HELLENIC REPUBLIC
National and Kapodistrian University of Athens
EST. 1837

School of Science
Department of Geology and Geoenvironment

From the evolution of seismological instruments to the deployment of dense local networks - Seismic Risk Management and Earthquake Early Warning in the Ionian Islands

Prof. Nicholas Voulgaris, Seismologist, National and Kapodistrian University of Athens

Workshop on Trends in Hardware and Software for monitoring and understanding Earthquake Dynamics
September 28 - October 1, 2022

SEISMOLOGY – HISTORICAL ERA (up to 1900)

Before the development of seismological instruments, information on earthquakes came from historic sources concerning the occurrence of major damaging events.

From the analysis of the distribution of the felt tremor strength and damage caused by a specific earthquake (intensity), it is possible to determine a macroseismic epicenter, depth and magnitude for a historical earthquake.

This information is important for the seismic history of an area. However, the data are of poor quality and scarce, as they only concern major earthquakes which had an impact on inhabited areas and were also documented.

A note written in Chios detailing the effects of the 1389 earthquake in the town of Chios: Code Ottobonianus Graecus n. 2381 (f. 335), Vatican library. (From Kouskouna & Makropoulos, 2004)

INSTRUMENTATION IN SEISMOLOGY – ANALOGUE ERA (1900-1964)

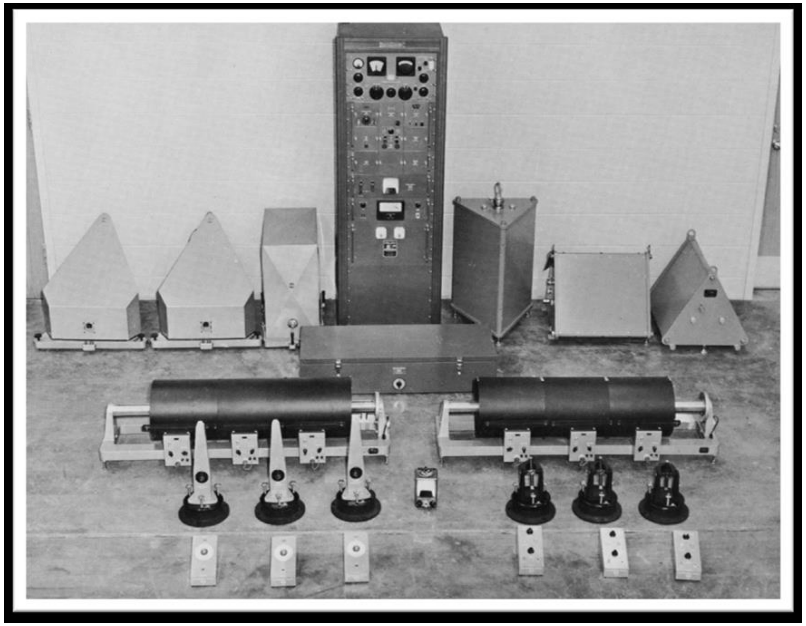
With the development of the first seismic sensors (seismometers) and analog recorders (seismographs) it became possible to actually measure the arrival times and characteristics of different types of seismic waves produced by an earthquake.

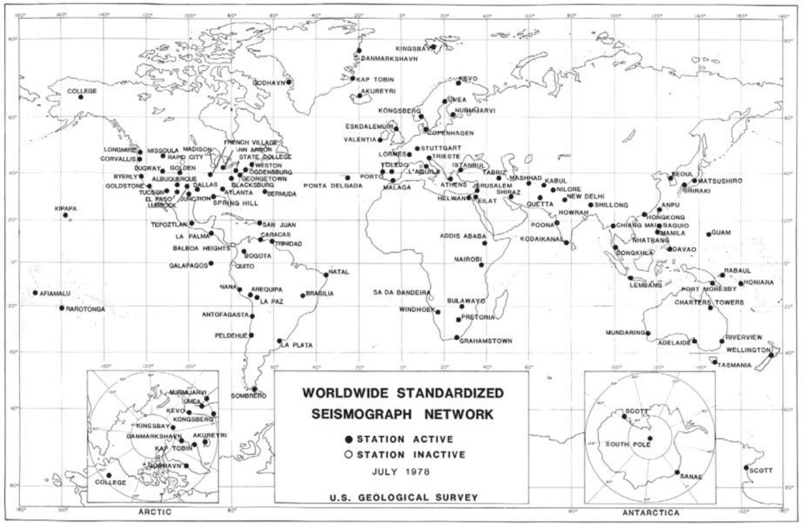
Global seismological projects developed during the Cold War, and particularly the World-Wide Standardized Seismograph Network (WWSSN) that was implemented in the 1960s, enabled seismology to become a truly quantitative science.

However, the first recording instruments were analogue (the seismograms were drawn on paper), and the data analysis was an inefficient and very time-consuming process, even for a small number of well recorded earthquakes.

In many cases, the recordings were made in-situ, and campaigns had to be planned for the collection of data from the field.

Computers were also in early development and data had to be input in the form of punch cards. These factors limited the quantity and quality of the obtained results.



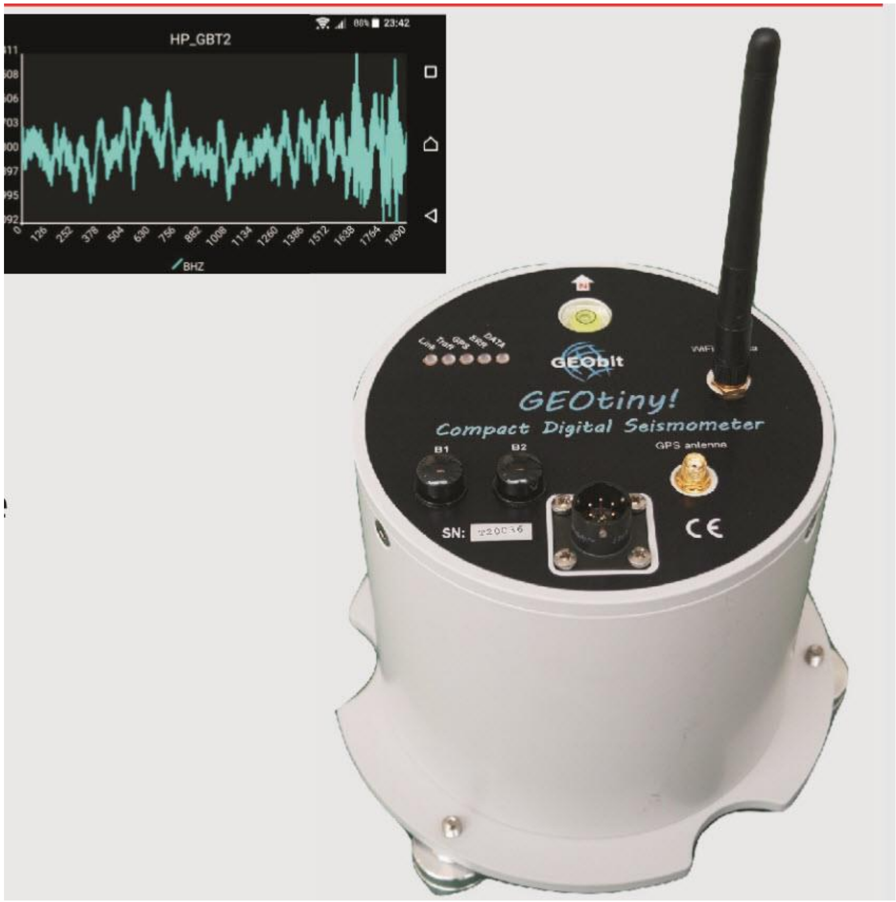


INSTRUMENTATION IN SEISMOLOGY – DIGITAL ERA

The development of the first digital seismographs in the 1970s enabled the immediate analysis of earthquake data with computers. The digitization also made real-time data transfer from the remote stations to the processing center more feasible.

This also permitted the automation of certain procedures. With the development of methods for automatic arrival-time picking, followed by the application of an earthquake location algorithm, it was possible to establish real-time earthquake monitoring.

Spectral analysis was also greatly facilitated, which is crucial for seismic microzonation studies for the determination of the ground response to strong earthquake motion and the assessment of seismic hazard for the mitigation of seismic risk.



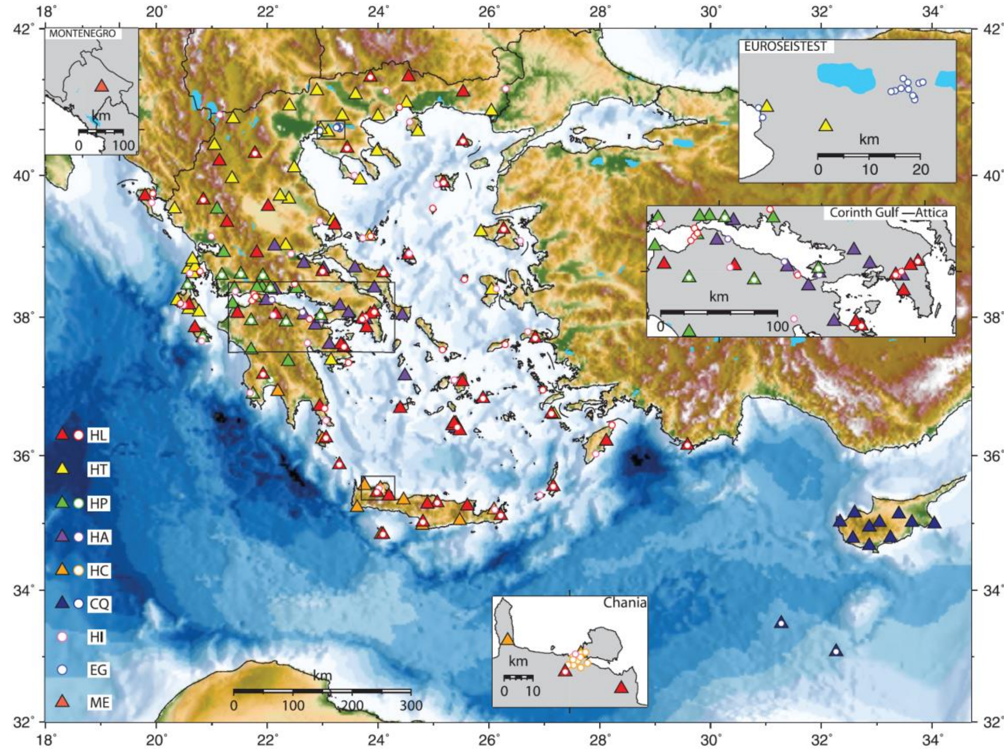
A compact seismometer and accelerometer with integrated digital data-logger (seismograph).

THE HELLENIC UNIFIED SEISMIC NETWORK (HUSN)

In Greece, different seismological agencies operate and maintain their own seismic networks. However, data sharing between institutes was not realized until 2007, when the Hellenic Unified Seismic Network (HUSN) was implemented.

HUSN is a virtual network, comprised of over 200 seismic stations. Real-time data are shared between the partners of HUSN, while archived data are available to the public via the European Integrated Data Archive (EIDA) hosted at the National Observatory of Athens (NOA). As of 2021, the EIDA@NOA node held about 27 TB of data, growing by ~3 TB per year.

The implementation of HUSN has greatly enhanced the capabilities of seismic monitoring in Greece, lowering the detection threshold for earthquakes of smaller magnitude, which permits the detailed analysis of microseismicity.



Map of open and active stations distributed through the NOA data center for the EIDA in October 2020. Stations are color-coded by network according to the legend. (Figure from Evangelidis et al., 2021)

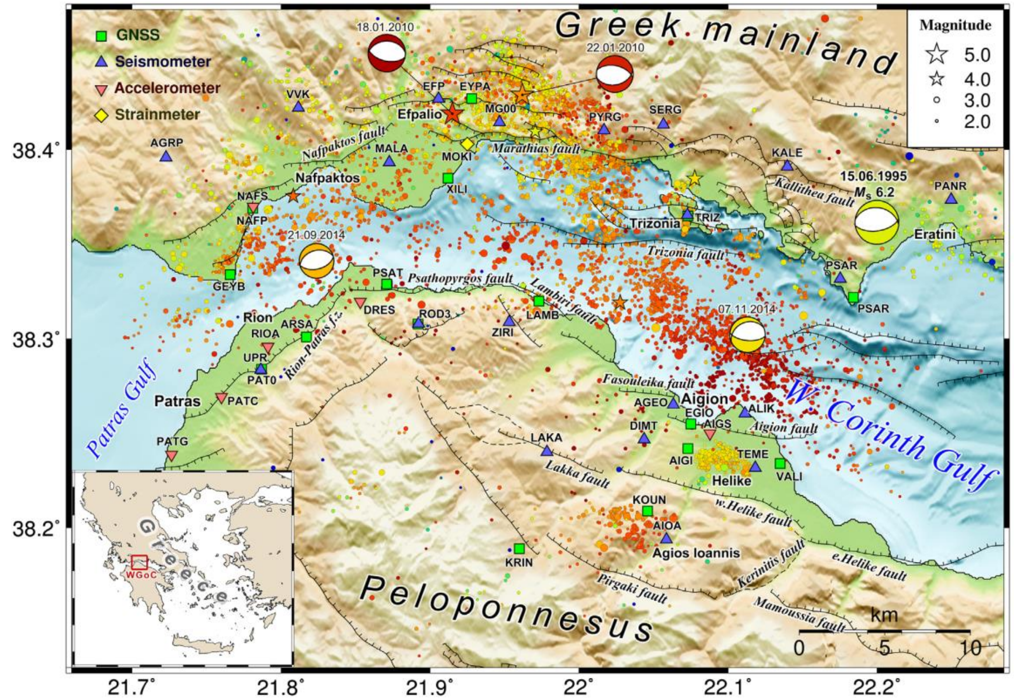
LOCAL SEISMOLOGICAL NETWORKS – THE CORINTH RIFT LABORATORY

The latter capabilities are greatly enhanced with the deployment of a local seismological network, i.e. with many stations installed within a small area.

In Greece, the Western Gulf of Corinth is being monitored since early 2000 by the Corinth Rift Laboratory network (CRLnet).

CRLnet comprises over 80 permanent stations within a 30km x 30km area, equipped with seismometers, accelerometers, Global Navigation Satellite Systems (GNSS), tide-gauges, and strainmeters, enabling the detailed monitoring of the fluctuations of the intense microseismicity and deformation (Kaviris et al., 2021).

Each year, CRLnet detects and locates over 10,000 earthquakes, with the catalogue being complete down to a magnitude of ~1.2.



