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**Environmental, Disaster, and Crises Management Strategies**

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# The early March 2021 Thessaly earthquake sequence

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# About

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# INTRODUCTION OF THE 22st ISSUE OF THE EDCMS NEWSLETTER

This Newsletter is the outcome of a fruitful collaboration and knowledge sharing between geologists, seismologists, physicists, geographers, and civil engineers interested in mapping and monitoring the March 2021 Thessaly earthquake sequence (March 3, Mw=6.3 and March 4, Mw=6.1) and its effects. It comprises:

- the brief review of the geology, the active tectonics in the earthquake affected area and the historical and the recent seismicity with all known historical and instrumental earthquakes in Thessaly Basin with emphasis on its northeastern part,
- the presentation of seismotectonic information for the affected area including the seismotectonic context, the preliminary locations of epicenters and the focal mechanisms of the mainshock and the aftershock sequence, the spatiotemporal evolution of the foreshock-aftershock sequence and the compilation of shakemaps,
- the presentation of the environmental effects triggered by the mainshock derived from post-earthquake field surveys conducted by several scientific teams shortly after the generation of the mainshock
- the presentation of damage to buildings and infrastructures conducted by UOA
- the results from monitoring of the early March 2021 sequence by temporarily installed portable network and its importance for the study of the post-earthquake sequence and the operation of the Hellenic Unified Seismic Network (HUSN)
- the results from slip models for both events on March 3 and 4 and their comparison with spaceborne observations,
- the presentation of results from the integration of geospatial technologies for the assessment of the earthquake impact on structures, infrastructures and critical facilities and
- the presentation of results from interferometric analysis of SAR data and geodetic data (GNSS)

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# GEOTECTONIC LOCATION & GEOLOGY OF THESSALY BASIN

## GEOLOGY OF THE EARTHQUAKE-AFFECTED AREA

The broader Thessaly area is located at the back-arc area of the Aegean microplate and is one of the most seismically active areas of Greece. The Thessaly plain, the largest plain of central Greece, is particularly interesting from both the neotectonic and active tectonics point of view, because it is a well-defined, inland basin, filled with recent Quaternary and Neogene sediments, in which intense seismicity has been observed during historical times, especially during the 20$^{th}$ century.

Within the Thessaly plain, altitudes range from 45m to 200m. The basin is surrounded by mountainous areas, with an average altitude exceeding 1000m. Antichassia and Kato Olympos mountains occupy the northern part of Thessaly area, Ossa, Mavrovouni and Pelion mountains dominate its eastern section, while the western and southern parts of the basin are occupied by the Pindos and Othrys ranges, respectively. In the middle of the Thessaly plain a morphological ridge exists, which consists of the mountains of Zarkos and Titanos. The axis of this ridge coincides with the tectonic lines of the area and divides the plain into an eastern and a western basin.

The Thessaly plain covers part of the Pelagonian and Subpelagonian geological zones. The area is characterized by strong stratigraphic complexity and tectonic deformation, of both the alpine and the post-alpine period. Specifically, the geological formations include alpine, molassic and post-alpine formations.

The basement and the margins of the affected area is mainly composed of gneisses of Paleozoic age, and of Neopaleozoic – Lower-Middle Triassic formations including gneiss schists, gneisses, schists with orthogneiss and marble intercalations at their lower members and schists at the upper members of the Neopaleozoic – Lower-Middle Triassic formations.

As regard the post-alpine deposits, the Holocene is represented by recent deposits in the river and torrent beds and terraces, alluvial deposits within the affected flood plains of Titarissios and Pineios Rivers and recent scree in slopes. Pleistocene talus cones, scree, fluvial-terrestrial and fluvial-lacustrine deposits are also part of the post-alpine deposits. Neogene marls and clays occur in the earthquake-affected area.

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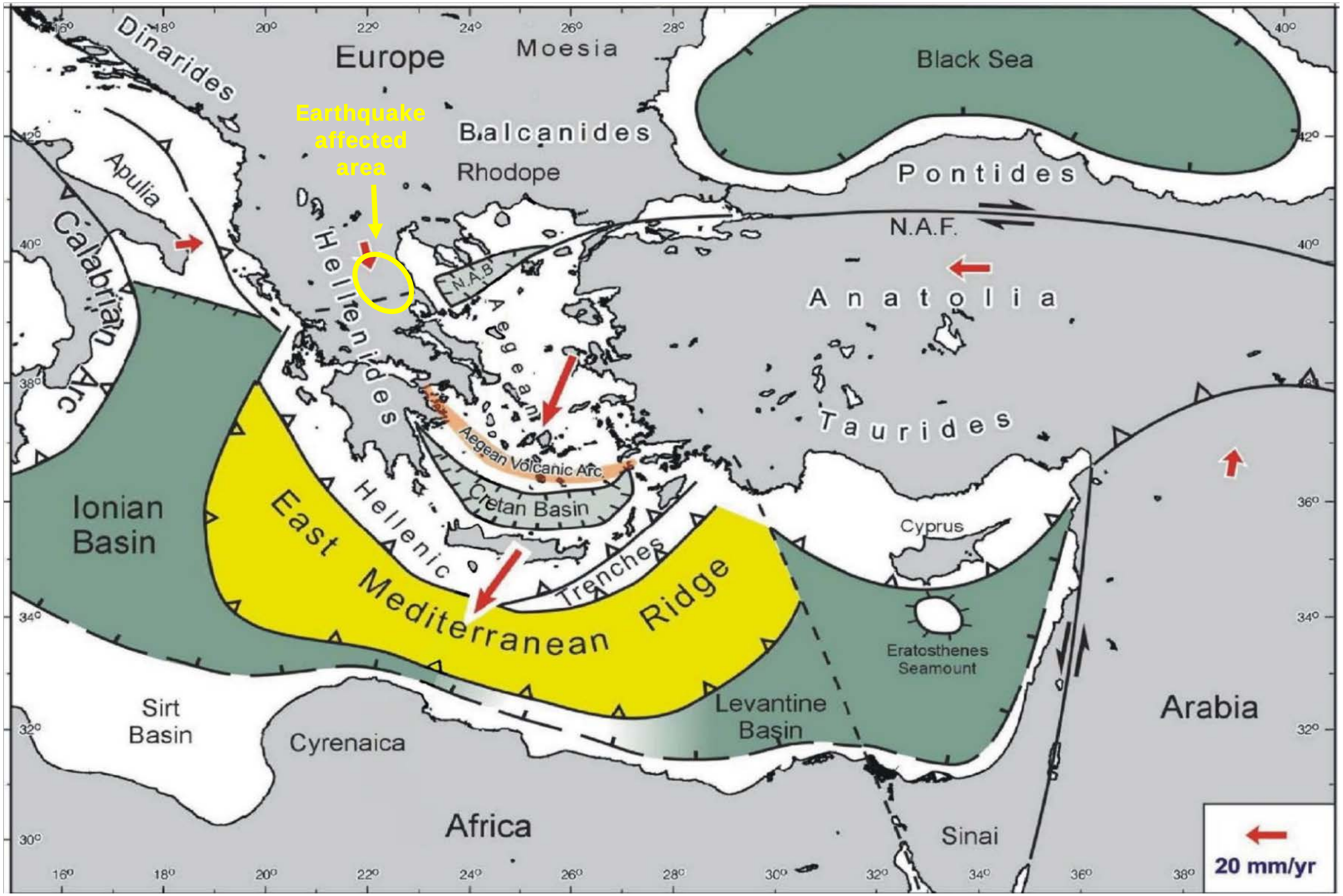
## MAIN TECTONIC ELEMENTS IN THE EASTERN MEDITERRANEAN REGION
### THE HELLENIC ARC & TRENCH SYSTEM




From *Papanikolaou et al. (2004)*

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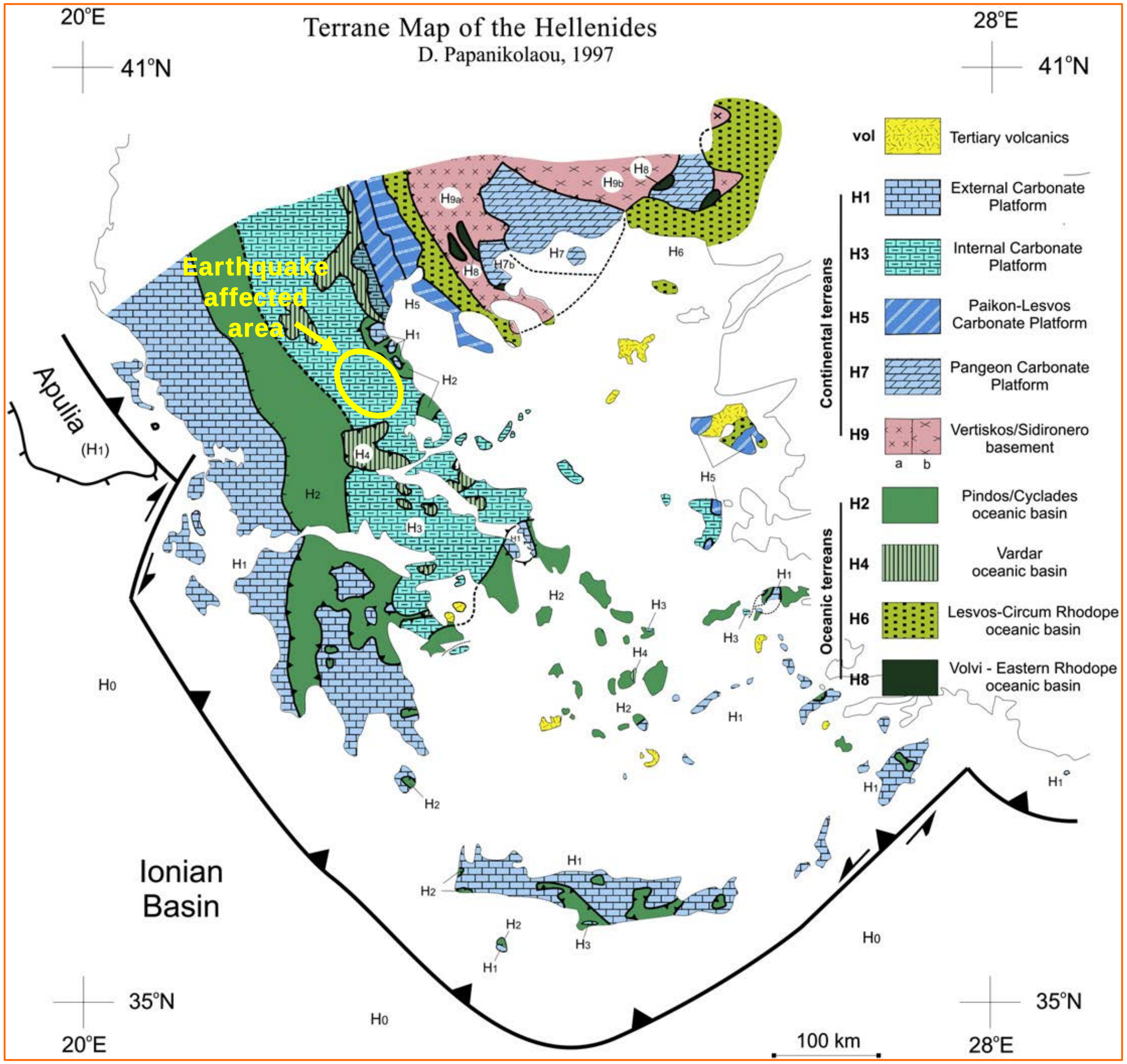
# GEOTECTONIC MAP OF GREECE
## TECTONOSTRATIGRAPHIC TERRANES




The earthquake-affected area comprises geological formations belonging to the tectonostratigraphic terrane **H3** of the Internal Carbonate Platform

From *Papanikolaou (1997)*

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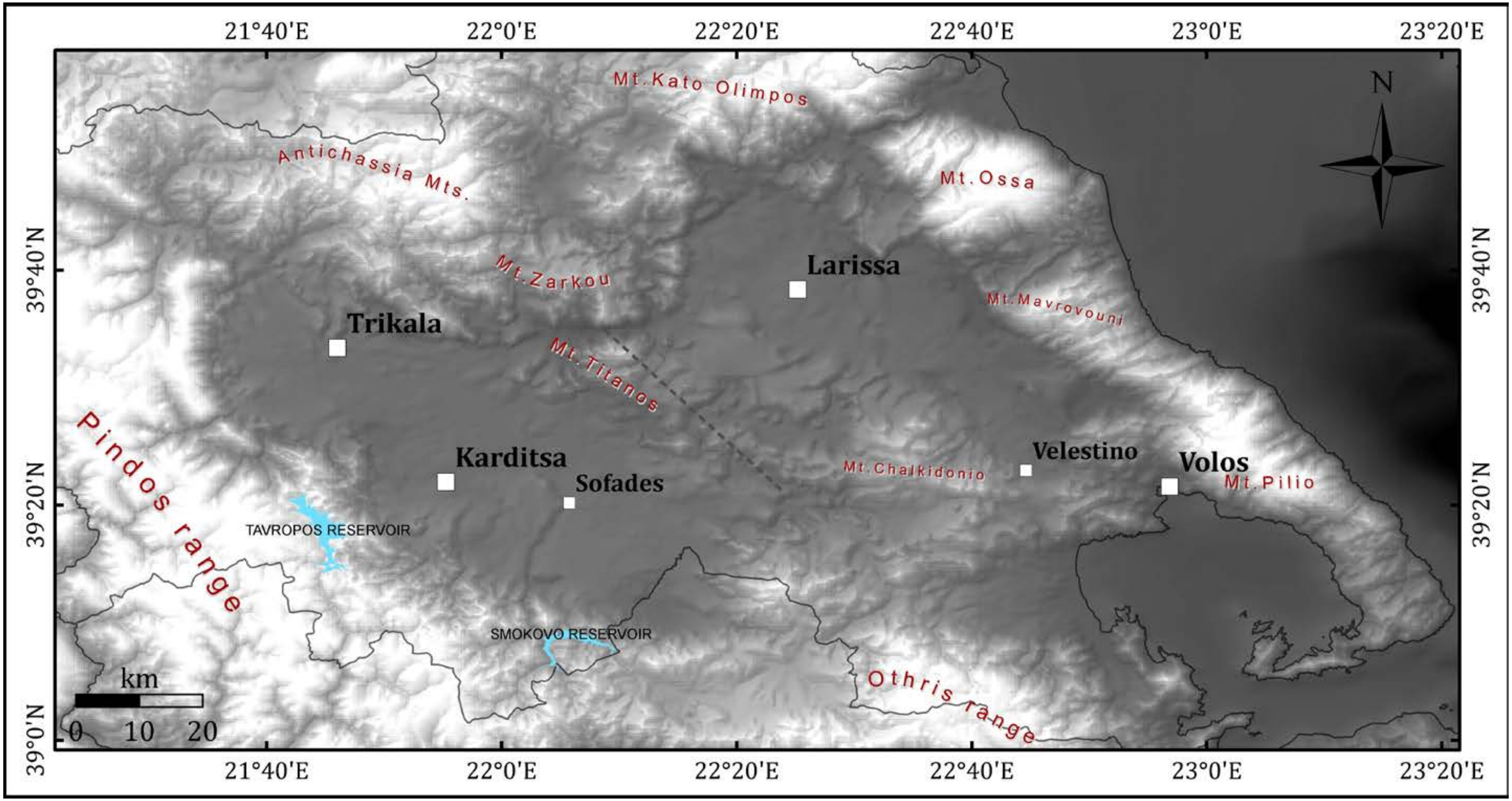
## MAIN MORPHOLOGICAL FEATURES OF THE THESSALY BASIN AREA




The main morphological units of the earthquake-affected area are the Larissa basin and the surrounding mountains of Antichassia and Zarkos.

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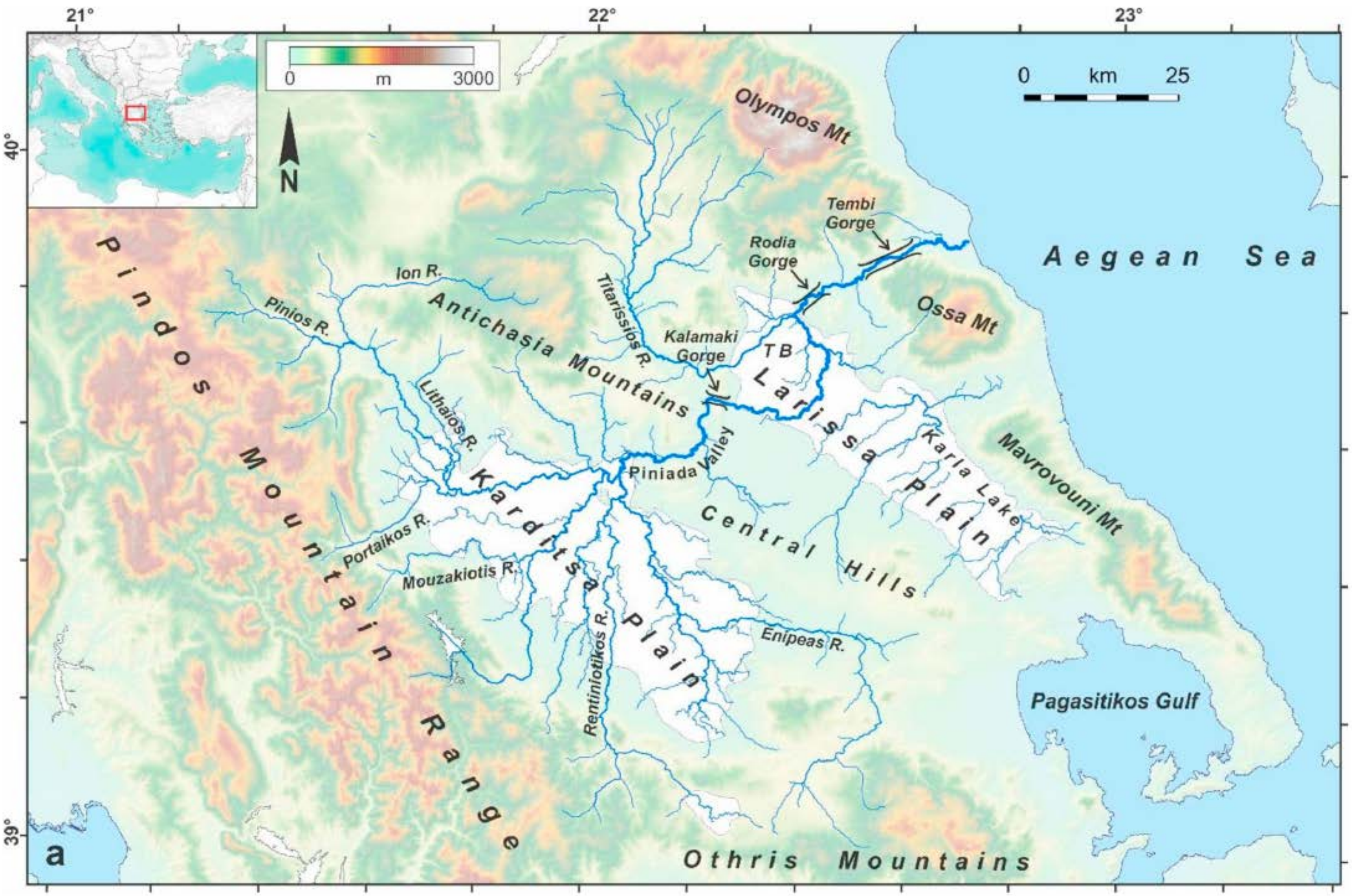
## MORPHOLOGY OF THE EARTHQUAKE-AFFECTED AREA




The main rivers of the earthquake-affected area are
the Pineios River in its southern part and the Titarissios River in its northern part.

From *Caputo et al. (2021)*

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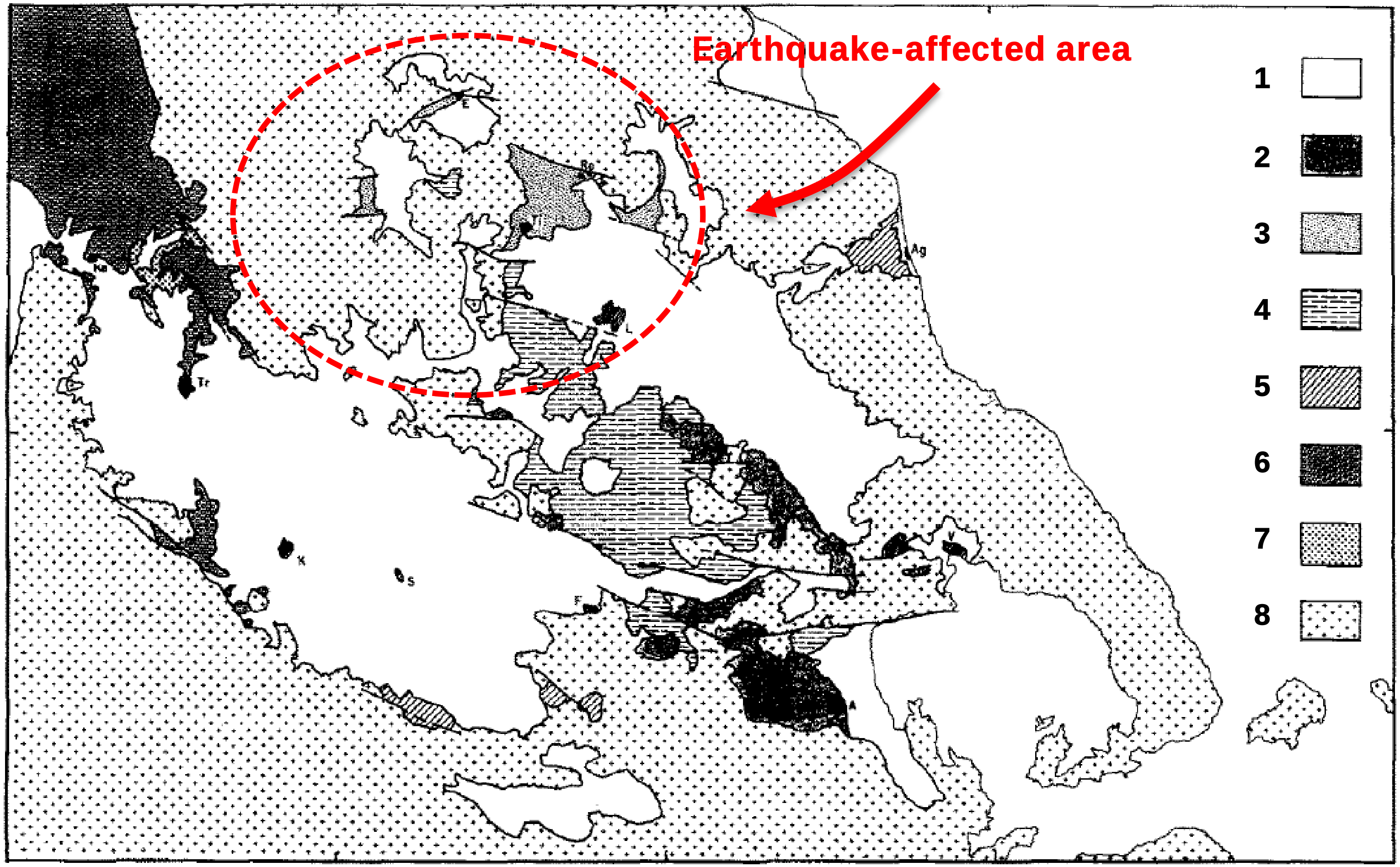
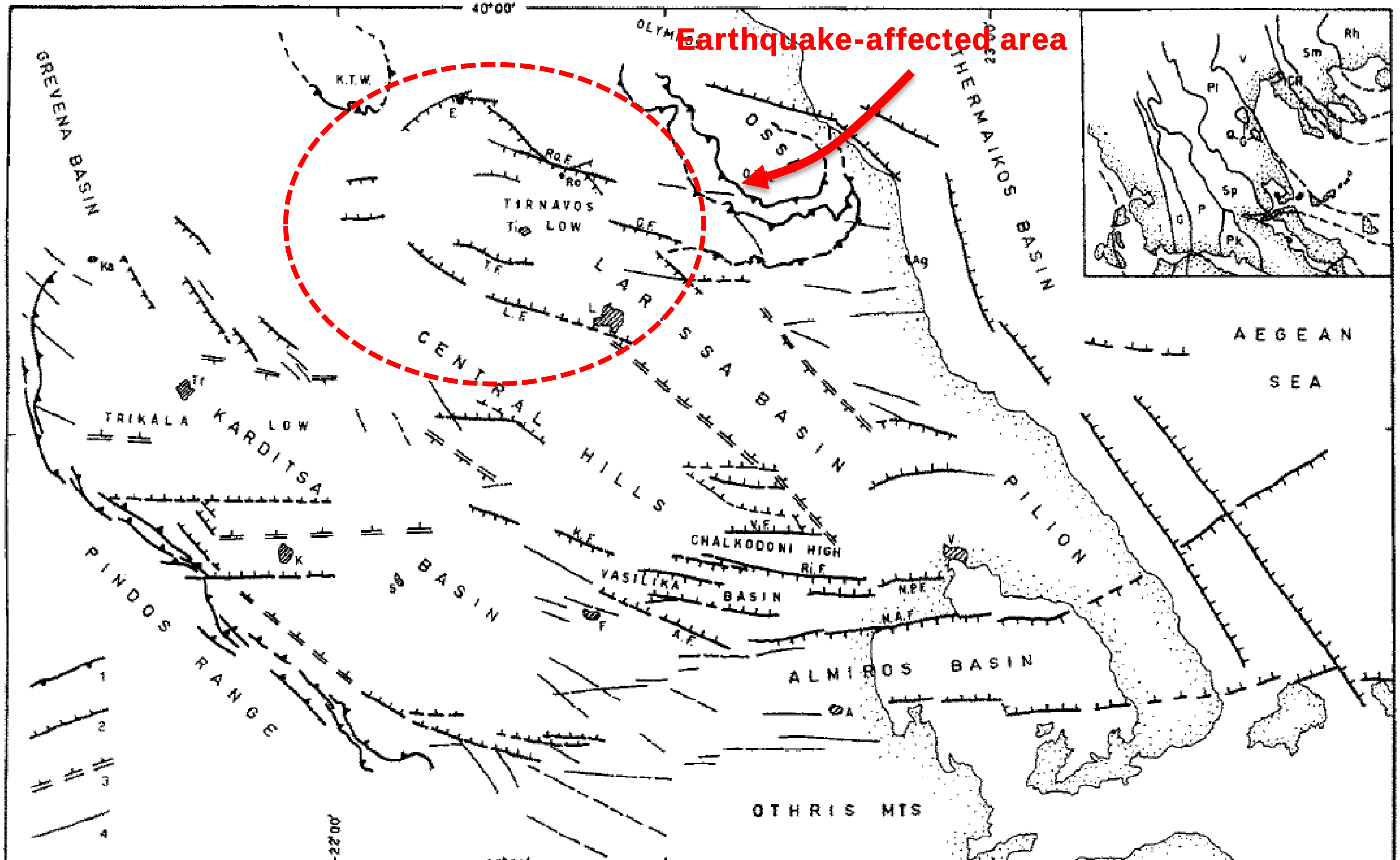
## AGE DISTRIBUTION OF OUTCROPPING LATE- AND POST-ALPINE SEDIMENTS IN THESSALY BASIN




**1**: Holocene; **2**: Villafranchian and/or Late Pleistocene; **3**: Pleistocene (lacustrine); **4**: Pliocene; **5**: Neogene; **6**: Oligocene-Burdigalian; **7**: Lutetian-Priabonian; **8**: Alpine substratum

From *Caputo and Pavlides (1993)*

## MAJOR TECTONIC STRUCTURES OF THESSALY BASIN




From *Caputo and Pavlides (1993)*

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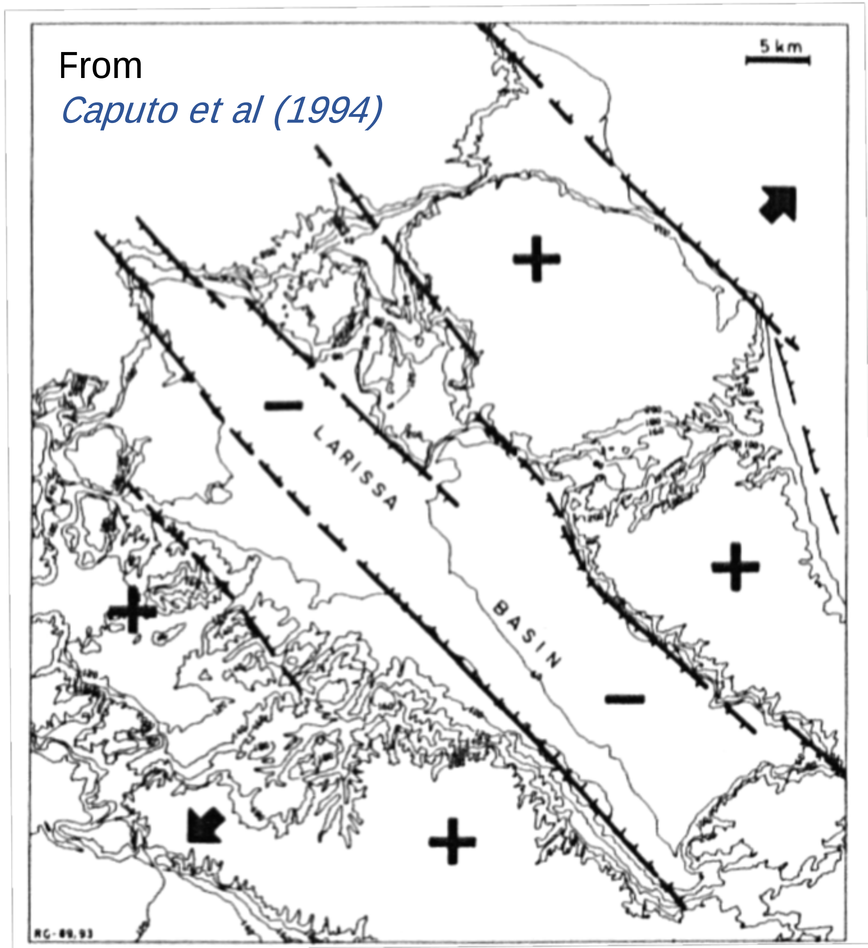
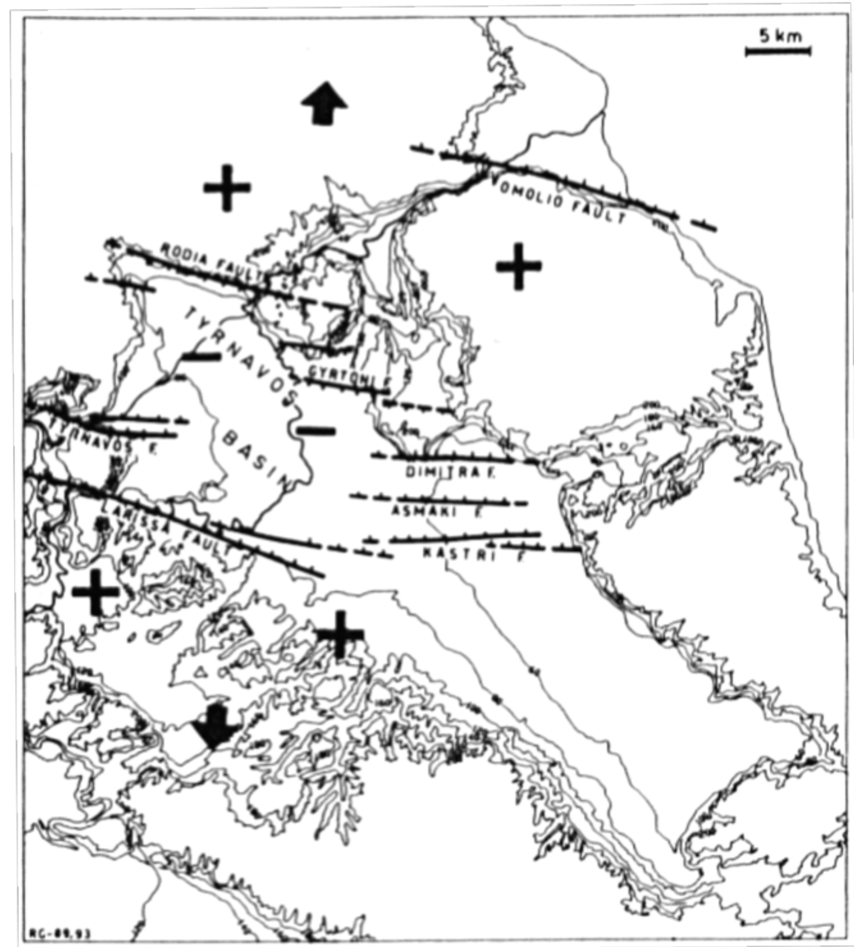
# THE PLIOCENE-QUATERNARY EVOLUTION OF LARISSA PLAIN

## THE LARISSA AND TYRNAVOS BASINS

From
*Caputo et al (1994)*




Structural map of Eastern Thessaly showing the major normal faults during the Pliocene – Lower Pleistocene extensional regime, which generated the NW-SE trending Larissa Basin.




Structural map of eastern Thessaly showing the major normal faults activated during the Middle Pleistocene – Holocene extensional regime, which generated the E-W trending Tyrnavos Basin.

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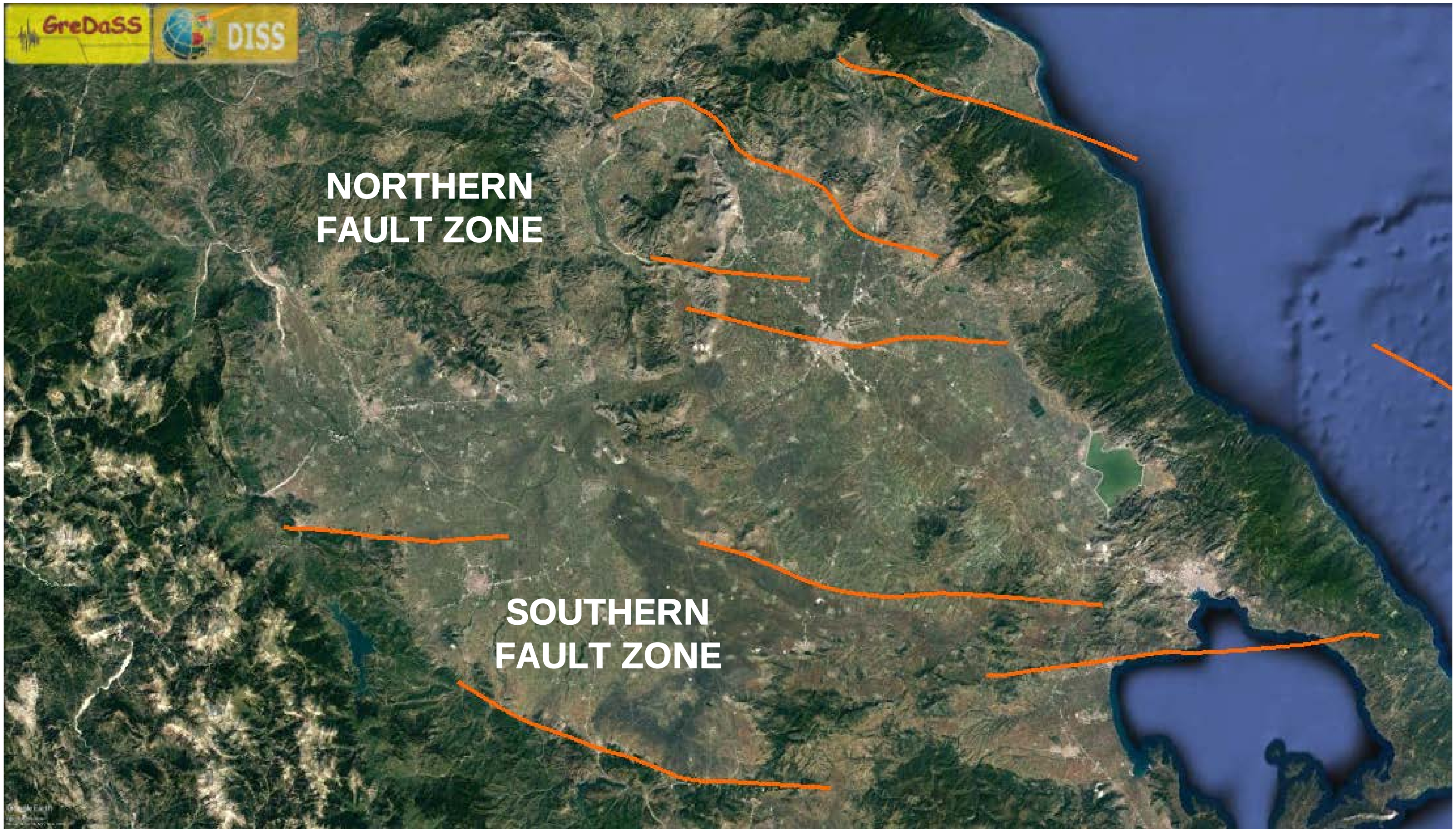
## SEISMOGENIC SOURCES IN THESSALY BASIN
### BASED ON THE GREEK DATABASE OF SEISMOGENIC SOURCES




The seismicity of Thessaly Basin is detected along two fault zones: the northern fault zone, which is associated with earthquakes with magnitudes up to 6.5 and the southern fault zone associated with earthquakes with magnitude up to 7.0.

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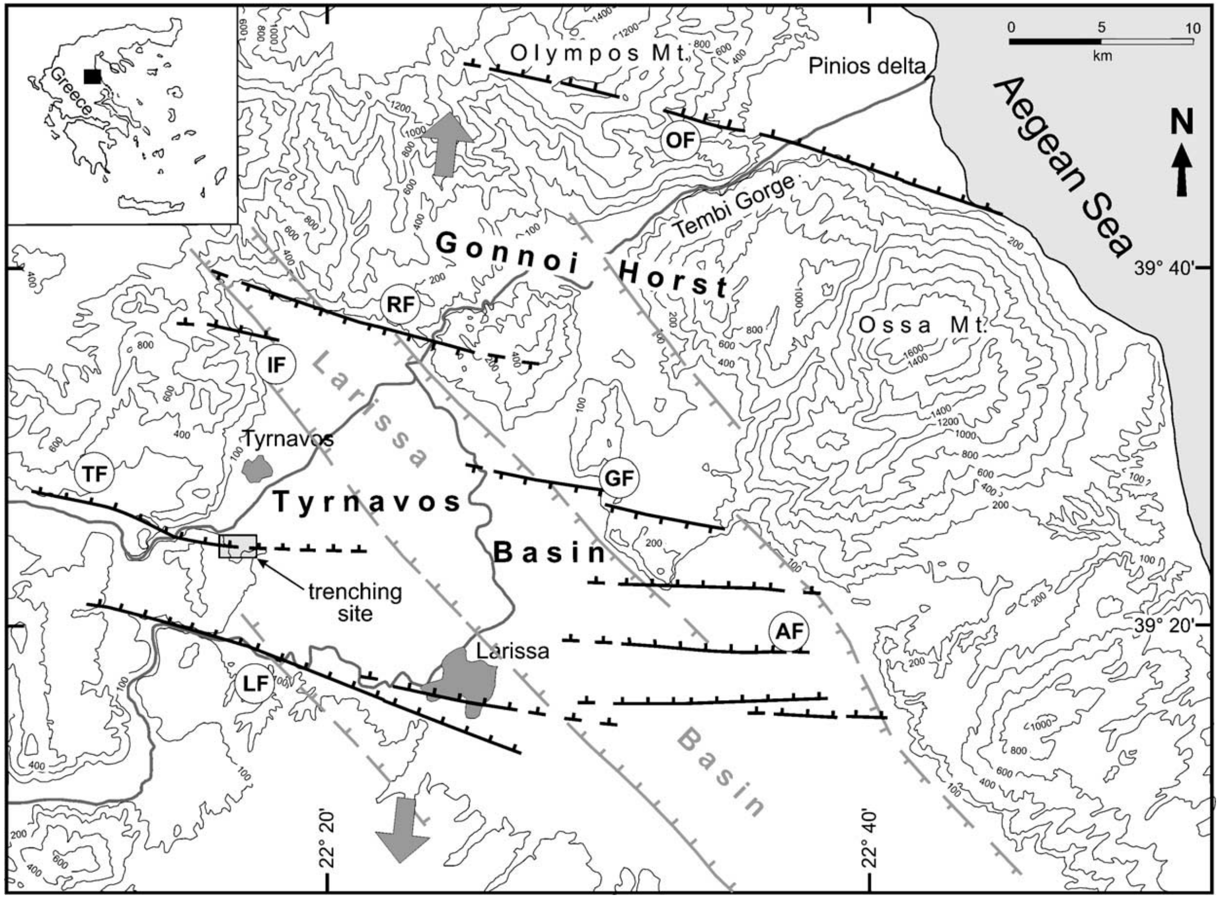
## TECTONIC SETTING OF THE EARTHQUAKE-AFFECTED AREA




Simplified tectonic map of eastern Thessaly. **Black lines**: active structures affecting the area since Middle Pleistocene associated to the E-W trending Tyrnavos Basin and Gonnoi Horst. **Grey lines**: major Pliocene – Early Pleistocene faults bordering the Larissa Basin. Barbs on the downthrown side of the faults. **TF**: Tyrnavos Fault; **RF**: Rodia Fault; **IF**: Ligaria Fault; **GF**: Gyrtoni Fault; **LF**: Larissa Fault; **AF**: Asmaki Fault; **OF**: Omolio Fault. Large grey arrows represent the active stress field affecting the area (From *Caputo et al., 2003*).

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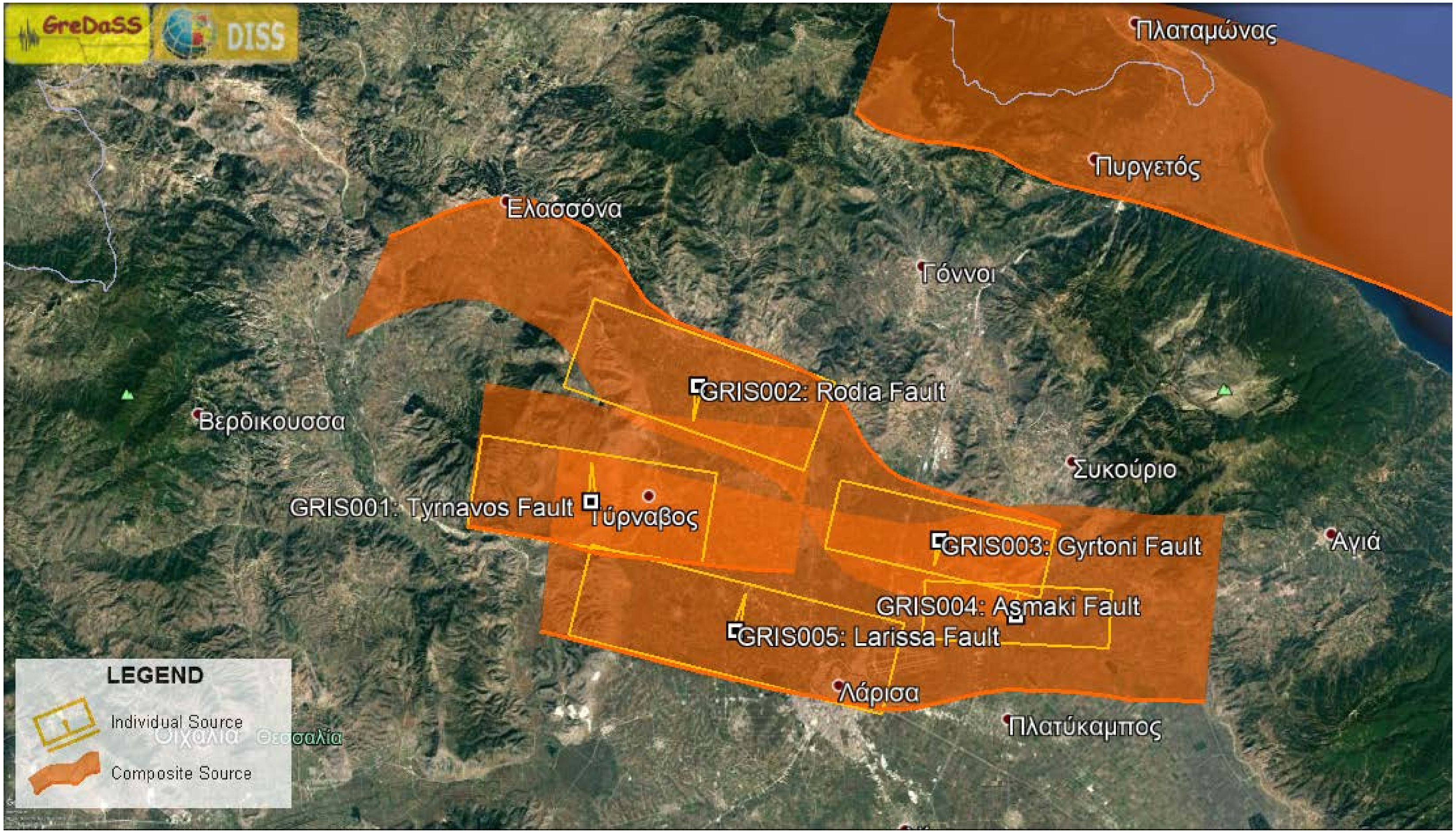
## SEISMOGENIC SOURCES IN NORTHERN THESSALY BASIN
## BASED ON THE GREEK DATABASE OF SEISMOGENIC SOURCES




From http://gredass.unife.it/gredassGM/
and http://gredass.unife.it/HTMLs_2.0/GRCS912INF.html

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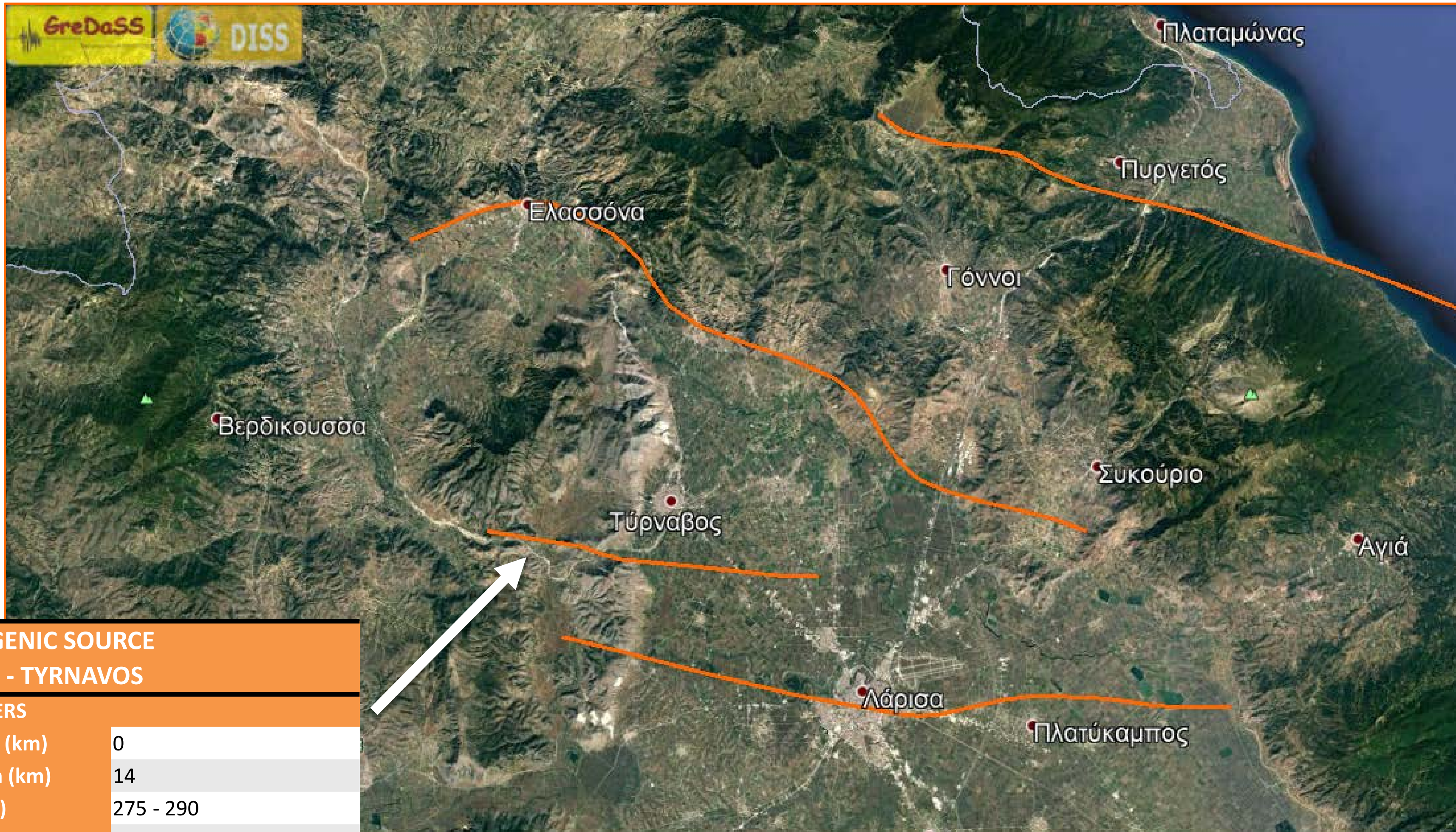
## SEISMOGENIC SOURCES IN NORTHERN THESSALY BASIN

### SEISMOGENIC SOURCE GRCS001 – TYRNAVOS




| SEISMOGENIC SOURCE GRCS001 - TYRNAVOS | |
|---|---|
| PARAMETERS | |
| Min Depth (km) | 0 |
| Max Depth (km) | 14 |
| Strike (deg) | 275 - 290 |
| Dip (deg) | 50 - 75 |
| Rake (deg) | 260 - 280 |
| Slip Rate (mm/y) | 0.05 - 0.4 |
| Max Magnitude (Mw) | 6.3 |

From http://gredass.unife.it/gredassGM/
and http://gredass.unife.it/HTMLs_2.0/GRCS001INF.html

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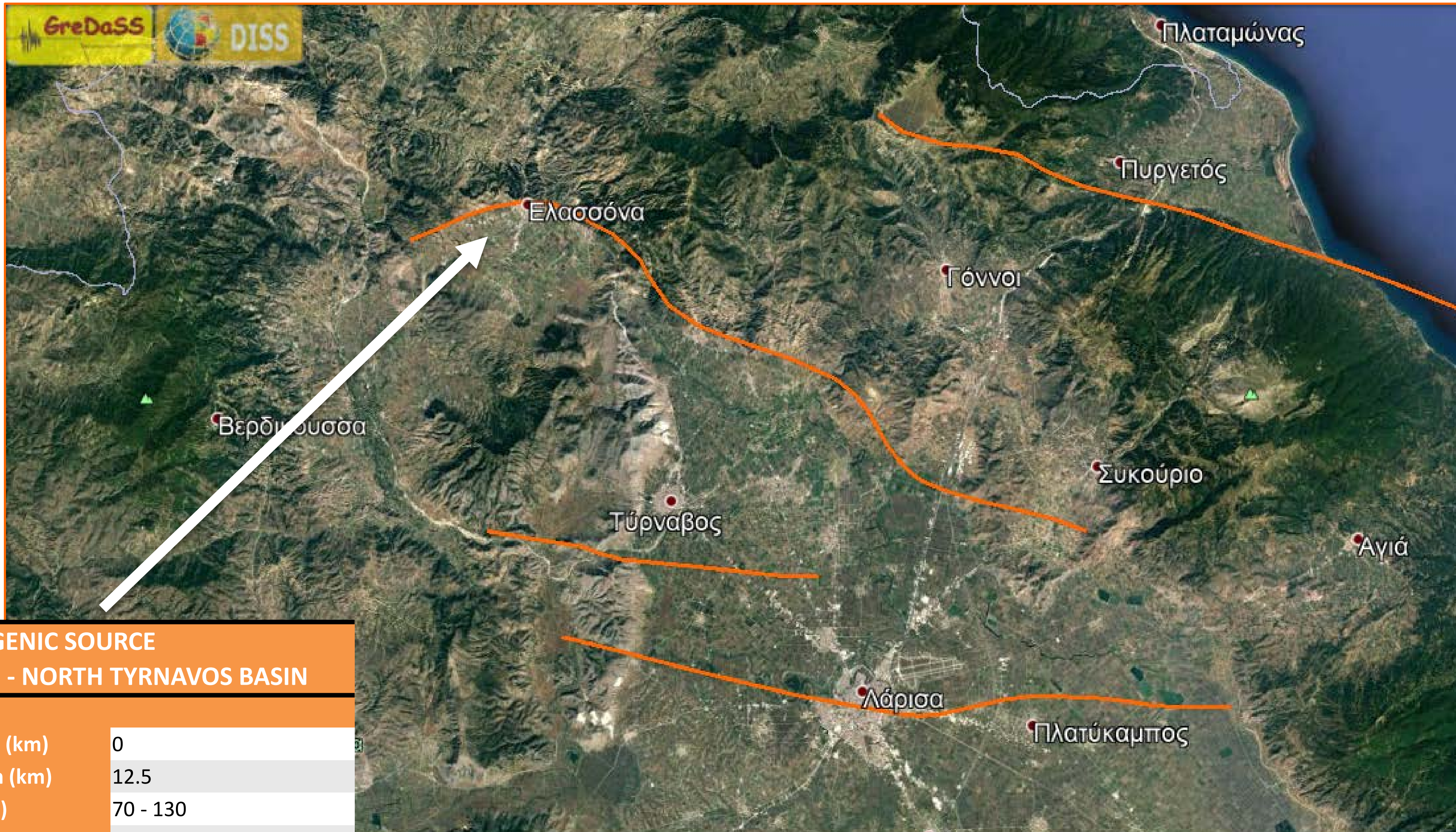
## SEISMOGENIC SOURCES IN NORTHERN THESSALY BASIN
### SEISMOGENIC SOURCE GRCS002 – NORTH TYRNAVOS BASIN




| SEISMOGENIC SOURCE GRCS002 - NORTH TYRNAVOS BASIN | |
|---|---|
| Parameter | |
| Min Depth (km) | 0 |
| Max Depth (km) | 12.5 |
| Strike (deg) | 70 - 130 |
| Dip (deg) | 55 - 75 |
| Rake (deg) | 260 - 290 |
| Slip Rate (mm/y) | 0.1 - 1 |
| Max Magnitude (Mw) | 6.2 |

From http://gredass.unife.it/gredassGM/
and http://gredass.unife.it/HTMLs_2.0/GRCS004INF.html

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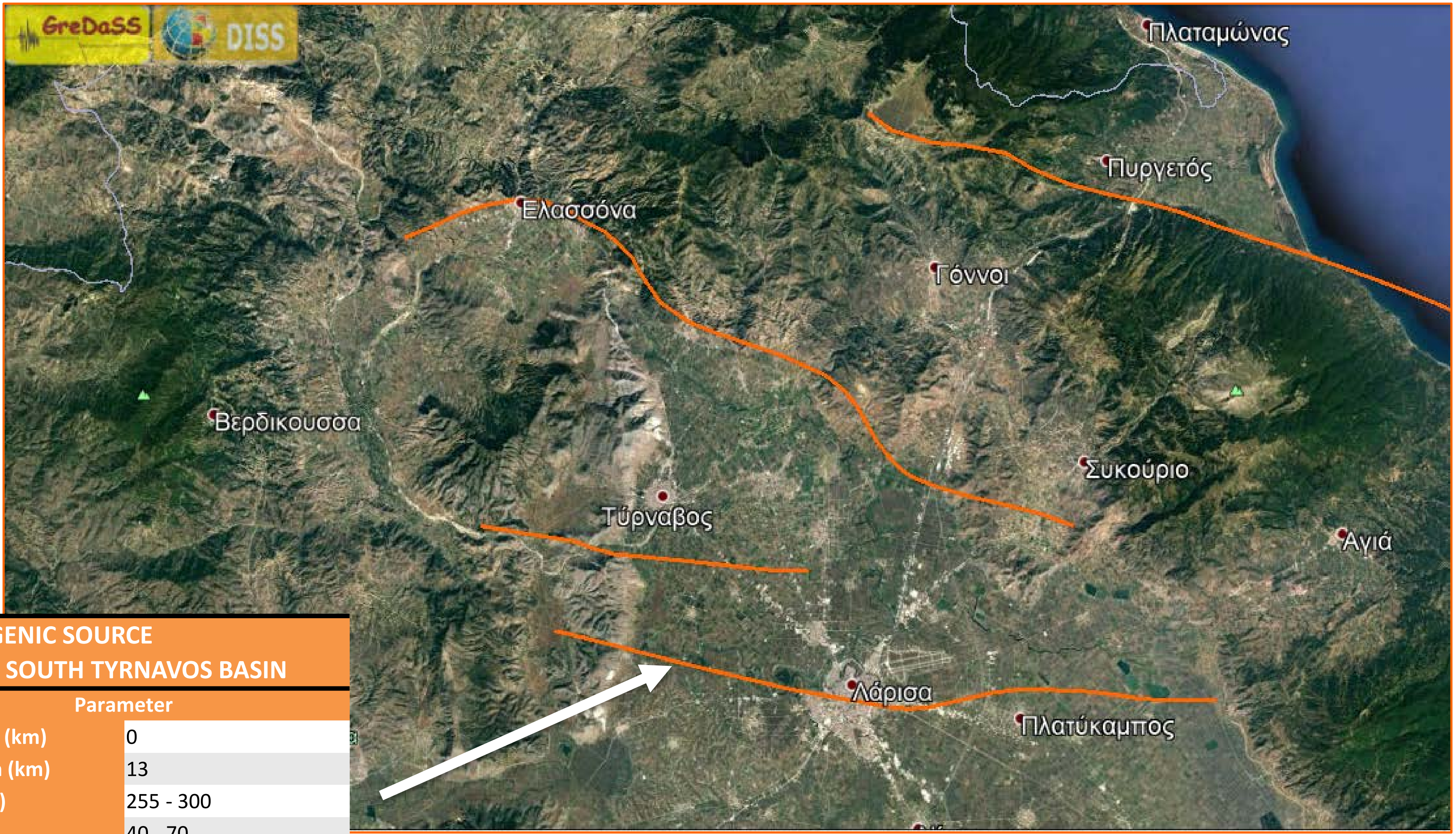
# SEISMOGENIC SOURCES IN NORTHERN THESSALY BASIN

## SEISMOGENIC SOURCE GRCS004 – SOUTH TYRNAVOS BASIN




| SEISMOGENIC SOURCE GRCS004 SOUTH TYRNAVOS BASIN | |
|---|---|
| Parameter | |
| Min Depth (km) | 0 |
| Max Depth (km) | 13 |
| Strike (deg) | 255 - 300 |
| Dip (deg) | 40 - 70 |
| Rake (deg) | 260 - 280 |
| Slip Rate (mm/y) | 0.1 - 0.5 |
| Max Magnitude (Mw) | 6.8 |

From http://gredass.unife.it/gredassGM/
and http://gredass.unife.it/HTMLs_2.0/GRCS002INF.html

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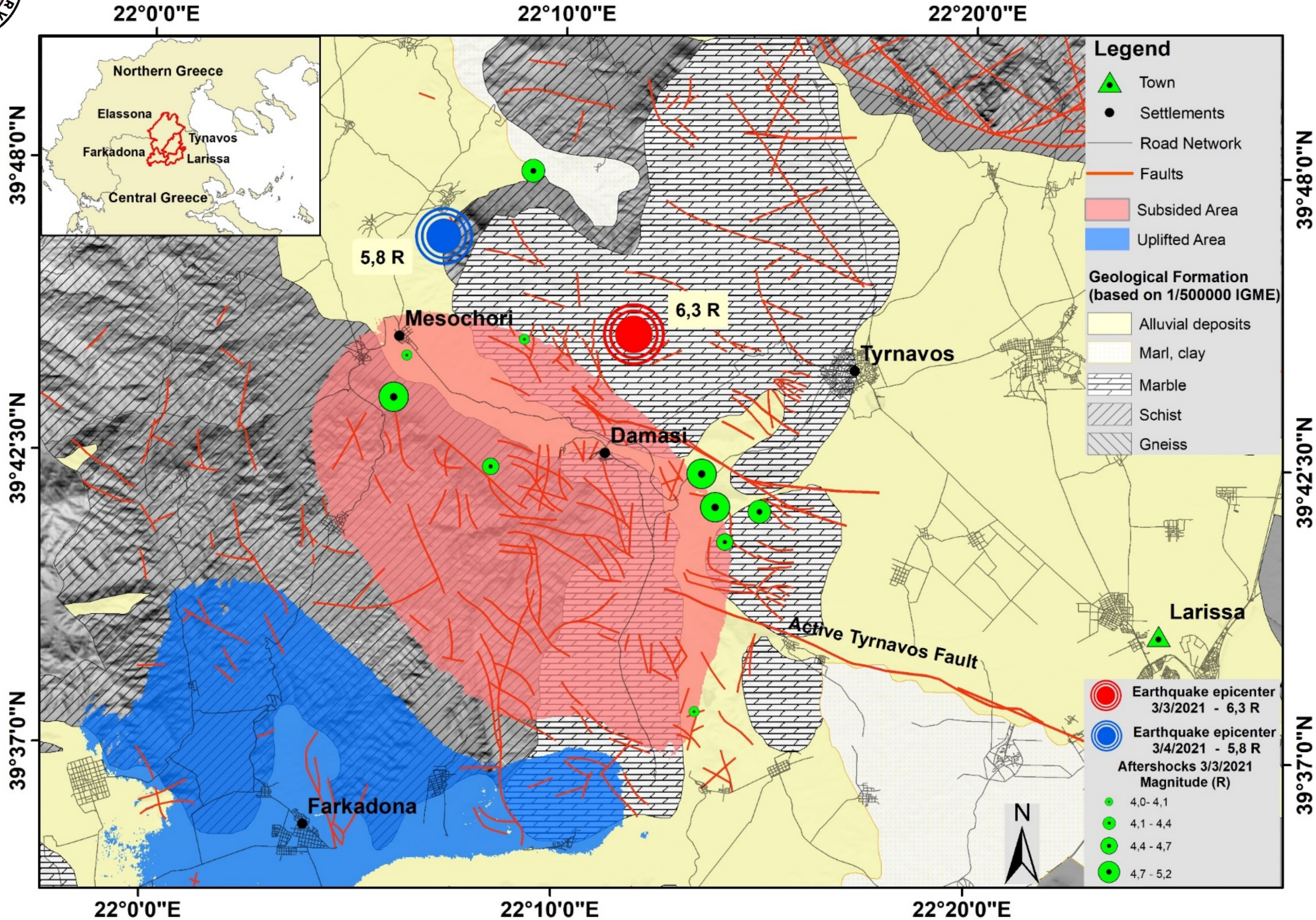
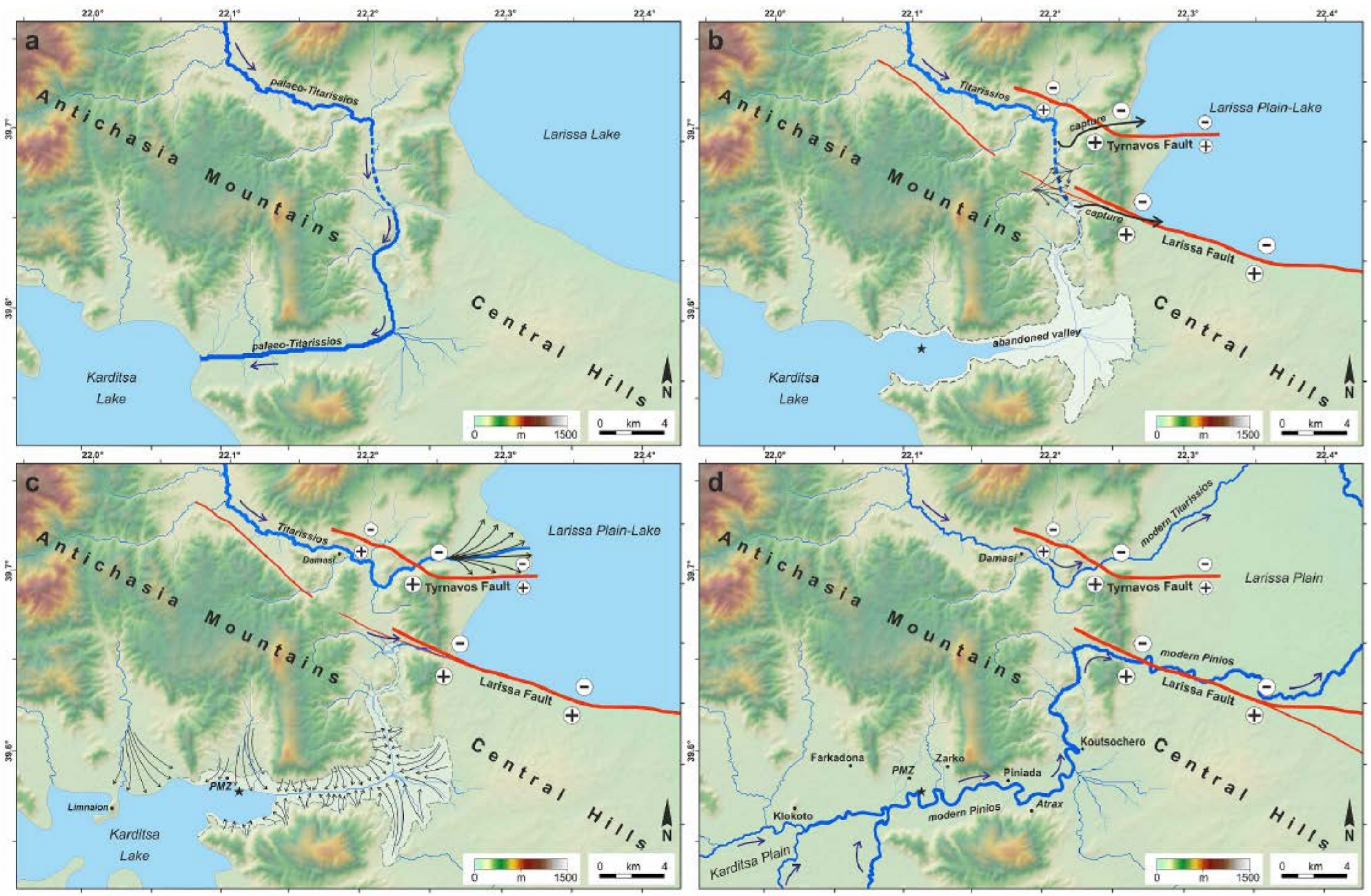
## GEOLOGY OF THE EARTHQUAKE-AFFECTED AREA



## MORPHOLOGY OF THE EARTHQUAKE-AFFECTED AREA




Reconstruction of the main course of the Titarissios River during Late Quaternary

From *Caputo et al. (2021)*

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## SEISMICITY IN THESSALY BASIN AND THE SURROUNDING AREA

The Thessaly basin has a well-known history of large earthquakes, with mainshocks having typical magnitudes between 6.0 and 7.0. The seismicity (instrumental and historic) follows the two discrete rupture zones of the Thessaly basin previously described. During the 20th century, eight major seismic sequences with mainshock magnitudes equal or larger than 6.0 have occurred in this area (1905, 1911, 1930, 1941, 1954, 1955, 1957, 1980), with the M=7.0, 1954 Sofades earthquake being the most destructive event, resulting in heavy damage in the towns and villages of the broader southern Thessaly region (Papastamatiou and Mouyaris, 1986; Papazachos and Papazachou, 2002). The M=6.8, 1957 Velestino earthquake and the M=6.5, 1980 Almyros earthquake, are two equally notable events, with similarly destructive consequences.

