MOREE : Réévaluation de l'aléa séisme et tsunami associé à la déformation extensive dans la zone de supra-subduction Ionienne (Péloponnèse, Grèce)

Projet scientifique dans le cadre de l'AO TelluS 2022, Action ALEAS – « Projet collaboratif »

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Objectifs

— Evaluate the relative importance of the current kinematics in the upper plate of the Ionian subduction with regards to the finite (Neogene) tecctonics and morphology.

— Characterize the possible role of the Ionian subduction in the deformation of the upper plate.

— Quantify the active kinematics of the Peloponnese to characterize deformation within and at the boundaries of this zone.

— Identify and map potentially seismic faults that accommodate the deformation.

— Model the seismic and tsunami hazard associated to these faults.

1 LE PROJET

1.1 Intérêt scientifique et état de l'art

In subduction zones, the overlaying lithosphere is generally the site of particularly active tectonics, including potential back-arc extension, partitioning of oblique deformation, and/or rapid vertical kinematics (e.g., in the Sunda Block in SE Asia). This variety of deformation modes and their particularly rapid kinematics have a direct impact on seismic and tsunami hazards, notwithstanding potential megathrust earthquakes.

In terms of crustal deformation, Southern Greece makes no exception among these supra-subduction zones : extensional basins, major strike-slip faults, accretionary prisms and vertical tectonics actively coexist. The current kinematics is fast, mostly linked with the extrusion of the Anatolian plate occurring at ≈ 30 mm.yr^{-1} (Figure 1), thus contributing to an intense seismicity : about 150 earthquakes of magnitude $M_\omega \geq 6.5$ occurred since 1800, 44 of which were followed by tsunamis of significant amplitude, and two historical earthquakes exceeded a magnitude $M_\omega \sim 8.0$ (e.g., west of Crete in 365 AD), calling for a better knowledge of the subduction parameters.

However, these elements reactivate a previous setting inherited from important alpine compressional structures and subsequent extension (normal faults and diapir tectonics).

Within this system, the mostly transpressional Matapan Trough (SW Peloponnese) is the site of numerous earthquakes with extensional focal mechanisms. The extension, resulting in a tilted-block morphology and normal fault scarps, is consistent with GNSS velocities that show an E-W extension from the SW Peloponnese to eastern Crete.

This configuration raises the question of the competition between volume and boundary forces in topography evolution above a converging plate boundary. Indeed, the Matapan Escarpment, rising more than 3 km, delimits a deep flexural basin, suggesting the presence of a crustal-scale ramp between the flexured Nubian slab and a thickened crustal backstop, particularly prone to collapsing towards the Ionian Sea (Figure 2).

Among the hypothesis, changes in subduction parameters (azimuth, dip, velocity, etc.) and/or the under-plating of crustal morpho-structures from the downgoing plate may also contribute to this dynamics. Indeed, the lithosphere