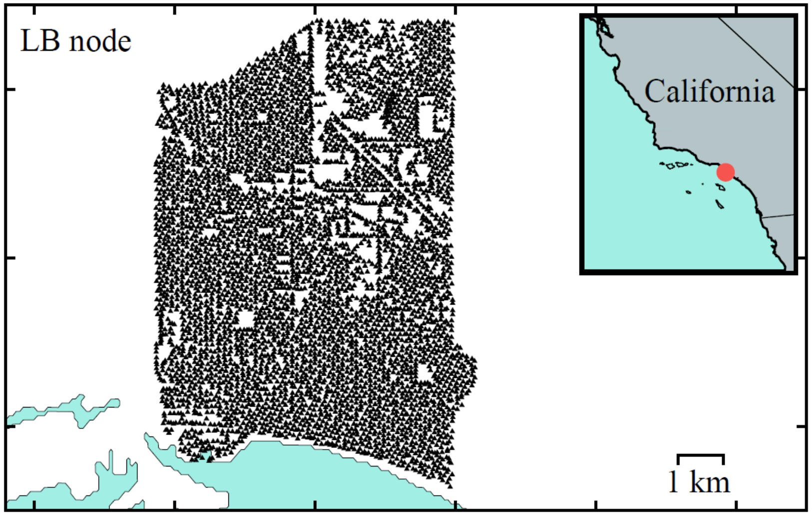
Seismological stations of CRLnet, including seismometers, accelerometers, GNSS stations and a strainmeter. (Figure from Kaviris et al., 2021).

INSTRUMENTATION IN SEISMOLOGY – "EXOTIC" TECHNOLOGIES

Advances in the technology permit the creation of ultra-dense arrays of seismic sensors, providing unprecedented high-resolution data for regional and local earthquake monitoring.

<u>Large-N arrays</u>

- **Nodal seismographs** are relatively cheap, autonomous and easy to install.
- <u>Pros</u>: They enable the implementation of an ultra-dense seismic network at an affordable cost.
- <u>Cons</u>: They are of limited power efficiency (autonomous operation for approx. one month) and data storage capacity, so they are only suitable for temporary networks. They also mostly lack real-data telemetry.
- Applications of nodal arrays include aftershock monitoring, as a part of a rapid response system, to obtain better coverage around rupture zones.

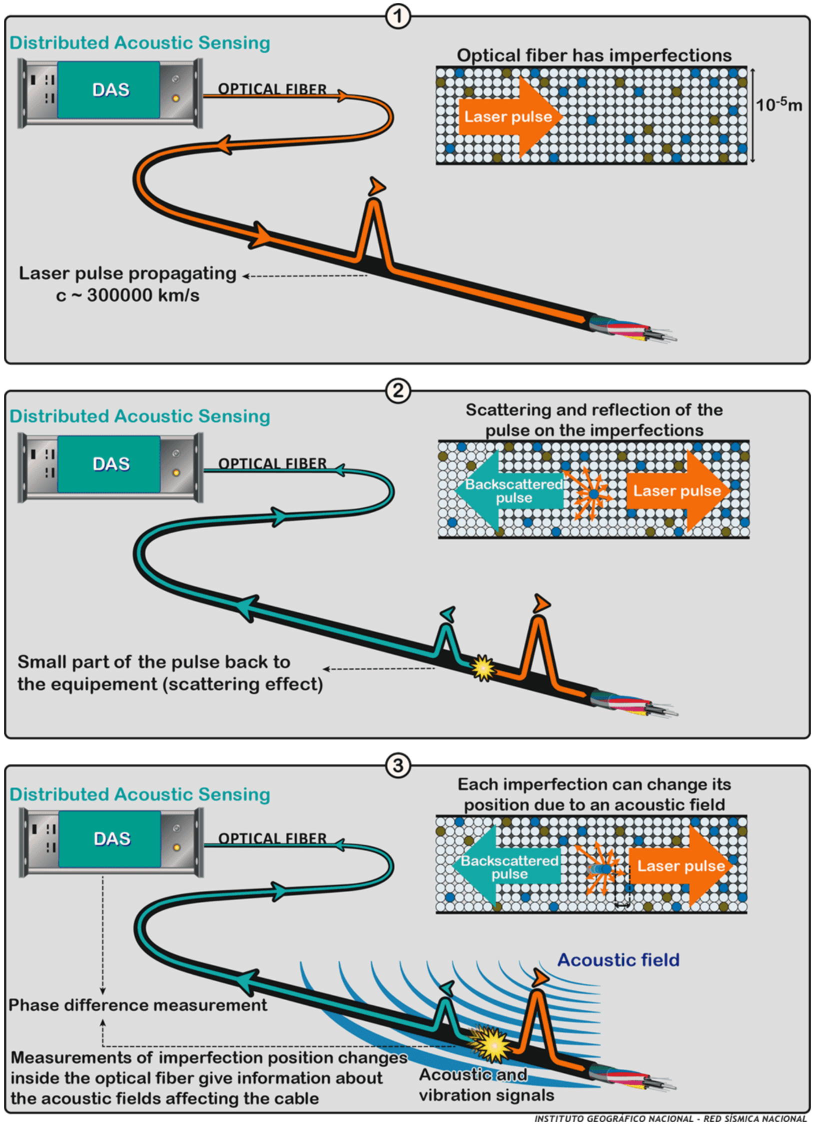


An array of **5200 nodes** installed in Long Beach, California. Note the 1 km scale. (From Li, 2021)

INSTRUMENTATION IN SEISMOLOGY – "EXOTIC" TECHNOLOGIES

Fiber-optic sensing

- A Distributed Acoustic Sensing (**DAS**) monitoring interrogator can convert a standard communications single mode fiber into thousands of extremely sensitive acoustic and vibration sensors with a spacing as small as 1 meter. This is achieved by sending light into the fiber and measuring the backscatter from the inherent impurities in fiberglass (Li, 2021).
- Pros: It creates an ultra-dense array along the optical fiber. The data can be available in real-time. High sampling rate (~KHz).
- Cons: The DAS instrument response and the relation of its measurements (dynamic strain / strain-rate along the fiber) with real ground motion is still a matter of research and experiment. The generated volume of data is immense (~**TB/day**), creating a real challenge for both its storage and processing.



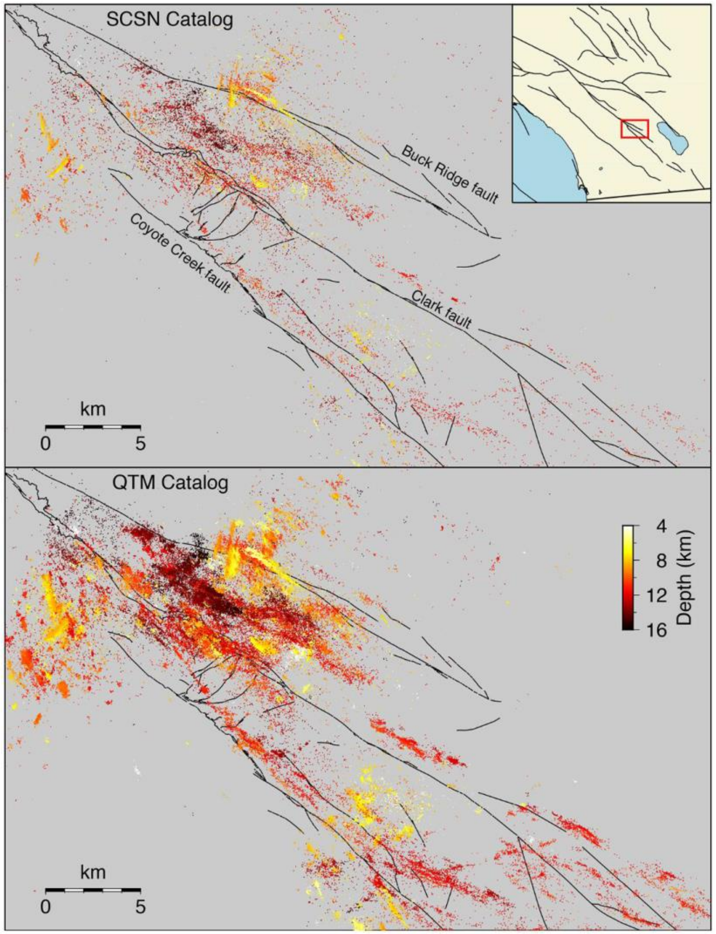
SEISMOLOGICAL ANALYSIS – BIG DATA

The constantly increasing volume of seismological data and the availability of new, exotic technologies, makes manual data processing, in the classic sense, practically impossible.

Traditional automatic P- and S-wave arrival-time picking methods, such as **STA/LTA**, were based on the detection of incoming seismic waves as an abrupt increase in the signal-to-noise ratio of the amplitude or another characteristic function.

More advanced methods, such as the "**template matching**" technique, exploit the similarity between correlated events (with similar source parameters) to detect and pick the P and S arrival-times for a large number of repeating earthquakes, using a small subset of manually analyzed template events. Such methods can lower the detection threshold by about one order of magnitude.

Due to the significant amount of data to be processed, arrays of hundreds GPUs are sometimes employed to reduce the processing time (e.g. Ross et al., 2019).



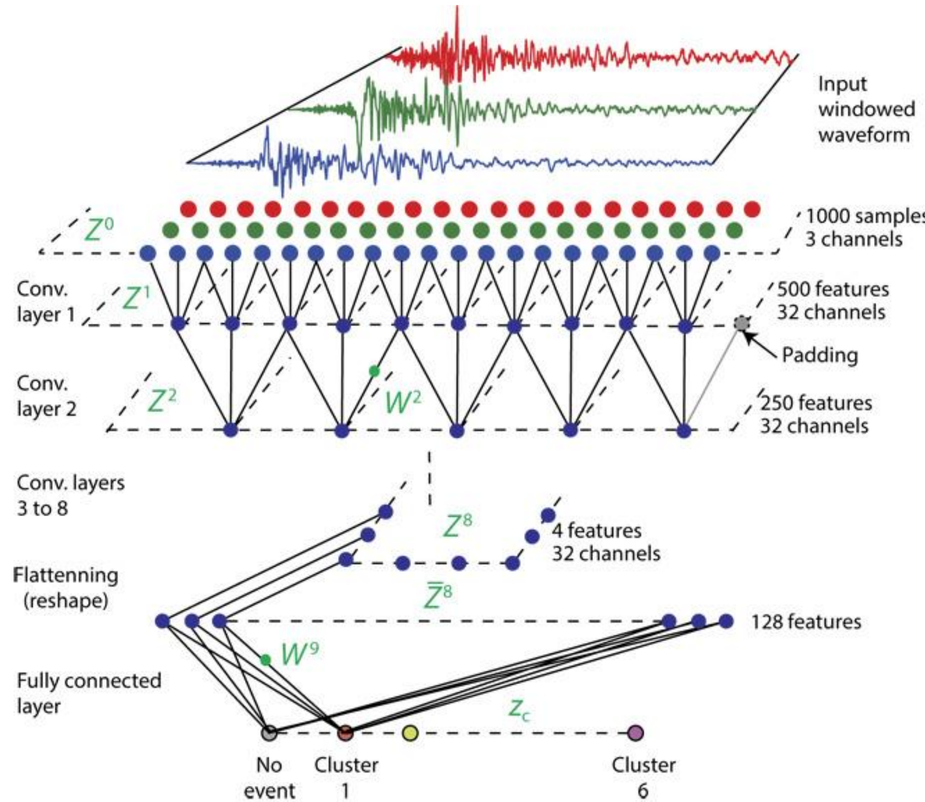
Seismicity of the San Jacinto fault zone (S. California), (top) initial SCSN Catalogue, (bottom) Quake Template Matching Catalogue of **1.81M** events (~tenfold increase). (From Ross et al., 2019)

SEISMOLOGICAL ANALYSIS – BIG DATA

Revolutionary advances in the field of **artificial intelligence** and **deep learning** for **pattern recognition** are also becoming a valuable tool for the automatic analysis of large databases of earthquake data.

The general concept of these methods is the creation of an **artificial neural network** (ANN) that is trained to recognize patterns of different seismic waves at a wide range of epicentral distances and distinguish them from noises.

These techniques can be used to determine the arrival-times of seismic waves, but also recognize and sort signals into categories, such as tectonic earthquakes, different types of volcano-tectonic events and explosions, landslides, anthropogenic noise etc.



Architecture of the ConvNetQuake ANN for earthquake detection. (From Perol et al., 2018)

TELEMACHUS PROJECT

- The act refers to the creation of an innovative system for the management of seismic risk in the Ionian Islands, an area characterized as the most seismically and tectonically active in Greece and one of the most active ones worldwide.
- The intense seismicity of this area is mainly attributed to the presence of the Cephalonia transform fault, as evidenced by the historical and the recent, instrumentally recorded seismicity, including large earthquakes with widespread effects on people, the natural environment, buildings and infrastructure of the Ionian Islands.
- The act includes:

  A. The preparation of various thematic maps (geological, geotechnical, neotectonic, morphotectonic, seismicity, seismic risk, secondary/accompanying geodynamic effects) and measurements of soil response and vulnerability of buildings, networks and infrastructures.

  B. The development of an innovative system for risk assessment and the support in defining the data exchange interfaces between the involved bodies, as well as facilitating their coordination, real-time data processing, standardization of information assessment procedures, decision making, action monitoring and recording, the automation of event archiving and reporting, the development of an SMS information system and the development of operational planning in a digital environment and Geographic Information Systems (GIS).

TELEMACHUS PROJECT

- The act also includes:

  C. The preparation/organization of operational plans and the pilot implementation of combined preparedness exercises, which are addressed to all involved institutional stakeholders at the local level and aim to familiarize those responsible with procedures and rational seismic risk management actions.

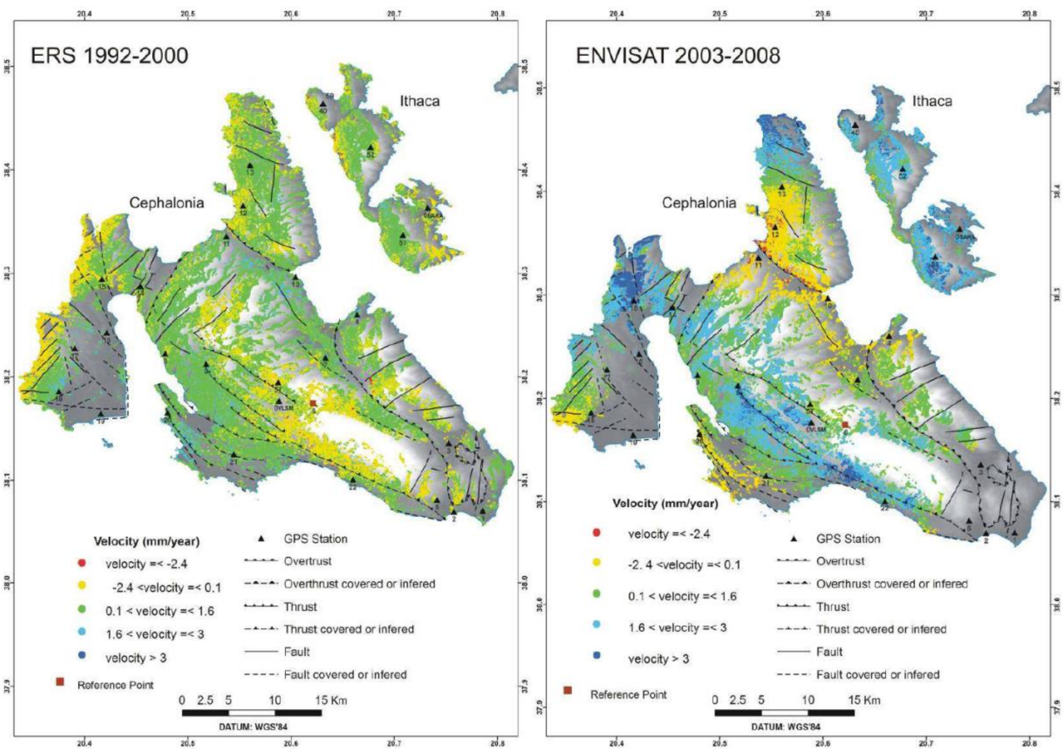
  The project foresees information-education actions and awareness raising which is one of the main tools for consolidating the products of the project and the capitalization of its results on a long-term basis.

