Only an island as impudent as Cephalonia would have the insouciance to situate itself upon a faultline that exposes it to the recurrent danger of cataclysmic earthquakes.

Captain Corelli’s Mandolin (1994)

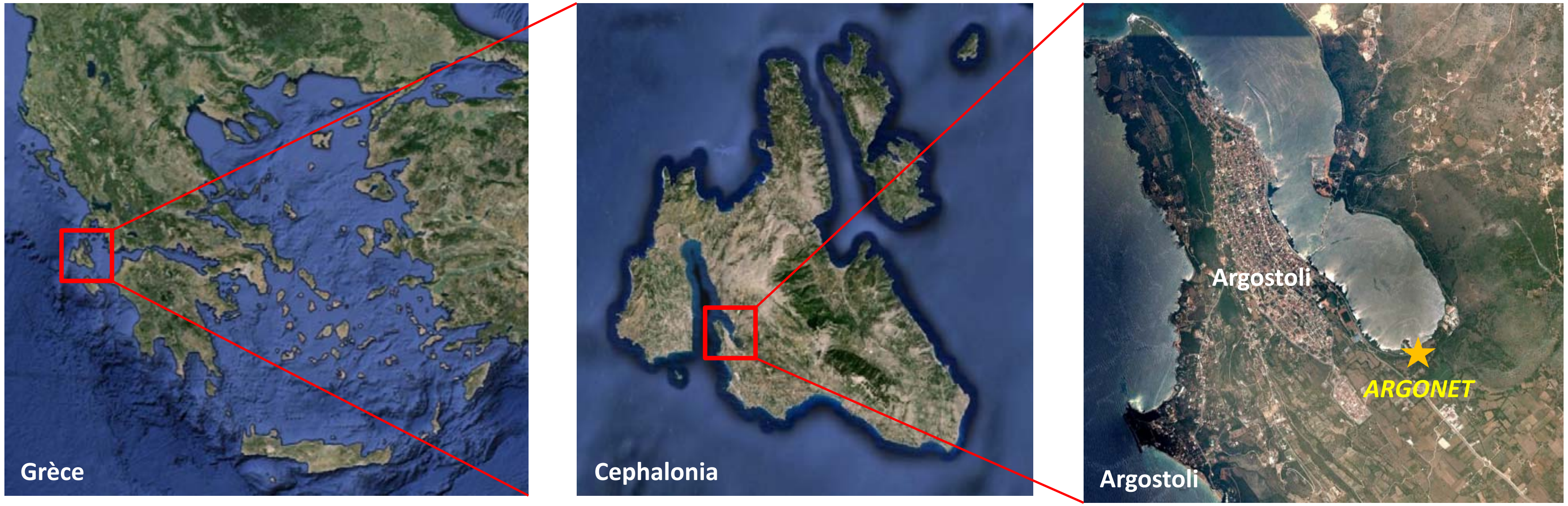
Louis de Bernières

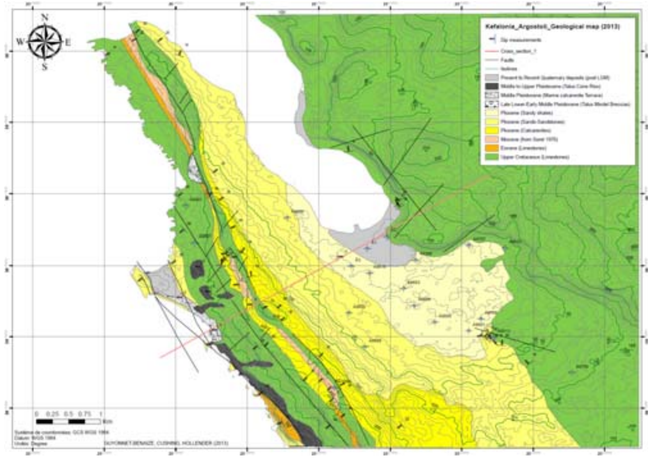
Argostoli Bay, Sunday, October 5, 2025

Cephalonia: A story of a natural laboratory for seismic hazard studies since 2011 and a reference site SIGMA3 studies

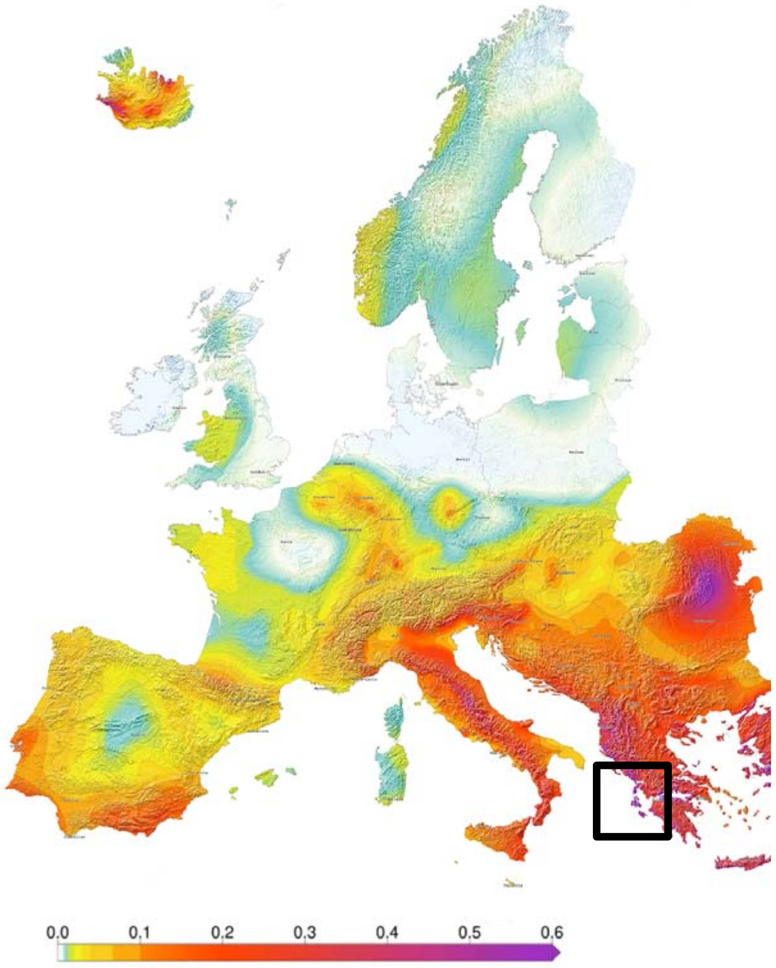
Fabrice HOLLENDER (CEA, ISTerre), Nikolaos THEODOULIDIS (ITSAK), Pierre-Yves BARD (ISTerre),
Armand MARSICAL (ISTerre), Agisilaos KONIDARIS (Ionian University), Zafeiria ROUMELIOTI (Univ. Patras),
Kiriaki KONSTANTINIDOU (ITSAK), Pauline RISCHETTE (CEA, ISTerre),
Vincent PERRON (CEA, ISTerre), Paola TRAVERSA (EdF), Elias El HABER (EdF) and many others…

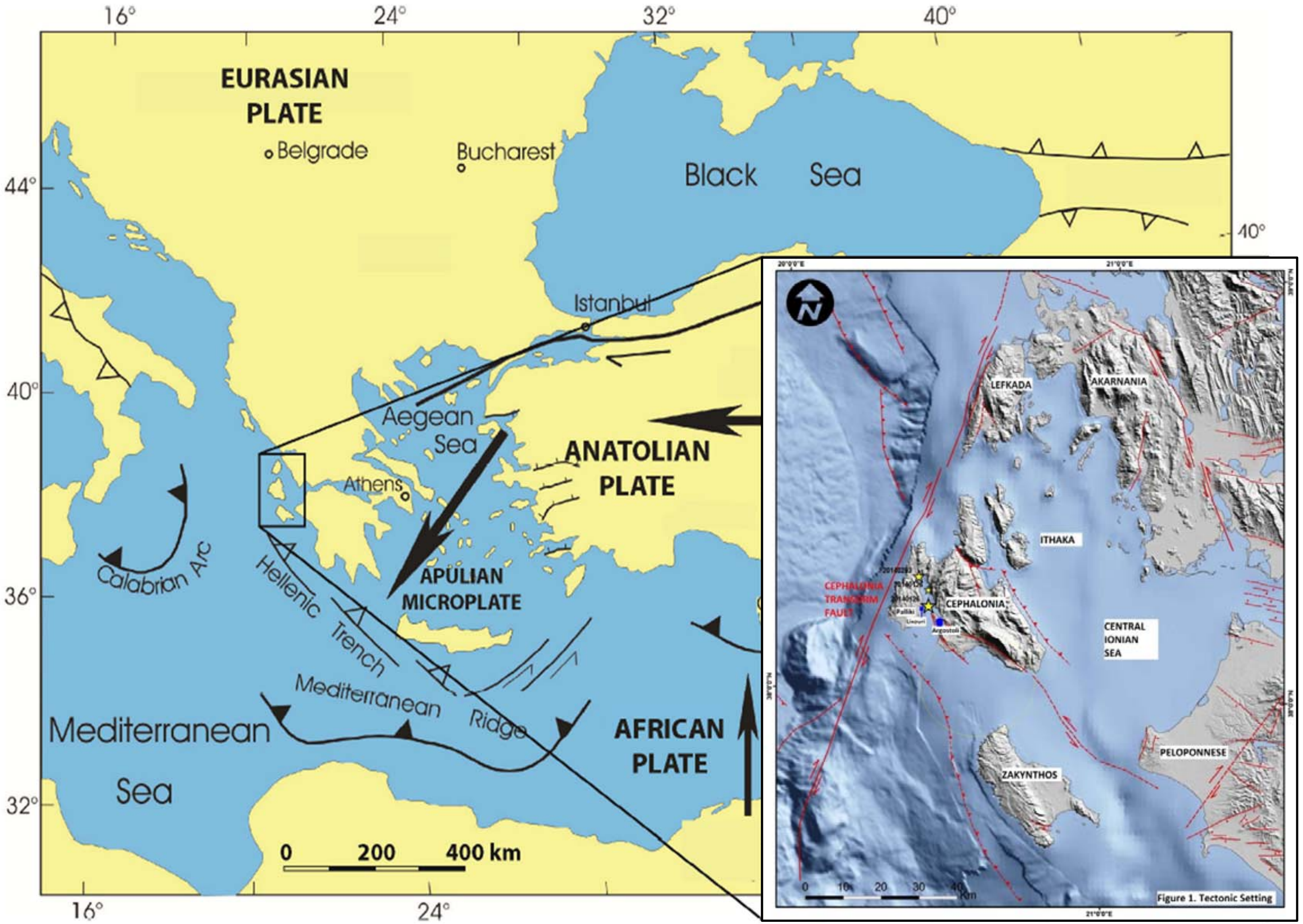
The island of Cephalonia, the town of Argostoli, the ARGONET vertical array


Grèce
Cephalonia
Argostoli
Argostoli
ARGONET


N
E
S
W
Kefalonia_Argostoli_Geological map (2013)
Faults
Pliocene (Sandy shales)
Pliocene (Calcarenites)
Eocene (Limestones)
Upper Cretaceous (Limestones)

Seismotectonic context


0,0
0,1
0,2
0,3
0,4
0,5
0,6


16°
24°
32°
40°
44°
40°
36°
32°
40°
EURASIAN PLATE
Belgrade
Bucharest
Black Sea
Istanbul
Aegean Sea
Athens
ANATOLIAN PLATE
APULIAN MICROPLATE
Calabrian Arc
Hellenic Trench
Mediterranean Ridge
Mediterranean Sea
AFRICAN PLATE
0 200 400 km
16°
24°
20°0'0"E
21°0'0"E
N
LEFKADA
AKARNANIA
ITHAKA
CEPHALONIA TRANSFORM FAULT
CEPHALONIA
Paliki
Lixouri
Argostoli
CENTRAL IONIAN SEA
ZAKYNTHOS
PELOPONNESE
0 10 20 30 40 Km
Figure 1. Tectonic Setting
21°0'0"E

The 1953 earthquake

- 7.2 on August 12, 1953, at 9:24 GMT
- 450 to 600 deaths
- After the EQ 100,000 inhabitants out of a total population of approximately 125,000 left the island.

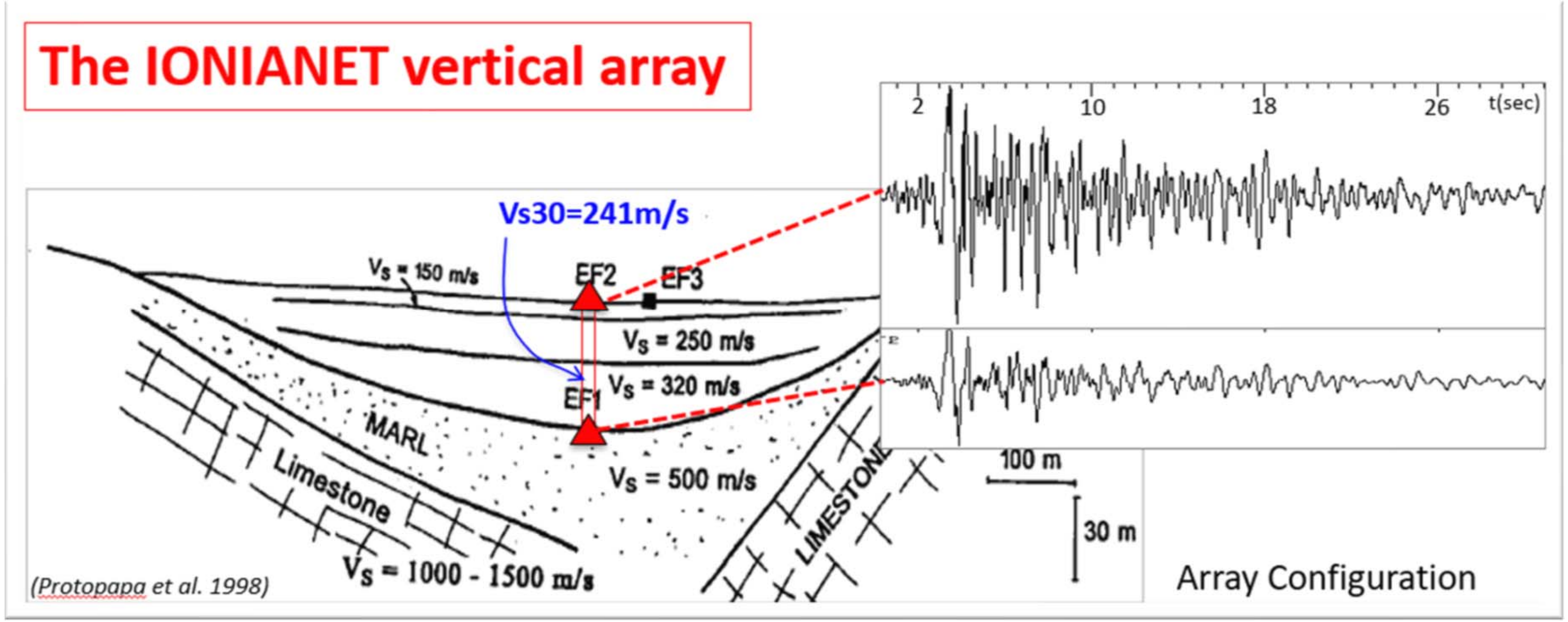
The first seismological studies carried out on Cephalonia

Early seismological measurements: Ionianet

Period: July 1998 – October 2000

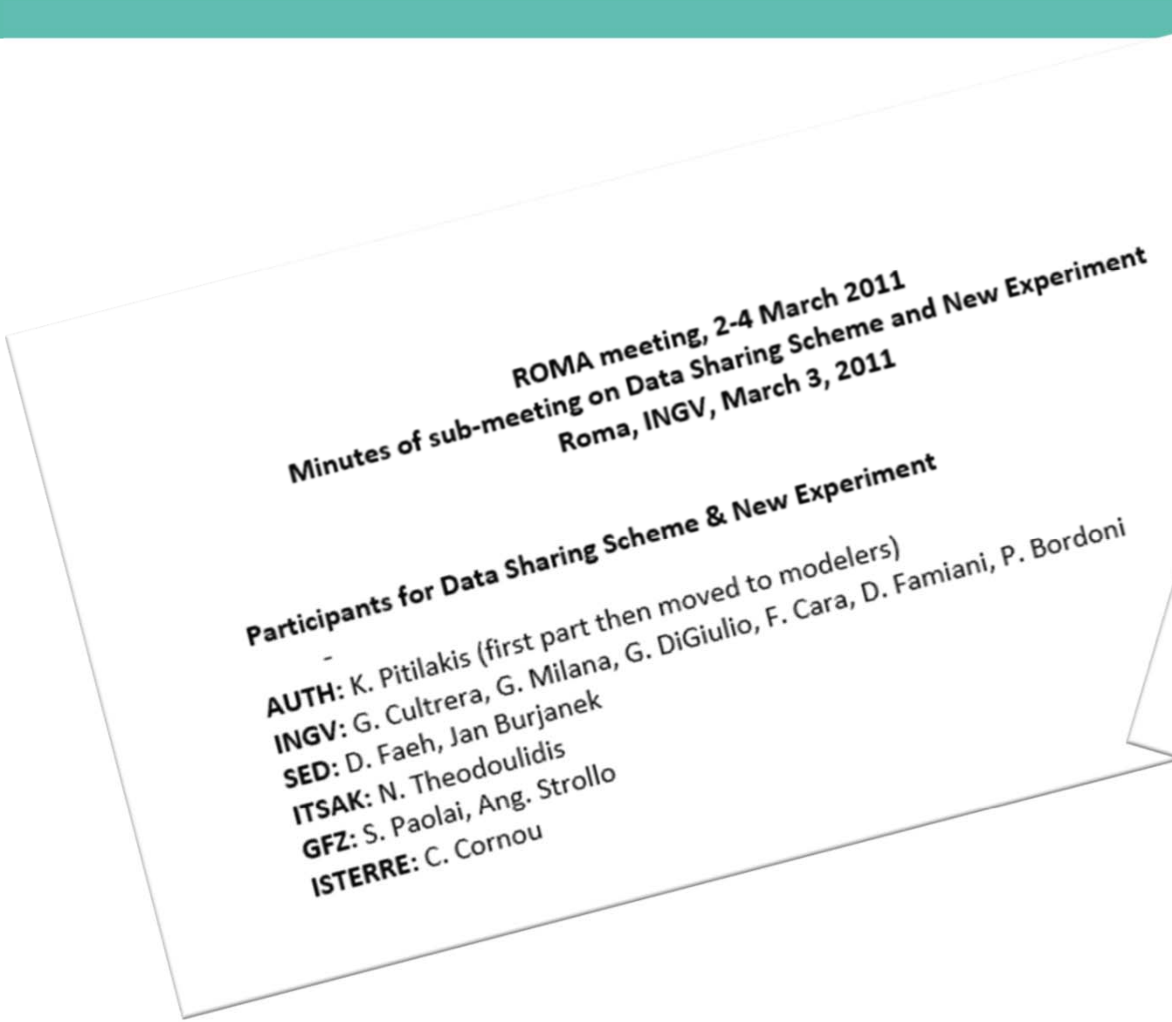
61 events, 3 stations→ 182 records

3.5≤M≤5.3   10km≤R≤125km


The IONIANET vertical array
2
10
18
26
t(sec)
Vs30=241m/s
Vs = 150 m/s
EF2
EF3
Vs = 250 m/s
Vs = 320 m/s
EF1
MARL
Limestone
Vs = 500 m/s
LIMESTONE
Vs = 1000 - 1500 m/s
100 m
30 m
Array Configuration

(Protopapa et al. 1998)