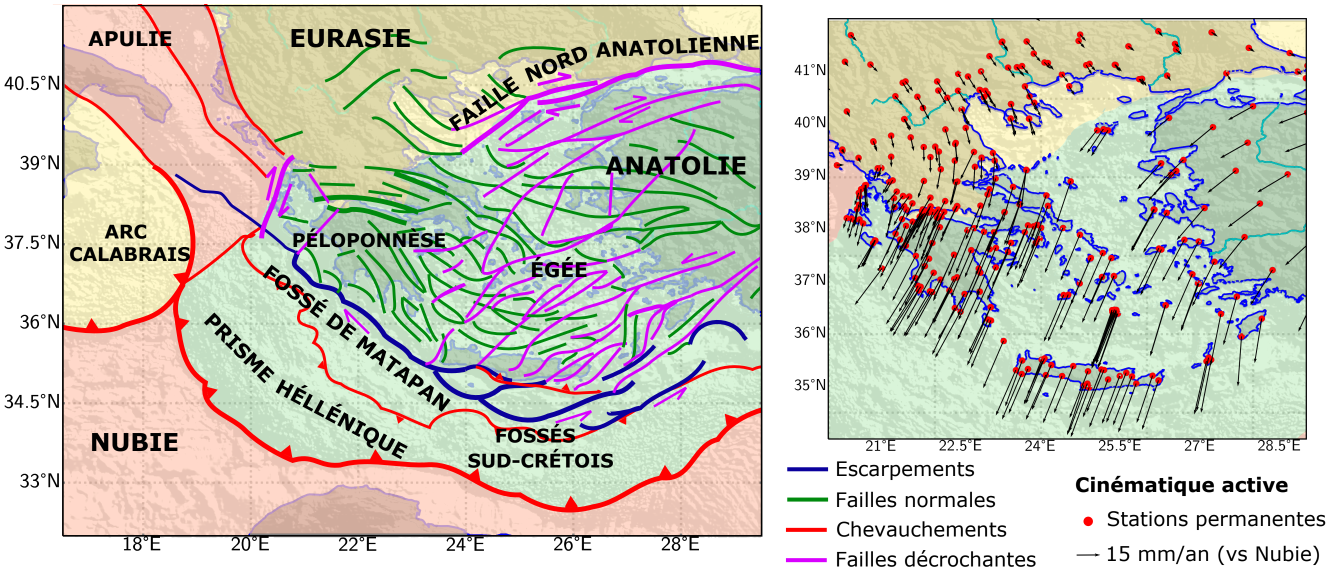

Figure 1: Geodynamic map of the Aegean domain showing the main active structures. *Current velocity field from [3]; faults modified from [10]*

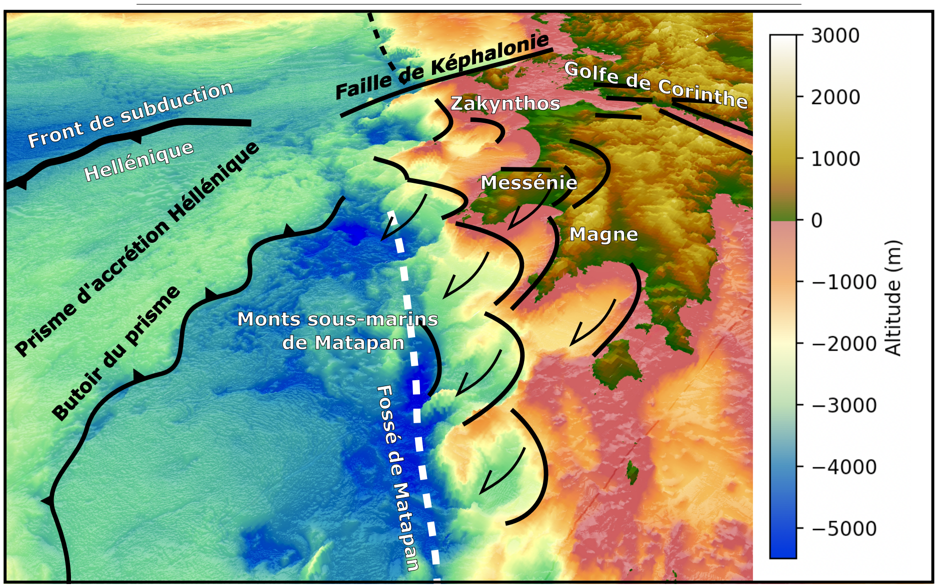

Figure 2: Working hypothesis : morphological clues of gravity-driven tectonics at the Matapan trench Oblique view towards the NW, vertical exaggeration $\times$ 5

generally uplifts above these asperities while it collapses in their wake [7]. This could partly explain the Neogene uplift of the Peloponnese, as shown by numerous marine terraces and raised alluvial fans [5]. The existing topography, which probably results from these processes, is at the origin of multiple slope destabilization phenomena, at all scales, from landslides (e.g., 1963 tsunami in the Gulf of Corinth), to earthquakes on faults bordering tilted blocks of crustal scale, whose rupture can reach magnitudes of ≈ 8 [9].