  In particular, the act includes the creation and production of special informational material, training and preparation of involved bodies, design of special media communication actions, information and training of special groups of the population, as well as information and training with a specific target for tourism industry.

- It is a holistic approach to natural / seismic risk management. In all interventions, e.g. drawing up special Action and Emergency Plans, carrying out information campaigns and awareness raising, special care is taken to account for persons with disabilities.

TELEMACHUS PROJECT - DEFORMATION

- Surface deformation was measured with techniques such as Permanent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR), Small BAseline Subset (SBAS) and other hybrid methods.
- The aim was to monitor ground surface deformation caused by (1) major seismic events with magnitude M>5.2 that occurred since 1992, and (2) non-seismic deformation that may be due to failure of geological formations including landslides, subsidence and other related movements.



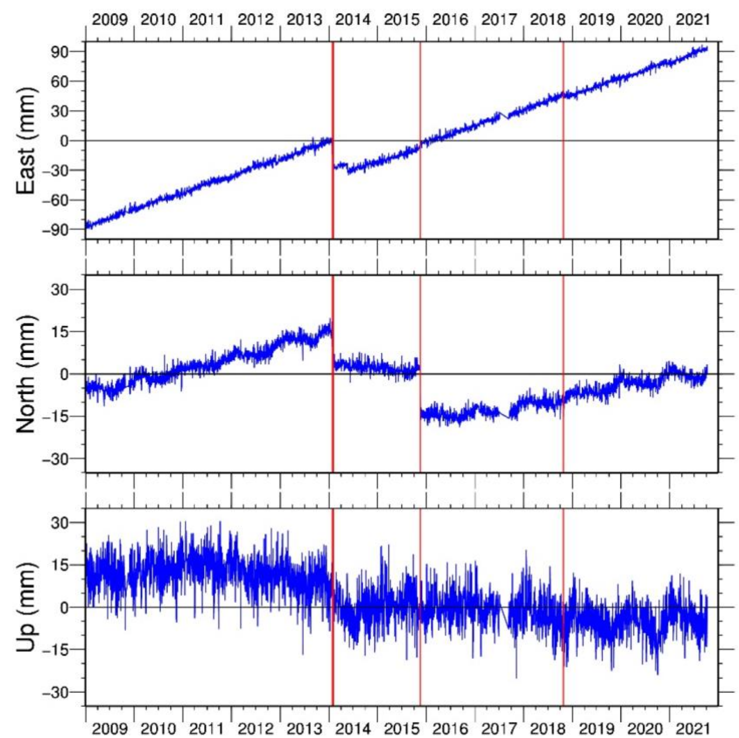
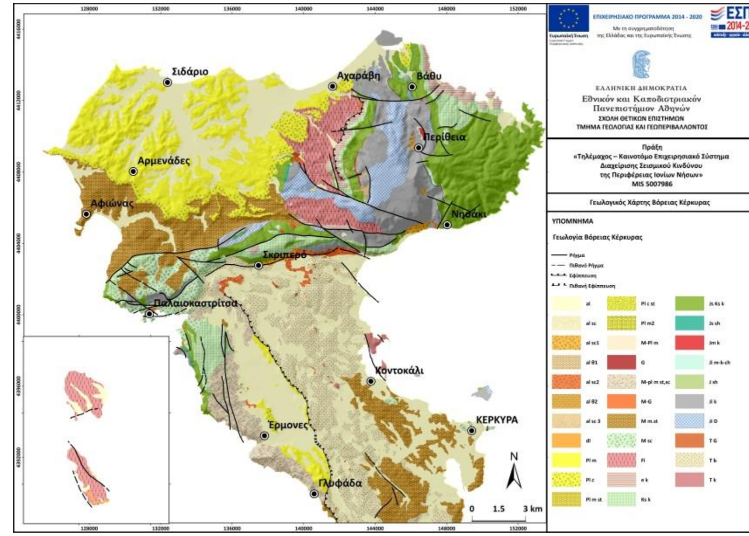
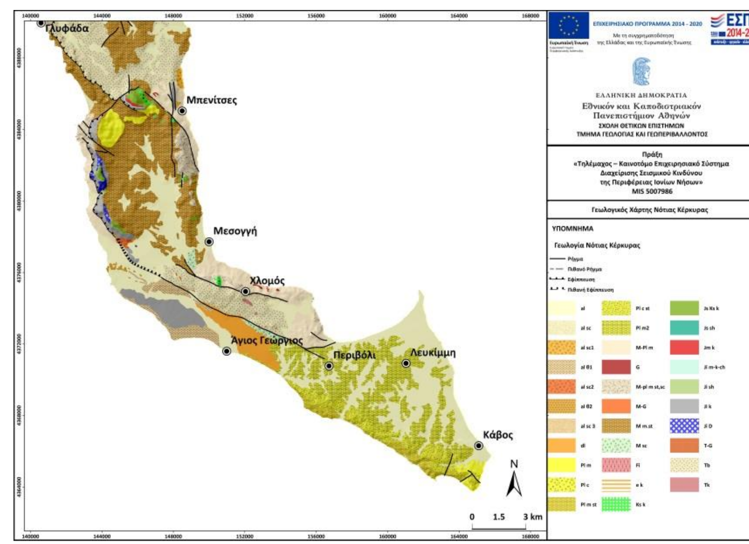


Figure on the right from Sakkas et al. (2022)

TELEMACHUS PROJECT – GEOLOGICAL MAPPING

- Detailed mapping of the geological formations of the Ionian Islands.
- Recording of their geometric characteristics.
- Separation of lithological units based mainly on their physical characteristics and mechanical behavior.
- Identification of fault zones and faults, which develop in Ionian Islands, with particular emphasis on the residential areas and their broader areas.
- Identification and mapping of discontinuities of the rock formations i.e. direction, slope, size, density, chasms, filling materials, etc.
- Microtectonic observations, measurements and processing from the study of discontinuities with an emphasis on those likely to be active due to a seismic event.
- Input and processing of all generated data in a Geographical Information Systems (GIS) environment and creation of a geological map for each area of interest.



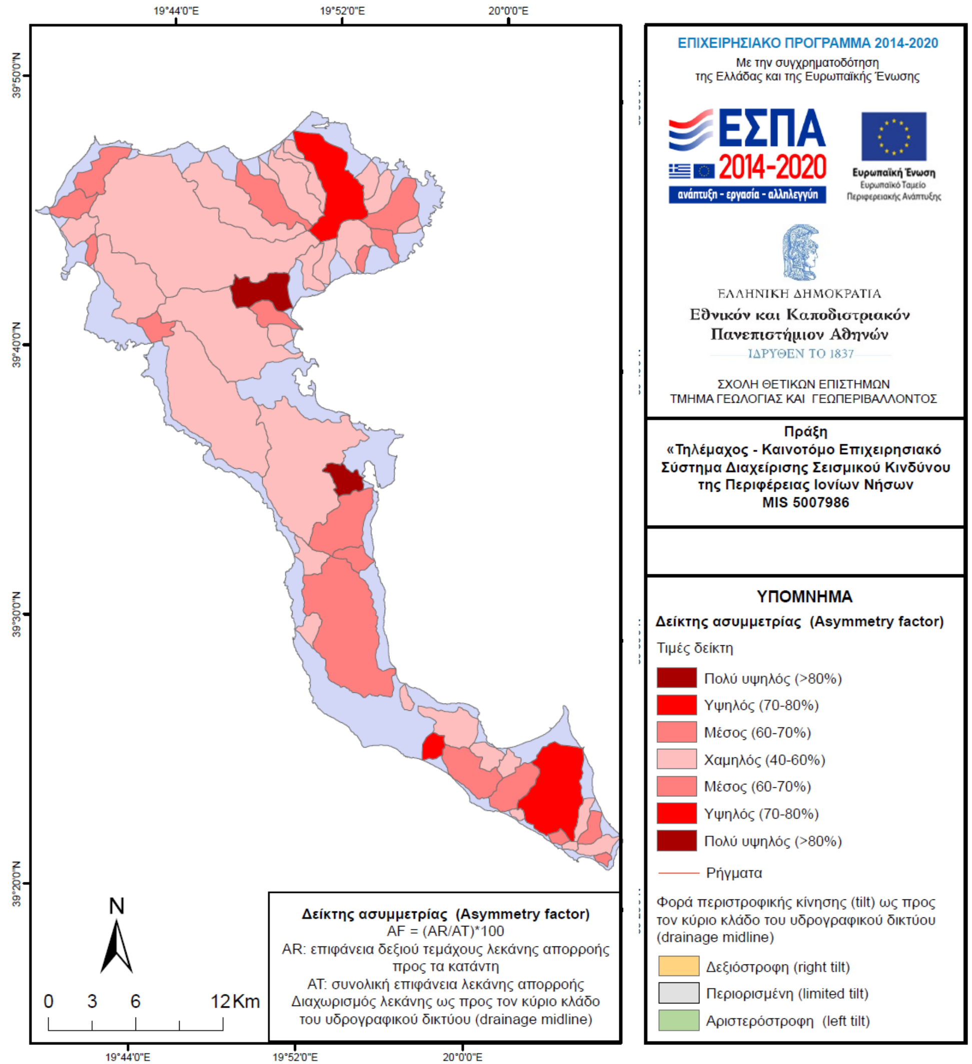


TELEMACHUS PROJECT – MORPHOTECTONIC MAPPING

- Neotectonic and morphotectonic maps contribute to the delineation of areas that present more or less intense seismic activity than those that appear inactive and are relatively safe.

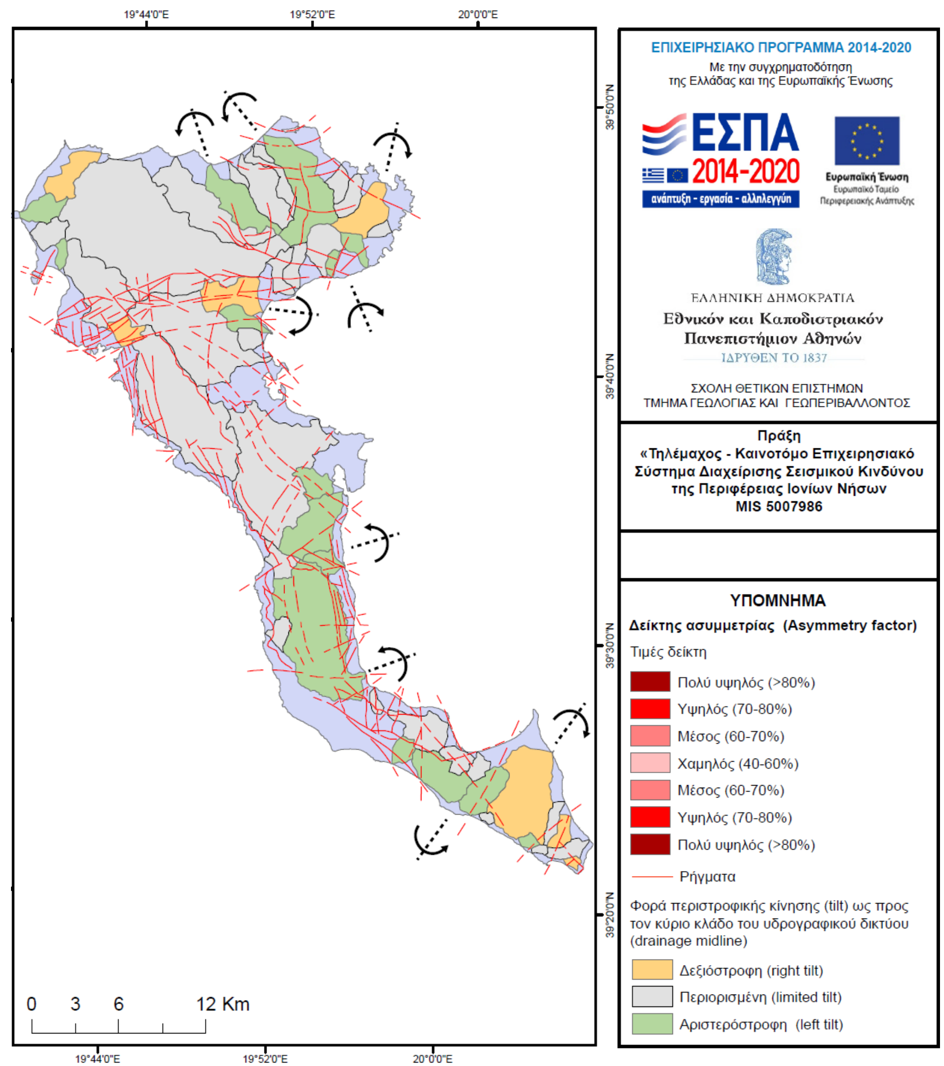
- They also define areas prone to the occurrence of accompanying geodynamic phenomena, such as landslides, subsidence, landslides, liquefaction, seismic gravity waves (tsunamis).

- From this study, the most stable areas for urban reconstruction emerge, as well as for the creation of new settlements or complexes, for the expansion and upgrading of existing ones and to avoid the creation of critical infrastructure in seismically dangerous areas.



TELEMACHUS PROJECT – MORPHOTECTONIC MAPPING

- Neotectonic and morphotectonic maps contribute to the delineation of areas that present more or less intense seismic activity than those that appear inactive and are relatively safe.
- They also define areas prone to the occurrence of accompanying geodynamic phenomena, such as landslides, subsidence, landslides, liquefaction, seismic gravity waves (tsunamis).
- From this study, the most stable areas for urban reconstruction emerge, as well as for the creation of new settlements or complexes, for the expansion and upgrading of existing ones and to avoid the creation of critical infrastructure in seismically dangerous areas.