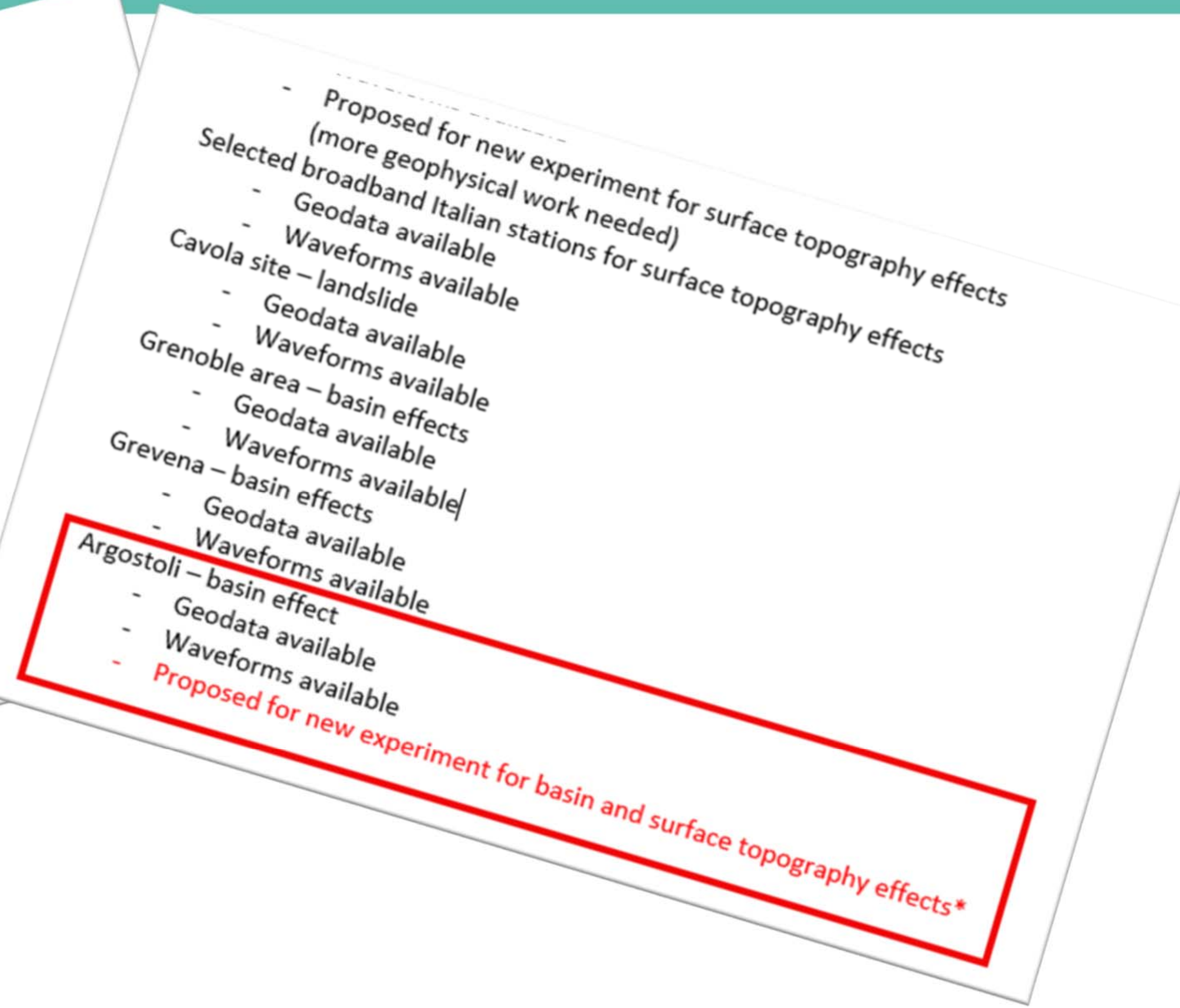
2011: The European NERA program



ROMA meeting, 2-4 March 2011
Minutes of sub-meeting on Data Sharing Scheme and New Experiment
Roma, INGV, March 3, 2011

Participants for Data Sharing Scheme & New Experiment

- **AUTH:** K. Pitilakis (first part then moved to modelers)
- **INGV:** G. Cultrera, G. Milana, G. DiGiulio, F. Cara, D. Famiani, P. Bordoni
- **SED:** D. Faeh, Jan Burjanek
- **ITSAK:** N. Theodoulidis
- **GFZ:** S. Paolai, Ang. Strollo
- **ISTERRE:** C. Cornou



- Proposed for new experiment for surface topography effects (more geophysical work needed)

Selected broadband Italian stations for surface topography effects
- Geodata available
- Waveforms available

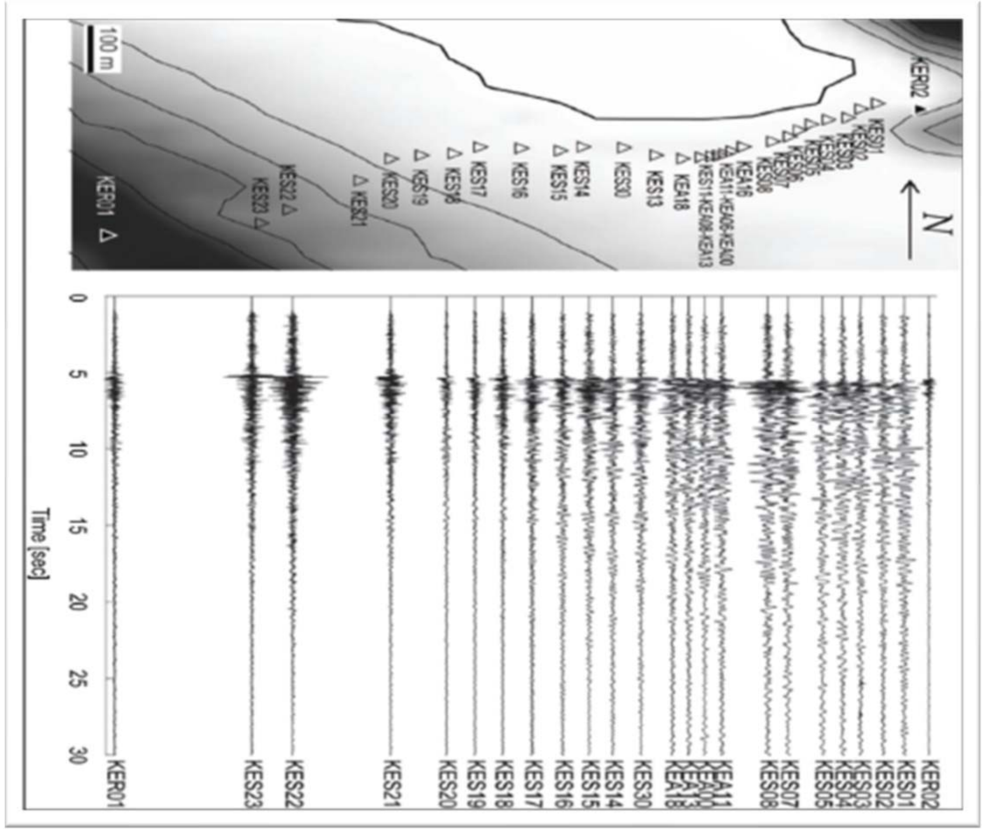
Cavola site – landslide
- Geodata available
- Waveforms available

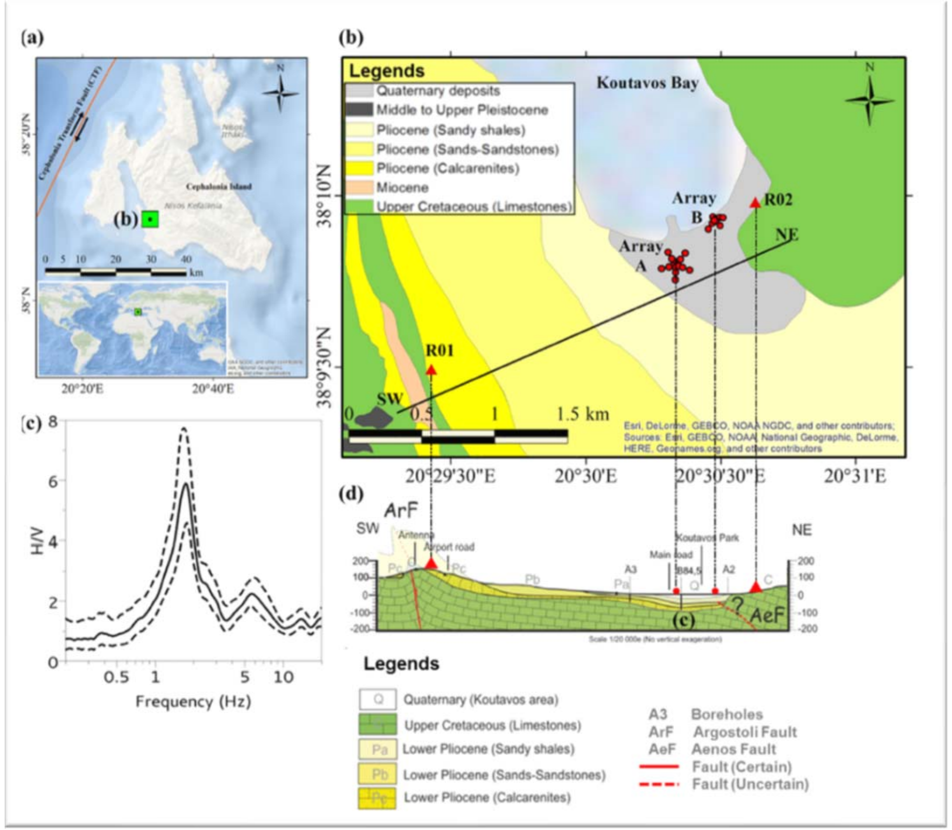
Grenoble area – basin effects
- Geodata available
- Waveforms available

Grevena – basin effects
- Geodata available
- Waveforms available

Argostoli – basin effect
- Geodata available
- Waveforms available
- Proposed for new experiment for basin and surface topography effects*

NERA program experiments




(a)
Cephalonia Island
(b)
0 5 10 20 30 40 km
20°20'E
20°40'E
(b)
Legends
Quaternary deposits
Middle to Upper Pleistocene
Pliocene (Sandy shales)
Pliocene (Sands-Sandstones)
Pliocene (Calcarenites)
Miocene
Upper Cretaceous (Limestones)
Koutavos Bay
Array B
Array A
R02
NE
R01
SW
0 0.5 1 1.5 km
38°10'N
38°9'30"N
20°29'30"E
20°30'E
20°30'30"E
20°31'E
(c)
H/V
Frequency (Hz)
0.5
1
5
10
0
2
4
6
8
(d)
ArF
SW
NE
AeF
Legends
Q Quaternary (Koutavos area)
Upper Cretaceous (Limestones)
Pa Lower Pliocene (Sandy shales)
Pb Lower Pliocene (Sands-Sandstones)
Pc Lower Pliocene (Calcarenites)
A3 Boreholes
ArF Argostoli Fault
AeF Aenos Fault
Fault (Certain)
Fault (Uncertain)

2011: The NERA program

Bull Earthquake Eng (2018) 16:529–560
https://doi.org/10.1007/s10518-017-0225-4

ORIGINAL RESEARCH PAPER

Basin effects on ground motion: the case of a high-
resolution experiment in Cephalonia (Gree

N. Theodoulidis[1] · G. Cultrera[2] · C. Cornou[3] ·
P.-Y. Bard[3] · T. Boxberger[4] · G. DiGiulio[5] · A.
D. Kementzetzidou[1,6] · K. Makra[1] · The Argost

Received: 13 February 2017 / Accepted: 3 September 2017 / Pub
© Springer Science+Business Media B.V. 2017

Abstract In this study data and results of a high-res
(Greece) regarding empirical basin effects are presented.
accelerometers were deployed in the basin of Argostoli
of 7 months (September 2011–April 2012). Due to high
and surrounding area this array recorded thousands of l
Data used in this work come from a selection of 162
3 km $\leq$ R $\leq$ 600 km, with magnitude range, 1.0 $\leq$ M

Argostoli NERA Team: Ch. Andreou (Technological Educational Ins
Greece), R. Bauz (GFZ German Research Centre for Geosciences, He
S. Bayle (Institut des Sciences de la Terre (ISTerre), Université de Gr
(GFZ German Research Centre for Geosciences, Helmholtz-Centre, P
Nazionale di Geofisica e Vulcanologia (INGV), Roma, Italy), R. Coglia
Vulcanologia (INGV), Roma, Italy), C. Cretin (Institut des Sciences de
Grenoble, Grenoble, France), A. Fodarella (Istituto Nazionale di Geofisi
Italy), E. Günther (GFZ German Research Centre for Geosciences, Helm
A. Konidaris (Technological Educational Institute of Ionian Islands, Arg
stitut des Sciences de la Terre (ISTerre), Université de Grenoble, Greno
German Research Centre for Geosciences, Helmholtz-Centre, Potsdam, G
Research Centre for Geosciences, Helmholtz-Centre, Potsdam, Germany),
Geofisica e Vulcanologia (INGV), Roma, Italy), G. Riccio (Istituto Nazio
(INGV), Roma, Italy), and A. Savvaidis (Institute of Engineering Seismolo
(ITSAK), Thessaloniki, Greece).

✉ N. Theodoulidis
ntheo@itsak.gr

G. Cultrera
giovanna.cultrera@ingv.it

C. Cornou
cecile.cornou@univ-grenoble-alpes.fr

P.-Y. Bard
Pierre-Yves.Bard@univ-grenoble-alpes.fr

T. Boxberger
tobias.boxberger@gfz-potsdam.de

ARGOSTOLI EXPERIMENT
[16/9/2011 - 16/4/2012]

...and AFTER WHAT?

Nikos Theodoulidis EPPO-ITSAK

NERA *Meeting in Rome, 26-28 March, 2012*

Geophysical Journal International

Geophys. J. Int. (2021) 224, 1849–1869
Advance Access publication 2020
doi: 10.1093/gji/ggaa529

multidimensional site effects

Cedex 9, France

surface geology and geometry are known to be
proportion of surface waves. As a consequence,
und-motion variability and site amplification.
ng that an understanding of physical patterns
to characterize and quantify them. However,
the complexity of such effects as well as the
lly in case of small sedimentary valleys. The
propagating across two 2-D dense seismic
the extent to which they are contributing to
deployed in the small-size, shallow alluvial
nia Island, Greece, and consisted of three-
es ranging from 5 to 160 m. A set of 46
d epicentral distances up to 200 km, was
essing technique, MUSIQUE. The phase
aves crossing the array were extracted, and
Rayleigh waves was obtained. The results
waves (up to 60 per cent of total energy),
mental frequency (~1.5 Hz) of the valley.
<3 Hz) while Rayleigh waves dominate
is observed, in a given frequency range,
waves, group velocities estimated from
he outcomes of this research provide a
ted surface waves and the 2-D/3-D site
e Argostoli. The method applied here
nulating seismic ground motion.

motions; Site effects; Wave propaga-

ly responsible for the amplification of
tion of locally generated surface waves
g. Kawase 1996). Especially, surface
es significantly modify the wavefield
on, leading to large amplifications, du-
icant ground strains (Moczo & Bard
cia *et al.* 1999; Cornou *et al.* 2003a,b;
Paolucci 2010). Such motions can
rces on structures and lifelines, par-
sedimentary valleys where edge-induced waves
reverberate within shallow layers and contribute to the generation

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1849

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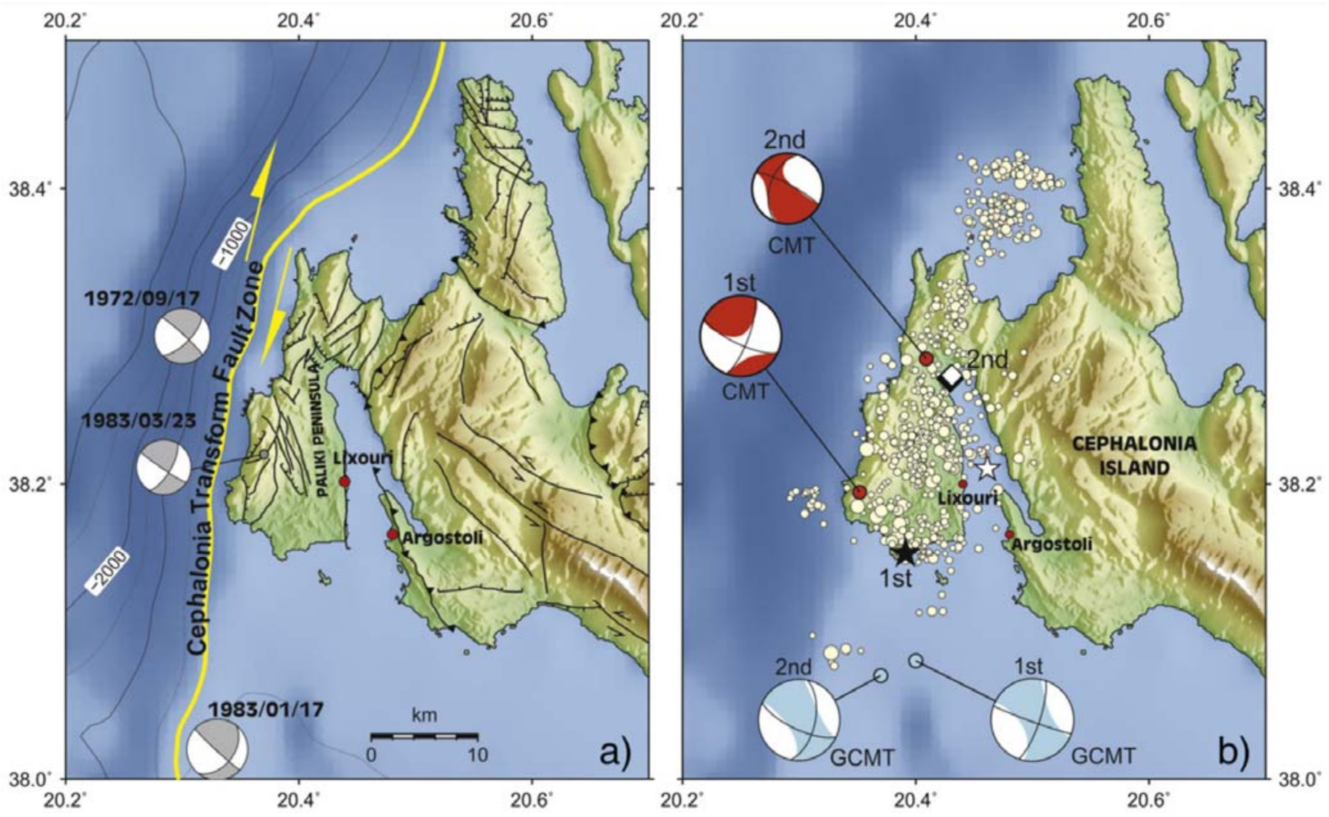
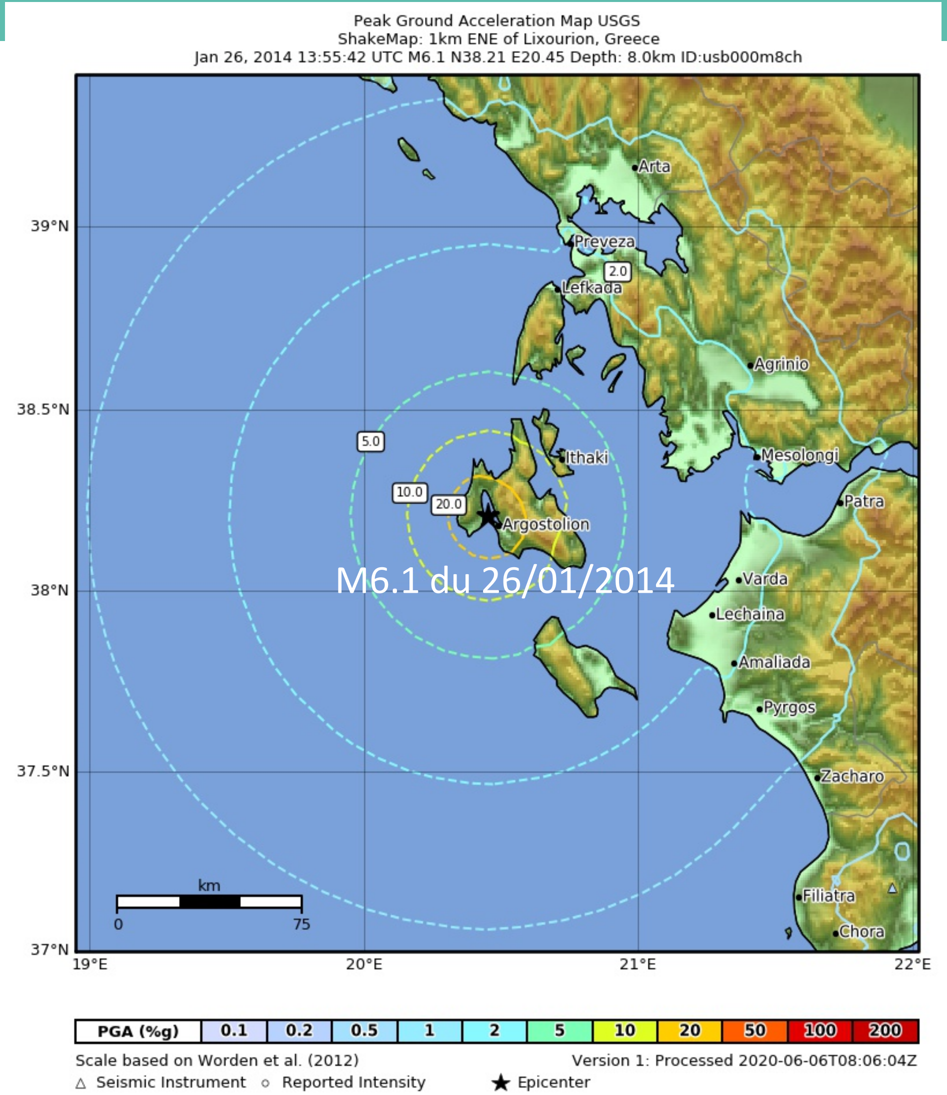
The SINAPS@ age