The Thessaly Basin is one of the most seismic active areas in Greece with a well-known history of earthquakes with magnitudes ranging from 6.0 to 7.0. Its seismicity is detected along two fault zones in the Thessaly Basin: the northern one, which is associated with earthquakes with magnitudes up to 6.5 and the southern one associated with earthquakes with magnitude up to 7.0.

The April 30, 1954, M=7.0 Sofades earthquake is the largest of them with significant impact on the local population and the built environment. It caused 25 fatalities and 157 injuries and generated severe structural damage to 15000 buildings in large cities of the Thessaly Basin including Karditsa, Larissa and Trikala among others.

*Liquefaction and surface faulting induced by the 1954 Sofades earthquake*

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## HISTORICAL AND RECENT EARTHQUAKES

| Nr | Name | Length in km | Azimuth | Slope | Slip angle | Occurrence year (earthquake magnitude) |
|---|---|---|---|---|---|---|
| 1 | **Meteora** | 26 | 90 | 43 | -90 | **1544** (6.4) \| **1665** (6.0) \| **1787** (6.0) |
| 2 | **Trikala** | 25 | 89 | 43 | -90 | **1621** (6.0) \| **1674** (6.0) \| **1735** (6.4) |
| 3 | **Pineios** | 22 | 69 | 43 | -90 | **1661** (6.2) |
| 4 | **Larissa** | 26 | 291 | 47 | -88 | **1668** (6.0) \| **1731** (6.0) \| **1781** (6.2) \| **1941** (6.3) |
| 5 | **Elassona** | 18 | 109 | 47 | -88 | **1766** (6.1) |
| 6 | **Keramidi** | 26 | 327 | 50 | -82 | **1905** (6.4) \| **1911** (6.0) \| **1930** (6.1) |
| 7 | **Agrafa** | 26 | 76 | 50 | -82 | **1514** (6.0) \| **1566** (6.4) \| **1966** (6.2) |
| 8 | **Sofades** | 52 | 271 | 47 | -88 | **1954** (7.0) |
| 9 | **Farsala** | 42 | 269 | 47 | -88 | **1743** (6.6) \| **1773** (6.4) \| **1957** (6.8) |
| 10 | **N. Anchialos** | 30 | 82 | 43 | -90 | **1864** (6.0) \| **1955** (6.2) \| **1980** (6.5) |
| 11 | **Arta** | 26 | 11 | 49 | -87 | **1967** (6.4) |

From *Panagiotopoulos and Papazachos (2008)*

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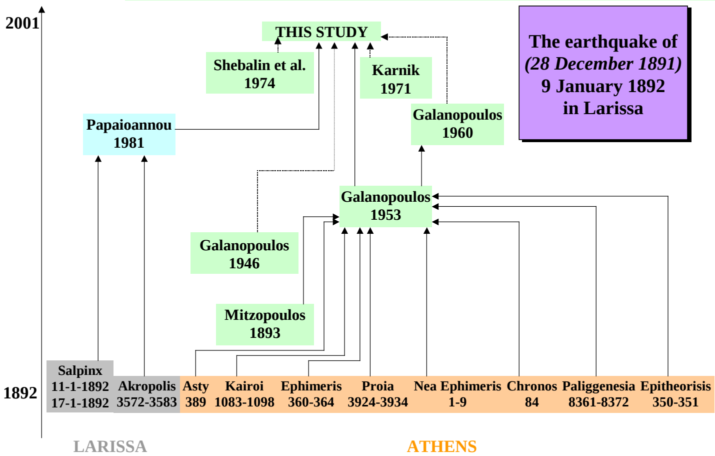
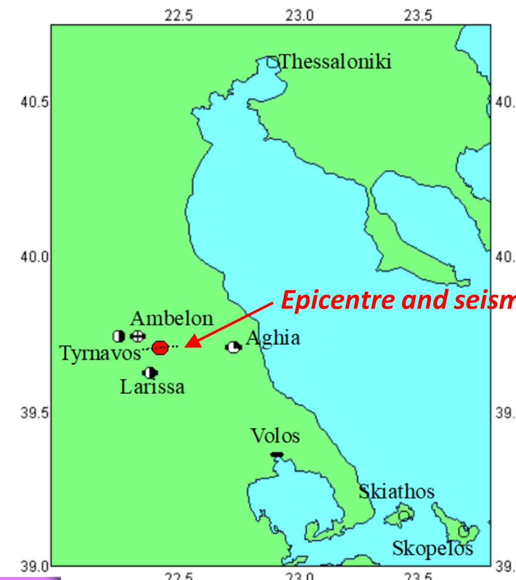
# HISTORICAL EARTHQUAKES

| Year | Mo | Da | Hr | Mi | Site | Lat(°N) | Lon(°E) | Io | Sc | Mw |
|---|---|---|---|---|---|---|---|---|---|---|
| 1892 | 01 | 09 | 08 | 15 (LT) | Larissa | 39.71 | 22.46 | 6-7 | EMS-98 | 5.0 |

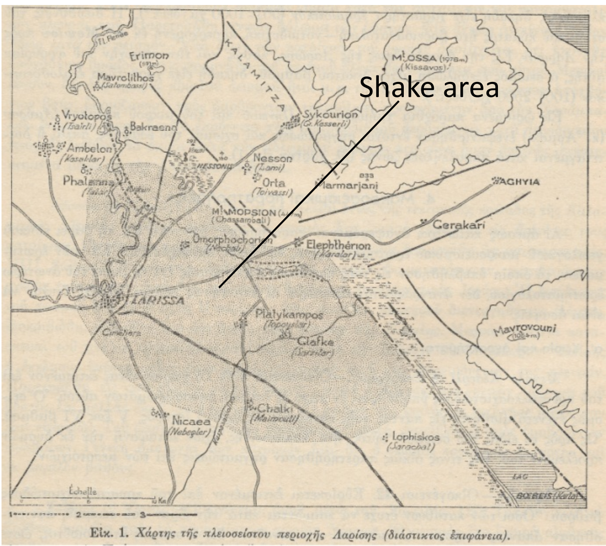



| EMS Intensities | |
|---|---|
| Larissa | 6.5 |
| Tyrnavos | 6 |
| Agia | 5.5 |
| Ambelon (Kazaklar) | 4.5 |

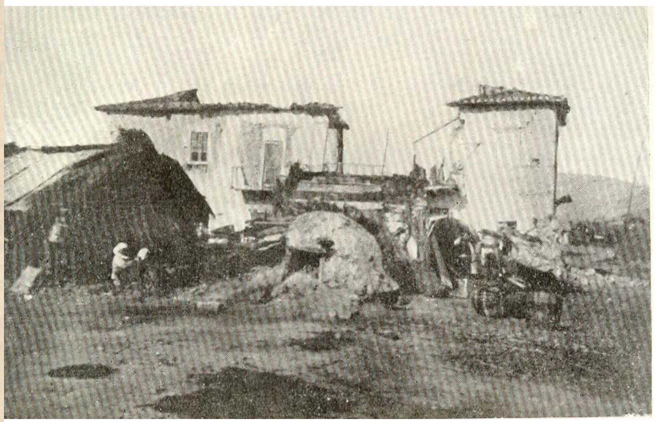
*Kouskouna (2001)*




**The earthquake of 1 March 1941 in Larissa**



Εἰκ. 1. Χάρτης τῆς πλειστοσείστου περιοχῆς Λαρίσης (διάστικτος ἐπιφάνεια).



*Papaioannou (2018)*

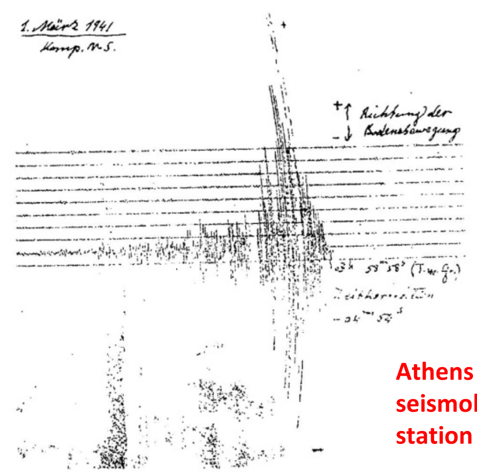
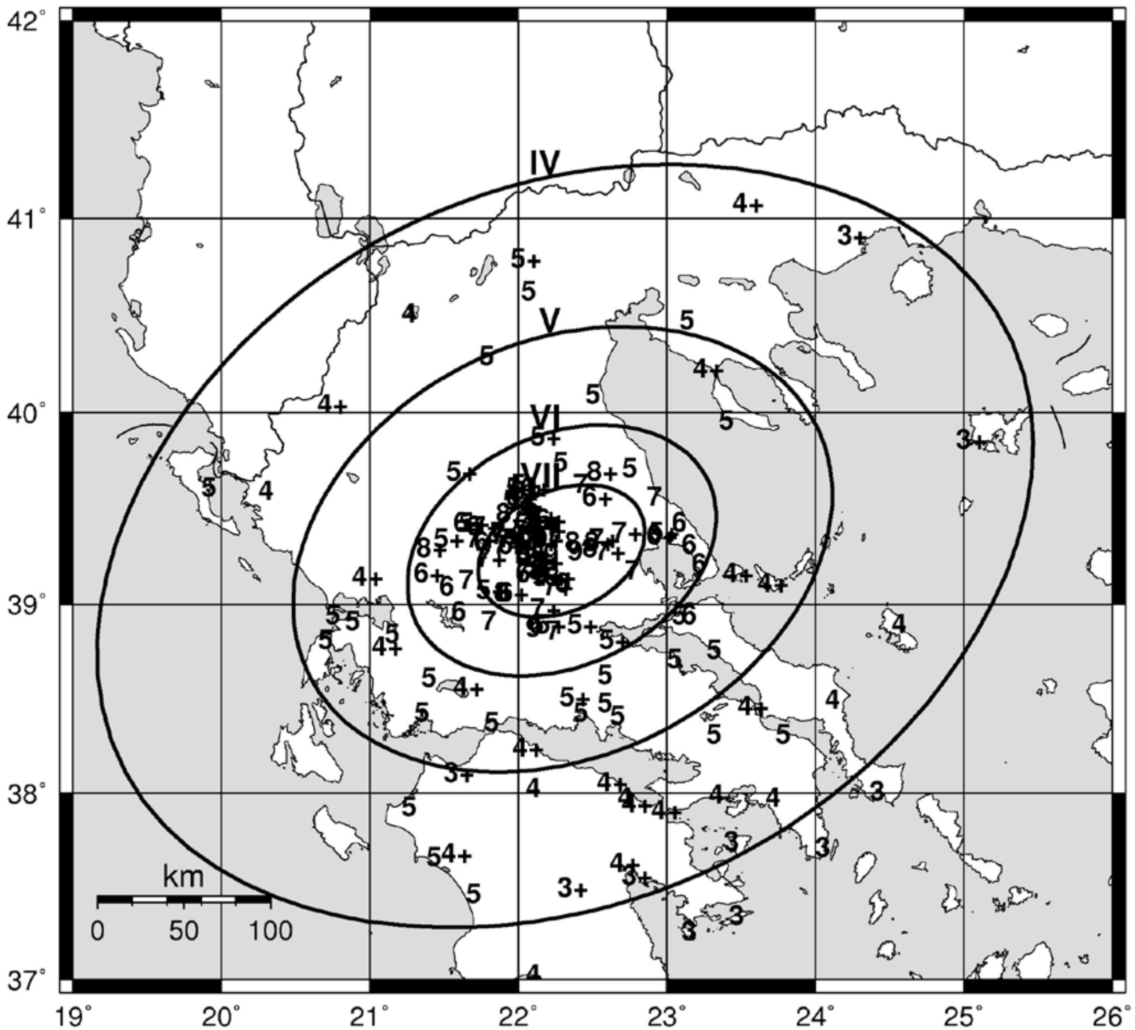


Abb. 1.
Athener Registrierung des Larissabebens, N-S-Komponente des Wiechertpendels.

## ISOSEISMAL MAPS OF PREVIOUS EVENTS
WITH IMPACT ON THESSALY BASIN




Isoseismal map of the April 30, 1954, M=7.0 Sofades earthquake

From *Papazachos et al. (1997)*

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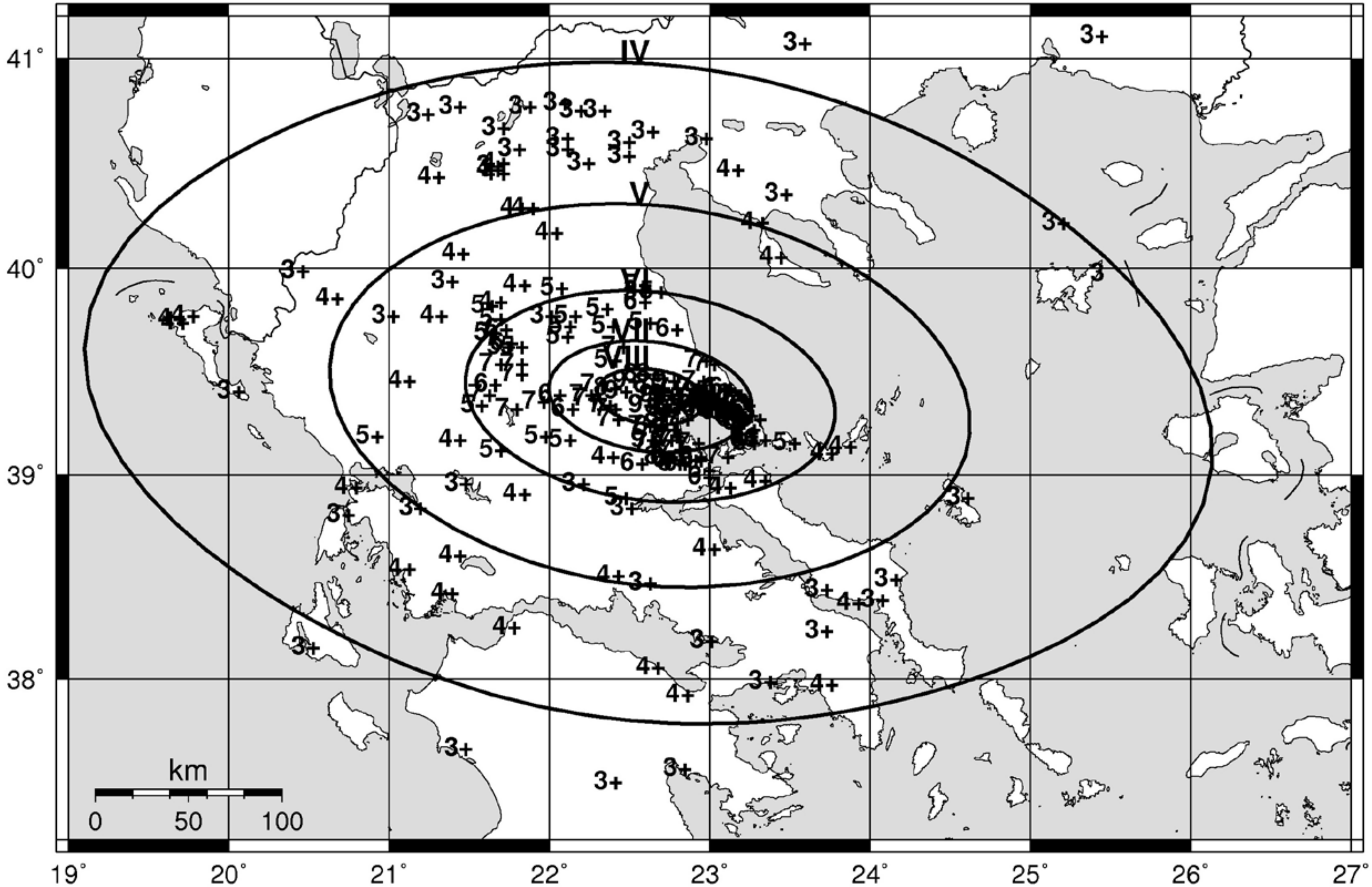
## ISOSEISMAL MAPS OF PREVIOUS EVENTS
## WITH IMPACT ON THESSALY BASIN




Isoseismal map of the March 8, 1957, M=6.8 Velestino earthquake

From *Papazachos et al. (1997)*

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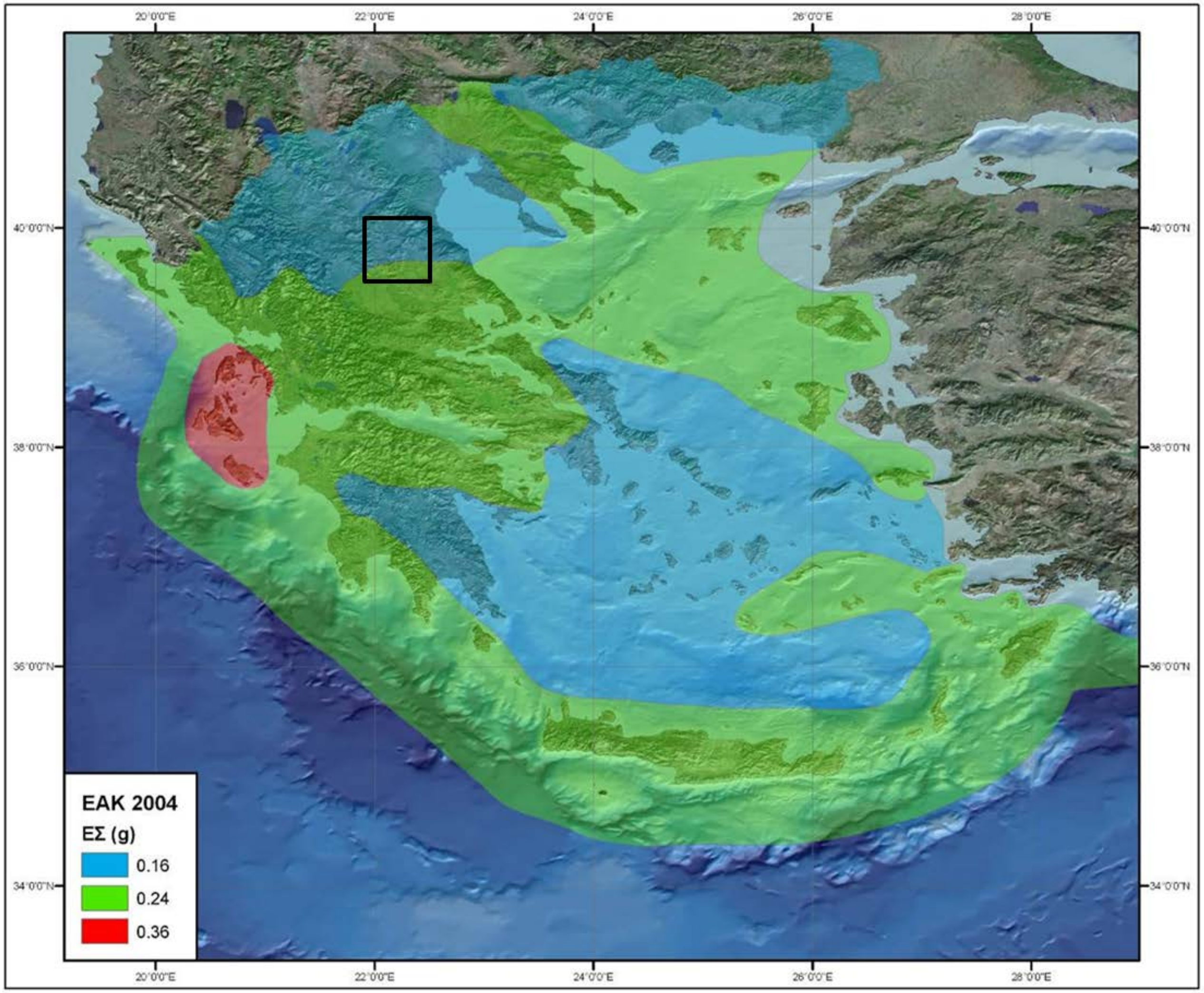
Department of Geophysics-Geothermics

# SEISMIC ZONES IN GREECE




The area of the March 2021 earthquake sequence, indicated by the black rectangle, belongs to two zones of the current Greek Building Code (EAK, 2003). The northern part (including Tyrnavos and Elassona) belongs to Zone I, with a Peak Ground Acceleration (PGA) value of 0.16g for a return period of 475 years. The southern part (including Larissa) belongs to Zone II with a PGA value of 0.24g.

From *EAK, 2003*

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# THE MARCH 3, 2021, Mw 6.3 & THE MARCH 4, 2021, Mw=6.1 THESSALY EARTHQUAKES

On March 3, 2021 (10:16:10 UTC) an earthquake struck Thessaly. The earthquake occurred in a region mainly characterized by normal faulting along NW-SE striking faults, that belong to the Northern Thessaly fault zone.

Based on various seismological observatories and institutes including the University of Athens (UOA), the Aristotle University of Thessaloniki (AUTH), the National Observatory of Athens (NOA), the Global Centroid Moment Tensor Catalog (GCMT), the United States Seismological Survey (USGS), the National Institute of Geophysics and Volcanology (INGV), the Kandilli Observatory and Earthquake Research Institute (KOERI), the Earthquake Research Department (ERD), the University of Nice Sophia-Antipolis, Valbonne, France (OCA), the Institute of Physics of the Globe of Paris (IPGP) and the German Research Centre for Geosciences (GFZ), the magnitude has been assessed as Mw 6.2 or 6.3 and its focal depth varied from 4 to 19 km. Based on the provided focal plane solutions, the mainshock was generated by the activation of an NW-SE striking normal fault.

The main shock was felt in the Thessaly basin and in the surrounding areas, from Athens in the south to the northern borders of Greece. Fortunately, it caused no fatalities, while only 3 people were slightly injured due to partial collapse of buildings with load-bearing masonry walls in Damasi village. The Disaster Management Special Units (EMAK) of the Hellenic Fire Service managed to rescue 6 people from the rubbles in the earthquake-affected villages of Mesochori and Magoula.

On March 4, 2021, (18:38:19 UTC), an earthquake struck the same area with magnitude varying from 5.8 to 6.3.

Based on the aforementioned seismological institutes, the parameters of the second earthquake were similar to those of the first earthquake. More specifically, it was generated by the rupture of a NW-SE striking normal fault and its focal depth varied from 7 to 17 km.

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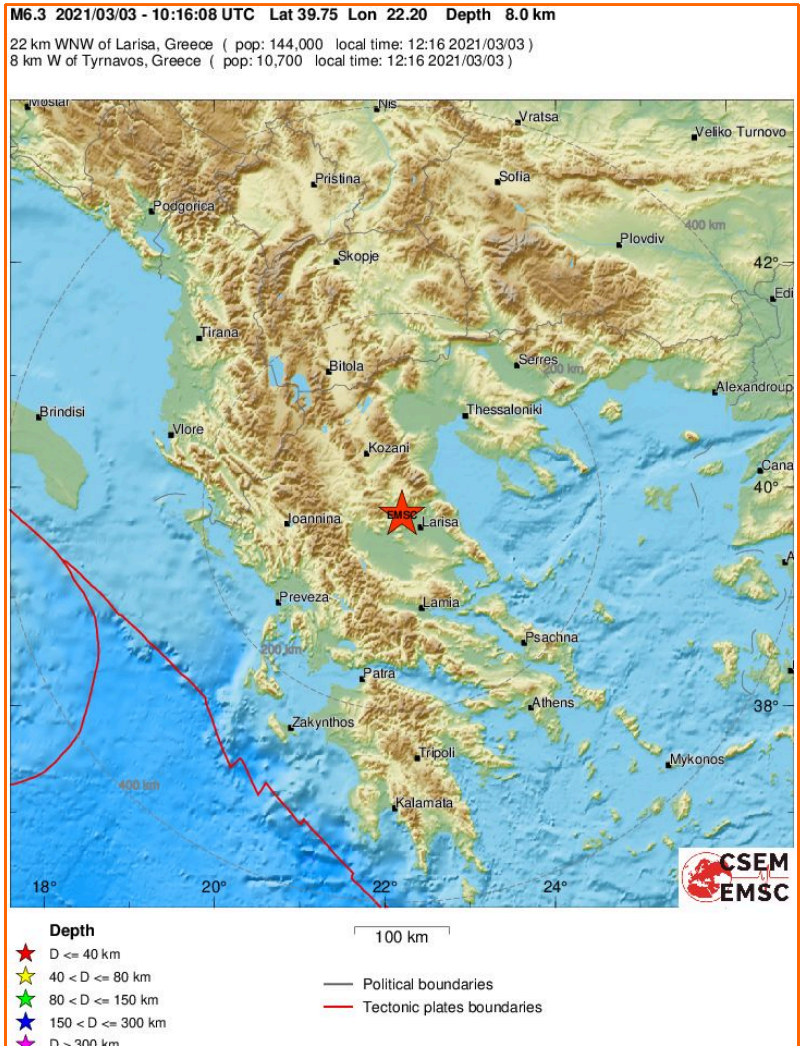
## EPICENTER LOCATION
## FOR THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE

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## EPICENTER LOCATION
## FOR THE MARCH 4, 2021, Mw=6.1 EARTHQUAKE


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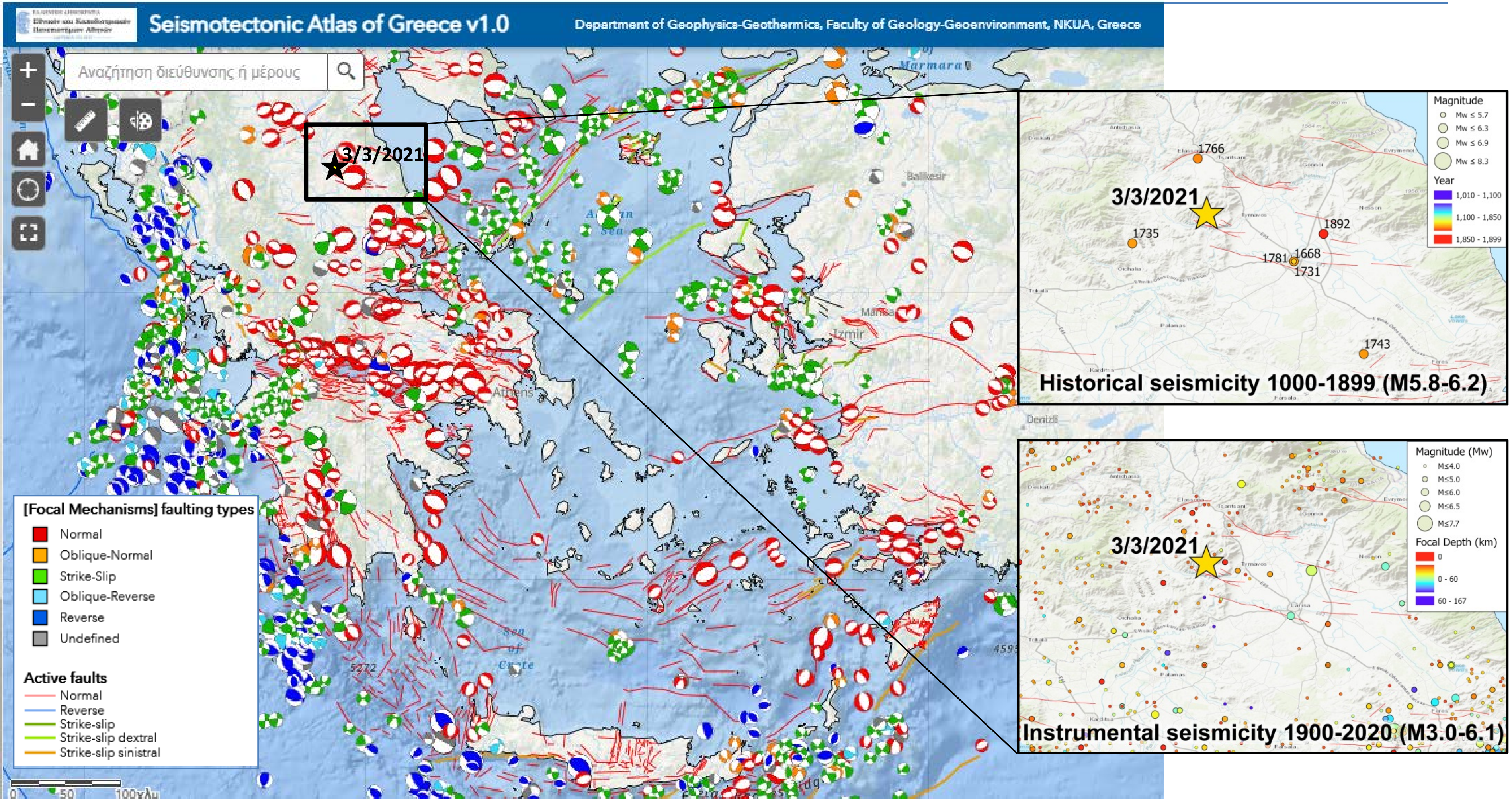
# THE EARLY MARCH 2021 THESSALY EARTHQUAKE SEQUENCE

## SEISMOTECTONIC CONTEXT




Snapshots from the New Seismotectonic Atlas of Greece (Kassaras et al., 2020). Interactive GIS application available at: http://www.geophysics.geol.uoa.gr/atlas.html

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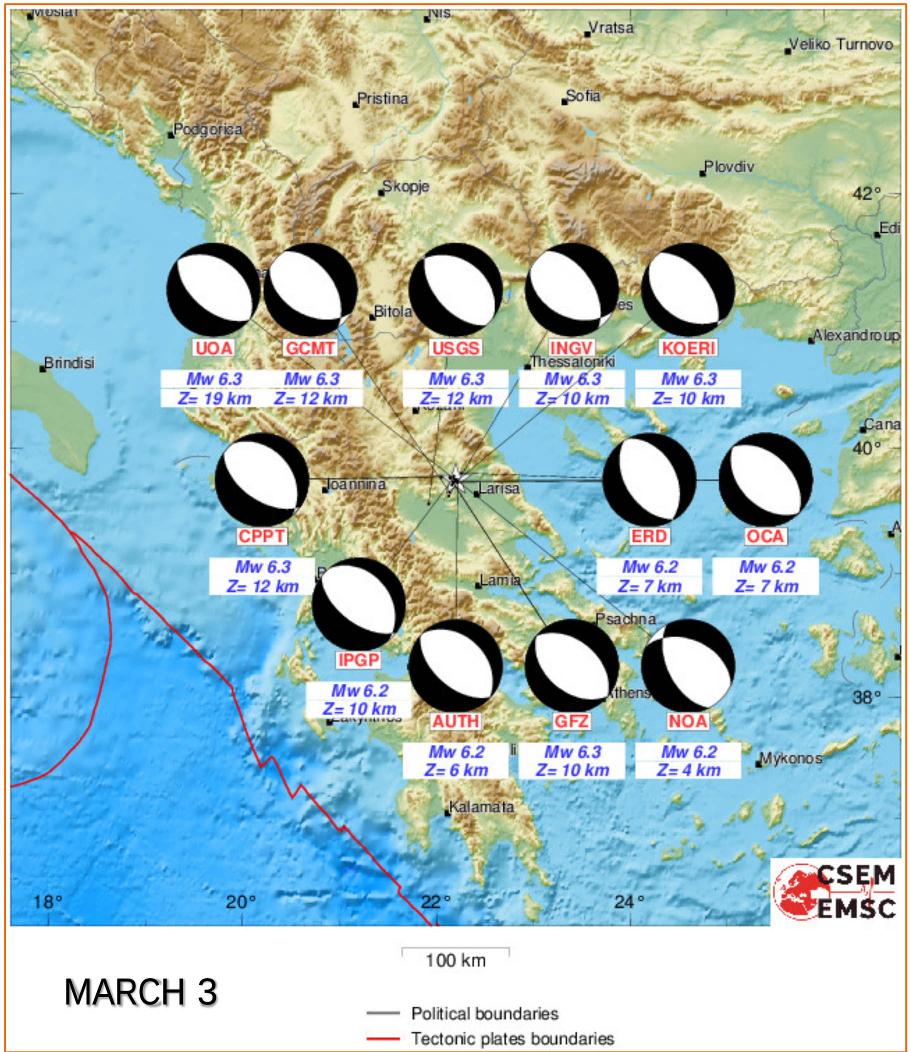
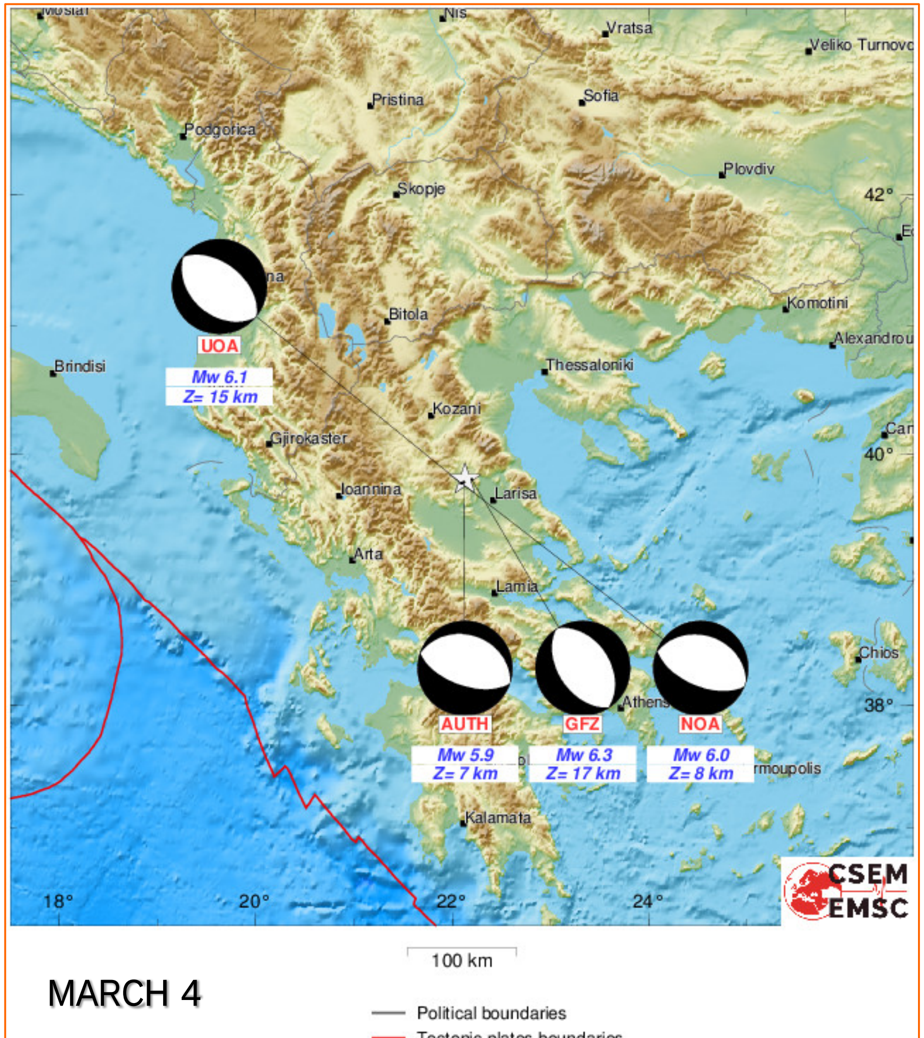
# QUICK SOLUTIONS AND REGIONAL MOMENT TENSORS
## FOR THE MARCH 3 AND MARCH 4, 2021 EARTHQUAKES




MARCH 3




MARCH 4

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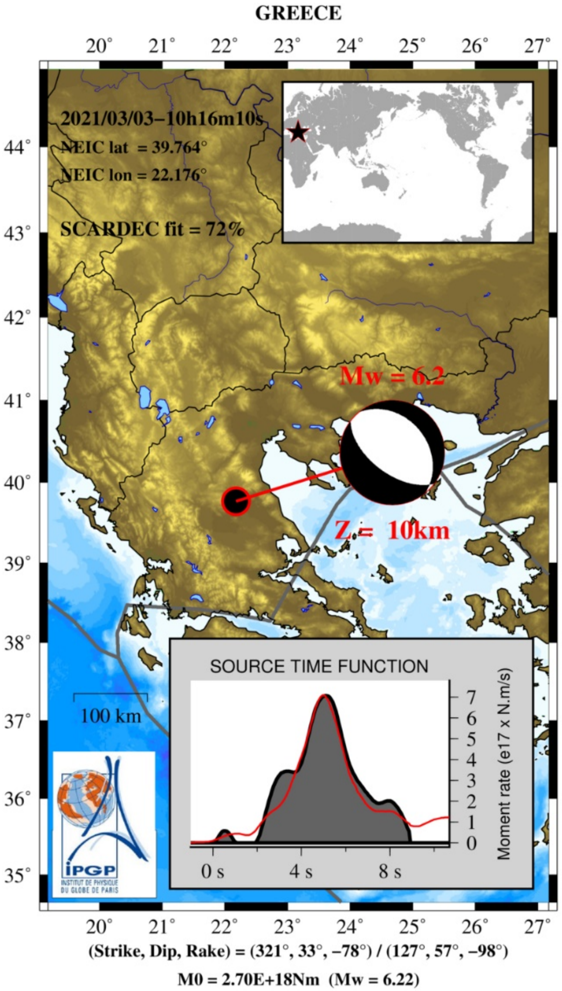
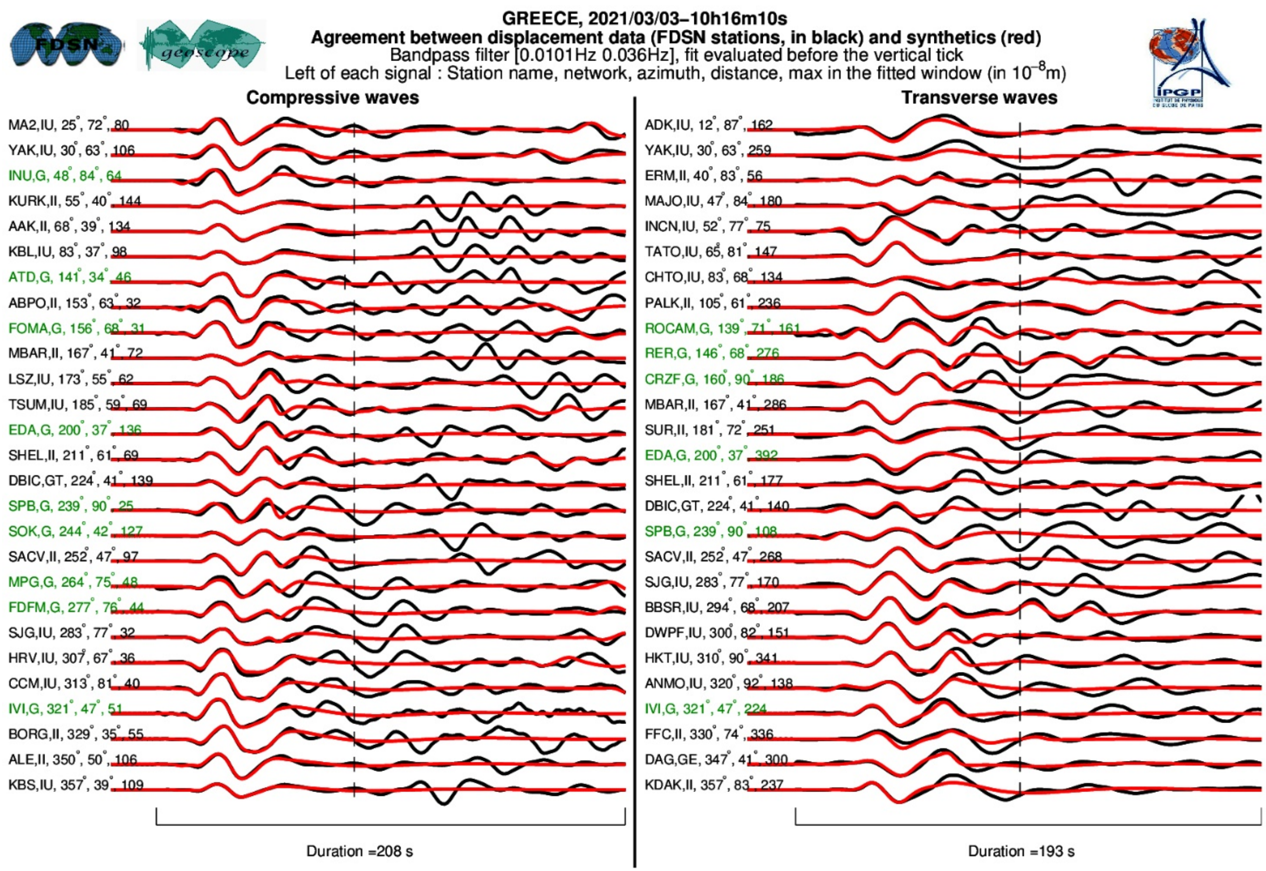
# QUICK SOLUTION
## FOR THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




http://geoscope.ipgp.fr/index.php/en/catalog/earthquake-description?seis=us7000df40

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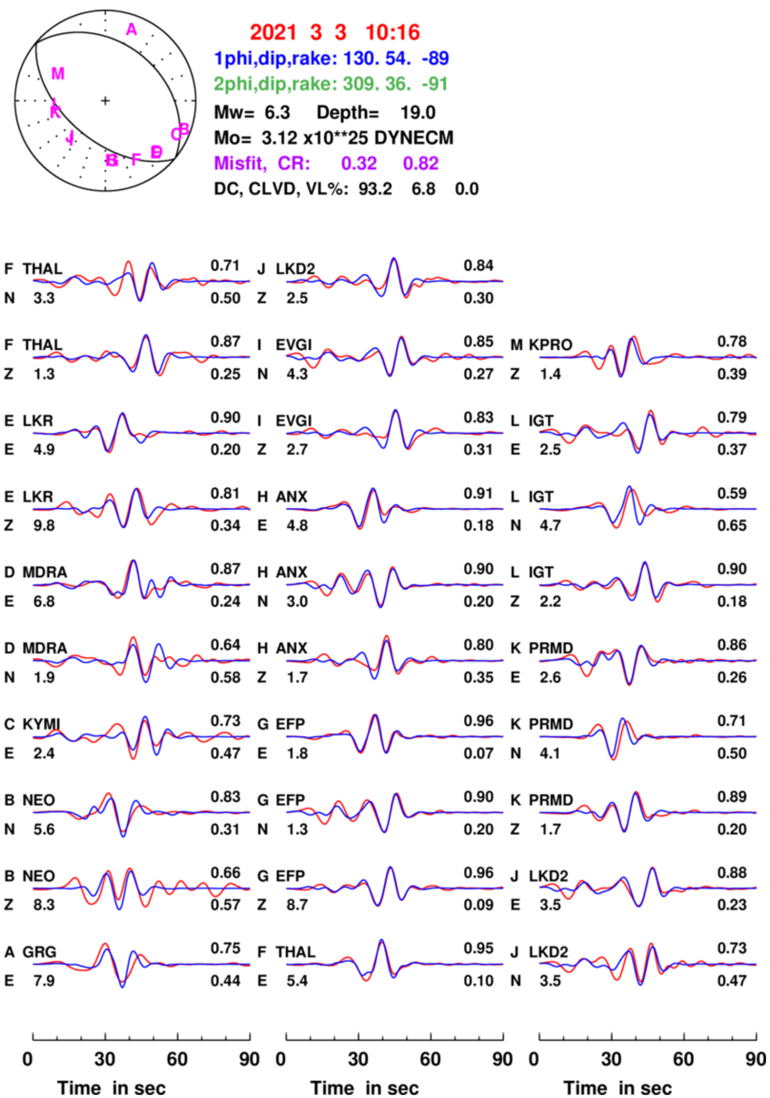
# THE 2021 THESSALY EARTHQUAKES
## FOCAL MECHANISM OF THE MARCH 3 EVENT




The focal mechanism of the March 3, $M_w$=6.3 mainshock was determined using regional moment tensor inversion. After the calculation of Green functions, using the frequency-wavenumber integration method, synthetic waveforms were obtained and compared with the recorded ones, following the procedure proposed by Papadimitriou et al. (2012).

The figure on the left presents the source parameters for the March 3, Mw=6.3 mainshock, where the red waveforms represent the recorded signals and the blue the synthetic ones. The obtained focal mechanism reveals normal faulting in a ~NW-SE direction. The preliminary centroid depth was determined at 19.0 km, while the seismic moment was calculated $M_0=3.12\cdot10^{25}$ dyn·cm, representing a moment magnitude equal to $M_w$=6.3.

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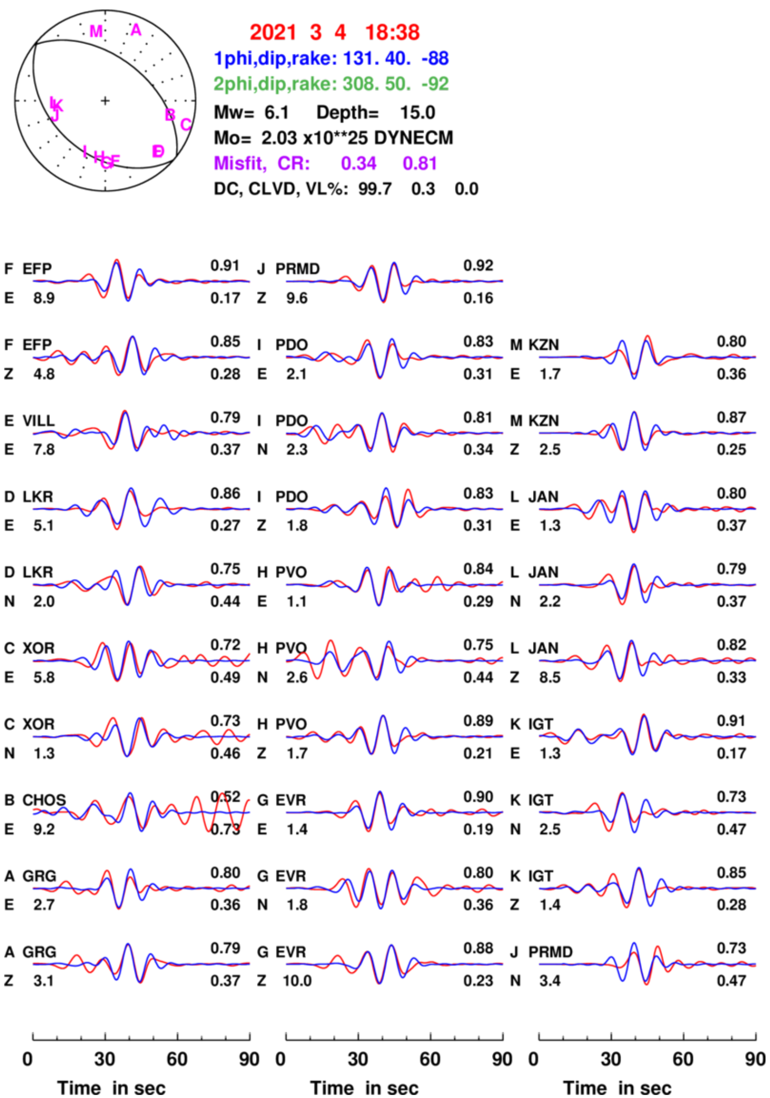
# THE 2021 THESSALY EARTHQUAKES
## FOCAL MECHANISM OF THE MARCH 4 EVENT




The day after the $M_w$=6.3 main event, another very strong earthquake occurred in the area. Similarly, the focal mechanism was determined through regional moment tensor inversion (Papadimitriou et al., 2012).

The figure on the left presents the source parameters for the March 4, 2021 shock, where the red waveforms represent the recorded signals and the blue the synthetic ones. As in the case of the mainshock, the obtained focal mechanism reveals normal faulting in a ~NW-SE direction. The preliminary centroid depth was determined at 15.0 km, while the seismic moment was calculated $M_0=2.03\cdot10^{25}$ dyn·cm, representing a moment magnitude equal to $M_w$=6.1.

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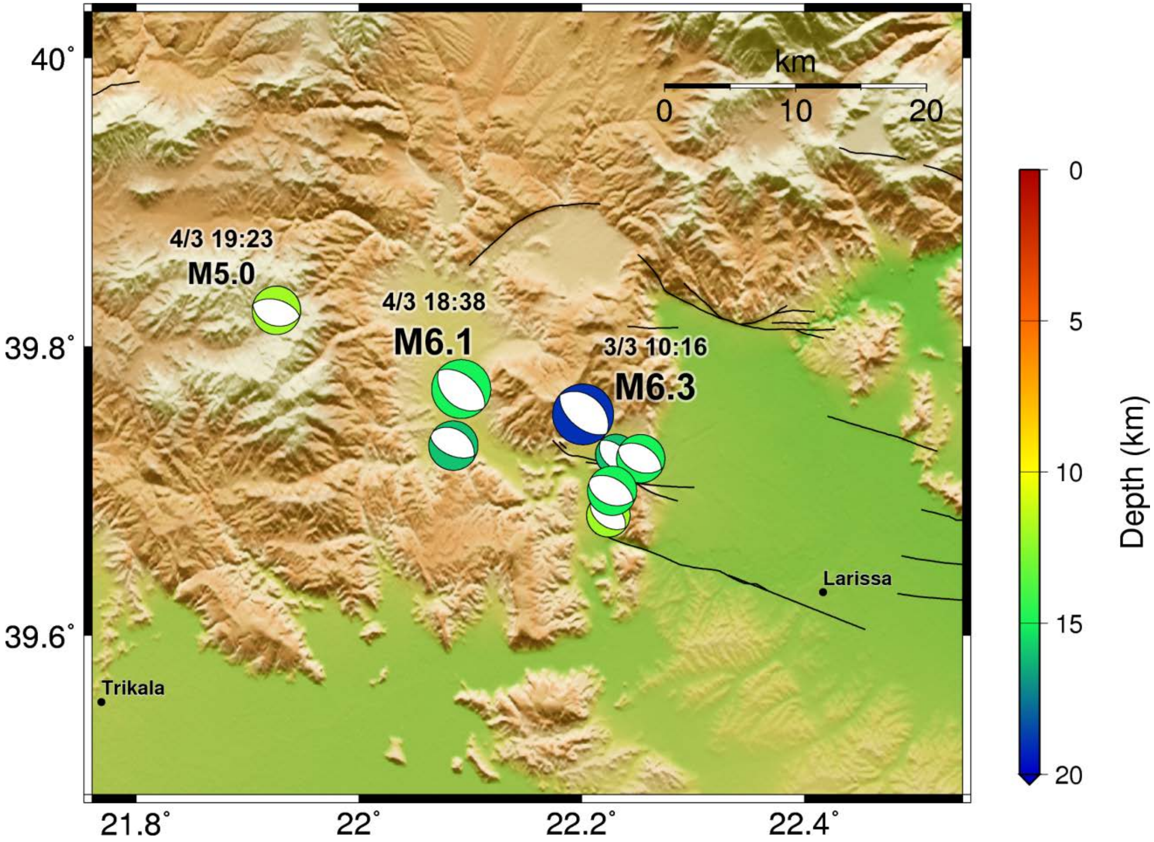
## FOCAL MECHANISMS




Focal mechanisms of the March 2021 main events and major aftershocks resolved at SL-NKUA using regional waveform modeling.

The solutions are consistent with normal faulting in a NW-SE direction. The nodal plane dipping NE is considered to represent the causative fault.

For more information, visit the web-page of Significant Earthquakes in Greece during 2021 at SL-NKUA:
http://www.geophysics.geol.uoa.gr/stations/gmaps3/leaf_significant.php?mapmode=mech&lng=en&year=2021

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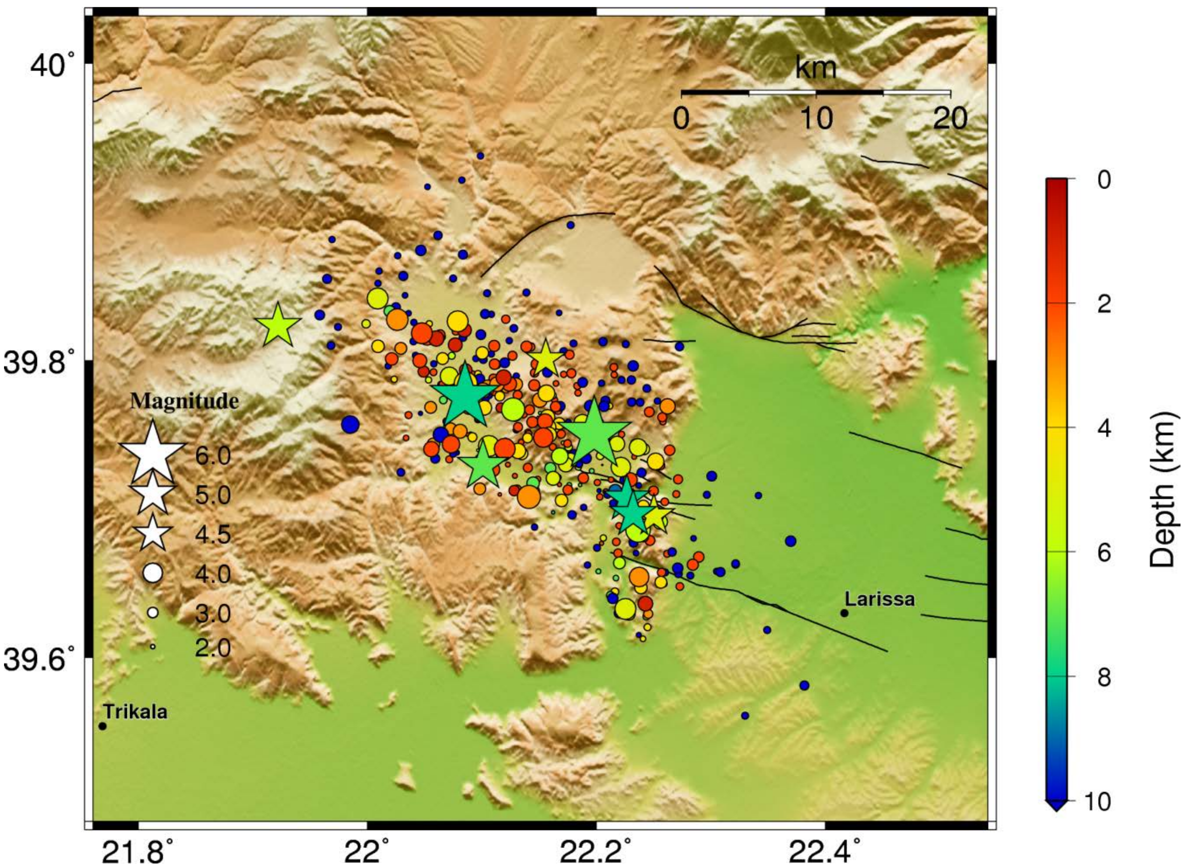
## PRELIMINARY LOCATIONS




Preliminary locations of over 390 events that were detected and analysed by the Seismological Laboratory of the National and Kapodistrian University of Athens (SL-NKUA) during the period between 28 February and 6 March 2021, including 20 foreshocks. The earthquakes were recorded by local and regional stations of the Hellenic Unified Seismological Network (HUSN). The major events with M≥4.5 are depicted by stars.

