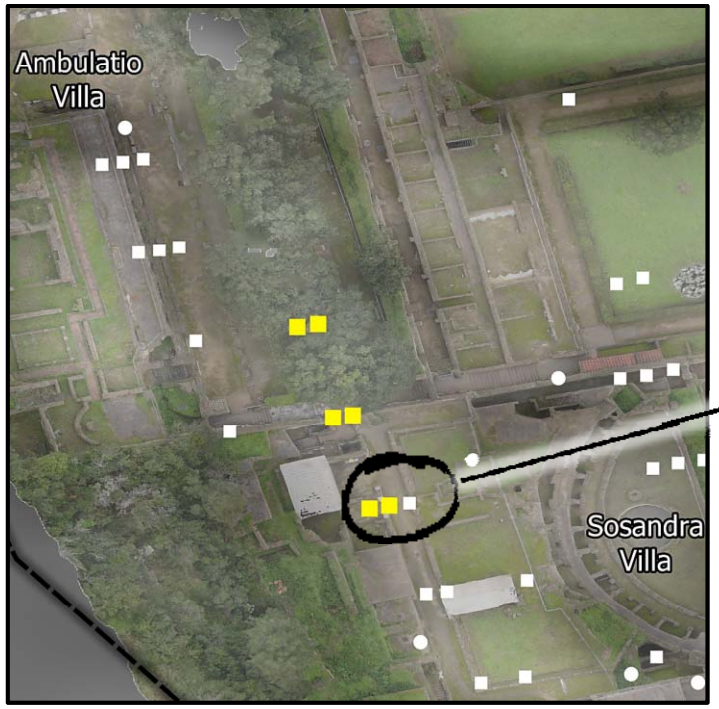


In collaborazione con

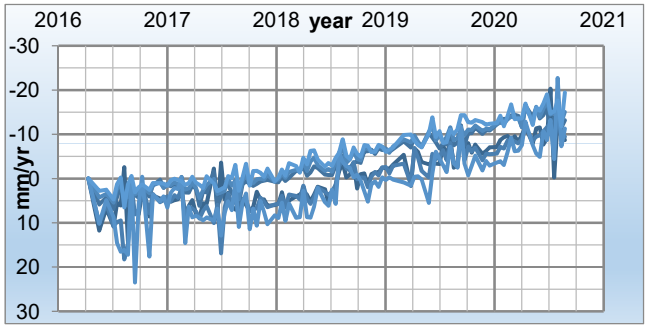
DESC LoS displacements (mm/year) scale 1:500

In collaborazione con

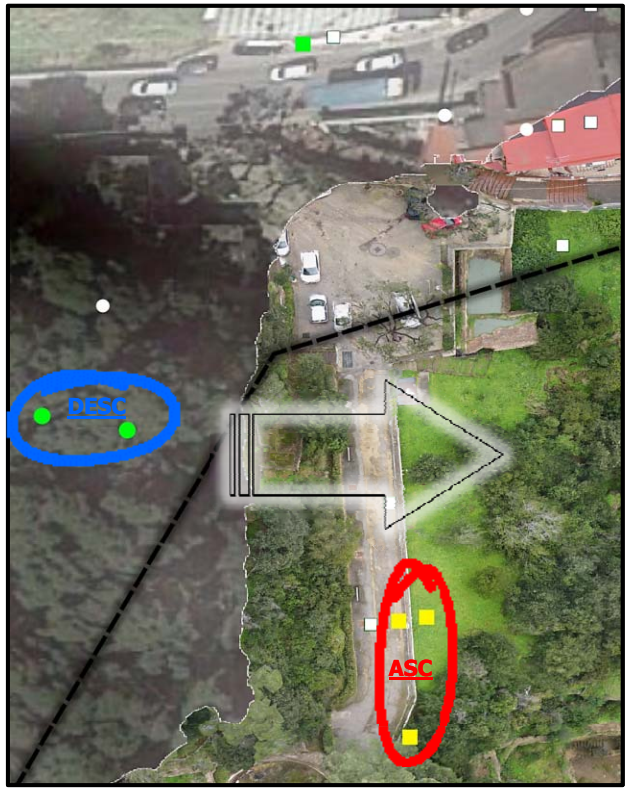




Ascending geometry seems to be more sensitive to radar targets in the site area; this is due mainly to "noise effect", then to East facing geometry of the slope too.
At the edge between *Ambulatio* and *Sosandra* villas a cluster of 6 PSs indicates, consistently, a relatively subsiding area.
The crack along the sidewall may indicate this masonry weakness, thus needs to be properly monitored.