SINAPS@ project

- Marsh 11, 2011: Accident of Fukushima
- Call for projects from the French agency ANR on topics related to nuclear safety
- SINAPS@ project accepted, including the deployment of a vertical accelerometric array in Argostoli (= Argonet)
- September 2013: first geophysical survey on Cephalonia Island
- January 26, 2014: M6.1 earthquake in Argostoli
- January 27-28, 2024: Official Kick-off meeting of SINAPS@, decision to launch a post-seismic survey

The January 26, 2014 earthquake


20.2°
20.4°
20.6°
38.4°
38.2°
38.0°
-1000
-2000
Cephalonia Transform Fault Zone
1972/09/17
1983/03/23
1983/01/17
PALIKI PENINSULA
Lixouri
Argostoli
km
0
10
a)
2nd
CMT
1st
CMT
2nd
CEPHALONIA
ISLAND
Lixouri
Argostoli
1st
2nd
1st
GCMT
GCMT
b)


Peak Ground Acceleration Map USGS
ShakeMap: 1km ENE of Lixourion, Greece
Jan 26, 2014 13:55:42 UTC M6.1 N38.21 E20.45 Depth: 8.0km ID:usb000m8ch

39°N
38.5°N
38°N
37.5°N
37°N
19°E
20°E
21°E
22°E
Arta
Preveza
Lefkada
Agrinio
Mesolongi
Ithaki
Patra
Argostolion
Varda
Lechaina
Amaliada
Pyrgos
Zacharo
Filiatra
Chora
2.0
5.0
10.0
20.0
km
0
75

PGA (%g)	0.1	0.2	0.5	1	2	5	10	20	50	100	200

Scale based on Worden et al. (2012)
Version 1: Processed 2020-06-06T08:06:04Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

M6.1 du 26/01/2014

The SINAPS@ post-seismic team experienced the second earthquake!

The February 6, 2014 earthquake

Fabrice’s awakening

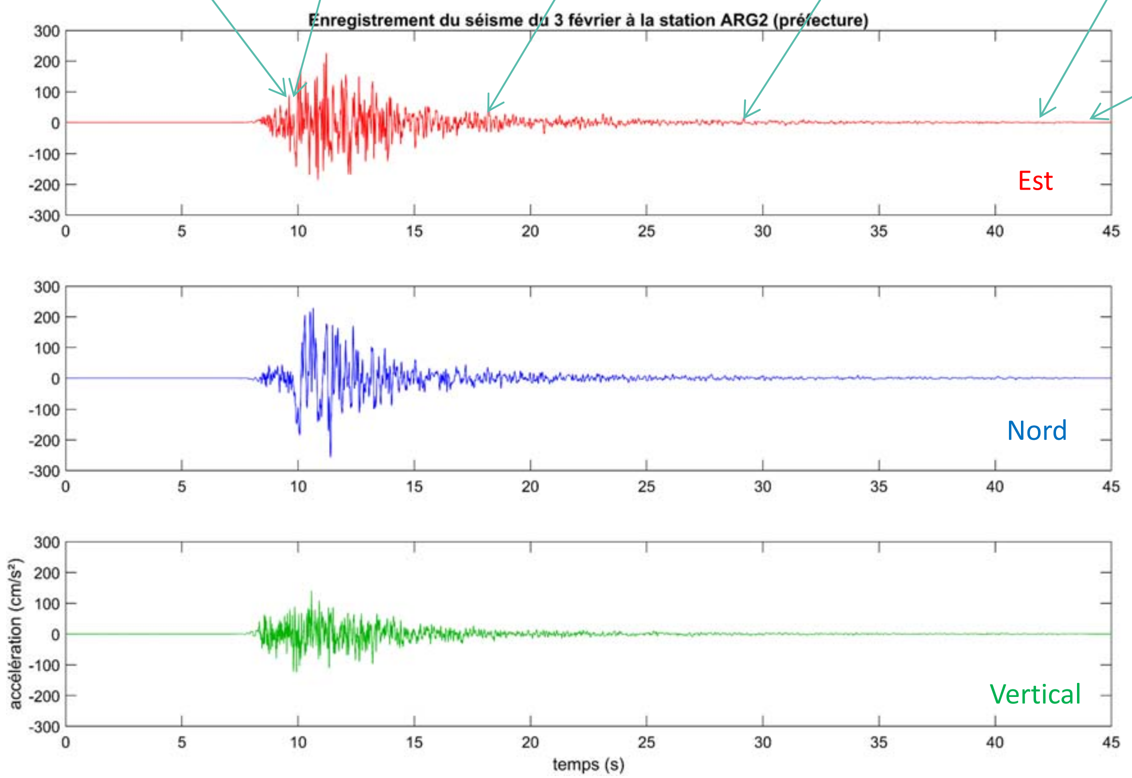
Vincent’ awakening

Um... in your opinion, what magnitude is it?

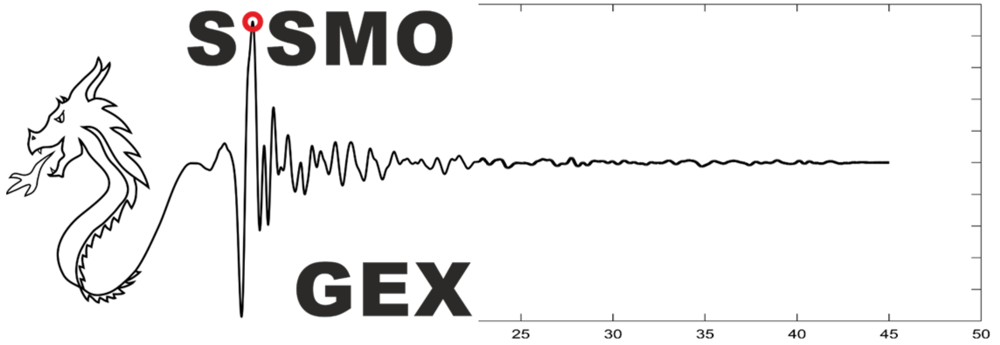
Awareness that this is a major earthquake...

We leave the hotel (without taking the elevator...)

We end the night in the car.



Filtered N component (0.05 - 1.5 Hz)



Post-seismic survey

26/1/14 earthquake

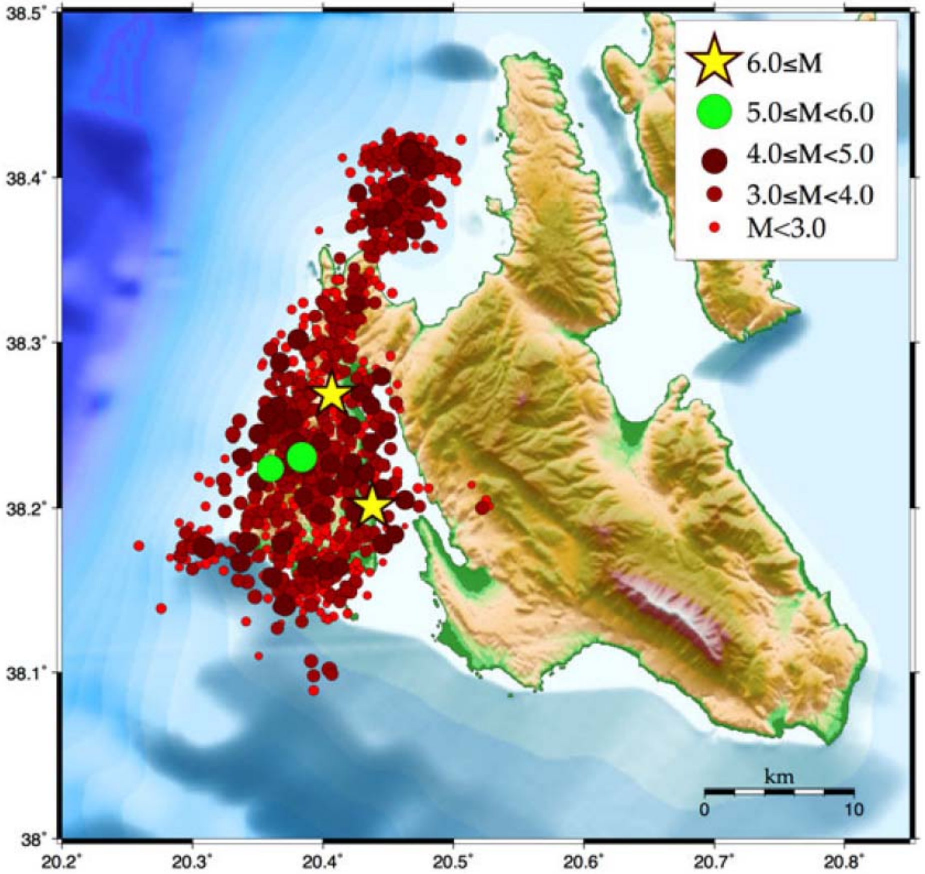
03/2/14 earthquake

Difficult fieldwork to meet scientific objectives

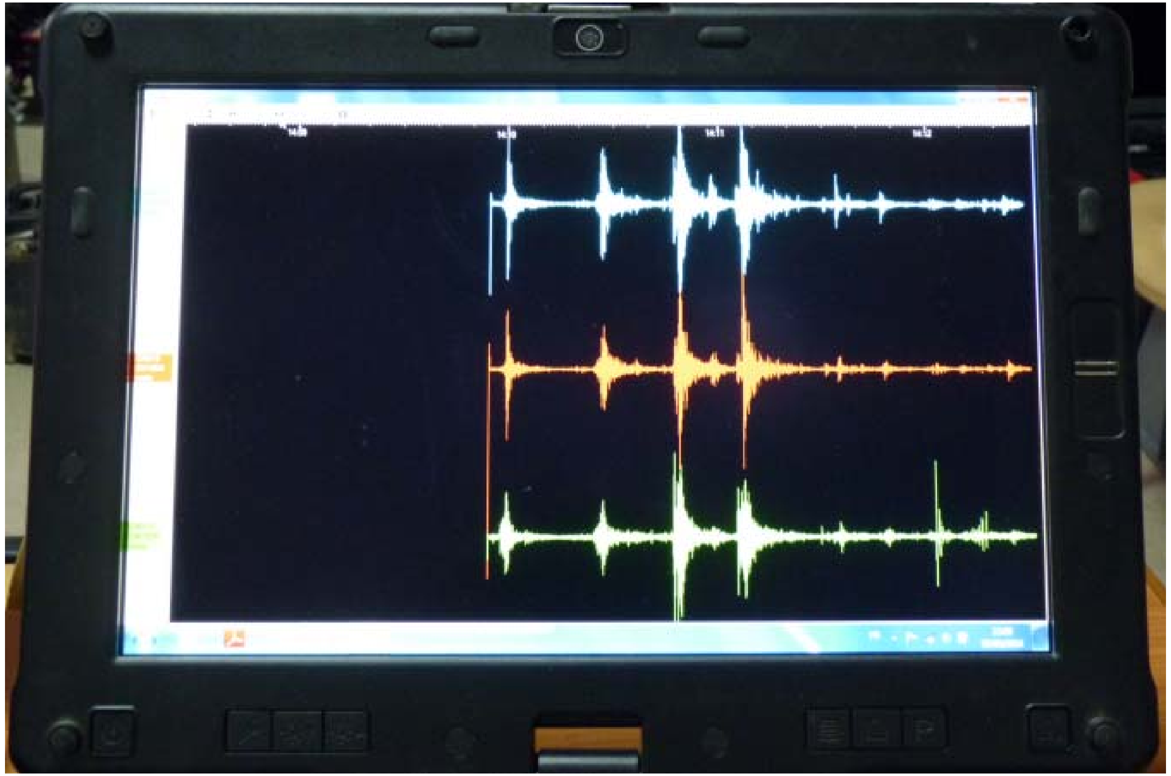
During the equipment test (Monday, February 3), an average of one replica was measured every 30 seconds.

Post-seismic survey

1075 aftershocks on February 12, 2014

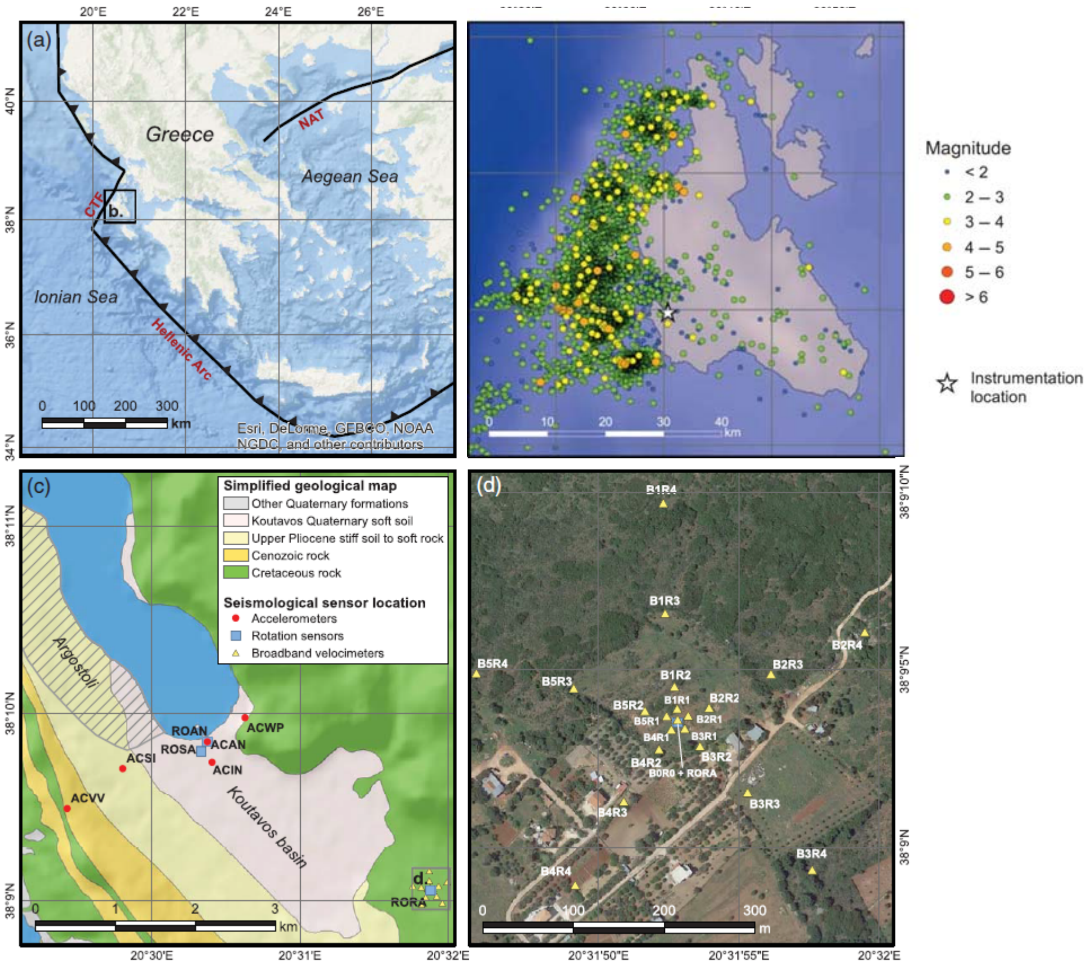

6.0≤M
5.0≤M<6.0
4.0≤M<5.0
3.0≤M<4.0
M<3.0
km
0
10
38.5°
38.4°
38.3°
38.2°
38.1°
38°
20.2°
20.3°
20.4°
20.5°
20.6°
20.7°
20.8°

During the equipment test (Monday, February 3), an average of one replica was measured every 30 seconds.