The $M_w$=6.3 mainshock's epicenter is located ~23 km WNW of Larissa city and ~43 km ENE of Trikala city. The aftershock sequence spans over 20 km in an NW-SE direction. The hypocenters are located at crustal depths, mainly shallower than 15 km.

Black lines depict active faults from the NOAfaults database (Ganas et al., 2018)

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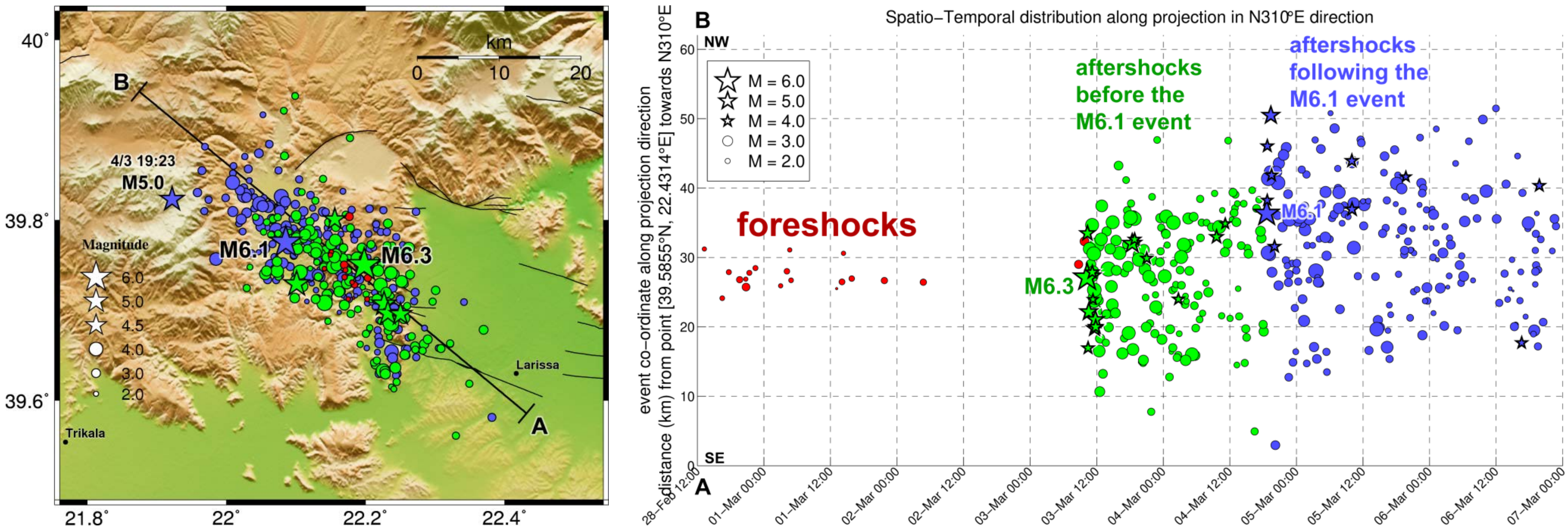
# SPATIOTEMPORAL EVOLUTION OF THE FORESHOCK-AFTERSHOCK SEQUENCE (28 February - 6 March 2021)




The preliminary results for the March 2021 earthquake sequence reveal the existence of foreshock activity (red) near the epicentral region where the $M_w$=6.3 mainshock occurred, with 20 events of magnitude 1.1 to 2.8 detected and located by SL-NKUA in the period between February 28 and March 3, two of which within two hours before the mainshock, which occurred at 10:16 UTC.

The aftershock zone (green) spans ~27km in a N310°E direction, with the mainshock being in the middle and major aftershocks occurring during the first hours at distances within ±10 km from the mainshock, including an $M_w$=5.2 event at 18:24 UTC.

The $M_w$=6.1 major event that occurred on March 4, 18:38 UTC triggered significant aftershocks (blue) towards NW, including an $M_w$=5.0 at 19:23 UTC, in a region where only few aftershocks had occurred after the $M_w$=6.3 event.

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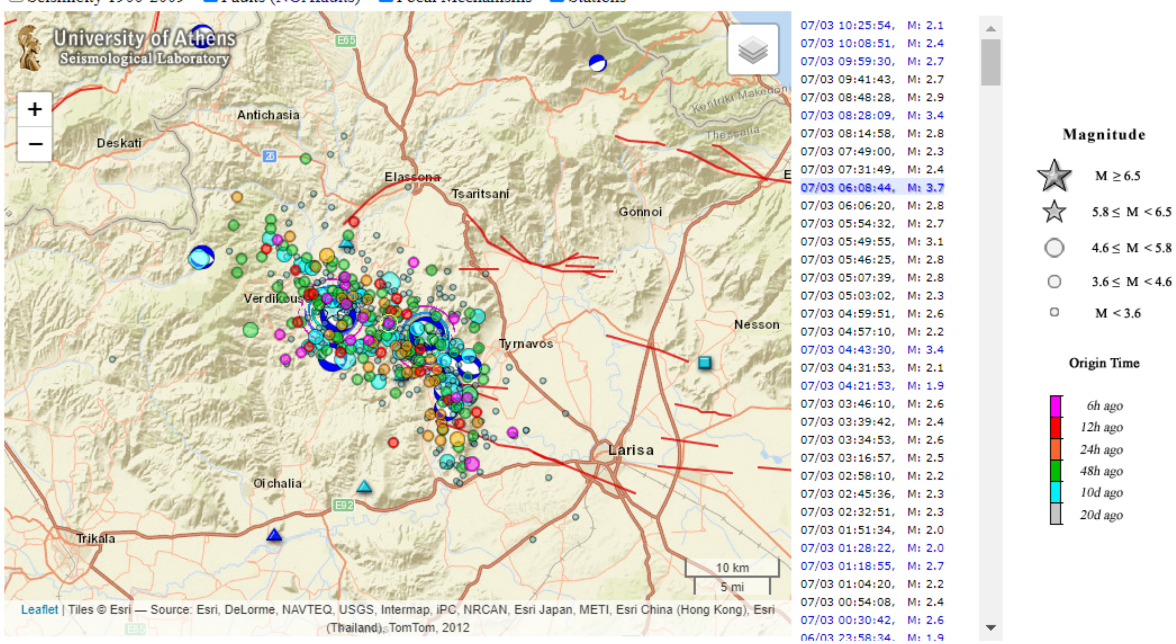
# SL-NKUA SPECIAL WEB-PAGE
## FOR MONITORING OF THE SEQUENCE

**Earthquakes of the last 8 days in the area of Larissa, Greece**

☐ Seismicity 1900-2009 ☑ Faults (NOAfaults) ☑ Focal Mechanisms ☑ Stations




Click on headers to sort table

| # | Sol. Type | Origin Time (GMT) | Epicentral Location | Latitude (°N) | Longitude (°E) | Depth (km) | Mag. | Foc.Mech. |
|---|---|---|---|---|---|---|---|---|
| 1 | M | 07/03/2021 10:25:54 | 26.8 km WNW of Larissa | 39.7630 | 22.1537 | 4.0 | 2.1 | - |
| 2 | M | 07/03/2021 10:08:51 | 33.6 km WNW of Larissa | 39.7860 | 22.0790 | 7.0 | 2.4 | - |
| 3 | M | 07/03/2021 09:59:30 | 31.5 km WNW of Larissa | 39.7807 | 22.1022 | 8.0 | 2.7 | - |
| 4 | A | 07/03/2021 09:41:43 | 30.9 km NE of Trikala | 39.7524 | 22.0214 | 10.0 | 2.7 | - |
| 5 | A | 07/03/2021 08:48:28 | 29.4 km WNW of Larissa | 39.7685 | 22.1224 | 2.0 | 2.9 | - |

Special interactive web-page for the seismicity in the March 2021 aftershock zone, automatically detected and manually analyzed at the SL-NKUA.

Data are updated as soon as an earthquake is automatically detected and located or manually analyzed.

The user can also display mapped active faults from the NOAfaults database (Ganas et al., 2018), past seismicity (Makropoulos et al., 2012), focal mechanisms determined at SL-NKUA and view real-time waveforms of local and regional HUSN stations.

To access the interactive seismicity monitoring map, visit the web-page at:
http://www.geophysics.geol.uoa.gr/stations/gmaps3/larissa_leaf.php?lng=en

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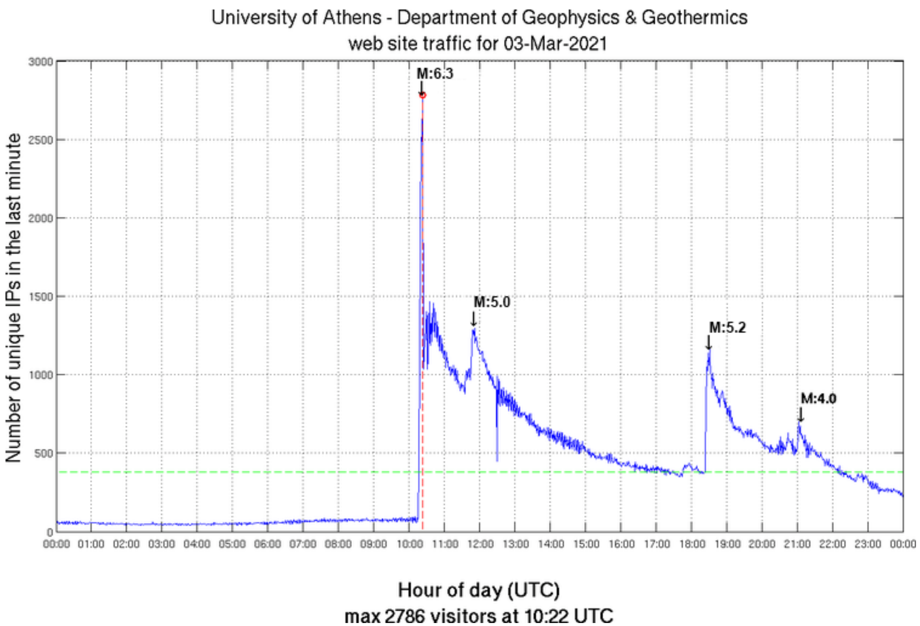
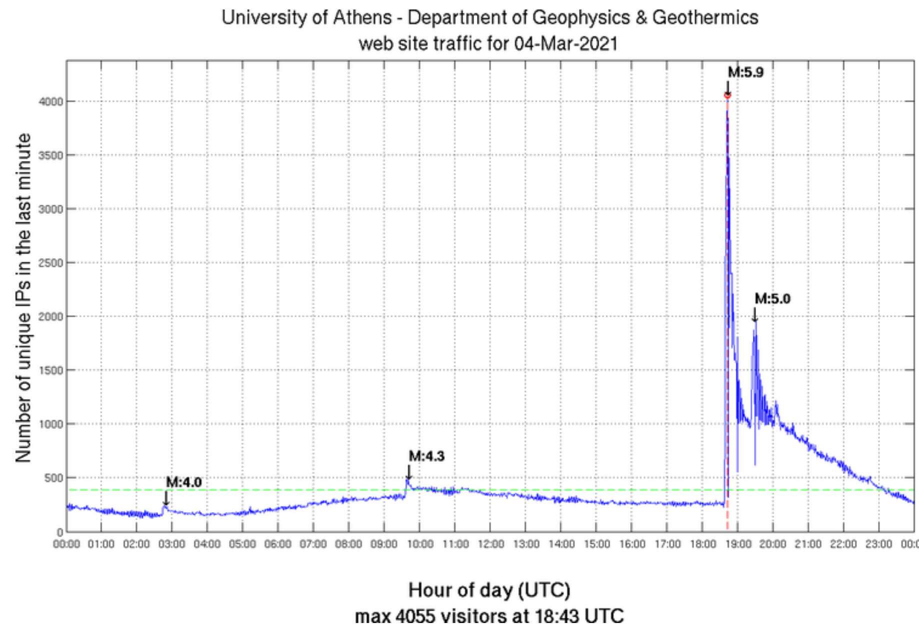
## SL-NKUA SPECIAL WEB-PAGE
## NETWORK TRAFFIC




The web-site of the Sector of Geophysics - Geothermics of the Department of Geology and Geoenvironment of the National and Kapodistrian University of Athens presented a significant spike in the network traffic. The number of unique visitors per minute reached 2786 shortly after the March 3, $M_w$=6.3 earthquake and 4055 after the March 4, $M_w$=6.1 earthquake at Damasi. Spikes in the network traffic are also observed after major aftershocks that were strongly felt by the local population.

The interactive map real-time seismicity in Greece as monitored by SL-NKUA can be visited at:
http://www.geophysics.geol.uoa.gr/stations/maps/recent.html

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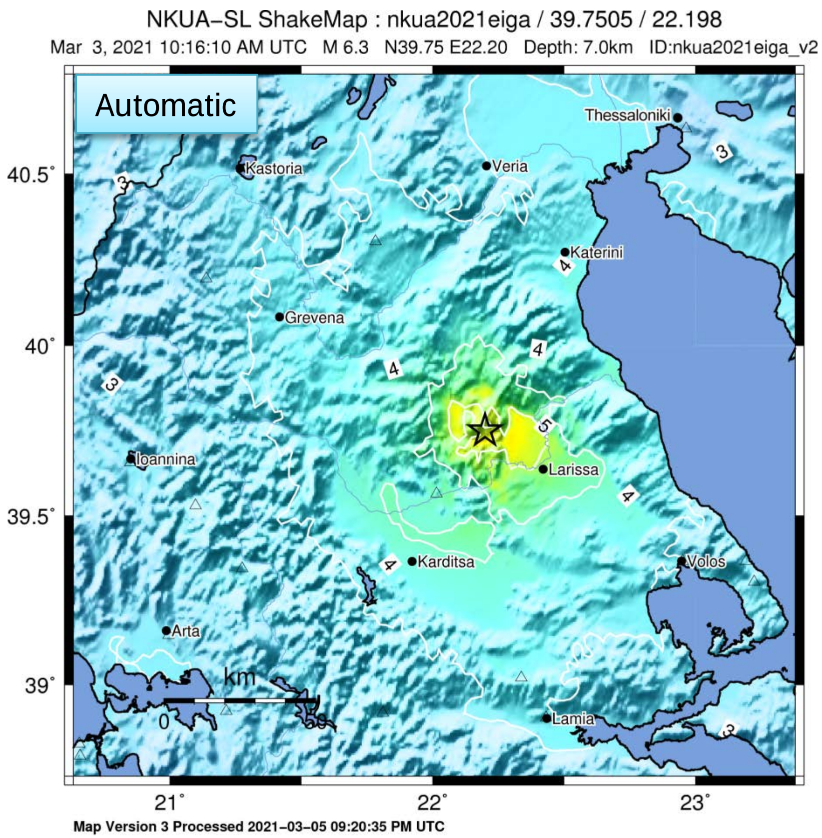
# SHAKEMAP (INTENSITY)
## FOR THE MARCH 3, 2021 EARTHQUAKE

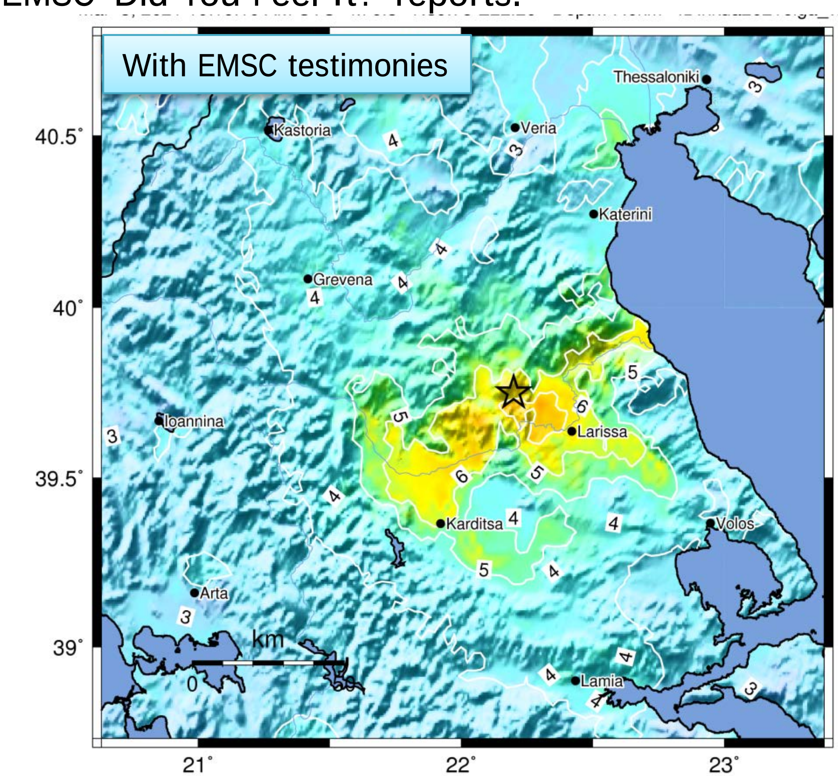



| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <0.05 | 0.3 | 2.8 | 6.2 | 12 | 22 | 40 | 75 | >139 |
| PEAK VEL.(cm/s) | <0.02 | 0.1 | 1.4 | 4.7 | 9.6 | 20 | 41 | 86 | >178 |
| INSTRUMENTAL INTENSITY | I | II–III | IV | V | VI | VII | VIII | IX | X+ |

Scale based upon Worden et al. (2012)

◀ Automatically generated ShakeMap (USGS, 2017) for the March 3, 2021, $M_w$=6.3 mainshock. The maximum expected intensity values reach VI near the epicentral area.

▼ Respective ShakeMap after adding information from EMSC 'Did You Feel It?' reports.




For more information about the 2021 Damasi $M_w$=6.3 mainshock, visit the event's web-page at SL-NKUA:
http://www.geophysics.geol.uoa.gr/stations/gmaps3/eventpage_leaf.php?scid=nkua2021eiga&lng=en

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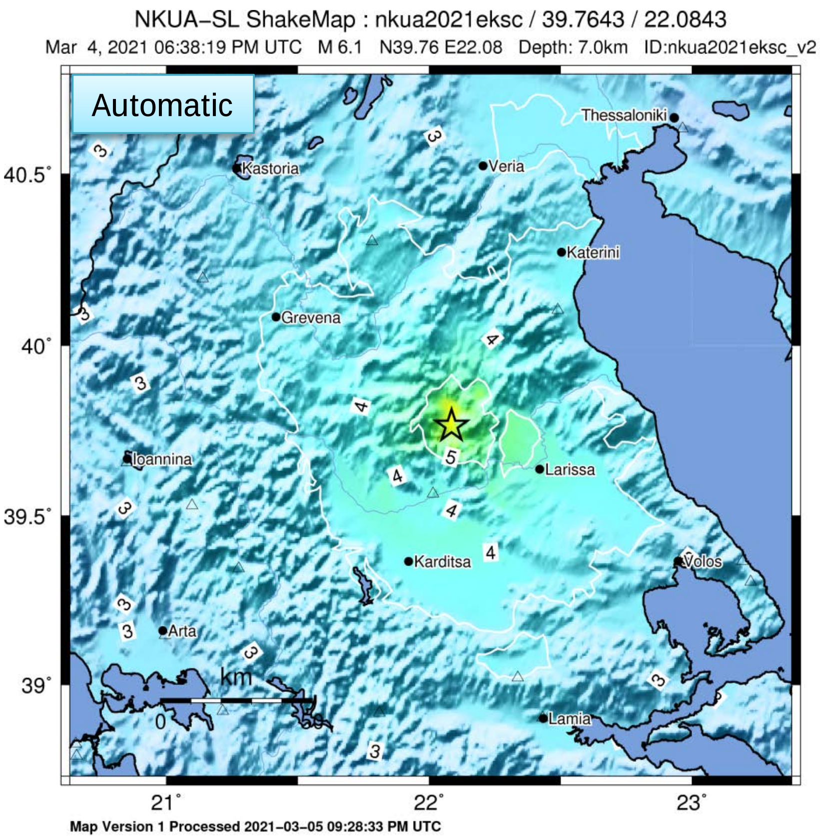
# SHAKEMAP (INTENSITY) FOR THE MARCH 4, 2021 EARTHQUAKE

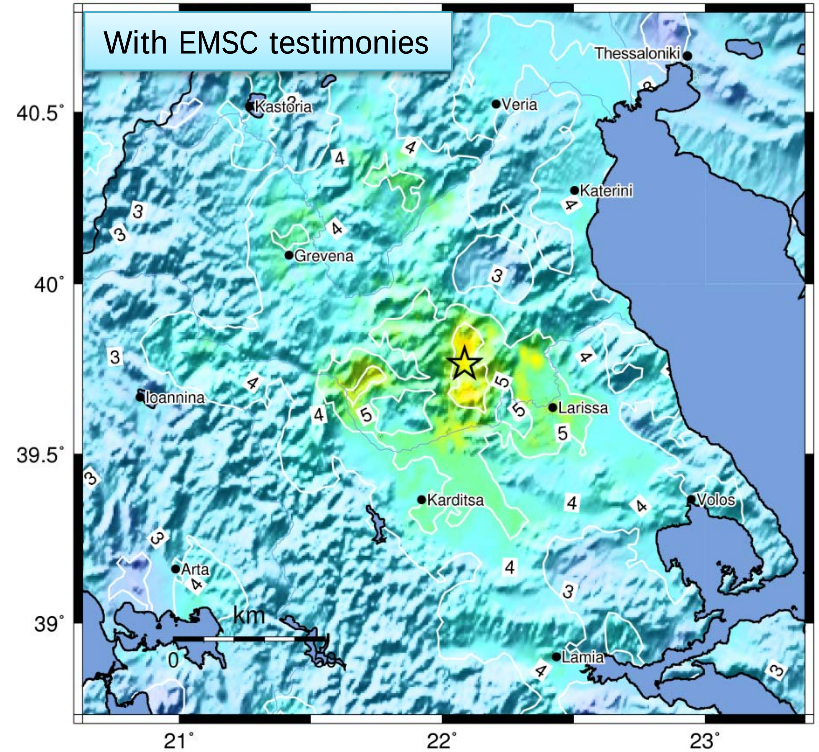



| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <0.05 | 0.3 | 2.8 | 6.2 | 12 | 22 | 40 | 75 | >139 |
| PEAK VEL.(cm/s) | <0.02 | 0.1 | 1.4 | 4.7 | 9.6 | 20 | 41 | 86 | >178 |
| INSTRUMENTAL INTENSITY | I | II–III | IV | V | VI | VII | VIII | IX | X+ |

Scale based upon Worden et al. (2012)

◀ Automatically generated ShakeMap (USGS, 2017) for the March 4, 2021, $M_w$=6.1 main event. The maximum expected intensity values reach VI near the epicentral area.

▼ Respective ShakeMap after adding information from EMSC 'Did You Feel It?' reports.




For more information about the 2021 Damasi $M_w$=6.1 major event, visit its web-page at SL-NKUA:
www.geophysics.geol.uoa.gr/stations/gmaps3/eventpage_leaf.php?scid=nkua2021eksc&lng=en

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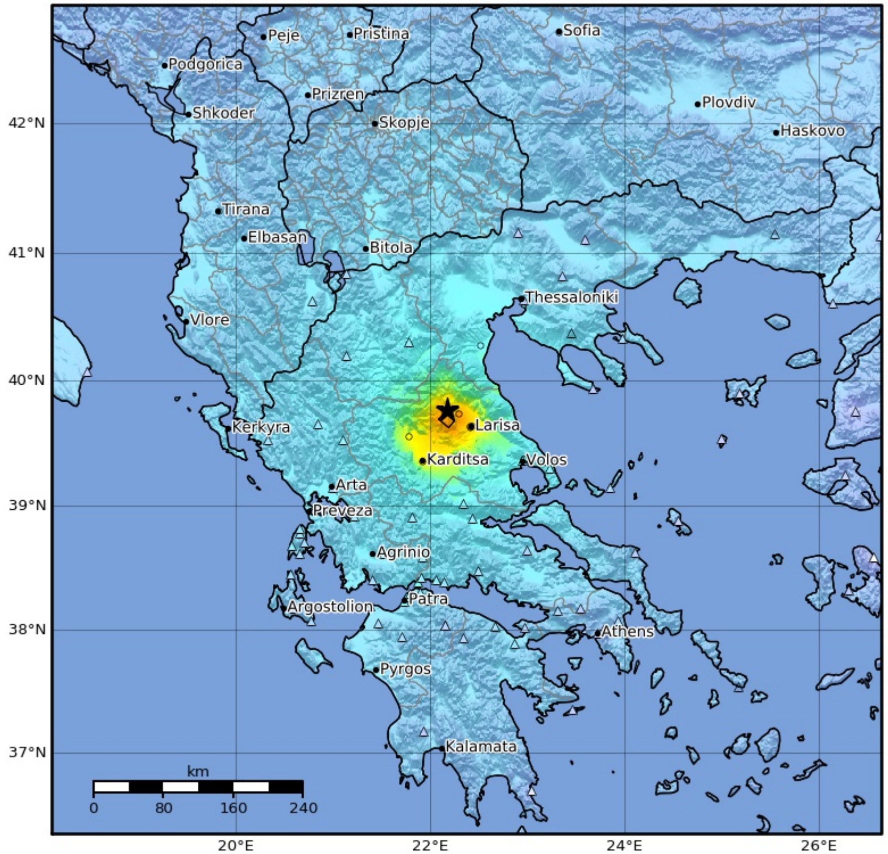
USGS science for a changing world

# INTENSITY MAPS
## FOR THE MARCH 3, 2021 EARTHQUAKE

ITSAK

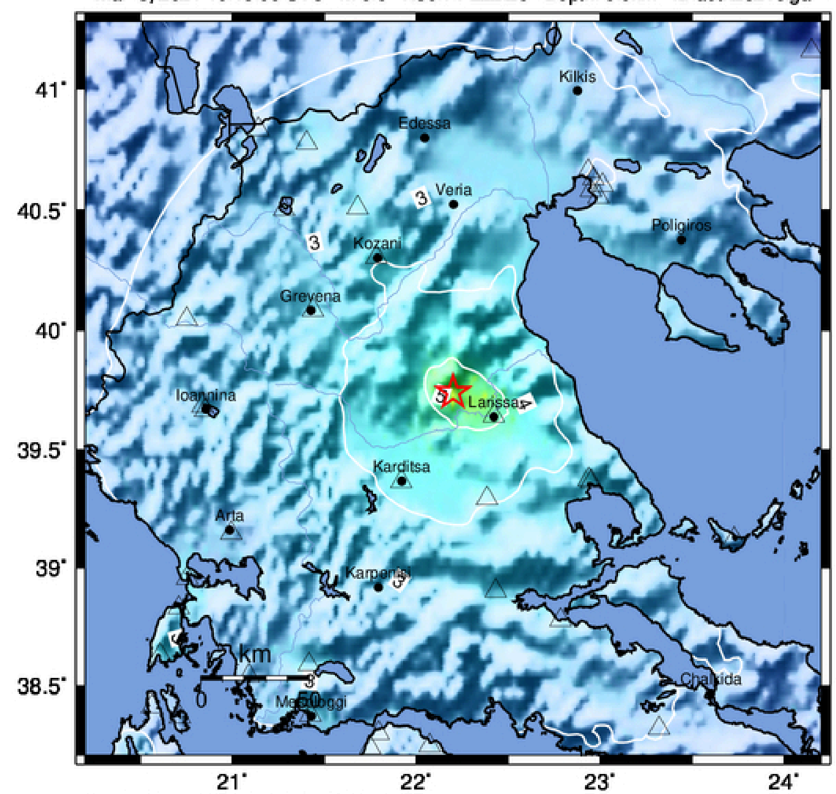
Macroseismic Intensity Map USGS
ShakeMap: 10 km WNW of Týrnavos, Thessaly, GR
Mar 03, 2021 10:16:10 UTC M6.3 N39.76 E22.18 Depth: 10.0km ID:us7000df40




| 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 7: Processed 2021-03-07T11:39:44Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture

ITSAK ShakeMap : Thessaly – C. Greece
Mar 3, 2021 10:16:08 UTC M 5.9 N39.74 E22.20 Depth: 0.0km ID:auth2021eiga




Map Version 2 Processed 2021–03–03 10:28:10 UTC

| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <0.05 | 0.3 | 2.8 | 6.2 | 12 | 22 | 40 | 75 | >139 |
| PEAK VEL.(cm/s) | <0.02 | 0.1 | 1.4 | 4.7 | 9.6 | 20 | 41 | 86 | >178 |
| INSTRUMENTAL INTENSITY | I | II–III | IV | V | VI | VII | VIII | IX | X+ |

Scale based upon Worden et al. (2012)

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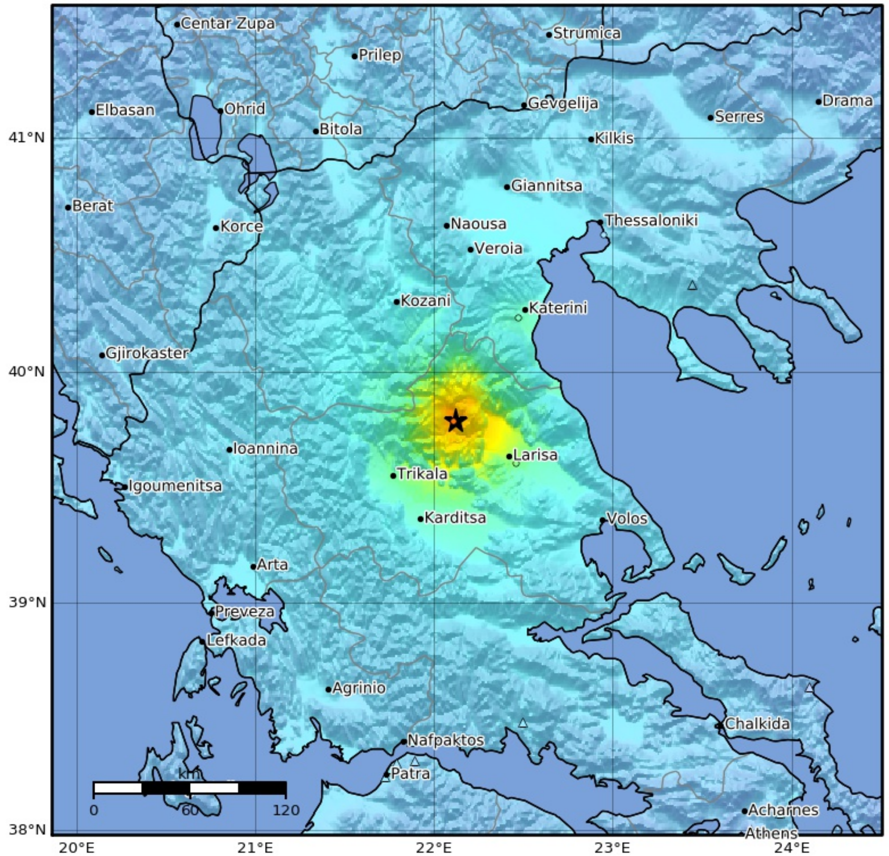
# INTENSITY MAPS
## FOR THE MARCH 4, 2021 EARTHQUAKE

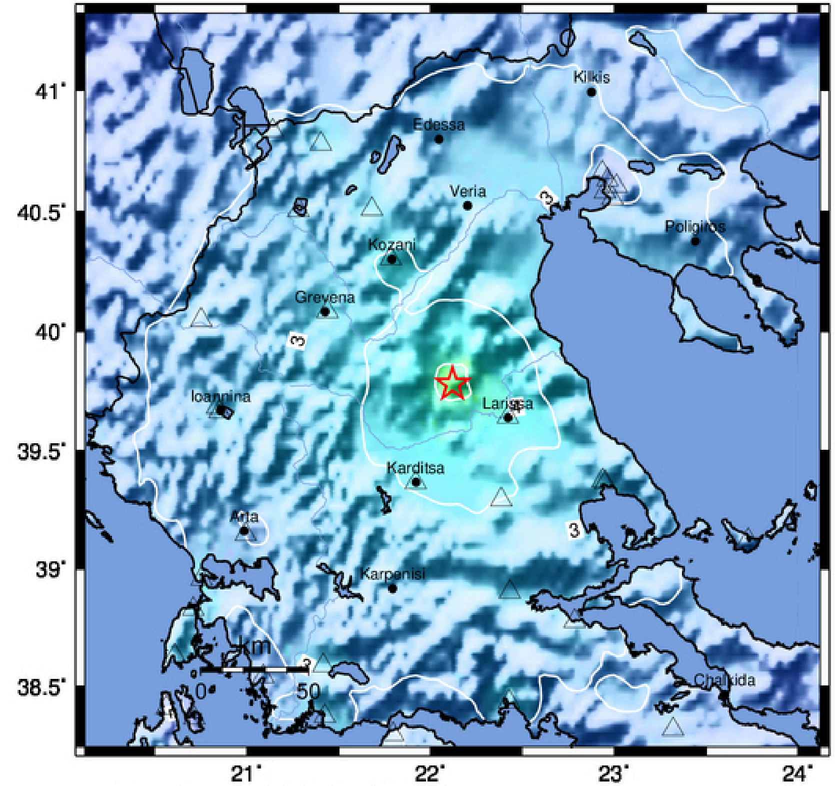
Macroseismic Intensity Map USGS
ShakeMap: 12 km E of Verdikoússa, Thessaly, GR
Mar 04, 2021 18:38:19 UTC M5.8 N39.79 E22.12 Depth: 10.0km ID:us7000dfku




| 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 7: Processed 2021-03-07T08:39:08Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

ITSAK ShakeMap : Thessaly – C. Greece
Mar 4, 2021 18:38:17 UTC M 5.8 N39.78 E22.12 Depth: 10.0km ID:auth2021eksc




Map Version 2 Processed 2021–03–05 12:47:11 UTC

| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <0.05 | 0.3 | 2.8 | 6.2 | 12 | 22 | 40 | 75 | >139 |
| PEAK VEL.(cm/s) | <0.02 | 0.1 | 1.4 | 4.7 | 9.6 | 20 | 41 | 86 | >178 |
| INSTRUMENTAL INTENSITY | I | II–III | IV | V | VI | VII | VIII | IX | X+ |

Scale based upon Worden et al. (2012)

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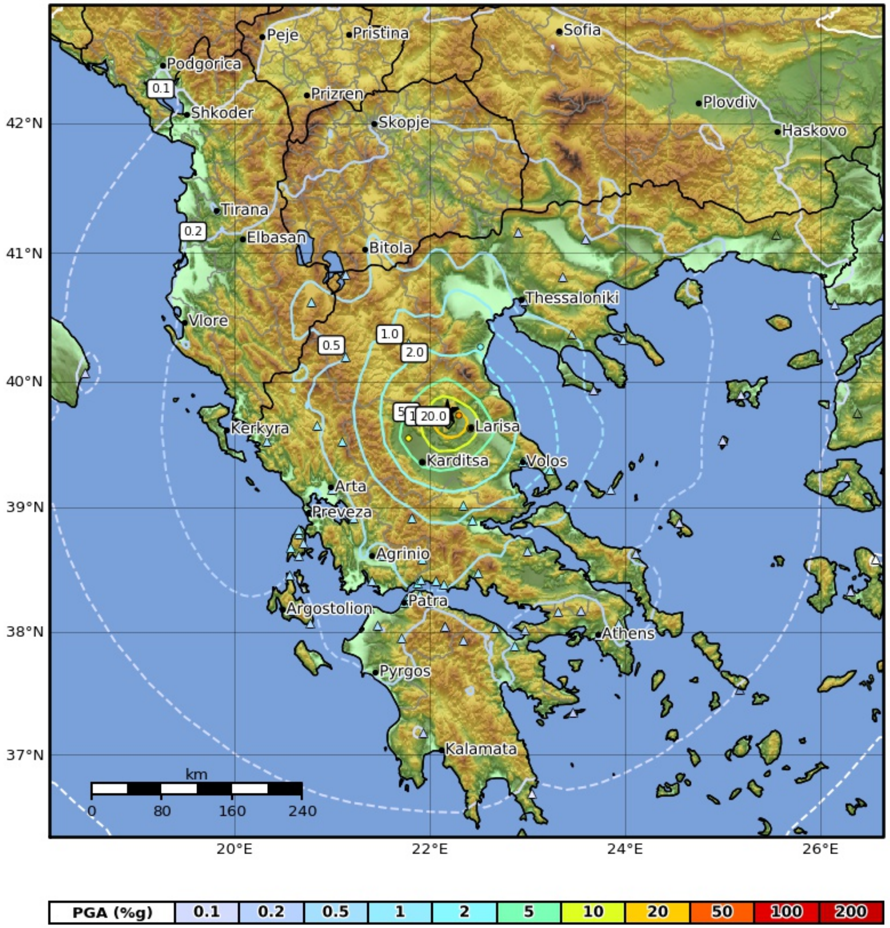
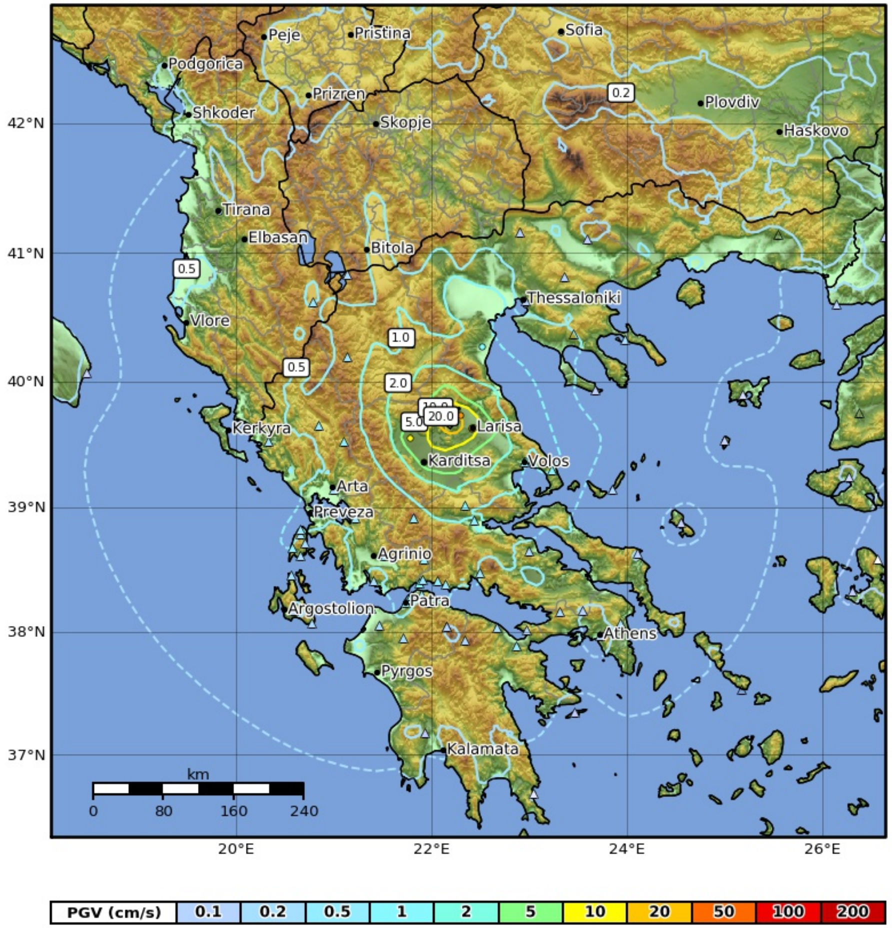
# PEAK GROUND ACCELERATION & PEAK GROUND VELOCITY MAPS
## FOR THE MARCH 3, 2021 EARTHQUAKE

Peak Ground Acceleration Map USGS
ShakeMap: 10 km WNW of Týrnavos, Thessaly, GR
Mar 03, 2021 10:16:10 UTC M6.3 N39.76 E22.18 Depth: 10.0km ID:us7000df40




Scale based on Worden et al. (2012) Version 7: Processed 2021-03-07T11:39:44Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▬ Rupture

Peak Ground Velocity Map USGS
ShakeMap: 10 km WNW of Týrnavos, Thessaly, GR
Mar 03, 2021 10:16:10 UTC M6.3 N39.76 E22.18 Depth: 10.0km ID:us7000df40




Scale based on Worden et al. (2012) Version 7: Processed 2021-03-07T11:39:44Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▬ Rupture

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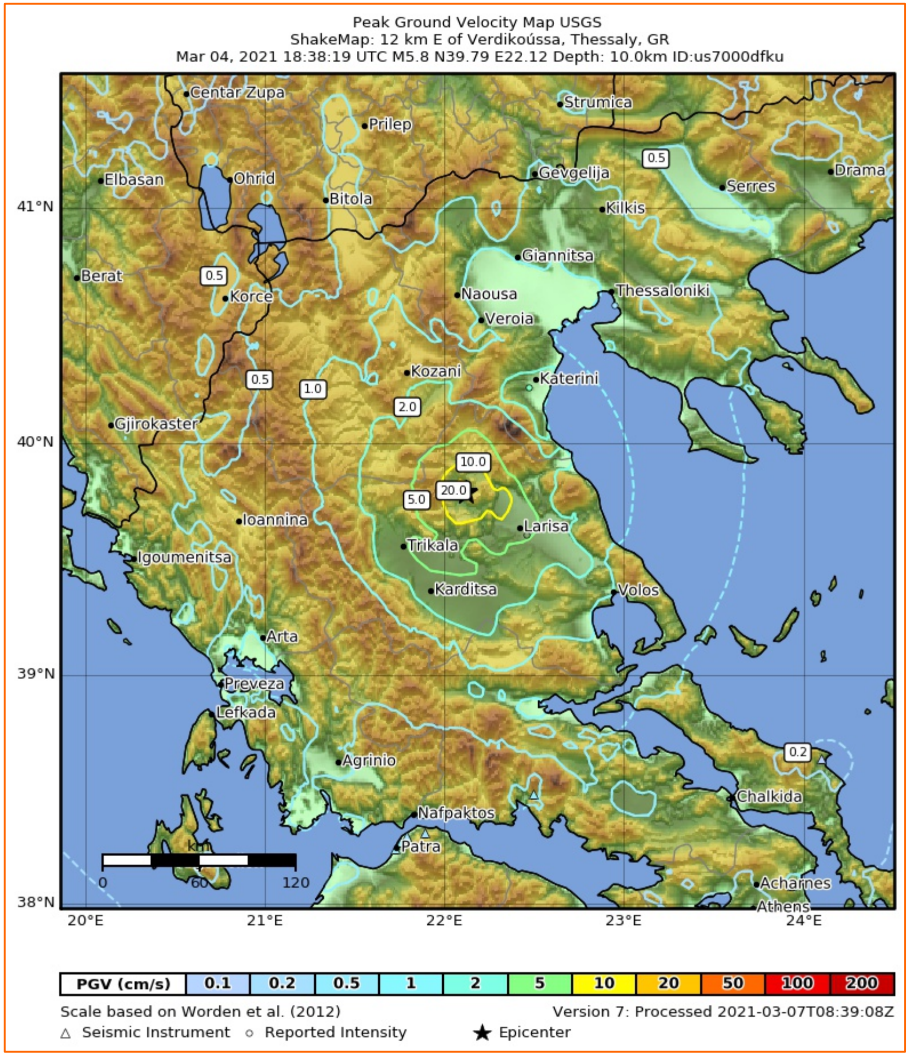
## FOR THE MARCH 4, 2021 EARTHQUAKE

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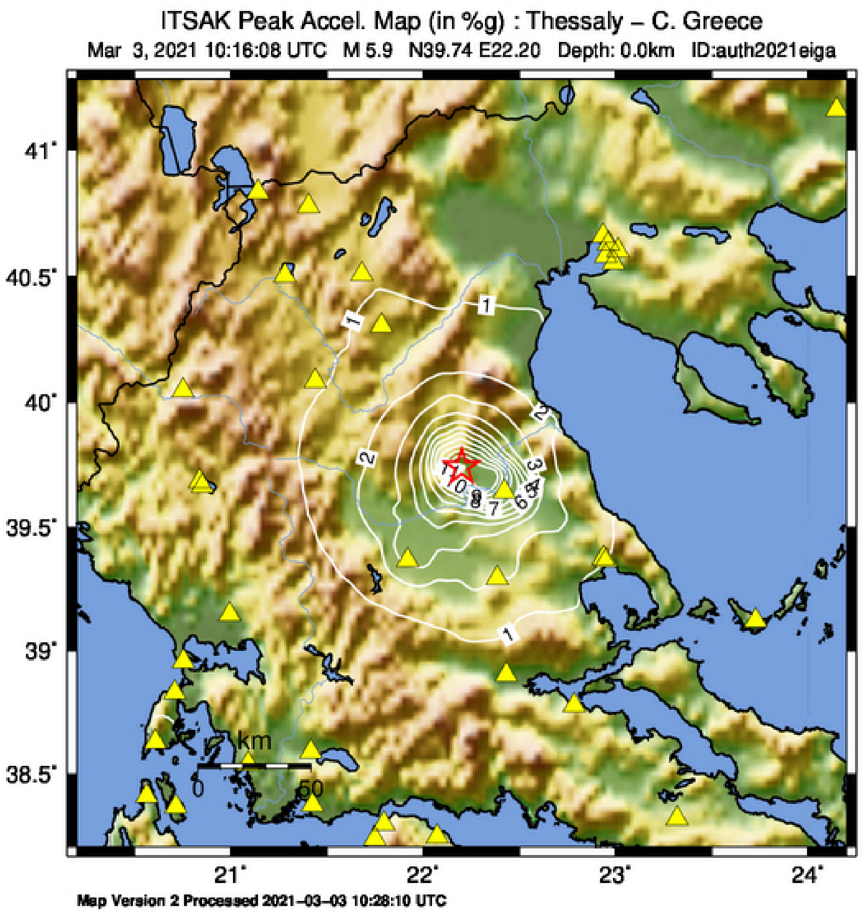
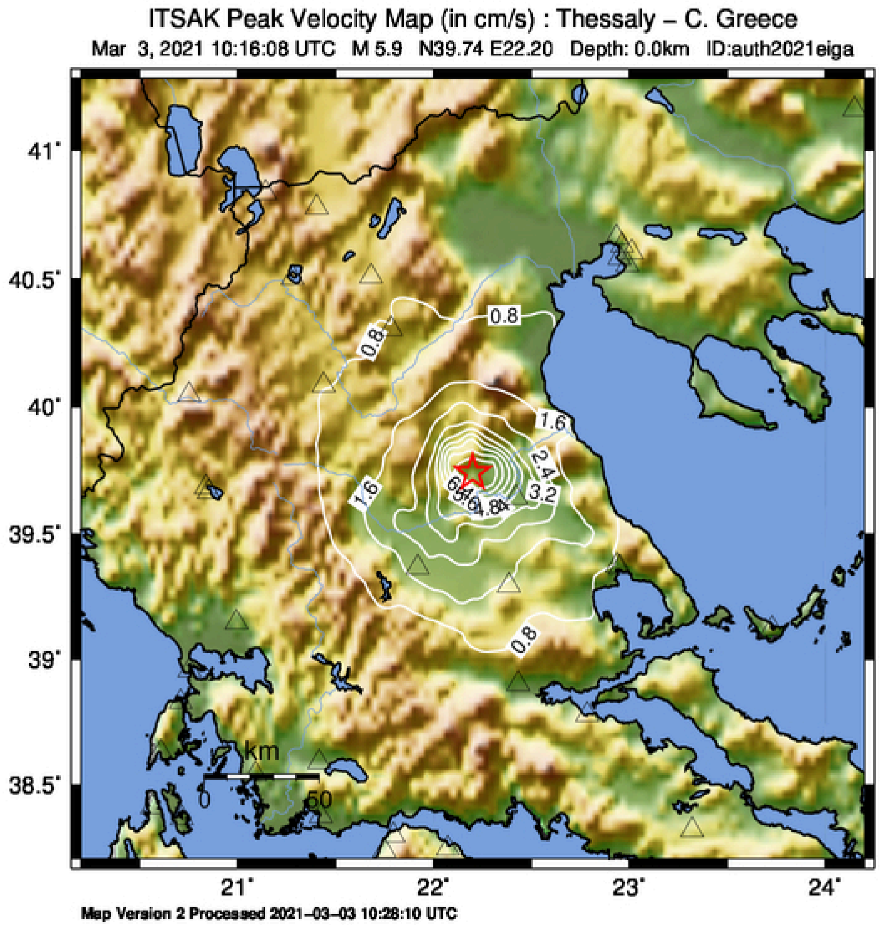
# PEAK GROUND ACCELERATION & PEAK GROUND VELOCITY MAPS
## FOR THE MARCH 3, 2021 EARTHQUAKE

http://shakemaps. itsak.gr



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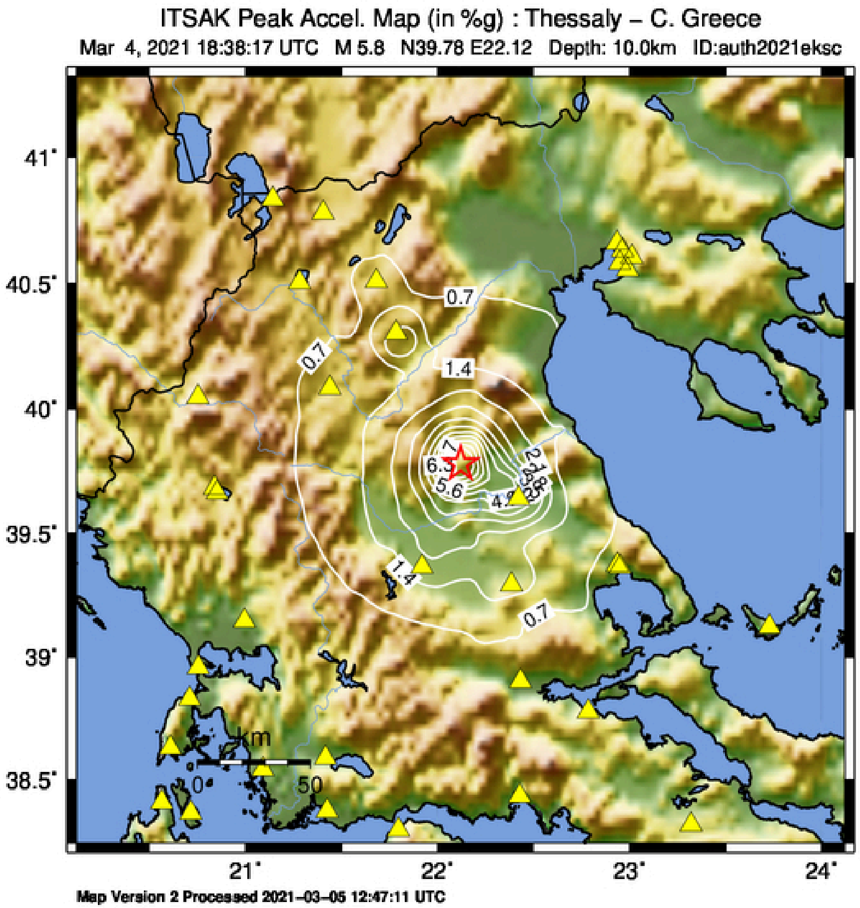


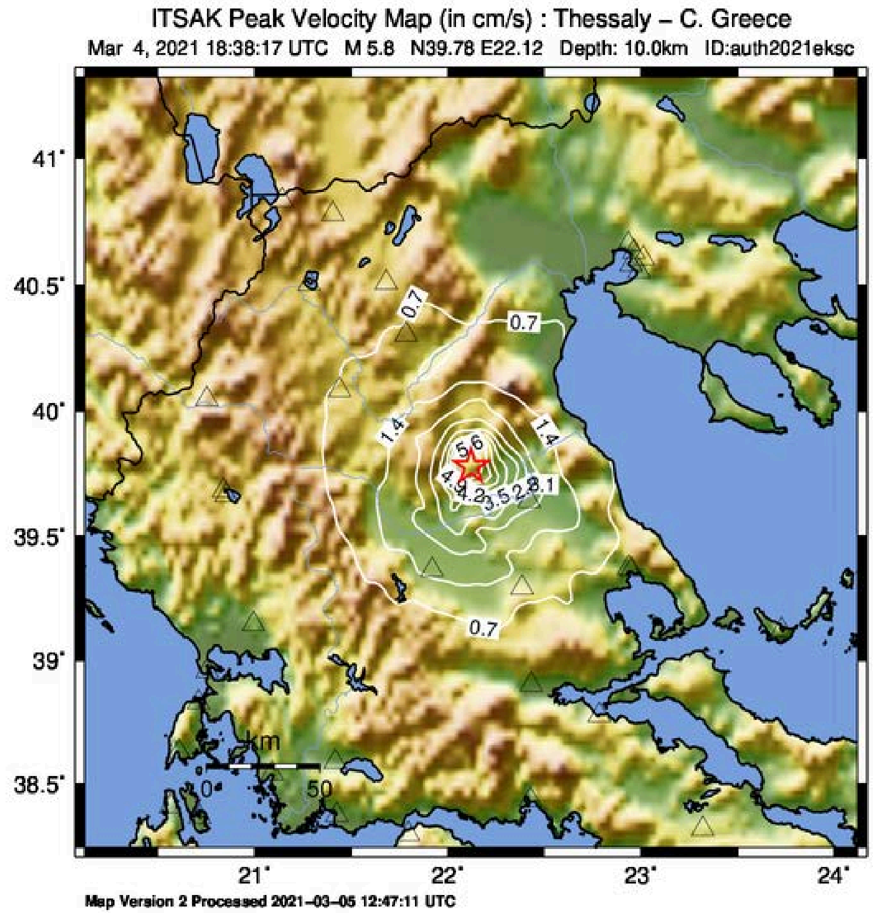

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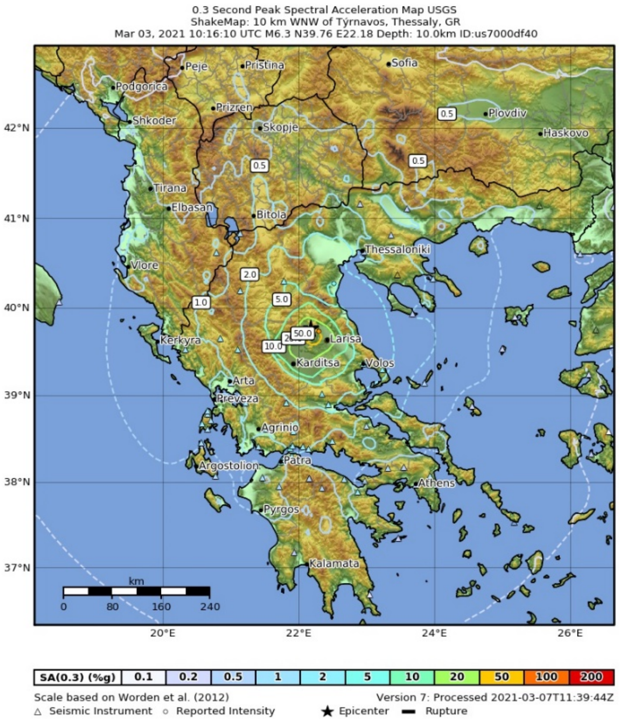
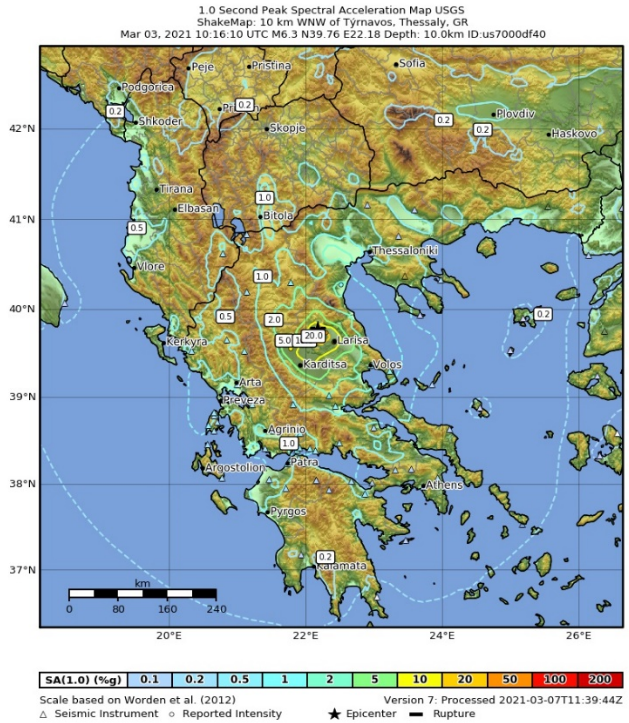
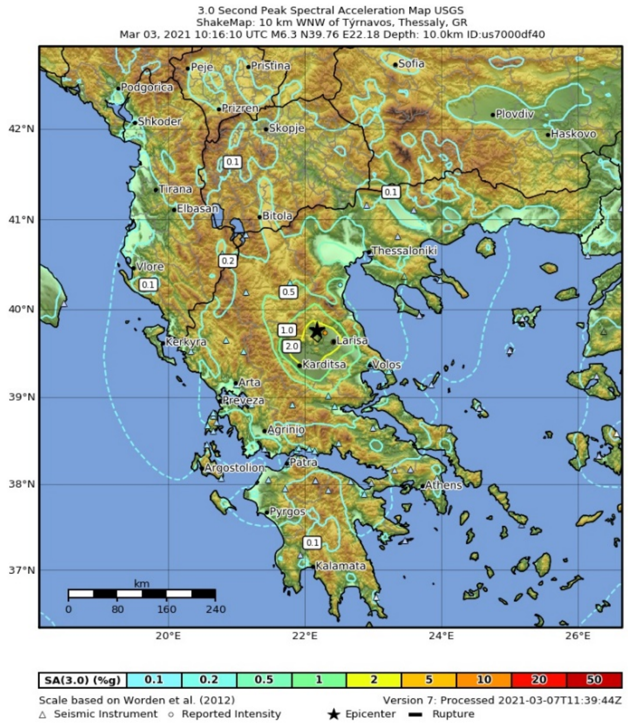
# SPECTRAL RESPONSE
## FOR THE MARCH 3, 2021 EARTHQUAKE



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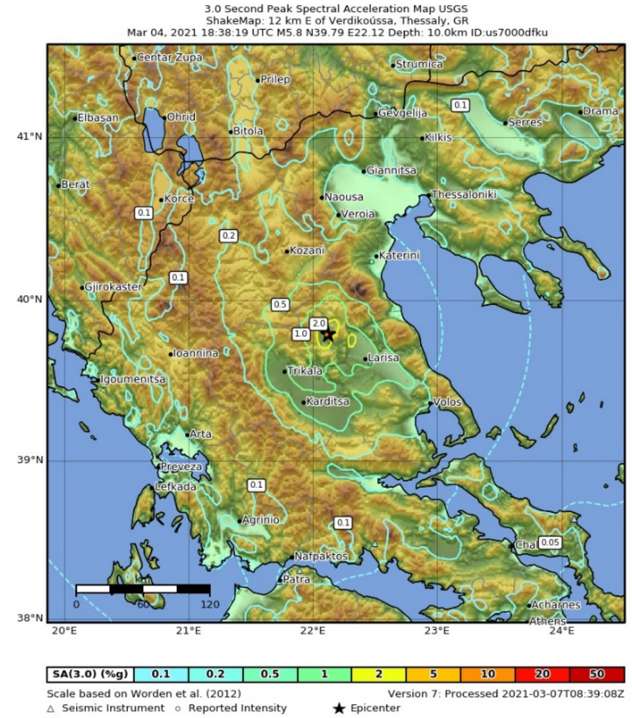
# SPECTRAL RESPONSE
## FOR THE MARCH 4, 2021 EARTHQUAKE