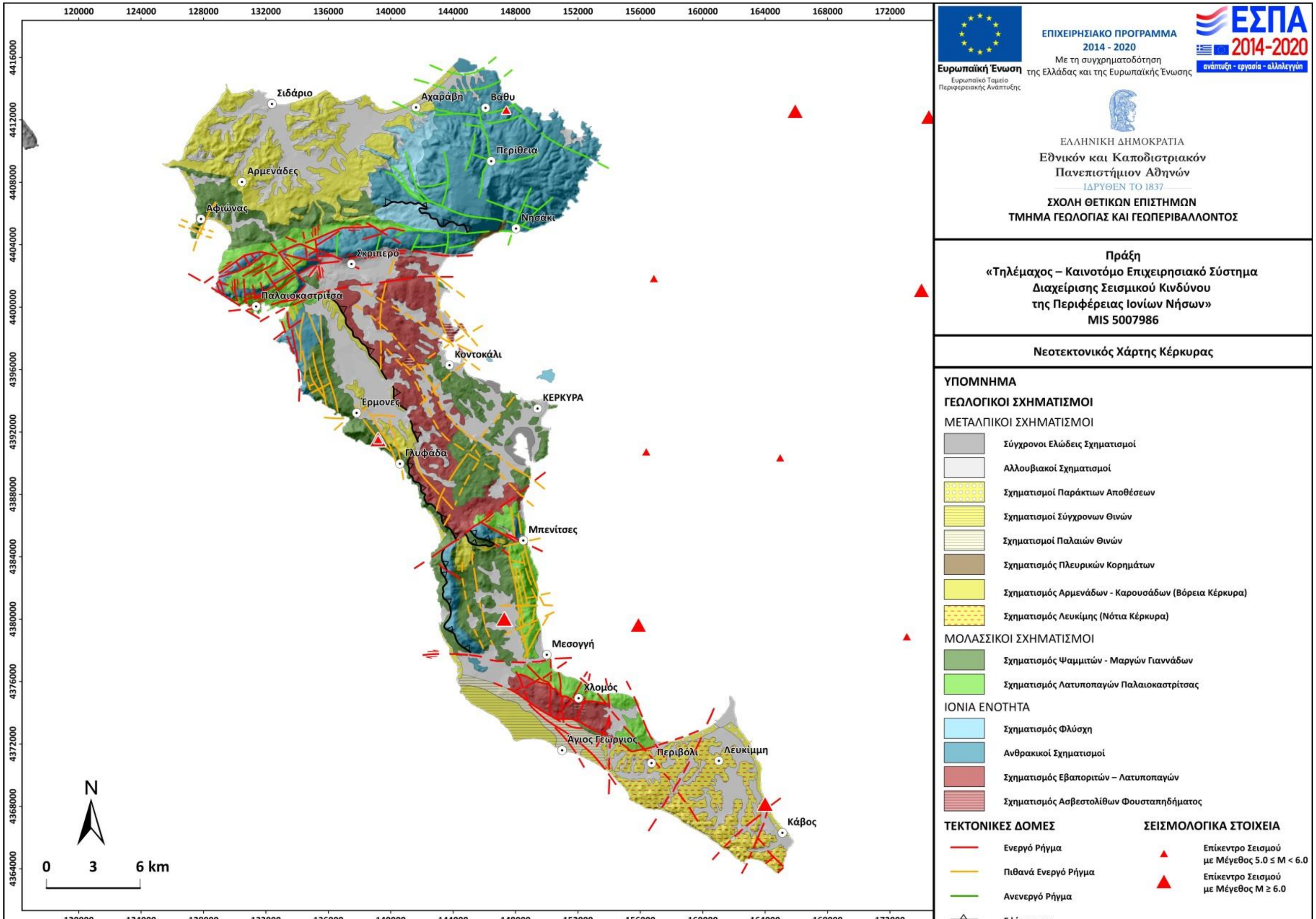


HELLENIC REPUBLIC
National and Kapodistrian University of Athens
EST. 1837

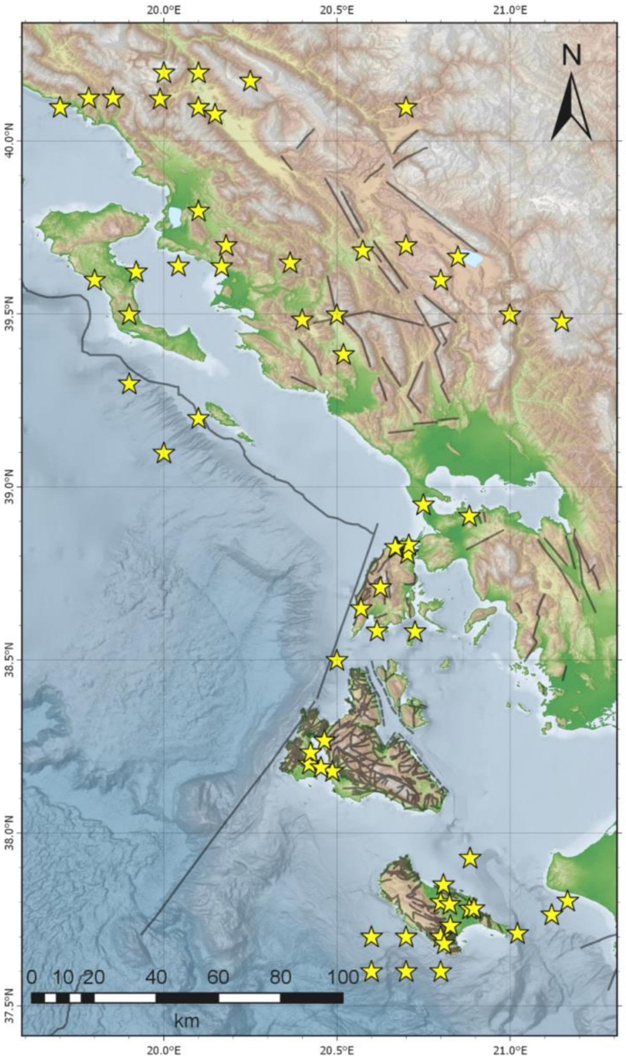
School of Science
Department of Geology and Geoenvironment

Corfu Summer Institute
Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece

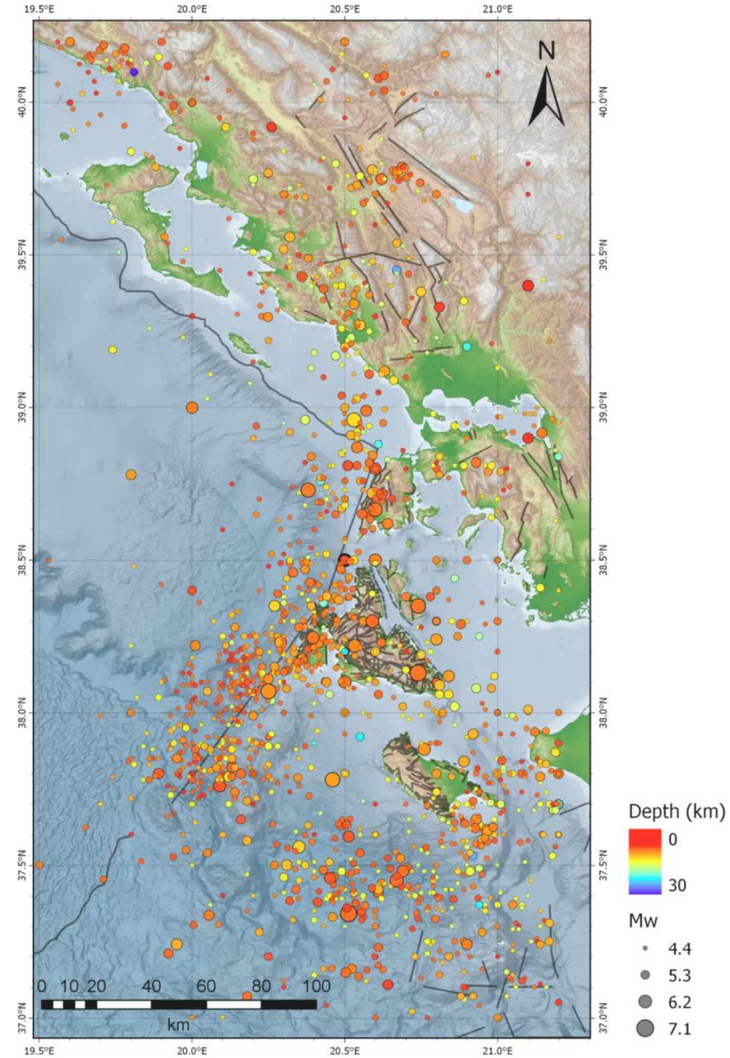
TELEMACHUS PROJECT – NEOTECTONIC MAPPING



TELEMACHUS PROJECT - SEISMICITY

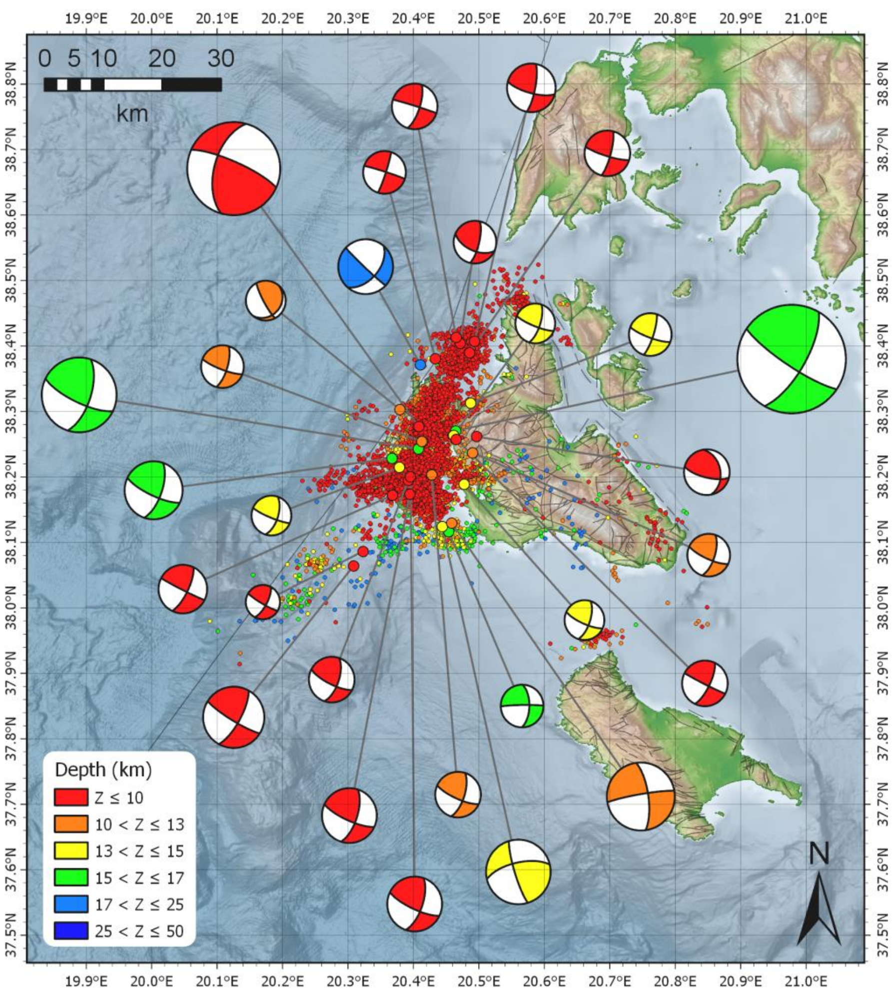


Historical Seismicity (358-1898)

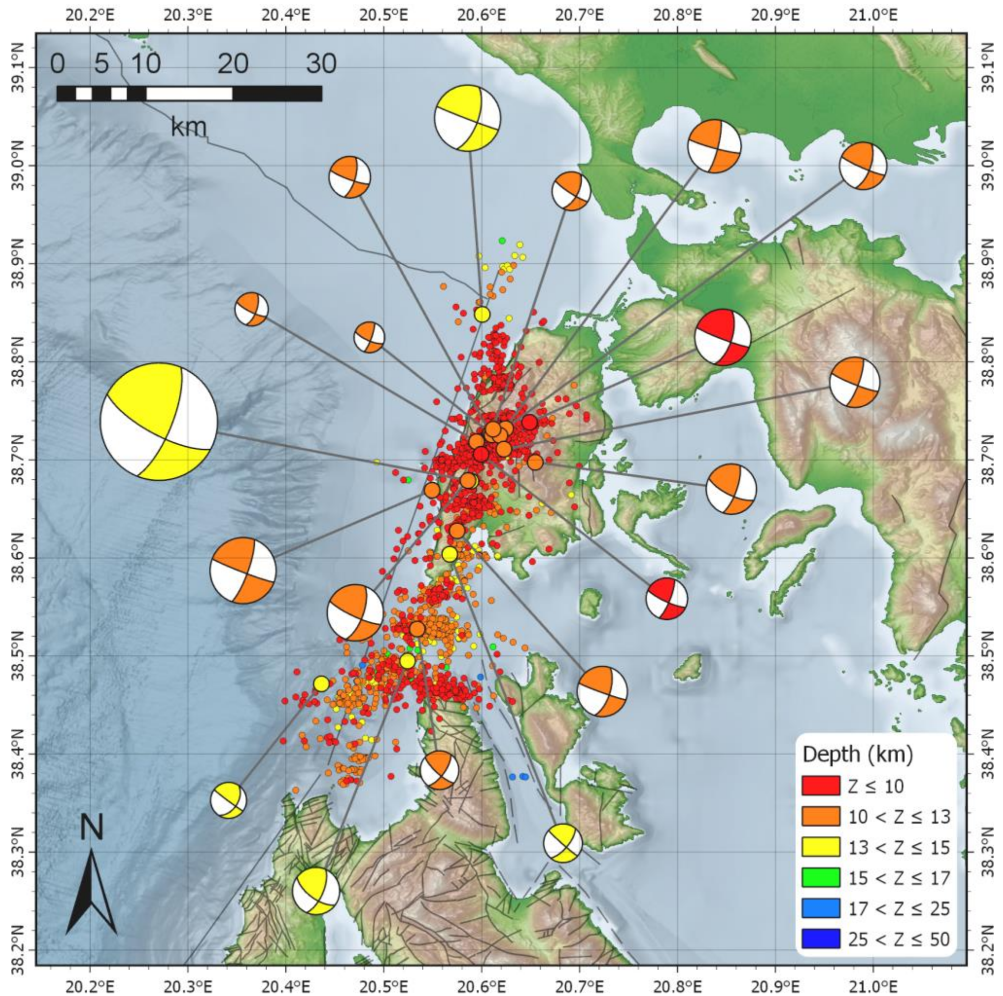


Instrumental Seismicity (1900-2018, $M_w \geq 4.1$)