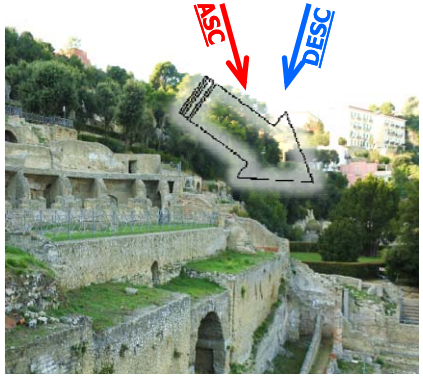
In collaborazione con

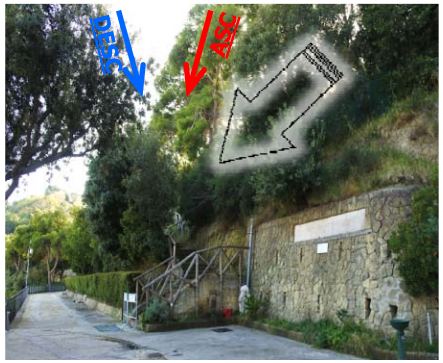


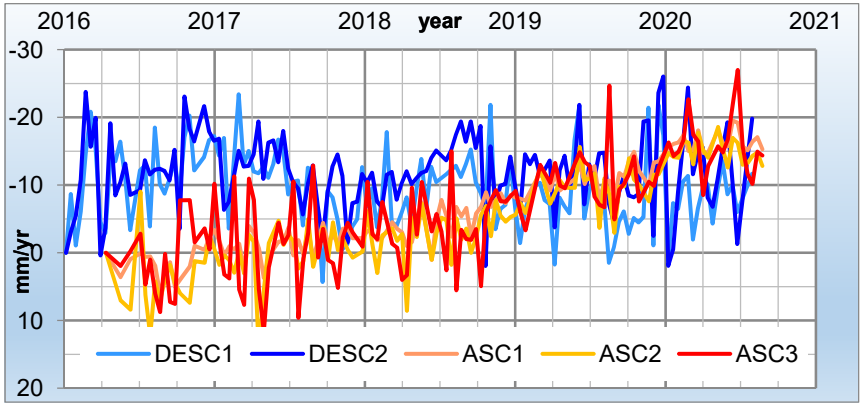
The combined interpretation of the PS, moving away from the ASC satellite and approaching the DESC satellite, shows the prevalence of the horizontal movement of slow slope sliding eastward, i.e., seaward.

LoS differential displacement (mm/yr)