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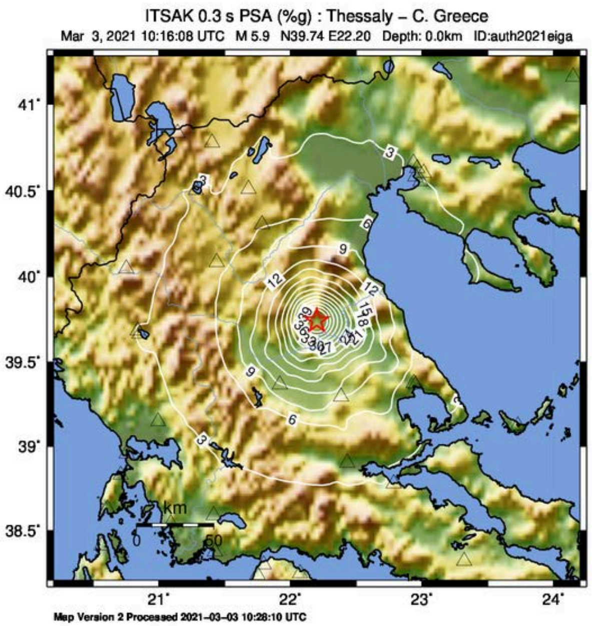
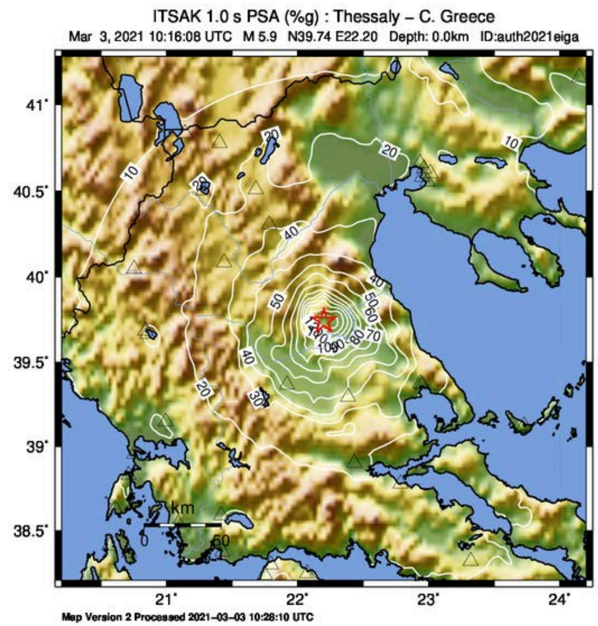
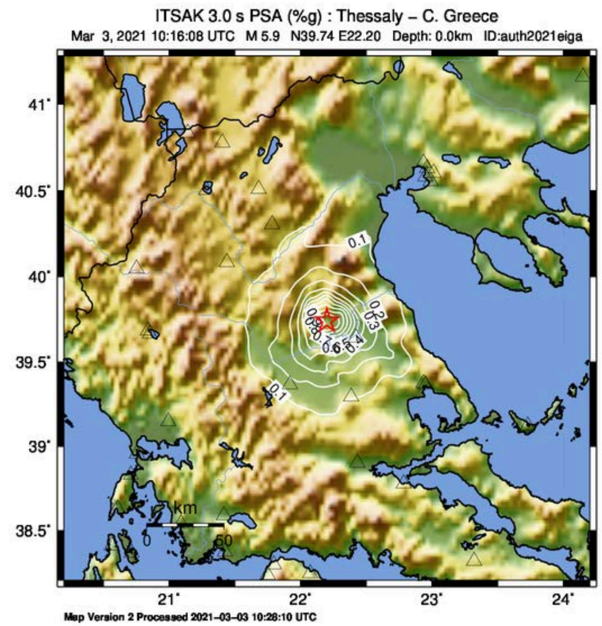
ITSAK

# SPECTRAL RESPONSE
## FOR THE MARCH 3, 2021 EARTHQUAKE



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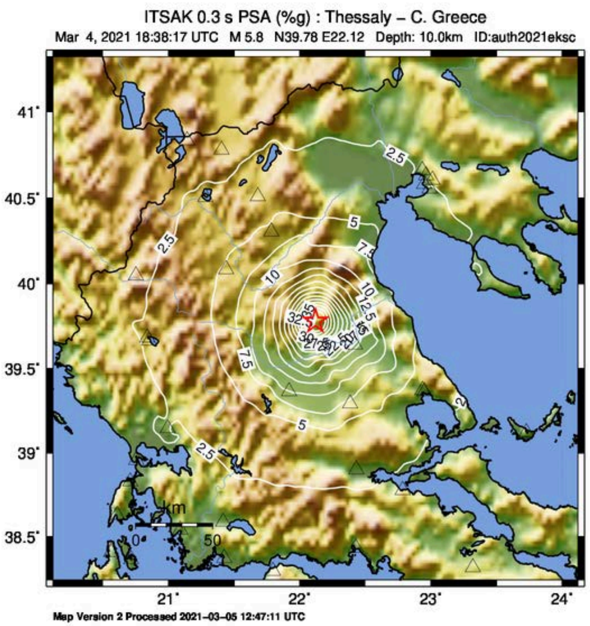
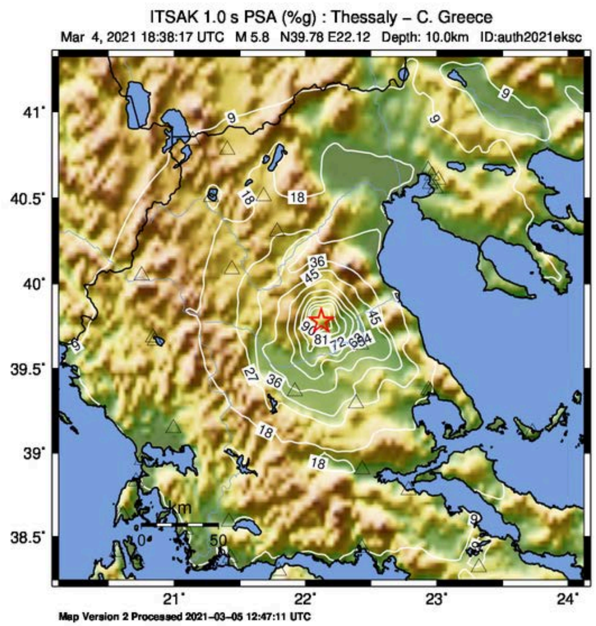
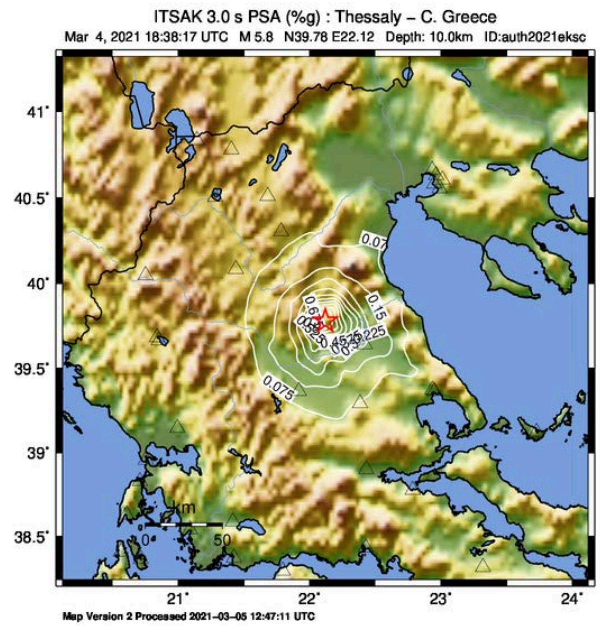
# SPECTRAL RESPONSE
## FOR THE MARCH 4, 2021 EARTHQUAKE



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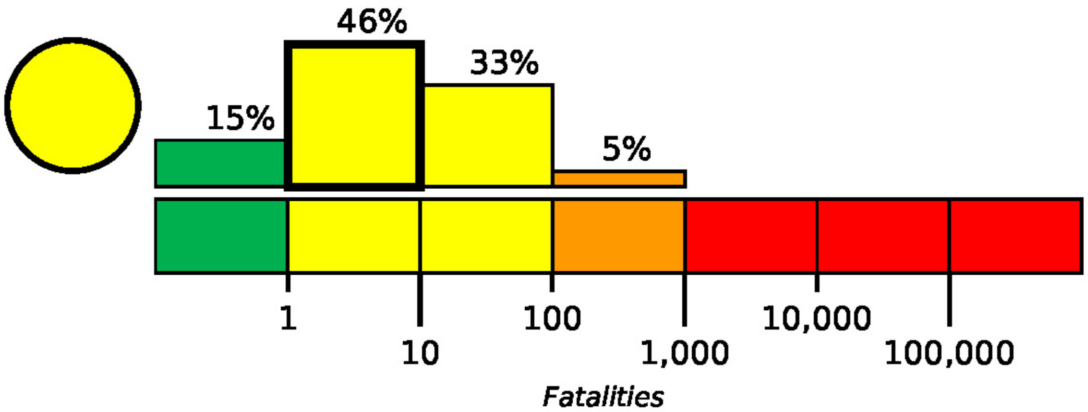
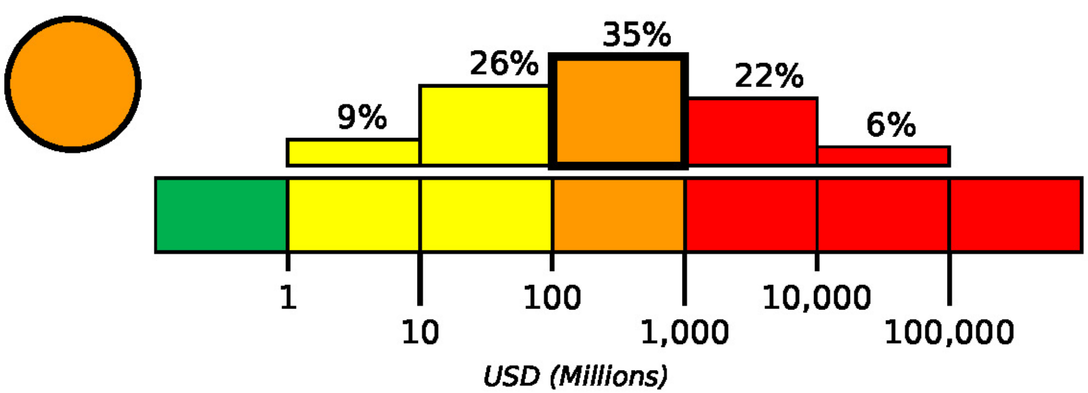
## ESTIMATED POPULATION EXPOSURE
INDUCED BY THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE

### Estimated Fatalities




Yellow alert for shaking-related fatalities. Some casualties are possible.

### Estimated Economic Losses




Orange alert for economic losses. Significant damage is likely and the disaster is potentially widespread. Estimated economic losses are less than 1% of GDP of Greece. Past events with this alert level have required a regional or national level response.

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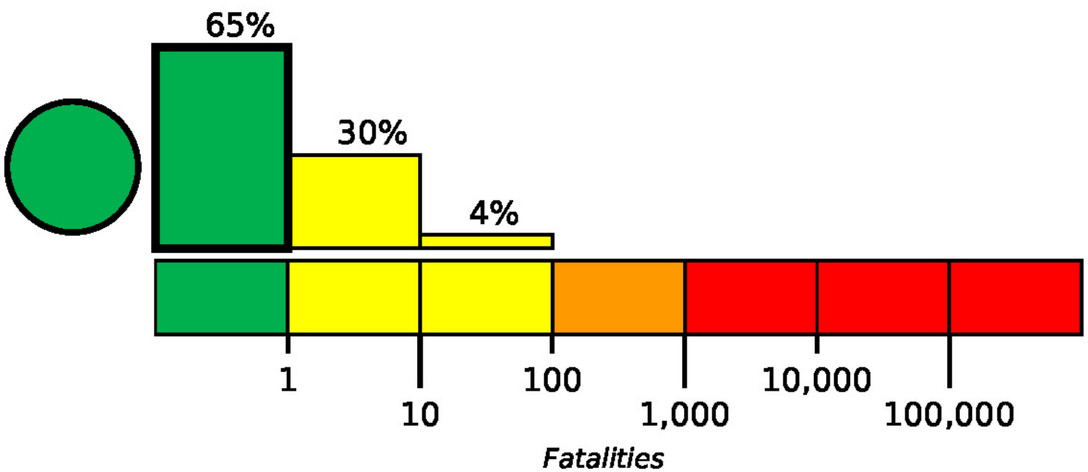
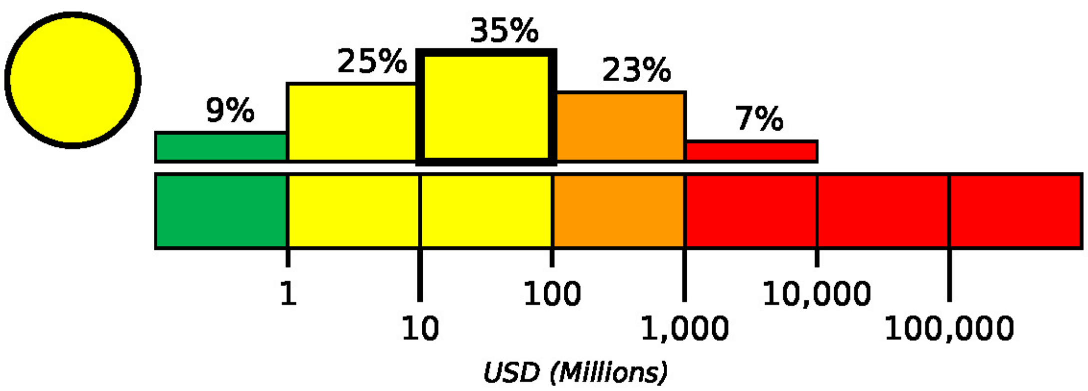
## ESTIMATED POPULATION EXPOSURE
## INDUCED BY THE MARCH 4, 2021, Mw=6.1 EARTHQUAKE

### Estimated Fatalities




Green alert for shaking-related fatalities. There is a low likelihood of casualties.

### Estimated Economic Losses




Yellow alert for economic losses. Some damage is possible and the impact should be relatively localized. Estimated economic losses are less than 1% of GDP of Greece. Past events with this alert level have required a local or regional level response.

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## MONITORING THE TYRNAVOS-ELASSONA EARTHQUAKE SEQUENCE

Papazachos and Chatzis (Department of Geophysics, AUTH) presented the monitoring of the Tyrnavos - Elassona seismic sequence by the portable network of the Department of Geophysics (AUTH) and highlighted its importance for the study of the post-earthquake sequence and the operation of the Hellenic Unified Seismic Network.

Taking into account the modern technological developments and the improvement of the densification of the Hellenic Unified Seismic Network, it is important to note that the March 3, 2021, Mw=6.3 earthquake with epicenter in the Tyrnavos-Elassona area and considerable effects in the Titarissios and Pineios river beds (Damasi, Mesochori, Amouri, Praetorio, etc.), was generated in an area with relatively sparse coverage of the permanent seismic network. In the nearby area (< 50km), three permanent seismological stations (TYRN, THL and LIT) are operating, while more seismological stations were located at distances larger than 70 km. Another nearby station (LRSO) was out of order. Although the existence of digital accelerometers helped significantly in the study of the earthquakes in the early hours of the sequence, it was clear that the monitoring of the post-earthquake sequence could be enhanced by the installation of a denser, local network of seismographs.

The above findings led the Laboratory of Geophysics (AUTH) to install a post-seismic monitoring network. For this purpose, they installed a dense post-seismic network of six (6) broadband seismographs (codes TYR1 to TYR6, Centaur digitizers and Trillium Compact 120s seismometers from Nanometrics Company) in the area of the earthquake sequence. The installation of the seismographs started within the first 48 hours after the generation of the March 3 event with the station TYR1 (Damasouli) and was completed on the March 7 with the station of Megalo Eleftherochori (TYR6). At the same time, staff of the Laboratory of Geophysics (AUTH; Karakostas and Papadimitriou) relocated the repaired LRSO station to a new location (NESN code) in the Nessonas Municipality, with reduced level of environmental noise. The final distribution of the post-seismic monitoring network of the Tyrnavos-Elassona sequence is presented in the following figure.

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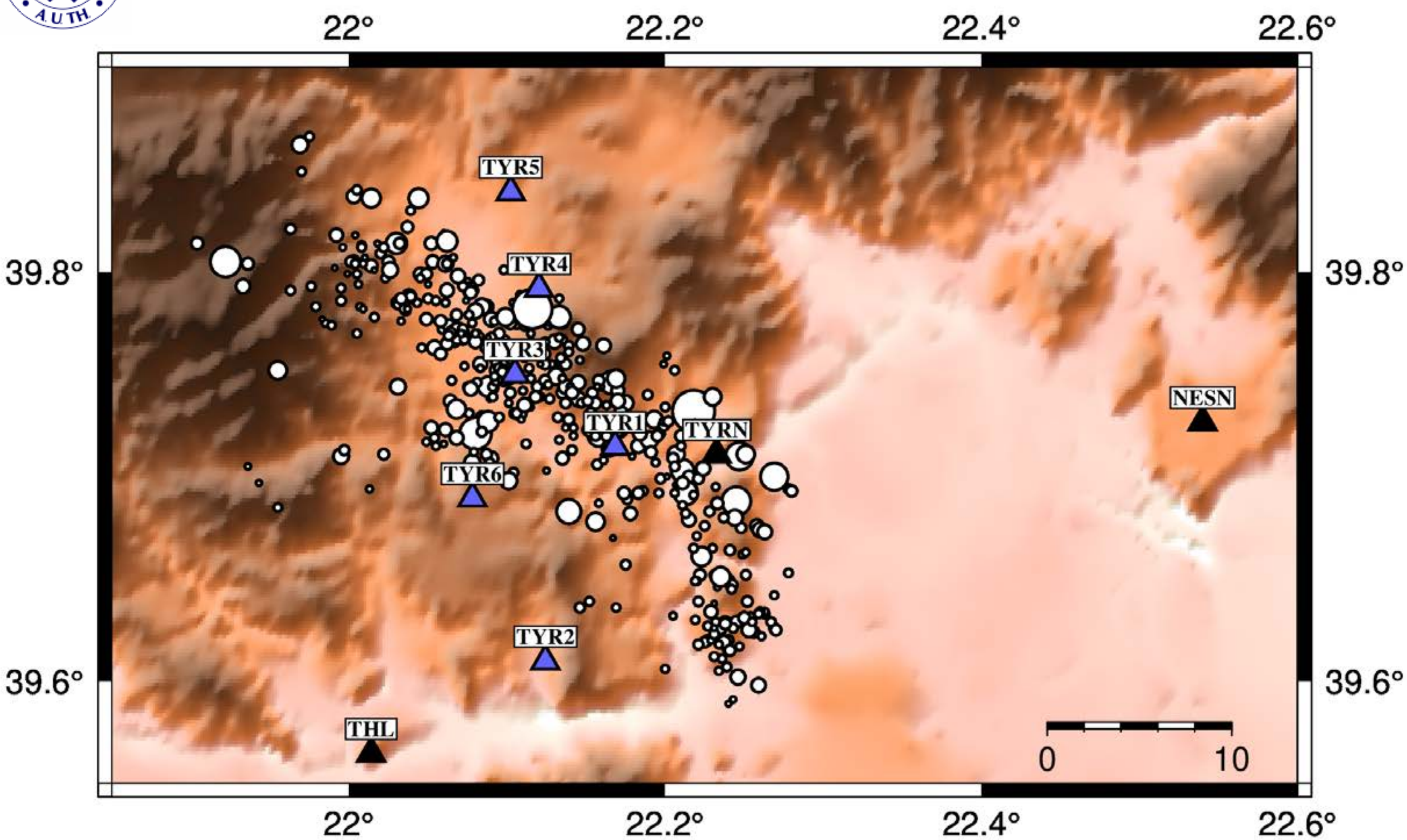
## MONITORING THE TYRNAVOS-ELASSONA EARTHQUAKE SEQUENCE




Spatial distribution of the permanent (black triangles) and temporary (blue triangles) seismic monitoring network of the post-seismic sequence of the Tyrnavos-Elassona earthquake. The ~450 epicenters of earthquakes with M>2.0 are also presented, for which there are solutions by the analysts of the Seismological Network of the Aristotle University of Thessaloniki.

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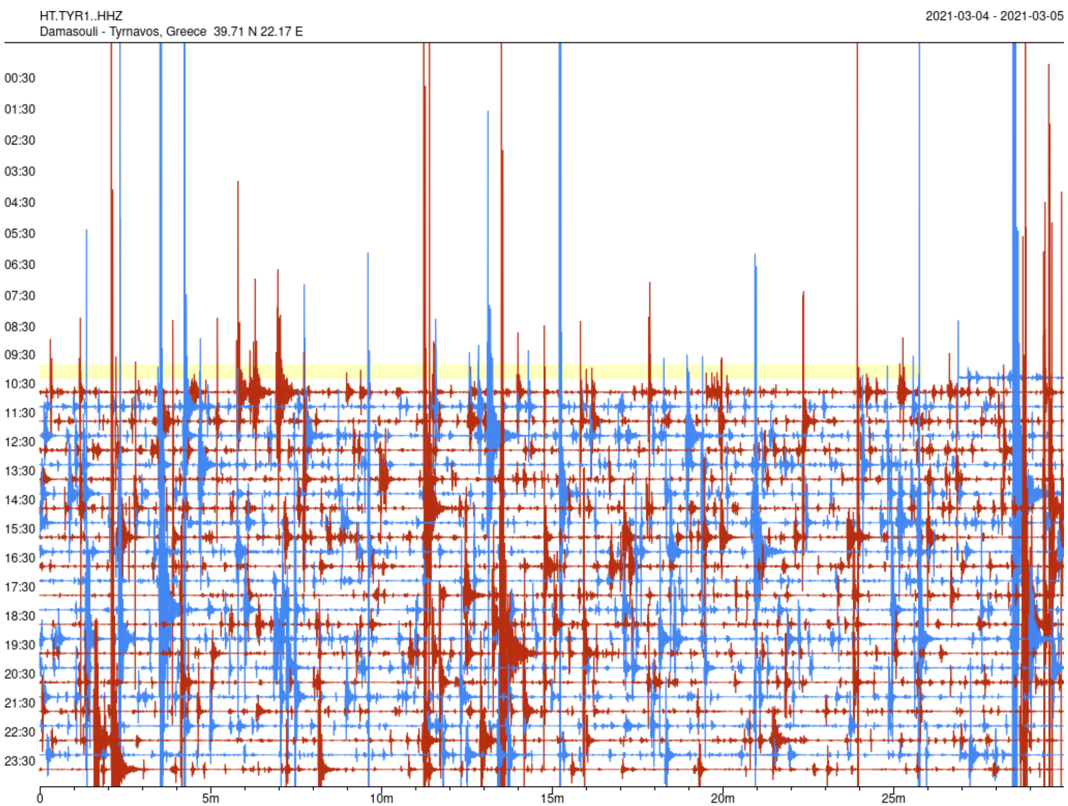
# MONITORING THE TYRNAVOS-ELASSONA EARTHQUAKE SEQUENCE




Drum plot of the temporary seismological station TYR1 of the seismic network for monitoring the aftershock sequence of Tyrnavos - Elassona

As seen from the figure with the spatial distribution of the permanent and the temporary seismic network and the epicenters of 450 earthquakes with M>2.0, the post-seismic network generally covers adequately the seismic sequence, despite the fact that the sequence extended towards NW during the first 48 hours (Verdikoussa area). Despite the small delay in the installation of the network, a large number of aftershocks were recorded since the installation, as shown by the drum plot of the temporary seismicological station of Damasi (TYR1) on March 5, 2021.

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# MONITORING THE TYRNAVOS-ELASSONA EARTHQUAKE SEQUENCE

Indicative images from the installed seismographs of the temporary network for monitoring the post-earthquake sequence of the Tyrnavos – Elassona earthquake.

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# MONITORING THE TYRNAVOS-ELASSONA EARTHQUAKE SEQUENCE

It should be noted that the installation of the temporary seismological network of the Laboratory of Geophysics of the Aristotle University of Thessaloniki in the area of Tyrnavos – Elassona is of particular importance, not only for monitoring the seismic sequence, but also for understanding the distribution of the damage induced by the mainshock, as well as for the development of a standard model of cooperation and operation of the Hellenic Unified Seismic Network. In particular:

(A) The next figure shows the change of the root-mean-square (RMS) value of the travel times and the standard depth error, as derived from the analyses of seismologists of the Laboratory of Geophysics of Aristotle University of Thessaloniki for the epicenters presented above in the figure of the spatial distribution of the 450 earthquake epicenters. It is clear from the figure that the installation of the seismic network significantly reduced the errors in the aftershocks' location, although in a different way for each magnitude group, as expected. It should be noted that the standard errors were already quite satisfactory (1.5-2km), due to the existence of the permanent stations Tyrnavos (TYRN), Klokoto (THL) and Litochoro (LIT), but they were significantly reduced to about ~ 1 km with the gradual installation of the local network. A similar decrease is observed in the average travel time error (RMS), especially for smaller earthquakes ($M < 3.5$). Note that the mean square error of travel times of the largest earthquakes ($M > 3.5$) in Figure (4) is greater than that of the smaller earthquakes ($M < 3.5$). This is due to the greater focal lengths of the seismic phases of the strongest earthquakes, resulting in increase of time intervals due to the complexity of the geophysical structure of the crust and the upper mantle in the study area.

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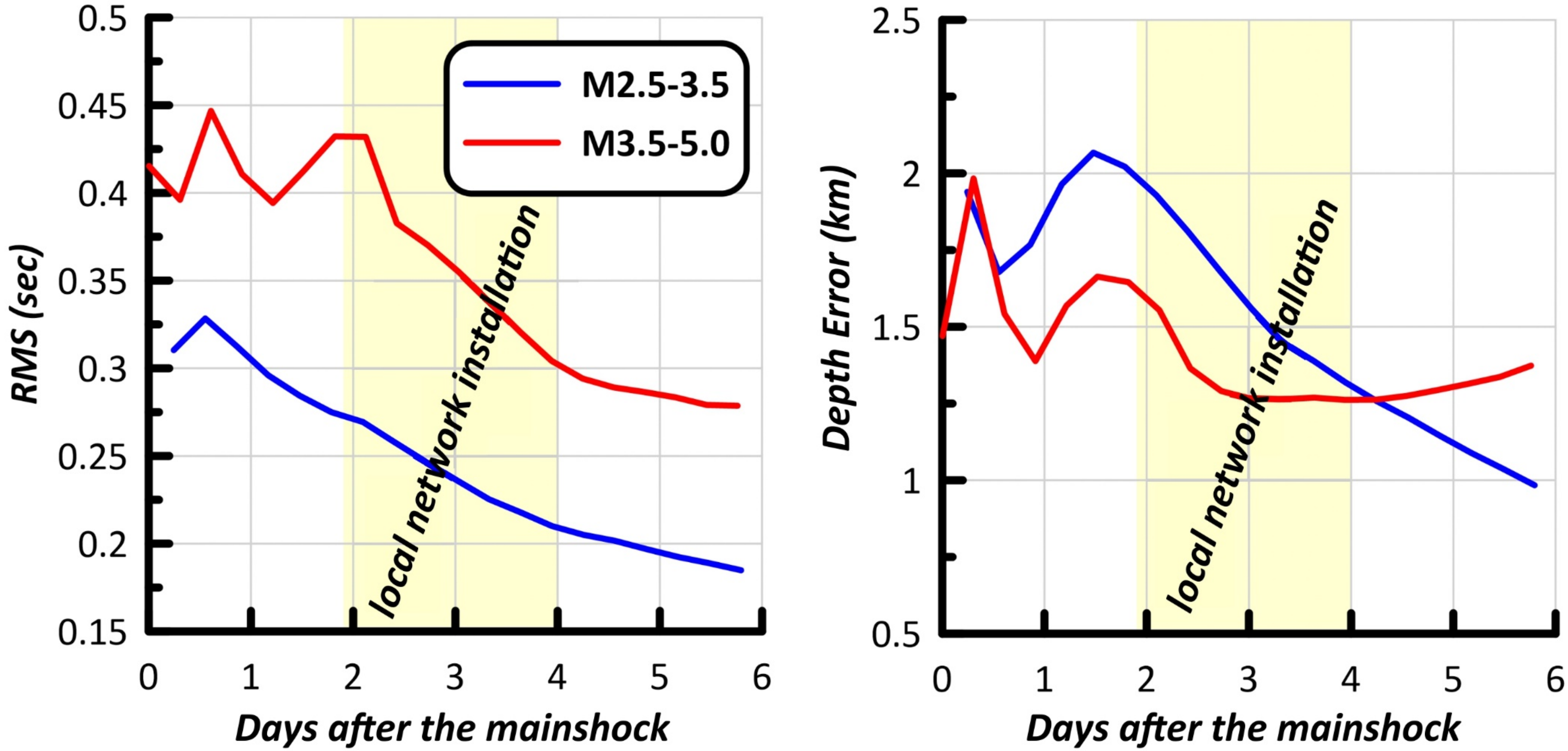
## MONITORING THE TYRNAVOS-ELASSONA EARTHQUAKE SEQUENCE




Smoothing variation of the mean square error of travel times (RMS) and the standard depth error of the post-earthquake sequence of the March 3, 2021 earthquake. The ~ 450 epicenters of earthquakes with M> 2.0 are also presented.

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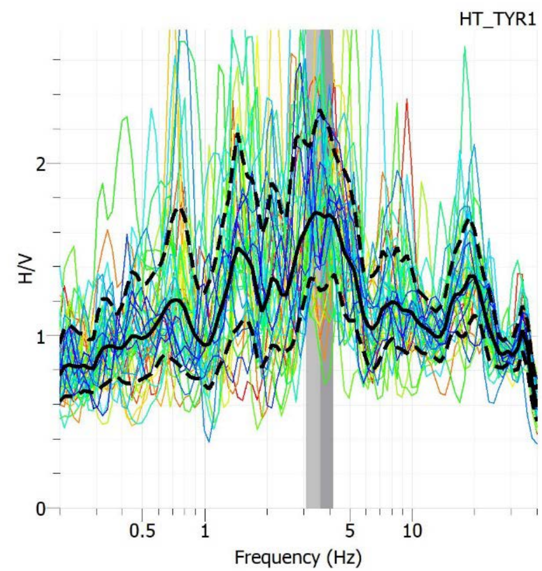
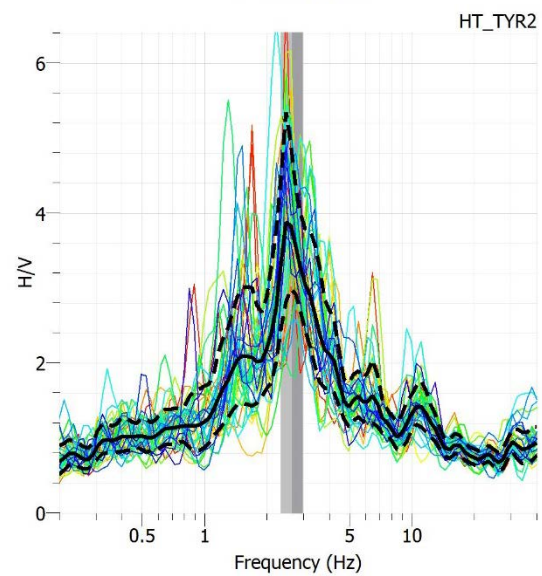
## MONITORING THE TYRNAVOS-ELASSONA EARTHQUAKE SEQUENCE

(B) The installation of the seismological stations was done mainly in places that could have access to the internet, so that the easy transmission of information in real time is possible. The data from the installation sites show that some sites are in rocky subsoil, as shown by the H / V ratio of the figure to the right for station TYR1, which shows small values (<2) throughout the spectral range. But in other places, there are significant peaks in the H / V spectral ratios, indicative of significant soil amplification. As can be seen from the H / V spectral ratio for station TYR2 (Zarko of Trikala) in the figure to the right, there are significant amplifications (at least 3.5) at intermediate frequencies (~ 2.5-3Hz). This result shows that the heaviest damage in the villages of the Titarissios River valley, especially in the low lands (Damasi, Mesochori, Amouri, Praetorio, etc.) in relation to adjacent villages founded on the basement (Damasouli, Domeniko, etc.) are attributed also to the effect of soil amplification in Holocene deposits on which the respective villages are founded.



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## MONITORING THE TYRNAVOS-ELASSONA EARTHQUAKE SEQUENCE

C) In contrast to the previous post-seismic sequences, where the installation of a local network by one or more seismological departments was done independently, and the data collected was only available to scientists of that department, the installation of the Tyrnavos temporary seismic network was followed by a new approach: The data was made available from the first moment by the Department of Geophysics of the AUTH to the entire Greek and the international seismological community, after being routed in real time to all seismological departments. In particular, all seismological stations have already been registered at the International Seismological Center (ISC), while the raw data are already available from the European Integrated Data Archive (EIDA) (http://eida.gein.noa.gr/), which operates at the Geodynamic Institute of NOA. We believe that this new approach should be the trigger for closer cooperation between scientific institutions and universities, but also the emergence of a new way of operational and scientific response to similar seismic sequences in the future. A similar approach was followed by the Geodynamic Institute of NOA in the case of the 2020 Samos earthquake with installation of 2 post-earthquake monitoring stations, a fact that highlights the importance of this approach.

*It should be noted that the installation of the network could not be done without the help of many people. Indicatively, we would like to thank the families of Th. Kanata (Damasouli village) and T. Karakosta (Mesochori village), the Director of the Elementary School of Zarkos Mrs. Kallitsounaki, Dr. Athanassios Ganas from the Geodynamic Institute of the NOA for the station in Zarkos village, the presidents of the Domenikos, Evangelismos and Megalo Eleftherochori communities Mr. Psomiadis, Liuras and Tapsas respectively for offering spaces in the community stores, the Mayor of Tyrnavos. Above all, however, we would like to thank the staff of the Department of Geophysics of the Aristotle University of Thessaloniki (Professors and Laboratory Teaching Staff as well as the PhD students), as well as the seismologists of the other seismological institutions and universities of the Hellenic Unified Seismic Network, who are the invisible and tireless workers, who responsibly and consistently analyze not only the data derived from temporary installed network but also the seismicity of Greece.*

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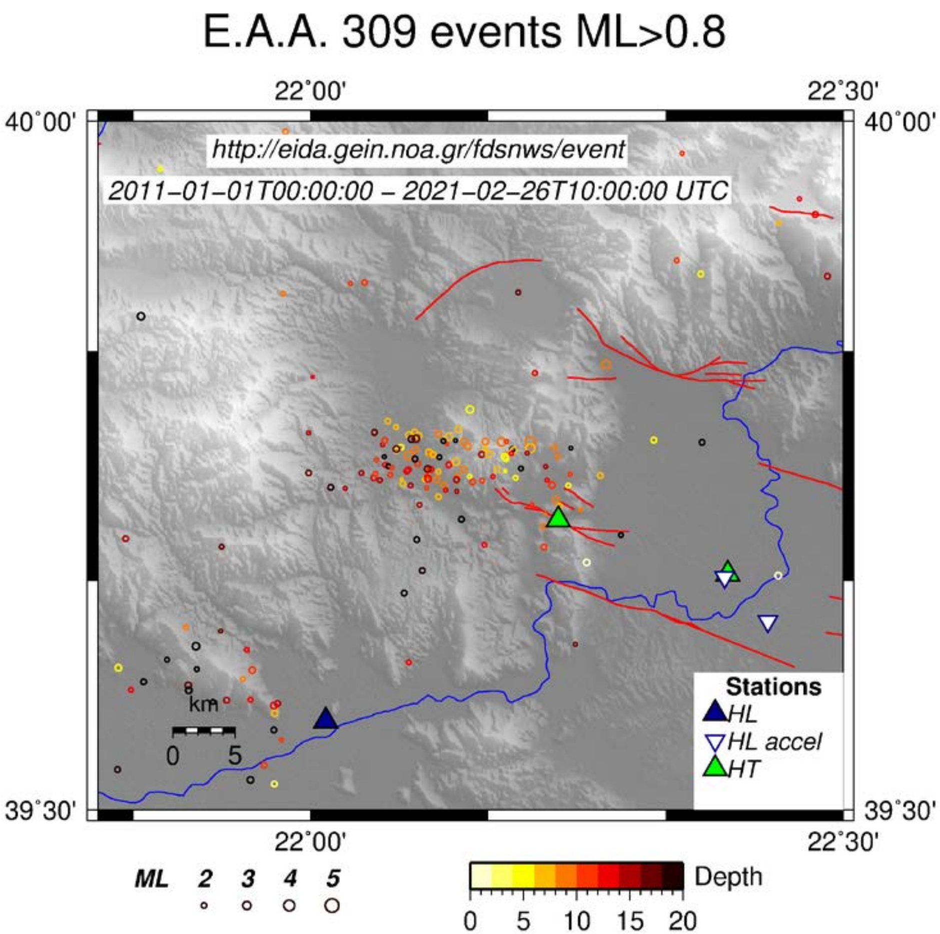
# MONITORING THE ONGOING SEISMICITY




Evangelidis, Karastathis and Tselentis from the Institute of Geodynamics of the National Observatory of Athens reported on the monitoring of the ongoing seismicity of Tyrnavos area.

Since 2011, more than 300 events have been detected from the Hellenic Unified Seismic Network in the extended fault area near Tyrnavos. This background seismicity extends in a range between 0.8 and 3.6 in the local magnitude (ML) scale.

◄ Background seismicity in the area since 2011

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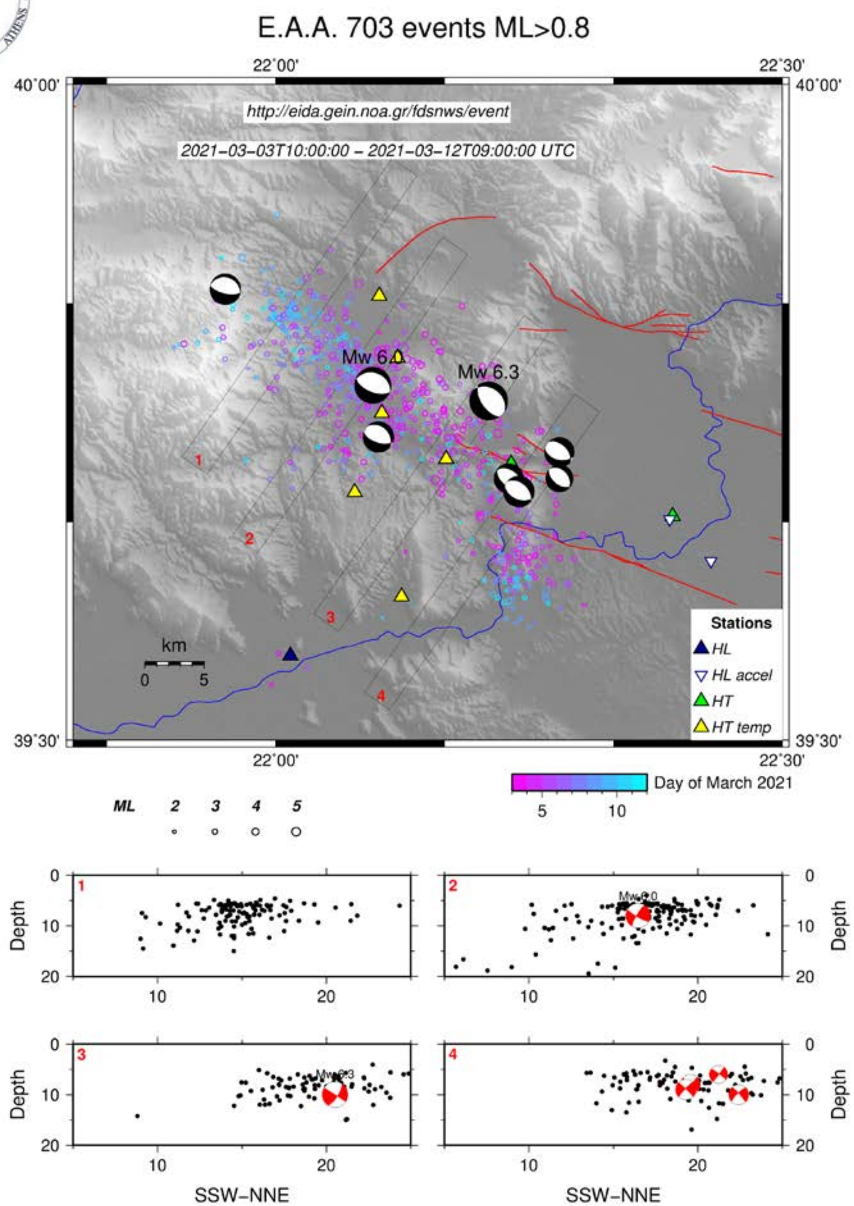


# MONITORING THE ONGOING SEISMICITY

On 27.02.2021 a seismic activity has been initiated, with events ranging between ML=1.5 and ML=2. In this epicentral area, a major earthquake of magnitude ML=6.0 occurred on March 3, 2021 at 10:16 UTC (12:16 in local time). Waveform inversion of regional records from good quality broadband stations, equipped mostly with STS2 sensors, revealed a moment magnitude of Mw=6.3 originating from a low angle normal fault (305/33/-108 in strike/dip/rake). Several aftershocks were followed, with the largest ~Mw=5.0 concentrating to the southeast. On the next day at 18:38 UTC, another major event of Mw=6.0 occurred just ~8km northwestwards. In general, most aftershocks follow a fault surface dipping to the north at low angles. The extended disrupted area covers ~45 km in a NNW-SSE direction and 20 km in a NE-SW direction. Geographically, one week after the mainshock occurrence, aftershocks tend to concentrate at the two edges of the disrupted area.

◀ Seismicity in the area since 27.02.2021

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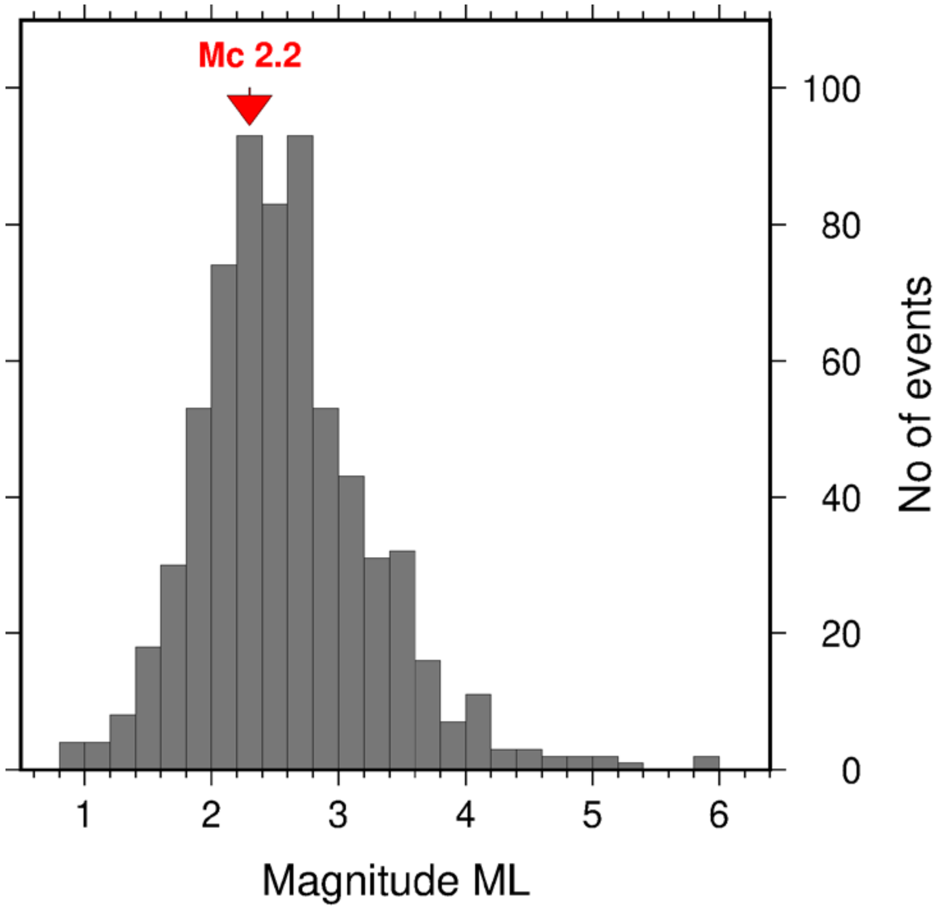
## MONITORING THE ONGOING SEISMICITY




More than 703 earthquakes have been recorded from HUSN and analyzed by NOA within 10 days with a magnitude of completeness (Mc) of 2.2. The Mc has been gradually reduced as the installation of a local seismic network by the University of Thessaloniki has been proceeded. Waveform data from these stations were directly incorporated in the near realtime acquisition system of HUSN via SeedLink and are accessible through the national and regional ORFEUS EIDA at NOA (http://eida.gein.noa.gr/).

◀ Number of recorded events per local magnitude since 03.03.2021

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## MONITORING THE ONGOING SEISMICITY

NOA Moment tensors for the largest events

| Origin Time | Longitude | Lattitude | Depth | Strike | Dip | Rake | Mw |
|---|---|---|---|---|---|---|---|
| 2021-03-03T10:16:08 | 22.2102 | 39.7591 | 10 | 305 | 33 | -108 | 6.3 |
| 2021-03-03T10:34:08 | 22.2835 | 39.7270 | 10 | 314 | 48 | -69 | 4.9 |
| 2021-03-03T11:35:57 | 22.2318 | 39.7000 | 8 | 303 | 42 | -95 | 4.9 |
| 2021-03-03T11:45:45 | 22.2478 | 39.6996 | 9 | 311 | 44 | -78 | 5.1 |
| 2021-03-03T11:49:03 | 22.2812 | 39.7037 | 6 | 317 | 37 | -83 | 4.5 |
| 2021-03-04T18:24:08 | 22.1013 | 39.7316 | 10 | 314 | 33 | -68 | 5.1 |
| 2021-03-04T18:38:19 | 22.0958 | 39.7710 | 8 | 287 | 31 | -95 | 6 |
| 2021-03-04T19:23:51 | 21.9502 | 39.8442 | 6 | 288 | 24 | -86 | 5.1 |

The estimated moment tensors for the largest event reveal a median strike of ~310N and dip of ~35° towards the northeast.

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## STRONG MOTION PARAMETERS

Strong Motion parameters for the first main event

| 2021-03-03T10:16:08 ML6.0, Mw6.3 | | | | | | |
|---|---|---|---|---|---|---|
| Station | Net | Lat[°N] | Lon[°E] | Elev. [m] | Epic. Distance [km] | Max PGA [%g] |
| GINA | HL | 39.6689 | 22.3892 | 74 | 17.2 | 13.8508 (HNN) |
| LAR4 | HI | 39.6422 | 22.4219 | 80 | 20.6 | 9.969 (HNN) |
| THL | HL | 39.5647 | 22.0143 | 0.0 | 25.1 | 5.4073 (HHE) |
| TRKA | HL | 39.5531 | 21.7661 | 118 | 40.9 | 3.7351 (HNE) |

Strong Motion parameters for the second main event

| 2021-03-04T18:38:19 ML5.9, Mw6.0 | | | | | | |
|---|---|---|---|---|---|---|
| Station | Net | Lat[°N] | Lon[°E] | Elev. [m] | Epic. Distance [km] | Max PGA [%g] |
| GINA | HL | 39.6689 | 22.3892 | 74 | 24 | 4.7403 (HNN) |
| THL | HL | 39.5647 | 22.0143 | 0.0 | 25 | 3.0828 (HHE) |
| LAR4 | HI | 39.6422 | 22.4219 | 80 | 27.8 | 4.7486 (HNN) |
| TRKA | HL | 39.5531 | 21.7661 | 118 | 37.8 | 3.821 (HNN) |

For the main **Mw=6.3 event on March 3, 2021,** the maximum Peak Ground Acceleration (PGA) of 0.138g was recorded at 17 km distance from the epicenter, east from the epicenter within the Larissa basin at Giannouli (HL.GINA). The nearest records in the west of 0.054g was at 25 km distance from the epicenter on bedrock at Klokotos, near Trikala city (HL.THL), whereas within Trikala city the PGA was 0.037g (HL.TRKA).

For the **Mw 6.0 event on March 4, 2021,** the maximum PGA of 0.047g was recorded at 25 km distance from the epicenter east from the epicenter within the Larissa basin at Giannouli (HL.GINA). The nearest records in the west of 0.030g was at 25 km distance from the epicenter on bedrock at Klokotos, near Trikala city (HL.THL), whereas within Trikala city the PGA was 0.038g (HL.TRKA).

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# FIRST ANALYSIS OF SAR INTERFEROMETRY AND GNSS DATA
## A SUMMARY FROM GI-NOA

A first analysis of the geodetic data that were gathered at the Institute of Geodynamics of the National Observatory of Athens, and processed by Ganas, Tsironi, Karasante and Valkaniotis, is also presented.

They used a set of ascending and descending SAR images acquired by the SENTINEL-1 satellites that are distributed routinely by the European Space Agency (ESA) free of charge. They also used GNSS data (at 30-s sampling interval) from permanent station KLOK near the epicenters that were provided by the NOANET network.

The co-seismic motion of station KLOK (Klokotos, Trikala) during the March 3, 2021 Mw=6.3 earthquake was 3.9 cm towards the southwest, while during the 2nd event (March 4, 2021 Mw=6.0) was 1.6 cm towards south.

Their preliminary results indicate that the March 3, 2021 rupture occurred on a north-dipping tensional (normal) fault located between the villages Zarko (Trikala) and Damasi (Larissa). The event of March 4, 2021 occurred towards the northwest of Damasi along a fault plane oriented WNW-ESE and created less deformation than the event of the previous day.

The use of InSAR was crucial to differentiate the ground deformation between the two ruptures.

*The GI-NOA team are indebted to ESA and Copernicus for providing access to SAR images. GNSS data were provided by NOANET open-data network.*

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## FIRST ANALYSIS OF SAR INTERFEROMETRY AND GNSS DATA
### SAR INTERFEROMETRY

InSAR is a form of side-looking imagery collected by repeating passes of a radar satellite over an area. Since 1992, the technique is used to measure how much the ground surface has moved roughly vertically between each pass of a satellite and can give vital information as to how much slip occurred on a fault. In the case of the March 2021 earthquakes the ruptured faults are "blind", i.e. they have no surface expression.

The GI-NOA team used the ascending images acquired by the European satellites Sentinel-1 (C-band data) on the tracks 102 and 175 and on the descending tracks 7 and 80. The interferograms (see next page) were made using the SNAP v8.0 software. The digital elevation model (DEM) used for the processing is the Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (doi number: /10.5066/F7PR7TFT).

During the stage of processing, the interferogram was formed by cross-multiplying the master image (the pre-event acquisition image) with the complex conjugate of the slave (the post-event image). The resulting phase represents the difference between the two images. Through the interferometric processing, they eliminate, as much as possible, sources of error to be able to isolate the remaining signal that is likely to be related to the ground displacement. They also enhanced the signal to noise ratio by applying the adaptive power spectrum filter of Goldstein and Werner (1998) with a coherence threshold of 0.4. The quality of the interferogram is good, both in terms of coherence and tropospheric noise.

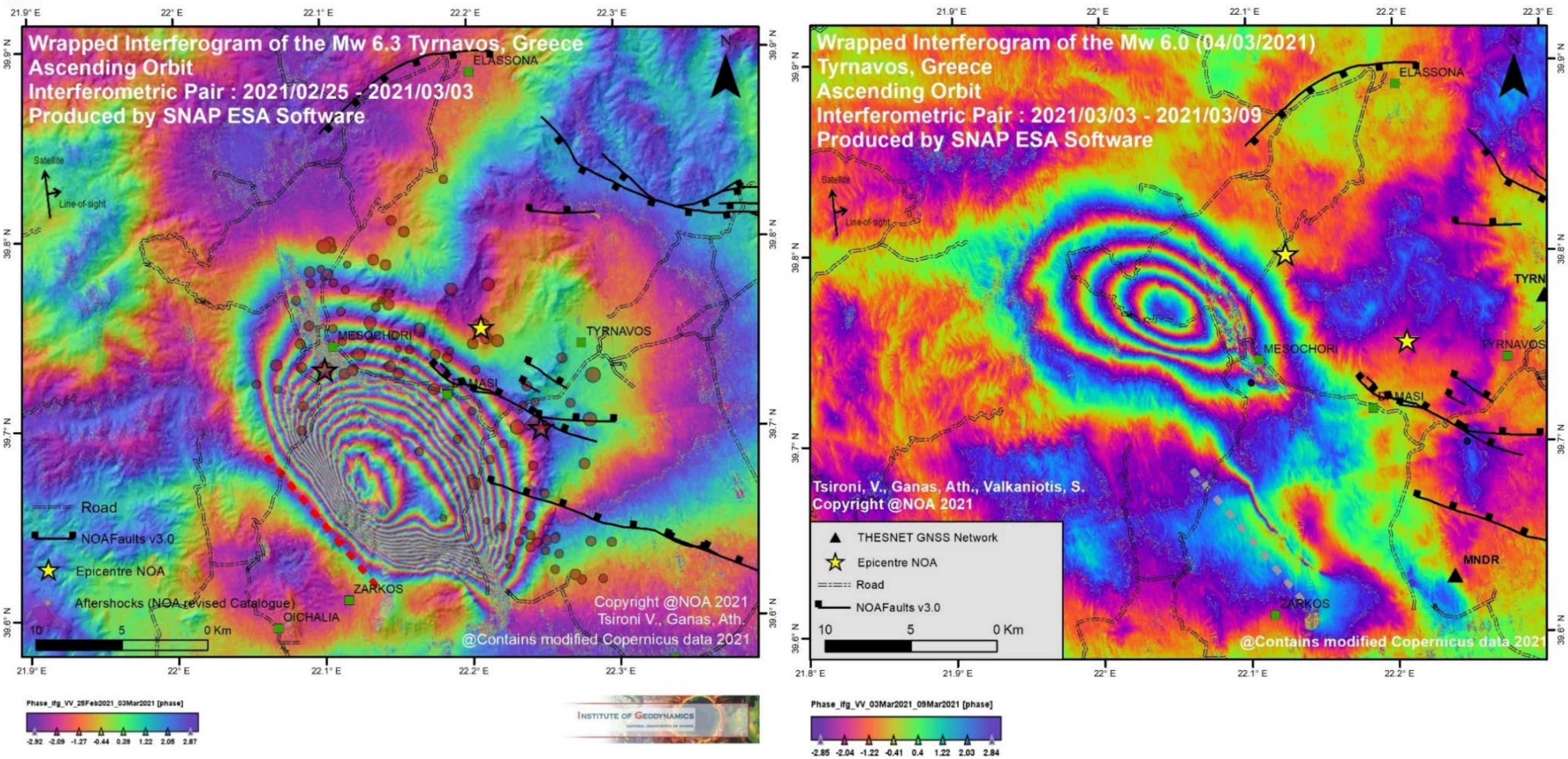
The interferogram of the first event shows 13 fringes corresponding to ground deformation in the Damasi area (left figure in the next page).

The interferogram of the second event shows 4 fringes corresponding to ground deformation in the Amouri area, about 10 km to the northwest (right figure in the next page). All fringes correspond to motion away from the satellite.

The subsidence is interpreted a result of co-seismic motion along blind normal faults, running NW-SE and dipping to the northeast.

# FIRST ANALYSIS OF SAR INTERFEROMETRY AND GNSS DATA

## SAR INTERFEROMETRY




The ascending orbit co-seismic interferograms (wrapped phase; cropped swath) over the Elassona – Tyrnavos – Damasi areas of Thessaly, central Greece. Left panel shows the image pair February 25 – March 3, 2021 (dark red circles are aftershocks). Right panel: 3 March – 9 March, 2021. The InSAR results show that the Titarissios river valley and large areas to the west and SW of Tyrnavos moved roughly downwards. The interferograms are draped over shaded relief. Black lines with teeth indicate normal faults from the NOA v3.0 database https://zenodo.org/record/4304613#.YExs_tyxVlc.

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# FIRST ANALYSIS OF SAR INTERFEROMETRY AND GNSS DATA

## CO-SEISMIC MOTION OF THE GNSS STATIONS

The GI-NOA team analyzed the Dual-frequency GPS data of the GNSS station KLOK belonging to NOANET (Ganas et al. 2008) and INGV (next figure). Station KLOK is occupied with a choke-ring antenna and its 10yr long time-series analysis indicate a very stable behavior (Argyrakis et al. 2020). The data processing was made at the Canadian online processing PPP (Precise Point Positioning) service https://www.nrcan.gc.ca/home. The station is located close (within ~20 km) to the epicenter of the M6.3 mainshock while the data cover four days before and four days after, including the 2nd earthquake (from 27 February 2021 to 8 March 2021). The sampling interval was 30 s, and the data were collected on a 24-hour basis. All records were complete (rejected epochs 0.00%) thus providing substantial observations for mapping the co-seismic displacement field and were included in our analysis. The daily positions are estimated in ITRF14 and converted to UTM (north) zone 34. The position uncertainties were converted onto the local geodetic frame, based on the given Cartesian (ECEF) sigma (95%) ones.

The co-seismic displacements were obtained from the difference between trend lines best fitting to time series of pre-seismic coordinates 4 days before the 1st event and of coordinates 4 days after the 2nd event.

The horizontal displacement pattern is in full agreement with the normal-slip kinematics of the rupture, i.e. extension oriented NE-SW.

The co-seismic displacements reached 2.3-cm of horizontal motion towards south and 3.1-cm towards west (for the 1st earthquake).

In addition, co-seismic displacement of 1.6-cm towards south was measured as a result of the 2nd event (4 March 2021; next figure). The next figure shows the position time series at station KLOK (Klokotos) that captured the seismic motion and the GNSS antenna.

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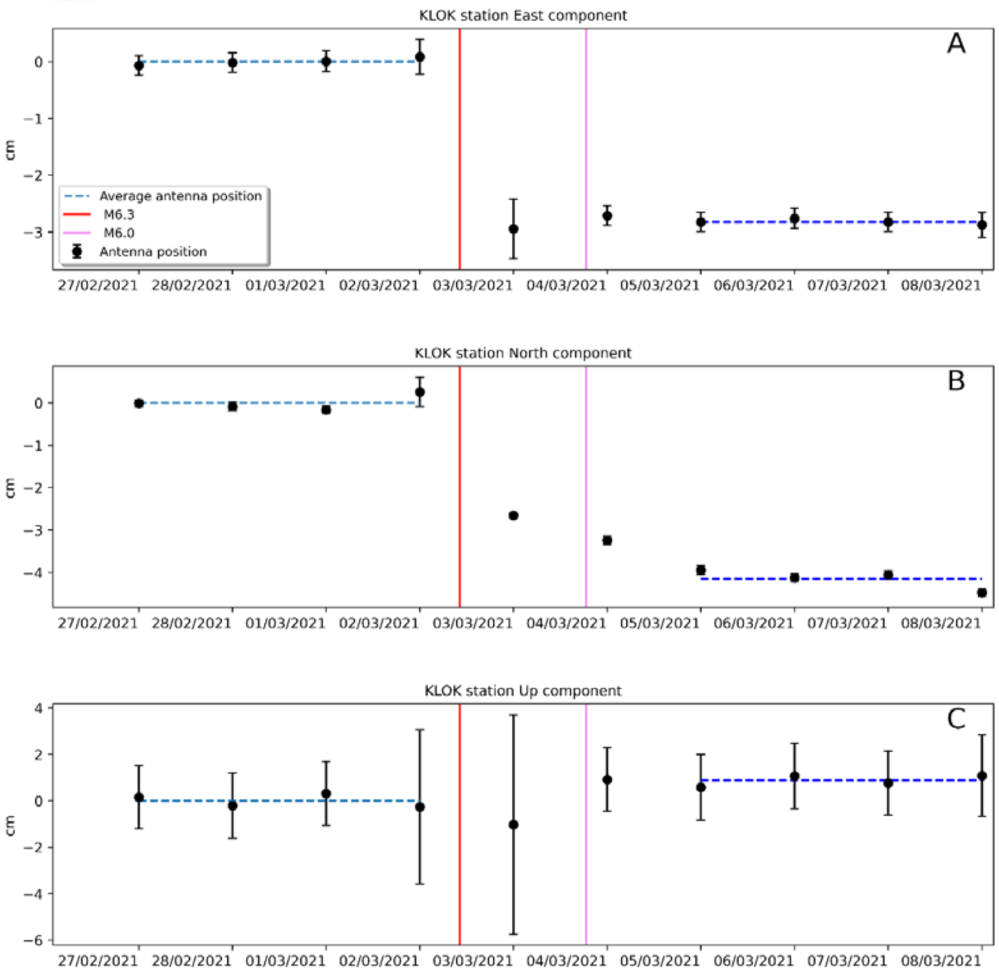
# FIRST ANALYSIS OF SAR INTERFEROMETRY AND GNSS DATA

## CO-SEISMIC MOTION OF THE GNSS STATIONS




| Component | 1st EQ Offsets (mm) | 2nd EQ offsets (mm) |
|---|---|---|
| **East** | -31.130 | 2.929 |
| **North** | -23.567 | -16.372 |
| **Up** | -9.679 | 16.565 |

Co-seismic displacements recorded at the GNSS station KLOK, Klokotos, Thessaly. The offsets on the vertical are within the margins of measurement error. The graph is presented in the left figure. Values in mm.

Position time series and 1-σ uncertainties (E, N, Up) of station KLOK (Klokotos; **A**: east, **B**: north, **C**: Up) during the period 27 February – 8 March 2021. The co-seismic offsets (see across dashed lines) are reported in the next table. The vertical lines indicate the timing of the two shocks.