Existing regional dynamic models [6, 11] are still debated, and the importance of the residuals with respect to the measured kinematic field [3], a fortiori within the Peloponnese itself, underlines the complexity of these dynamics. The observed kinematic field also proves difficult to reconcile with seismological data and finite deformations, which makes the identification and characterization of active faults to be taken with caution.

The morphological study of the Peloponnese also reveals a variety of extensional post-Alpine structures, such as crustal-scale gravity tectonics, north-south and east-west normal faults, and fissures interconnected with large thick-skin folds (Figure 3). While some of these structures were seismically active on a historical scale (e.g., the Gulf of Corinth), or at least can be explained by present-day kinematics, others appear to be hardly compatible with geodetic and seismological observations, and sometimes contradicting each other, suggesting the occurrence of boundary forces modifications since the Oligocene. The regional geodynamic changes that may have contributed to this evolution would imply a migration of the deformation from geological faults to young and less apparent structures. Therefore, a joint geological and geodetic approach may reveal fruitful to discuss the relevance of considering such faults for risk assessment.

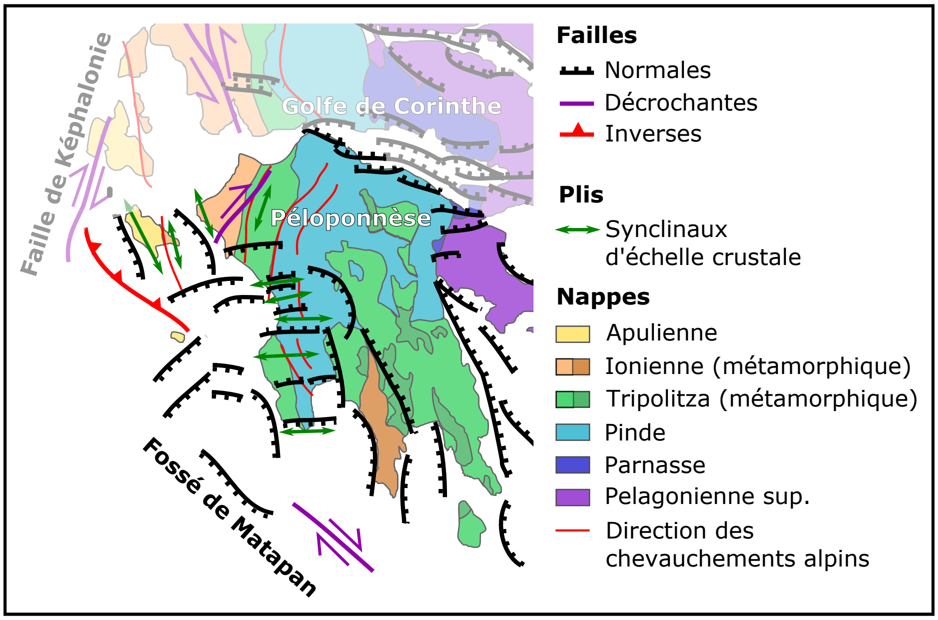

FIGURE 3: Simplified structural map of the Peloponnese. *Geological map from [12]; faults drawn from morphological, seismological and preliminary kinematic observations*

Many of these active structures, although having been extensively studied, still raise several questions :

— the issue of strain partitioning near the termination of the backstop : most of the active faults are at intermediate depths between the Ionian slab and the surface; they are sub-parallel to the slab but display a strong strike-slip component (e.g., 2008 Movri earthquake between 24 and 12 km depth; 2018 Zakynthos and 2014 Kephalonia earthquakes);

— the interaction between the slab and the long-wavelength topography (e.g., the origin the uplift of Messenia and Mani and its effect on the activity of their boundary faults, representing a great risk because of the vulnerability of the nearby metropolis of Kalamata);

— the variations of the seismic coupling from the seismogenic north (e.g., Kefalonia and Zakynthos) to the weak south : 10% seismic but with numerous potentially triggered surface faults;

— the possible existence of large ignored faults to the south and west of Kalamata, potentially capable of producing earthquakes of magnitudes 6-7;

— the vertical kinematics, well known in some places on the coast and very heterogeneous, poorly constrained by models and not yet really confirmed by geodesy.

