The Athens 19/07/2019 M_w5.1 earthquake – Preliminary macroseismic report

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1. Introduction

On 19 July 2019, 11:13 GMT (14:13 local time), a strong, damaging earthquake with magnitude M_w5.1 (Figure 1) and 16 km depth (NKUA solution) struck Athens, causing damage to its western suburbs. This moderate event signalled a general alarm in the whole metropolitan area with people rushing out of buildings, resulting in interruption of mobile communication for at least 2 hours and heavy traffic jams. The epicentre is located a few km north of Magoula (west Attica) and it is associated with a normal fault probably comprising the western segment of Parnitha normal fault (Ganas et al. 2001; 2004, Papadimitriou et al. 2002, Figure 1). Two decades ago (7/9/1999), the eastern segment of this fault was activated with an M_w6.0 earthquake (Papadopoulos et al. 2004; Papadimitriou et al. 2002), which resulted in 143 fatalities, considerable damage estimated at €3 billion to a large number of municipalities north, west and south of Athens, as well as in the capital itself. Damage was particularly heavy in the western and north-western suburbs of Athens, severely affecting a population of approx. one million (Kouskouna and Malakatas 2000). The mountainous area of Parnitha is a relatively low strain rate area of Central Greece (~50 ns/yr; Chousianitis et al. 2015) where the slip rates of active faults are less than 1 mm/yr (Ganas et al. 2005) and earthquake recurrence intervals are expected in the order of a few thousands of years.

This unexpected earthquake was the main cause for the stakeholders updating the national Seismic code so as to include 3 zones instead of the former 4, with the metropolitan area of Athens belonging to zone II, which predicts PGA=0.24g (EAK-2000, 2003). Post-seismic interventions in areas affected by the 1999 earthquake and also new buildings constructed under the more rigorous regulations of the new seismic code in replacement of the destroyed ones, likely contributed to the limited extent of damage during the recent earthquake, of course with respect also to its lower magnitude.

In this scientific report we present the results from an in-situ campaign in the epicentral area, conducted by our research team, including macroseismic surveying of structural damage and geoenvironmental effects, while data from

the post-seismic engineering inspection of the Directorate General for Natural Disasters Rehabilitation (DGNDR) were also implemented. Our goal is to provide a preliminary assessment of the distribution of seismic effects of the recent earthquake, which, in a future combination with those of the 1999 event could lead to a better understanding of the seismic wave-field and also of the seismic risk in the broader metropolitan area of Athens.

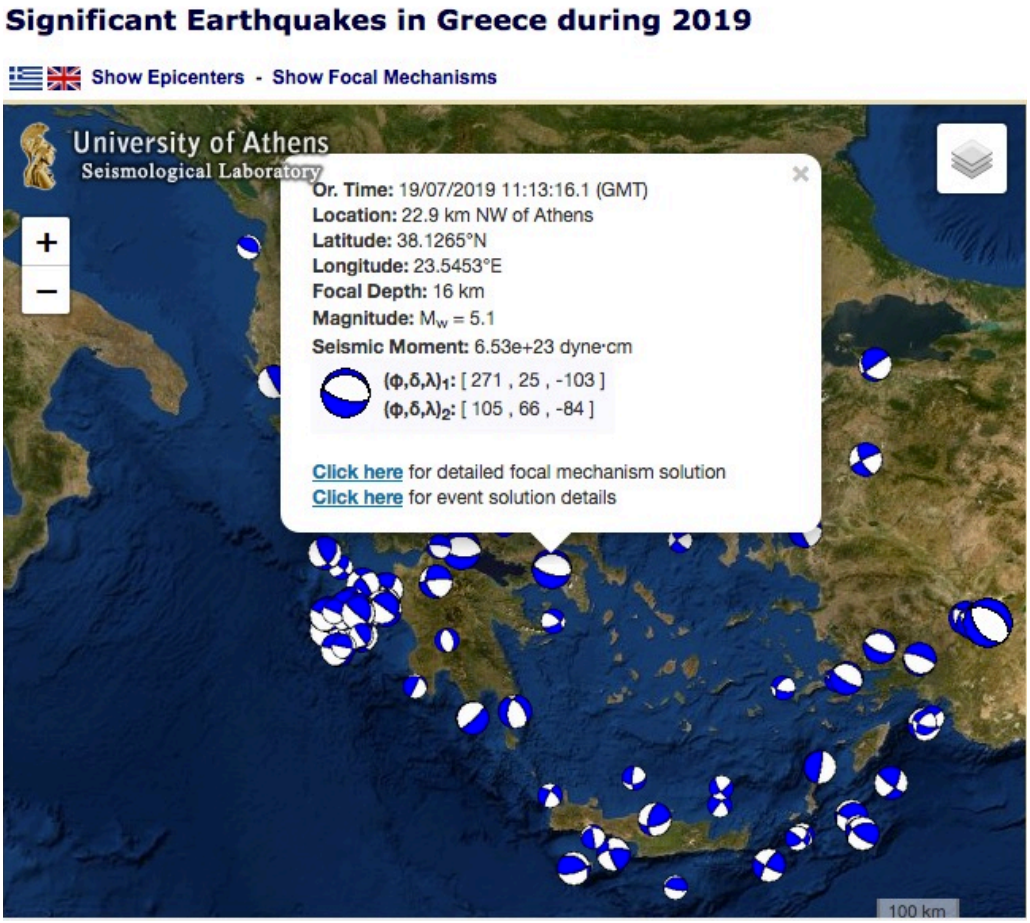


Figure 1. Parameters of the Athens 2019 earthquake (http://www.geophysics.geol.uoa.gr)