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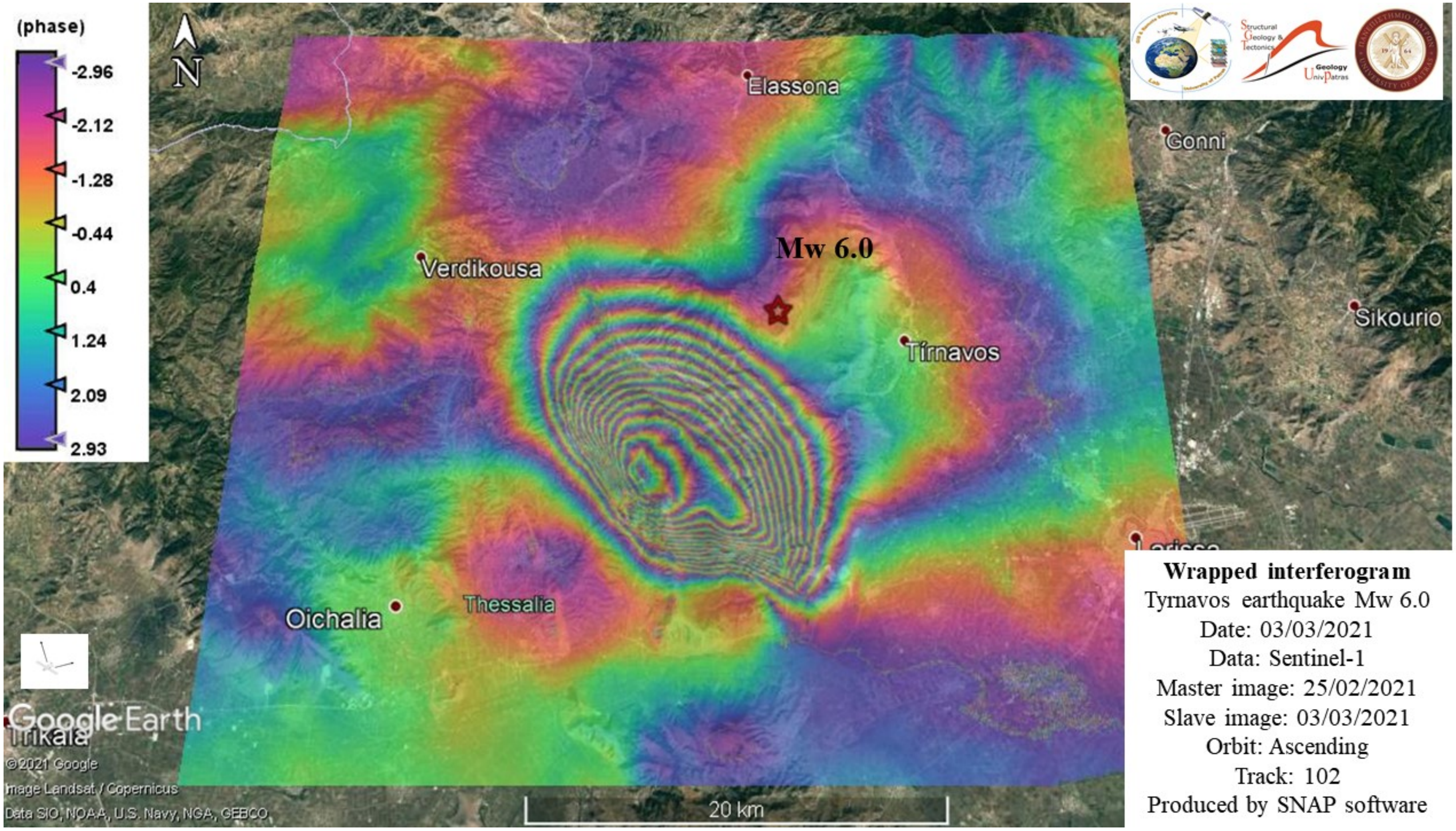
# SAR INTERFEROMETRY
## FOR THE MARCH 3, 2021 EARTHQUAKE




The scientific team of the University of Patras combined laboratory work and field mapping. Sentinel-1 data was processed and interferograms were produced by SNAP software.

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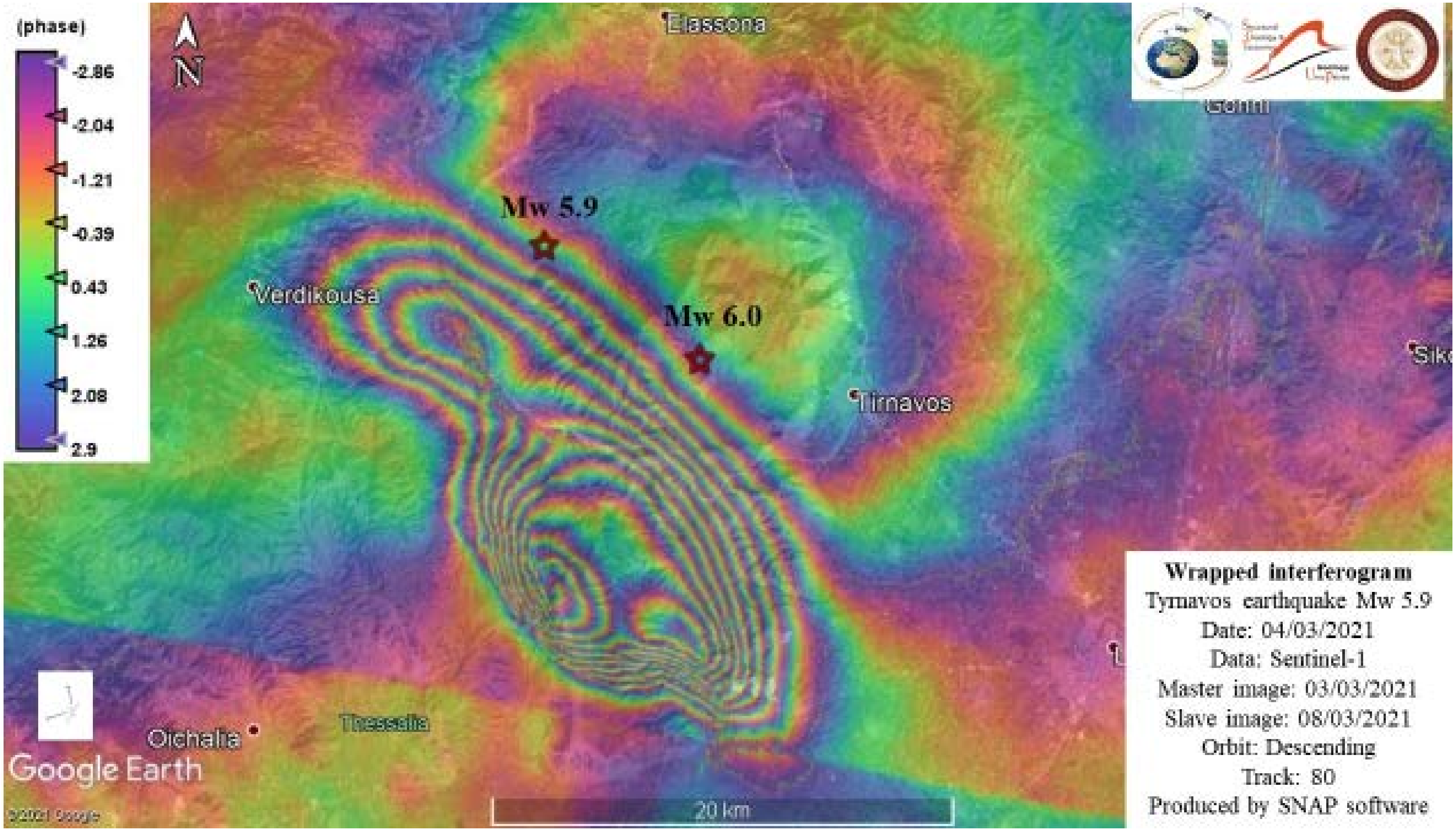
## SAR INTERFEROMETRY
## FOR BOTH EARTHQUAKES




Wrapped interferogram of the two earthquakes produced by SNAP software

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# FINITE-FAULT SLIP MODELS

## SLIP MODEL OF THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE

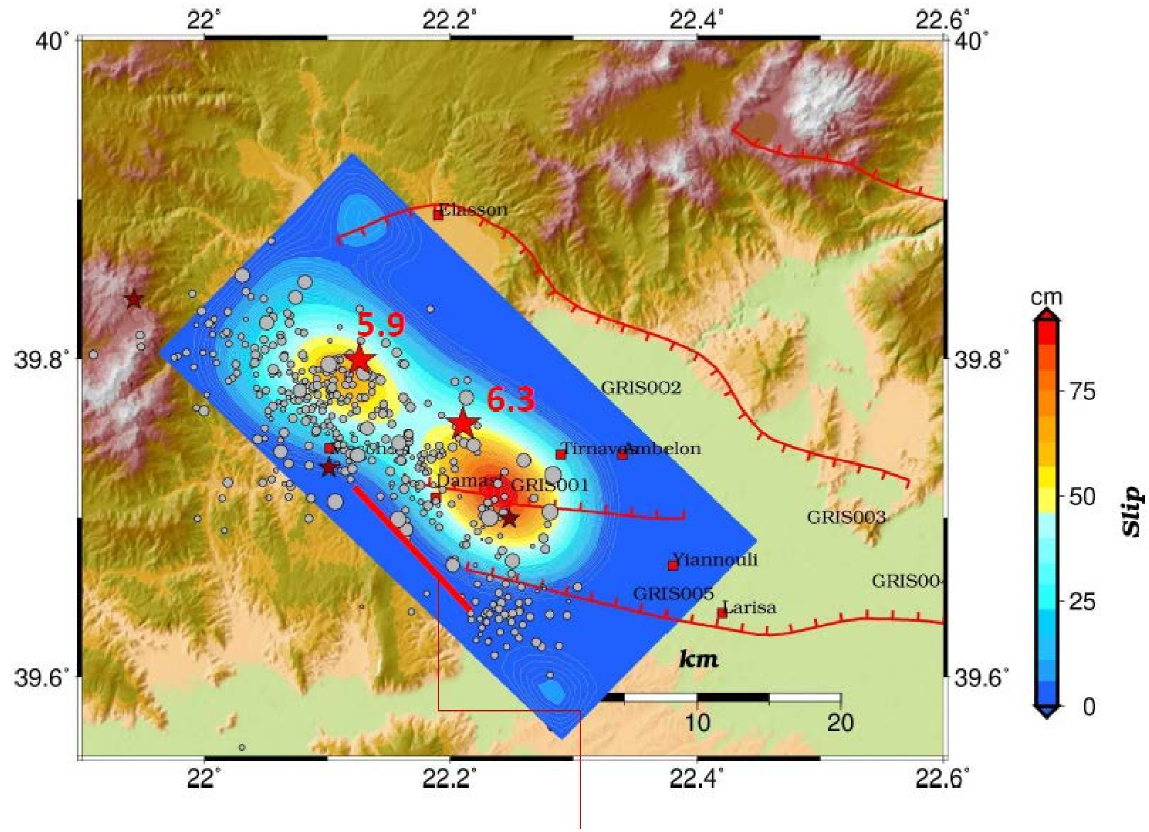
The finite-fault slip models are presented by Kiratzi from the Department of Geophysics (AUTH).

Major slip is confined SE of Mesochori, Vlachogianni villages.

Damasi village is located within the major slip patch, and this explains the damage pattern.

Note the small slip patch, near the location site of the 2nd M5.9 earthquake of March 4. It means that in this area there was a strong barrier, which did not entirely broke during the 1st event.

This was a lucky coincidence, because if it did rupture, the rupture would grow to become a M=6.5 or M=6.6 earthquake.




Estimated fault length associated with the March 3, 2021, M=6.3 earthquake of the order of 15 to 17 km.

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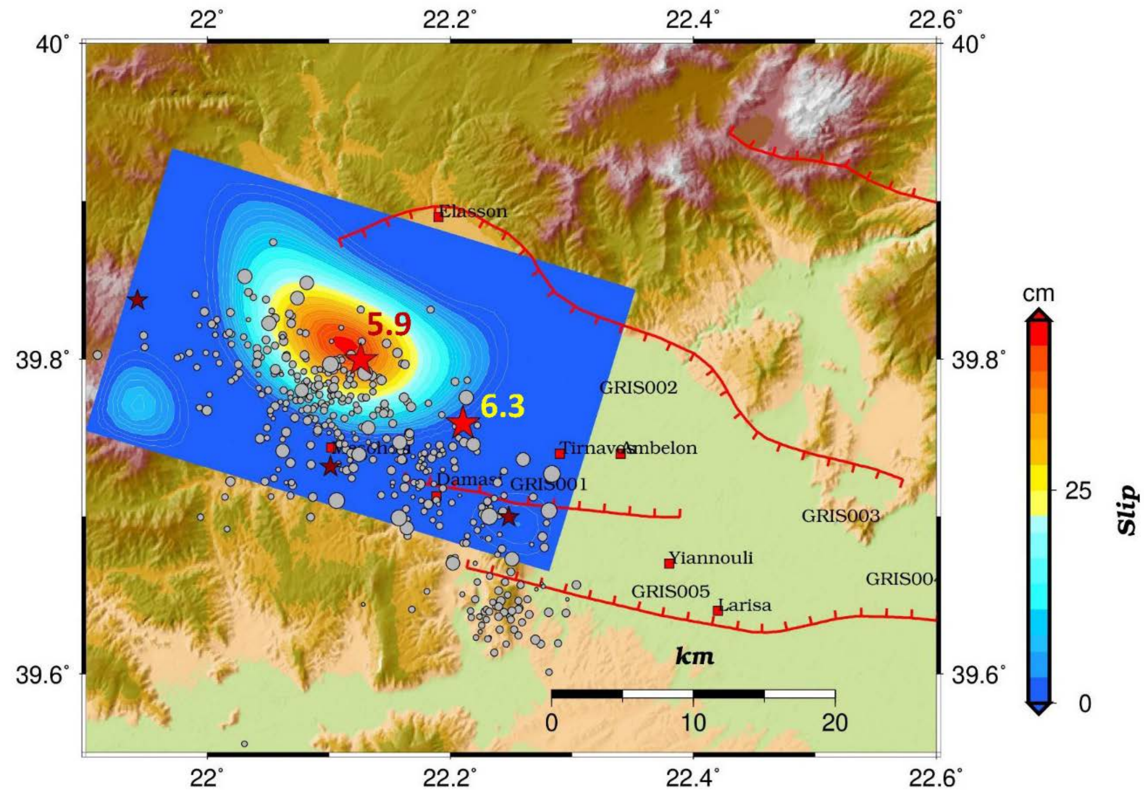
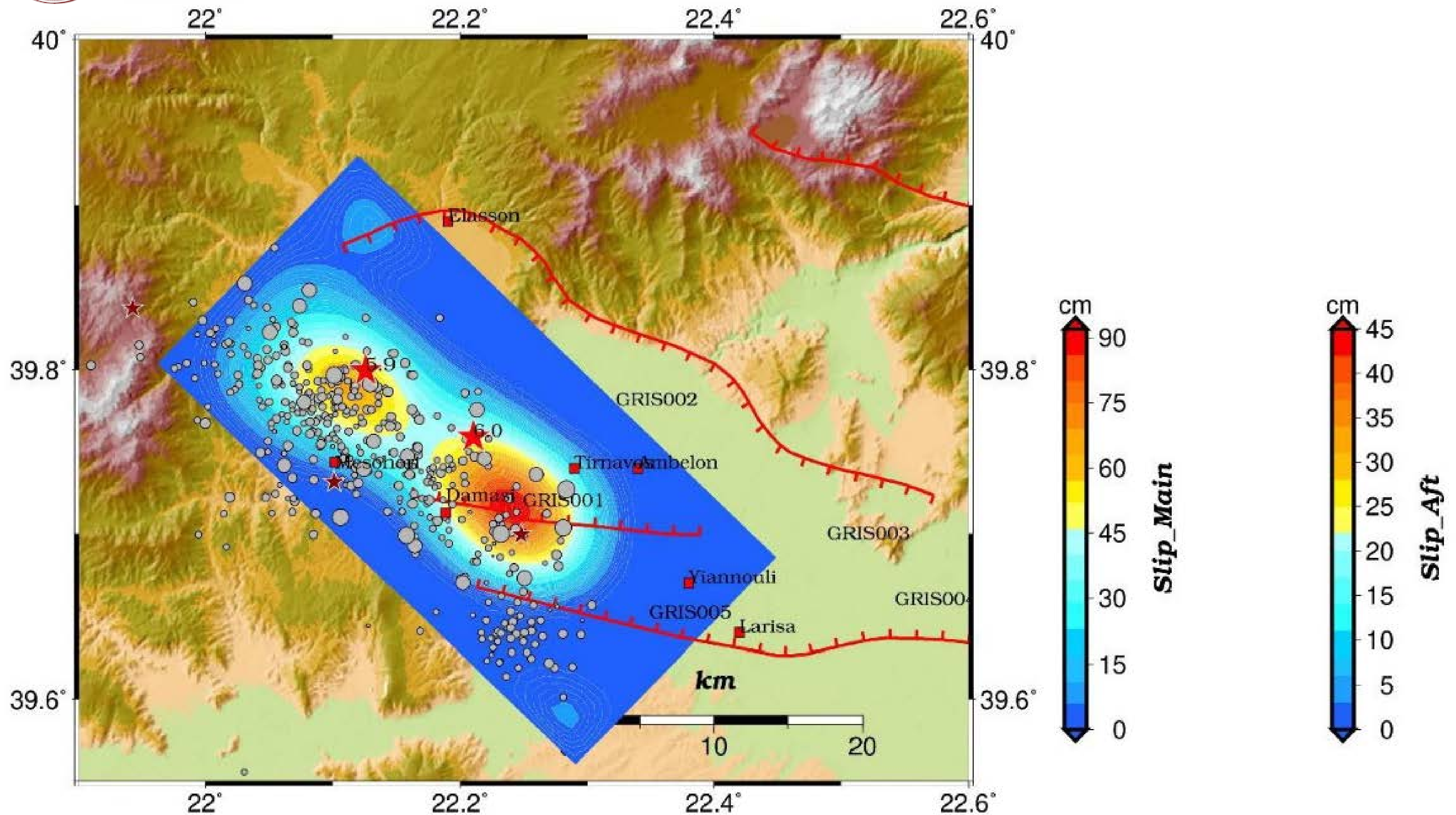
## FINITE-FAULT SLIP MODELS
### SLIP MODEL OF THE MARCH 4, 2021, Mw=5.9 EARTHQUAKE

Now clearly the previously partially ruptured asperity, slipped entirely to produce an M=5.9 earthquake.

No slip in the region that slipped during the March 3, 2021, M=6.3 earthquake.



## FINITE-FAULT SLIP MODELS
COMBINED SLIP OF BOTH EVENTS




Different scales due to different peak slip amplitudes

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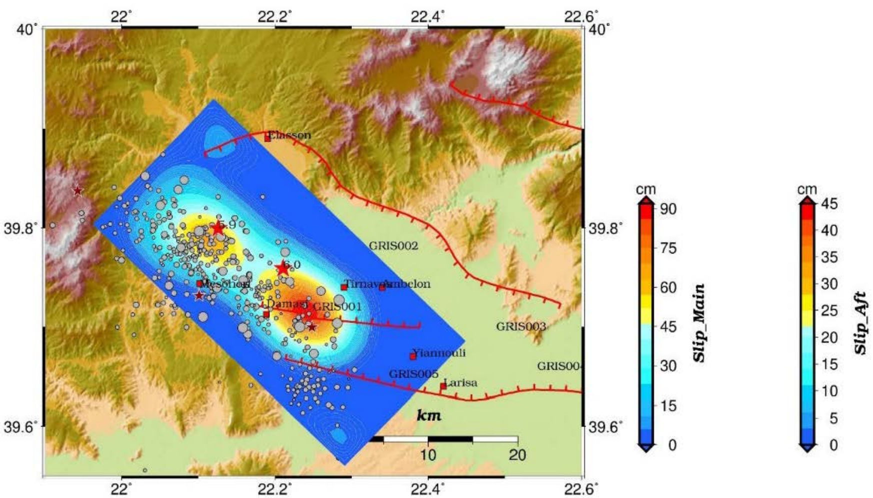
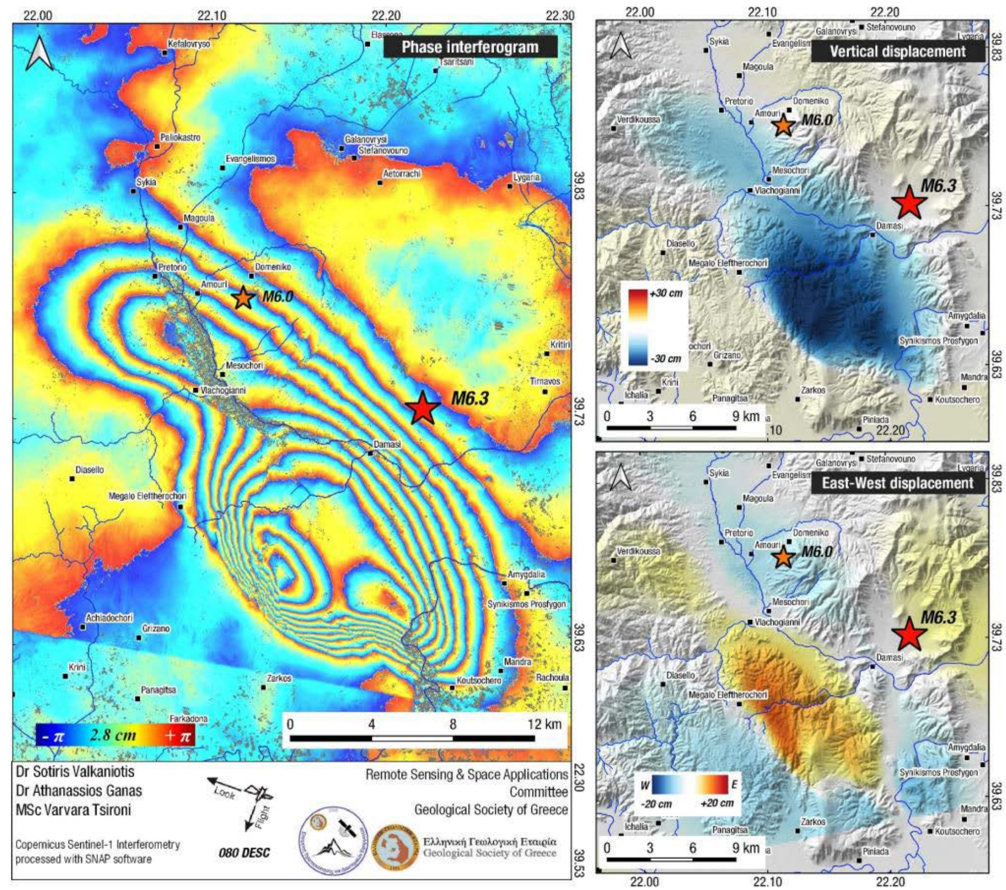
## COMPARISON OF SLIP MODELS WITH GEODETIC RESULTS




Compatible pattern with geodetic results

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## FINITE-FAULT SLIP MODELS

### CONCLUSIONS ON THE CAUSATIVE FAULT AND THE SLIP PROCESS

- A fault of ~27.5 km length ruptured in two episodes, separated by 1 day, to produce an M=6.3 and an M=5.9 earthquakes.
- The villages of Damasi, Vlachogianni, Mesochori project within the major slip patches.
- Surprisingly moderate dip angles (~35 deg) for what we expect for normal fault earthquakes. This small dip also increases the hazard as the fault plane projects with a larger area.
- Even though the two shocks cannot be connected to the known mapped faults of the area, the activation of the Tyrnavos and Larissa fault zones during the aftershocks, cannot be ruled out.
- Moreover, as these faults can host strong events, the hazard is still significant
- If we have difficulties to locate the fault with modern instrumentation, imagine how many historical earthquakes might have been miss-associated with known faults.
- This further renders the estimate of interevent times of earthquakes of a fault more difficult, not to mention the estimates of recurrence times.

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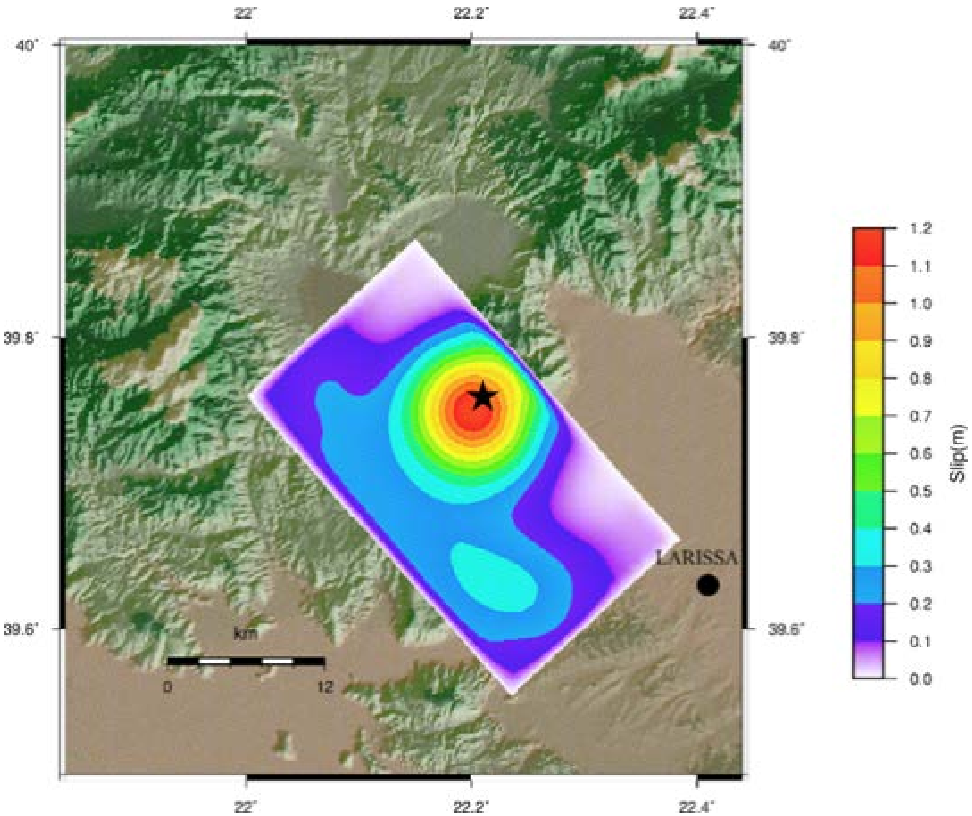
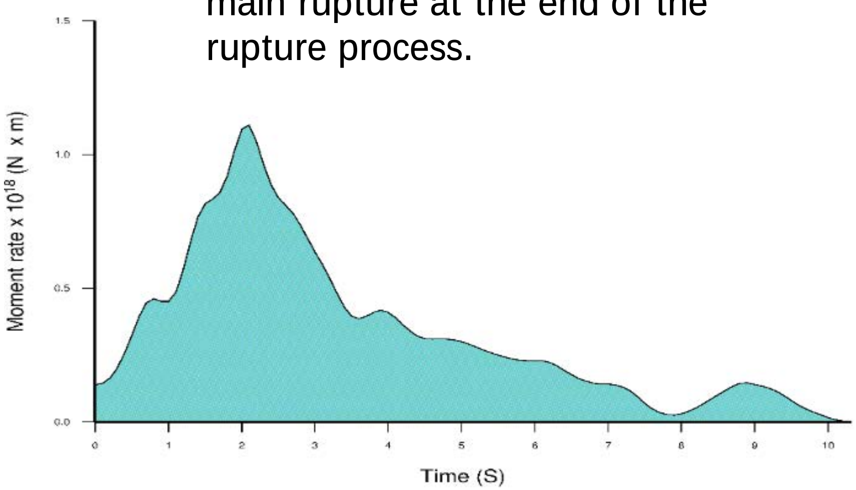
# SEISMIC SLIP IN THE FAULT PLANE OF THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE
## FROM THE INVERSION OF P WAVEFORMS AT TELESEISMIC DISTANCES (30°-90°)




◀ Horizontal projection of the slip distribution in the fault plane; maximum slip ~1.2 m near the hypocenter, minimum slip ~0.2 m near the surface.

▼ Seismic moment rate function. The largest amount of moment was released within the first ~4 sec of the rupture process in the main patch of the fault plane. A secondary patch was ruptured to the southeast of the main rupture at the end of the rupture process.




From Agalos, Papadopoulos, Triantafyllou

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# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Ascending Orbit (SNAP, SARSCAPE, GAMMA S/W) Results

The Earth Observation Team of the Harokopio University of Athens (Krassakis P., Lymperopoulos K., Karavias A., Bafi D., Gatsios T., Karatzia M., Gkougkoustamos I., Falaras T. and Parcharidis I.) applied geospatial technologies in order to assess the impact of the March 3 and March 4 earthquakes in the affected areas of Thessaly Basin.

They applied DInSAR analysis based on ESA Copernicus Sentinel satellite images. They produced co-seismic interferograms and displacement maps by using several software and they generated deformation sections in order to visualize the ground deformation due to the aforementioned earthquakes.

They used Sentinel-3 data before and after the March 3, Mw=6.3 earthquake in order to detect co-seismic land surface temperature anomalies and Sentinel-2 data before and after the March 3, Mw=6.3 earthquake in order to detect co-seismic variation in the Total Suspended Matter in the Polyphytos Reservoir located north of the earthquake-affected area.

Moreover, they studied the exposure of critical facilities and infrastructures to the surface deformation induced by the March 3, Mw=6.3 earthquake and the March 4, Mw=6.1 earthquake. These structures were laid over the DInSAR results in order to determine their exposure to the earthquake-induced surface deformation.

Educational facilities comprise child care centers, elementary, middle and high schools, health facilities include hospitals and health centers, infrastructures comprise bridges, national road and railways, cultural facilities include museums and archaeological sites.

HAROKOPIO UNIVERSITY OF ATHENS
DEPARTMENT OF GEOGRAPHY

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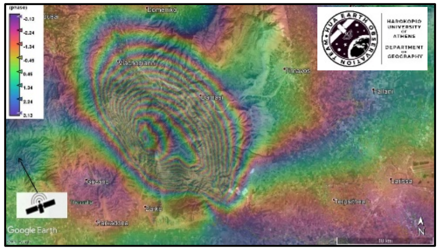
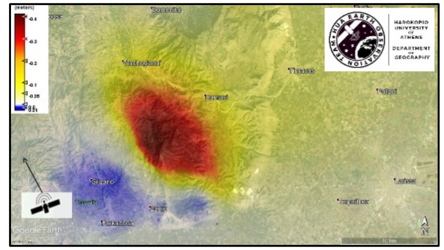
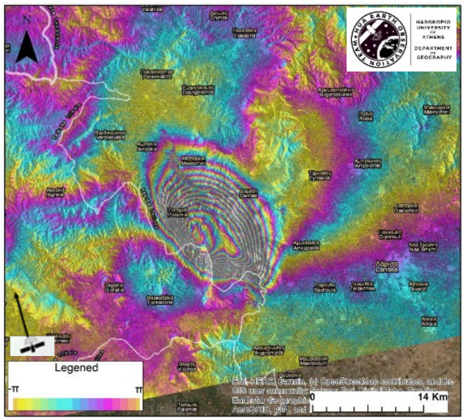
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Ascending Orbit (SNAP, SARSCAPE, GAMMA S/W) Results

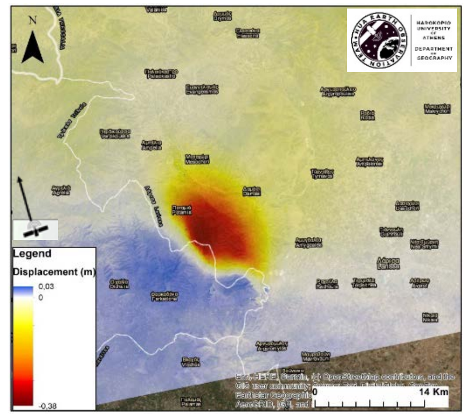


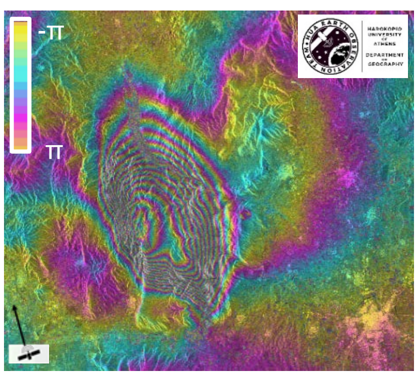

SNAP



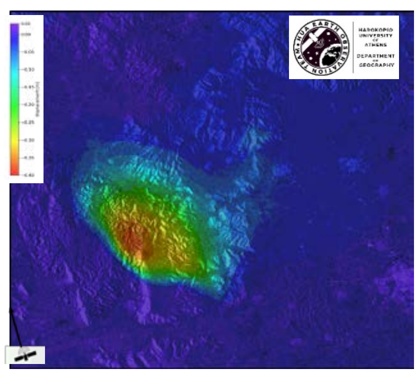




SARSCAPE




GAMMA



March 3, 2021,
M=6.3 Earthquake

Co-seismic interferograms and displacement maps were generated using the Ascending geometry (Orbit: 102, Master: 25/02, Slave: 03/03) and three softwares: SNAP, SARSCAPE and GAMMA

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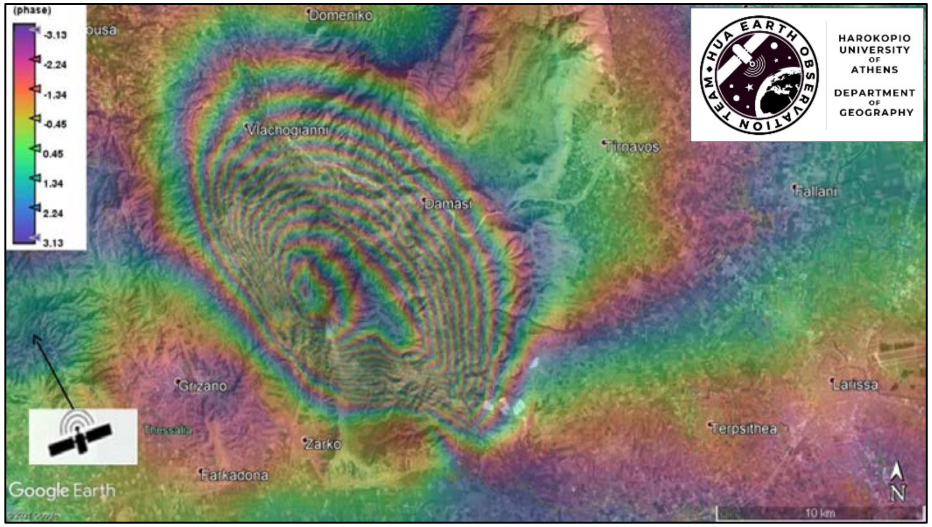
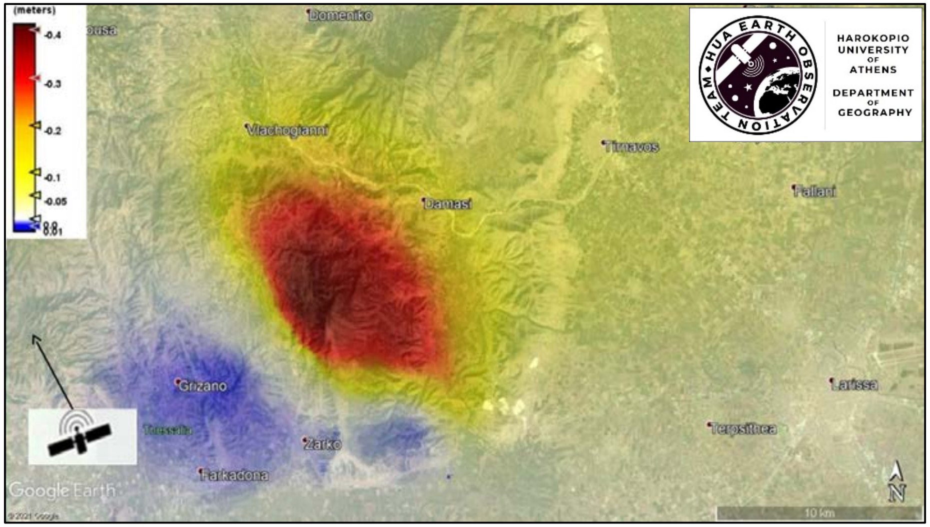
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Ascending Orbit Results (SNAP software)




March 3, 2021, M=6.3 Earthquake

A co-seismic interferogram and displacement map was generated using the Ascending geometry (Orbit: 102, Master: 25/02 16:24:15 GMT, Slave: 03/03 16:23:34 GMT) in the SNAP software. The displacement map shows subsidence up to 40 cm southwest of Damasi settlement and uplift up to 1 cm near Grizano settlement, after the Mw=6.3 earthquake including all the seismic events between 25/02 and 03/03.

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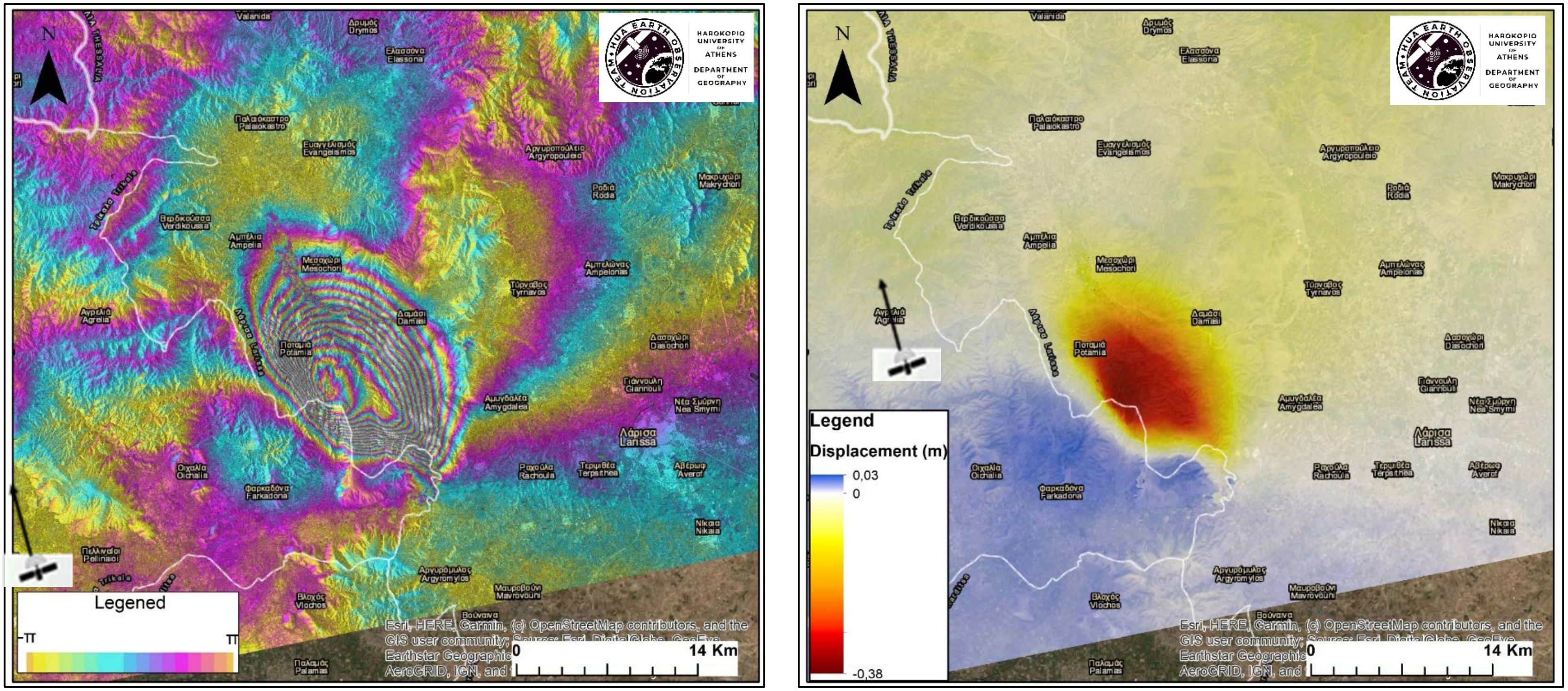
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Ascending Orbit Results (SARSCAPE software)




March 3, 2021, M=6.3 Earthquake

A co-seismic interferogram and displacement map was generated using the Ascending geometry (Orbit: 102, Master: 25/02 16:24:15 GMT, Slave: 03/03 16:23:34 GMT) in the SARSCAPE software. The displacement map shows subsidence up to 38 cm southwest of Damasi settlement and uplift up to 3 cm near Farkadona settlement, after the Mw=6.3 earthquake including all the seismic events between 25/02 and 03/03.

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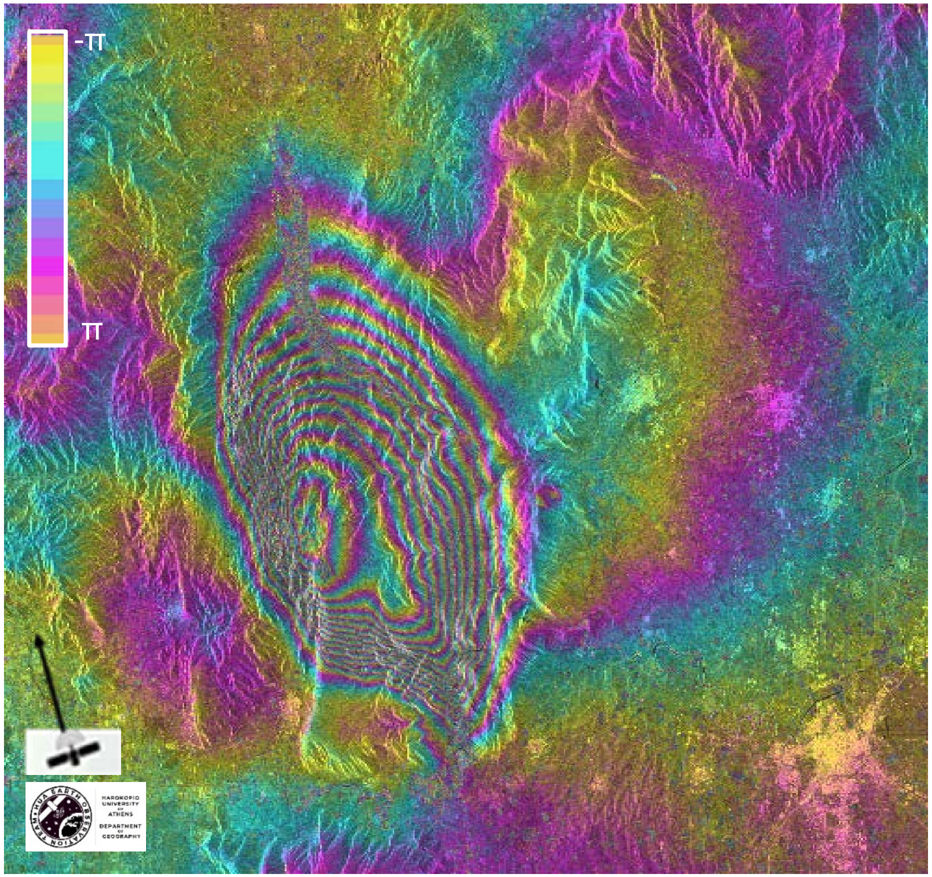
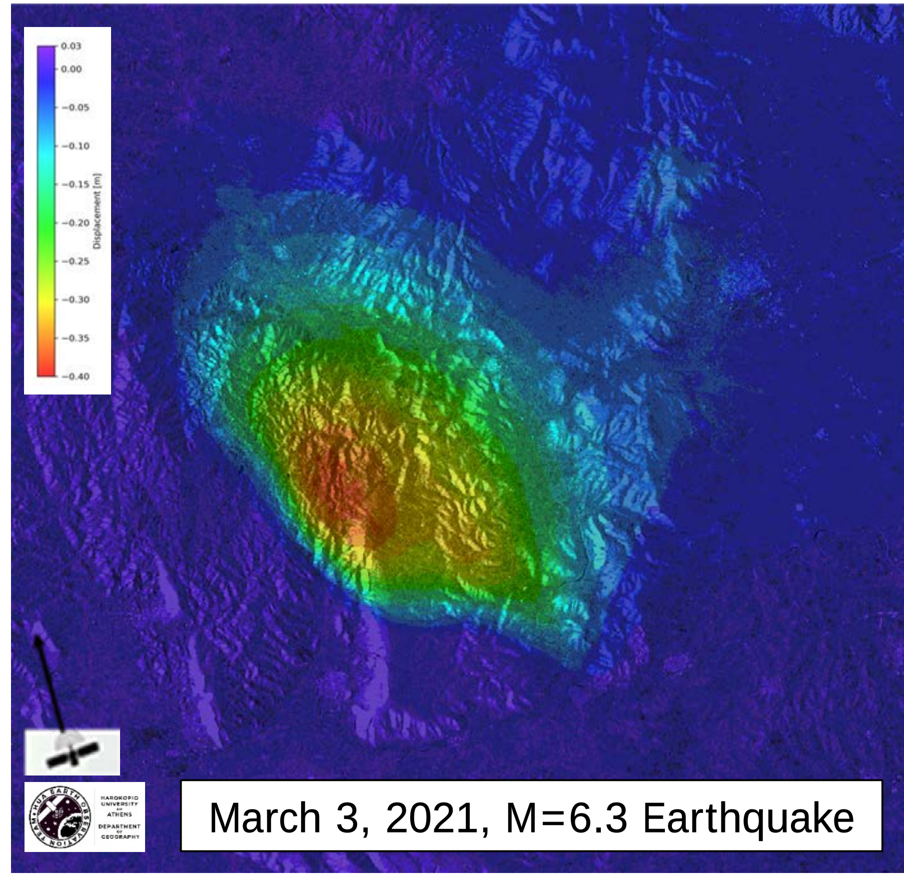
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Ascending Orbit Results (GAMMA software)




A co-seismic interferogram and displacement map was generated using the Ascending geometry (Orbit: 102, Master: 25/02 16:24:15 GMT, Slave: 03/03 16:23:34 GMT) in the GAMMA software. The displacement map shows subsidence up to 40 cm and uplift up to 3 cm, after the Mw=6.3 earthquake including all the seismic events between 25/02 and 03/03.

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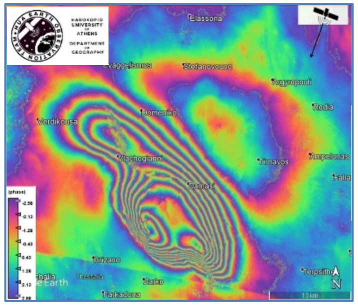
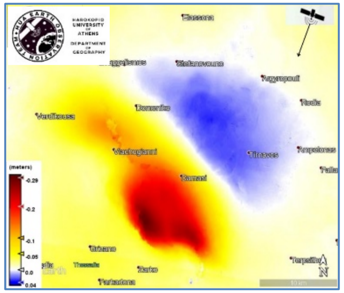
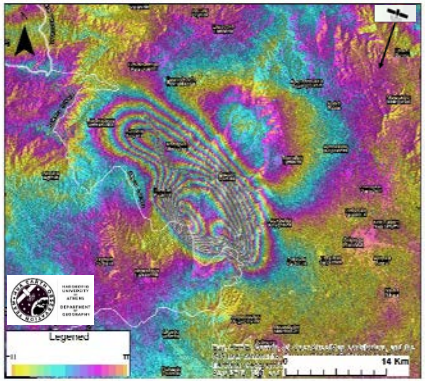
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Descending Orbit (SNAP, SARSCAPE, GAMMA S/W) Results

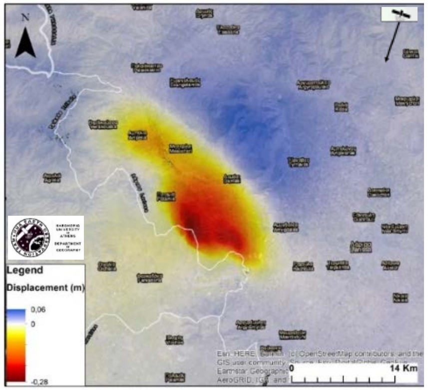


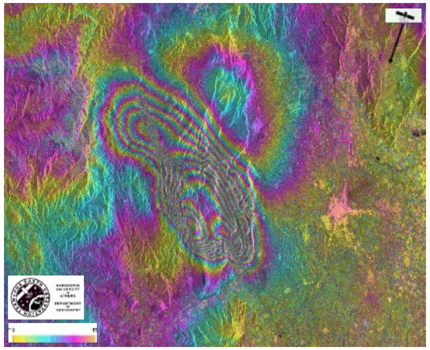
SNAP



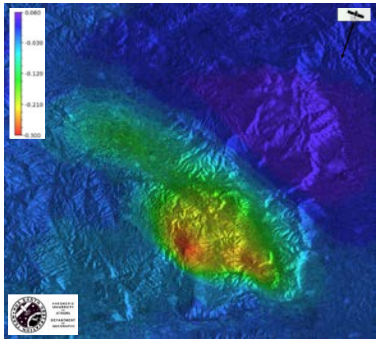


SARSCAPE





GAMMA



March 3, 2021,
Mw=6.3 earthquake
&
March 4, 2021
Mw=6.1 earthquake

Co-seismic interferograms and displacement maps were generated using the Descending geometry (Orbit: 80, Master: 24/02, Slave: 08/03) and three softwares: SNAP, SARSCAPE and GAMMA

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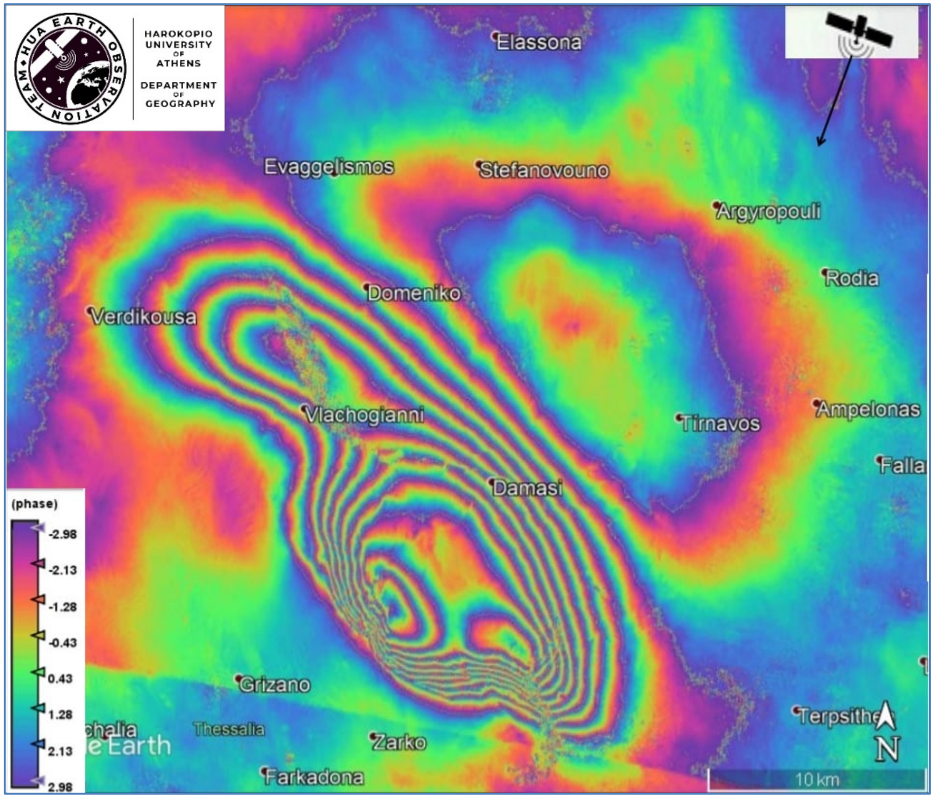
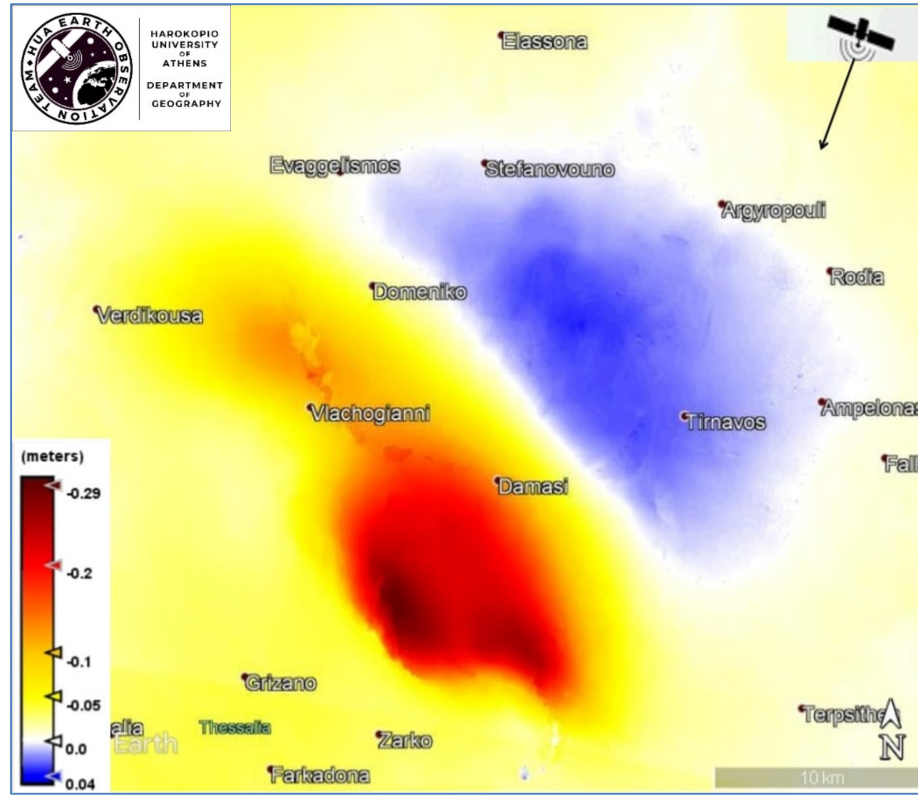
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Descending Orbit Results (SNAP software)




March 3, 2021, Mw=6.3 earthquake & March 4, 2021, Mw=6.1 earthquake

A co-seismic interferogram and displacement map was generated using the Descending geometry (Orbit: 80, Master: 24/02 04:39:54 GMT, Slave: 08/03 04:39:54 GMT) in the SNAP software. The results show subsidence up to 29 cm southwest of Damasi and uplift up to 4 cm near Tyrnavos, after the two major earthquake events (Mw=6.3 and Mw=6.1 respectively) including all the seismic events between 24/02 and 08/03.

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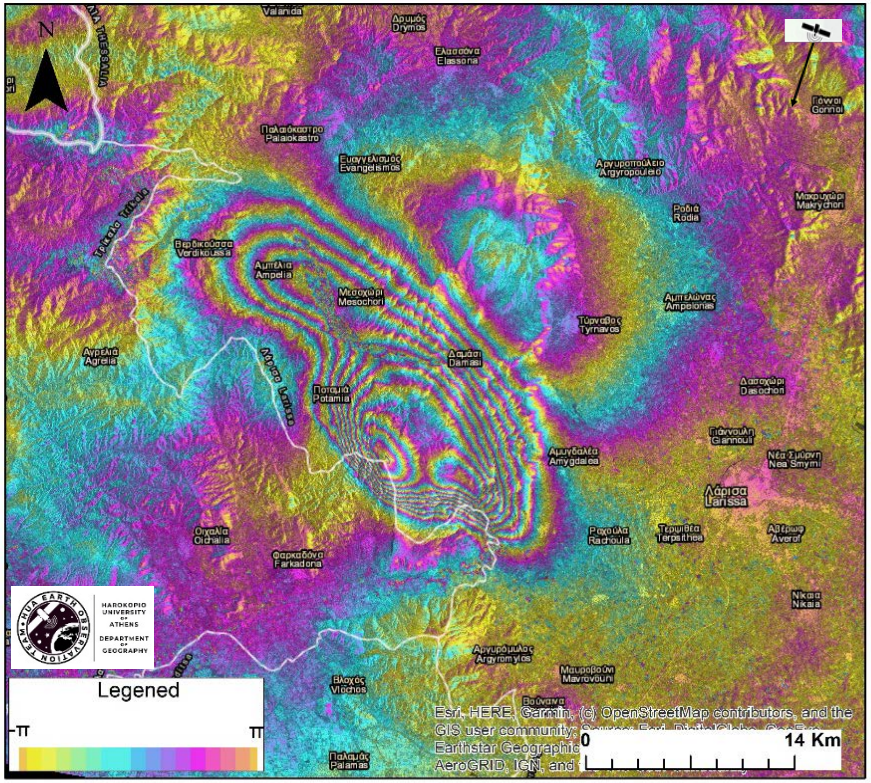
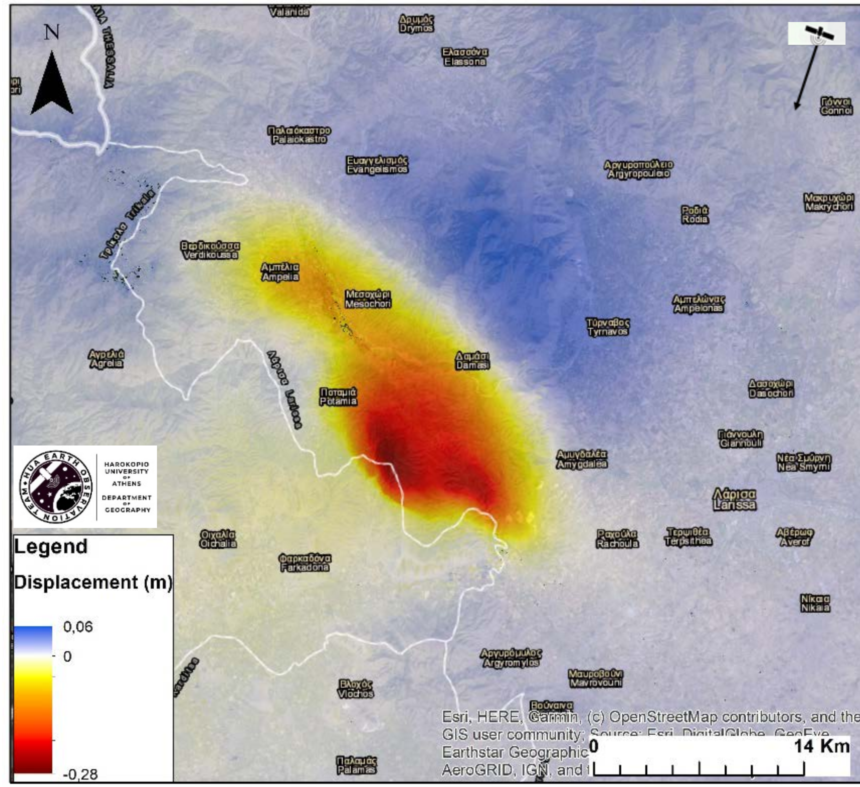
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Descending Orbit Results (SARSCAPE software)




March 3, 2021, M=6.3 earthquake & March 4, 2021, M=6.1 earthquake

A co-seismic interferogram and displacement map was generated using the Descending geometry (Orbit: 80, Master: 24/02 04:39:54 GMT, Slave: 08/03 04:39:54 GMT) in the SARSCAPE software. The results show subsidence up to 28 cm southwest of Damasi and uplift up to 6 cm near Tyrnavos, after the two major earthquake events (Mw=6.3 and Mw=6.1 respectively), including all seismic events between 24/02 and 08/03.