1.2 Plan de recherche et calendrier de réalisation

1.2.1 Méthodes

This project will rely on the collaboration of teams studying the question of the active deformation of the Peloponnese from the observation, the acquisition and/or the compilation of data up to its processing, modelling, and interpretation. By assimilating inputs from different disciplines, we will propose an updated evaluation of the size and location of the faults, their coupling rate, the *recurrence time* of earthquakes, and their tsunamigenic potential, which will have a direct incidence on the evaluation of the seismic and tsunami hazard in the region.

— **Geodesy** : re-measuring of GNSS campaign points observed at the beginning of the 2000s to densify the currently available velocity field (based on 5 to 10 years of data acquired at a limited number of permanent stations) ; installation of 2 permanent GNSS stations in Messenia to increase the current coverage ; creation of a new 37°N E-W profile of campaign points (the latitude of Kalamata) with an 3 km interval to eventually capture the short-wavelength deformation. At the scale of the Peloponnese, calculation of velocities along kinematic cross-sections ; production of a kinematic model of the Peloponnese, and a dynamic model of the associated stress field [8].

— **Seismology** : from existing catalogs, use of seismic swarms location and focal mechanisms data to identify and characterize active faults ; cross-checking with historical earthquakes to estimate the long-term deformation. In case of an earthquake, local use of InSAR to locate deformation on targeted faults and quantify their relative movements.

— **Geology and morpho-structural analysis** : mapping from digital terrain models (TanDEM-X or equivalent) and optical imagery (Pleiades) ; field missions to conduct morpho-structural studies of targeted tectonic systems and determine their vergence, extent and relative ages ; collection and integration of existing tectonic measurements [1] ; morphological and gravimetric study of the seaward extension of the main structures ; structural mapping of areas of interest (to be selected) and production of a synthetic structural map ; integration to the regional geodynamical context [12].

— **Geochronology** : compilation of marine terraces ages and discussion of vertical velocities ; ^{14}C dating of recent uplifted terraces ; U-Th dating ; selection of areas of interest for ulterior missions aiming at dating the active faults scarps (by thermoluminescence, etc.).

— **Modelling and hazard assessment** : realization of a 3D digital crustal deformation model (ADELI program or equivalent), combining structural and seismological observations to the geodesic deformation field ; estimation of the possible magnitudes on the main identified seismogenic faults ; discussion of the potential recurrence of earthquakes ; identification of the zones affected by this hazard.

1.2.2 Plan de recherche

(2021) : in may 2021, SB and MP conducted a reconnaissance mission designed to define the project and orient future missions ;

2021 : identification of structures of interest from satellite images and TanDEM-X DEM (whose sub-meter accuracy was checked for the Corinth Rift by PB and SB in 2020 [2]) ;

2022 : installation of 2 permanent GNSS stations in Messenia ;

2022 : geomorphology campaign for ground-truthing potentially active faults in Messenia and Mani ;

2022 : geodetic campaign in Messenia, Mani and Movri ;

2022 : tectonic campaign to better constraint coastal vertical kinematics ;

2023 : geodetic campaign at the eastern and northern boundaries of the region ;

2023 : tectonic geomorphology ;

2023 : crustal deformation modelling at the University of Montpellier ;

2024 : complementary mission, to be defined in 2023.

The field missions will be organized and coordinated by SB, who was previously involved in various GNSS missions in Italy, Greece and Iceland since 2016.

1.3 Résultats attendus et perspectives

The identification and study of the structures resulting from Neogene deformation of the Peloponnese will allow to refine the relative dating of the processes involved, thus the causal links existing between them or in relation with larger events. This will also provide new elements for discussing the geological inheritance in the region, which may happen through the reactivation of pre-existing faults, interference within fold directions, fold-fault interactions, or the intersection of alpine directions.

The re-evaluation of vertical geodetic velocities will provide data to assess the present persistence of the Neogene uplift of the Peloponnese, and the remeasuring of GNSS campaign points, associated with the study of seismological data, will allow to specify the extension directions and velocity gradients. This will allow to clarify the role of gravity tectonics and to identify the zones where deformation localizes, in order to better interpret this deformation, both geologically and from the hazard perspective.