2. Macroseismic survey

Immediately after the earthquake occurrence and in the following week, the Macroseismic Field Investigation Team of the Seismological Laboratory, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, visited the damaged areas and distributed questionnaires based on EMS-98 to a number of suburbs and towns surrounding the epicentre. In parallel, EMSC-CSEM received online 449 testimonies from approx. 200 localities, mainly from the Attiki prefecture (Figure 2). In the following table, the localities with total number of questionnaires and testimonies N≥2 are shown.

Figure 2. Map created with the testimonies provided by eyewitnesses to EMSC-CSEM (https://static2.emsc.eu/Images/INTENSITY_MAPS/78/780588/AUTOMATIC/AreaThreshold_5/EMS_98__RMW_Musson/LocMethod_PerClusterCity/DynamicClusters_MaxSize50/IntensityMapThumbnails.png)

Table 1. Localities and corresponding numbers of in situ questionnaires and/or online testimonies

Locality	Region	No Quest. No. Testim.	Source
Acharnes	Attiki	5	EMSC-CSEM
Agia Marina Neas Makris	Attiki	4	In situ
Agia Paraskevi	Attiki	6	EMSC-CSEM
Agios Dimitrios	Attiki	5	EMSC-CSEM
Agios Ioannis Rentis	Attiki	2	EMSC-CSEM
Agios Sotiras	Attiki	3	In situ
Agios Stefanos	Attiki	3	EMSC-CSEM
Aigaleo	Attiki	4	EMSC-CSEM
Aigina	Attiki	4	EMSC-CSEM
Alimos	Attiki	2	EMSC-CSEM
Amarousio	Attiki	17	EMSC-CSEM
Ano Liosia	Attiki	5 1	In situ EMSC-CSEM
Argyroupoli	Attiki	3	EMSC-CSEM
Aspropyrgos	Attiki	3 2	In situ EMSC-CSEM

Athens 1	Attiki	6 50	In situ EMSC-CSEM
Athens 2	Attiki	5	EMSC-CSEM
Athens 3	Attiki	5	EMSC-CSEM
Athens 4	Attiki	4	EMSC-CSEM
Athens 5	Attiki	9	EMSC-CSEM
Athens 6	Attiki	3	EMSC-CSEM
Athens 7	Attiki	7	EMSC-CSEM
Batsi	Kyklades	2	EMSC-CSEM
Chaidari	Attiki	4	EMSC-CSEM
Chalandri	Attiki	11	EMSC-CSEM
Chalkida	Evvoia	3	EMSC-CSEM
Cholargos	Attiki	5	EMSC-CSEM
Chora Parou	Kyklades	2	EMSC-CSEM
Dionysos	Attiki	5	EMSC-CSEM
Drapetsona	Attiki	2	EMSC-CSEM
El. Venizelos airport	Attiki	2	EMSC-CSEM
Elefsina	Attiki	4 3	In situ EMSC-CSEM
Elliniko	Attiki	2	EMSC-CSEM
Fyli	Attiki	3	In situ
Galatsi	Attiki	2 3	In situ EMSC-CSEM
Gerakas	Attiki	4	EMSC-CSEM
Glyfada	Attiki	12	EMSC-CSEM
Ilion	Attiki	2 3	In situ EMSC-CSEM
Ilioupoli	Attiki	5	EMSC-CSEM
Kaisariani	Attiki	2	EMSC-CSEM
Kalamata	Messinia	3	EMSC-CSEM
Kalívia Thorikoú	Attikí		
Kallithea	Attiki	8	EMSC-CSEM
Kato Chalandri	Attiki	4 1	In situ EMSC-CSEM
Keratsini	Attiki	6	EMSC-CSEM
Kifisia	Attiki	3 6	In situ EMSC-CSEM
Korinthos	Korinthia	4	EMSC-CSEM
Koropi	Attiki	2	EMSC-CSEM
Korydallos	Attiki	2	EMSC-CSEM
Kymi	Evvoia	3	EMSC-CSEM
Loutraki	Korinthia	2	EMSC-CSEM
Magoula	Attiki	6 2	In situ EMSC-CSEM
Mandra	Attiki	5 1	In situ EMSC-CSEM
Metamorfosi	Attiki	2	EMSC-CSEM
Nea Chalkidona	Attiki	2	EMSC-CSEM