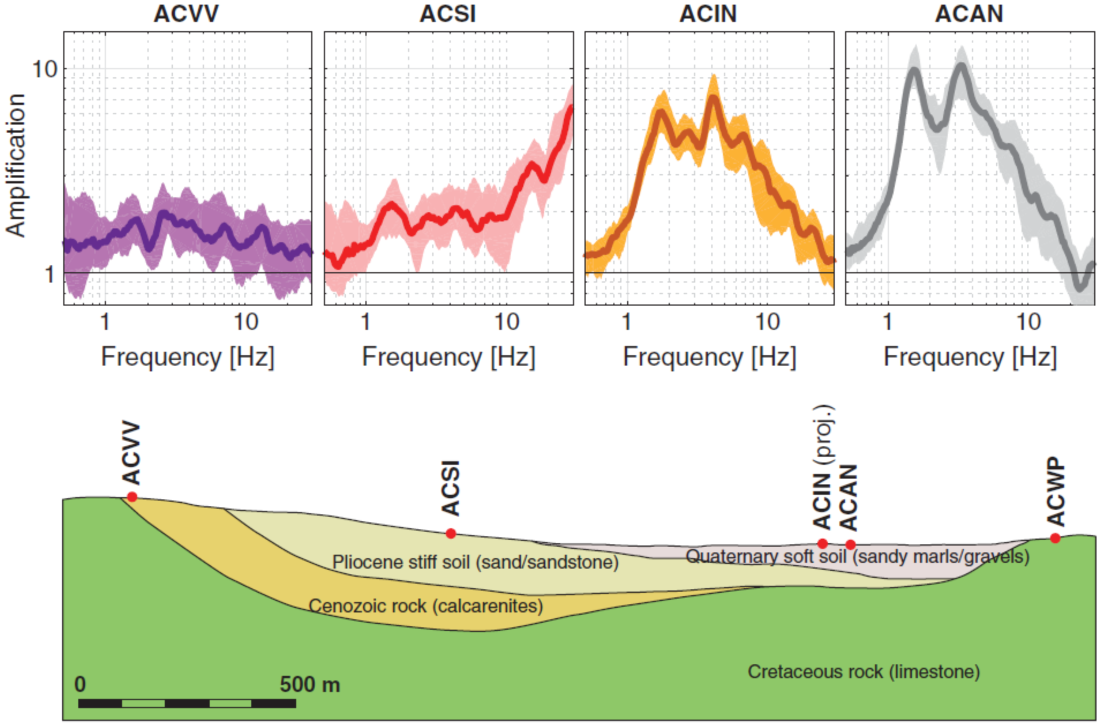
Scientific objectives of the mission

Several thousand earthquakes recorded



20°E
22°E
24°E
26°E
40°N
38°N
36°N
34°N
(a)
Greece
Aegean Sea
Ionian Sea
NAT
CTF
b.
Hellenic Arc
0 100 200 300 km
Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors
0 10 20 30 40 km
Magnitude
< 2
2 – 3
3 – 4
4 – 5
5 – 6
> 6
Instrumentation location
(c)
Simplified geological map
Other Quaternary formations
Koutavos Quaternary soft soil
Upper Pliocene stiff soil to soft rock
Cenozoic rock
Cretaceous rock
Seismological sensor location
Accelerometers
Rotation sensors
Broadband velocimeters
Argostoli
ROAN
ROSA
ACAN
ACWP
ACSI
ACIN
ACVV
Koutavos basin
d.
RORA
0 1 2 3 km
38°11'N
38°10'N
38°9'N
20°30'E
20°31'E
20°32'E
(d)
B1R4
B1R3
B2R4
B5R4
B5R3
B1R2
B2R3
B5R2
B1R1
B2R2
B5R1
B2R1
B4R1
B3R1
B4R2
B3R2
B0R0 + RORA
B3R3
B4R3
B3R4
B4R4
0 100 200 300 m
38°9'10"N
38°9'5"N
38°9'N
20°31'50"E
20°31'55"E
20°32'E

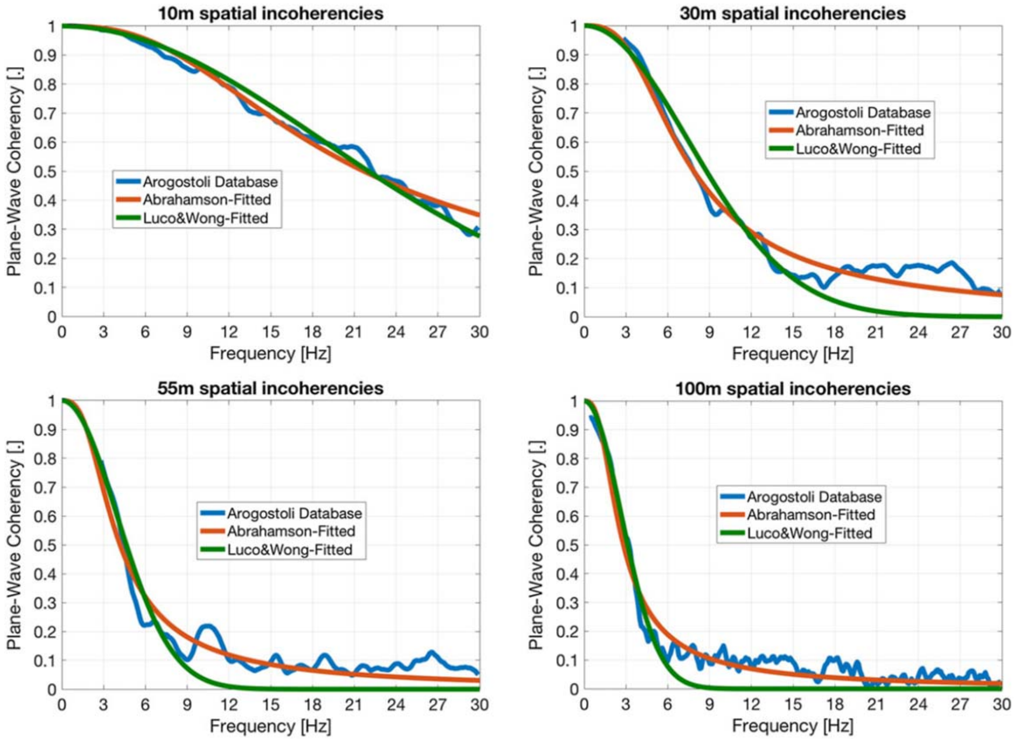
Assessment of site effects in the Koutavos basin



Perron et al., 2018

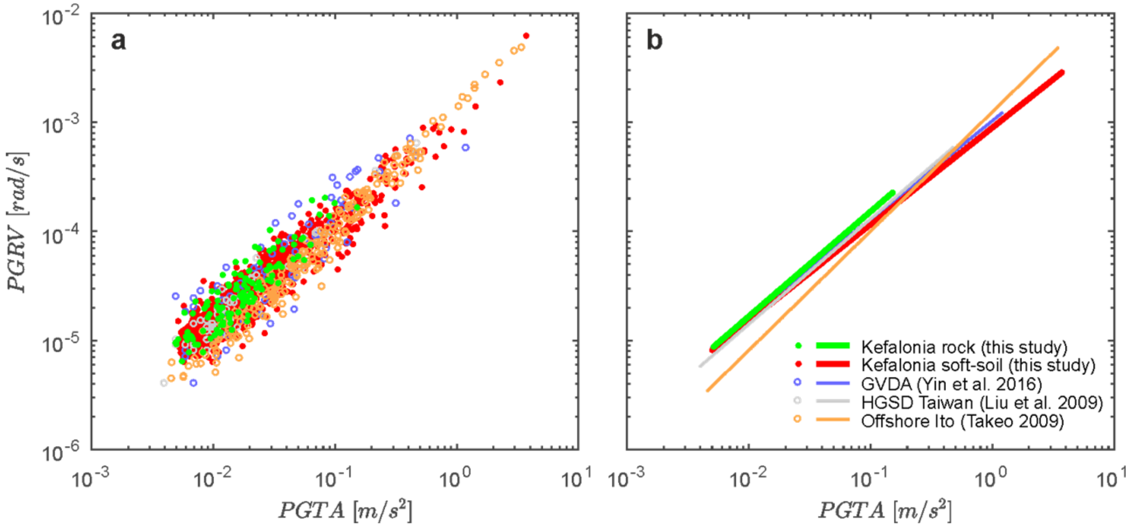
Scientific objectives of the mission

Evaluation of the spatial coherence of seismic motion on a rock and sediment network



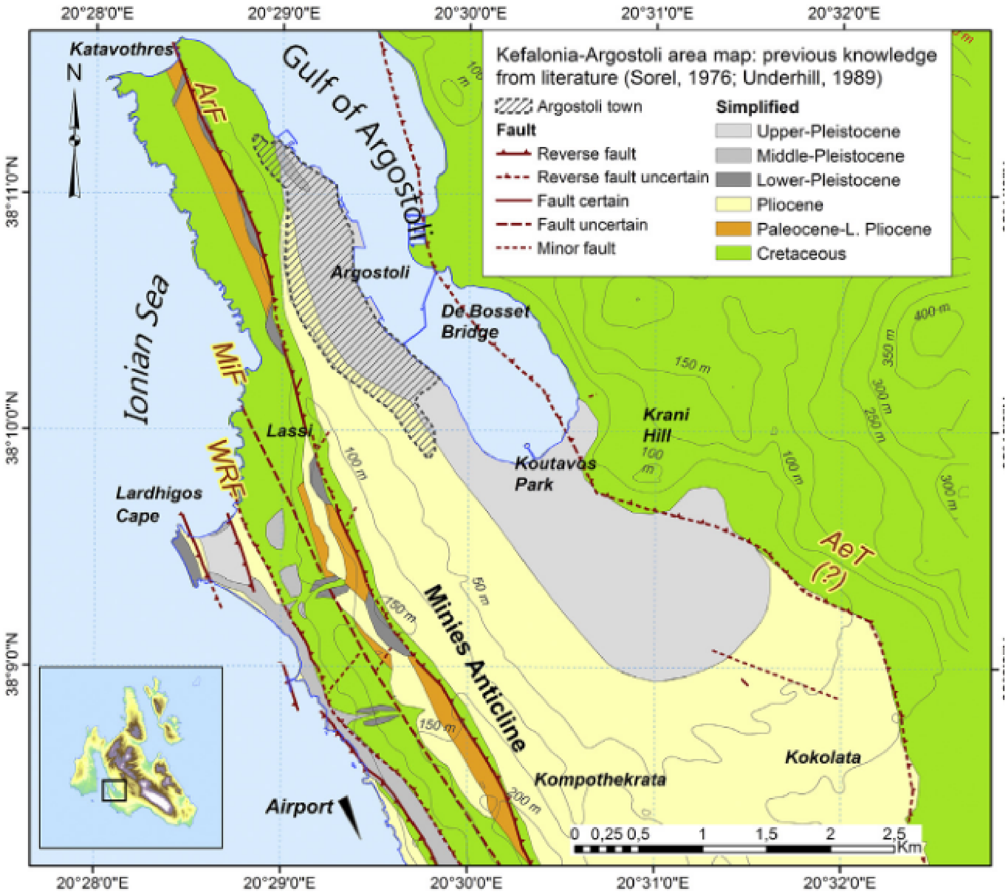
Svay et al., 2017
Imtiaz et al., 2018

Measurement of the rotational component of seismic moti

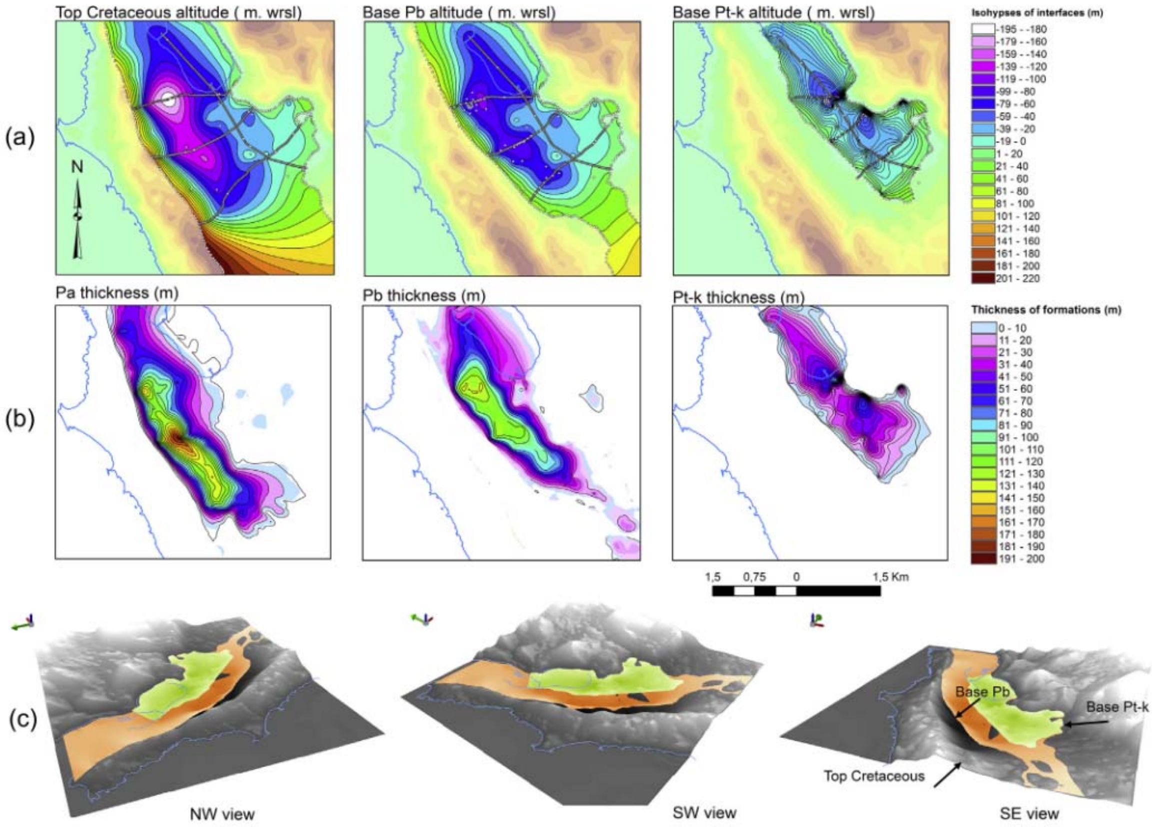


Sbaa et al., 2017

3D geological model



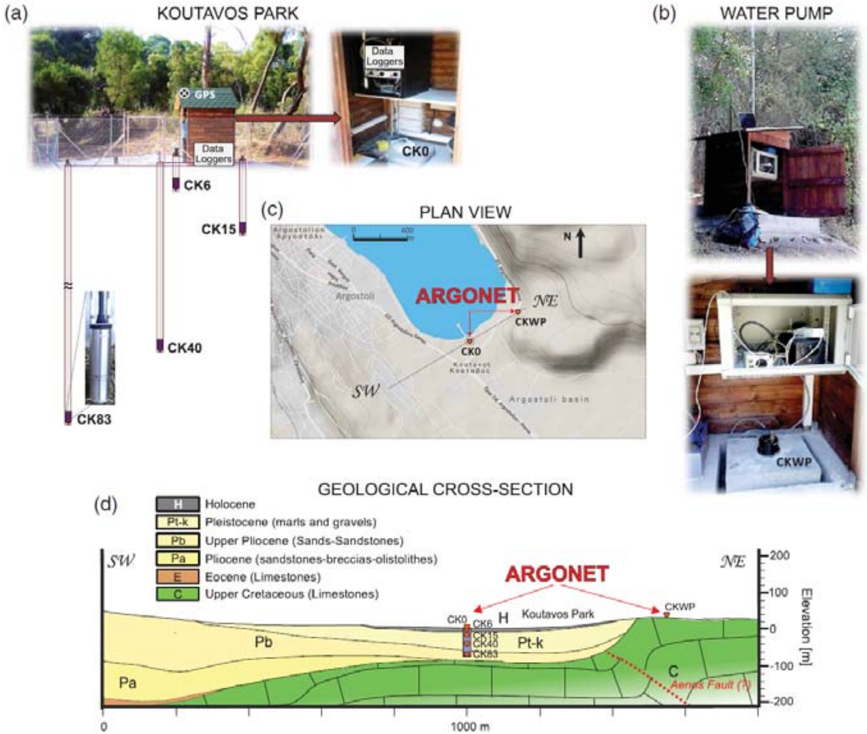
20°28'0"E
20°29'0"E
20°30'0"E
20°31'0"E
20°32'0"E
38°11'0"N
38°10'0"N
38°9'0"N
Kefalonia-Argostoli area map: previous knowledge from literature (Sorel, 1976; Underhill, 1989)
Argostoli town
Fault
Reverse fault
Reverse fault uncertain
Fault certain
Fault uncertain
Minor fault
Simplified
Upper-Pleistocene
Middle-Pleistocene
Lower-Pleistocene
Pliocene
Paleocene-L. Pliocene
Cretaceous
Katavothres
N
Gulf of Argostoli
ArF
Ionian Sea
Argostoli
De Bosset Bridge
MiF
Lassi
WRF
Lardhigos Cape
Koutavos Park
Krani Hill
AeT (?)
Minies Anticline
Kompothekrata
Kokolata
Airport
150 m
100 m
50 m
200 m
250 m
300 m
350 m
400 m
0 0,25 0,5 1 1,5 2 2,5 Km



(a)
Top Cretaceous altitude (m. wrsl)
Base Pb altitude (m. wrsl)
Base Pt-k altitude (m. wrsl)
N
Isohypses of interfaces (m)
-195 - -180
-179 - -160
-159 - -140
-139 - -120
-119 - -100
-99 - -80
-79 - -60
-59 - -40
-39 - -20
-19 - 0
1 - 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121 - 140
141 - 160
161 - 180
181 - 200
201 - 220
(b)
Pa thickness (m)
Pb thickness (m)
Pt-k thickness (m)
Thickness of formations (m)
0 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100
101 - 110
111 - 120
121 - 130
131 - 140
141 - 150
151 - 160
161 - 170
171 - 180
181 - 190
191 - 200
1,5 0,75 0 1,5 Km
(c)
NW view
SW view
Base Pb
Base Pt-k
Top Cretaceous
SE view

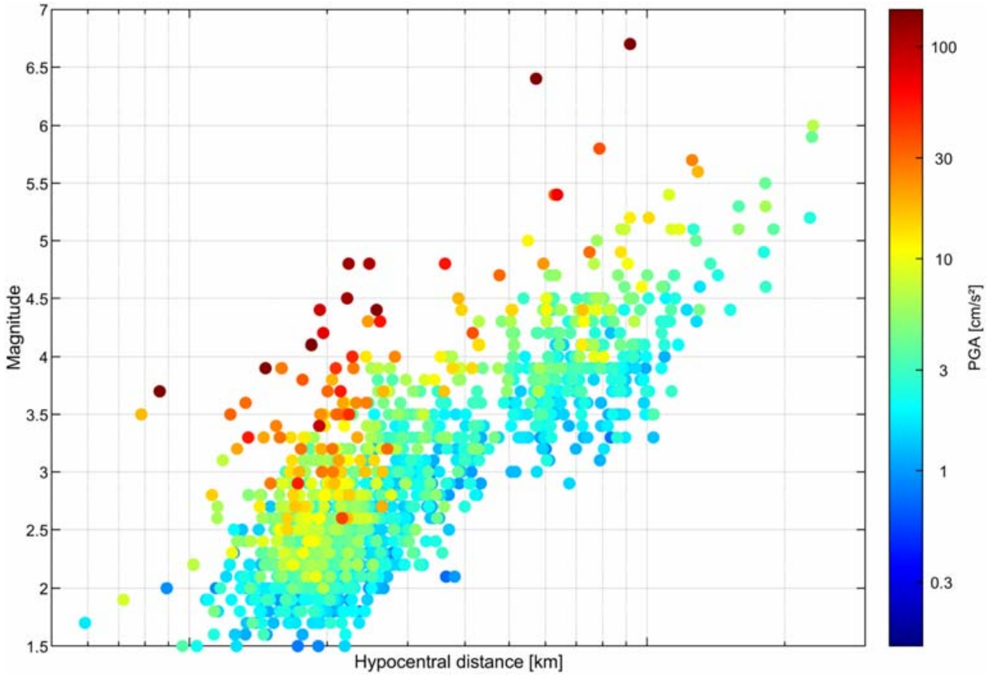
Cushing et al., 2020

The ARGONET vertical accelerometric array


(a)
KOUTAVOS PARK
GPS
Data Loggers
CK0
CK6
CK15
CK40
CK83
(b)
WATER PUMP
CKWP
(c)
PLAN VIEW
ARGONET
NE
SW
N
CKWP
CK0
Argostoli
Argostoli basin
(d)
GEOLOGICAL CROSS-SECTION
H Holocene
Pt-k Pleistocene (marls and gravels)
Pb Upper Pliocene (Sands-Sandstones)
Pa Pliocene (sandstones-breccias-olistolithes)
E Eocene (Limestones)
C Upper Cretaceous (Limestones)
SW
NE
ARGONET
CK0
CK6
CK15
CK40
CK83
H
Koutavos Park
CKWP
Pb
Pt-k
Pa
C
Aenos Fault (?)
Elevation [m]
200
100
0
-100
-200
0
1000 m

4 borehole accelerometers at different depths
2 surface accelerometers (sediment & rock)
2 surface rotation sensors
2 meteorological stations