- < -10
- -10 – -5
- -5 – -2
- -2 – 2
- 2 – 5
- 5 – 10
- > 10







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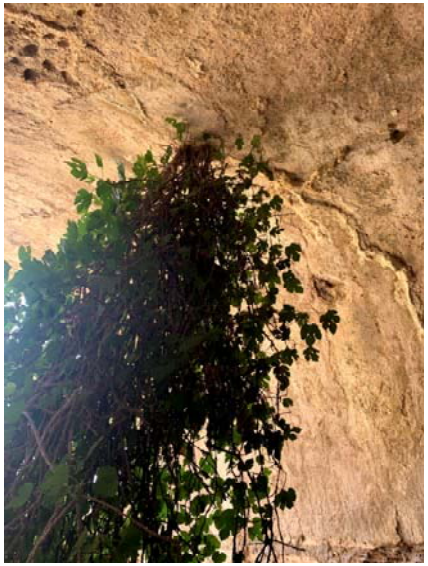
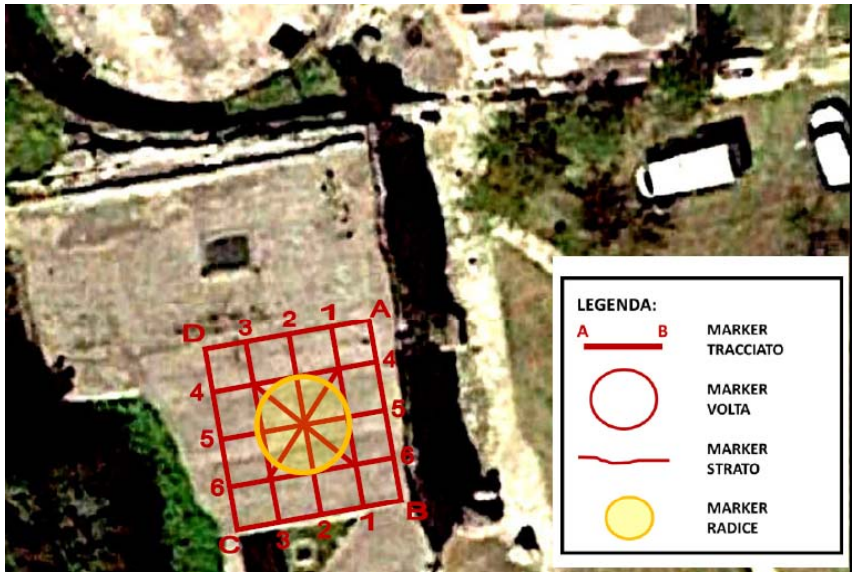
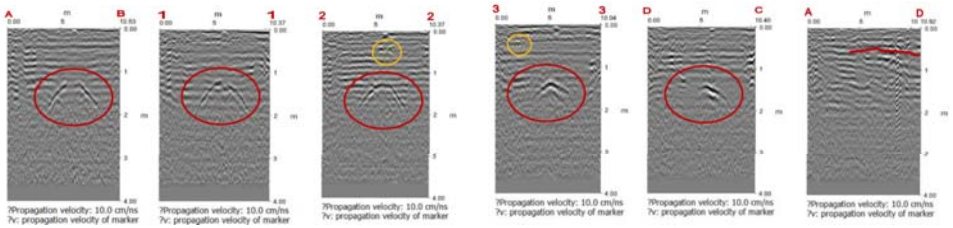
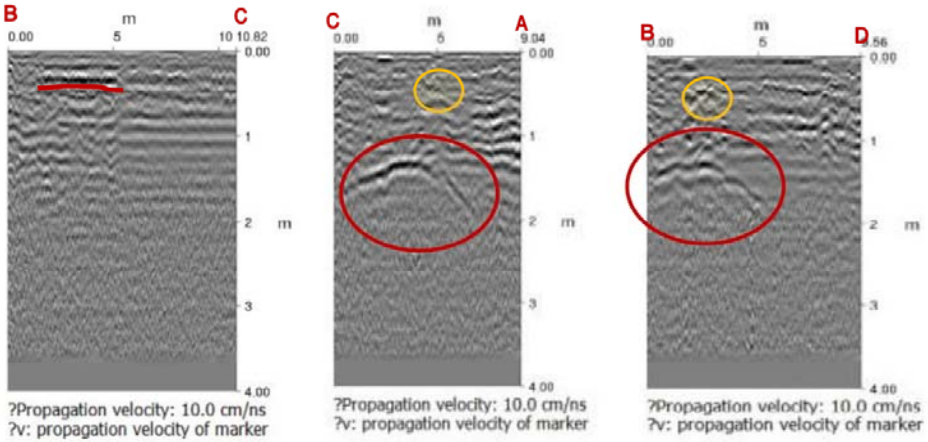
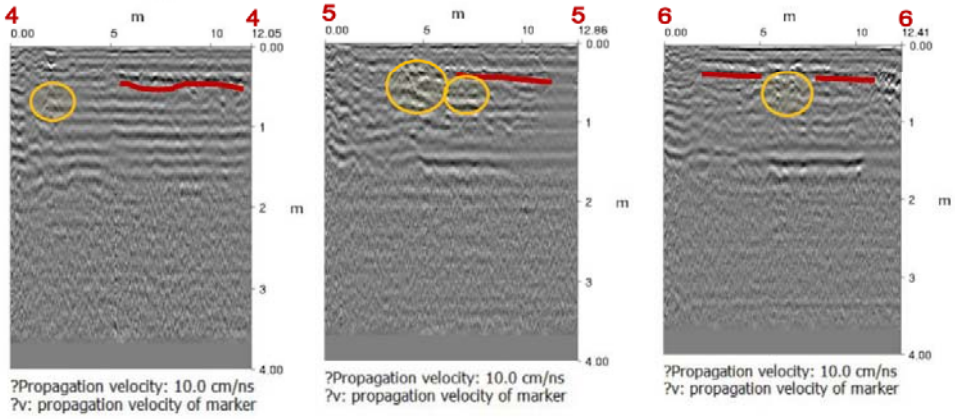