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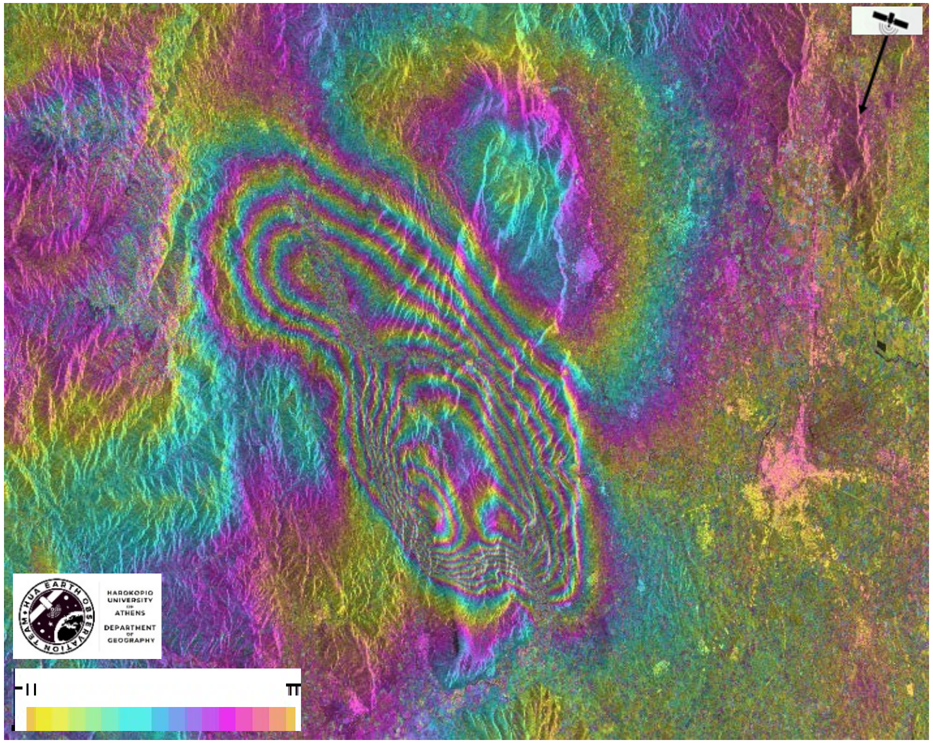
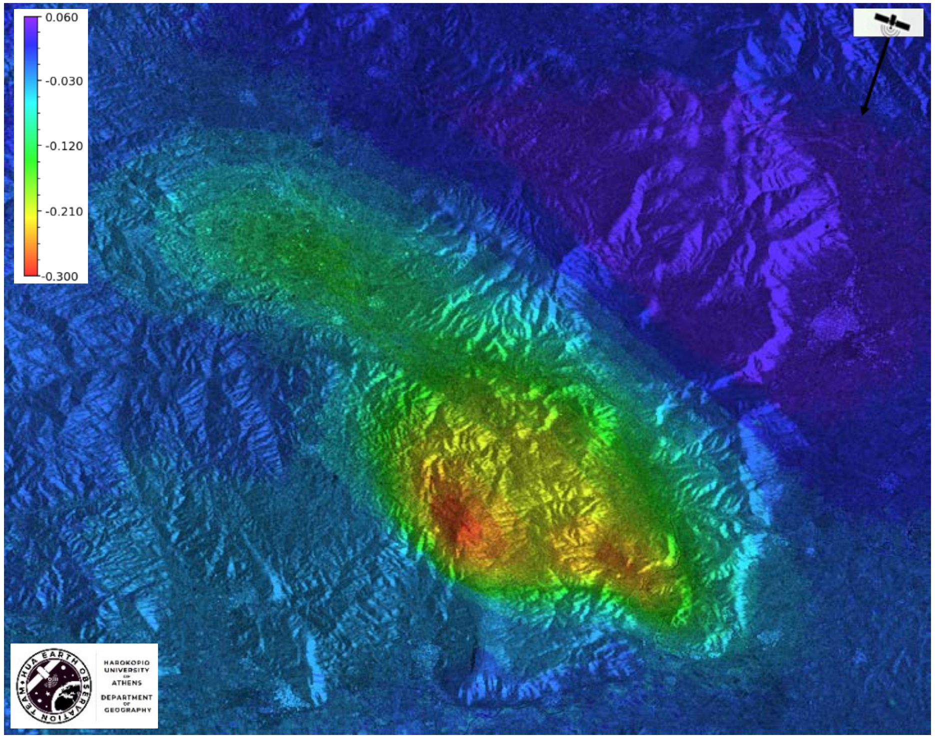
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DInSAR – Sentinel-1 Descending Orbit Results (GAMMA software)






March 3, 2021, M=6.3 earthquake & March 4, 2021, M=6.1 earthquake

A co-seismic interferogram and displacement map was generated using the Descending geometry (Orbit: 80, Master: 24/02 04:39:54 GMT, Slave: 08/03 04:39:54 GMT) in the GAMMA software. The results show subsidence up to 30 cm and uplift up to 6 cm, after the two major earthquake events (Mw=6.3 and Mw=6.1 respectively), including all the seismic events between 24/02 and 08/03.

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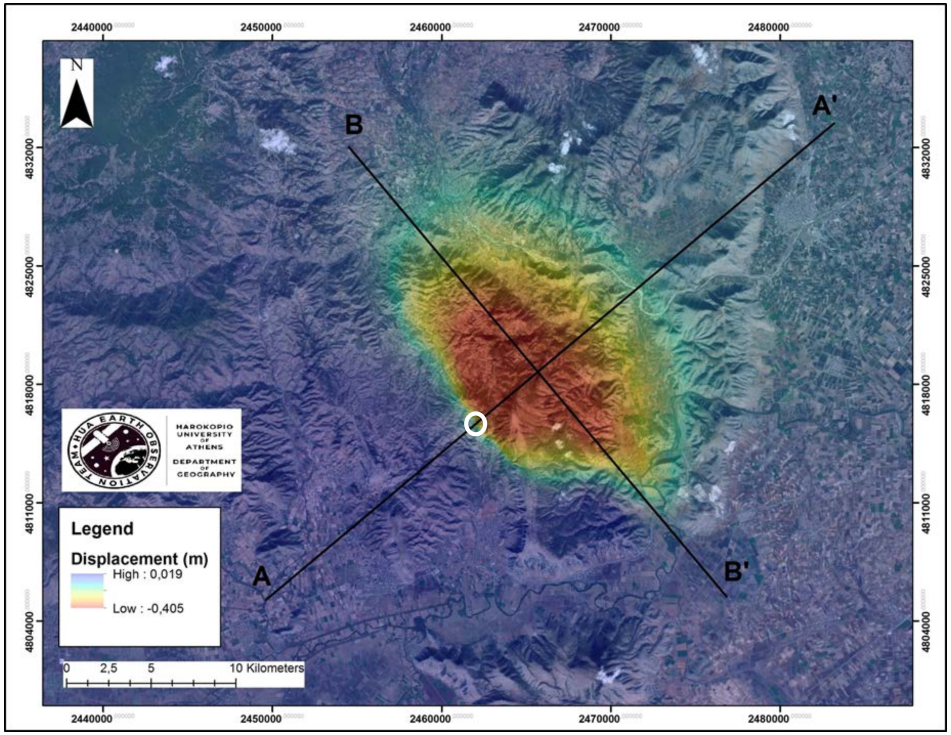
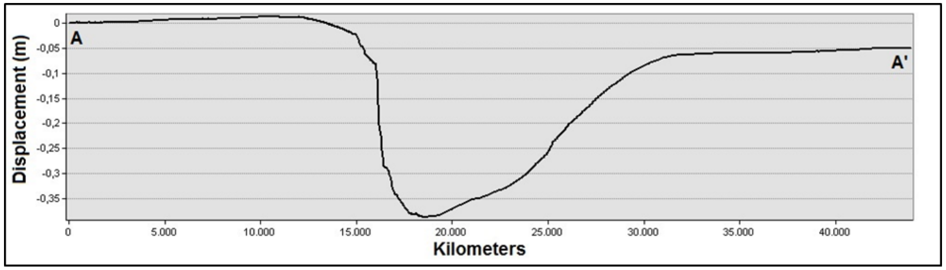
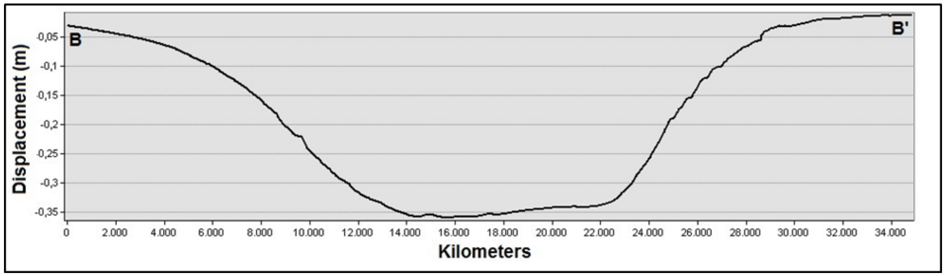
## Deformation sections of Sentinel-1 Ascending geometry DInSAR results after the March 3, Mw=6.3 earthquake




Two sections were generated in order to visualize the ground deformation due to the Mw=6.3 earthquake. It is notable that in the 15 km of the AA' section, the subsidence is very abrupt.

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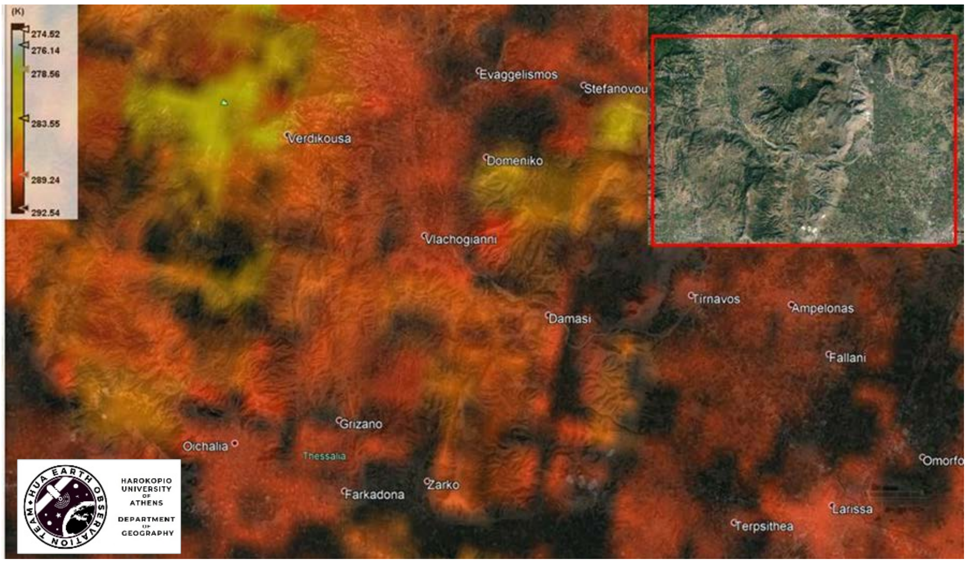
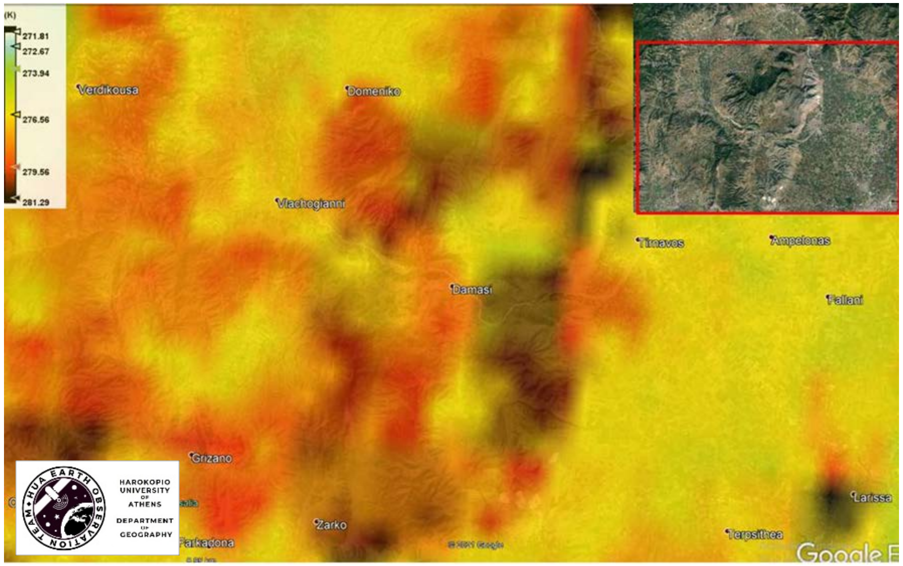
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## DEFORMATION SECTIONS OF SENTINEL-1 ASCENDING GEOMETRY

## DINSAR RESULTS AFTER THE MARCH 3, MW=6.3 EARTHQUAKE




Day surface temperature based on processing of Sentinel 3A LST product, date and time of acquisition 3_3_2021 T: 9:01 GMT, so the acquisition was done some hours before the first seismic event. Temperature rates are in Kelvin ($T_{(°C)} = T_{(K)} - 273.15$).




Night surface temperature based on processing of Sentinel 3B LST product, date and time of acquisition 3_3_2021 T: 19:38 GMT, so the acquisition was done some hours after the first seismic event. Temperature rates are in Kelvin ($T_{(°C)} = T_{(K)} - 273.15$).

No co-seismic Land Surface Temperature anomaly was observed

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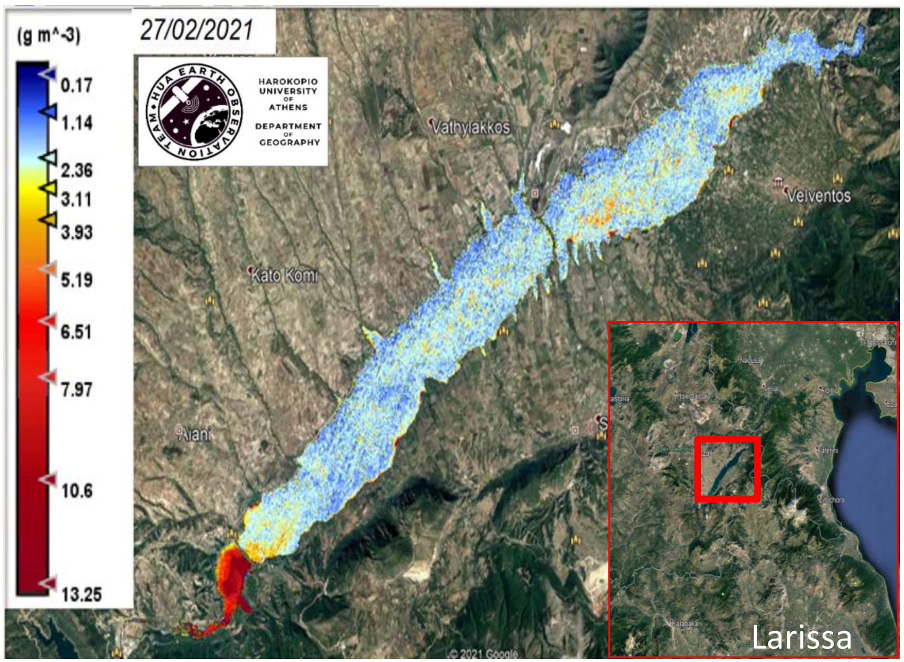
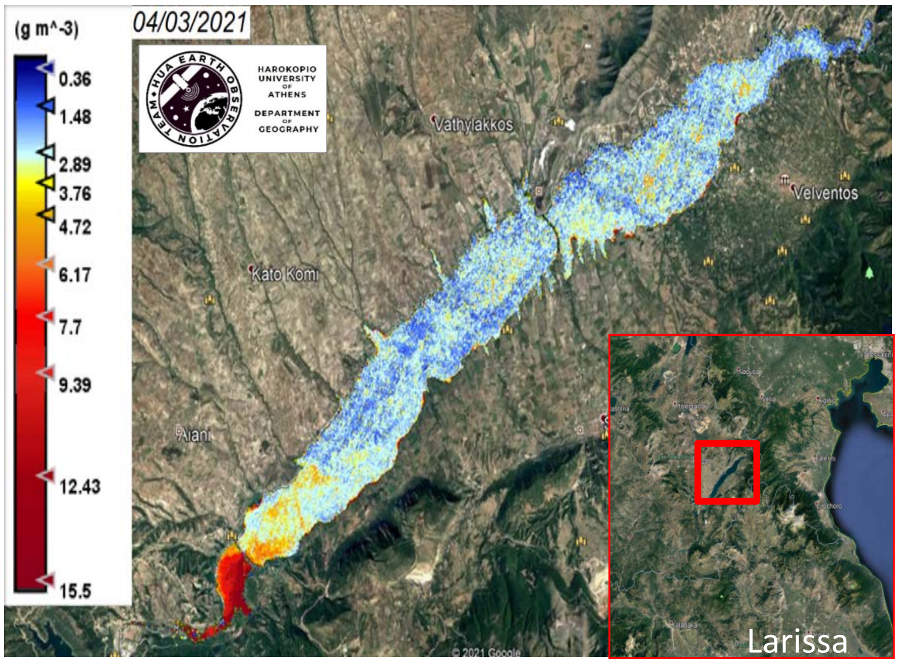
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## TOTAL SUSPENDED MATTER FROM SENTINEL-2 DATA BEFORE AND AFTER THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




Total Suspended Matter (TSM), before the first seismic event based on processing Sentinel-2A 1C product, date and time of acquisition 27_02_2021 T: 9:20 GMT.




Total Suspended Matter (TSM), after the first seismic event based on processing Sentinel-2B 1C product, date and time of acquisition 04_03_2021 T: 9:20 GMT.

No co-seismic variation in TSM was observed

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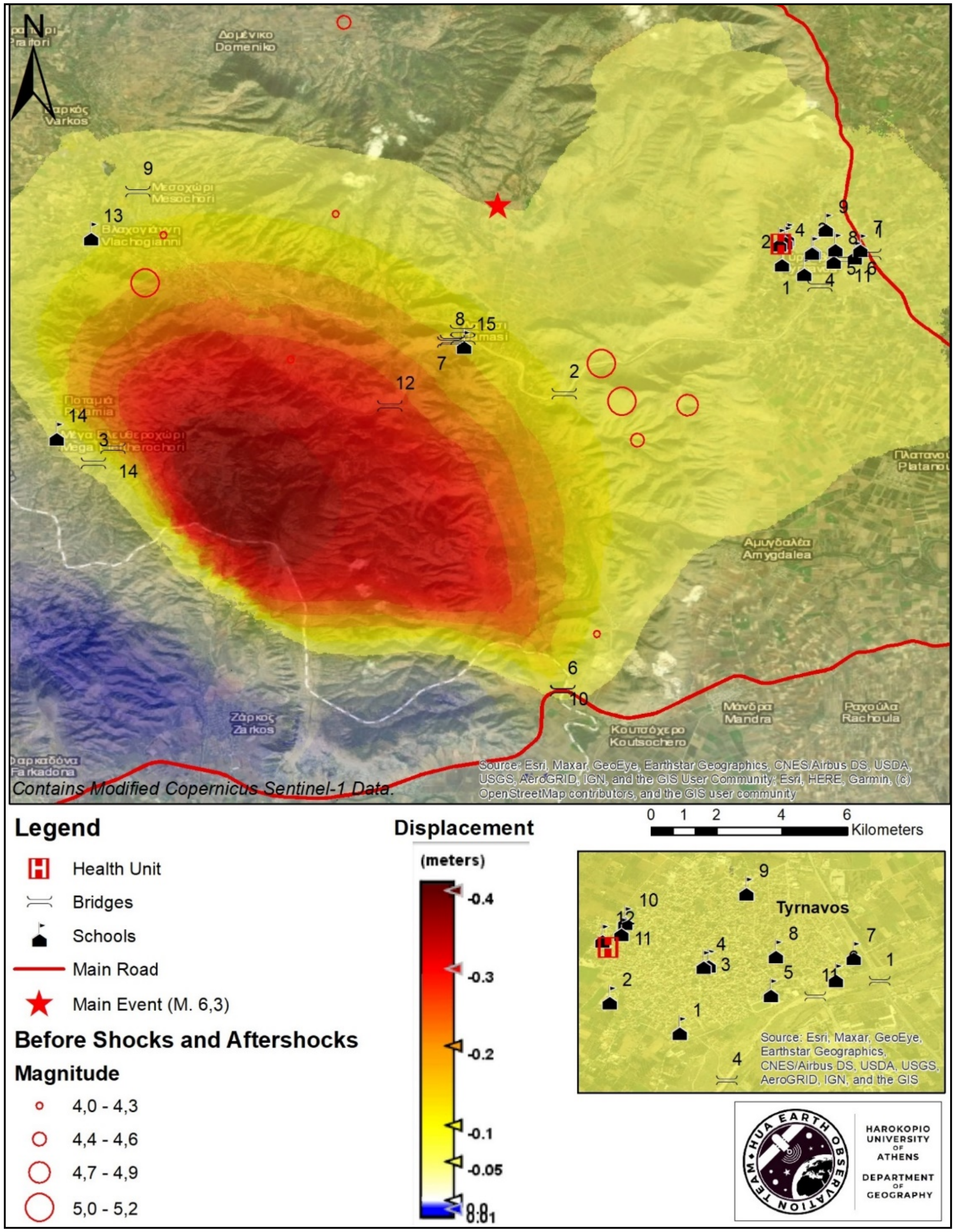
# SCHOOLS, BRIDGES & HOSPITALS EXPOSURE AFTER THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




| School ID | SCHOOL NAME | Displacement (m) |
|---|---|---|
| 1 | 4th Elementary School of Tyrnavos | -0,058 |
| 2 | 1st Professional High School of Tyrnavos | -0,058 |
| 3 | 2nd Elementary School of Tyrnavos | -0,057 |
| 4 | 1st Kindergarten of Tyrnavos | -0,057 |
| 5 | 1st Middle School of Tyrnavos | -0,056 |
| 6 | 1st Elementary SchoolTyrnavos | -0,055 |
| 7 | Boarding School of Tyrnavos | -0,054 |
| 8 | 2nd Kindergarten of Tyrnavos | -0,055 |
| 9 | 5th Elementary School of Tyrnavos | -0,054 |
| 10 | 2nd Middle School of Tyrnavos | -0,057 |
| 11 | 3rd Elementary School of Tyrnavos | -0,057 |
| 12 | Nursery School | -0,057 |
| 13 | Elementary School of Vlachogianni | -0,088 |
| 14 | Elementary School of Megalo Eleftherochori | -0,059 |
| 15 | Elementary School of Damasi | -0,137 |

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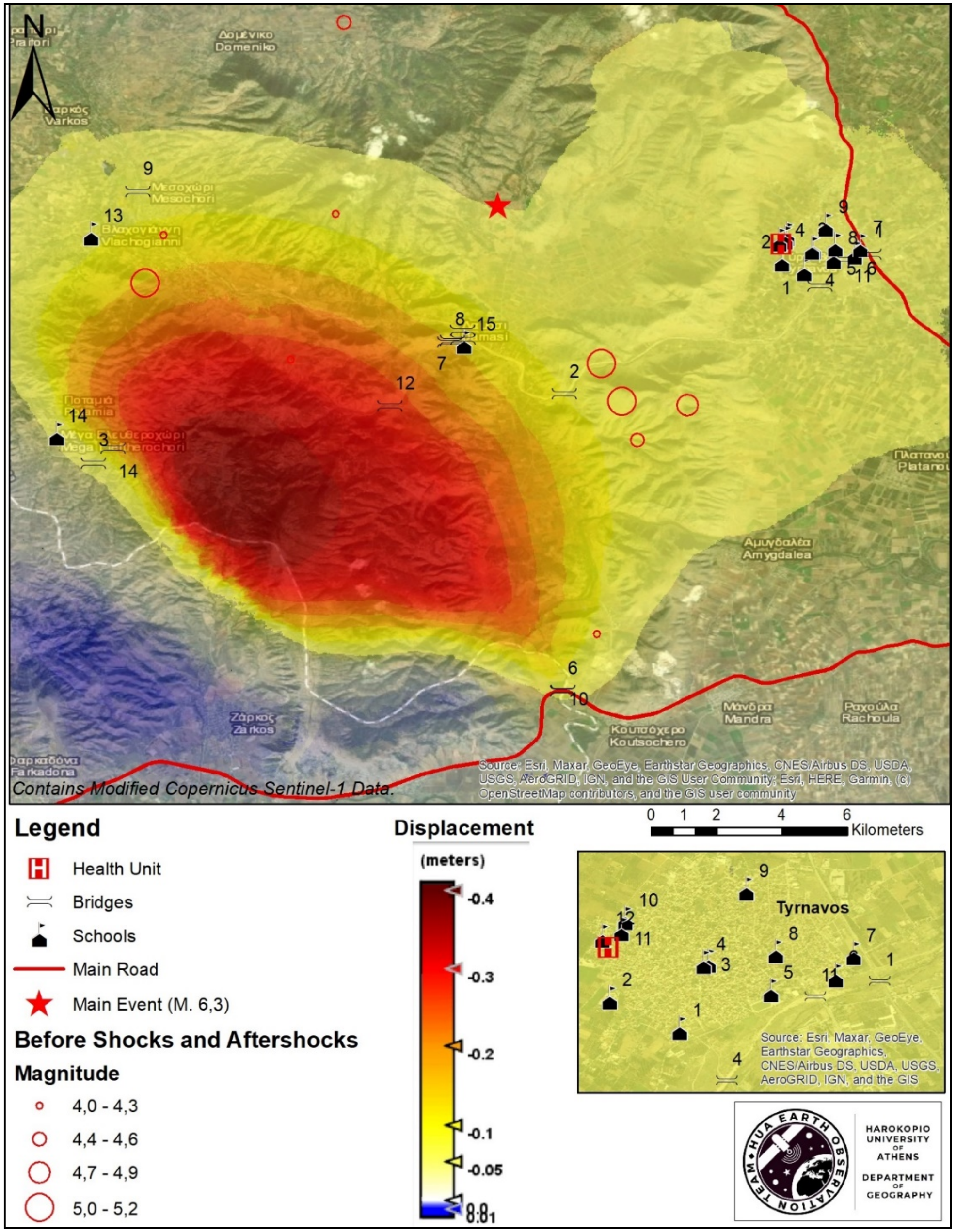


# SCHOOLS, BRIDGES & HOSPITALS EXPOSURE
## AFTER THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE

| BRIDGE ID | BRIDGE NAME | Displacement (m) |
|---|---|---|
| 1 | Larissa – Elassona | -0,055 |
| 2 | Damasi – Koutsochero | -0,099 |
| 3 | - | -0,064 |
| 4 | - | -0,0579 |
| 5 | - | -0,128 |
| 6 | Larissa – Trikala | -0,070 |
| 7 | - | -0,146 |
| 8 | - | -0,150 |
| 9 | Mesochori – Vlachogianni | -0,080 |
| 10 | Larissa – Trikala | -0,070 |
| 11 | Larissa – Tyrnavos | -0,056 |
| 12 | - | -0,273 |
| 13 | - | -0,136 |
| 14 | - | -0,147 |

| HOSPITAL id | HEALTH FACILITY NAME | Displacement (m) |
|---|---|---|
| 1 | Tyrnavos Health Centre | -0,057 |

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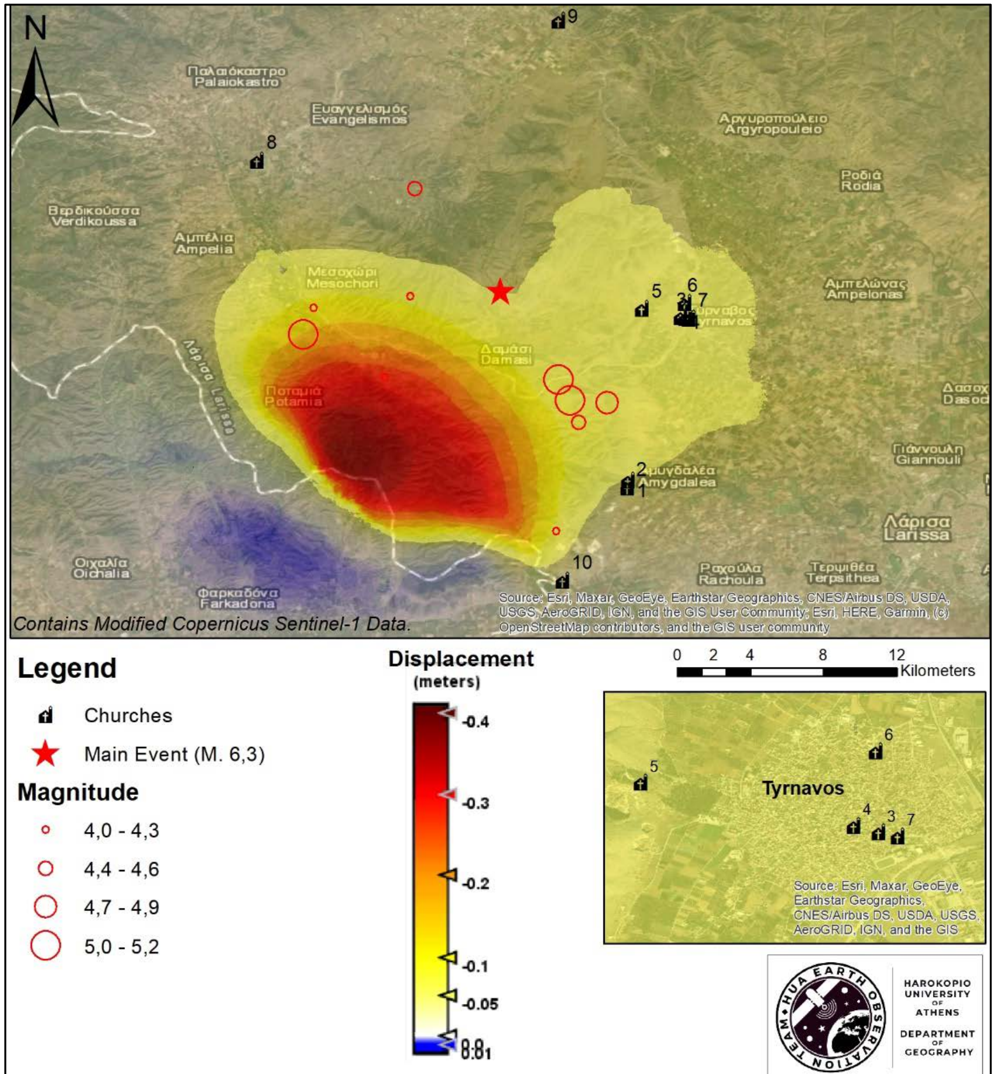
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## CHURCHES & DEFORMATION IN METERS AFTER THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




| CHURCH id | CHURCH NAME | Displacement (m) |
|---|---|---|
| **1** | Agios Nikolaos | -0,048 |
| **2** | Amygdalea Cemetery | -0,046 |
| **3** | Agios Nikolaos Tourachan | -0,057 |
| **4** | Panagia Faneromeni | -0,056 |
| **5** | Profitis Ilias | -0,058 |
| **6** | Agios Antonios | -0,055 |
| **7** | Agia Paraskevi | -0,056 |
| **8** | Agios Georgios | -0,016 |
| **9** | Agios Nikolaos, Tsaritsani village | -0,024 |
| **10** | Agios Nikolaos, Koutsochero village | -0,027 |

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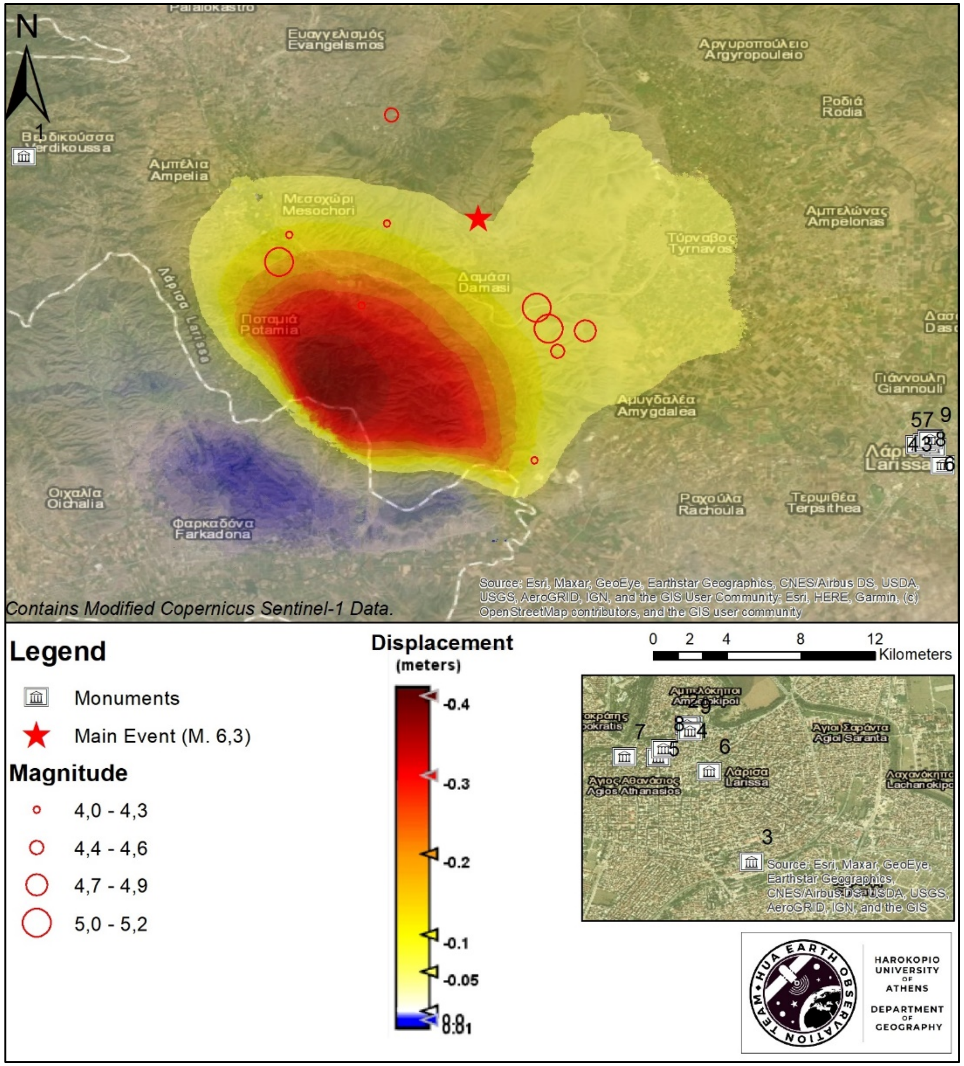
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## MONUMENTS & DEFORMATION IN METERS AFTER THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




| MONUMENT ID | NAME | DISPLACEMENT (M) |
|---|---|---|
| 1 | - | -0,028 |
| 2 | Larissa Doll Museum | -0,022 |
| 3 | Larissa Railway Museum | -0,020 |
| 4 | Museum of Cereals and Flour | -0,022 |
| 5 | 1st Ancient Theater of Larissa | -0,022 |
| 6 | Larissa Yeni Mosque | -0,022 |
| 7 | 2nd Ancient Theater of Larissa | -0,023 |
| 8 | Saint Achillios Basilica | -0,022 |
| 9 | Mill of Pappas | -0,022 |

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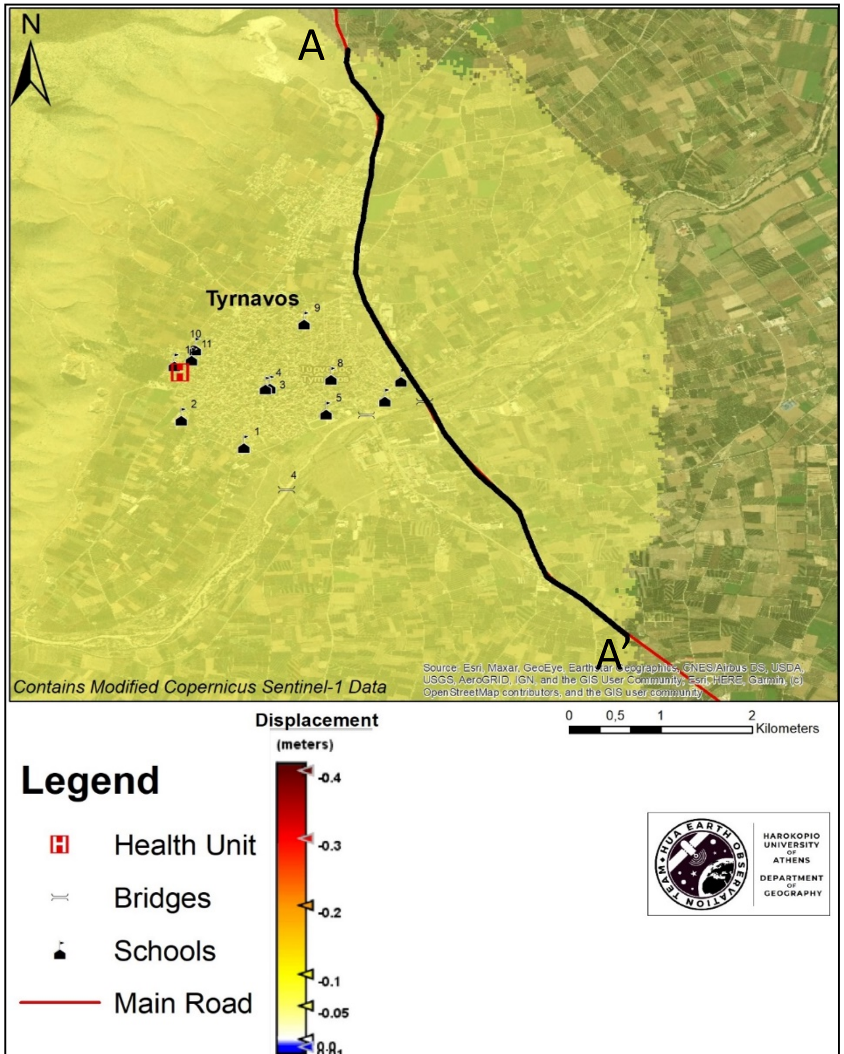
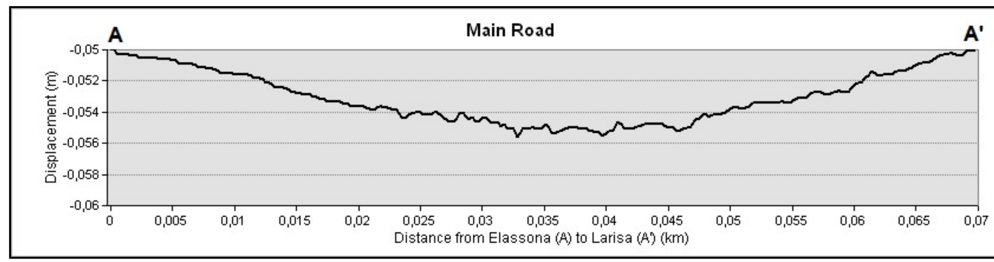
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## EXPOSURE OF THE NATIONAL ROAD FROM ELASSONA TO LARISSA AFTER THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




Local exposure data for the area of Tyrnavos

Histogram showing the deformation along National Road from Elassona to Larissa

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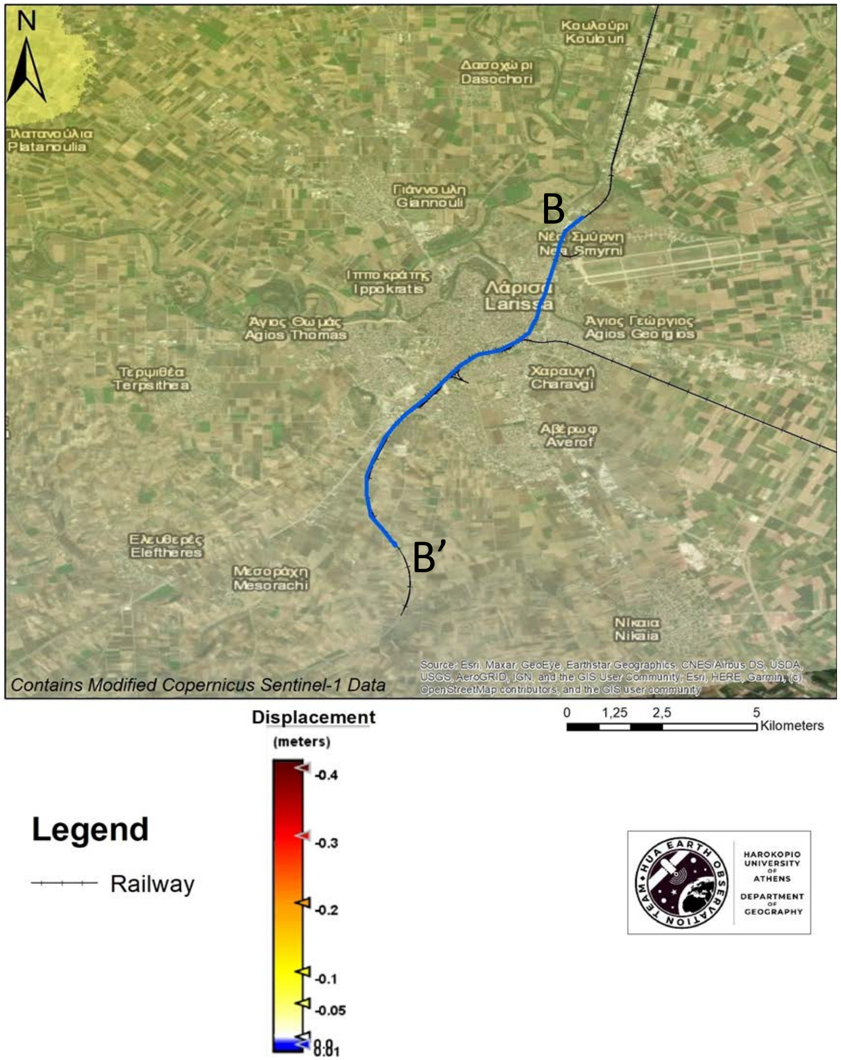
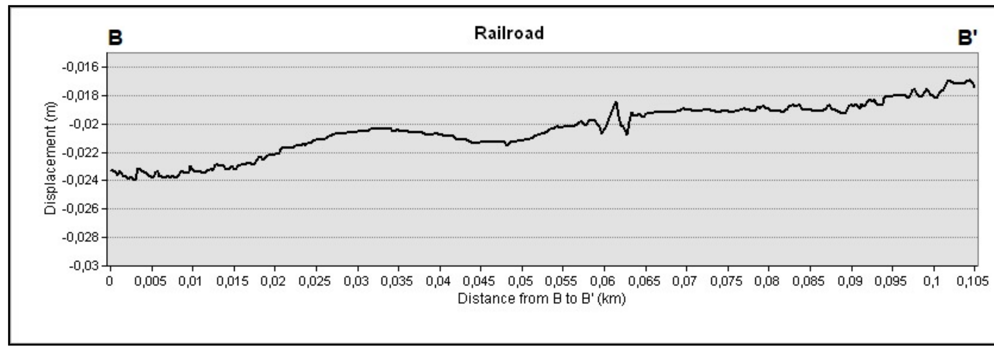
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## NATIONAL RAILWAY NETWORK EXPOSURE
## AFTER THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




Histogram showing the deformation along National Railway Network. An anomaly was observed due to noise signature.

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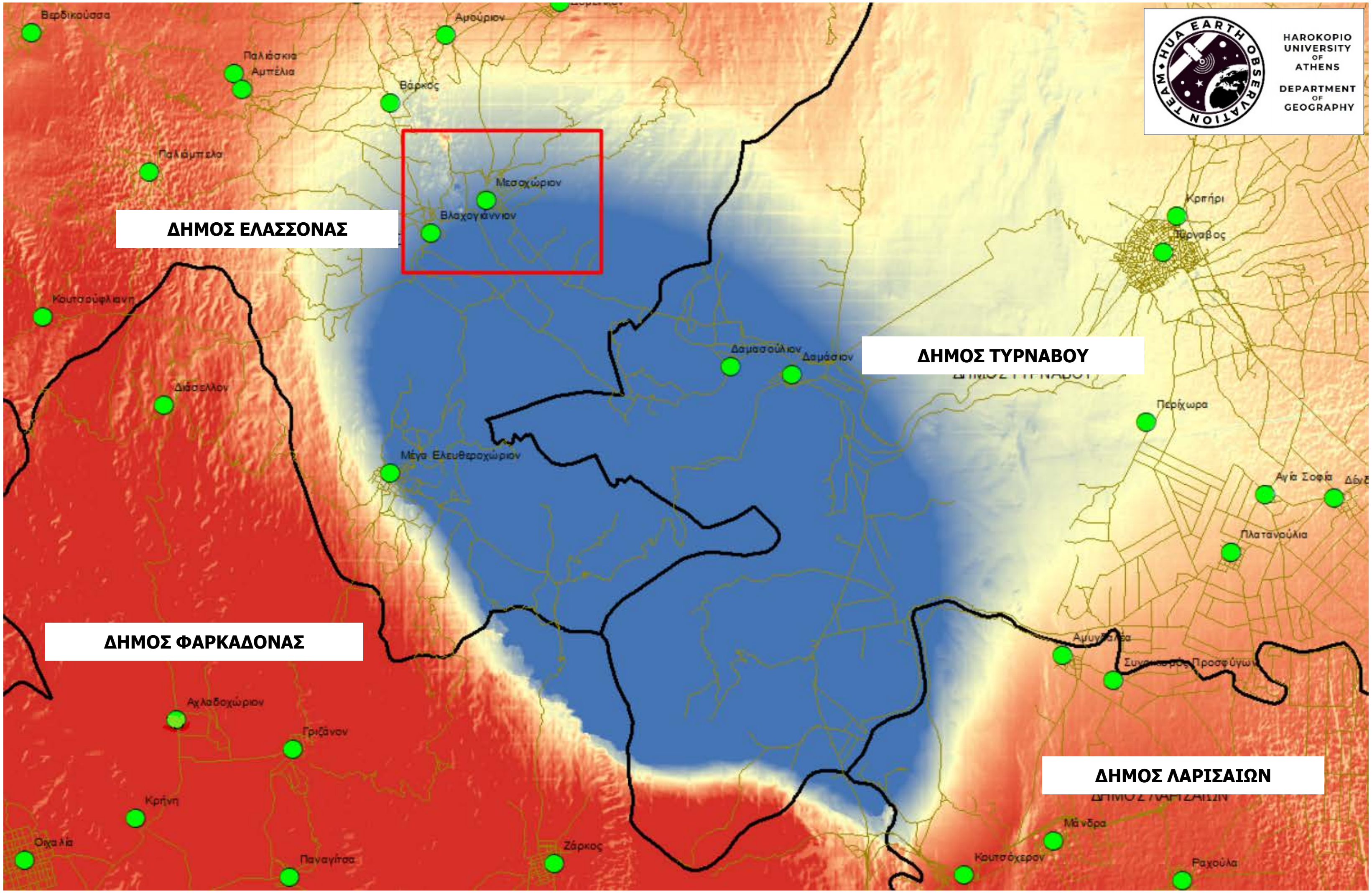
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

## MUNICIPALITIES AFFECTED
## FROM THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE



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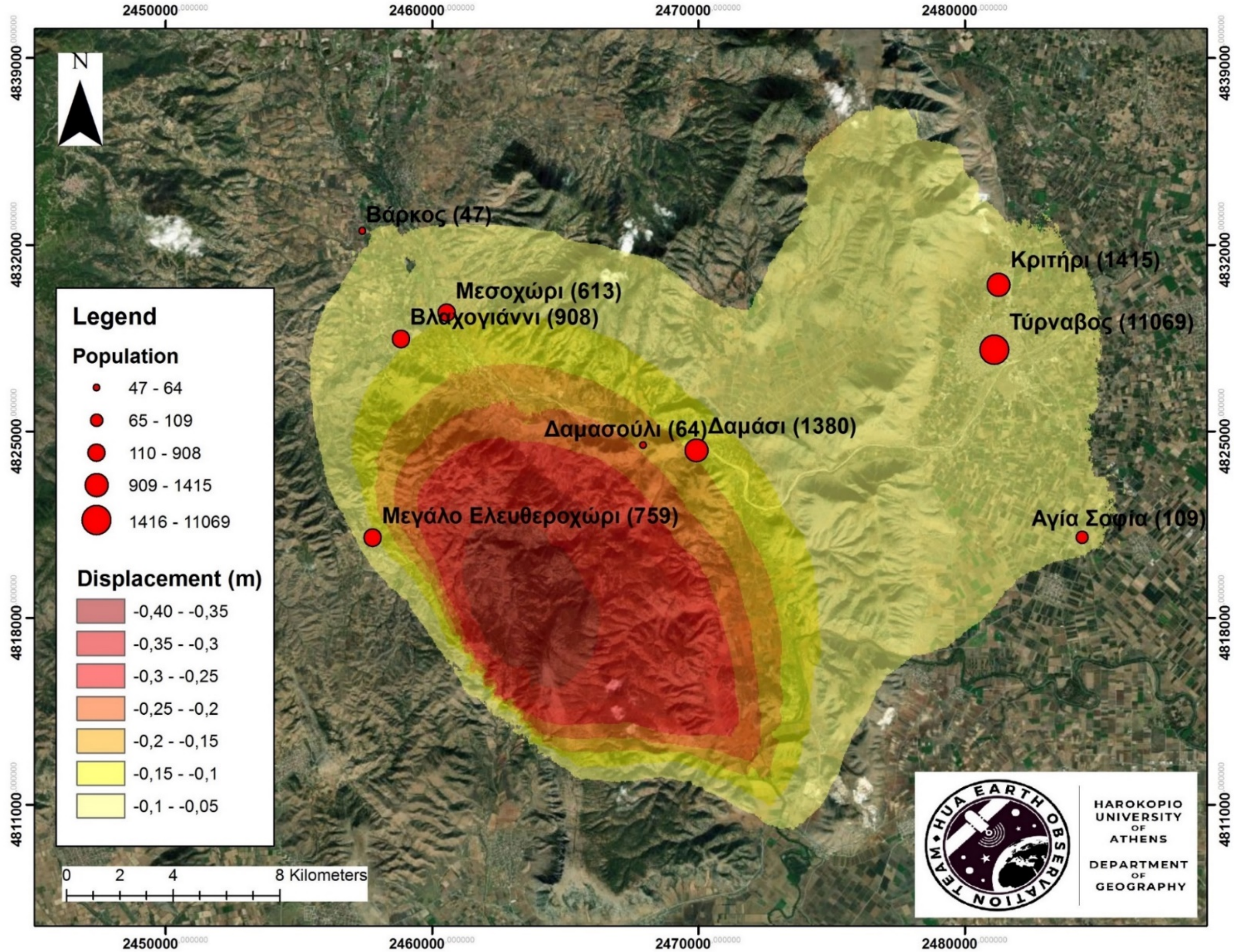
## POPULATION AFFECTED
## FROM THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE



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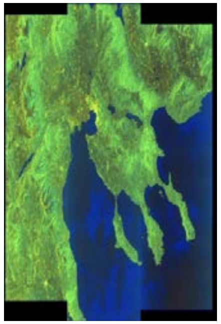
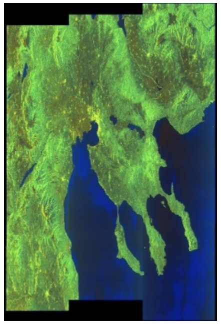
# INTEGRATION OF GEOSPATIAL TECHNOLOGIES ON EARTHQUAKE IMPACT ASSESSMENT

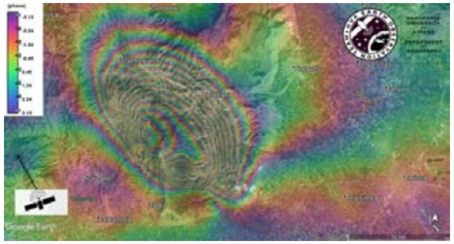
## FLOW CHART & DATA SOURCES OF THE WORK OF THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE



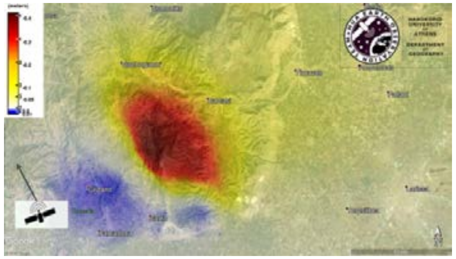
MASTER 25-2-2021
Date-time: 2021-02-25
T16:24:15.719Z



SLAVE 3-3-2021
Date and time: 2021-03-03
T16:23:34.672Z
Ingestion in platform
Date- time: 2021-03 03
T18:06:39.546Z



Wrapped interferogram
(in phase)
date-time: 3-3-2021
T 22:11 (local time)



Unwrapped interferogram
(displacement map in m)
date-time 3-3-2021
T 23:18 (local time)

**DATA SOURCES**

ESA Copernicus

OpenStreetMap (OSM)

National Observatory of Athens - Geodynamics Institute (NOA-GI)

Hellenic Survey of Geology and Mineral Exploration (HSGME)

Institute of Engineering Seismology and Earthquake Engineering (ITSAK)

European-Mediterranean Seismological Centre (EMSC)

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## EARTHQUAKE ENVIRONMENTAL EFFECTS
## TRIGGERED BY THE MARCH 3, 2021, Mw=6.3 THESSALY EARTHQUAKE

Post-event field surveys in the earthquake-affected area for mapping the earthquake environmental effects were conducted by several teams from universities, institutes and organizations including:

- the Department of Geology and Geoenvironment in the University of Athens (Lekkas, Kranis, Skourtsos, Mavroulis and Gogou)
- the Department of Geology in the Aristotle University of Thessaloniki (Pavlides, Chatzipetros, Sboras, Kremastas and Chatziioannou)
- the Department of Geology in the University of Patras (Koukouvelas, Nikolakopoulos, Kyriou, Apostolopoulos, Zygouri, Verroios, Belesis and Tsentzos)
- the School of Civil Engineering of the Democritus University of Thrace (Papathanassiou)
- the Geodynamic Institute of the National Observatory of Athens (Ganas and Valkaniotis) and
- the Hellenic Survey of Geology and Mineral Exploration (Galanakis and Konstantopoulou)

These surveys aimed not only to map the earthquake environmental effects in the affected area but mainly to detect the causative fault of the March 3, 2021, Mw=6.3 earthquake and the March 4, 2021, Mw=6.1 earthquake.

Primary effects directly linked to the earthquake energy and in particular to the surface expression of the seismogenic source were not detect in the field, as these lines are written.

The March 3, 2021, Mw=6.3 Thessaly earthquake triggered primary and secondary environmental effects in the earthquake-affected area.

The secondary earthquake environmental effects included mainly liquefaction phenomena as well as ground cracks and slope failures comprising rockfalls and landslides.

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## EARTHQUAKE ENVIRONMENTAL EFFECTS
## TRIGGERED BY THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE

**Liquefaction phenomena** were observed in several sites located within the Titarissios and the Pineios river beds. These areas are characterized by recent unconsolidated river deposits and shallow underground water level. Based on information provided by local people, the underground water level was measured as 6 m from the surface.

More specifically, liquefaction was observed in the area located southeast of Vlachogianni village (Titarissios River bed), in the area located northwest of Koutsochero village (Pineios River bed) and in the area between Farkadona and Pineiada (Pineios River bed).

The aforementioned phenomena comprised ejection of liquefied material from ground cracks and formation of typical forms of liquefaction including individual sand boils, alignment of sand boils along ground cracks as well as water and sand fountains mainly reported by local people, who worked in the fields at the time of the mainshock.

The diameter of the sand boils varied from some cm to several meters. In some cases, large craters were formed from which the liquefied material was ejected. The extend of the ejected material indicates the intensity of the triggered phenomena and the severity of the earthquake ground motion.

The observed liquefaction covered fields and caused extensive cracks to roads constructed close to the Titarissios River.

**Lateral spreading** was also detected in several sites along the Titarissios and Pineios Rivers. Characteristic examples were also observed along river banks in Damasi and Koutsochero areas.

**Ground cracks** were also formed and affected the road network. A typical example was observed along the road from Mesochori to Vlachogianni.

**Slope movements** were triggered in several sites with abrupt natural and artificial slopes. They included rockfalls and landslides in slopes composed of scree and alpine formations. Rockfalls were generated along the road from Tyrnavos town to Damasi area, in Damasi village, in Domeniko village, in the mountains of Zarkos area, in Elassona and in Meteora. Fortunately, these phenomena resulted in no damage to buildings and infrastructures.

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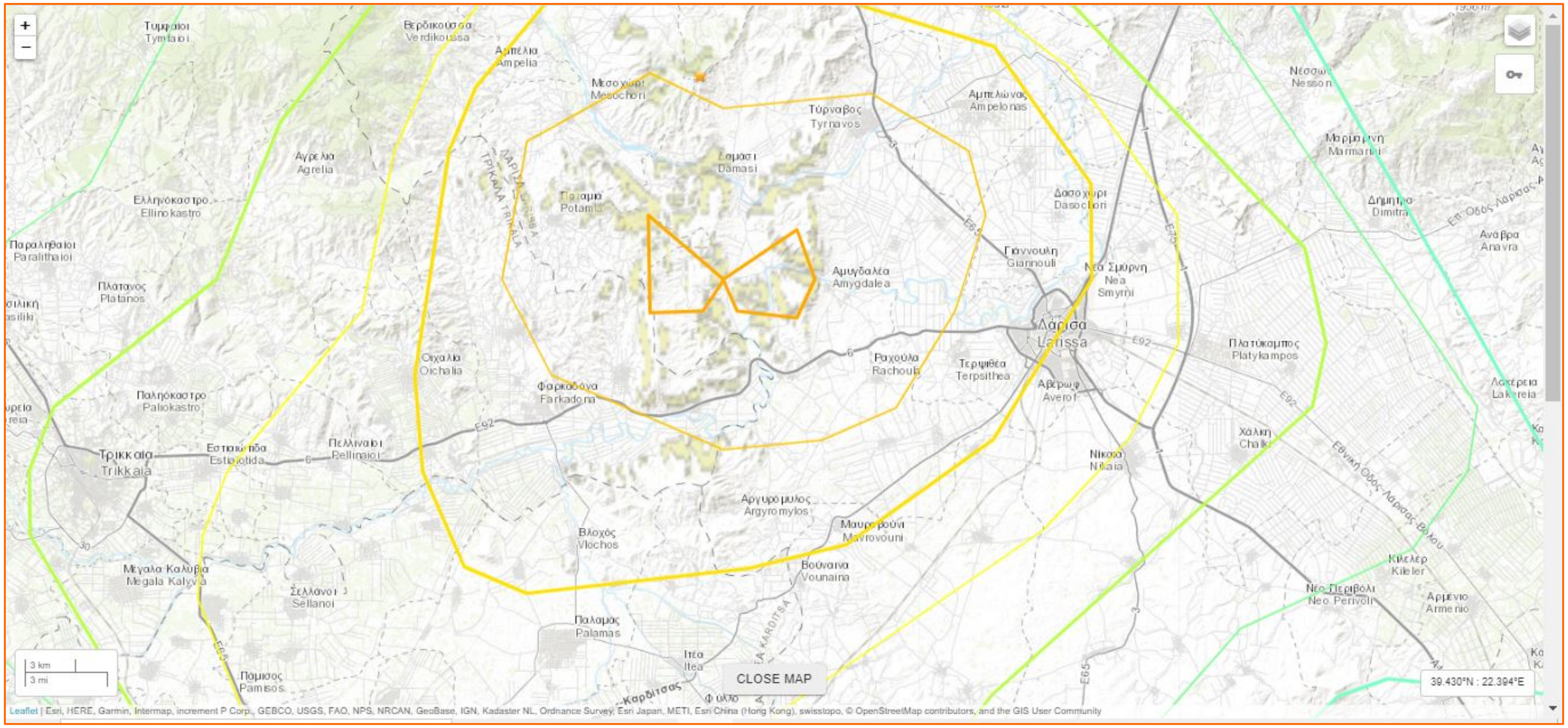
# ESTIMATED GROUND FAILURES
## INDUCED BY THE MARCH 3, 2021 Mw=6.3 EARTHQUAKE

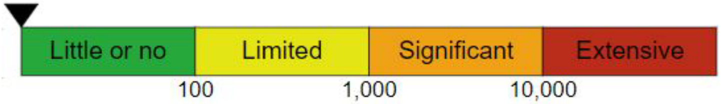
## LANDSLIDE MAP




Estimated Area Exposed to Hazard


Little or no landsliding is expected, but some landslides could have occurred in highly susceptible areas.

Estimated Population Exposure




The number of people living near areas that could have produced landslides in this earthquake is low, but landslide damage or fatalities are still possible in highly susceptible areas. This is not a direct estimate of landslide fatalities or losses.

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# SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## SLOPE FAILURES

Rockfalls were generated along slopes in Damasi area. The affected slopes are composed of scree.

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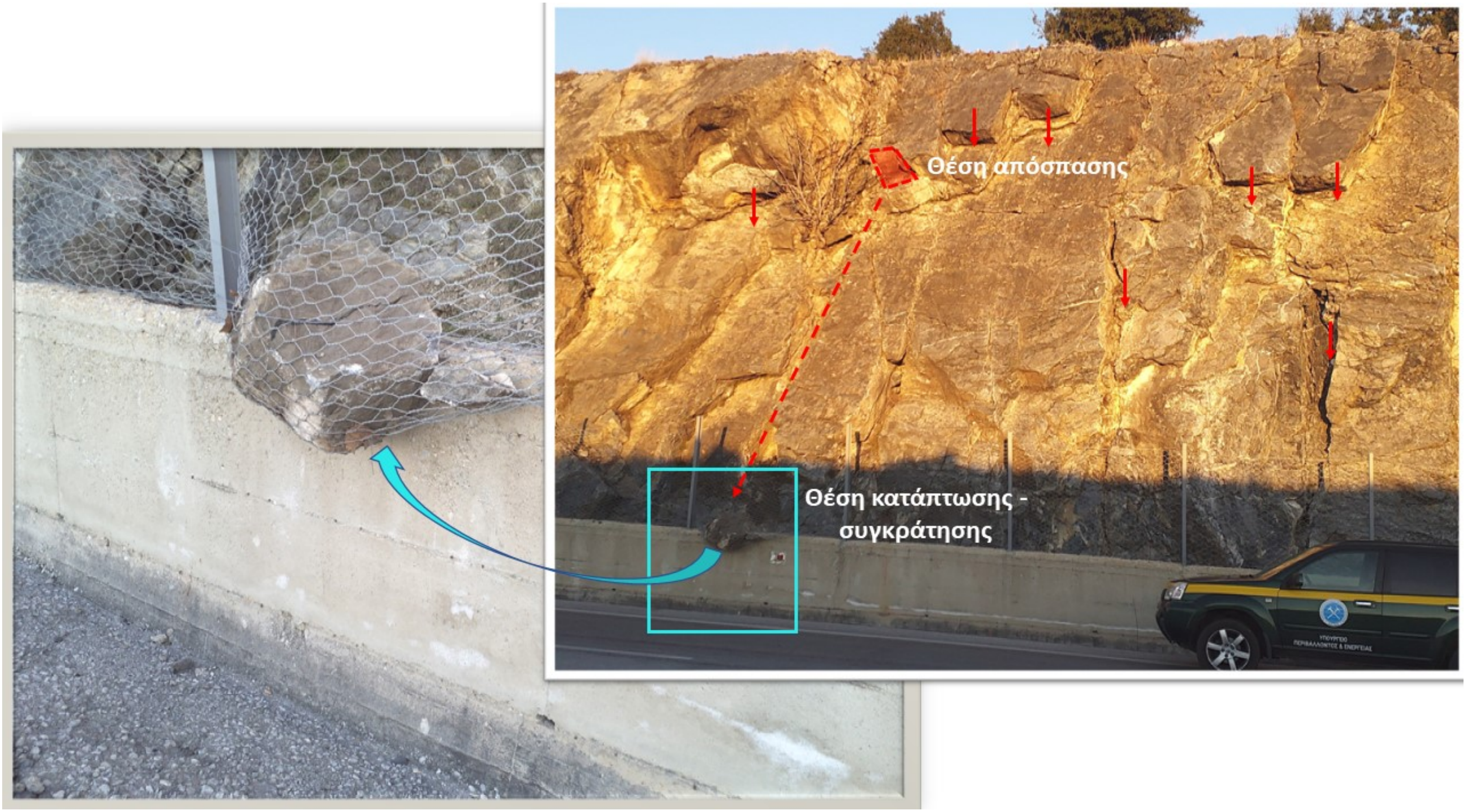
## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
### SLOPE FAILURES




At Meluna, along a slope of the new national road Larissa-Elassona, fragmented marbles fell from heights of 5-30 meters due to the first earthquake. The rock masses that were detached did not cause damage to the road network since the slope failure protection measures worked and the traffic was not disrupted.