Nea Erythraia	Attiki	2 3	In situ EMSC-CSEM
Nea Filadelfeia	Attiki	4	EMSC-CSEM
Nea Ionia	Attiki	2	In situ
Néa Ionía	Magnisía	4	EMSC-CSEM
Nea Makri	Attiki	14 5	In situ EMSC-CSEM
Nea Peramos	Attiki	2	In situ
Nea Smyrni	Attiki	7	EMSC-CSEM
Neo Irakleio	Attiki	2	EMSC-CSEM
Neo Psychiko	Attiki	2	EMSC-CSEM
Nikaia	Attiki	4	EMSC-CSEM
Oinofyta	Voiotia	2	EMSC-CSEM
Oinoi	Attiki	8 1	In situ EMSC-CSEM
Palaio Faliro	Attiki	8	EMSC-CSEM
Pallini	Attiki	5	EMSC-CSEM
Papagos	Attiki	2	EMSC-CSEM
Paradeisos Amarousiou	Attiki	5	EMSC-CSEM
Pefki	Attiki	2	EMSC-CSEM
Peristeri 1	Attiki	5	EMSC-CSEM
Peristeri 2	Attiki	16 4	In situ EMSC-CSEM
Piraeus 1	Attiki	4	EMSC-CSEM
Piraeus 2	Attiki	4	EMSC-CSEM
Piraeus Port	Attiki	3	EMSC-CSEM
Porto Germeno	Attiki	5	In situ
Porto Rafti	Attiki	2	EMSC-CSEM
Salamina	Attiki	2	EMSC-CSEM
Skiathos	Magnisia	2	EMSC-CSEM
Spata	Attiki	2	EMSC-CSEM
Stefani	Attiki	2	In situ
Terpsithea	Attiki	3	EMSC-CSEM
Vilia	Attiki	10	In situ
Voula	Attiki	4	EMSC-CSEM
Vouliagmeni	Attiki	2	EMSC-CSEM
Vrilissia	Attiki	5	EMSC-CSEM
Vyronas	Attiki	2	EMSC-CSEM
Xylokastro	Korinthia	2	EMSC-CSEM
Zografos	Attiki	6	EMSC-CSEM

2.1 Damage

Damage due to the Athens 2019 earthquake was reported from several localities in the Attiki prefecture. In downtown Athens a couple of abandoned buildings partially collapsed and failure of non-structural elements was observed in a few others. In Piraeus port, part of an old conveyor collapsed (Photo 1). Taking into

account the high vulnerability of a few isolated cases, the earthquake produced, in general, only slight-to-moderate damage mainly to non-structural elements.

Damage was observed by the survey team from the northern and western suburbs (Photos 2-10).

Photo 1. Left: damage abandoned structure at the port of Piraeus. Centre: damage to the Pantanassa bell tower, Right: partial collapse to old buildings Source: iefimerida.gr - https://www.iefimerida.gr/ellada/seismos-stin-athina-eleghoi-oi-zimies-se-foto

Photos 2-3: Ano Liosia

Photo 4: Aspropyrgos

Photo 5: Stefani

Photo 6: Dafni monastery (temporarily closed, slight non-structural damage)

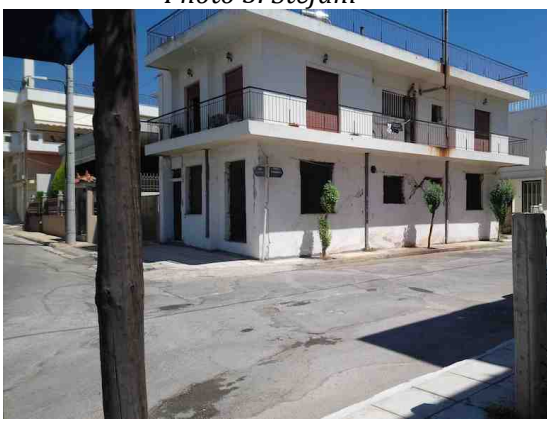
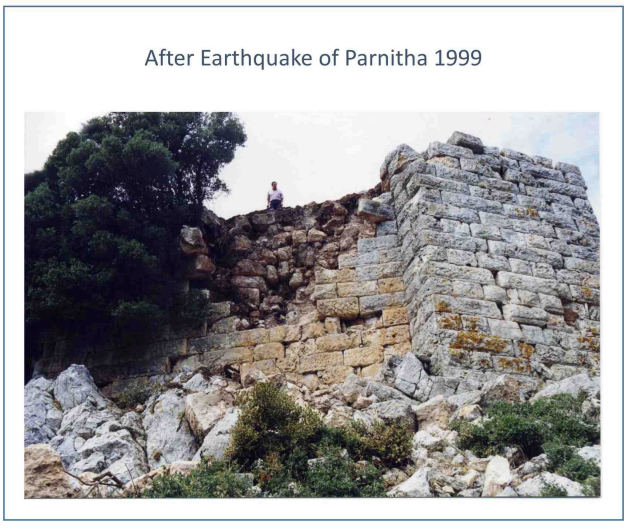
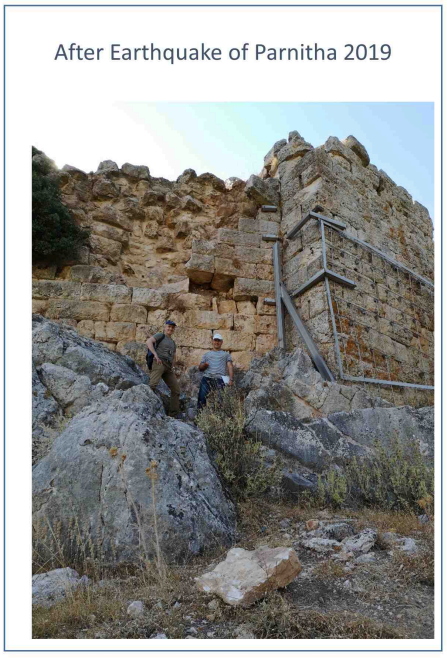


Photo 7: Ano Liosia





Photos 8-9: Fyli castle

Photo 10: Fyli castle field photographs of 24 July 2019. Numbers refer to photo position round the castle (centre – satellite image by Google Earth).