Notably, this project should help to better understand the occurrence of a number of earthquakes that may have surprised by their location or their nature, such as the 2008 Movri earthquake, in pure strike-slip and without surface fault, or the 2018 Zakynthos earthquake, mostly strike-slip on a very shallow reverse fault.

The region is of a clear didactic interest for the teaching of geology in high school and CPGE schools. In this context, simplified diagrams and explanatory texts will be published in order to support teachers in their lectures about the risks associated with subduction.

Finally, the relatively low frequency of devastating tsunamis in the Mediterranean, on the scale of human memory, hides a downside : inhabitants and tourists are generally unaware of it, and the authorities may not be ready to react. One of the fundamental contributions of the tsunami simulations carried out in the wake of this project will therefore be their ability to effectively inform the population and decision-makers of this hazard by displaying possible scenarii.

2 MOYENS NECESSAIRES À LA RÉALISATION DU PROJET

2.1 Equipements disponibles ou nécessaires à la réalisation du projet

The project will use the resources of the INSU geophysical park, the reservations (12 GNSS receivers and antennas) will be made in the upcoming months.

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5 Collaborations

This project deals with a region that is already well documented, for which the existence of pre-existing observations, publications and models gives the best chances to improve its understanding through a multidisciplinary approach, allowed by the permanent dialogue between teams specialized in the various approached fields.

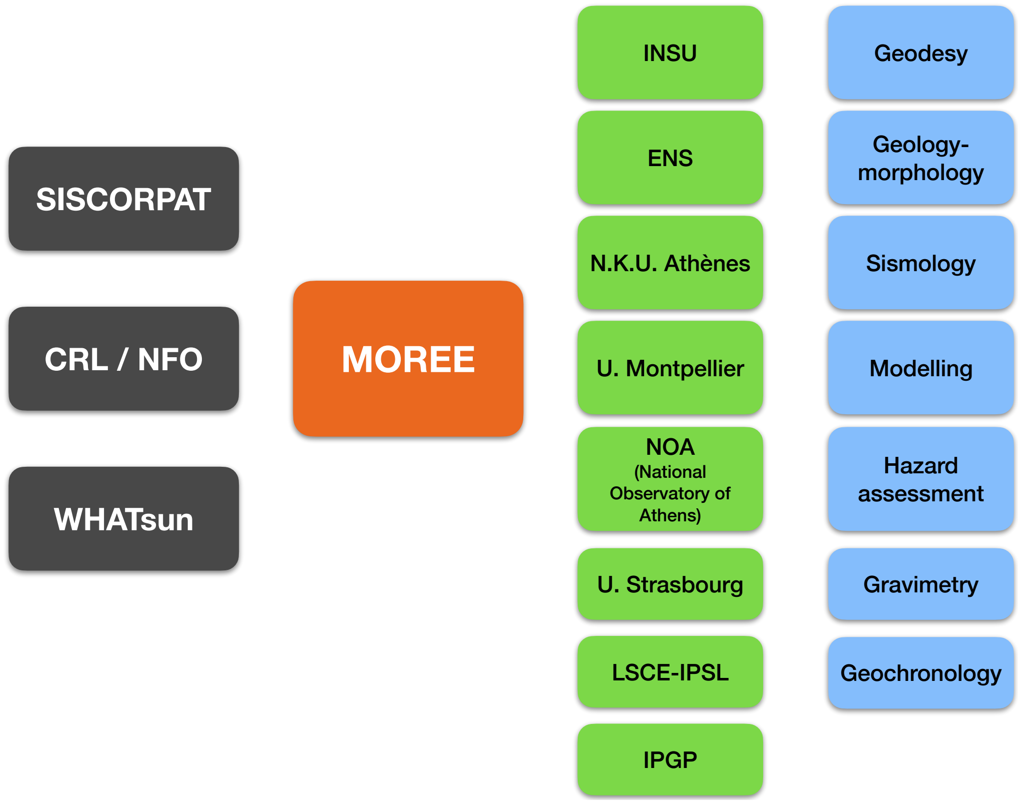

FIGURE 4: Articulation de ce projet au sein de ses différents partenaires.