TELEMACHUS PROJECT – SEISMICITY

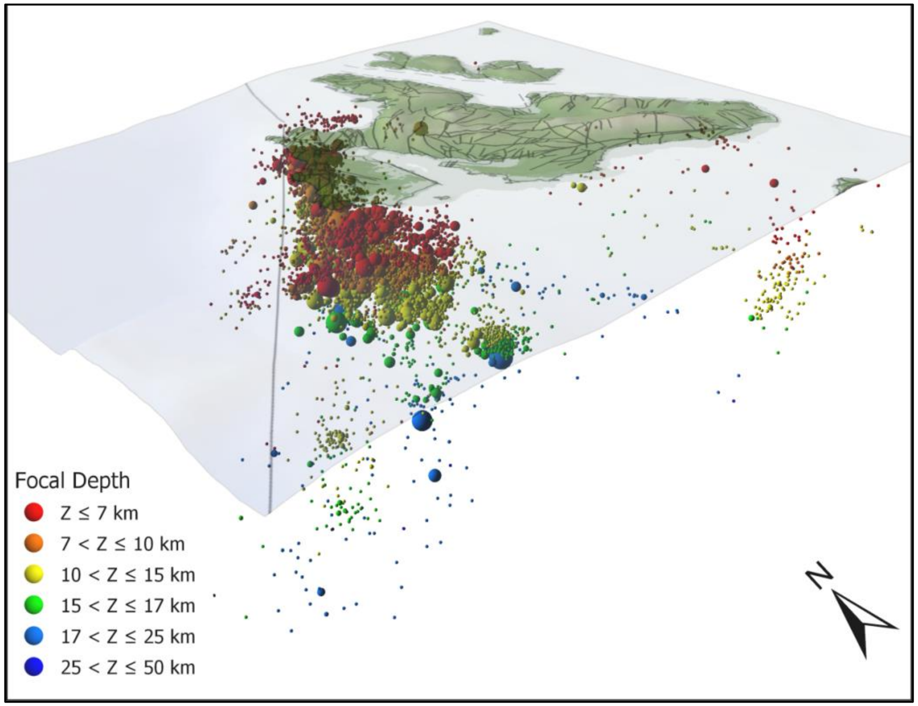


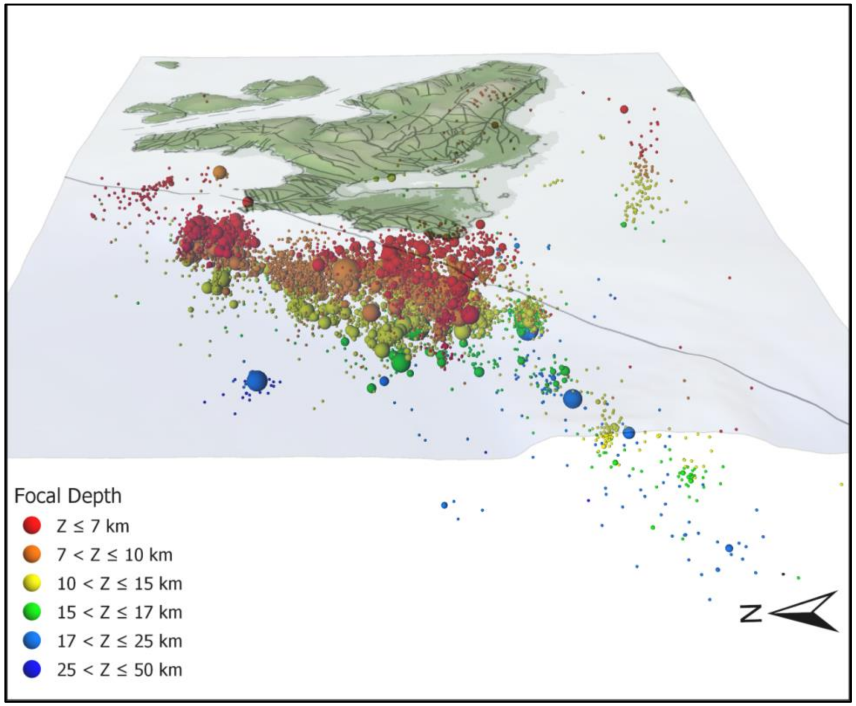
Relocated epicenters of the
2014 Cephalonia aftershock sequence



Relocated epicenters of the
2015 Lefkada aftershock sequence

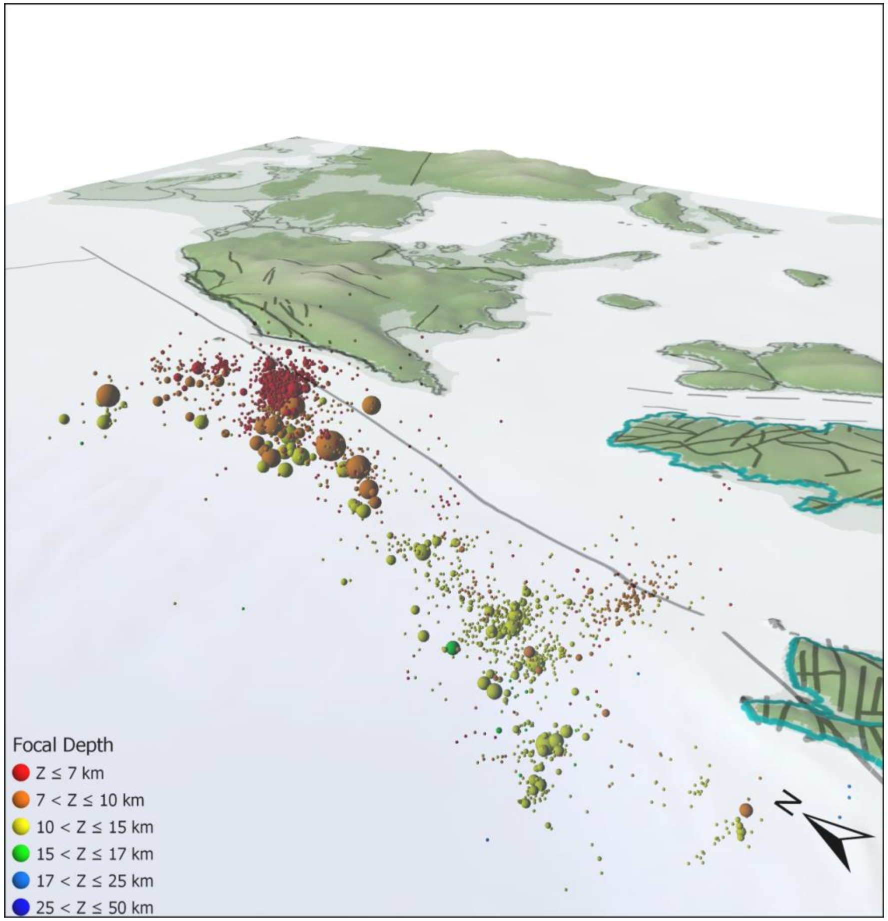
TELEMACHUS PROJECT – SEISMICITY

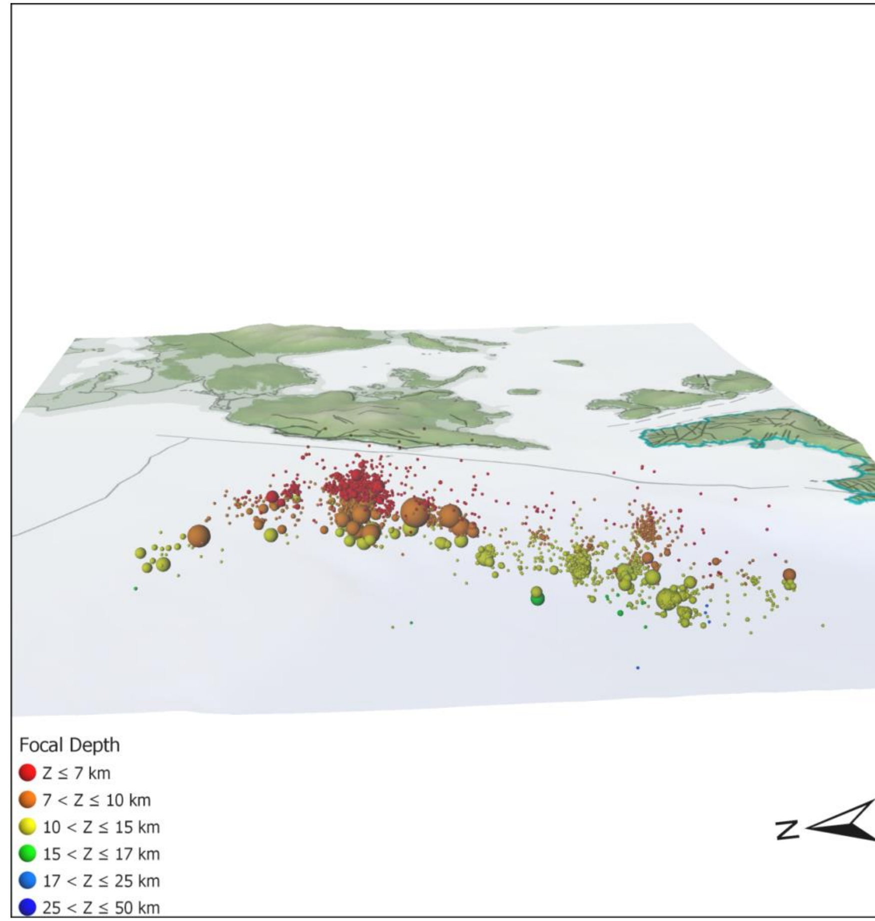




3D view of the 2014 Cephalonia aftershock sequence hypocenters

TELEMACHUS PROJECT – SEISMICITY





3D view of the 2015 Lefkada aftershock sequence hypocenters

TELEMACHUS PROJECT – SECONDARY GEODYNAMIC EFFECTS (e.g. LANDSLIDES)

Assessment of the risks of liquefaction, landslides and the occurrence of seismic gravity waves (tsunamis) in the Ionian Islands.

Liquefaction risk assessment includes:

(1) Recording of places where liquefaction phenomena have occurred in the past, and historically vulnerable areas, creating a history of liquefaction phenomena and analyzing the main factors that have influenced the manifestation of these phenomena.

(2) Geological and geotechnical identification of vulnerable areas.

(3) Application of liquidation risk assessment method in a Geographical Information Systems (GIS) environment.

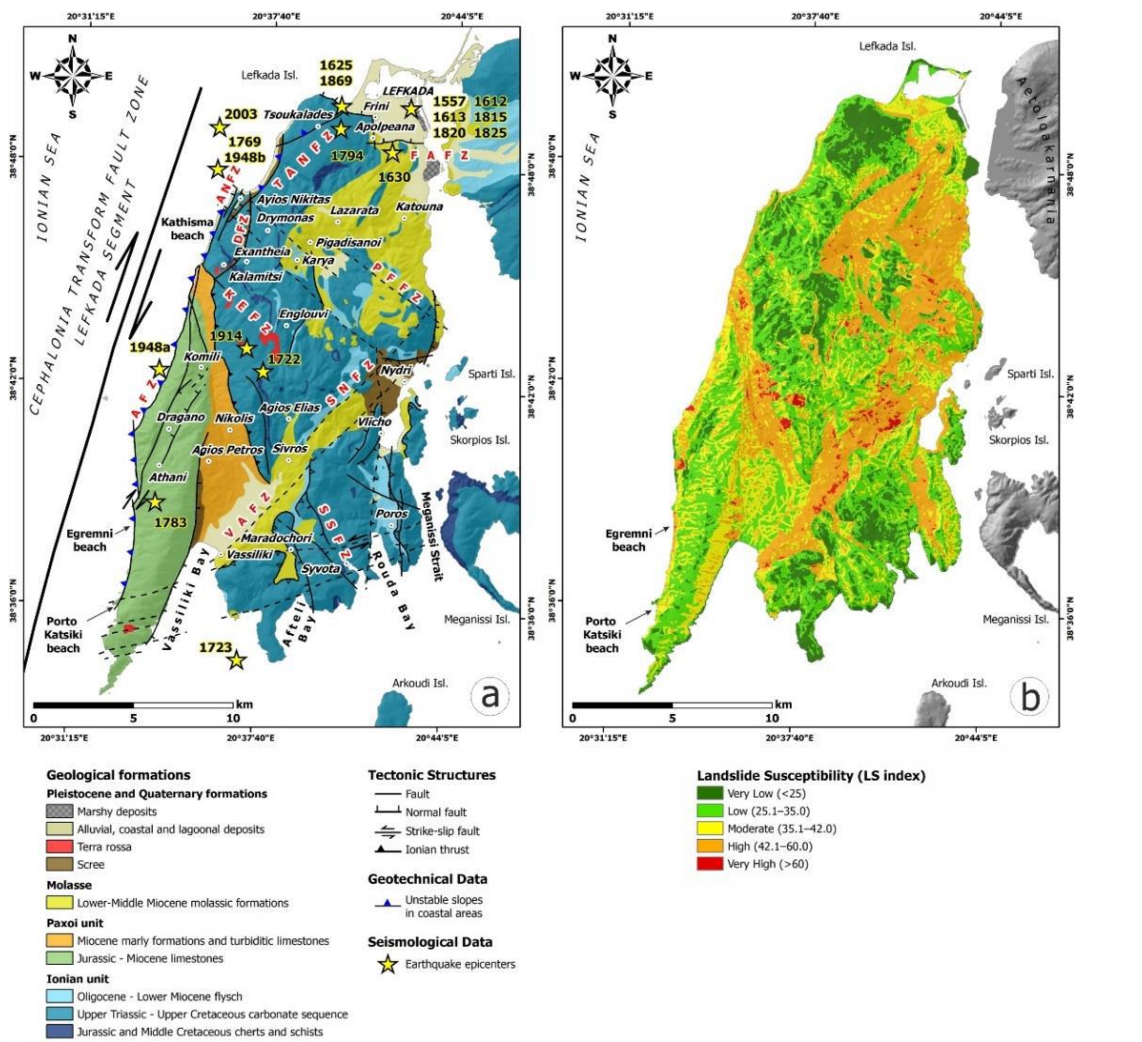


Figure from Mavroulis et al. (2022)

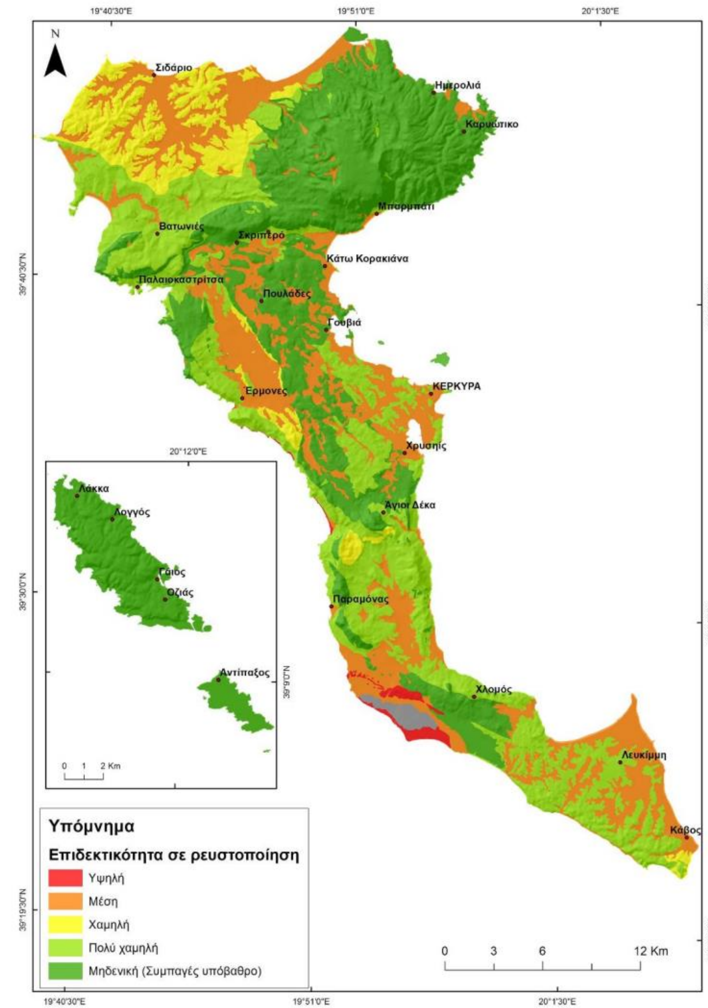
TELEMACHUS PROJECT – SECONDARY GEODYNAMIC EFFECTS (e.g. LANDSLIDES)

The assessment of the landslide risk in the Ionian Islands includes:

(1) Analysis of failure history of geological formations on slopes and historically vulnerable areas, compilation of historical failure list of geological formations on slopes.