2.2 Initial damage inspections

Following the earthquake, nearly 4,500 applications for building inspections were submitted to the Ministry of Infrastructure and Transport. The initial inspections performed by the teams of engineers of the Ministry's Directorate General for Natural Disasters Rehabilitation, concluded that 821 of the buildings suffered mainly slight-to-moderate non-structural damage, characterized as temporarily unusable, or "yellow" (Figure 3), i.e. safe for users after minor interventions (EPPO-ITSAK). The final inspections results are due end of August 2019.

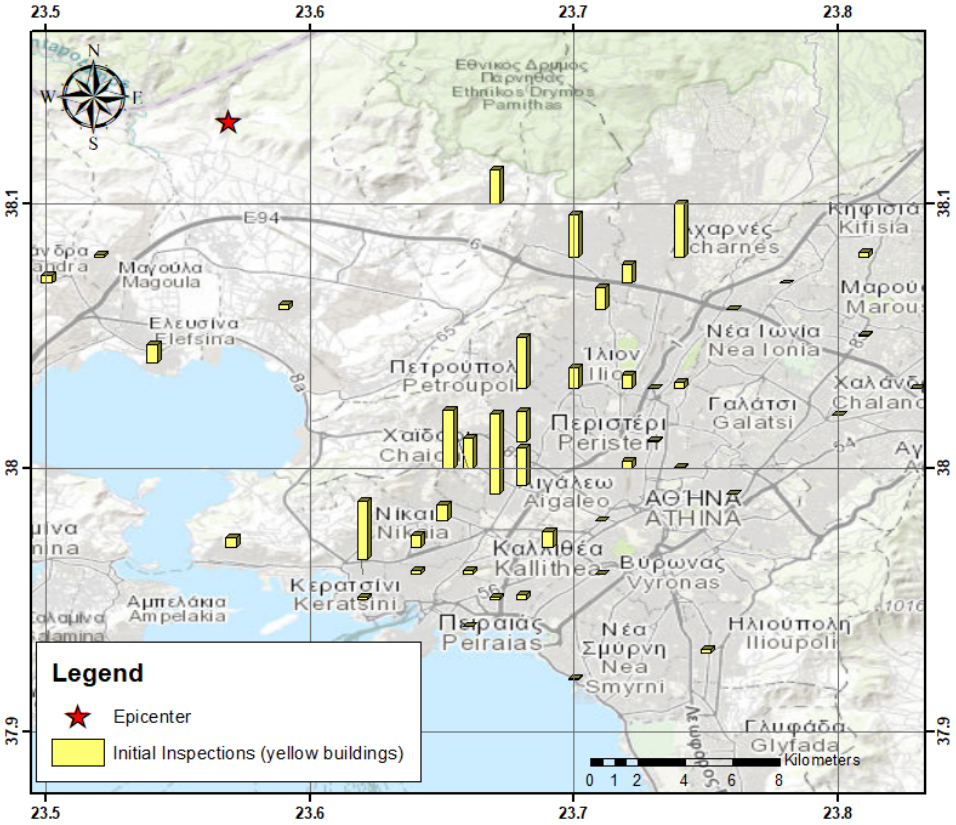


Figure 3. Distribution of initial building inspections per municipality. Maximum: 97 deemed temporarily unusable ("yellow") buildings at Petroupoli municipality.

2.3 Seismogeological effects

A Field Investigation Team of the Institute of Geodynamics, National Observatory of Athens performed a field survey for the identification of slope failure effects (Photos 11-12). The survey found evidence of minor rock falls along the road network to the SE of the epicentre. The ancient Fyli castle was also affected with evidence of further weakening of the eastern tower–external wall of the structure. No landslides were triggered. No surface breaks were observed as was expected due to the moderate magnitude of the mainshock. Moreover, in the area north of Magoula we did not observe any bedrock scarp or outcropping fault plane.

Photo 11: On the road between Ano Liosia and Fyli

Photo 12: Aigaleo ring road

3. EMS-98 Intensity assignment

EMS-98 intensity assignment was performed for a total number of 205 localities using the questionnaire responses, testimony reports, preliminary damage inspections and photographic material collected on damage and slope failures. These localities are towns, villages, suburb municipalities, or municipal boroughs. For example, Athens is divided into 7 municipal boroughs and Piraeus into 5.

Table 2. Sample questions and responses from the questionnaires distributed in southern Peristeri municipality

Question	**Indoors**	**Outdoors**
Where were you at the time of the earthquake	13	3
On which floor	Ground floor: 10 First: 2 Second: 1	-
Did others nearby feel the earthquake	Yes: 13	Yes: 3
Did you hear sound	Yes: 13	Yes: 3
Were you frightened	Yes: 10 No: 2 N/A: 1	No: 3
Were others nearby frightened	Yes: 11 No: 0 N/A: 2	Yes: 1 No: 2
Did you find it difficult to stand	No: 13	No: 3
Did windows and doors rattle	Yes: 13	Yes: 2 No: 1
Did hanging objects swing	Yes: 4 No: 6 N/A: 3	-
Did objects fall or break	Yes: 4 No: 9	-
Did furniture move	Yes: 2 No: 11	-

Did you notice any damage	No	No
Did you notice any effects on the environment	No	No

The procedure followed for localities with no damage was the expert-judgement analysis of macroseismic information collected through questionnaires and testimonies (see Table 1 for an example). In such cases, EMS-98 intensity values ranged between 2 and 5.