In collaborazione con


LEGENDA:
A B
MARKER TRACCIATO
MARKER VOLTA
MARKER STRATO
MARKER RADICE

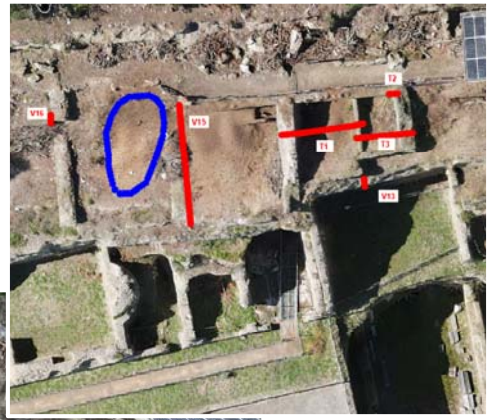



?Propagation velocity: 10.0 cm/ns
?v: propagation velocity of marker


?Propagation velocity: 10.0 cm/ns
?v: propagation velocity of marker

Field Survey: quadro dei danni

Rilievo 3D



Restituzione

frattura

scivolamento del suolo, dilavamento accentuato

Fotointerpretazione

In collaborazione con

Ipotesi preliminare sistema di monitoraggio in situ da integrare nel sistema del PACF

- **Fessurimetri: stazioni di misura di spostamento (tipo A) N° 10**
- **Termoigrometro: stazioni di misura della temperatura e dell'umidità relativa) (tipo B) n° 12**
- **Tiltmetro: stazione di misura delle rotazioni (tipo C)**
- **Intervento/sistemazione (tipo D) N° 1**
- **Accelerometro/velocimetro: stazioni di misura dinamico (tipo E) N°1**

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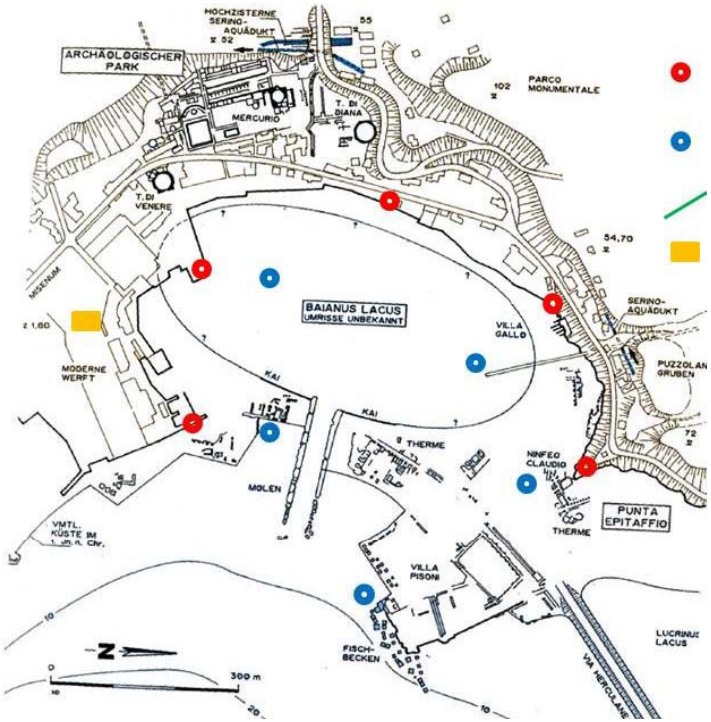
Ipotesi preliminare sistema di monitoraggio in situ da integrare nel sistema del PACF



- **Stazioni di videosorveglianza N° 5**
- **Boe multi parametriche n° 5 (photogrammetry, sonar, etc.)**
- **Recinzione semisommersa**
- **Centrale di trasmissione e raccolta dati**