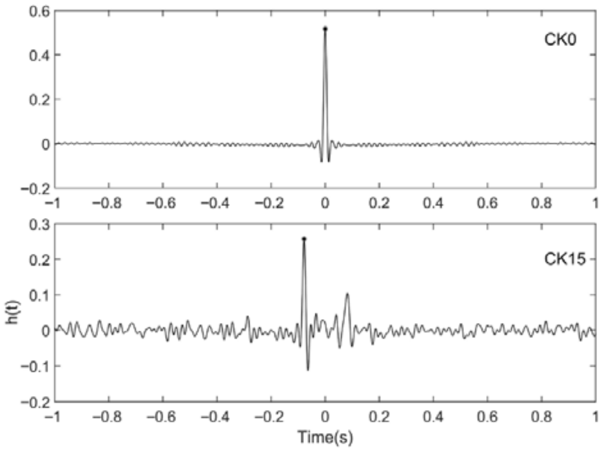
Theodoulidis et al., 2018

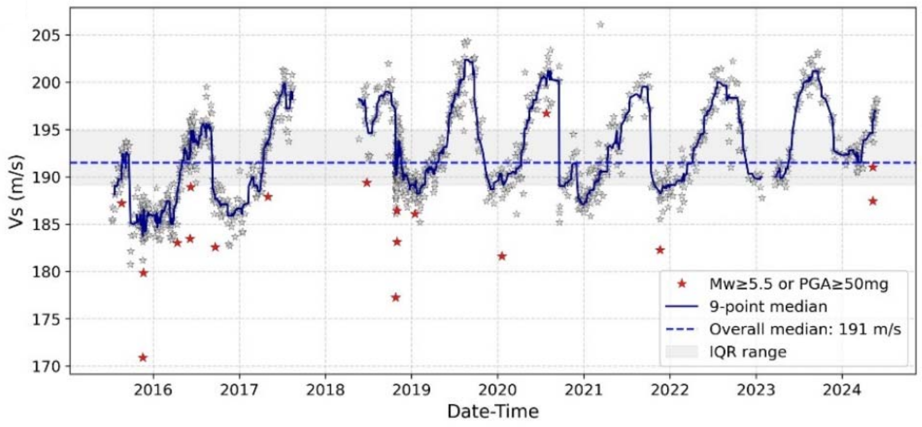


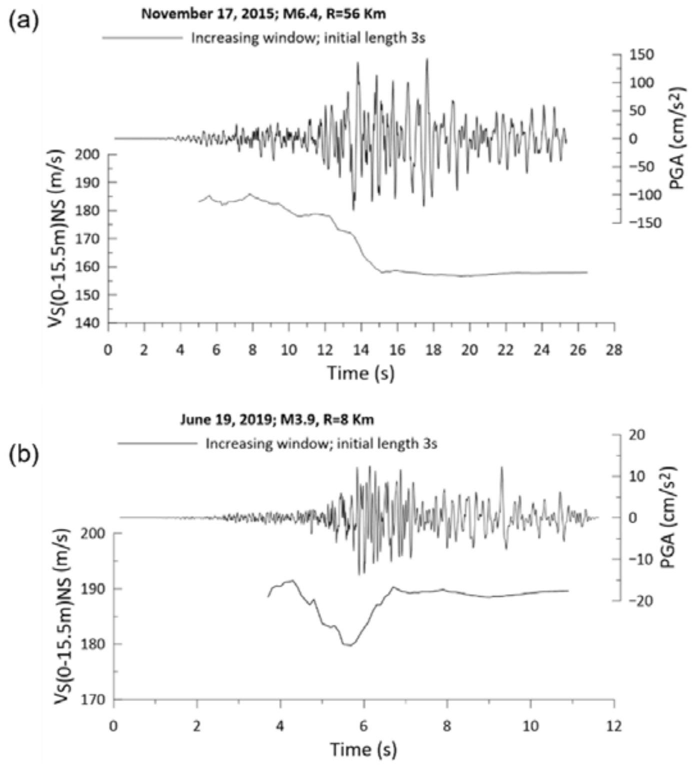
Installed in July 2015,
Database (version 2025) : more than 1500 events with an excellent signal-to-noise ratio. Open data.

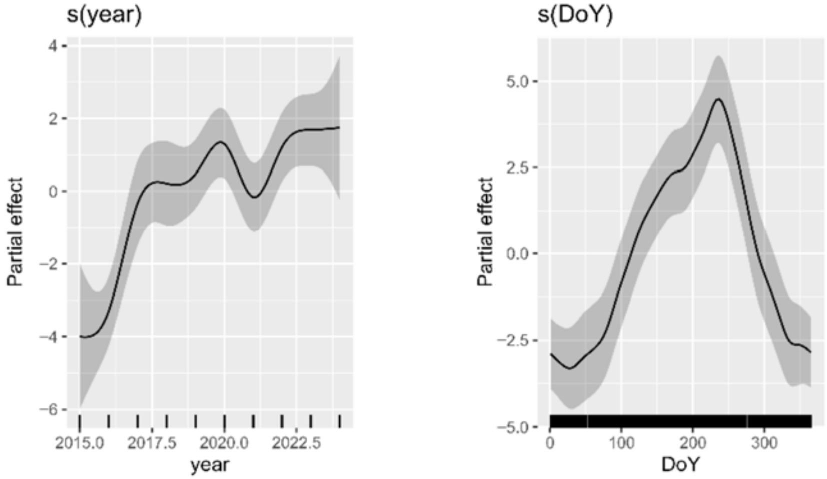
Long-term objective: produce data to validate 3D numerical simulations that take non-linearity into account.

Measurement highlighting seasonal variations and slight non-linearities







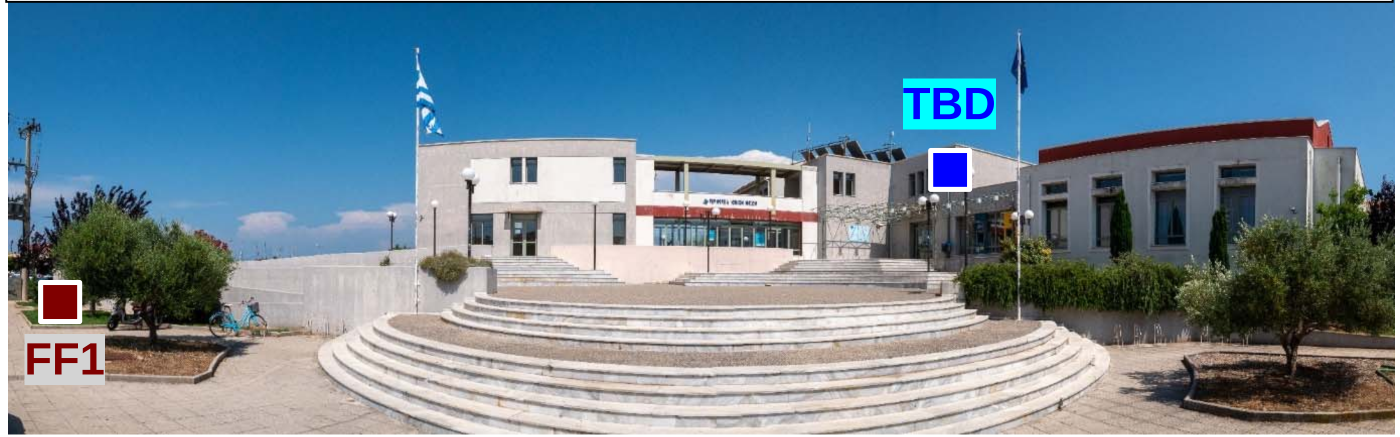


The early SIGMA-3 age

ΣIGMA^3

Building effect of seismic recordings

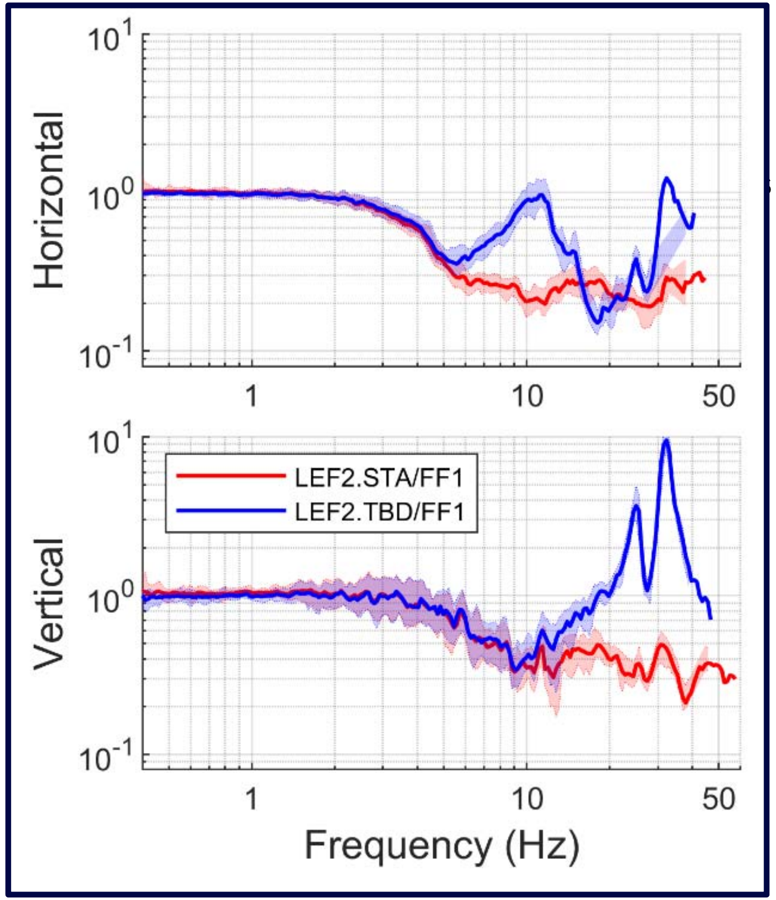
West side view



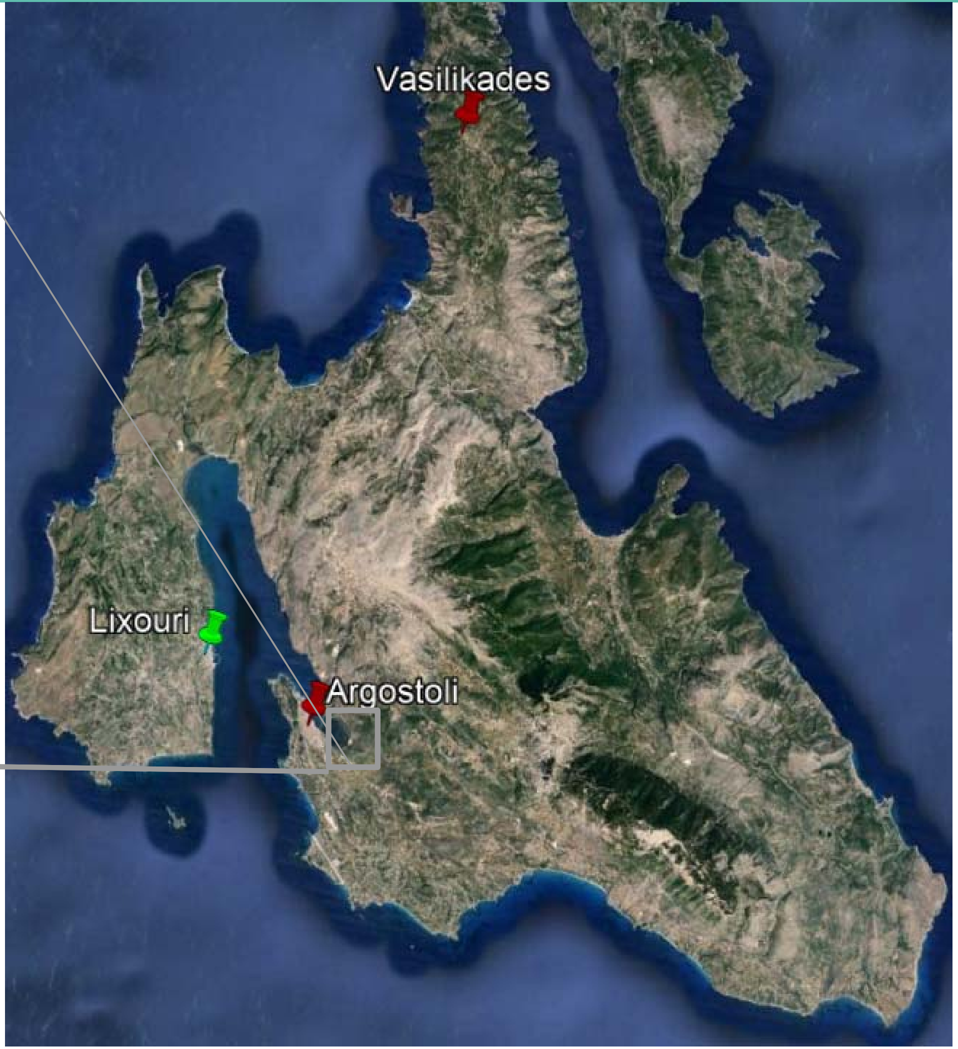
🟥 **STA : in the basement with LEF2**

East side view

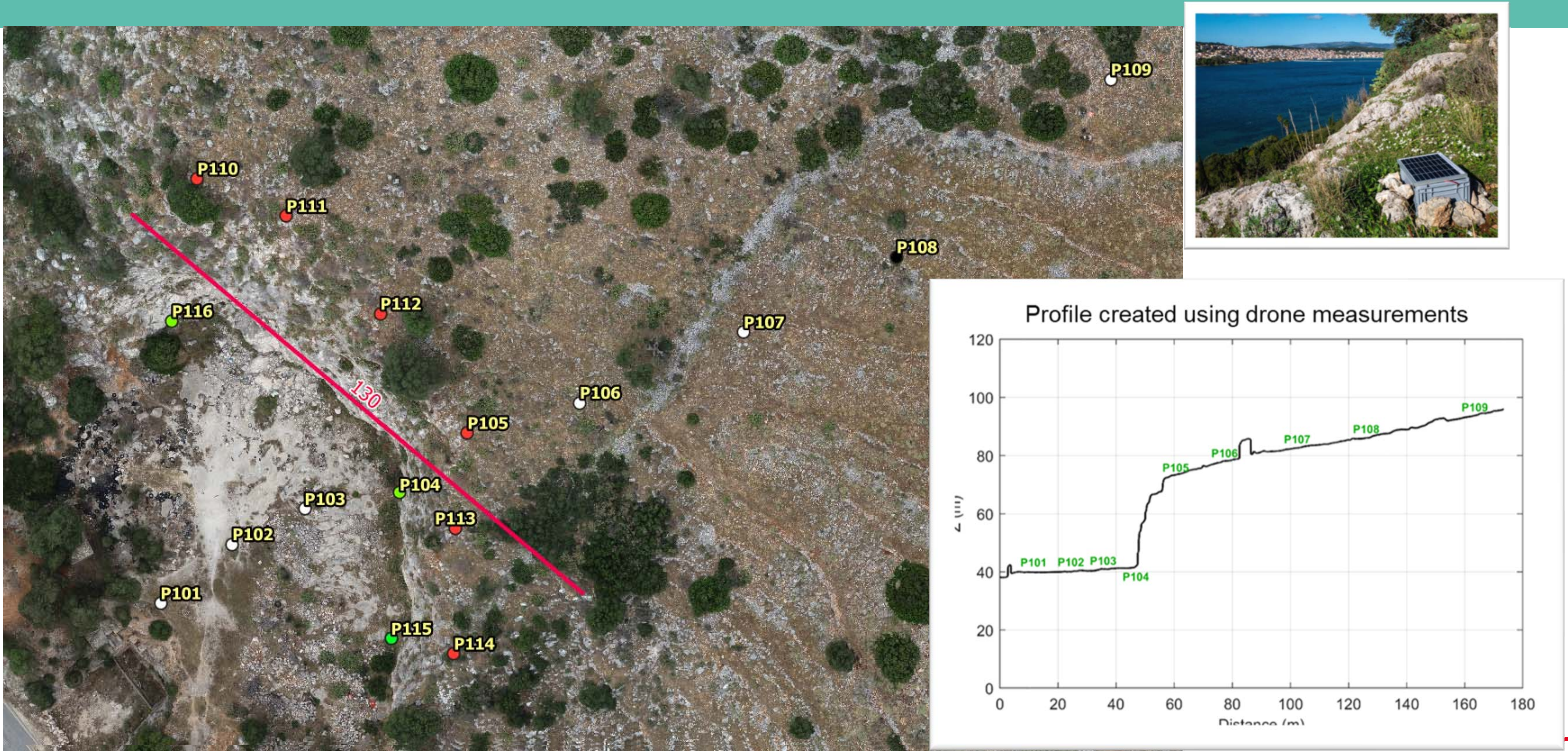
- **Pauline Rischette's thesis**
- **3 sites over 9 on Cephalonia**



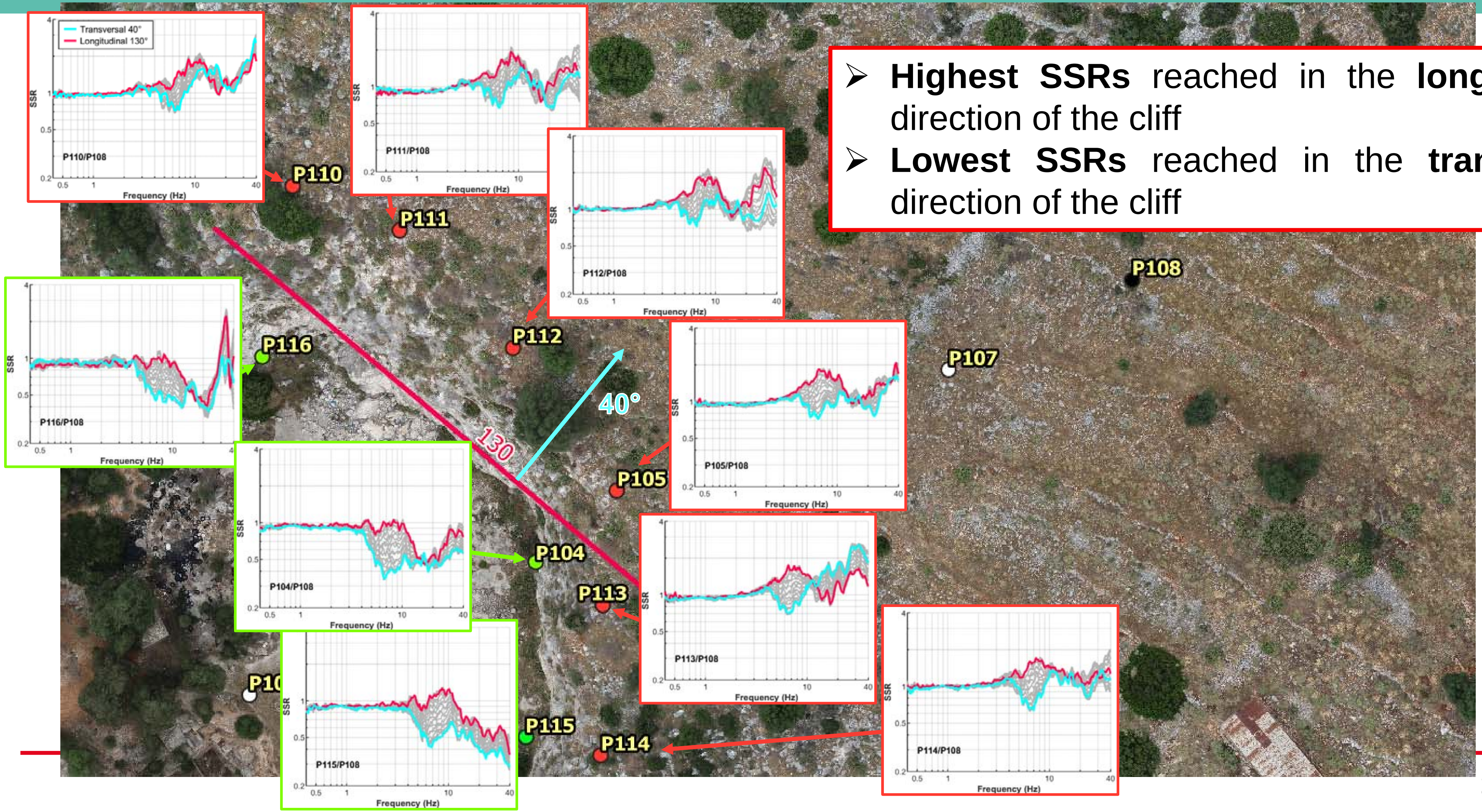
Topography effect: ArgoScarp experiment


Vasilikades
Lixouri
Argostoli

Topography effect: ArgoScarp experiment


P110
P111
P116
P112
130
P105
P106
P104
P103
P113
P102
P101
P115
P114
P109
P108
P107
Profile created using drone measurements
120
100
80
60
40
20
0
Z (m)
0
20
40
60
80
100
120
140
160
180
Distance (m)
P101
P102
P103
P104
P105
P106
P107
P108
P109