5.1 Laboratoire de Geologie, École Normale Supérieure de Paris

The Geology Laboratory of the ENS (Paris) gathers a team of researchers and PhD students of various profiles, available and interested in the questions of this project, and by the geodynamics of the Mediterranean in general.

Simon Bufféral is preparing a Ph.D on the dynamics of the Ionian supra-subduction zone, co-supervised by Manuel Pubellier for the aspects of geological and morphological analyses, and Pierre Briole, whose research in geodesy serve as a reference in the region. Hélène Lyon-Caen will be available to discuss the seismological data ; Javier Escartin the tectonics and marine seismicity ; Nicolas Chamot-Rooke the geodynamics ; Alexis Rigo the localized deformation ; Jean-Arthur Olive the fault modeling ; Matthias Delescluse the marine geophysics, and Luce Fleitout the gravimetry data and mechanical modelling of the deformation

5.2 Université de Montpellier

The University of Montpellier will provide its expertise in geophysics, imaging and rheology modelling, in particular Frédéric Gueydan, Christel Tiberi, Fanny Garel and Jean Chéry, already involved in the matters of the geodynamics of the Mediterranean.

5.3 National Kapodistrian University of Athens (NKUA) - National Observatory of Athens (NOA)

The identification, location, enumeration and characterization of active faults will allow the production of a new neotectonic map of the Peloponnese, which can be used as a reference for further hazard studies, in close collaboration with the NKUA (Haralambos Kranis) and the NOA (Panagiotis Elias).

5.4 Laboratoire des Sciences du Climat et de l'Environnement

The LSCE-IPSL (Catherine Kissel) has been approached to perform ^{14}C and U-Th isotopic dating.

5.5 Corinth Rift Laboratory

This work will be articulated with the research conducted at the Near Fault Observatory of the Corinth Rift. The results obtained will improve the understanding of the seismicity at the Corinthian Rift, and conversely the work at the Near Fault Observatory, notably in the framework of the SISCORPAT project (submitted by Pascal Bernard in 2020), will allow a better understanding of the boundary forces existing north of the area of interest.

The investment of the team members, notably PB, P. Elias and SB, in the Corinth Rift Laboratory (crlab.eu), is an important asset in terms of field experience, access to geodetic and seismological data, and academic and institutional links in Greece. In the framework of this project, this collaboration will be strengthened with the participation of the various other teams involved in the CRL observatory, notably the IPGP (Pascal Bernard).

5.6 CEA/DASE - WHATsun

The results obtained during this project will be used as input for the West Hellenic Arc Tsunami (WHATsun) project, financed by the LRC Y. Rocard and gathering the ENS, CEA and Greek collaborators around the issue of tsunami hazard in Greece. In that framework, SB and PB already realized multiple simulations of tsunamis in the Mediterranean (e.g., [4]) using the TAITOKO program, in collaboration with Audrey Gailler and Philippe Heinrich (Geophysical Studies and Hazards Laboratory, CEA).

The preliminary results call for a better knowledge of the associated faults, as will provide this project. Indeed, they indicate a propagation of the order of ten minutes between the epicenters of the earthquakes and the surrounding demographic and economic centers, frequently located on the coast. In case of need for early warning, any delay, even of the order of a minute, can have catastrophic consequences on the possibilities of evacuation and sheltering of the populations. However, the effectiveness of an early warning network, to be built, depends largely on the location of monitoring devices (instruments at the coast, buoys at sea, etc.), which must be thought not only in for megathrust earthquakes, but also in anticipation of ruptures associated with the deformation of the margins, potentially more frequent and even closer to the coast. Thus, the results of tsunami simulations on faults identified during the MOREE project will ultimately help the proposal of a tide gauge settlement map to optimize a future operational tsunami monitoring network in the Mediterranean.