(2) Geological and geotechnical identification of vulnerable areas.

(3) Application of landslide susceptibility zoning and in particular the Analytical Hierarchical Process method with the addition of the Weighted Linear Combination method in the context of Multicriteria Analysis in a Geographic Information Systems (GIS) environment. This method has been successfully applied in corresponding environments to calculate the distribution of Landslide Susceptibility Index (LSI) values.



Map of landslide risk in Corfu, Paxos and Antipaxos. Red areas show the highest risk while green areas show the lowest.

TELEMACHUS PROJECT – GEOTECHNICAL MAPPING

Τηλέμαχος – Καινοτόμο Επιχειρησιακό Σύστημα Διαχείρισης Σεισμικού Κινδύνου της Περιφέρειας Ιονίων Νήσων

ΠΕ 1.6. Μετρήσεις Απόκρισης Εδαφών και Κατάταξη Εδαφών κατά ΝΕΑΚ

Π 1.6. Γεωτεχνικοί Χάρτες

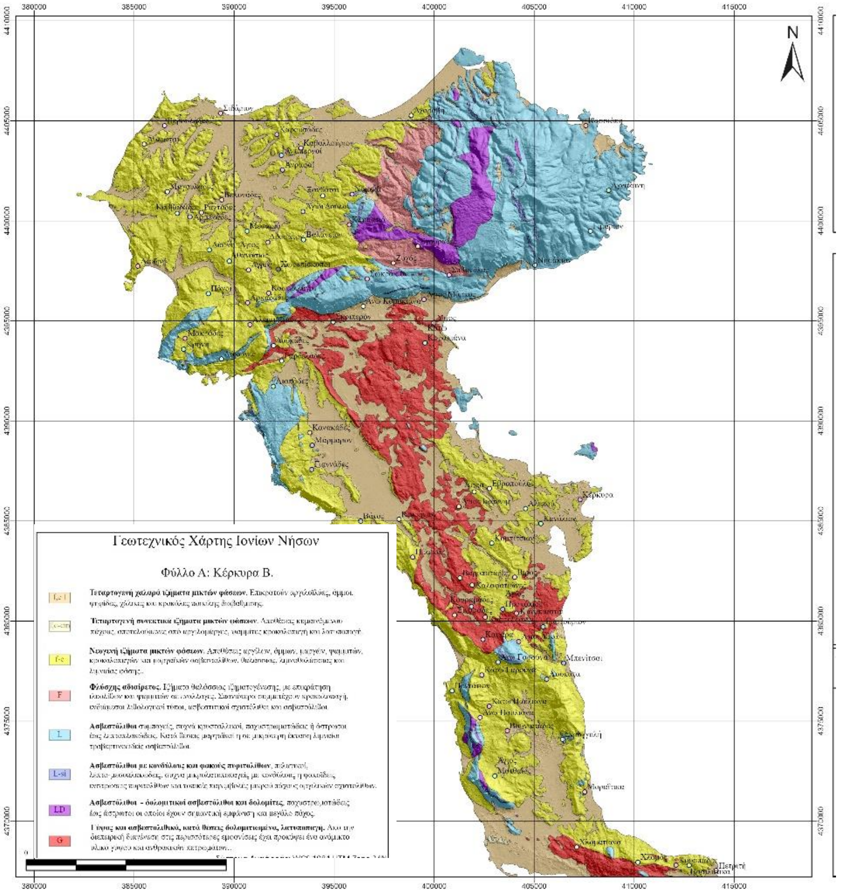
Ερευνητική Ομάδα: Βούλγαρης Νικόλαος, Αλεξόπουλος Ιωάννης, Βασιλάκης Εμμανουήλ, Σακκάς Βασίλειος, Δίλαλος Σπυρίδων, Φίλης Χρήστος, Κονσολάκη Αλίκη, Πετράς Αθανάσιος, Γιαννόπουλος Ιωάννης

Classification of soils according to the New Greek Anti-Seismic Regulation (NEAK) and based on already published recent scientific data and updated scientific results.

This includes:

(1) Collection of existing geological data based on geological maps, various studies, doctoral theses, diploma theses, scientific publications, etc. and categorization of soils according to the New Greek Anti-Seismic Regulation (NEAK).

(2) Correlation with macroseismic data and iso-seismic maps



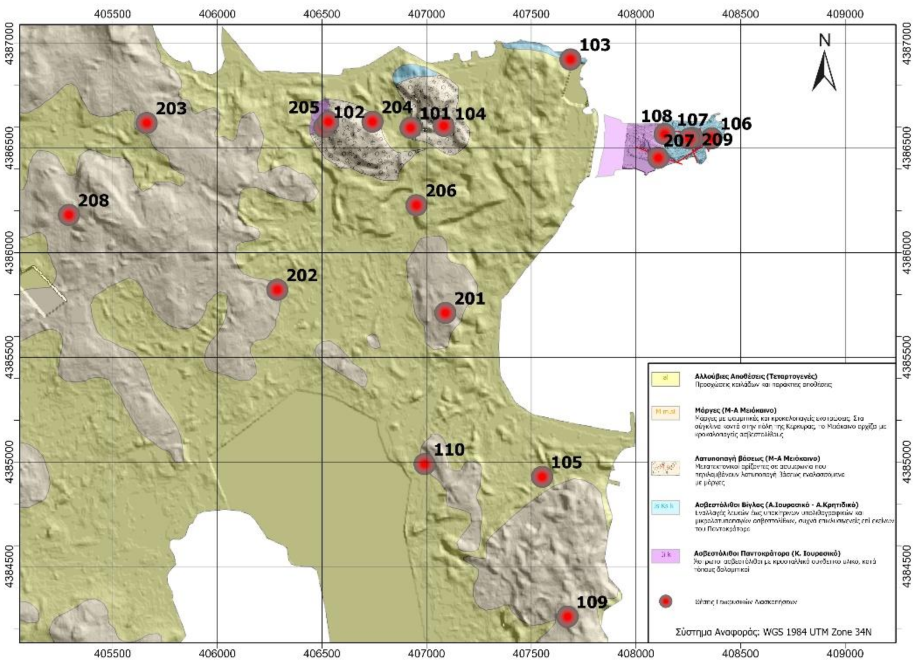
HELLENIC REPUBLIC
National and Kapodistrian University of Athens
EST. 1837

School of Science
Department of Geology and Geoenvironment

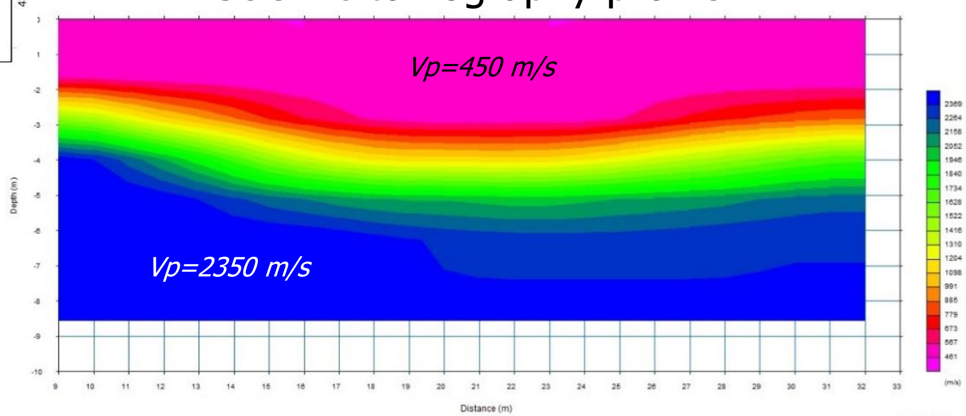
Corfu Summer Institute
Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece

TELEMACHUS PROJECT – GEOTECHNICAL MAPPING

In-situ geophysical measurements (Vp, Vs) for the determination of the elastic moduli of the geological subsurface formations



Seismic tomography profile



Pantokratora Limestones (Ji k)							
Location	Vp (m/s)	Vs30 (m/s)	ρ (kg/m³)	Poisson ratio	E (GPa)	K (GPa)	μ (GPa)
102	800/2.400 (3,0m)	1.050	2.650	0,38	8,07	13,07	2,92
205	800/2.600 (2,5m)	700	2.650	0,46	3,79	16,94	1,30
207	450/1.100 (2,5m)	420	2.540	0,41	1,27	2,74	0,45

TELEMACHUS PROJECT – SEISMIC HAZARD

The seismic hazard assessment includes:

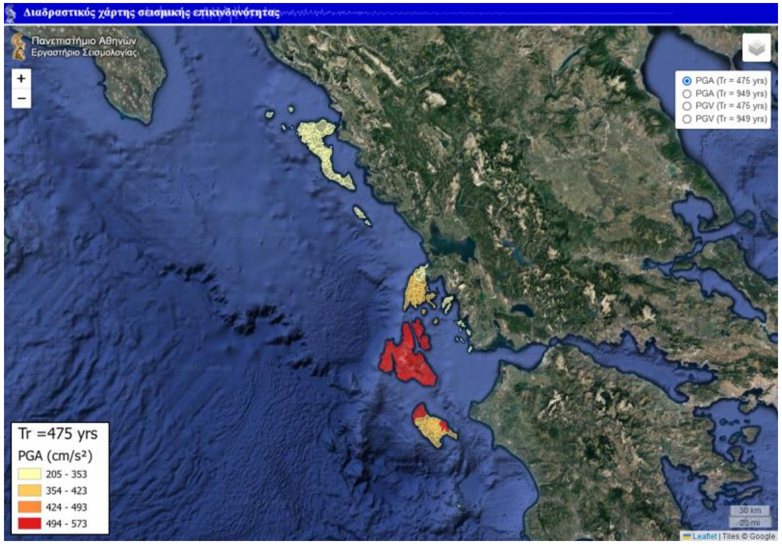
(1) Utilization of seismological data and various probabilistic and deterministic analysis methodologies for the construction of seismic hazard maps in terms of various parameters (displacement, velocity, acceleration, Arias intensity, etc.).

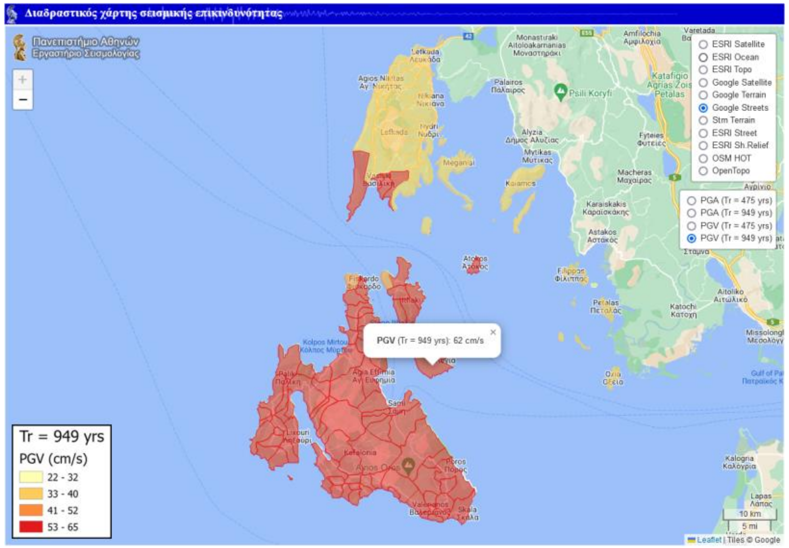
(2) Calculation of the seismic hazard due to specific known active faults.

(3) Probabilistic spectra.

(4) Comparison with NEAK data and, on a case-by-case basis, proposals for re-adjustment of existing values.

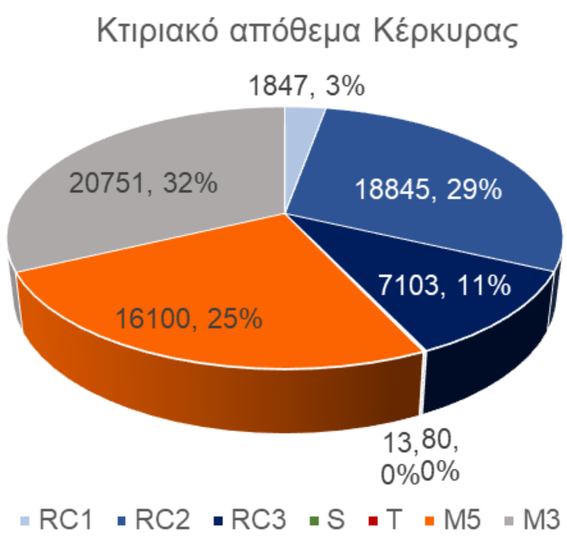
(5) Construction of interactive seismic hazard maps (figures on the right).