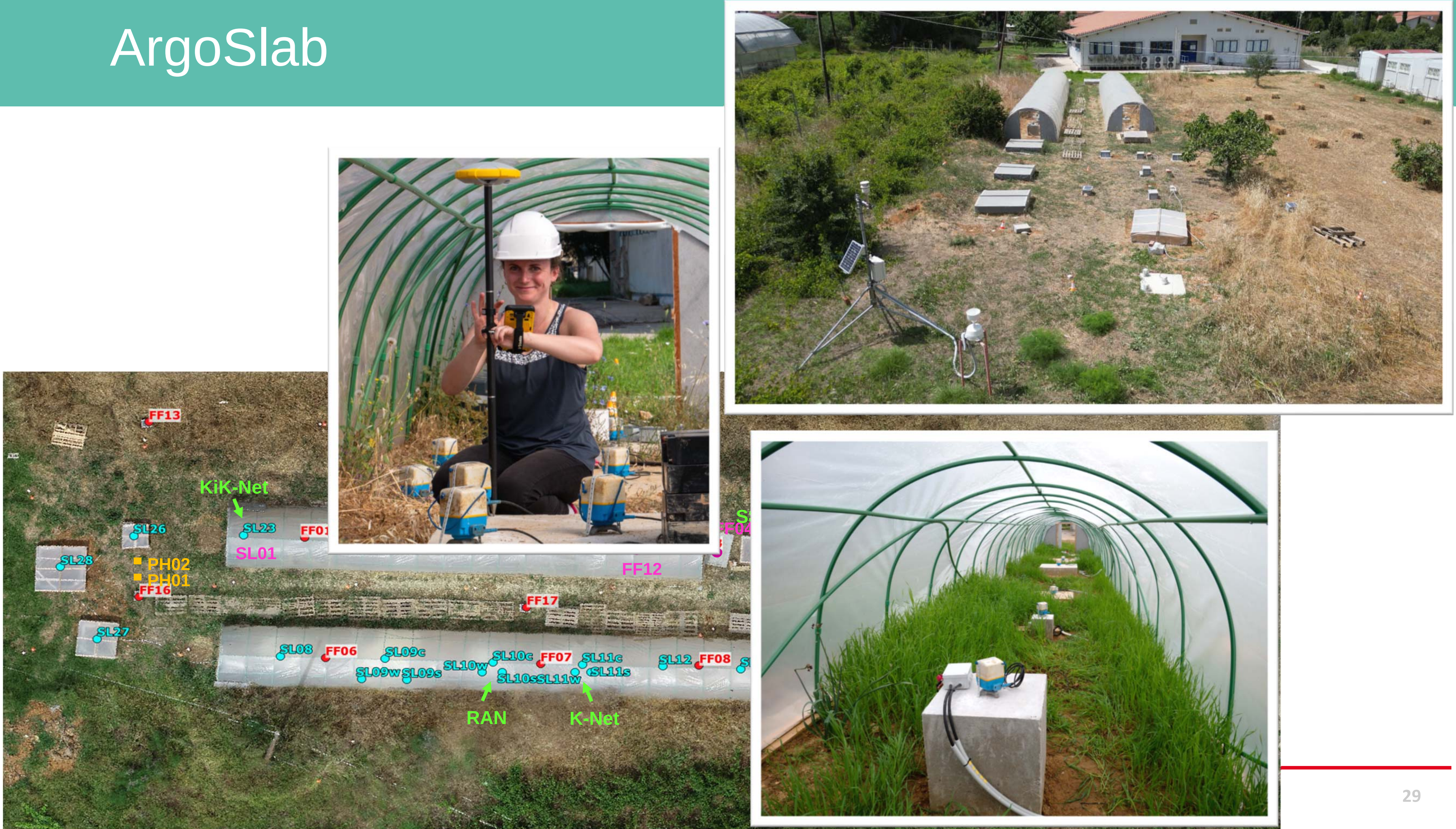
Topography effect: ArgoScarp experiment



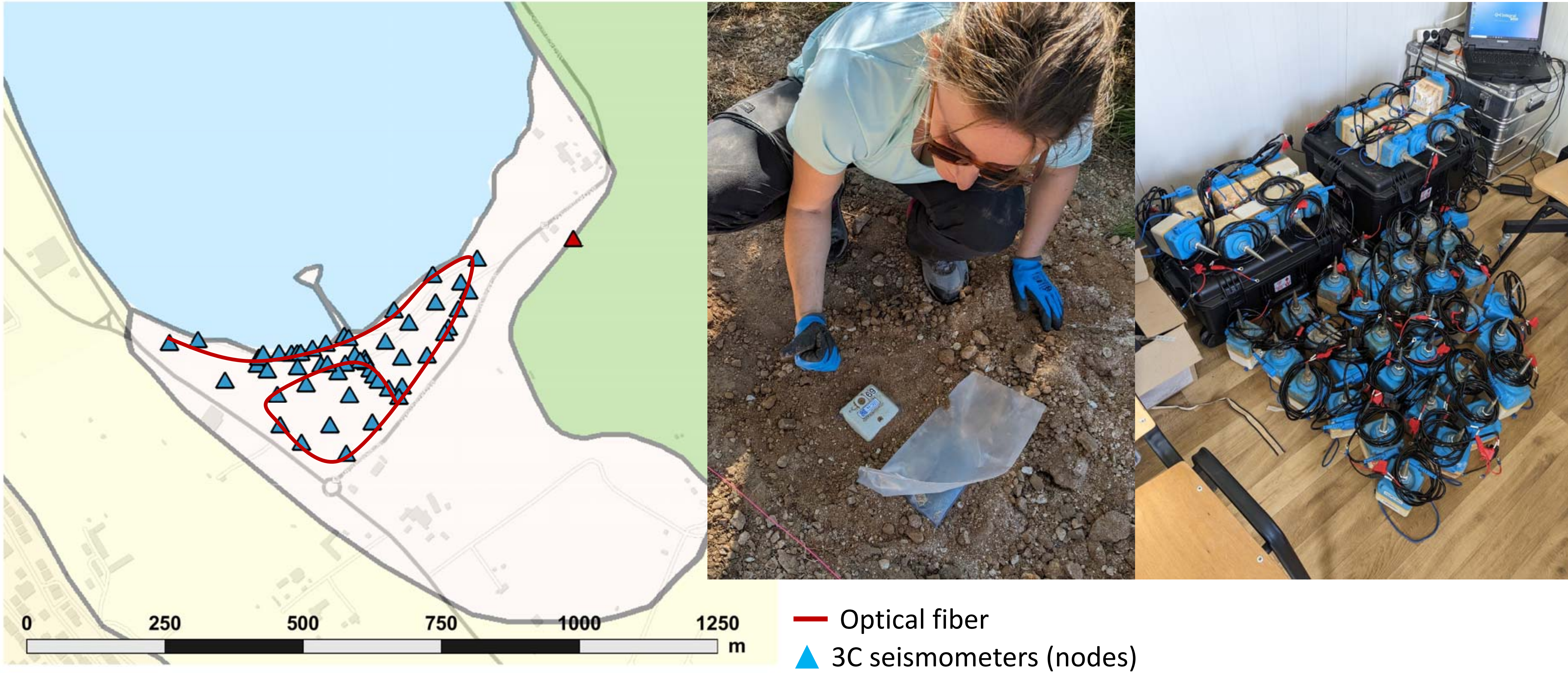
Transversal 40°
Longitudinal 130°
SSR
Frequency (Hz)
P110/P108
P111/P108
P112/P108
P116/P108
P105/P108
P104/P108
P113/P108
P115/P108
P114/P108
P110
P111
P112
P116
P108
P107
40°
130
P105
P104
P113
P10
P115
P114

- **Highest SSRs** reached in the **longitudinal** direction of the cliff
- **Lowest SSRs** reached in the **transversal** direction of the cliff

ArgoSlab


FF13
KiK-Net
SL26
SL23
FF0
SL01
SL28
PH02
PH01
FF16
FF12
F04
FF17
SL27
SL08
FF06
SL09c
SL09w
SL09s
SL10w
SL10c
SL10s
FF07
SL11c
SL11w
SL11s
SL12
FF08
RAN
K-Net

ArgoDAS-1 and dense node array


0
250
500
750
1000
1250
m
Optical fiber
3C seismometers (nodes)

The SIGMA-3 next age

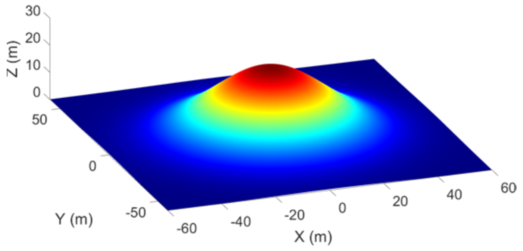
ΣIGMA^3

October 2025 campaign: a very broad partnership!

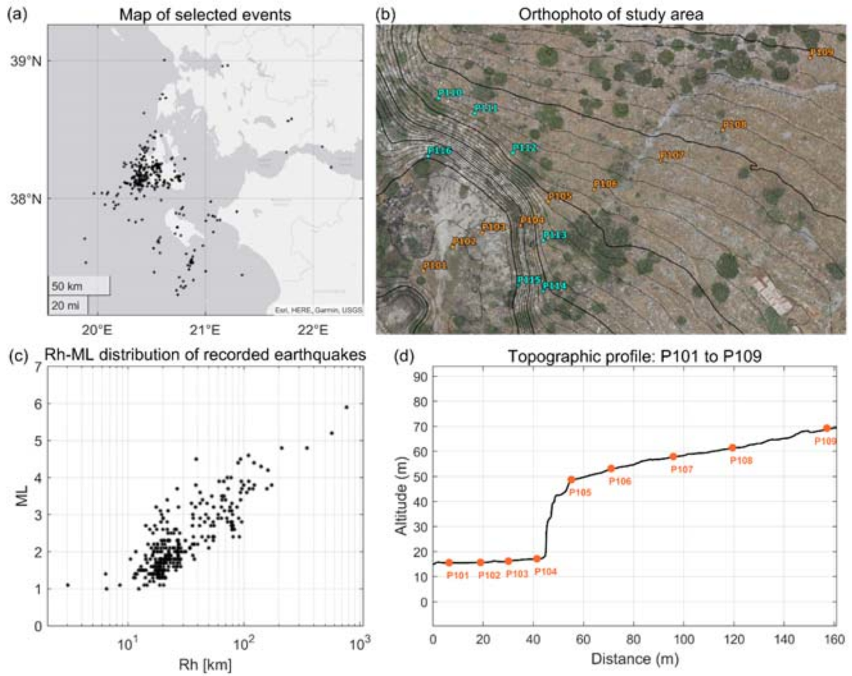
Rémy BURLOT (for CEA), Eirini CHATZIANAGNOSTOU (CEA/ISTerre), Cécile CORNOU (ISTerre), Frédéric DADOUN (Geodesia), Elias El HABER (EdF), Fabrice HOLLENDER (CEA), Philippe REIFFSTECK (UGE), Zafeiria ROUMELIOTI (Univ. Patras), Nikos THEODOULIDIS (ITSAK), Paola TRAVERSA (EdF), drillers from GEOT.ER, 'trencher' team from Tzouganatos, etc.

The BENTO benchmark

- BENTO – BEnchmark of 3D Numerical simulations on TOpographic sites
- Organized as part of the upcoming ESG2026 conference, in collaboration with CEA–EdF–ISTerre
- Phase 1: verification on “canonical” cases.
- Phase 2: validation on a small area with very strong short-wavelength curvature (ArgoScarp data).
- Phase 3: validation on a larger area with long-wavelength curvature (measurements on Mount Ainos).



ArgoScarp expriment, BENTO phase 3

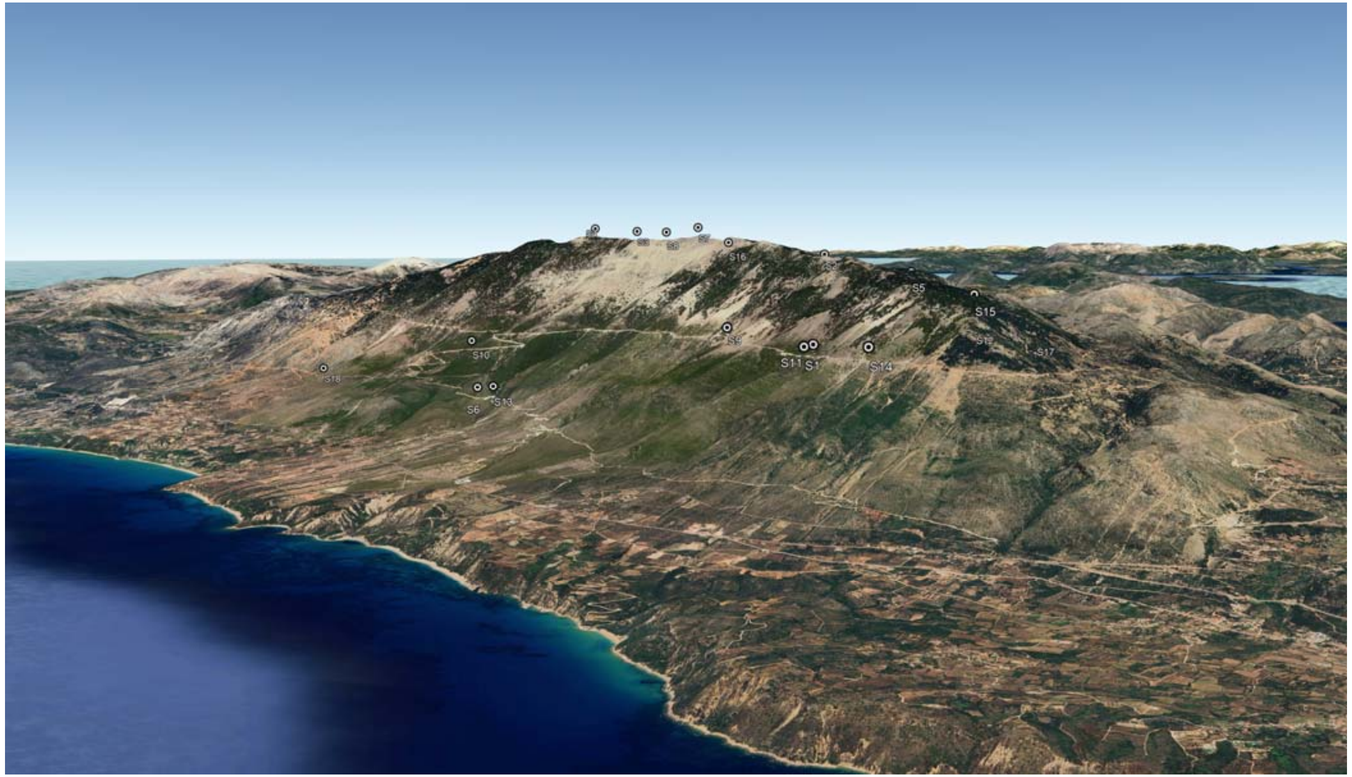


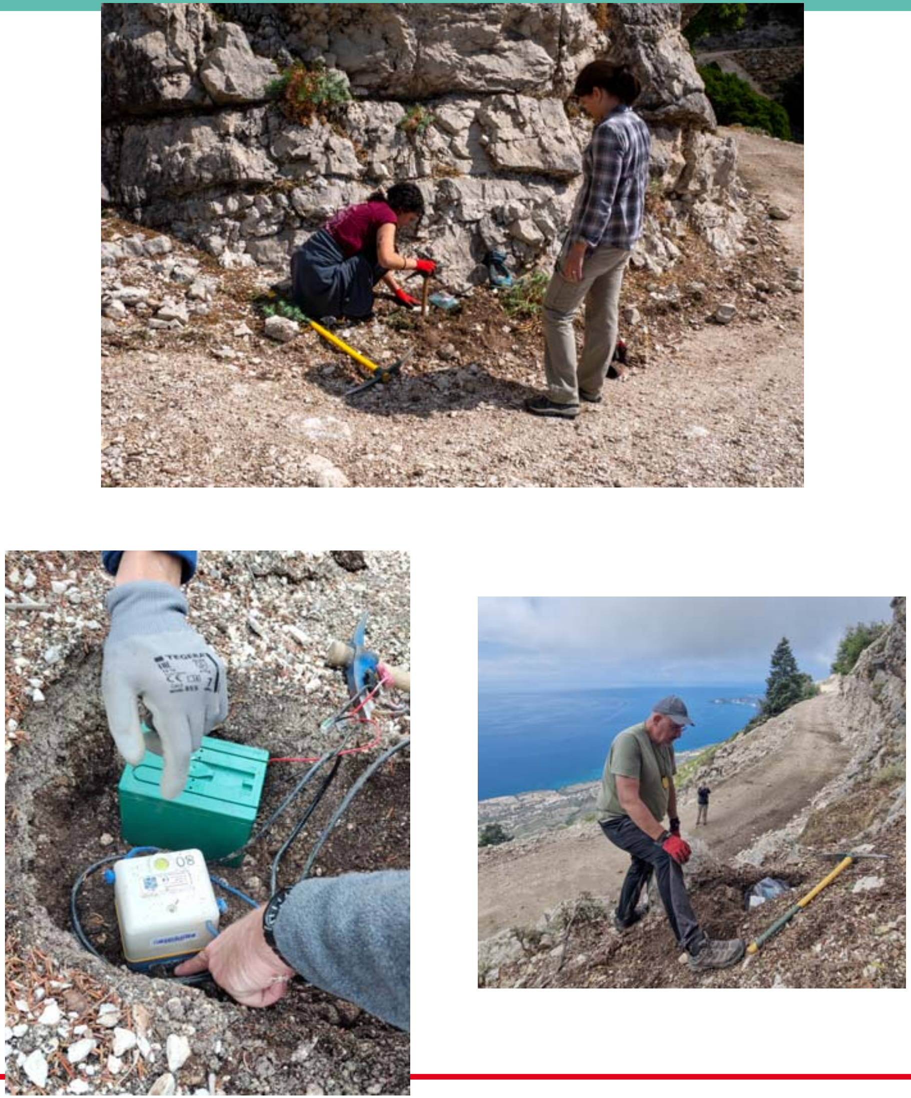
Expérience ArgoScarp :
effets topo à courte longueur d’onde

Base de données utilisée pour le benchmark “BENTO”