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# SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## SLOPE FAILURES

In Domeniko village of the Elassona Municipality, close to the Byzantine church of Ayoi Anargyroi, a boulder of about five cubic meters was detached from the gneiss formation. This boulder is unstable and there is a risk of rolling down towards the church. The staff of the Hellenic Survey of Geology and Mineral Exploration proposed either removal of the boulder due to easy access or fragmentation with mechanical method.

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## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
### SLOPE FAILURES

On the steep slopes of the provincial road downstream of the Holy Monastery of Panagia Olympiotissa, which is composed of river deposits, boulders of various sizes were detached.

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## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
### GROUND CRACKS


Extensive and deep ground cracks were also generated by the Mw=6.3 earthquake of March 3, 2021. Some were observed close to river beds along with ejected liquefied material (left, middle), while others were parallel to the seismic fault (Vlachogianni) as it is derived from the focal mechanisms provided by several seismological institutes and observatories.

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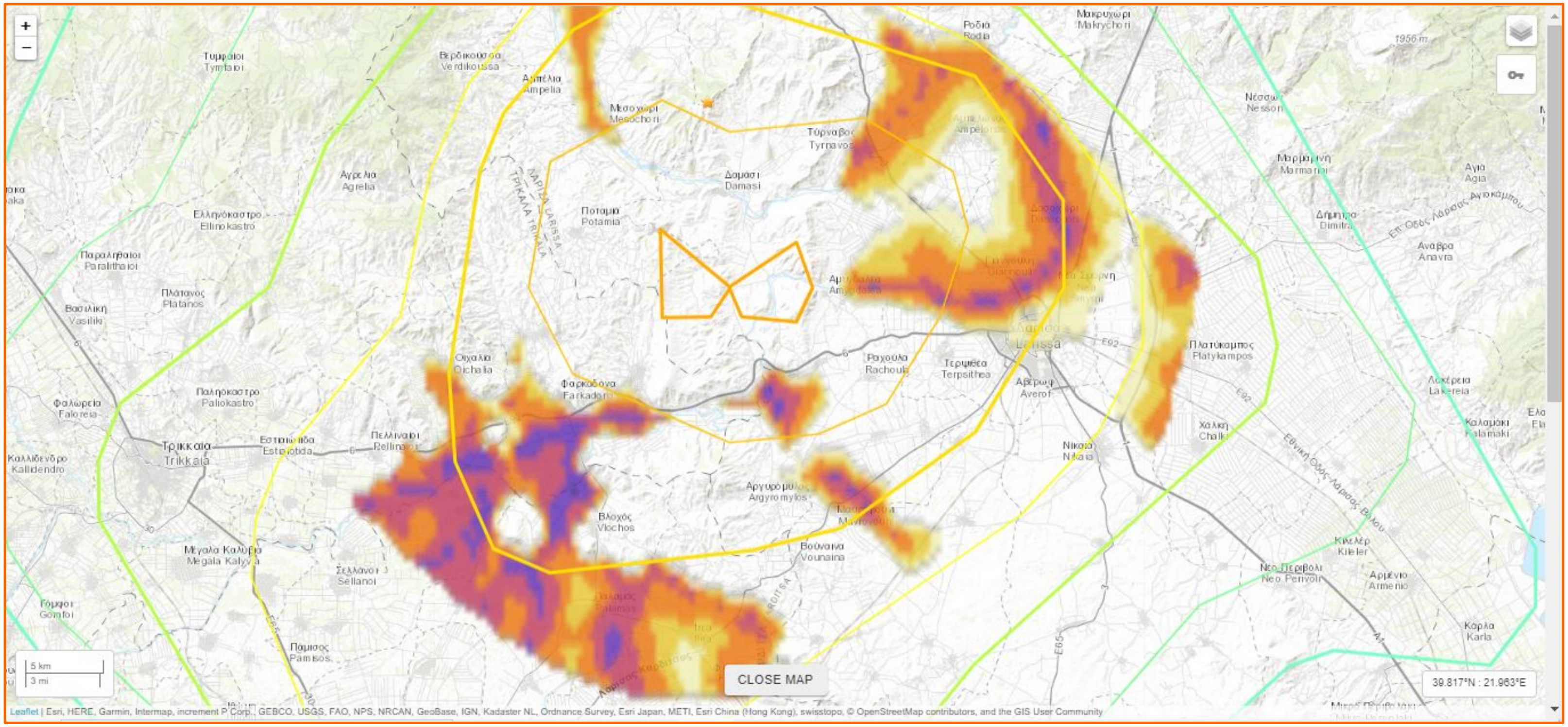
# ESTIMATED GROUND FAILURES
## INDUCED BY THE MARCH 3, 2021 Mw 6.3 EARTHQUAKE

## LIQUEFACTION MAP




**Estimated Area Exposed to Hazard**


Liquefaction triggered by this earthquake is estimated to be limited in severity and (or) spatial extent.

**Estimated Population Exposure**


The number of people living near areas that could have produced liquefaction in this earthquake is limited. This is not a direct estimate of liquefaction fatalities or losses.

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## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
### LIQUEFACTION WITHIN TITARISSIOS RIVER BED


Extended liquefaction phenomena in the area located southeast of Vlachogianni village, east of the Titarissios River. The grey spots in the green fields correspond to ejected liquefied material.

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# SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## LIQUEFACTION WITHIN TITARISSIOS RIVER BED

Sand boils along ground cracks in a field located southwest of Vlachogianni village

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# SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## LIQUEFACTION WITHIN TITARISSIOS RIVER BED


Extended liquefaction phenomena in the area located southeast of Vlachogianni village, east of the Titarissios River. The grey spots in the green fields correspond to ejected liquefied material.

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## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
LIQUEFACTION WITHIN TITARISSIOS RIVER BED

Individual sand boils in a field located southeast of Vlachogianni village, east of the Titarissios River

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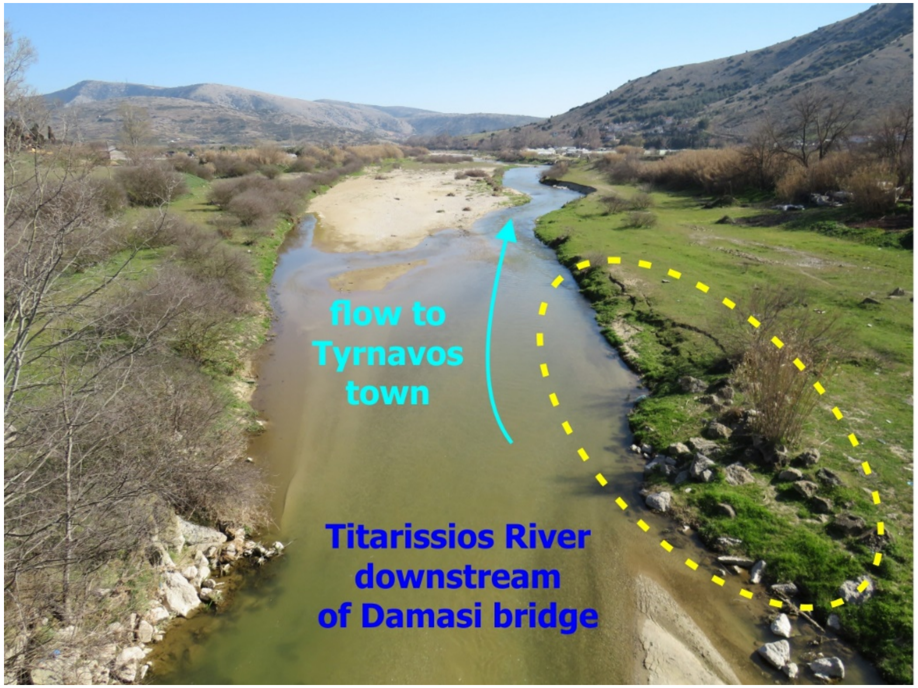
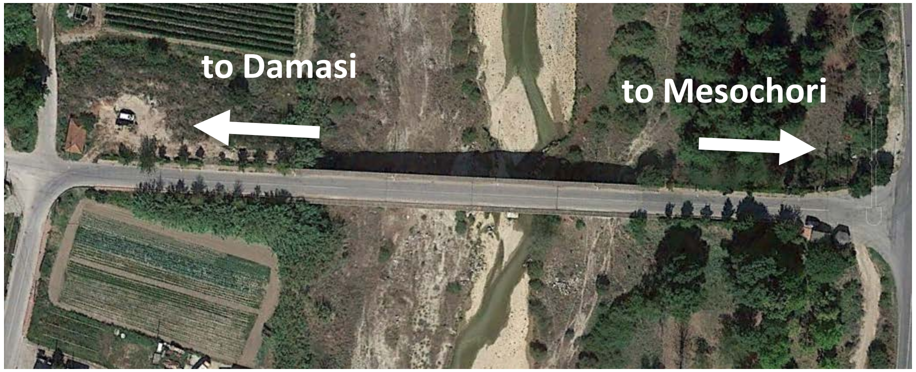
## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## LIQUEFACTION WITHIN TITARISSIOS RIVER BED





Lateral spreading along the banks of Titarissios River. The site is located downstream of the Damasi Bridge. It is significant to note that the Damasi bridge suffered heavy damage by the first earthquake. Thus, the authorities decided to temporarily close it for vehicles.



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# SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## LIQUEFACTION & LATERAL SPREADING ALONG RIVER BANKS



(**Left**) Lateral spreading along the Pineios River banks, (**middle**) liquefaction phenomena in the fields close to Pineios River and (**right**) ground cracks arranged parallel to the Pineios River. It is significant to note that these secondary earthquake environmental effects were observed close to the bridge of Pineios River located close to the Koutsochero village. The bridge suffered cracks and damage due to seismic pounding between bridge segments.

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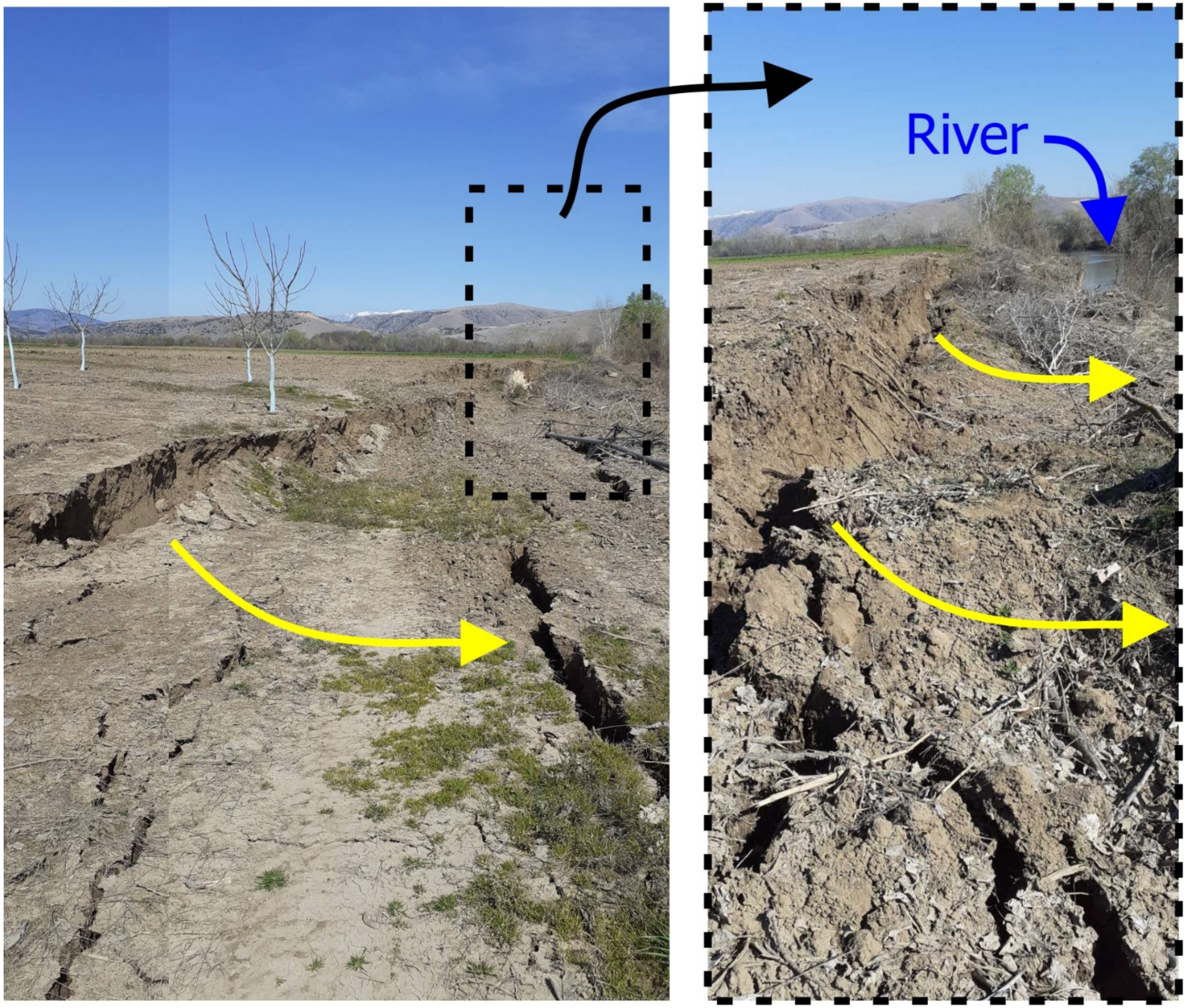
## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
### LATERAL SPREADING ALONG RIVER BANKS




Lateral spreading along the banks of Pineios River in the area of Koutsochero village

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# SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## LIQUEFACTION BETWEEN PINIADA AND FARKADONA

Liquefaction phenomena were also generated in the southwestern part of the affected area. More specifically, in the Pineios River bed from Pineiada to Farkadona. They comprise sand boils along ground cracks with length up to 60 meters. They are attributed to the lithology of the river deposits, the shallow water level in the river bed and to the intense earthquake ground motion.

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## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
### LIQUEFACTION BETWEEN PINIADA AND FARKADONA

More typical examples of the generated liquefaction phenomena in the southwestern part of the affected area. Large craters were formed, from which the liquefied material has been ejected and partially covered the adjacent field. The extend of the liquefied material indicate the intensity of the earthquake ground motion.

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# SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## LIQUEFACTION BETWEEN PINEIADA AND FARKADONA

Dozens of soil liquefaction occurrences, such as sand craters and flows were mapped in areas adjacent to Pineios and Titarissios Rivers. These figures of sand flow and craters are impressive examples from the liquefied area located southeast of Pineiada village.

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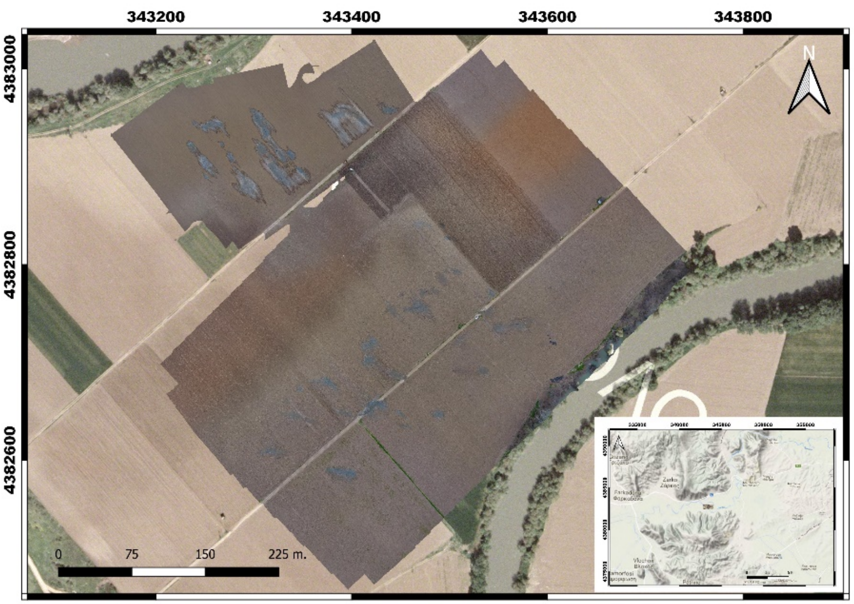
## SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## COMPARISON OF HISTORICAL AND CURRENT SATELLITE IMAGES FOR LIQUEFACTION ANALYSIS

The liquefaction phenomena were mapped in great detail with UAVs. Comparison with current and historical satellite images, show that in the area of Pinios river the liquefaction is clearly associated with older abandoned meanders of the river, indicating a differentiated composition, more susceptible to liquefaction.




▲ Orthorectified image of the liquefied areas (gray spots). Images from a series of high flying UAV campaigns have been combined with orthophotos from the Cadastral project of Greece.


▲ Comparison with current and historical satellite images, show that in the area of Pineios river the liquefaction is clearly associated with older abandoned meanders of the river, indicating a differentiated composition, more susceptible to liquefaction

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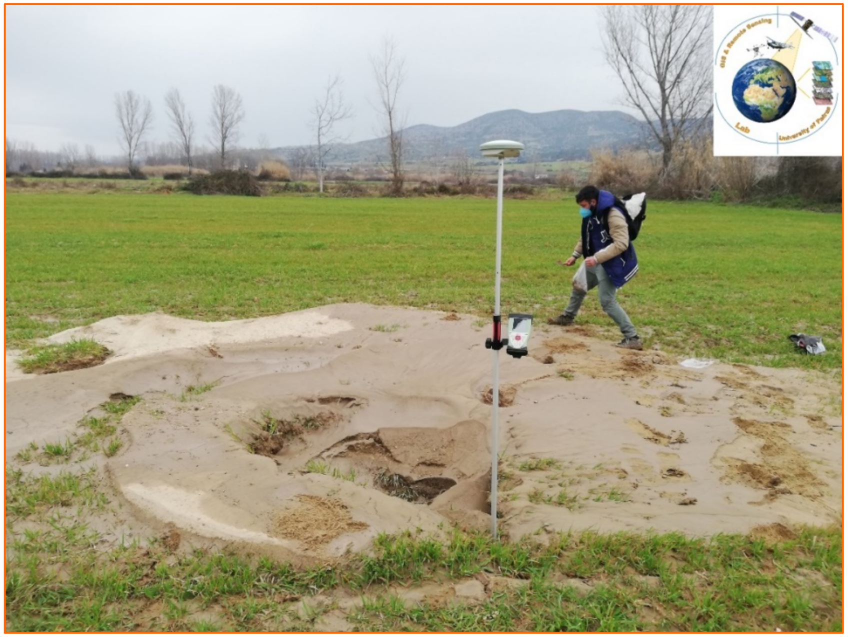
Structural Geology & Tectonics
Geology Univ Patras

# SECONDARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## MAPPING OF LIQUEFACTION WITH UAV AND RTK GNSS RECEIVERS



The scientific team of the University of Patras (Koukouvelas, Nikolakopoulos, Kyriou, Apostolopoulos, Zygouri, Verroios, Belesis, Tsentzos) mapped with UAVs and RTK GNSS receivers several ground cracks and liquefaction phenomena in the broader area of Damasi, Mesochori and Vlachogianni.

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# PRIMARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## STUDY ON THE VLACHOGIANNI FAULT

Field work conducted by the University of Patras revealed the Vlachogianni fault as reactivated during the main earthquake.

Most of the work of the University of Patras, Department of Geology, concentrated within this fault. On the basis of their field work, the minimum length of the Vlachogianni Fault is about 10 km and forms a fault zone. The true length of the fault is under investigation since its prolongation towards the W or to the E is not easily recognized. In parallel they are mapping the tectonic geomorphology of this fault.

Nevertheless the fault is related with surface rupture traces correlated with the main earthquake of March 3, 2021. In close proximity with the fault trace, they mapped innumerable lateral spreading, and liquefaction sand boils, all mapped with UAV flights and traced with RTK GNSS. Overall the fault affects young deposits of the Titarissios River, where it forms an active compound fault scarp (next figure). Because of the young age of the river-bed sediments (not enough time is elapsed to allow the fault to express itself on the topography) and of the competition of fast alluvial processes versus tectonics the fault is poorly preserved.


▲ Surface trace of the co-seismic rupture in Vlachogianni area. The photo shows part of the compound fault scarp and the offset as well. The photo is looking west. Surface offset on the fault trace is over than 25 cm.

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# PRIMARY EARTHQUAKE ENVIRONMENTAL EFFECTS

## PALEOSEISMOLOGICAL STUDY OF THE VLACHOGIANNI FAULT

The scientific team of the University of Patras mapped several places showing clear tectonic expression, although the intense geographic and cultural modifications due to human activities disturbed the near surface stratigraphy. As a consequence, they found only one favorable site for trenching near the Titarissios River. Paleoseismological trenching in Greece has proved to be a powerful tool in recognizing strong past earthquakes. We employed two single-slot "California style" trenches and followed standard trenching methods (left figure below). The main trench was 10 m long and 2.0 m wide, while it's maximum depth was almost 2.5 m. The single-slot trench was excavated across a 1 m high fault scarp. The trench walls were cleaned and mapped manually and with LiDAR (right figure below), using a 0.5 x 1m reference grid of non-stretch string. Photo mosaics of the exposure were developed using image processing software. The surface traces offset matches directly the subsurface exposure within the trench.


Palaeoseismological trench from above. Drone footage of the California style trench at Meschori area and LiDAR mapping of the excavated trench

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## PRIMARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## PALEOSEISMOLOGICAL STUDY OF THE VLACHOGIANNI FAULT


Detail of the fault in the palaeoseismological trench

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## PRIMARY EARTHQUAKE ENVIRONMENTAL EFFECTS
## PALEOSEISMOLOGICAL STUDY OF THE VLACHOGIANNI FAULT

The fault trace as mapped by UAV

The fault trace was mapped by
RTK GNSS receiver

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## PRIMARY EARTHQUAKE ENVIRONMENTAL EFFECTS
### IMPACT ON THE ROAD

Mapping extensive ground cracks generated by the March 3, 2021, Mw=6.3 earthquake near Damasi village

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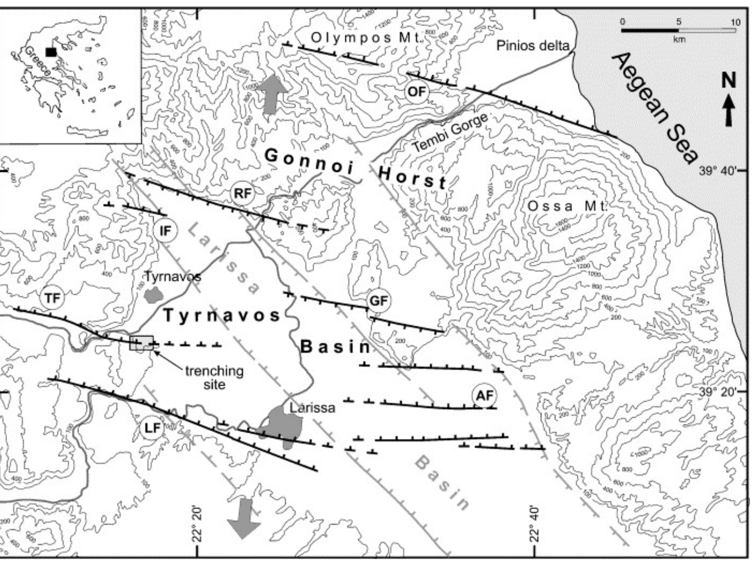
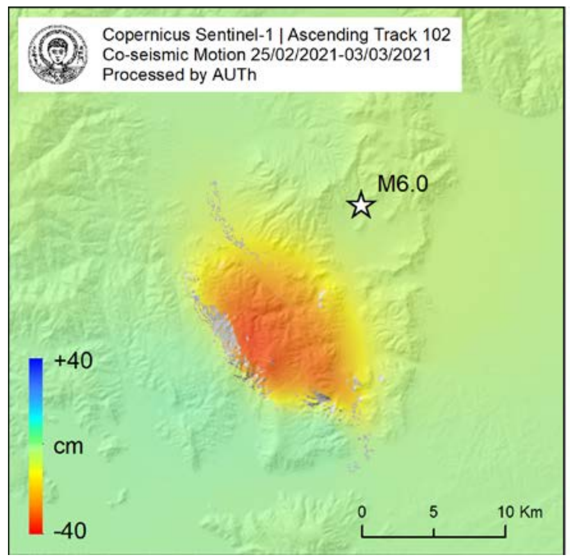
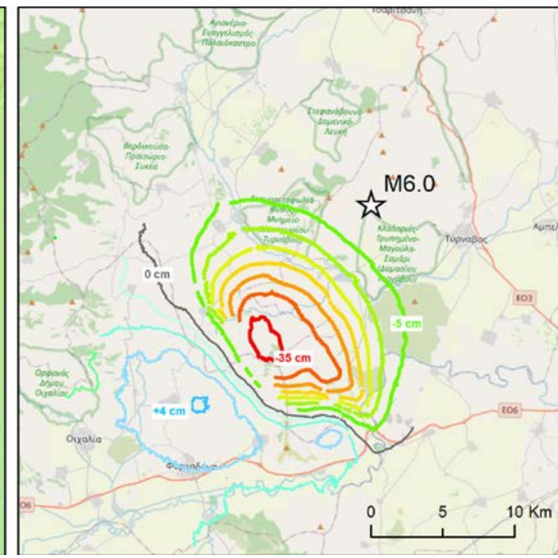
# FIELD WORK AND ANALYSIS OF INTERFEROMETRIC INFORMATION
## FOR IDENTIFYING THE CAUSATIVE FAULT

Field work conducted by members of the Earthquake Geology Research Group of the Department of Geology of AUTH and the analysis of interferometric information (Foumelis personal communication) show that the well-known and studied Tyrnavos fault, as well as the Titarissios valley fault, which is the NW extension of the known Larissa fault, did not generate the mainshock, although they appear to have been triggered and partially activated by the main seismogenic fault as sympathetic structures.



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# FIELD WORK & ANALYSIS OF INTERFEROMETRIC INFORMATION FOR IDENTIFYING THE CAUSATIVE FAULT

As far as the insofar unknown and unmapped seismic fault is concerned, fieldwork conducted by members of the Earthquake Geology Research Group of the Department of Geology of AUTH showed that there are characteristic geological indications in the Pelagonian bedrock, consisting of Paleozoic mica schist and gneiss (e.g. Kilias and Mountrakis, 1987; Kilias et al., 1991), suggesting that a low angle normal fault has acted as a hidden or blind fault during the earthquake.

This low angle normal fault, which acted as a hidden or blind fault during the earthquake, is associated with the bedrock schistosity, as well as with small high angle reverse faults of the Pelagonian anticline. The presumed seismic fault extends in the broader area between the villages of Zarko and Megalo Eleftherochori, as an inherited shear zone.

Geological indications include outcrops of the post Alpine shear zone, located along the boundary between interferometrically indicated uplift and subsidence terrains (line 0 of displacement in the surface deformation map), the existence of cataclasite and fault gouge in the shear zone, which indicates reactivation of the fault in brittle conditions during the neotectonic period (inverse tectonics) and slickenlines compatible with the active stress field.

Fault surfaces strike at N160°E and dip at 50° on average, which is in good agreement to the published focal mechanisms by Greek and other international Institutes.

Coseismic indicators include small, ruptured fault surfaces with detached rock slabs and pieces, as well as small-scale soil fractures following the trace of the mapped fault, with negligible vertical displacement and small heave (up to 2 cm).

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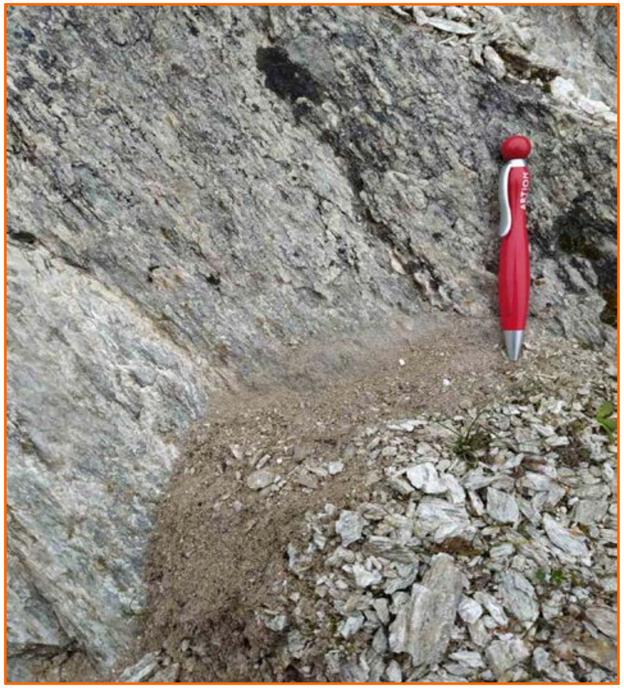
# FIELD WORK & ANALYSIS OF INTERFEROMETRIC INFORMATION

## GEOLOGICAL INDICATIONS FOR IDENTIFYING THE CAUSATIVE FAULT



▲ Fault surface of the low-angle normal fault in the bedrock, believed to be a strand of the causative fault zone

▶ A zone of intense brittle shearing, accompanied by fault gouge and cataclasite within the low-angle normal fault zone.

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# FIELD WORK & ANALYSIS OF INTERFEROMETRIC INFORMATION
## COSEISMIC INDICATIONS FOR IDENTIFYING THE CAUSATIVE FAULT

Coseismic surface cracks in the soil cover, following the inferred strike and location of the causative fault zone in the bedrock

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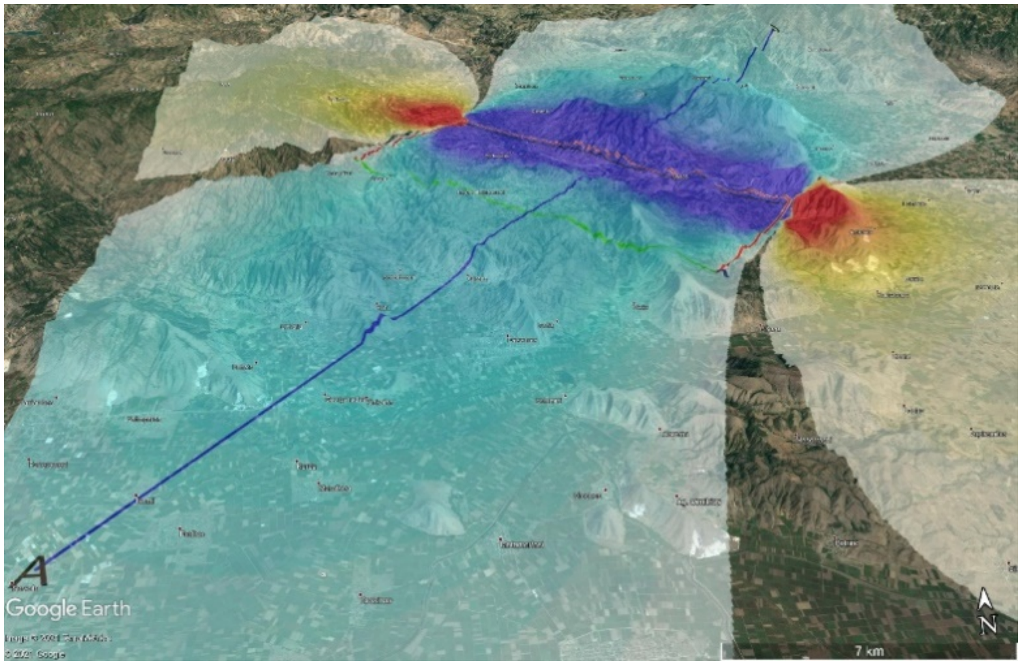
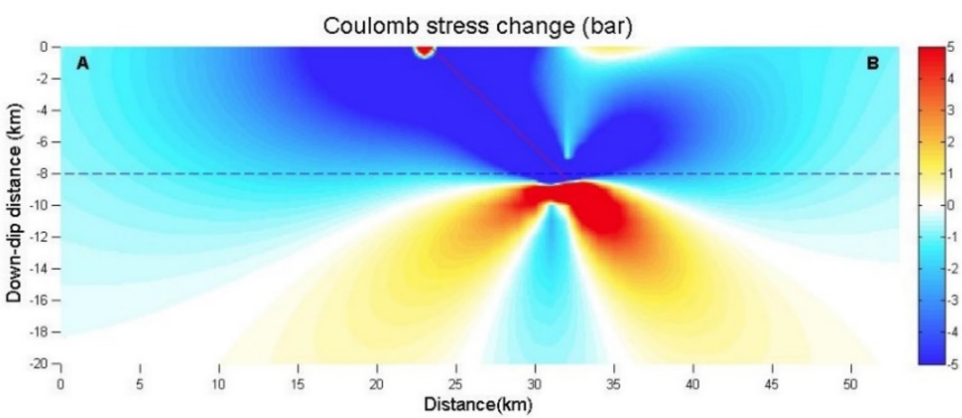
## SEISMIC FAULT MODEL & COULOMB STATIC STRESS CHANGES




The seismic fault model (seismic source) of the mainshock is based on the GFZ's moment tensor solution (strike, dip and rake), the scalar relationships of Wells & Coppersmith (1994; length and width), and the interferograms along with the site observations (position).

The Coulomb static stress changes are calculated for receiver faults similar to the seismic source at a depth of 8 km. A vertical cross-section normal to the source's strike is also calculated.

Results show stress-load beyond the tips of the fault, suggesting a triggering scenario for faults of similar geometry and kinematics located in this red area. The northwestern edge of the fault (red-yellow) activated during the second event of 4th of March.

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## PRELIMINARY MODEL OF THE SEISMIC SOURCE


A preliminary model of the seismic source is showing vertical displacement on the ground

The seismic source is also used to model the vertical displacement on the ground after using the Okada formulae. The maximum calculated vertical displacement is 2.93 cm. Both Coulomb and Okada calculations were performed with the Coulomb v3.3 application (Toda et al., 2005; Lin & Stein, 2004).

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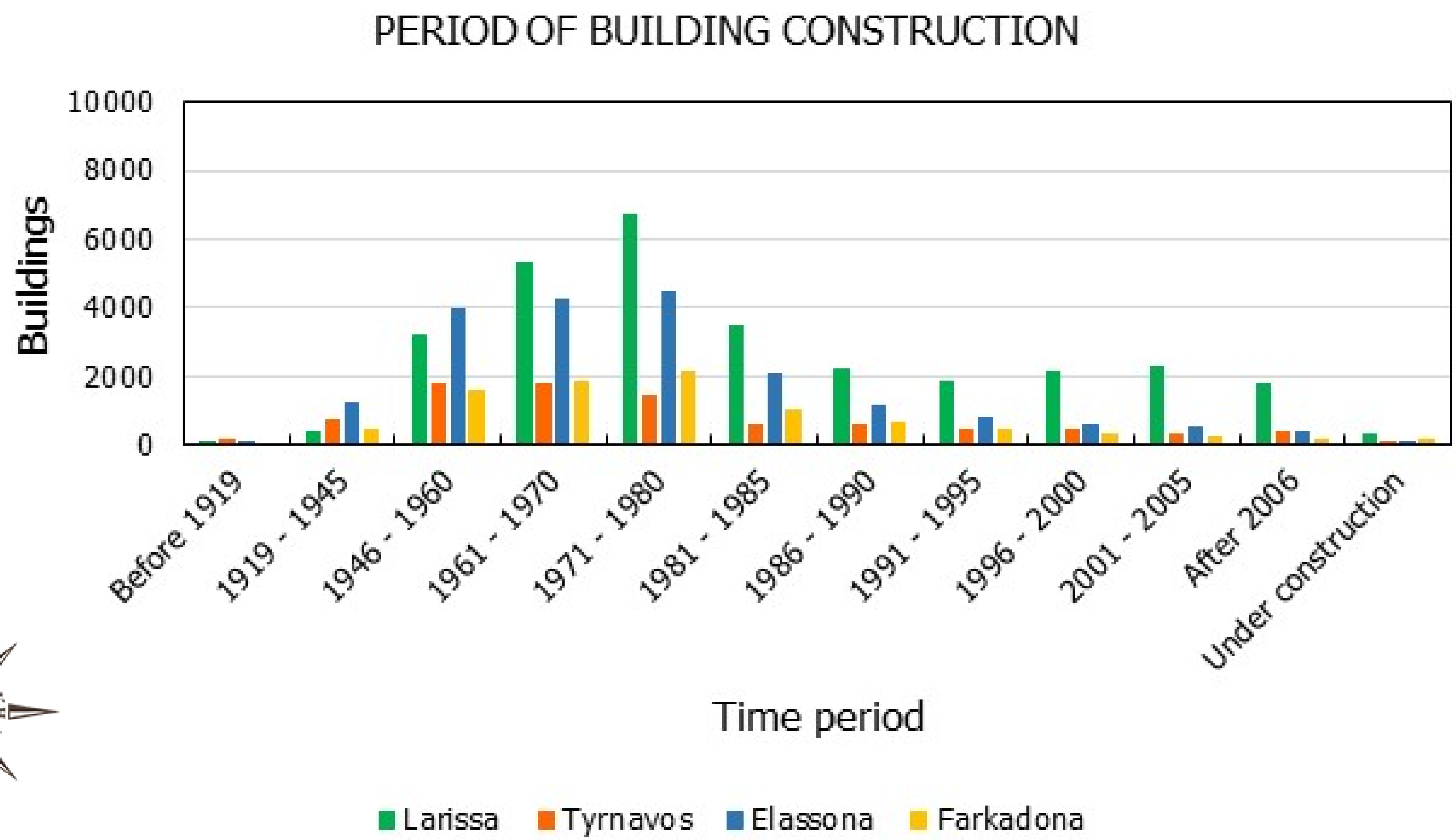
# PERIOD OF CONSTRUCTION
## FOR BUILDINGS IN THE EARTHQUAKE-AFFECTED AREA




Data from the 2011 Building Census of Greece conducted by the Hellenic Statistical Authority

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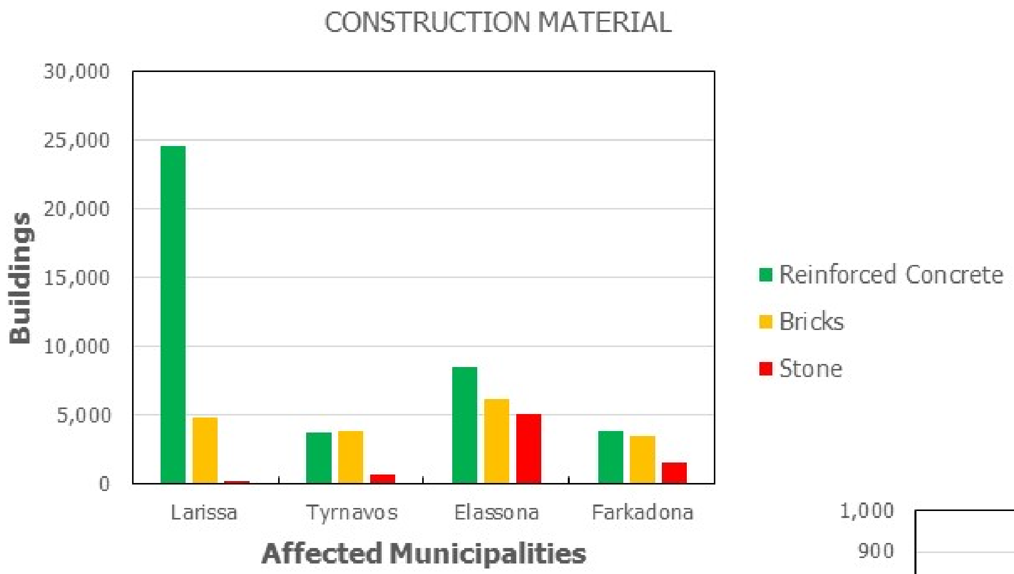
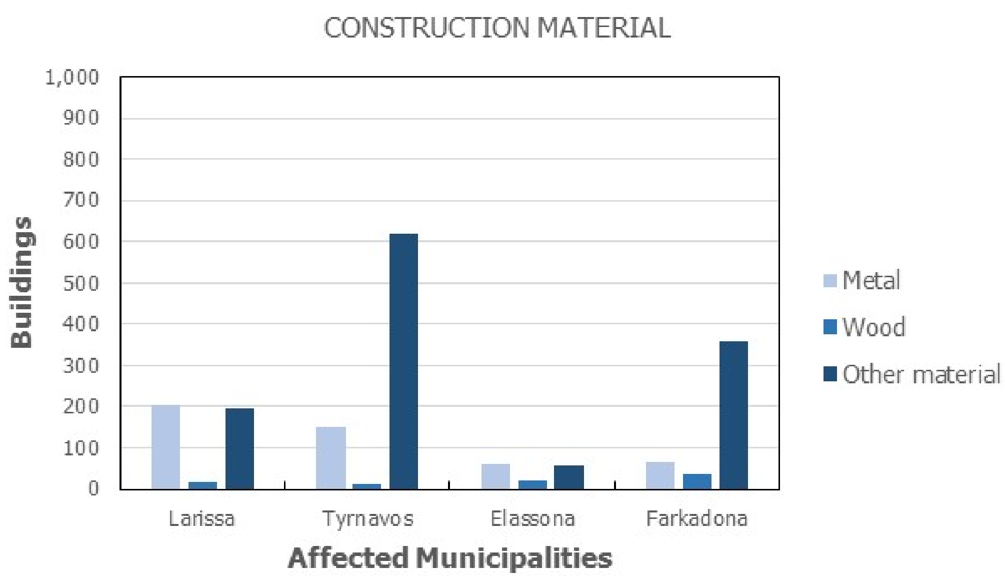
# CONCTRUCTION MATERIAL
## OF BUILDINGS IN THE EARTHQUAKE-AFFECTED AREA




Data from the 2011 Building Census of Greece conducted by the Hellenic Statistical Authority




GENERAL POPULATION CENSUS 2011
HELLENIC STATISTICAL AUTHORITY

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# BUILDING DAMAGE
## TRIGGERED BY THE MARCH 2021 EARTHQUAKES IN THESSALY BASIN

The damage induced by the March 3, 2021, Mw=6.3 earthquake in Thessaly Basin were mainly observed in settlements founded on recent deposits of the Titarissios River bed.

The worst affected building type is the old unreinforced masonry buildings with load-bearing walls. These buildings suffered mainly heavy damage on their structural elements comprising vertical cracks at wall intersections due to the lack of horizontal band beams, failures of the upper part of the walls attributed to the interaction between roof structure and perimeter walls as well as partial or total collapse due to poor quality mortar and poor workmanship resulting in disintegration of masonry units and loss of support to floors.

As regards the recently constructed buildings with reinforced concrete frame and infill walls, they remained intact by the earthquake in general. They suffered damage on their non-structural elements comprising detachment of plasters from infill walls, detachment of infill walls from the surrounding reinforced concrete frame and detachment of tiles from roofs and of cladding from walls. However, there are some cases of reinforced concrete buildings that suffered structural damage including damage to columns of the ground floor.

The most affected villages within the Titarissios River bed are Damasi, Damasouli, Mesochori, Vlachogianni, Amouri, Praetorio, Varkos, Sykia, Evangelismos and Magoula villages as well as the Tyrnavos town. Limited damage were observed in other villages located outside the Titarissios River bed.

The March 4, 2021, Mw=6.1 earthquake aggravated damage induced by the first earthquake.

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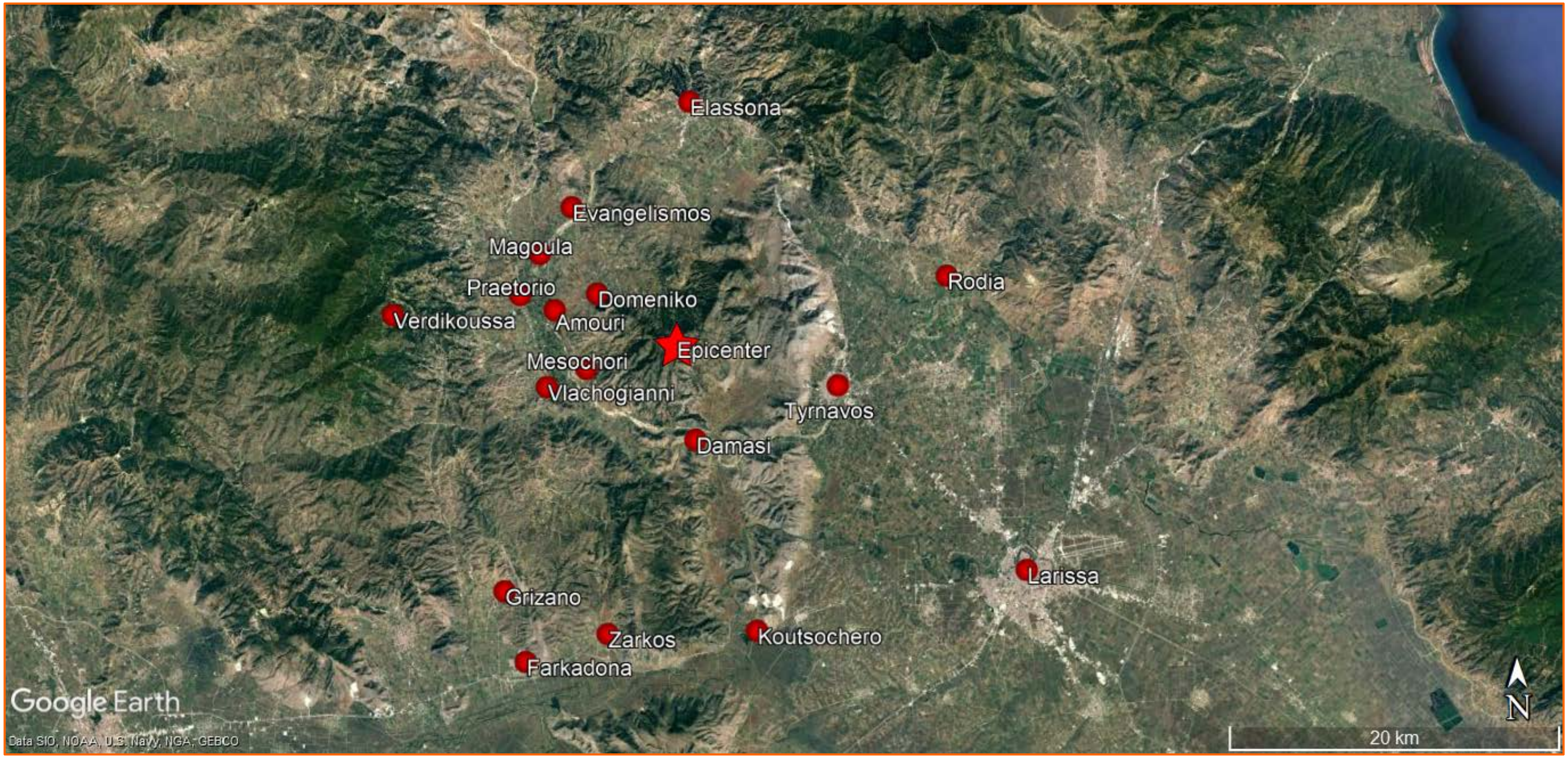
# SETTLEMENTS IN TITARISSIOS & PINEIOS RIVER BEDS




The residential areas affected by the March 3, 2021 earthquake are founded on recent river deposits of the Titarissios and Pineios Rivers. These areas from north to south are: Elassona, Evangelismos, Magoula, Praetorio, Domeniko, Verdikoussa, Amouri, Mesochori, Vlachogianni, Damasi, Tyrnavos, Grizano, Farkadona, Zarkos and Koutsochero settlements and Larissa city.

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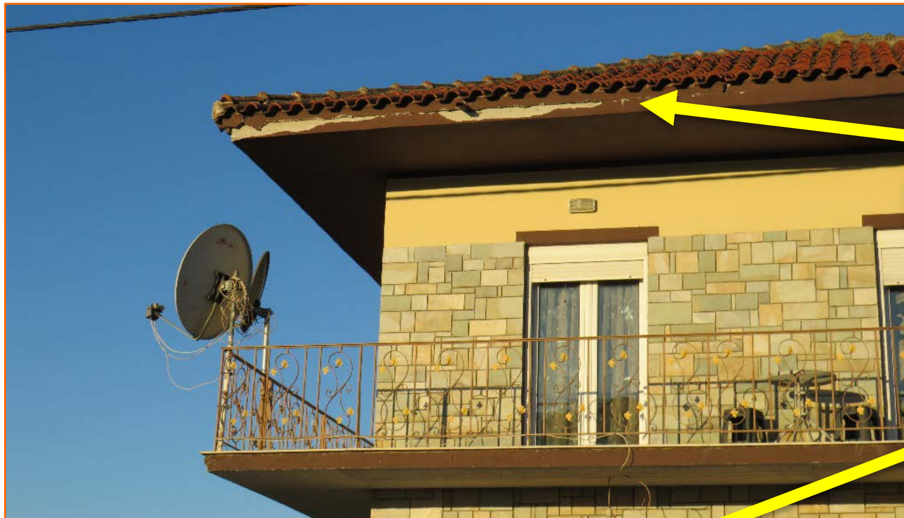
# NON-STRUCTURAL DAMAGE TO REINFORCED CONCRETE BUILDINGS

## MESOCHORI VILLAGE



The majority of the reinforced concrete (RC) buildings of the earthquake affected area remained intact by the earthquake. Slight damage was observed to non-structural elements of the buildings. Typical example of slight damage are the detachment and fall of cornices, roof tiles and exterior wall cladding composed of different materials. We observed that the free standing or lightly anchored objects in stiffer structures suffered more damage compared to those standing in more flexible ones.

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# NON-STRUCTURAL DAMAGE TO RC BUILDINGS
## MESOCHORI VILLAGE

▲ Non-structural damage to building with RC frame and infill walls. It comprised detachment of plaster from the infill walls and extensive cracking of brick walls. The upper floor remained intact by the earthquake. The much softer ground floor is functioning as a kind of base isolator, absorbing thus, in its body, the seismic motion. The observed damage of the few partition brick walls is a physical consequence.

◀ Pounding of adjacent buildings was also observed due to their different dynamic characteristics. This pounding caused damage on the adjacent building with load bearing masonry walls.

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# STRUCTURAL DAMAGE TO RC BUILDINGS
## DAMASI VILLAGE

Non-structural damage to R/C buildings were limited. Some cases were observed in the most affected villages, like Damasi village. Non-structural damage comprise detachment of the infill walls from the surrounding RC frame and partial collapse of the infill walls. Compression damage in the lower parts of the columns were also observed in RC building of the same village, an indication of the presence of strong vertical component of the seismic motion – a basic characteristic dominating in epicentral regions.

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# STRUCTURAL DAMAGE TO RC BUILDINGS
## DAMASI VILLAGE

Damage to an RC building in Damasi village. Non-structural damage comprises detachment and fall of large pieces of plaster along the connection of the infill walls with the surrounding RC frame, detachment of the infill wall from the frame. Structural damage includes loss of concrete in the upper body of the RC column, exposure and slight buckling of reinforcement bars. The horizontal quite large cracks and the failure of the plaster at the ceiling of the cantilever constitute indication of the effect of strong vertical seismic component.

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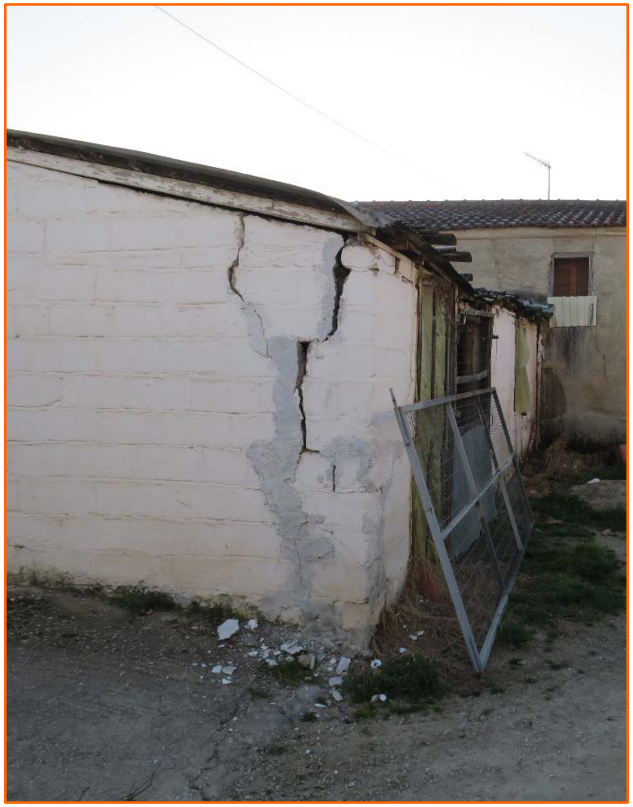
# DAMAGE TO BUILDINS WITH LOAD-BEARING MASONRY WALLS
## VERTICAL CRACKS



Severe vertical cracks and gaps were frequently formed and propagated along the height of the bearing wall intersections. This damage is attributed to the absence of horizontal banding means (beams, tie rods), which could provide structural integrity and the adequate connections between the bearing walls at the wall intersections and between the bearing walls and the roof. It is significant to note that the chimneys are standing intact, which is also an indication of the dominating vertical component of the seismic motion.

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# DAMAGE TO MASONRY BUILDINS WITH LOAD-BEARING WALLS
## VERTICAL CRACKS AT WALL INTERSECTIONS

Due to the lack of the aforementioned horizontal band beams, each wall acts individually in in-plane as well as out-of-plane directions under the earthquake loads resulting in vertical cracks at the wall intersections. With these more general views, one could observe the complete lack of diagonal cracks in the masonries.

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# DAMAGE TO MASONRY BUILDINS WITH LOAD-BEARING WALLS

## DAMAGE DUE TO FLEXIBLE ROOF-WALL INTERACTION

Failures of the upper part of the walls were also attributed to the interaction of roof structure and perimeter walls. This type of damage did not reach collapse condition, but the masonry buildings were unusable during the emergency period. It is also observed that the two layers of the masonry are functioning independently, without connection between them.

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# DAMAGE TO MASONRY BUILDINS WITH LOAD-BEARING WALLS

## DAMAGE DUE TO FLEXIBLE ROOF-WALL INTERACTION

Heavier damage including collapse attributed to interaction of roof structure and perimeter walls. The observed damage are almost symmetrical distributed around the plan of the structure, as shown for example in the top left image.

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# DAMAGE TO MASONRY BUILDINS WITH LOAD-BEARING WALLS

## DAMAGE DUE TO FLEXIBLE ROOF-WALL INTERACTION




One may well observe the similarity of the incurred damage (at the central part of the walls) independently of the type and the age of the structure. This similarity is due to the same structural scheme and flexibility of almost all roofs. This flexibility is along their vertical axis and is proportional to the ratio of the opening of the roof over the crest height. This ratio is quite large, and it is rather sensitive to vertical vibrations.

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# DAMAGE TO MASONRY BUILDINS WITH LOAD-BEARING WALLS
## DAMAGE DUE TO FLEXIBLE ROOF-WALL INTERACTION

The incurred damage present almost the same manner independently of the mechanical characteristics of the underlying structures. This type of damage (at the center of the perimetric walls), may be attributed to:

- high flexibility of the roof due to rather large ratio of roof opening over crest height,
- the strong seismic vertical component that is exciting the roof, which, in turn, pushes the walls outwards.

Actually, due to the vertical vibration of the roof, the damaging phase of its motion is the downwards one, at which the friction between roof and wall takes its maximum value. At that phase the central parts of the roof deforms outwards carrying away the underlying wall. At the upwards phase of the roof motion, the friction is annulated and its inwards deformation has not any effect on the integrity of the wall, as far as that particular seismic response of the structure is concerned. The vertical motion of the corners of the roof is almost negligible due to the much higher stiffness concentrated diagonally. Therefore the corners are functioning as a type of, relatively to the rest of the roof, firm support. In other words we could say that in this case, the inclined plane parts of the roofs are feathering.

◀ In Damasi village

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# DAMAGE TO MASONRY BUILDINS WITH LOAD-BEARING WALLS
## DAMAGE DUE TO POOR MORTARS

The old unreinforced masonry buildings consist of poor quality mortar. Those types of poor quality mortar are rich in clay, which is highly aquatic. Due to the entry of the moisture into the mass of the wall from the ground and / or from the roof, the friction between mortar and stone blocks, which is beneficial for the strength and stability of the wall, is dramatically reduced until annulated. Actually, the moisture convert clay from a bonding to a slippery material.

◄ In Mesochori village

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# DAMAGE TO INFRASTRUCTURES
## BRIDGES


Bridges are usually equipped with expansion joints in order to effectively overcome the impact of creep, shrinkage and thermal effects. Bridge structures are at risk of experiencing earthquake-induced pounding between adjacent decks or between the deck and the adjacent abutment. This pounding is attributed to the presence of these expansion joints, which are usually a few centimeters wide.




Pounding-induced damages attributed to the presence of these expansion joints were observed in several bridges in the earthquake-affected area. Pineios bridge close to Koutsochero Village is one of these examples.

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# DAMAGE TO INFRASTRUCTURES
## BRIDGES


Northern bridge of Damasi village. The observed damage are attributed to pounding between bridge segments attributed to the presence of expansion joints.

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# DAMAGE TO INFRASTRUCTURES
## ROAD NETWORK





Damage to road leading from Mesochori to Vlachogianni was attributed to the earthquake ground motion and to the generated liquefaction phenomena affecting the area between the aforementioned villages.

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# DAMAGE TO MONUMENTAL STRUCTURES
## AFFECTED CHURCHES

Churches in the earthquake-affected area suffered damage to the load-bearing masonry walls, arches, roofs, plasters and their bell tower.

▲ Characteristic damage induced by the first earthquake in the Ayios Dimitrios church in Mesochori village.

◀ Damage was aggravated by the second earthquake, which was generated the next day.

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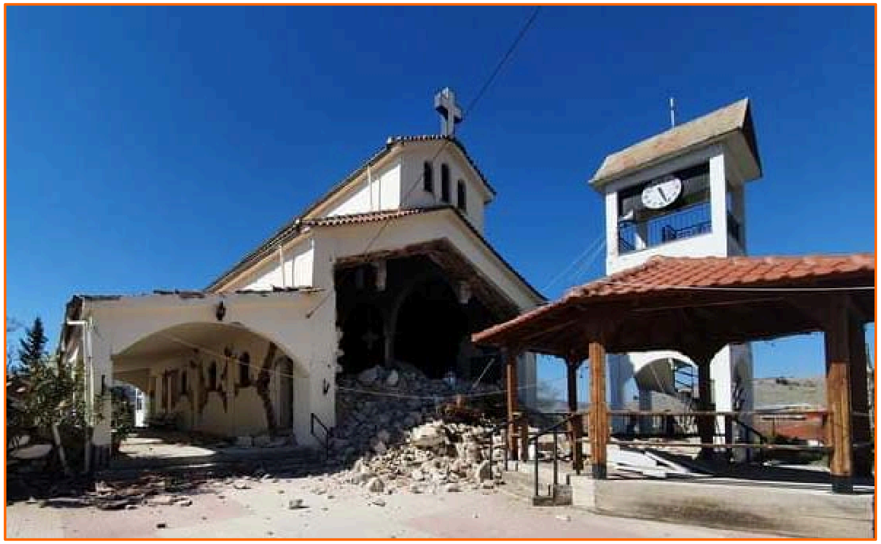
## DAMAGE TO MONUMENTAL STRUCTURES
### AFFECTED CHURCHES



Partial and total collapse of the old and new masonry churches of Agios Nikolaos in Koutsochero village. The old structure completely collapsed, while the new one suffered collapse of its walls behind the altar.