For damaged localities, intensity was estimated using the aforementioned data together with the preliminary damage inspections and collected photographic material. Slope failure observations were used for additional verification of intensity values. Figure 4 represents the assigned intensities distribution, which fall within the range 2-6/7 and the respective isoseismals for degrees 2 and 4.

3.1 Example of intensity assignment in Peristeri

Peristeri municipality is a large, populated area in western Attiki (Figure 4). Administratively, it is divided into two municipality boroughs, the northern (Peristeri 1) and the southern (Peristeri 2). Sixteen questionnaires were distributed in southern Peristeri municipality, and 4 testimonies are reported online to EMSC-CSEM. In the following table, the summary of responses to a number of questions and felt reports for indicative intensity assignment is presented.

Summary: The earthquake was felt by all, indoors and outdoors. Most were frightened. Small objects of ordinary stability fell and some furniture shifted (Grünthal, Ed., 1998). These observations lead to intensity 6, for the diagnostics "effects on humans" and "effects on objects" of the European Macroseismic Scale 1998. In addition, 36 out of 140 inspected buildings had slight to moderate damage, which concurs with the damage description for intensity 6 in the scale (Damage of grade 1 is sustained to many buildings of vulnerability class A and B; a few of class A and B suffer damage of grade 2; a few of class C suffer damage of grade 1). The final buildings inspections are not likely to increase this value of intensity.

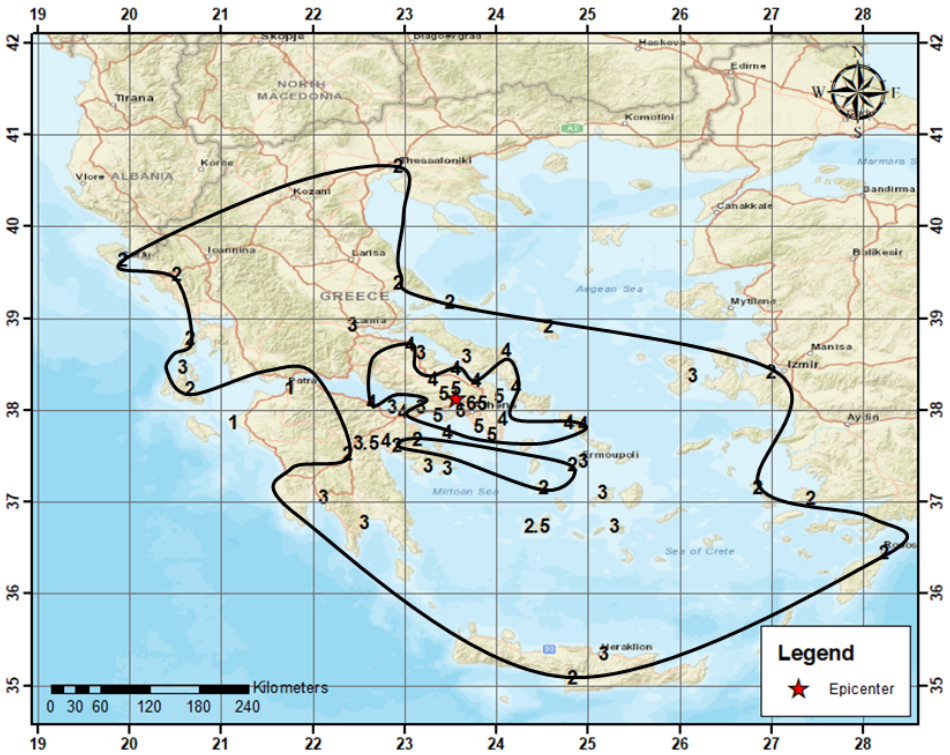


Figure 4. EMS-98 macroseismic intensity distribution of the 2019 Athens earthquake and respective isoseismals for degrees 2 and 4.

4. Macroseismic parameters

The resulting intensity data was used as input for independent macroseismic parameters estimation. We applied the MEEP package developed by Musson and Jimemez (2008), with the coefficients estimated by Kouskouna et al. (2019, in press) for the area of Greece. The results of the 4 methods used in MEEP package (Centroid, MEEP, Bakun, Pairwise) for epicentral coordinates, equivalent moment magnitude and focal depth, accompanied by their uncertainties, are presented in Table 3. An overestimation of the instrumentally-determined moment magnitude by 0.3 units (except for the Bakun method) is observed, taking into account the sensitivity of the methods with regard to all intensity levels distribution. Slight changes are expected with the final intensity dataset. Finally, Figure 5 shows the distribution of instrumental and macroseismic epicentres and EMS-98 intensity distribution in Attiki area. All macroseismic epicentres from the 4 MEEP package methods are shifted to SE with respect to the instrumental determination.