5.7 Université de Strasbourg

The University of Strasbourg will be approached to consider its possible aggregation to the project in 2022, as they previously conducted a gravimetric campaign to better constrain the structure of the Gulf of Corinth, calling for a continuation of this work to the south.

6 BUDGET

2 geodetic campaigns : measurement of ≈ 70 geodetic sites in the Peloponnese, during 2 campaigns deploying 12 GNSS receivers.

Campaigns of 13 d, i.e., 10 d effective, employing 3 teams of 2 persons (including Greek and French students) deploying 4 receivers each, left 48 to 72 h on site, in 3 blocks of measurements, i.e., a total of 36 points measured per mission ; 72 in total.

Among those points, 45 were measured in the years 1990-2010 and are expected to produce immediate results, and 25 new ones will be installed, notably along a profile at latitude 37, which will start produce results after 10 y, and immediately in case of an earthquake, in which case we will contact the TelluS committee and plan a remeasurement mission.

- 2022 : West Peloponnese (Messinia, Magne, Movri) ;
- 2023 : East Peloponnese.

Total : 2×13 k€ including travel and accommodation for 6 people, 3 car rentals and purchase of consumable.

Installation of 2 GNSS permanent stations (2022)
Total : 3 k€ including travel, accommodation and car rental for SB and PE.

3 tectonic/geomorphology missions :

- 2022a : geomorphology - active faults in Messenia-Mani ;
- 2022b : coastal vertical kinematics ;
- 2023 : tectonic geomorphology.

Total : 3×3 k€ including travel, accommodation and 1 car rental for 2 people 10 days.

3 stays in Athens (5 d) to meet the Greek collaborators :

- 2022 : SB + PB
- 2023 : SB + MP
- 2024 : SB + PB + MP

Total : 2×1.7 + 2.1 k€ including tickets, accommodation and car rental.

Stay of SB in Montpellier (2023) : 3 k€ (2 months accommodation).

Invitation of Greek collaborators to Paris :

- 2022 : Haralambos Kranis (10 d) ;
- 2023 : Panagiotis Elias (10 d).

Travel exepenses will be covered by their institutions.
Total : 2×1 k€.

Seminars gathering the different collaborators :

- 2022 : meeting in Paris for collaborators from Paris, Montpellier, Strasbourg and Nice : 1 k€ of transport costs for 10 participants.

— 2023 : organization of a seminar at the Navarino Environmental Observatory (costanavarino.com/environment/navarino-environmental-observatory : located in Pylos, at the center of the area covered by this project) : 5 d including two geological excursions (Messenia/Mani) for 30 p. (travel supported by ther funds), with an estimated cost of 10 k€ (accommodation and car rental), of which half (5 k€) will come from Greek partners.

Total : 1+5 k€.

Participation to the EGU : 3×1 k€ including travel, accommodation and registration fee for SB.

Geochronology (2022) : Contribution to the isotopic datings that will be performed by the CEA : 3.5 k€

Publication fees : $1 + 1 + 2$ k€ (2022/2023/2024)

Total budget asked :

— 2022 : 31.2 k€

— 2023 : 28.7 k€

— 2024 : 5.1 k€ (to be reevaluated in 2022)

Total : 65 k€

Of which :

— Missions : 38 k€ or 58%.

— Collaborations and seminars : 16.5 k€ or 25%.

— Conferences and publications : 7 k€ or 11%.

— Consumable : 3.5 k€ or 6%

Co-financements

6.0.1 National Kapodistrian University of Athens - National Observatory of Athens

Co-funding of a seminar in NEO in 2023 (5 k€).
Journey of P. Elias and H. Kranis to Paris (1 k€).

6.0.2 National Observatory of Athens

The NOA has provided 1 receiver and infrastructure for the installation of a permanent station in Finikouda (Messenia) – 13.5 k€.

6.0.3 ENS

The ENS-PSL will provide 1 receiver for the installation of a permanent station in Messenia (9 k€).

6.0.4 University of Athens

The University of Athens will provide the funds for a Greek student to come and stay et ENS in Paris.

6.0.5 LSCE

The LSCE will contribute to the isotopic dating.