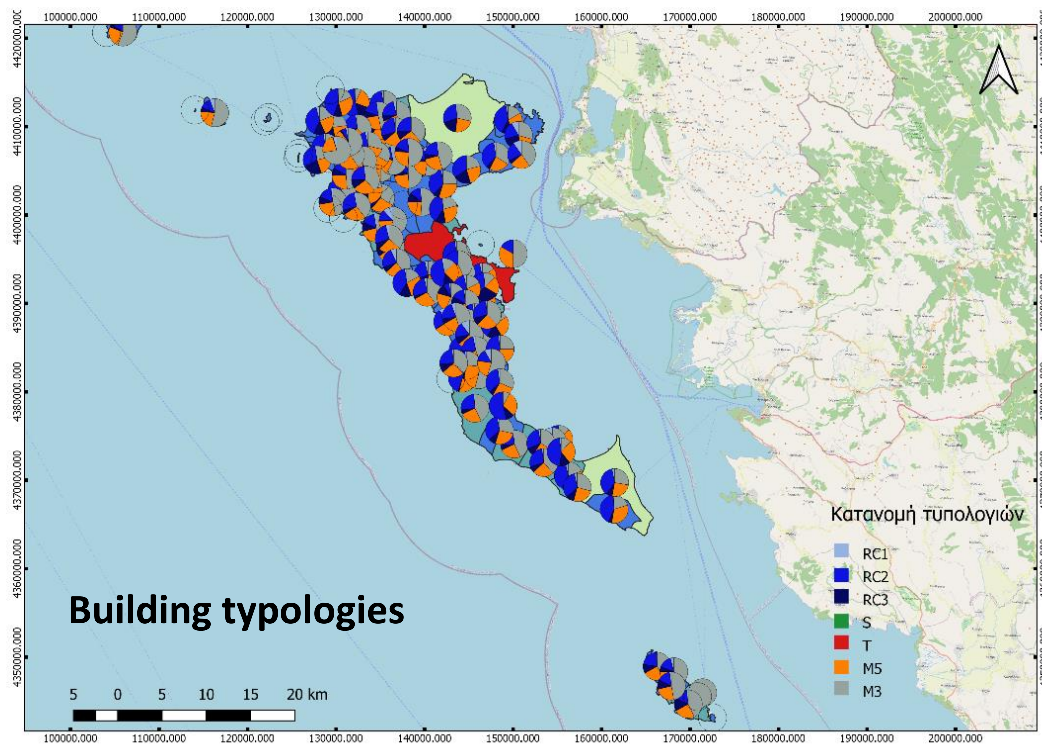




TELEMACHUS PROJECT – VULNERABILITY (BUILDING STOCK)

- Determination of the behavior of buildings during strong seismic vibrations and assessment of their vulnerability in order to strengthen them for their effective anti-seismic reinforcement and protection, and possibly consider and update of the anti-seismic regulation.
- With the construction of urban fabric vulnerability maps, the most vulnerable areas within the residential units of the Ionian Islands were identified, which is important information for the immediate response of those involved in the management of a seismic disaster.

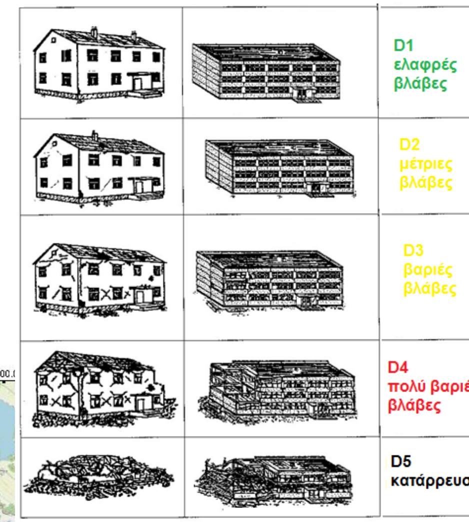


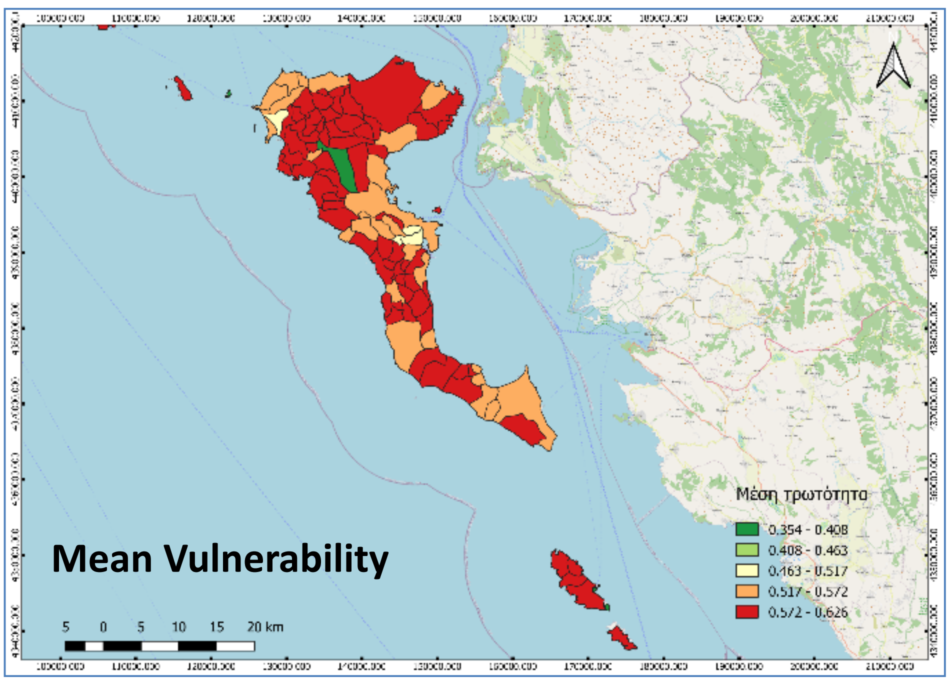


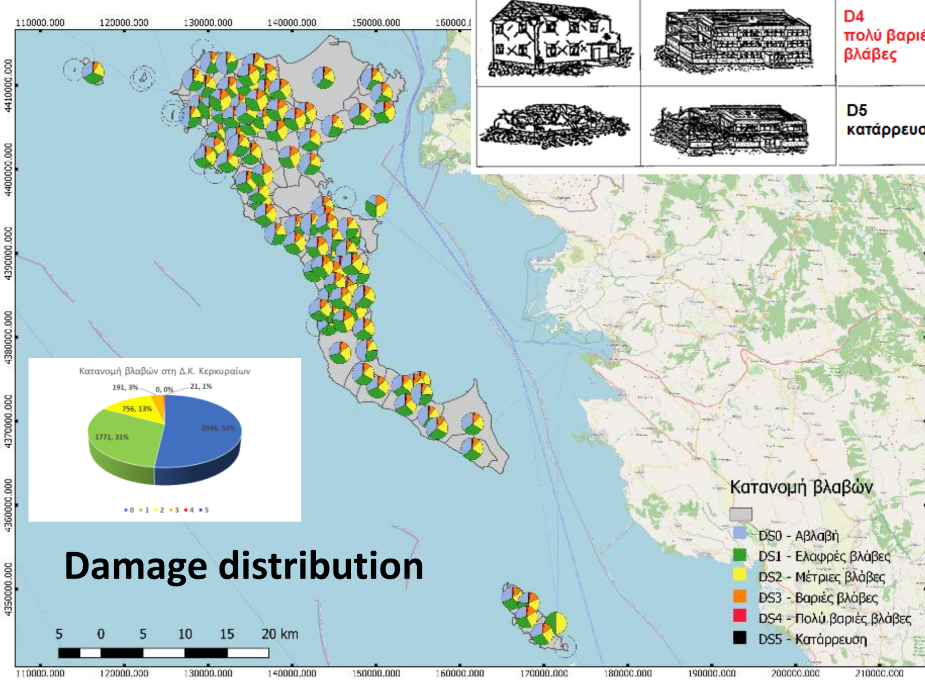
TELEMACHUS PROJECT – VULNERABILITY AND SEISMIC RISK

- Seismic Risk (R) is the convolution between Seismic Hazard (H), Exposure (E) of the assets and Vulnerability (V).
- In the presented example for Corfu Island, showing the distribution of expected damage per local community, it is observed that for almost all the communities the greater percentage of the building stock remains unharmed for constant hazard <240cm/s², despite the average high vulnerability of the island's buildings.

$$R = H \times E \times V$$







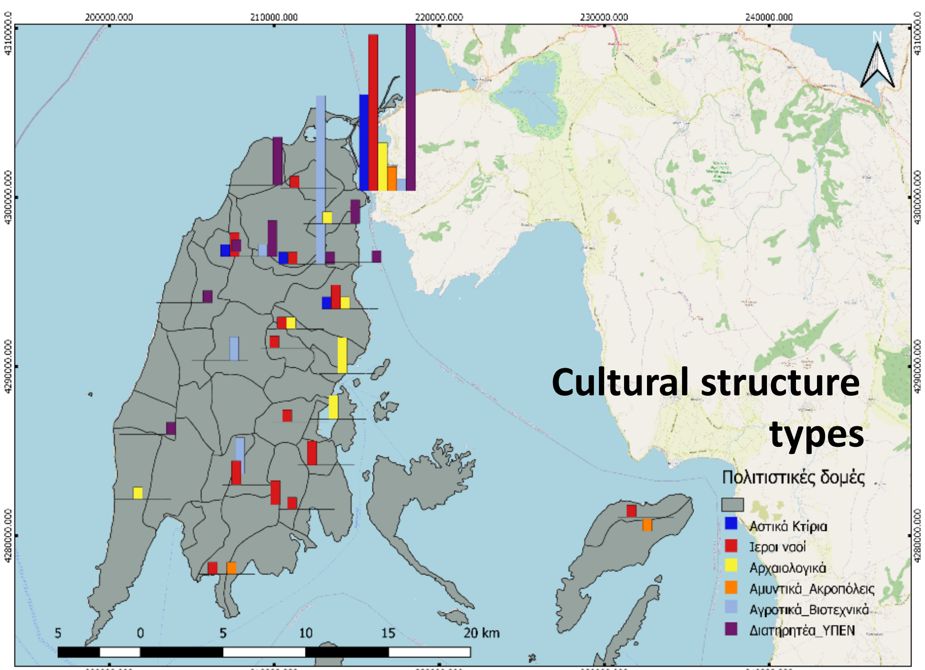
TELEMACHUS PROJECT – SEISMIC RISK (MONUMENTS)

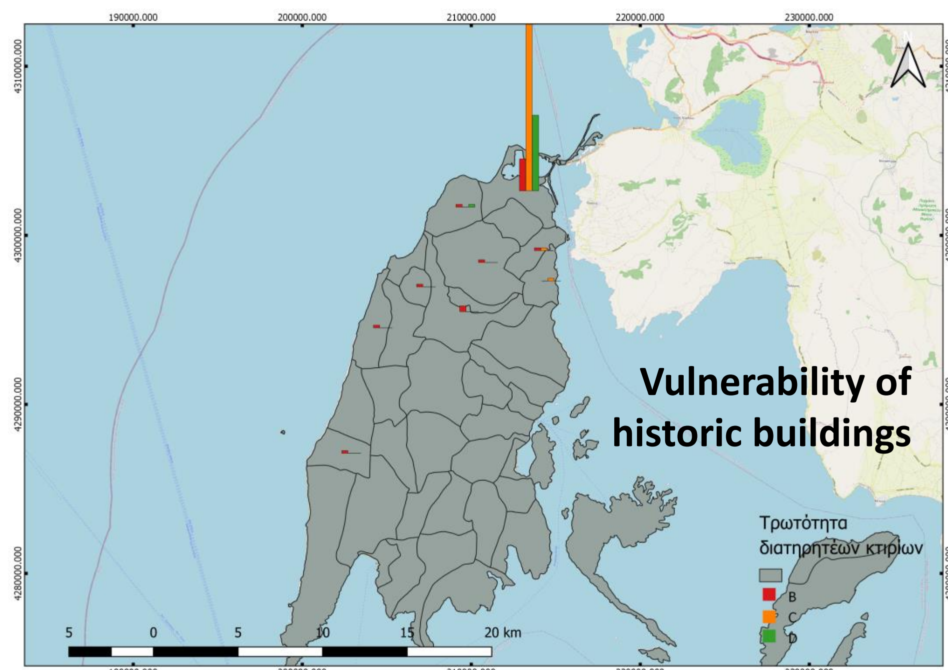
The cultural structures were registered and their vulnerability was assessed. The following was carried out:

(1) Identification of seismically vulnerable structures including traditional settlements, historic (preserved) buildings as well as historical and monumental structures.

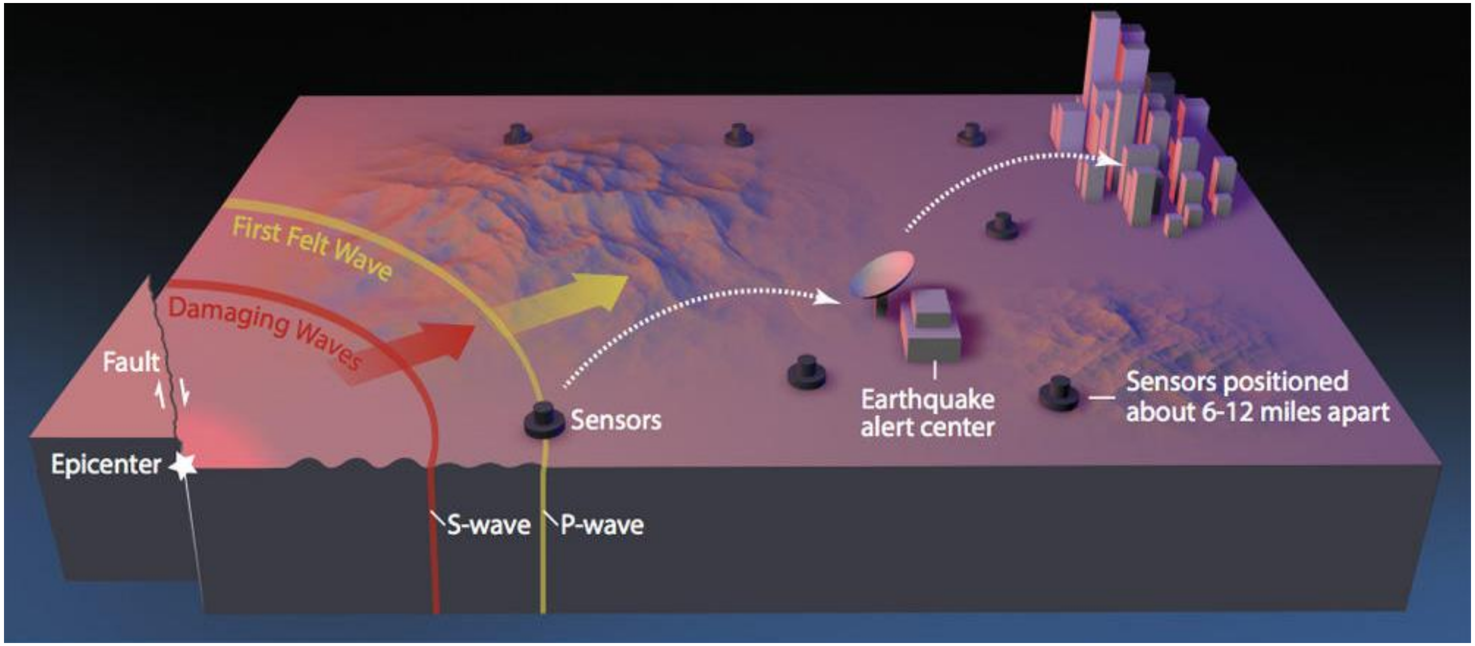
(2) Calculation of average vulnerability for these structures.

In the example below, the spatial distribution of different types of cultural structures (left) and the vulnerability of historic buildings (right) per community in Lefkada Island is presented.





EARTHQUAKE EARLY WARNING - CONCEPT



- The concept of Earthquake Early Warning (EEW) is to provide alerts of impending strong ground motion, caused by significant earthquakes, before it arrives to target sites of interest.