Table 3. MEEP results for macroseismic parameters estimation of the 2019 Athens earthquake

Method	**Lat**	**Lon**	**+/-km**	**Mw**	**+/-**	**D**	**+/-km**
Centroid	38.037	23.680	4.0	5.4	0.1	19	8
MEEP	38.042	23.629	4.6	5.4	0.1	18	7
Bakun	38.095	23.605	4.5	5.1	0.1		
Pairwise	38.050	23.622	1.9	5.4	0.1		

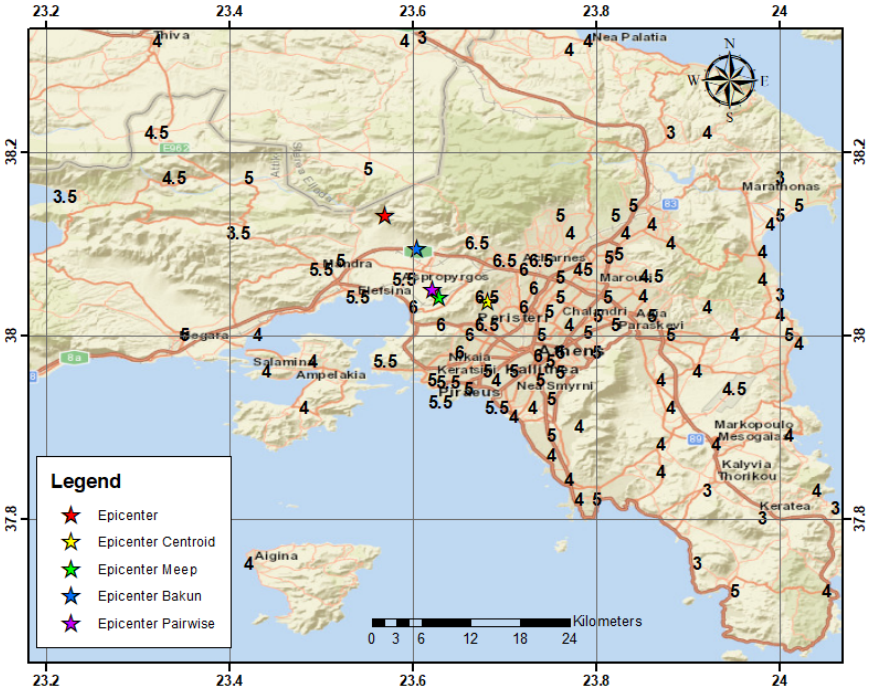


Figure 5. The 2019 Athens earthquake EMS-98 intensity distribution in Attiki area and associated instrumental (red) and macroseismic epicentres.

5. Aftershock sequence and fault model

The relation of the 2019 to the 1999 event is apparent through their aftershock sequences distribution (Figure 6). The area covered by the 2019 aftershocks (red dots) is considerably smaller, indicating that the activated western fault segment is smaller than the 1999 eastern one. The 4-day aftershock distribution (110 events) is clustered around the mainshock, and mostly towards the north. A smaller cluster formed a few km to the SE of the mainshock.

A preliminary fault model indicates that a rectangle of 6 km (long) by 4 km (wide) may fit the seismic source. The orientation of the source is ESE-WNW (N106°E) and the dip-angle is 60° towards south. This geometry resembles greatly the 1999 seismic source (Atzori et al. 2008), thus it is possible to consider the 2019 source as the western continuation of the 1999 event. In this preliminary study we need to consider both options concerning the position of the 2019 fault plane inside the crust, i.e. that the mainshock originated in the slip centroid (model 1) or from the bottom end of the fault with the rupture growing updip (model 2). The respective solutions are presented as surface projections of the two fault segments in Figure 7.