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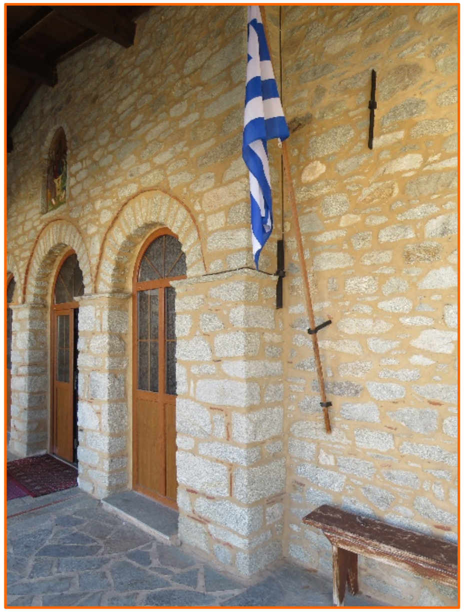
# DAMAGE TO MONUMENTAL STRUCTURES
## UNAFFECTED CHURCHES

Agia Triada orthodox church
in Vlachogianni village



The seismic performance of churches depends on the geological formation of their foundation and on their strengthening. The church in Vlachogianni village remained untouched by the earthquakes. It is founded on alpine formations and moreover it has been reinforced with the installation of steel ties in the bell tower and in the other parts of the construction. The steel ties are placed in critical key points for the stability of the structure.

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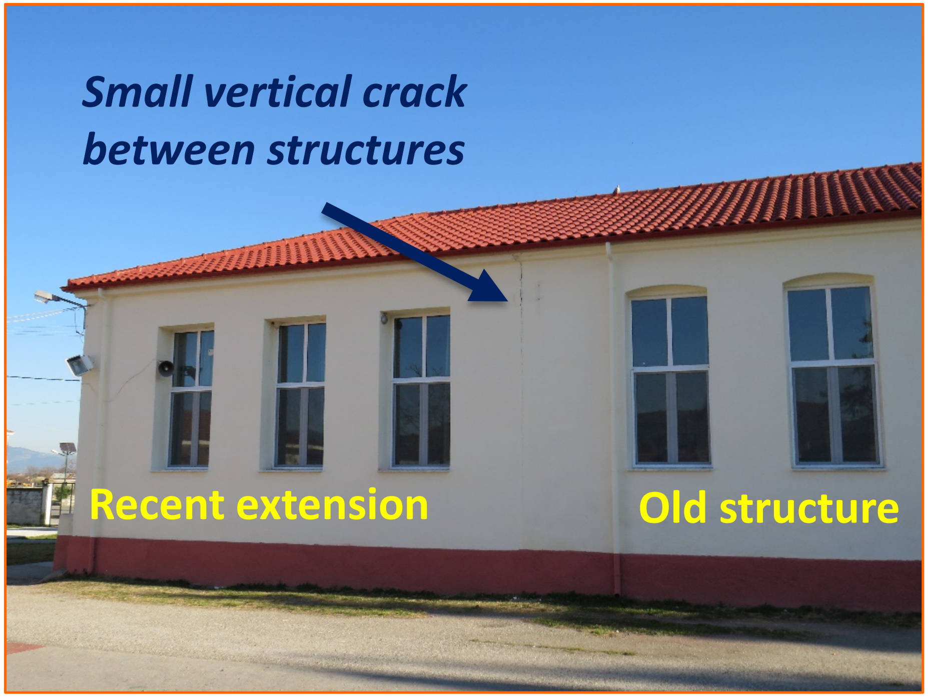
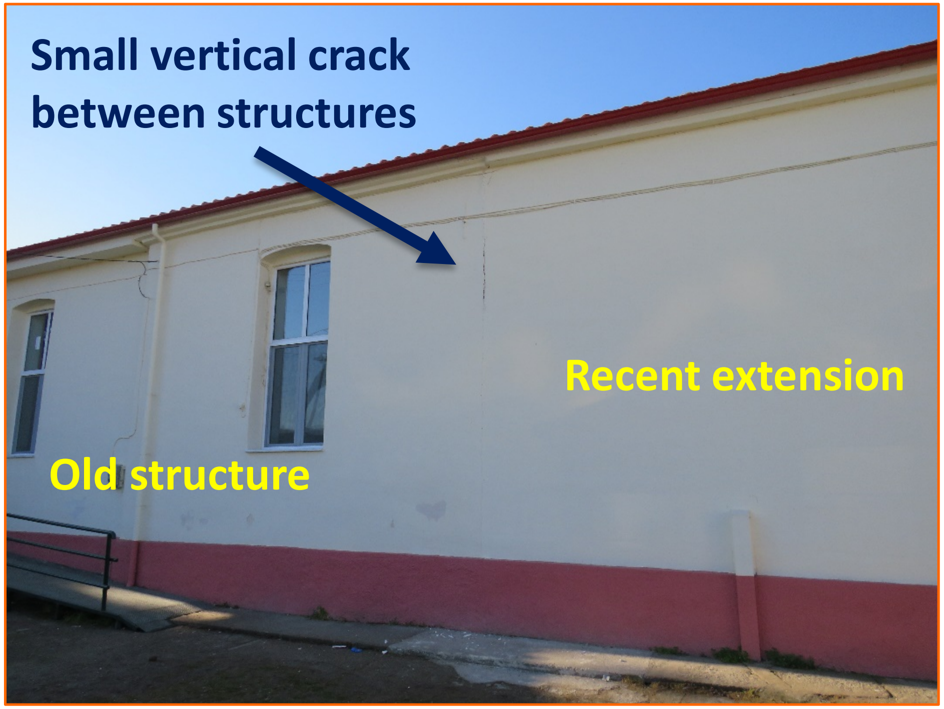
## DAMAGE TO SPECIAL STRUCTURES
### SCHOOLS


The primary school of Vlachogianni village, where cracks were formed between the old structure and its recent extension due to their different dynamic characteristics. This problem is frequently observed. The solution is simple: either we build the new structure at a distance from the old one, or we adequately tie together the two structures, after a proper structural design.

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## DAMAGE TO SPECIAL STRUCTURES
### SCHOOLS

The primary school in Damasi village is an over 80-year-old building with load-bearing masonry. It suffered severe structural damage due to the Mw 6.3 earthquake comprised partial collapse of its walls and was on the verge of total collapse after the earthquake.

It is significant to note that 63 students and 10 teachers were in the building when the earthquake struck the area. They immediately abandoned the buildings and now they are all safe.

Historical photos from [https://www.larissanet.gr/](https://www.larissanet.gr/)

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# DAMAGE TO SPECIAL STRUCTURES

## SCHOOLS

Views of the earthquake-generated building damage from the interior of the elementary school in Damasi village presented in the previous page. The masonry walls partially collapsed affecting only the school equipment.

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## DAMAGE TO SPECIAL STRUCTURES
### SCHOOLS

The school was demolished few days after the mainshock, as a new modern and safe building is going to be built in Damasi village.

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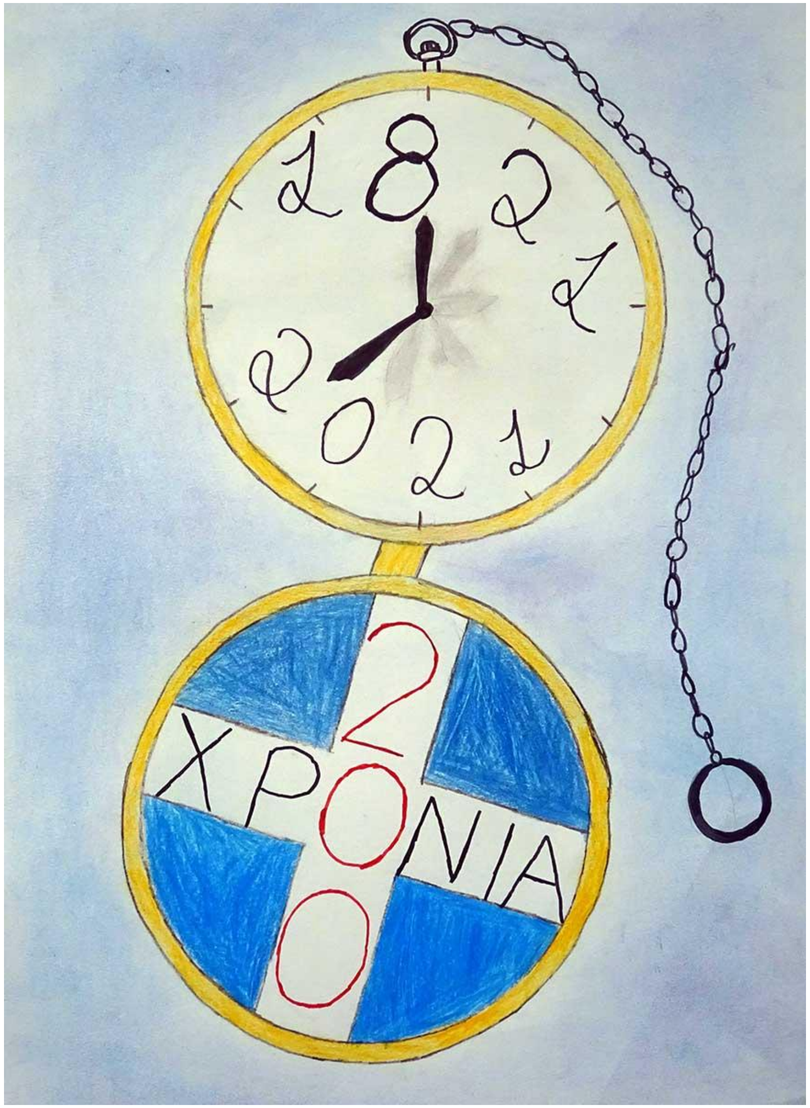
# THE ELEMENTARY SCHOOL OF DAMASI VILLAGE
## 200 YEARS PAST – A RESOURCE FOR THE FUTURE




In the context of the celebration of the 200th Anniversary of the Greek Revolution of 1821, the Regional Directorate of Primary and Secondary Education of Thessaly, organized a student poster and logo competition on "200 Years Past; a resource for the future", approved by the Ministry of Education.
The competition was held from January 15 to February 19, 2021 . Its main purpose comprises the awareness, reflection and creative involvement of students of all types of schools through their projects.

The creative imagination, the talent of the children was captured through their works (portraits, symbols, important historical moments, modern heroes in the battle against the COVID-19 pandemic etc.) in a special way connecting the events of 1821 with its present and future carrying a variety of messages.

The Elementary School of Damasi, participating in the student poster and logo competition, won the 1st Prize in the category of Logo, among more than 400 participations from all schools, of all educational levels of Thessaly, with the excellent work of the students from the 6th grade.

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# BUILDING INSPECTIONS

## RESULTS OF THE FIRST DEGREE INSPECTION

Shortly after a destructive earthquake in Greece with impact on the built environment, the engineers involved in the disaster management. The rapid visual inspections, performed immediately after the earthquake last ten up to twenty days, depending on the intensity and the damage extent and aim primarily to protect the residents, to contribute to the continuation of the basic functions and the identification and definition of the affected area. The post-earthquake assessment procedure consists of two degrees of inspections:

(a) the first degree inspection is a rapid visual inspection that evaluates the buildings and classifies them into two categories: usable or unusable (should not be used until re-inspection is performed) and

(b) the second degree inspection (re-Inspection) that is performed only to the buildings characterized unusable during the first stage. The buildings that are re-inspected, are classified in three categories regarding their usability and damage: buildings suitable for use, buildings temporarily unsuitable for use or buildings dangerous for use, depending on the observed damage. The duration of the secondary inspection is proportional to the intensity of the earthquake and the extent of the induced damage.

The results of the first degree inspection in the earthquake affected area in Thessaly basin were announced on March 12, 2021.

- A total of 5079 buildings were inspected. 4533 of them are residential. 1820 have been deemed temporarily unusable and will be re-inspected during the second degree inspection.
- 148 business premises have been inspected. 49 of them are temporarily and will be re-inspected during the second degree inspection.
- 66 of 132 special structures including temples and public buildings were characterized unusable. 211 of 247 warehouses were characterized temporarily unusable until the second inspection.

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# BUILDING INSPECTIONS
## RESULTS OF THE FIRST DEGREE INSPECTION

Until March 12, 2021, the following inspections were conducted:

- 1308 in Farkadona Municipality,
- 1311 in Tyrnavos Municipality
- 1558 in Elassona Municipality,
- 392 in Larissa Municipality
- 46 in Killerer Municipality
- 275 in Palamas Municipality
- 62 in Tempi Municipality
- 19 in Agia Municipality,
- 84 in Meteora Municipality and
- 24 in Trikala Municipality

Inspections were conducted in school buildings, health facilities and justice buildings:

### Elassona Municipality

- 11 usable and 14 unusable school buildings
- The Elassona Health Center was inspected and deemed usable
- The Elassona Magistrate's Court was temporarily unsuitable

### Tyrnavos Municipality

- 26 usable and 13 unusable school buildings
- The Agricultural Clinic of Tyrnavos was inspected and deemed usable

### Palamas Municipality

- 25 usable and 6 unusable school buildings

### Farkadona Municipality

- 17 usable and 14 unusable school buildings

### Larissa Municipality

- Inspections in 12 school buildings, all usable
- Inspections in the General Hospital of Larissa, at the Mental Health Center of Larissa, at the Health Center of Larissa and at the EFKA of Larissa and everything was deemed suitable for use.
- The Larissa Courthouse was also inspected and deemed usable.

### Killerer Municipality

- Inspections in 5 school buildings, all usable

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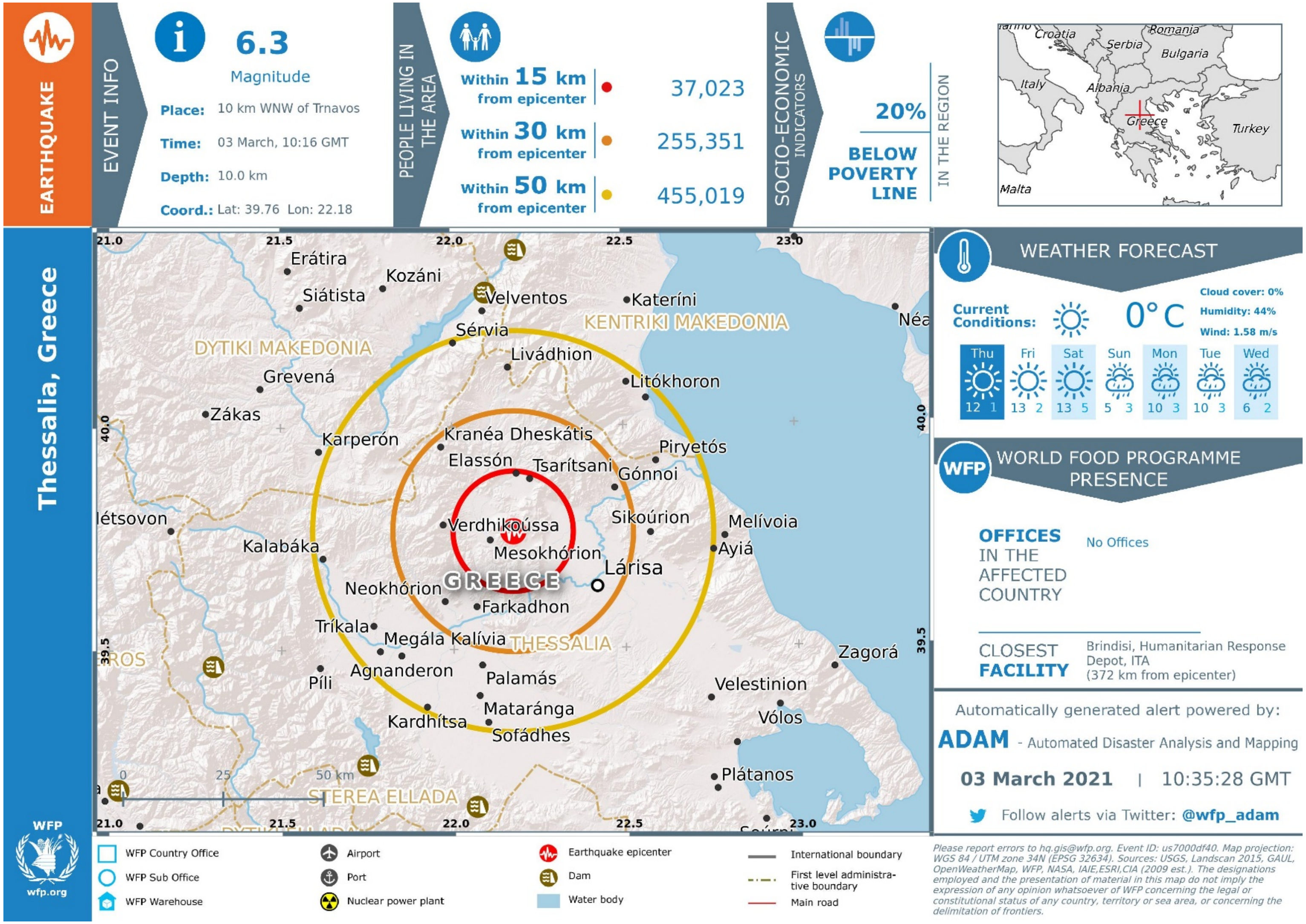
# DISASTER ALERT AND EMERGENCY RESPONSE

## FIRST ANNOUNCEMENT OF THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




Automatic Disaster Analysis and Mapping (ADAM) Disaster Alerts: https://twitter.com/WFP_ADAM

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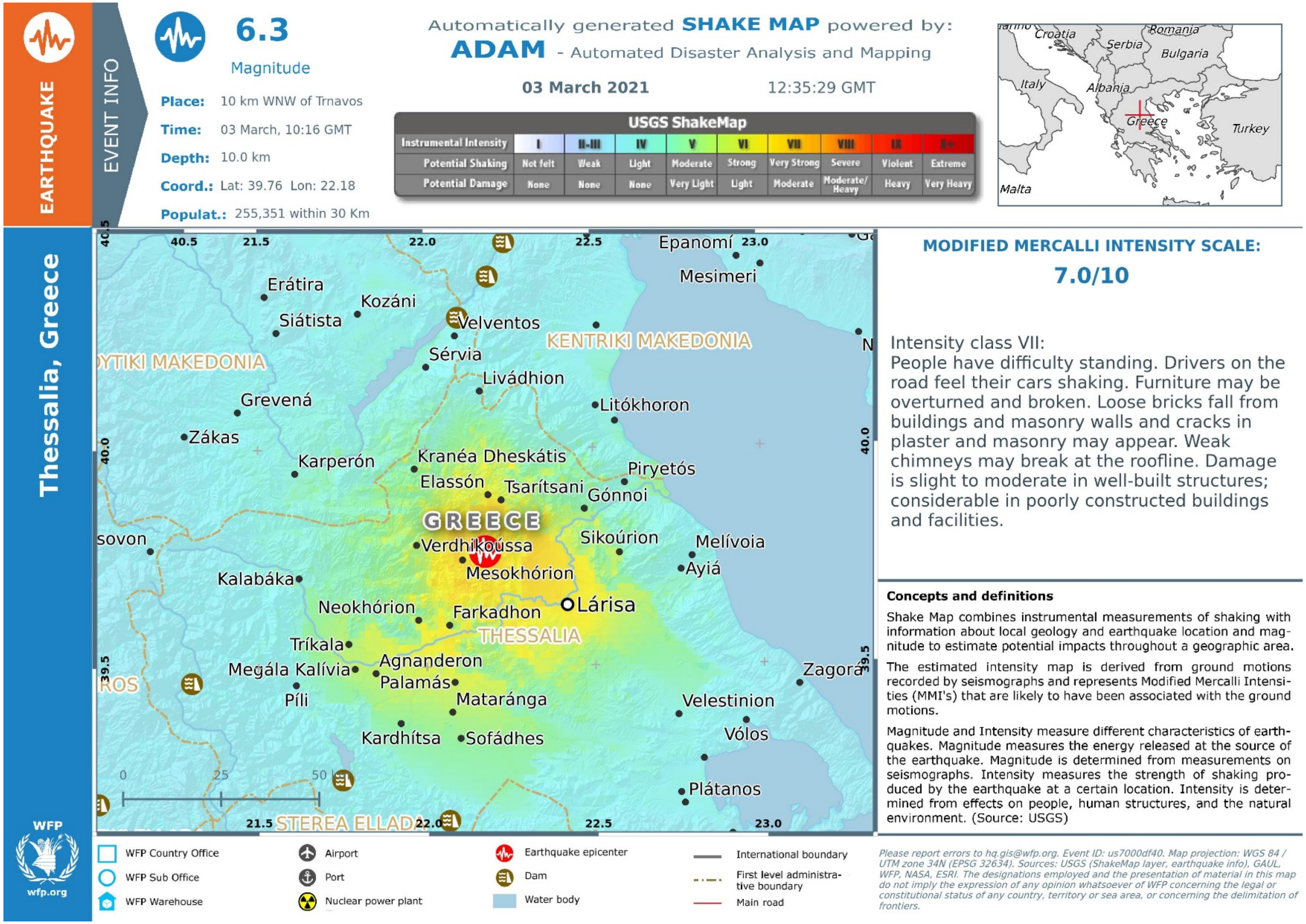
# DISASTER ALERT AND EMERGENCY RESPONSE

## EARLY IMPACT ESTIMATION FOR THE MARCH 3, 2021, Mw=6.3 EARTHQUAKE




Automatic Disaster Analysis and Mapping (ADAM) Disaster Alerts: https://twitter.com/WFP_ADAM

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## DISASTER MANAGEMENT
### FIRST RESPONSE

The Civil Protection authorities were on high alert and on full alert after the March 3, 2021, Mw=6.3 earthquake that occurred at 12:16 (local time) near the cities of Larissa and Elassona.

All forces involved in the management of the adverse effects induced by the earthquake remained on full alert for immediate assistance and intervention if needed, while the General Plan for emergency response and immediate/short-term management of earthquakes effects "ENCELADUS" has immediately been activated.

The Civil Protection authorities including the Hellenic Fire Service, the Hellenic Police, the National Center For Emergency Assistance, the regional and local administrative bodies were in increased readiness and moved towards the earthquake-affected area in order to assess the impact of the generated earthquake.

By mandate of the Chief of the Hellenic Fire Service, all the Disaster Management Special Units (E.M.A.K. – D.M.S.U.) of the Hellenic Fire Service were put on increased alert.


General Plan for Emergency Response and Immediate/Short-Term Management of Earthquakes Effects" with the code name Enceladus". Available at https://www.civilprotection.gr/sites/default/gscp_uploads/sxedio_egkelados.pdf

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## DISASTER MANAGEMENT
### INTERVENTION

Teams of the 1st, 2nd, 7th and 8th Disaster Management Special Units went to the affected area in order to conduct search and rescue (SAR) operations, where needed.

Moreover, a helicopter of the Hellenic Fire Service carries out aerial reconnaissance of the wider area in order to detect possible damage and immediate intervention, while a special team of EMAK drones approached the area in order to map slope failures and building collapse.

It is noted that the Deputy Minister of Civil Protection and Crisis Management and the General Secretary of Civil Protection were in constant communication from the National Operational Center for Crises Management with all the competent bodies and coordinated and monitored all actions of services and agencies involved in the management of the earthquake disaster.

A team comprised the Under-Secretary to the Prime Minister, the General Secretary of Infrastructure, the head of the Hellenic Armed Forces, the National Commander of Civil Protection and the Deputy Chief of the Hellenic Fire Service were on the way to the earthquake affected area.

A coordination meeting was immediately convened at the Coordination Operations Center set up in Tyrnavos town, with the participation of the aforementioned government members, the head of the Hellenic Armed Forces and all involved bodies (Hellenic Fire Service, Hellenic Police, National Center For Emergency Assistance, regional and local administrative bodies) and in constant communication with the Deputy Minister of Civil Protection and Crisis Management and the General Secretary of Civil Protection.

Among the first decisions taken by the authorities, 3 hotels in Trikala city and 2 in Larissa city have been leased by the Region of Thessaly for affected residents, who do not wish to spend the night in their homes located in the earthquake-affected areas. The affected residents, who wished to go to these hotel units were requested to contact with the Tyrnavos and Elassona Municipalities.

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## DISASTER MANAGEMENT
### INTERVENTION

In addition, the Civil Protection authorities with the contribution of the Hellenic Armed Forces and voluntary teams and organizations, set up a large emergency shelter in an open air football stadium in Damasi village. The initial equipment comprised 100 military-type tents, 10 generators, 2000 blankets, 200 sleeping bags, 500 beds and other emergency supplies and related equipment, while more than 150 tents have already been allocated by the Region of Thessaly and by the Hellenic Armed Forces for the temporary accommodation of the earthquake-affected local population.

Moreover, the operations center of the Hellenic Fire Service has received 80 calls since the earthquake and an elderly man was rescued from his partially collapse house in the area of Mesochori village and two elderly people have been rescued from their partially collapse house in Magoula village. 50 calls for immediate transport of elderly people and patients were also recorded and the related actions were conducted by the Hellenic Fire Service in collaboration with the National Center for Emergency Assistance.

In total, 6 people from Mesochori and Magoula villages were rescued by the Disaster Management Special Units of the Hellenic Fire Service, after the March 3, 2021, Mw=6.3 earthquake.

Patrols of the Hellenic Police and the Hellenic Fire Service continued during the emergency response phase, while the Disaster Management of the Hellenic Fire Service remained on high alert.

Taking into account the first scientific results announced by the Geodynamic Institute of the National Observatory of Athens and the Earthquake Planning and Protection Organization, citizens in the earthquake affected areas were called to stay in open and safe sites for the next few hours, as strong aftershocks were expected.

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## DISASTER MANAGEMENT




Meetings of all authorities and agencies involved in the earthquake disaster management in Tyrnavos - Elassona area were headed by the Prefect of Thessaly. These meetings aim to the assessment of the post-earthquake situation and the immediate and effective coordination of all involved during the emergency response phase and during the recovery. These meetings are conducted in the frame of the “Enceladus” plan, which is the General Plan for emergency response and immediate/short-term management of earthquakes effects in Greece.

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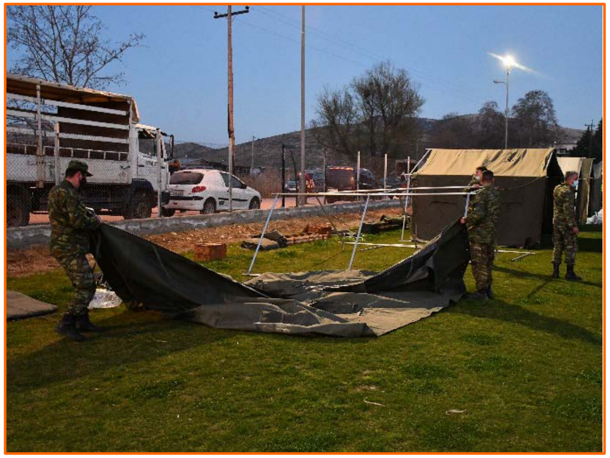
# DISASTER MANAGEMENT

## EMERGENCY SHELTERS



Emergency shelters were established based on the existed open spaces. They were mostly military type tents in open air spaces including stadiums and open municipal spaces. The authorities involved in the earthquake disaster management along with the contribution of the Hellenic Armed Forces provided homeless or frightened population with emergency supplies during their staying in shelters.

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## DISASTER MANAGEMENT
### EMERGENCY SHELTERS AND TEMPORARY HOUSING



In addition to the tents used in the emergency shelters, camper vans were used. They were installed in a specially designed municipal area or in safe yards of damages houses in affected villages of the area. Few days later, container-type houses were also set up for the temporary housing of the affected people who lost their properties.

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## DISASTER MANAGEMENT
### EMERGENCY SHELTERS AND TEMPORARY HOUSING


The location of emergency shelters serves two primary functions: providing temporary residence where affected people can avoid secondary damage such as fires, floods and diseases, and allowing first responders to efficiently perform search and rescue operations.

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# DISASTER MANAGEMENT
## CONTRIBUTION OF VOLUNTARY TEAMS

At this extraordinary moment, the entire voluntary mechanism was immediately mobilized, proving its readiness and at the same time expressing its full and practical support to the earthquake-affected population of Thessaly plain, who lost their properties in just a few seconds. Volunteers have always been on the side of the vulnerable groups of the population and are ready at any time to offer help not only within the country, but also where there is a need.

Among other significant activities, the volunteers performed the following actions:

- distribution of humanitarian aid, gathered from various sources, including equipment for the homeless, long-term food and personal hygiene items,
- participation in the organization of temporary emergency shelters for the affected population distribution of meals and humanitarian aid to affected people in the emergency shelters and elsewhere necessary
- relief actions to organizations, churches, institutions and individuals, where requested,
- providing support and guidance, especially for people with special needs and reduced mobility,
- assessment of needs of the affected population,
- provision of psychological support and counseling to residents with significant psychological stress attributed to the adverse effects of the earthquake.

There was a nationwide mobilization for emergency supplies concentration after the March 3, 2021 earthquake. Emergency relief supplies were distributed to those in need. They were provided by governmental authorities and donated by individuals and various sources. With this nationwide mobilization, Greeks sent a strong message of humanity, solidarity and hope to the earthquake-affected population. Despite the difficult situation due to the evolving SARS-CoV-2 pandemic, the collective effort paid off, the need for emergency supplies was fully addressed.

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# DISASTER MANAGEMENT
## CONTRIBUTION OF VOLUNTARY TEAMS

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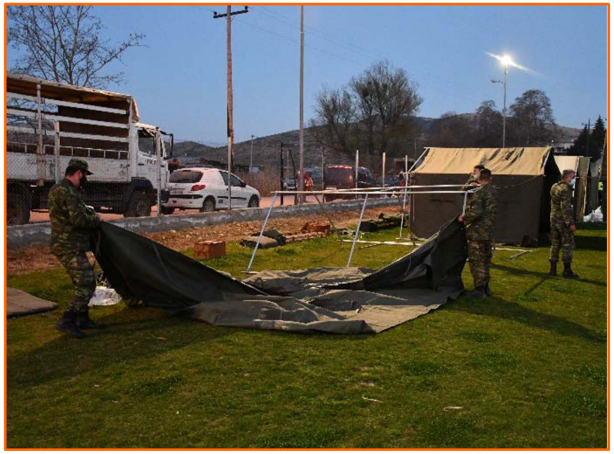
## DISASTER MANAGEMENT
## CONTRIBUTION OF THE HELLENIC ARMED FORCES

As regards the Hellenic Armed Forces, their response and their mobilization was immediate under the command of the Chief of the General Staff of National Defense (GEETHA). The Hellenic Armed Forces assisted the management of the earthquake disaster in the Thessaly plain always in excellent cooperation with the public authorities, the voluntary teams and the affected local population.

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Ο.Α.Σ.Π.

# RAISING EARTHQUAKE AWARENESS IN LARISSA REGION
## EDUCATIONAL ACTIVITIES ON DECEMBER 2020


ΘΕΣΣΑΛΙΑ

Λάρισα: Επιμορφωτικά εξ αποστάσεως σεμινάρια για εκπαιδευτικούς για την Αντισεισμική Προστασία Δημοτικών Σχολείων

1 Δεκεμβρίου 2020

TheNewspaper.gr


Σεμινάρια για εκπαιδευτικούς για την αντισεισμική προστασία δημοτικών σχολείων

1 Δεκεμβρίου 2020, 15:46 Εκπαίδευση, Σχολεία Ανάγνωση: 3 λεπτά

larissanet.gr

On December 2-4, 2020, EPPO implemented two webinars at Thessaly Region, in order to be appropriately educated and adequately trained the teachers for earthquakes. The teachers were trained to follow specific documented preparedness and evacuation procedures in case of an earthquake and to teach basic safety concepts to students, including drills and other learning activities.

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# RAISING EARTHQUAKE AWARENESS IN LARISSA PREFECTURE
## EDUCATIONAL ACTIVITIES ON DECEMBER 2020


*Information on EPPO's webinars for teachers at Prefecture of Larissa (12/2020) from national and local mass and social media*

https://www.facebook.com/316339618825379/photos/a.316373798821961/1084748411984492/?type=3&theater

The webinars took place in collaboration with the Division of Primary Education of Larissa. They were very important, because three months later the abovementioned strong earthquake hit Thessaly Region and the school community was well prepared to handle the emergency situation safely and effectively. A great example of this safe and effective handling of the emergency situation is the case of the Elementary School in the affected Damasi village. 63 students and 10 teachers followed the emergency plan and safely abandoned a school building on the verge of total collapse.

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Ο.Α.Σ.Π.

# RAISING EARTHQUAKE AWARENESS IN LARISSA PREFECTURE

## ACTIVITIES OF EPPO IN THESSALY BETWEEN 2016 AND 2020

*EPPO's seminar for child care providers of Tirnavos and Elassona Municipalities*


EPPO implemented training seminars for child care centers' personnel, in collaboration with Larissa, Tirnavos and Elassona Municipalities. EPPO provided education to the child care providers by utilizing a mix of brief information along with discussion, in an effort to expand their knowledge and to improve their skills on earthquake management to the specific settings.

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# RAISING EARTHQUAKE AWARENESS IN LARISSA PREFECTURE
## ACTIVITIES OF EPPO IN THESSALY BETWEEN 2016 AND 2020


*EPPO's seminars for teachers of Prefecture of Larissa and child care providers of Larissa Municipality*

Moreover, the EPPO staff implemented training seminars for School's Directors and teachers responsible for school earthquake planning. The seminars took place in collaboration with the Divisions of Education of Larissa of Ministry of Education and Religious Affairs.

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# RAISING EARTHQUAKE AWARENESS IN LARISSA PREFECTURE
## ACTIVITIES OF EPPO IN THESSALY BETWEEN 2016 AND 2020


The EPPO staff and its President participated to the Conference “Preparedness of City and Citizens in case of Earthquake”, that organized by Larissa Municipality

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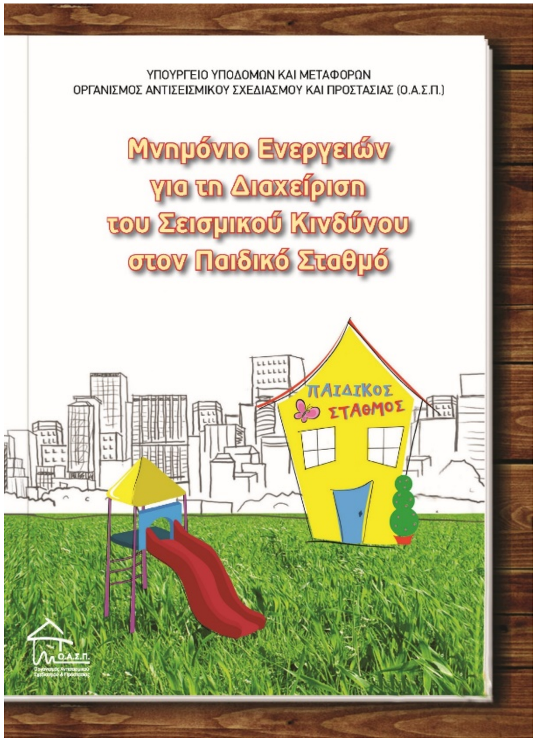
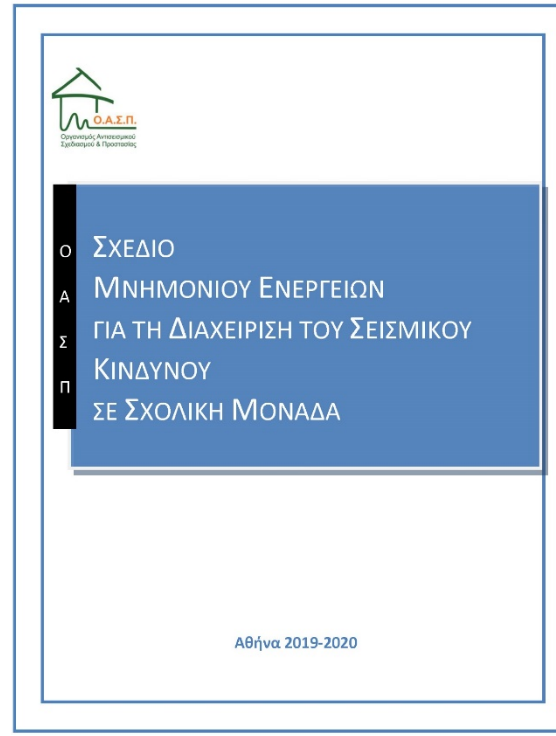
# RAISING EARTHQUAKE AWARENESS IN LARISSA PREFECTURE
## ACTIVITIES OF EPPO ON SEPTEMBER 2020




◀ Handbook on Earthquake Emergency Planning for Child Care Centers

▶ Handbook on Earthquake Planning for Schools




On September 2020, EPPO sent the "Handbook on Earthquake Emergency Planning for Child Care Centers" to all Municipalities of the country, by the Central Union of Greek Municipalities. The Handbook is a useful guide that provides all the essential knowledge and practical instructions required for the kindergartens staff. The Organization also sent the "Handbook on Earthquake Planning for Schools" to all school units, by the Ministry of Education and Religious Affairs. This Handbook is written for administrators, teachers and support staff involved in earthquake preparedness at school. Its purposes are to guide them in assessing risks and planning and carrying out protection measures, and to develop skills and provisions for earthquake preparedness, response, and rapid recovery.

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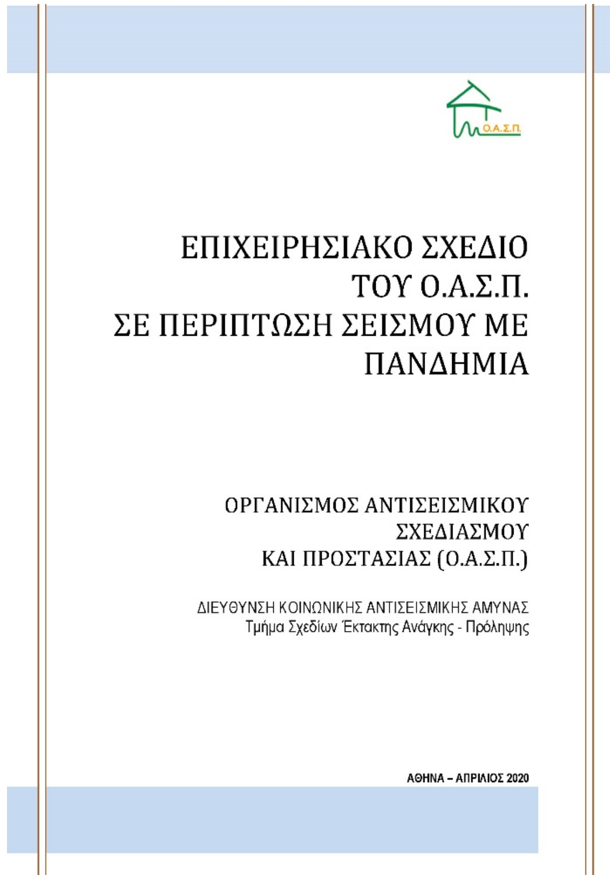
# RAISING EARTHQUAKE AWARENESS IN LARISSA PREFECTURE

## ACTIVITIES OF EPPO ON SEPTEMBER 2020

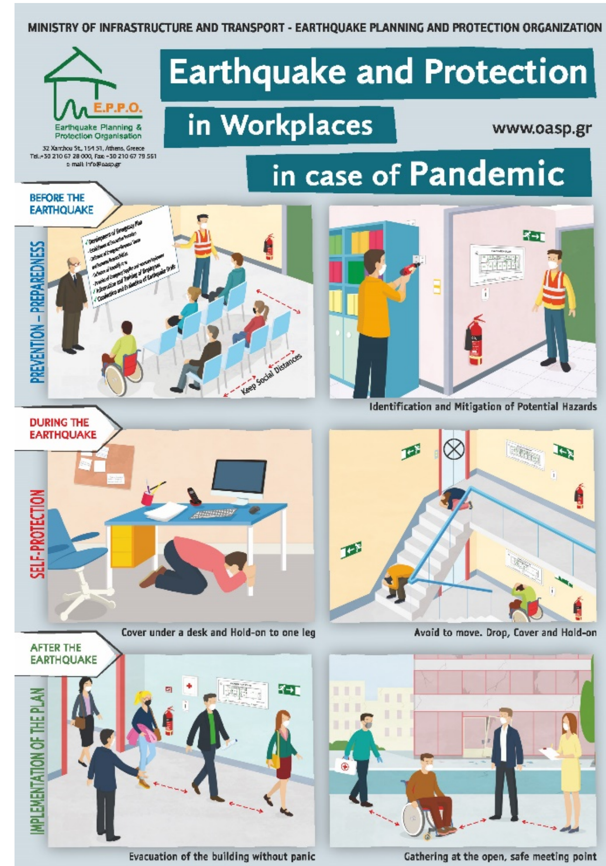



ΕΠΙΧΕΙΡΗΣΙΑΚΟ ΣΧΕΔΙΟ
ΤΟΥ Ο.Α.Σ.Π.
ΣΕ ΠΕΡΙΠΤΩΣΗ ΣΕΙΣΜΟΥ ΜΕ
ΠΑΝΔΗΜΙΑ

ΟΡΓΑΝΙΣΜΟΣ ΑΝΤΙΣΕΙΣΜΙΚΟΥ
ΣΧΕΔΙΑΣΜΟΥ
ΚΑΙ ΠΡΟΣΤΑΣΙΑΣ (Ο.Α.Σ.Π.)

ΔΙΕΥΘΥΝΣΗ ΚΟΙΝΩΝΙΚΗΣ ΑΝΤΙΣΕΙΣΜΙΚΗΣ ΑΜΥΝΑΣ
Τμήμα Σχεδίων Έκτακτης Ανάγκης - Πρόληψης

ΑΘΗΝΑ – ΑΠΡΙΛΙΟΣ 2020




The poster “Earthquake Protection in Workplaces”, and the poster “Earthquake Protection in Workplaces in case of Pandemic” to Municipalities, by the Ministry of Interior highlight the importance of improving workplace’s earthquake safety by students and teachers in educational facilities and employers and employees in working environment amid the COVID-19 pandemic.

Newsletter of
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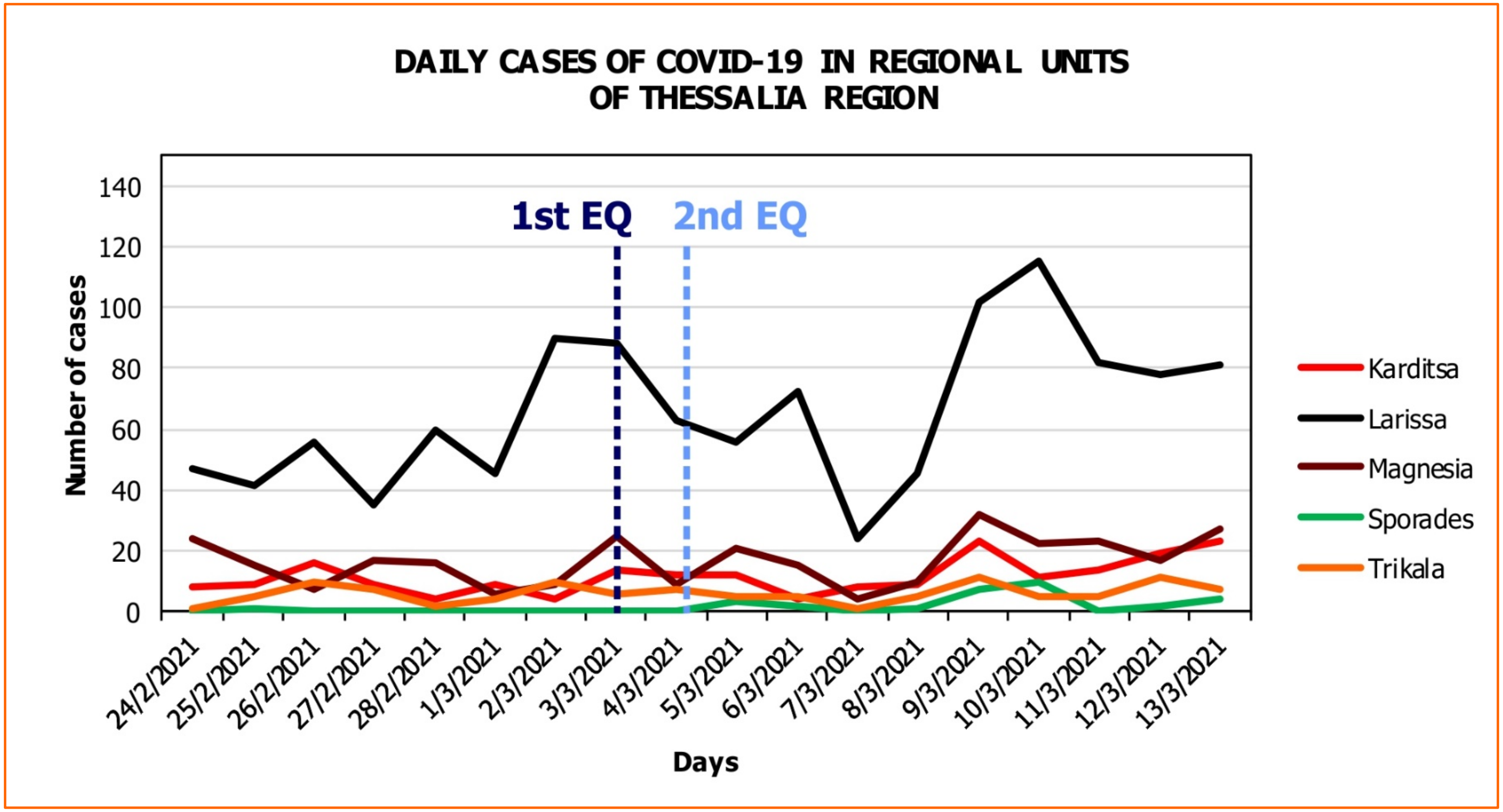
# THE EVOLUTION OF THE COVID-19 PANDEMIC IN THE EARTHQUAKE AFFECTED AREA

NATIONAL PUBLIC HEALTH ORGANIZATION




Based on the National Public Health Organization recordings of the laboratory confirmed daily recorded cases of COVID-19 in the regional units of Thessaly Region, it is concluded that there was significant viral load mainly in the regional unit of Larissa before the generation of the studied earthquakes, which still exists in the post-event period. However, no significant increase in the daily recorded COVID-19 cases has been observed in the regional units of the Thessaly plain.

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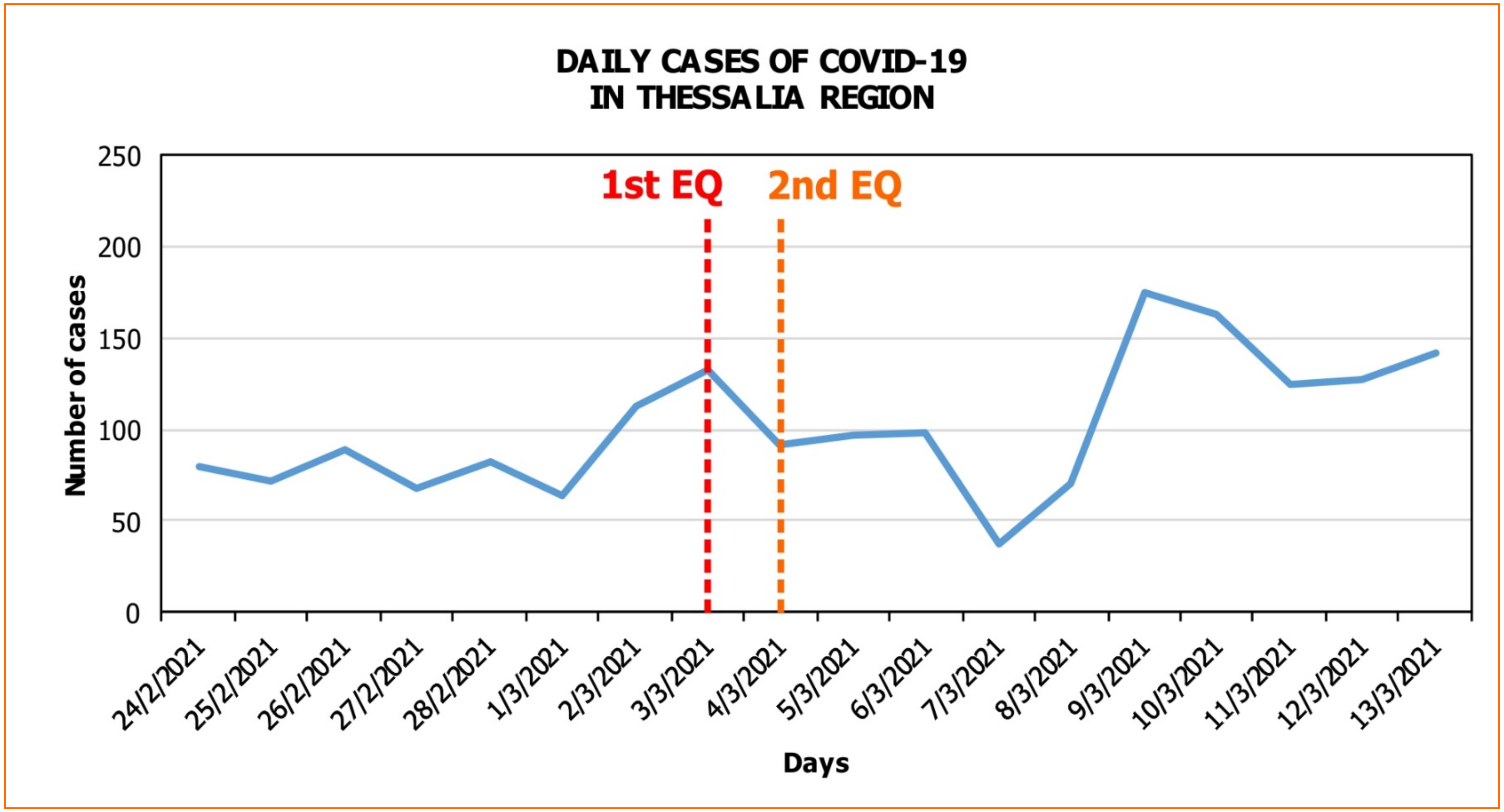
NATIONAL PUBLIC HEALTH ORGANIZATION

# THE EVOLUTION OF THE COVID-19 PANDEMIC IN THE EARTHQUAKE AFFECTED AREA




It is significant to note that after 5 days from the generation of the March 3, Mw=6.3 earthquake the total number of daily recorded COVID-19 cases in the Thessaly Region remains stable at three digits. This fact indicates that the virus is still present and is capable of triggering a disruptive local outbreak if the measures are relaxed.

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# THE EVOLUTION OF THE COVID-19 PANDEMIC IN THE EARTHQUAKE AFFECTED AREA

NATIONAL PUBLIC HEALTH ORGANIZATION

*NPHO in Mesochori*

As these lines are written, the Thessaly Region along with the contribution of the staff of the Hellenic National Public Health Organization (NPHO) have adopted significant measures for controlling the COVID-19 pandemic. More specifically, specialized staff of the NPHO serve the citizens in the affected villages and in the emergency shelter site in Damasi. Mass rapid testing took place in the affected villages within the Titarissios River bed (Damasi, Mesochori, Magoula, Domeniko, Praetori and Vlachogianni villages) in order to control further spreading of the virus in the community. More tests will be conducted in Tyrnavos town and in Damasi, Amouri, Mesochori, Mandra, Amygdalea and Koutsochero villages

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## CONCLUSIONS

On March 3, 2021, an Mw=6.3 earthquake stuck the northeastern part of the Thessaly basin. The earthquake occurred in a region mainly characterized by normal faulting along NW-SE striking faults that belong to the Northern Thessaly fault zone. Its magnitude has been assessed as Mw 6.2 or 6.3 and its focal depth varied from 4 to 19 km. Based on the provided focal plane solutions, the mainshock was generated by the rupture of an NW-SE striking normal fault.

The main shock was felt in the Thessaly basin and in the surrounding areas, from Athens in the south to the northern borders of Greece. Fortunately, it caused no fatalities, while only 3 people were slightly injured due to partial collapse of buildings with load-bearing masonry walls in Damasi village.

On March 4, 2021, (18:38:19 UTC), another earthquake struck the same area with magnitude varying from 5.8 to 6.3. Based on post-event field surveys in the earthquake-affected area, the second earthquake aggravated damage on buildings affected by the first earthquake and increased the anxiety of the local population.

The aftershock sequence has been monitored by all seismological laboratories of Greece. In general, most aftershocks follow a fault surface dipping to the north at low angles. The extended disrupted area covers ~45 km in a NNW-SSE direction and 20 km in a NE-SW direction. Geographically, one week after the mainshock occurrence, aftershocks tend to concentrate at the edges of the disrupted area.

For the March 3, Mw=6.3 event, the maximum Peak Ground Acceleration (PGA) of 0.138g was recorded at 17 km distance east from the epicenter, within the Larissa basin, at Giannouli (HL.GINA). The nearest records in the west was 0.054g at a distance of 25 km from the epicenter, on bedrock at Klokotos, near Trikala city (HL.THL), whereas within Trikala city the PGA was 0.037g (HL.TRKA).

For the March 4, event, the maximum PGA was of 0.047g recorded at a distance of 25 km east of epicenter within the Larissa basin at Giannouli (HL.GINA). The nearest records in the west was 0.030g at a distance of 25 km from the epicenter on bedrock at Klokotos, near Trikala city (HL.THL), whereas within Trikalla city the PGA was 0.038g (HL.TRKA).

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## CONCLUSIONS

As regards the earthquake environmental effects, the March 3, 2021, Mw=6.3 earthquake induced extensive liquefaction phenomena in fields close to rivers, which mainly attributed to the synergy of the strong earthquake ground motion, the unconsolidated river deposits and to the shallow groundwater table close to the rivers of the affected area. Typical forms of liquefaction were observed including ejection of liquefied material along ground cracks, individual sand boils, sand boils along ground cracks, large craters and lateral spreading along river banks. Moreover, the earthquake triggered slope movements along abrupt slopes comprising mainly detachment of unstable blocks and subsequent rockfalls, as well as ground cracks.

Based on post-event field surveys conducted by the University of Thessaloniki, clear earthquake environmental effects directly and clearly related to the earthquake energy and in particular to the surface expression of the causative fault were not detected. However, there are geological and coseismic indications suggesting that a low angle normal fault has acted as a hidden or blind fault during the Mw=6.3 earthquake. The already mapped active faults in the earthquake-affected area comprising the well-known and studied Tyrnavos fault did not generate the mainshock although they appear to be partially activated by the main seismogenic fault as sympathetic structures.

Field work conducted by the University of Patras revealed the Vlachogianni fault as reactivated during the main earthquake. On the basis of our field work the minimum length of the Vlachogianni Fault is about 10 km and forms a fault zone. The true length of the fault is under investigation since its prolongation towards the west or to the east is not easily recognized. Nevertheless the fault is related with surface rupture traces correlated with the main earthquake event on March 3. In close proximity with the fault trace innumerable lateral spreading, and liquefaction sand boils were generated and all mapped with UAV flights and traced with RTK GNSS. Overall the fault affects young deposits of the Titarissios River, where it forms an active compound fault scarp. Because of the young age of the river-bed sediments and of the competition of fast alluvial processes versus tectonics the fault is poorly preserved.

## CONCLUSIONS

The March 3, 2021, Mw=6.3 earthquake caused heavy structural damage to old unreinforced masonry buildings with load-bearing masonry walls in villages founded on recent deposits of Titarissios and Pineios Rivers' beds. The recently constructed reinforced concrete buildings remained relatively intact by the earthquake.

The worst affected building type is the old unreinforced masonry buildings with load-bearing walls. These buildings suffered mainly heavy damage on their structural elements comprising mainly vertical cracks at wall intersections due to the lack of the horizontal band beams, failures of the upper part of the walls attributed to the interaction between roof structure and perimeter walls as well as partial or total collapse due to poor quality mortar and poor workmanship resulting in disintegration of masonry units and loss of support to floors.

As regards the recently constructed buildings with reinforced concrete frame and infill walls, they remained intact by the earthquake in general. They suffered damage on their non-structural elements comprising detachment of plasters from infill walls, detachment of infill walls from the surrounding reinforced concrete frame and detachment of tiles from roofs and of cladding from walls. However, there are some cases of reinforced concrete buildings that suffered structural damage including damage to columns of the ground floor.

The most affected villages were distributed within the Titarissios River bed and in particular are Damasi, Damasouli, Mesochori, Vlachogianni, Amouri, Praetorio, Varkos, Sykia, Evangelismos and Magoula villages as well as the Tyrnavos town. Limited damage were observed in other villages located on the mountainous areas around the Titarissios River bed.

A temporary seismological network installed in the earthquake affected area has also contributed not only to the monitoring the seismic sequence, but also to the understanding of the earthquake-induced damage distribution, as well as to the development of a standard model of cooperation and operation of the Hellenic Unified Seismic Network.

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## CONCLUSIONS

In order to accurately locate the causative fault and determine the slip process of both earthquakes, modern and innovative techniques were applied by using seismological and satellite data. Based on finite-fault slip models, it is concluded that a fault of ~27.5 km length ruptured in two episodes, separated by one day, to produce an M=6.3 and an M=5.9 earthquakes. Based on this monitoring, it is shown that the heaviest damage in the villages of the Titarissios River valley, especially in the low lands (Damasi, Mesochori, Amouri, Praetorio, etc.) in relation to adjacent villages founded on the basement (Damasouli, Domeniko, etc.) are attributed also to the effect of soil amplification in Holocene deposits on which the respective villages are founded.

This was a lucky coincidence, because if it did rupture at once, the rupture would grow to become an M=6.5 or M=6.6 earthquake. The most affected villages of Damasi, Vlachogianni, Mesochori project within the major slip patches and this could explain the distribution and the intensity of the earthquake-induced damage.

Even though the two shocks cannot be connected to the already mapped faults of the area, the activation of the Tyrnavos and Larissa fault zones during the aftershocks cannot be ruled out.

Moreover, geospatial technologies were also applied in order to assess the impact of the March 3 and March 4 earthquakes in the affected areas of Thessaly Basin. DInSAR analysis was based on ESA Copernicus Sentinel satellite images. Coseismic interferograms and displacement maps compiled by using several softwares and deformation sections were constructed in order to visualize the ground deformation due to the aforementioned earthquakes. The displacement maps show subsidence up to 40 cm southwest of Damasi village and uplift up to 6 cm in the southwestern part of the earthquake affected area after the studied earthquakes on early March.

From the comparison of the slip models with the geodetic results, it is concluded that there is compatibility.

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## CONCLUSIONS

The exposure of critical facilities and infrastructures to the surface deformation induced by the March 3, Mw=6.3 earthquake and the March 4, Mw=6.1 earthquake was studied based on DInSAR results. Educational facilities comprise child care centers, elementary, middle and high schools, health facilities include hospitals and health centers, infrastructures comprise bridges, national road and railways, cultural facilities include museums and archaeological sites.

The schools in the most affected area, the majority of which are buildings with load-bearing masonry, suffered heavy structural damage. The over-80-year-old elementary school in Damasi village is a characteristic example of such a building, which was on the verge of collapse after the March 3 earthquake. In order to avoid unpleasant situations in the future, the first degree inspections and the second degree (re)inspections of the educational activities must be completed soon. The damaged school buildings must be effectively repaired and the programs for raising awareness on earthquake risk reduction and preparedness must be expanded for teaching staff and students at all levels of education.

A great example from the earthquake affected area that could be considered as a result of these educational activities is the safe and effective handling of the emergency situation by the teachers and the proper and effective response of students from Damasi village during the March 3, Mw=6.3 earthquake.

As regards the disaster management and especially the actions during the emergency response, the actions taken shortly after the generation of the March 3, Mw=6.3 earthquake were according to the “Enceladus” plan and comprised initial notification of the earthquakes, earthquake alerts and announcements, first assessment of the impact and mobilization and response of the state authorities, search and rescue operations where needed, first-aid treatment and medical care, psychosocial support of the affected population, hazard mitigation, awareness and education for the earthquake effects and protective measures due to the continuous aftershock sequence, provision of essential emergency supplies, provision of emergency shelters and procedures of housing restoration and immediate financial relief measures.

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## CONCLUSIONS

All these actions were effectively conducted by the Civil Protection authorities and agencies along with the contribution of the Hellenic Armed Forces and voluntary teams and organizations. The nationwide mobilization sent a strong message of humanity, solidarity and hope to the earthquake-affected population, which has to cope with geological hazards amid the COVID-19 pandemic.

The viral load in the Region of Thessaly indicates that the virus is still present and is capable of triggering a disruptive local outbreak if the measures are relaxed. The Region of Thessaly along with the contribution of the staff of the Hellenic National Public Health Organization (NPHO) have adopted significant measures for controlling the COVID-19 pandemic including mass rapid testing in the earthquake-affected areas in order to help slow the spread of the virus and its mutations in the affected community.

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# The early March 2021 Thessaly earthquake sequence

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