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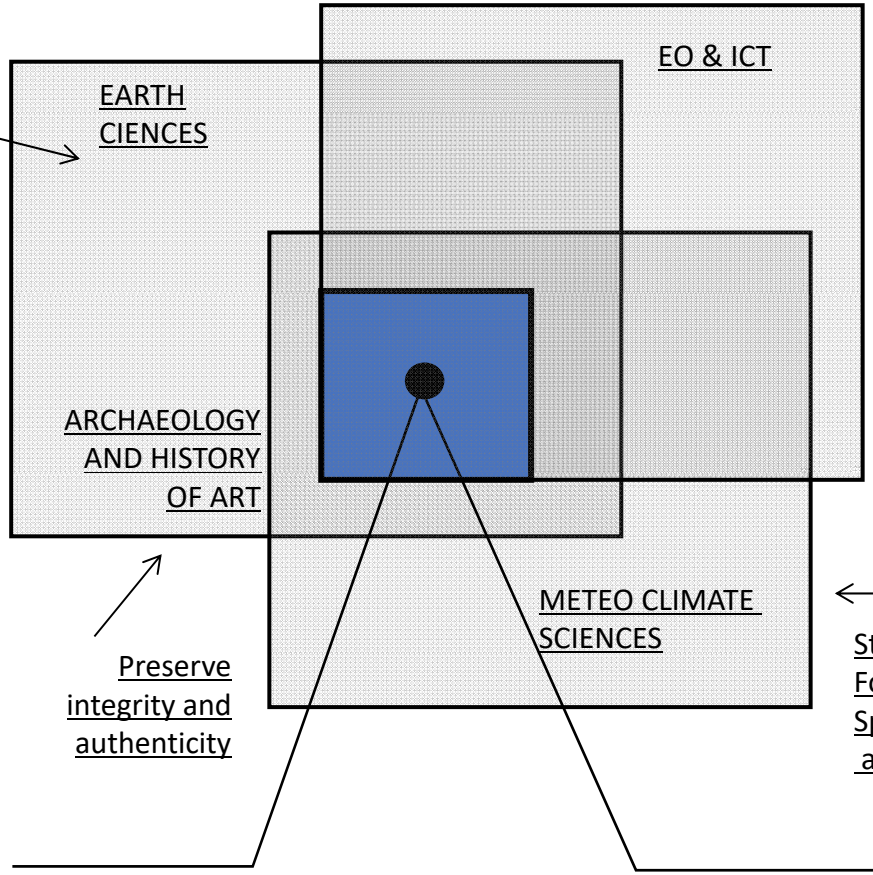
L'approccio OLISTICO e il nuovo paradigma

Increase understanding of geohazard dynamics

1. Localizzazione dei beni e tipologia dei processi e loro relativo innesco meteo-climatico
2. integrare gli approcci che provengono dalle scienze della terra (mappe di pericolosità dei fenomeni) e quelle delle scienze meteo climatiche definendo variabili e parametri di modellazione a fini previsionali.
3. le politiche di prevenzione e controllo degli effetti dei cambiamenti climatici e delle pericolosità naturali, sono ora supportate da dati di osservazione della terra, che possono essere utilizzati in alcuni casi per ridurre la mancanza di conoscenza e calibrare i dati in situ;



Monitoring and evolution trend
Short and long period effects

4.dopo l'identificazione degli asset più vulnerabili, e grazie al monitoraggio continuo, gli interventi di mitigazione devono essere implementati seguendo le priorità.

Le soluzioni devono essere verdi e blu.

Preserve integrity and authenticity

Strong and accurate Forecasting model at different Spatial and temporal resolution and scale

Risk scenario implementation to mitigate Climate change effects and other geo environmental threats

A shared culture for an interdisciplinary approach

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Prospettive Future

- Supporto di ISPRA all'implementazione delle LL.GG. finali del PIANO straordinario

- Disponibilità nella fase di testing del Portale della sicurezza (HUB tecnologico) anche come liaison tra:

1. Futura implementazione dei servizi operativi nazionale di OE (Movimenti del terreno, marino costieri, clima, suolo etc.);

2. Allineamento e interoperabilità con altri ministeri per i servizi spaziali (MASE, MIMIT, MIT etc.);

3. Allineamento e interoperabilità con altri parchi archeologici nazionali per i servizi geo spaziali sia in contribuzione che in fruizione;

Obiettivo finale da traguardare a scala paese e la messa a disposizione di dati, servizi e prodotti a tutti gli operatori (con accessi e credenziali differenziate) pubblici e privati coinvolti nell'ambito del monitoraggio e protezione preventiva del patrimonio culturale nazionale