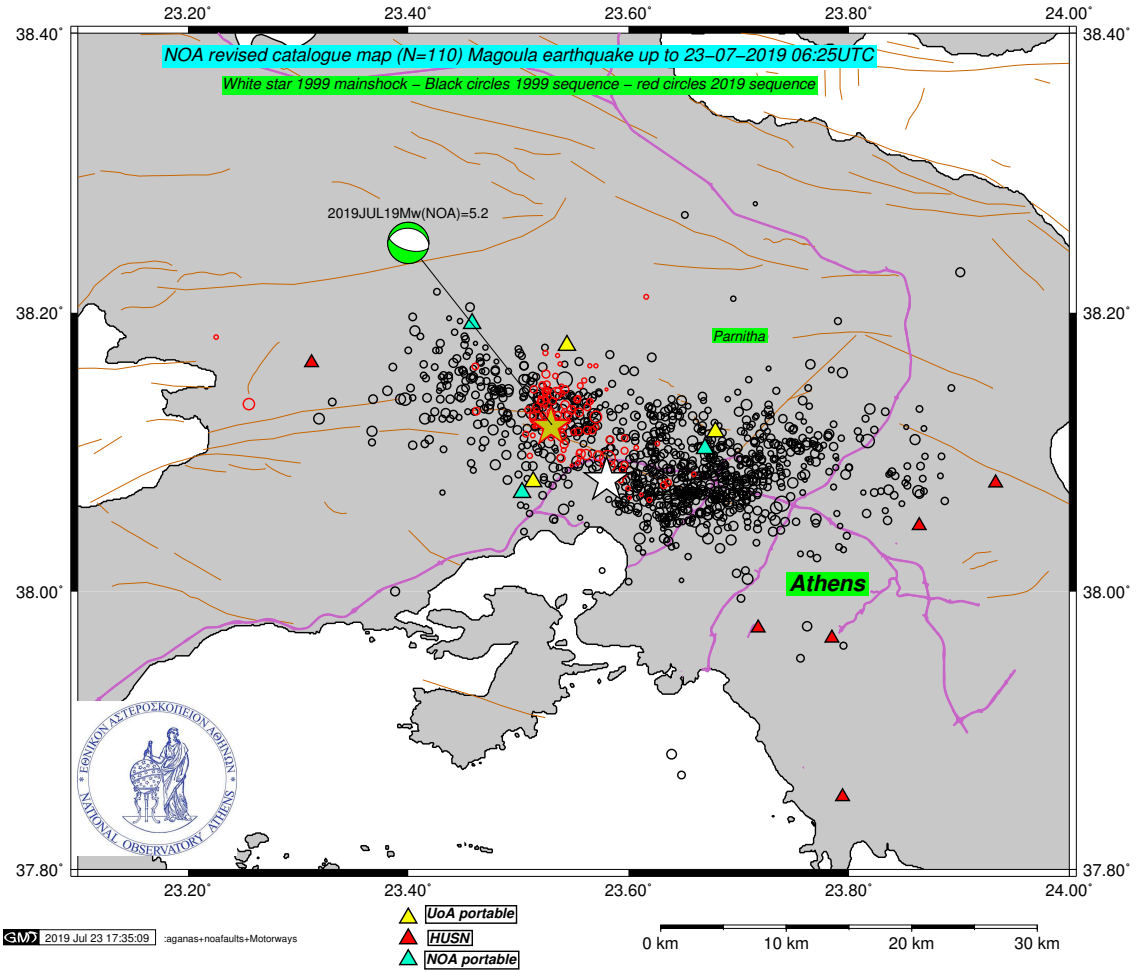


Figure 6. Aftershocks distributions of the 2019 and 1999 Athens earthquakes

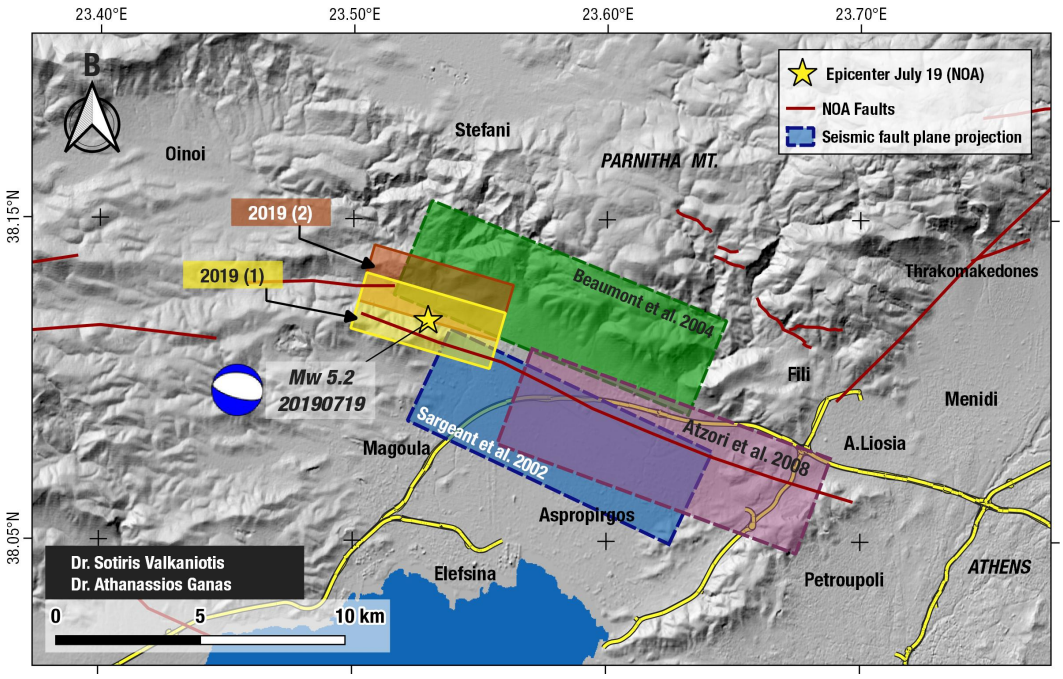


Figure 7. Seismic fault plane surface projections solutions for the 2019 and 1999 Athens earthquakes

6. Real-time shaking maps

According to the preliminary report of EPPO-ITSAK, the highest Peak Ground Acceleration (PGA) was recorded at Moschato accelerometric station equal to 165cm/s^2. In Peristeri station 135 cm/s^2 and in Kifissia station around 50cm/s^2 were recorded. Available shaking maps were issued from the Geodynamic Institute of National Observatory of Athens (https://accelnet.gein.noa.gr/shakemaps/), the EPPO-ITSAK (http://shakemaps.itsak.gr/) and the National and Kapodistrian University of Athens-NKUA (http://macroseismology.geol.uoa.gr/realtime/). In Figure 8, the PGA distribution and PGR of NKUA is presented, based on five Ground Motion Prediction Equations available for Greece (Sakkas et al. 2019). Online html files at http://macroseismology.geol.uoa.gr/realtime/19-Jul-2019 11 13 16 (GMT) 22.9 km NW of Athens 38.1265N 23.5453E 8km M 5.1.html/.