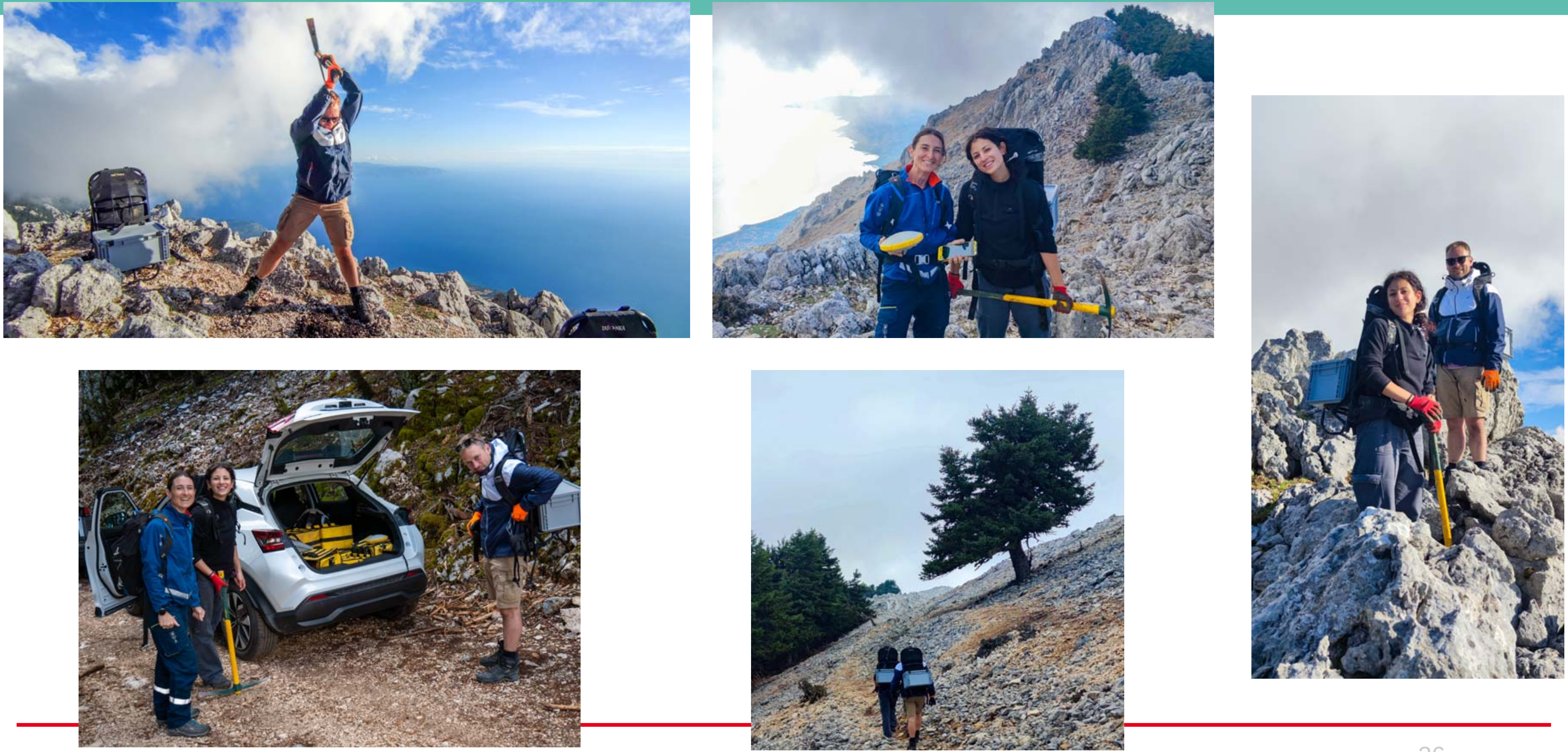
Launch of measurements for BENTO Phase 3

- 18 measurement points for a duration of 3 to 4 months


S16
S5
S15
S9
S10
S12
S17
S18
S11
S1
S14
S6
S13



Launch of measurements for BENTO Phase 3



Launch of measurements for BENTO Phase 3

Launch of measurements for BENTO Phase 3

Two jurists preparing a collaboration agreement and discussing intellectual property

‘Only an island as indolent as Cephalonia would allow itself to be infested by such troupes of casual and impertinent goats’

Captain Corelli’s Mandolin (1994),

Louis de Bernières

Drilling operation

- Installation of optical fiber on boreholes
- Installation of pore pressure probes
- In situ non-linearity parameter with cyclic test

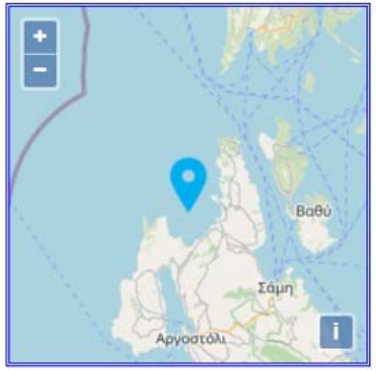
Installation of pore-pressure sensors

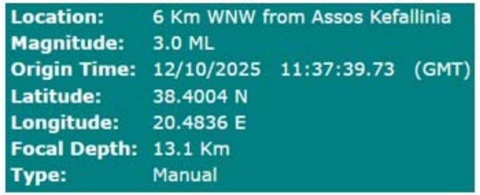
- 4 sensors at 3.5, 5.5, 7.5 and 15.5 m (zone of low CPT N-values, accelerometer depth)
- Vibrating-wire cone-tip sensors (GeoSense probe), to be pushed to the bottom of the borehole

Installation of pore-pressure sensors

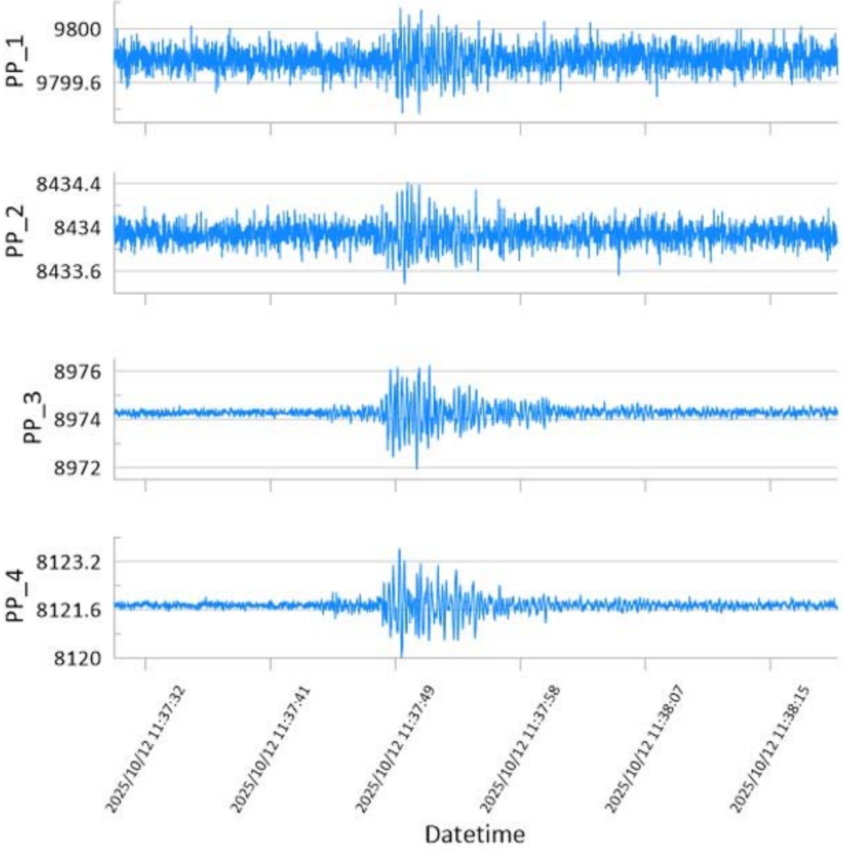
Installation of pore-pressure sensors

First earthquake recorded with the pressure sensors





Location:	6 Km WNW from Assos Kefallinia
Magnitude:	3.0 ML
Origin Time:	12/10/2025 11:37:39.73 (GMT)
Latitude:	38.4004 N
Longitude:	20.4836 E
Focal Depth:	13.1 Km
Type:	Manual

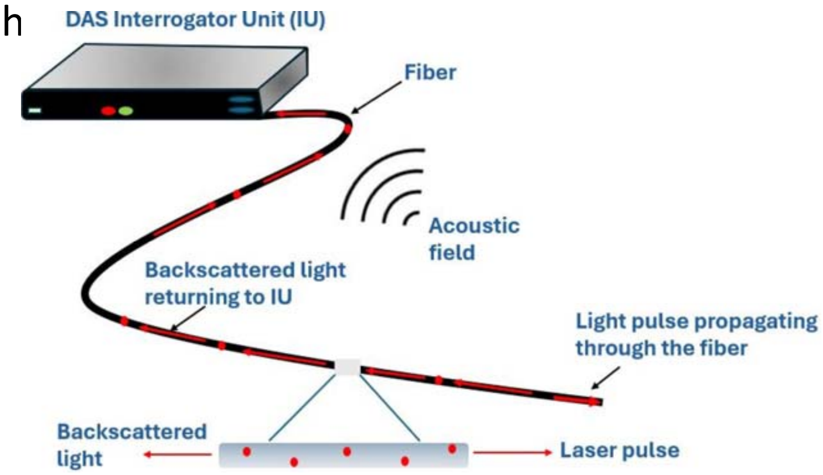


ARGO-DAS2

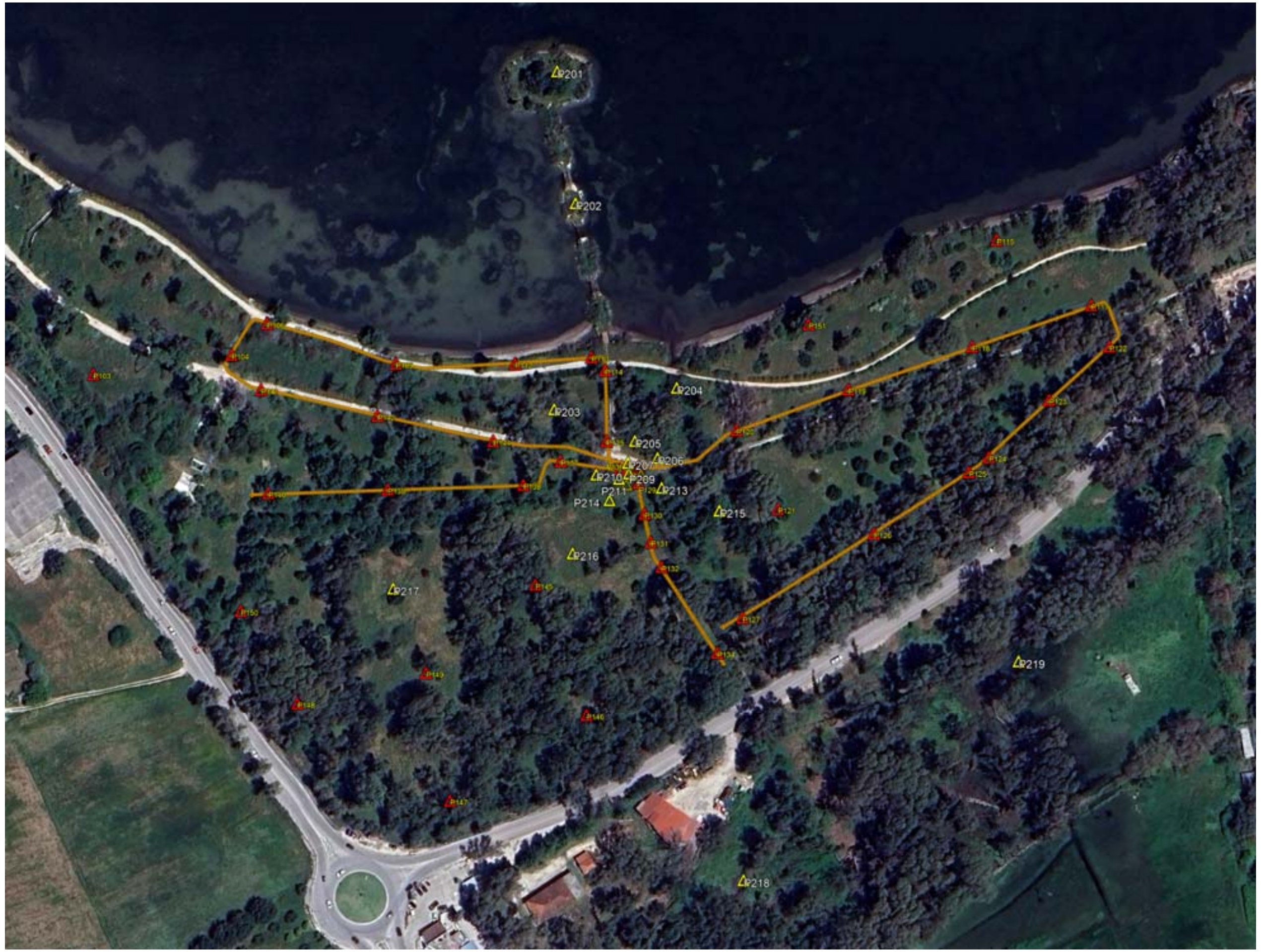
- DAS (Distributed Acoustic Sensing):
  - Principle: the optical fiber acts as a dense array of sensors, continuously measuring strain variations along its path using laser backscattering.
  - Interest: enables the acquisition of seismic measurements with very high spatial resolution (metric scale) over several kilometers, without deploying point sensors.

- ARGODAS1 (2023): initial measurements taken as part of a collaboration between CEA and ISTerre (but measurement issues with the interrogator worked only 9 days of data were collected).

- ARGODAS2 (2025): new measurements on the same fiber, but with the addition of fibers in boreholes.
  - Approximately 1,400 m of horizontal fiber.
  - + 2 boreholes (20 and 50 m) of vertical fiber.
  - + 62 nodes for validation/calibration of DAS measurements.
  - Collaboration between EdF, CEA, and ISTerre as part of SIGMA-3.
  - Fibers and nodes installed, DAS measurements themselves over a period of 2 to 3 months (starting in November)


DAS Interrogator Unit (IU)
Fiber
Acoustic field
Backscattered light returning to IU
Light pulse propagating through the fiber
Backscattered light
Laser pulse

ARGO-DAS2


P201
P202
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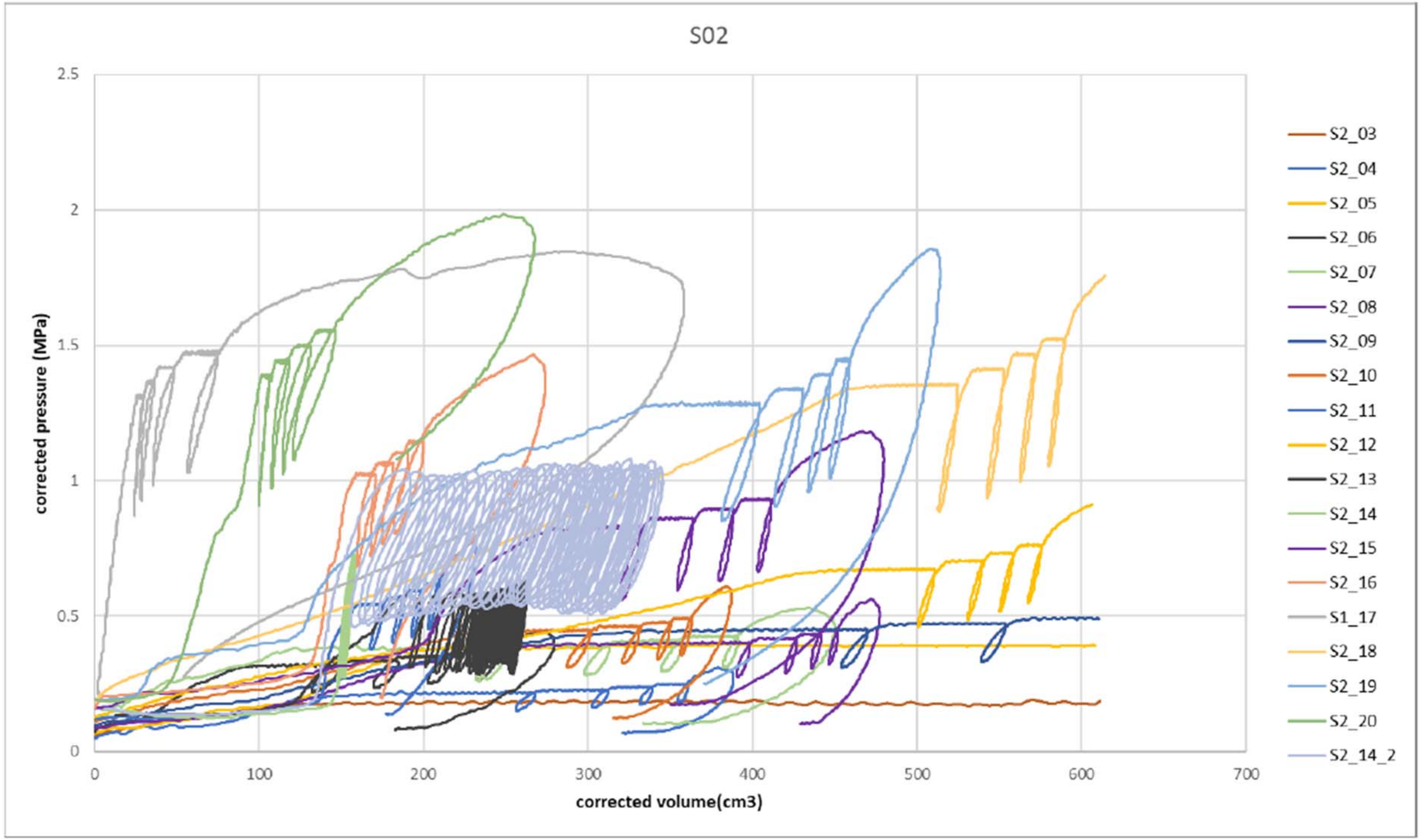
P218
P219
P151
P114
P121
P130
P131
P132
P127
P126
P125
P124
P149
P146
P147