- It is based on the rapid extraction of important information from the early seismic pulse of the faster, but weaker, P-waves, at stations in the vicinity of the epicenter.

- Seismic wave data from remote seismological stations which arrive at the main acquisition server need to be processed in real-time to produce an alert as soon as a solution of high likelihood is established.

- The time window of the first alert depends on the epicentral distance of a target site, the availability of a dense network of stations in the vicinity of the epicenter and the latency caused by waveform data transfer and processing.

EARTHQUAKE EARLY WARNING - CONCEPT

The figure shows an example of a real-time alert generated using the PRESTo (PRobabilistic and Evolutionary early warning SysTem) EEW software for an event that occurred in the Western Gulf of Corinth.

The first solution was available only 6 sec after the origin time, allowing for a 4 sec window before the S-waves arrival at the city of Patras, at an epicentral distance of 30 km.

One of the difficulties with EEW is the correct estimation of the earthquake magnitude from the peak displacement of the first pulses of seismic waves that arrive at the stations near the epicenter. For very strong earthquakes, the recorded amplitudes may saturate at close distances, which can lead to underestimation of magnitude.

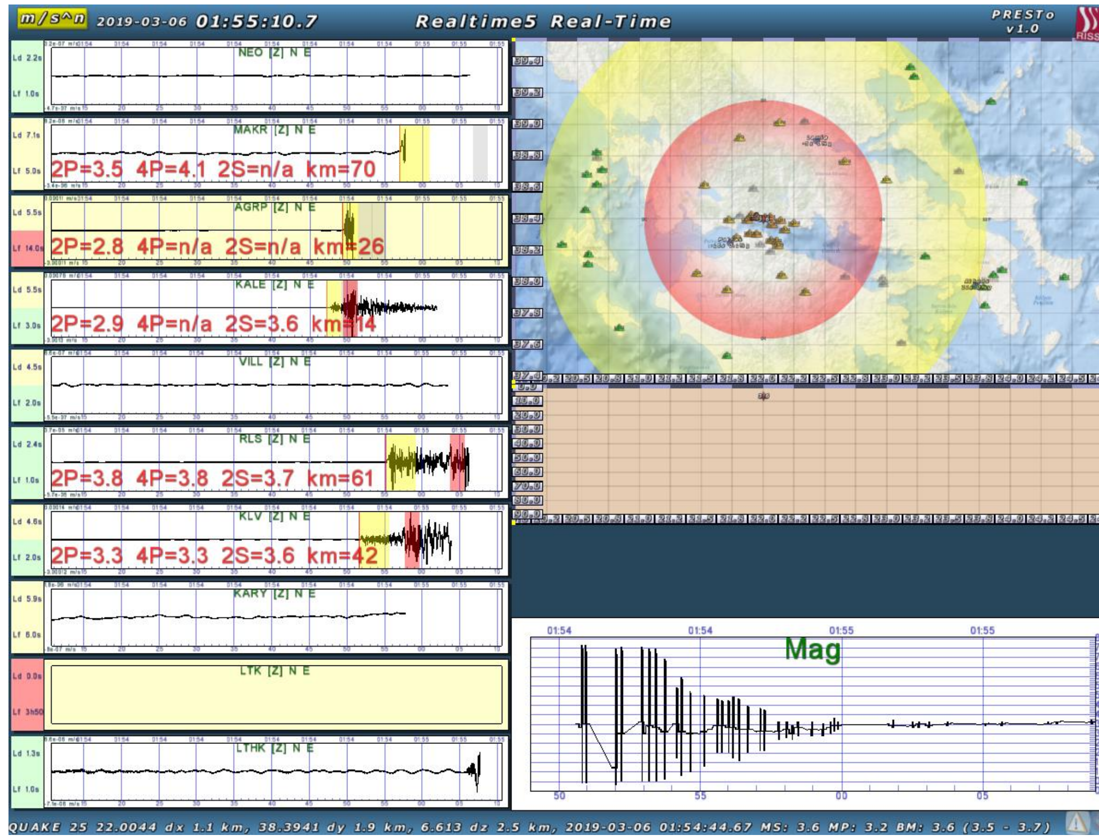


Figure from Kapetanidis et al. (2019)

EARTHQUAKE EARLY WARNING - CONCEPT

How rapidly a 1st solution/alert is produced largely depends on the density of the seismological network near the epicenter and the data transmission latency. The figure shows the time elapsed between the 1st location reported by the EEW software and the origin time of the earthquake. Evidently, the best-covered region is the Western Gulf of Corinth, due to the local CRL-network. Other regions with relatively high network density at the time (2018-2019) include the Lefkada Island, where the Aristotle University of Thessaloniki operates a local network, and, partly, Athens.

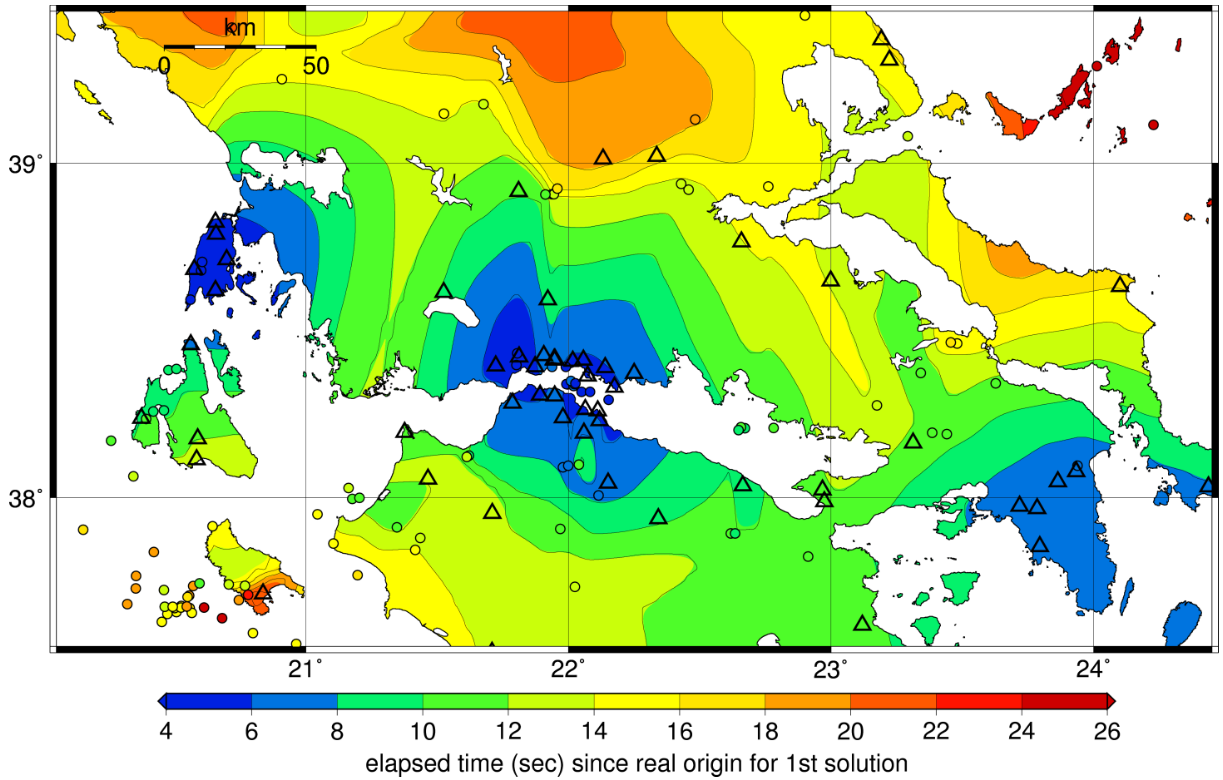


Figure from Kapetanidis et al. (2019)

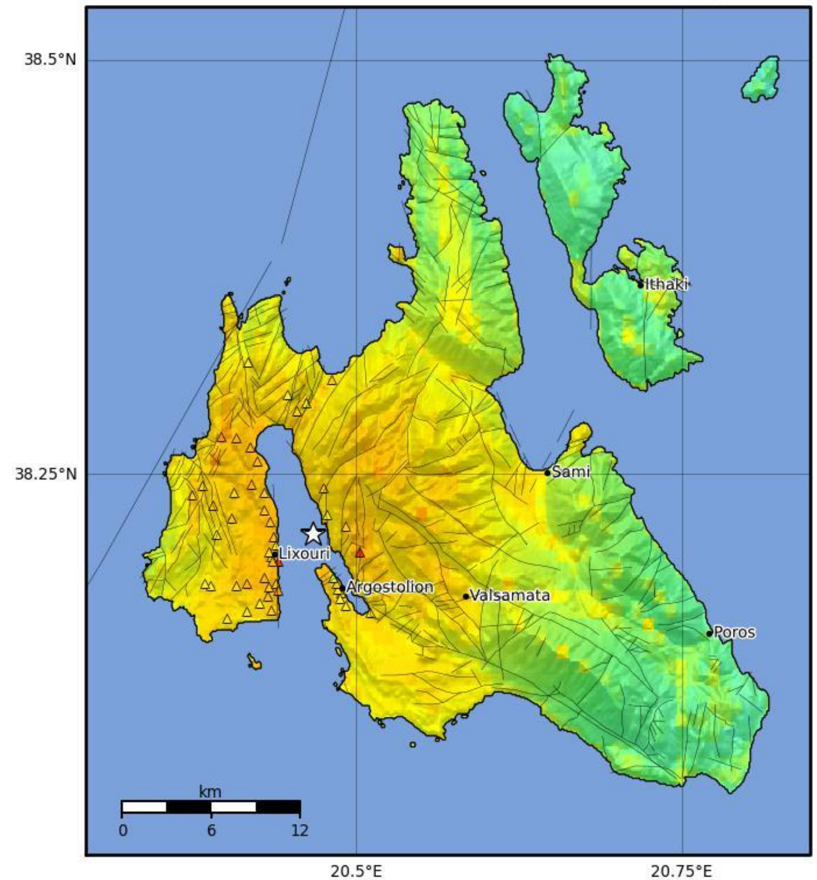
EARTHQUAKE EARLY WARNING – QUICK HAZARD MAPS

Besides the generation of a rapid alert for the occurrence of a strong earthquake, another purpose of an EEW system is to rapidly produce shakemaps from the available information of the early alert.

This can be achieved after the determination of the source parameters, including magnitude, by calculating theoretical values of various intensity measures using empirical Ground Motion Prediction Equations (GMPEs) and the knowledge of ground conditions (rock or soft/hard soil) in the affected area.

Information on the peak ground acceleration (PGA) and velocity (PGV), and, if possible, estimated degree of damage at specific target sites in the affected area, is important for rapid response and civil protection services.

Macroseismic Intensity Map NKUA
ShakeMap: Kefalonia 2014 EQ1 / 38.2133 / 20.4672
Jan 26, 2014 13:55:42 UTC M6.1 N38.21 E20.47 Depth: 16.0km ID:kef2014_eq1a



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012) Version 1: Processed 2022-06-11T14:21:39Z
△ Seismic Instrument ○ Reported Intensity ☆ Epicenter

ACKNOWLEDGEMENTS

This research was partly funded by the project “Telemachus: Innovative Seismic Risk Management Operational System of the Ionian Islands” (MIS 5007986) which is part of the Regional Operational Programme «Ionian Islands 2014-2020» and is co-financed by the European Regional Development Fund (ERDF) (National Strategic Reference Framework NSRF 2014-20)

REFERENCES

Evangelidis, C.P., Triantafyllis, N., Samios, M., Boukouras, K., Kontakos, K., Ktenidou, O.-J., Fountoulakis, I., Kalogeras, I., Melis, N.S., Galanis, O., Papazachos, C.B., Hatzidimitriou, P., Scordilis, E., Sokos, E., Paraskevopoulos, P., Serpetsidaki, A., Kaviris, G., Kapetanidis, V., Papadimitriou, P., Voulgaris, N., Kassaras, I., Chatzopoulos, G., Makris, I., Vallianatos, F., Kostantinidou, K., Papaioannou, C., Theodoulidis, N., Margaris, B., Pilidou, S., Dimitriadis, I., Iosif, P., Manakou, M., Roumelioti, Z., Pitilakis, K., Riga, E., Drakatos, G., Kiratzi, A., Tselentis, G.-A., 2021. Seismic Waveform Data from Greece and Cyprus: Integration, Archival, and Open Access. Seismol. Res. Lett. 92, 1672–1684.

Kapetanidis, V., Papadimitriou, P. & Kaviris, G., 2019. Earthquake Early Warning application in Central Greece, Bull. Geol. Soc. Greece, Proc. of the 15th Int. Congress, Athens, 22-24 May, 2019, Sp. Pub. 7, GSG2019-095.

Kaviris, G., Elias, P., Kapetanidis, V., Serpetsidaki, A., Karakonstantis, A., Plicka, V., De Barros, L., Sokos, E., Kassaras, I., Sakkas, V., Spingos, I., Lambotte, S., Duverger, C., Lengliné, O., Evangelidis, C.P., Fountoulakis, I., Ktenidou, O.-J., Gallovič, F., Bufféral, S., Klein, E., Aissaoui, E.M., Scotti, O., Lyon-Caen, H., Rigo, A., Papadimitriou, P., Voulgaris, N., Zahradnik, J., Deschamps, A., Briole, P., Bernard, P., 2021. The Western Gulf of Corinth (Greece) 2020–2021 Seismic Crisis and Cascading Events: First Results from the Corinth Rift Laboratory Network. Seism. Rec. 1, 85–95.

Kouskouna, V., Makropoulos, K., 2004. Historical earthquake investigations in Greece. Ann. Geophys. 47, 723–731.

Li, Z., 2021. Recent advances in earthquake monitoring i: Ongoing revolution of seismic instrumentation. Earthq. Sci. 34, 177–188.

Mavroulis, S., Vassilakis, E., Diakakis, M., Konsolaki, A., Kaviris, G., Kotsi, E., Kapetanidis, V., Sakkas, V., Alexopoulos, J.D., Lekkas, E., Voulgaris, N., 2022. The Use of Innovative Techniques for Management of High-Risk Coastal Areas, Mitigation of Earthquake-Triggered Landslide Risk and Responsible Coastal Development. Appl. Sci. 12, 2193.

Perol, T., Gharbi, M., Denolle, M., 2018. Convolutional neural network for earthquake detection and location. Sci. Adv. 4.

Ross, Z.E., Trugman, D.T., Hauksson, E., Shearer, P.M., 2019. Searching for hidden earthquakes in Southern California. Science (80-.). 364, 767–771.

Sakkas, V., Kapetanidis, V., Kaviris, G., Spingos, I., Mavroulis, S., Diakakis, M., Alexopoulos, J.D., Kazantzidou-Firtinidou, D., Kassaras, I., Dilalos, S., Vassilakis, E., Kotsi, E., Tselentis, G., Lekkas, E., Voulgaris, N., 2022. Seismological and Ground Deformation Study of the Ionian Islands (W. Greece) during 2014–2018, a Period of Intense Seismic Activity. Appl. Sci. 12, 2331.

Thank you for your attention!