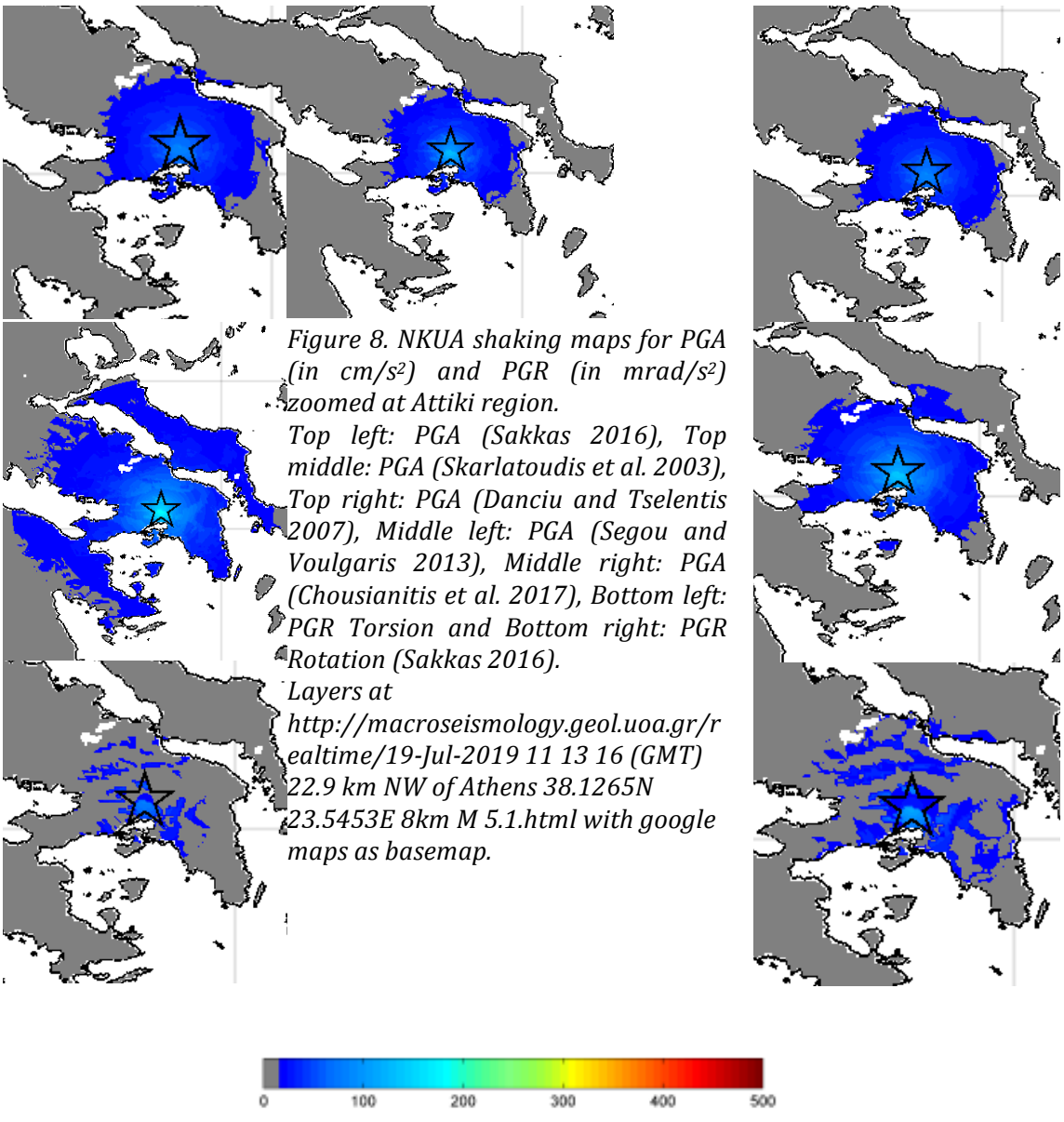


Figure 8. NKUA shaking maps for PGA (in cm/s^2) and PGR (in mrad/s^2) zoomed at Attiki region. Top left: PGA (Sakkas 2016), Top middle: PGA (Skarlatoudis et al. 2003), Top right: PGA (Danciu and Tselentis 2007), Middle left: PGA (Segou and Voulgaris 2013), Middle right: PGA (Chousianitis et al. 2017), Bottom left: PGR Torsion and Bottom right: PGR Rotation (Sakkas 2016). Layers at http://macroseismology.geol.uoa.gr/realtime/19-Jul-2019 11 13 16 (GMT) 22.9 km NW of Athens 38.1265N 23.5453E 8km M 5.1.html with google maps as basemap.

7. Comments

EMS-98 intensity values are preliminary estimations at the affected localities.

The general observation of intensity distribution for the Athens 2019 earthquake is that the heaviest damage and, consequently, highest intensities are observed to the east and southeast of the earthquake epicentre. This fact may be attributed to local soil conditions and directivity effects (Papadimitriou et al. 2002). This was also observed during the 1999 M6.0 earthquake with intensity values of 8 and 9 inside the Athens basin, while intensities near the epicentre were 7 (Papadopoulos et al. 2004).

Acknowledgements

Figure 7 was prepared using the Generic Mapping Tool (GMT) software by Wessel et al. (2013).

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