ARGO-DAS2

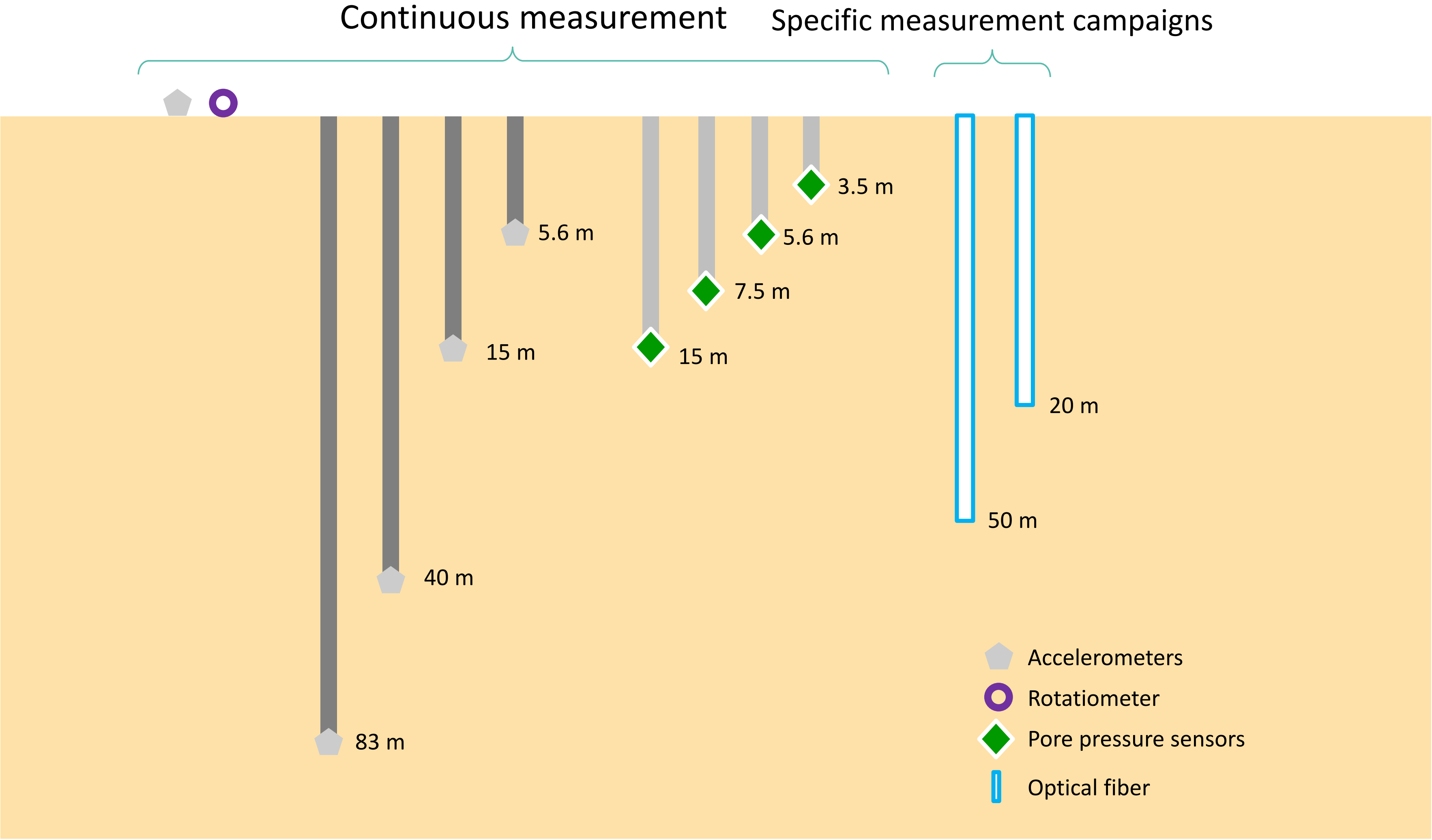
In situ cyclic pressure tests

- Collaboration between EdF, CEA, and Gustave Eiffel University as part of SIGMA-3:
- 2 x 18 measurements (from 3 to 20 m) of nonlinear parameters using a cyclic pressure gauge

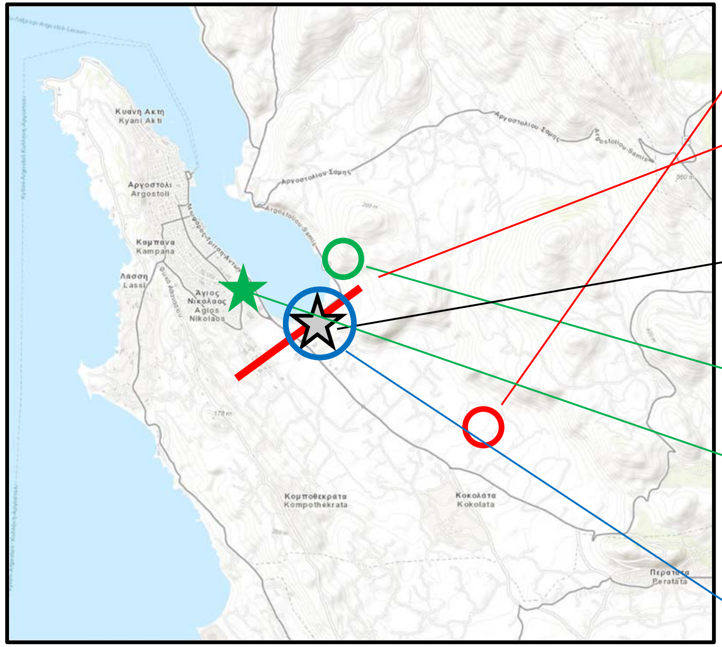
In situ cyclic pressure tests



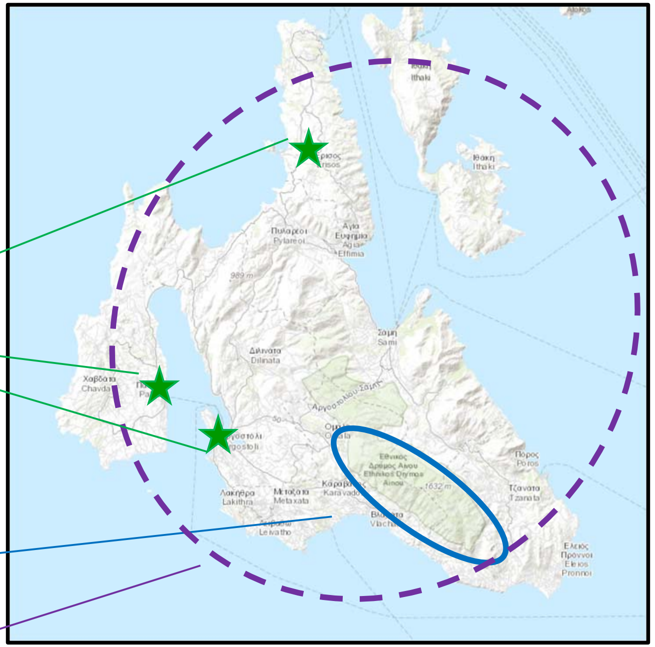
ARGONET, current instrumentation setup


Continuous measurement
Specific measurement campaigns
3.5 m
5.6 m
5.6 m
7.5 m
15 m
15 m
20 m
50 m
40 m
83 m
Accelerometers
Rotatiometer
Pore pressure sensors
Optical fiber

Earthquake event databases


Κυανη Ακτη
Kyani Akti
Αργοστόλι
Argostoli
Αργοστολίου-Σάμης
Καμπανα
Kampana
Λάσση
Lassi
Άγιος Νικόλαος
Agios Nikolaos
Κομποθεκρατα
Kompothekrata
Κοκολατα
Kokolata
Περατατα
Peratata

- Dense network, 21 broadband seismometers (post-2014 sequence): 1800+ earthquakes
- 5 accelerometers + 1 rotational sensor (post-2014 + 2015 sequence): 4000+ earthquakes
- **ARGONET : 6 accéléromètres + 2 rotatiomètres : (2015-2025) : 1500+ EQ**
- ArgoScarp +BENTO (2022-2023), 16 nodes : 300+ EQ
- ArgoSlab (2022-2025), 55 nodes : 900+ EQ
- SSI-experiments (hundred of events)
- ArgoDAS (60 nodes + fiber, acquisition in progress
- ??? OSCAR benchmark (location kept secret…) ???
- BENTO/Ainos 18 nodes (2025): acquisition in progress
- ArgoLoc (?): whole island, 60 nodes for one year, installation planned for March 2026



Scientific production from Sinaps@ and Sigma programs from Cephalonia experiments: 15 peer-reviewed articles’

Ground-Motion Dependency on Seasonal Variations: Observations at the ARGONET Array, Cephalonia, Greece
Variation in Seismic Wave Velocities at Shallow Depth and the Masking of Nonlinear Soil Behavior Based on the ARGONET (Cephalonia, Greece) Vertical Array Data
Rainfall-Induced Variation of Seismic Waves Velocity in Soil and Implications for Soil Response: What the ARGONET (Cephalonia, Greece) Vertical Array Data Reveal
applied sciences
Earth, Planets and Space
Open Access
Accelerometer, Velocimeter Dense-Array, and Rotation Sensor Datasets from the Sinaps@ Postseismic Survey (Cephalonia 2014–2015 Aftershock Sequence)

Bulletin of Earthquake Engineering
https://doi.org/10.1007/s10518-025-02221-x

ORIGINAL ARTICLE

The SSRc method as a practical solution for evaluating site response using far apart stations: applications in Western Greece and South-Eastern France

I. Grendas[1] · F. Hollender[2,3] · V. Perron[2] · N. Theodoulidis[1] · M. Buscetti[2,3] · P. Traversa[4]

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Abstract
The Standard Spectra Ratio (SSR) of S-wave earthquake ground-motion, is a commonly applied technique between a target and a nearby reference-site, that provides Site spectral-Amplification Factor (SAF[f]). The required "nearby reference-site" constitutes a significant restriction of the SSR technique, which however, has been partially overcome, by relaxing it, based on a recent study, using an analytical, time-consuming 10-step analysis, using the Spectral Factorization method on Coda-waves (SFC). A first effort on this direction, has been earlier proposed by Phillips and Aki (Bull Seismol Soc Am 76:627–648, 1986), based on a more sophisticated technique on coda-waves, using vertical-component data, considering however an undefined reference-site, as the average of all studied-stations. Here, a new simplified empirical technique of SAF[f] computation at a target site with respect to a distant reference one, is examined as a combination of SSR and SFC methods, satisfying at the same time their main advantages, i.e. the easy application of SSR and the use of longer target-reference site distance of SFC. This SSR technique based on coda-waves (SSRc), has been applied in the past in several cases but based on a nearby reference-station. Here, it is modified to make use of a distant reference-station from the target one as well and is demonstrated and applied for several stations in two areas of different seismicity level: the low-to-moderate and the high seismicity areas of southeastern-France and western-Greece, respectively. The results are encouraging in further applying this alternative SSRc technique, compared to those retrieved by different methodologies and datasets, supporting its valid and effective application.

Keywords Site Amplification Factor (SAF) · Standard Spectral Ratio (SSR) · Coda waves · Distant reference-station

Extended author information available on the last page of the article

Published online: 29 July 2025

Springer

Cushing EM, Hollender F, Moiriat D, Guyonnet-Benaize C, Theodoulidis N, Pons-Branchu E, Sépulcre S, Bard P-Y, Cornou C, Dechamp A, Mariscal A, Roumelioti Z (2020) Building a three dimensional model of the active Plio-Quaternary basin of Argostoli (Cephalonia Island, Greece): An integrated geophysical and geological approach. Engineering Geology 265:105441. https://doi.org/10.1016/j.enggeo.2019.105441

Grendas I, Theodoulidis N, Bard P-Y, Perron V, Hatzidimitriou P, Hollender F (2022a) Can site effects be estimated with respect to a distant reference station? Performance of the spectral factorization of coda waves. Geophysical Journal International 230:1–28. https://doi.org/10.1093/gji/ggac040

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Grendas I, Hollender F, Perron V, Theodoulidis N, Buscetti M, Traversa P (2025a) The SSRc method as a practical solution for evaluating site response using far apart stations: applications in Western Greece and South-Eastern France. Bull Earthquake Eng. https://doi.org/10.1007/s10518-025-02221-x

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Perron V, Gélis C, Froment B, Hollender F, Bard P-Y, Cultrera G, Cushing EM (2018a) Can broad-band earthquake site responses be predicted by the ambient noise spectral ratio? Insight from observations at two sedimentary basins. Geophysical Journal International 215:1442–1454. https://doi.org/10.1093/gji/ggy355

Perron V, Hollender F, Mariscal A, Theodoulidis N, Andreou C, Bard P, Cornou C, Cottereau R, Cushing EM, Frau A, Hok S, Konidaris A, Langlaude P, Laurendeau A, Savvaidis A, Svay A (2018b) Accelerometer, Velocimeter Dense-Array, and Rotation Sensor Datasets from the Sinaps@ Postseismic Survey (Cephalonia 2014–2015 Aftershock Sequence). Seismological Research Letters 89:678–687. https://doi.org/10.1785/0220170125

Roumelioti Z, Hollender F, Guéguen P (2020) Rainfall-Induced Variation of Seismic Waves Velocity in Soil and Implications for Soil Response: What the ARGONET (Cephalonia, Greece) Vertical Array Data Reveal. Bulletin of the Seismological Society of America 110:441–451. https://doi.org/10.1785/0120190183

Roumelioti Z, Hollender F, Theodoulidis N, Grendas I (2025) Variation in Seismic Wave Velocities at Shallow Depth and the Masking of Nonlinear Soil Behavior Based on the ARGONET (Cephalonia, Greece) Vertical Array Data. Applied Sciences 15:10727. https://doi.org/10.3390/app151910727

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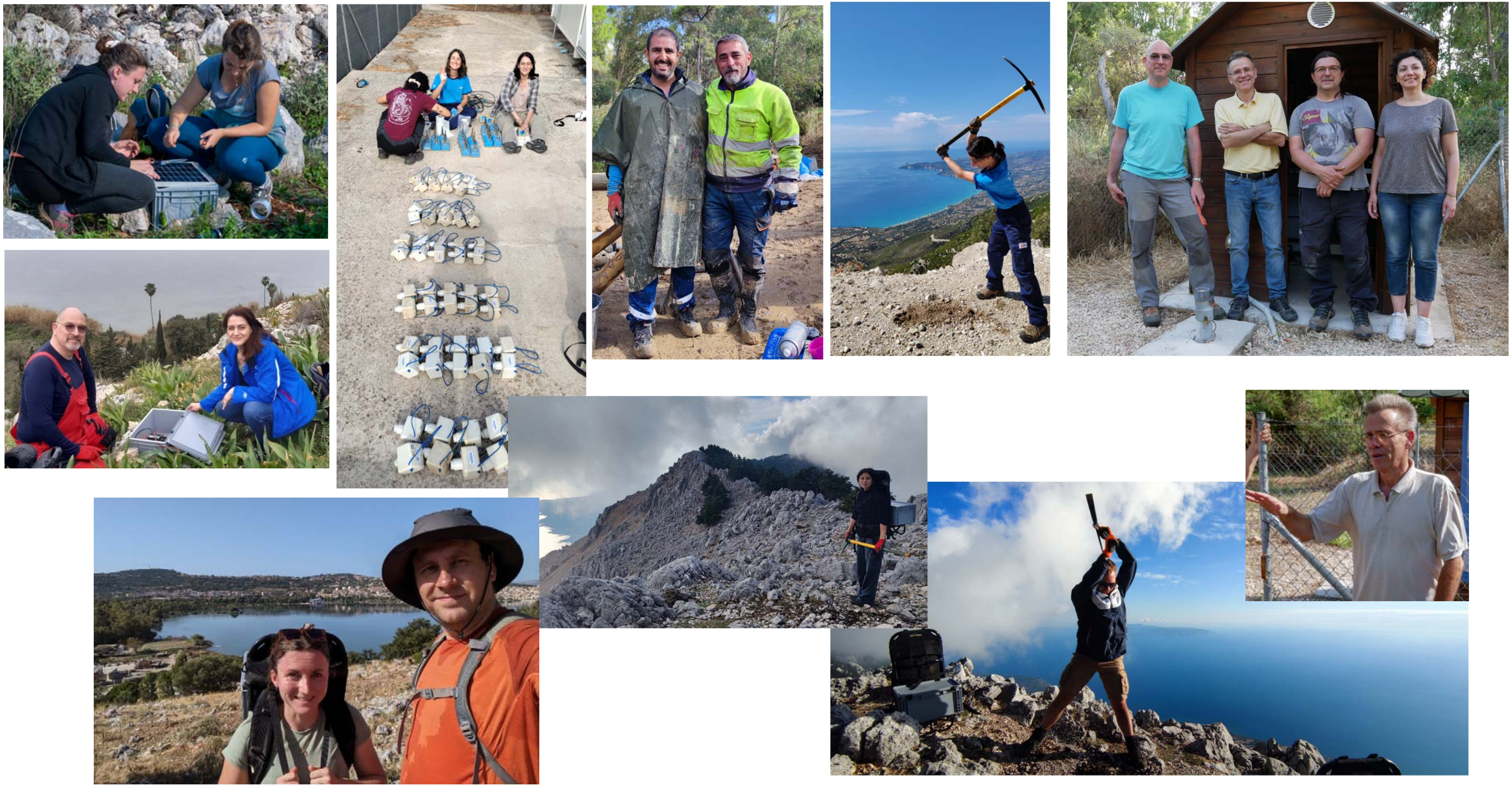
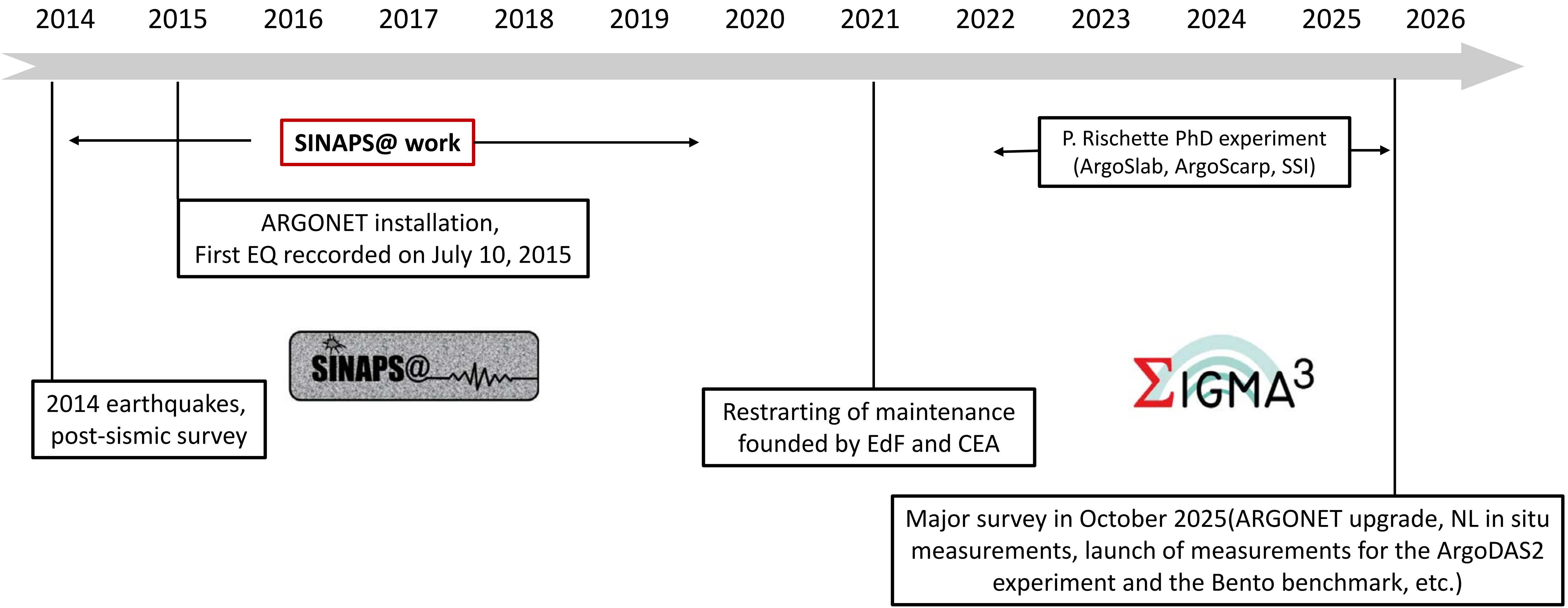
Touhami S, Lopez-Caballero F, Clouteau D (2020) A holistic approach of numerical analysis of the geology effects on ground motion prediction: Argostoli site test. J Seismol. https://doi.org/10.1007/s10950-020-09961-0



Thank you for you attention!

The major milestones of ARGONET and Cephalonia test-site


2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

SINAPS@ work

ARGONET installation,
First EQ reccorded on July 10, 2015

2014 earthquakes,
post-sismic survey

SINAPS@

P. Rischette PhD experiment
(ArgoSlab, ArgoScarp, SSI)

Restrarting of maintenance
founded by EdF and CEA

ΣIGMA3

Major survey in October 2025(ARGONET upgrade, NL in situ measurements, launch of measurements for the ArgoDAS2 experiment and the Bento benchmark, etc.)