Turkish Journal of Earth Sciences

http://journals.tubitak.gov.tr/earth/

Research Article

Turkish J Earth Sci
(2021) 30: 851-861
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doi:10.3906/yer-2110-6

Recent earthquake activity of March 2021 in northern Thessaly unlocks new scepticism on Faults

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Received: 11.10.2021 • **Accepted/Published Online:** 24.10.2021 • **Final Version:** 30.10.2021

Abstract: This short opinion article presents and highlights new and old problems related to active geological faults, as seismic sources, after the experience of the last March 3 and 4, 2021 (M_w6.3 and M_w6.0, respectively) Tyrnavos-Elassona earthquakes in northern Thessaly, Greece. Although the active faults in the area are very well studied, demonstrating typical geomorphic features that intensely affect the morphological relief, it seems that the earthquakes were produced by unknown faults emerging in the mountainous area (alpine basement). Primary (?) coseismic ruptures, however, were also observed northwards along the Titarissios valley. A geological interpretation of the faulting mechanism is also proposed. The existence of a new unknown source in an intermontane area is problematic. The role of inherited alpine structures seems more important today than in the past. The strike of the two new seismogenic sources, responsible for the two strongest events of the 2021 earthquake succession, differs from the previously known active faults. This forces us to reconsider older views on the direction of development of active faults and the orientation of the stress field. Concerns are being raised about how new structures can be detected and their role in seismic hazard assessment, especially when located near or within the urban fabric, in cities that are now constantly expanding and being established in new, often loose soils.

Key words: Seismotectonics, northern Thessaly earthquake, detachment fault, hidden faults

1. Introduction

On March 3 and 4, 2021, two strong earthquakes of M_w6.3 and M_w6.0, respectively, struck the area near Tyrnavos and Elassona in northeastern Thessaly, central Greece (Figures 1 and 2), followed by many aftershocks, few of which being above M_L5.0, jolting the population that lives across much of the Larissa plain. The epicentre of the mainshock lies about 15 km to the northwest of the city of Larissa, 7 km west of the town of Tyrnavos and 15 km south of town of Elassona (Figure 2). The Tyrnavos fault, i.e. the closest fault to the mainshock, is known from various investigations, such as morphotectonic mapping, palaeoseismological research, geophysical surveys and satellite image analysis (Caputo et al., 2004, 2006; Tsodoulos et al., 2016). According to the palaeoseimological investigations, the fault is associated with previous strong earthquakes. Similar to this fault, northern Thessaly is dominated by E-W- to WNW-ESE-trending (typical strike N110°S) active faults and NNW-SSE older neotectonic structures that shape the Thessalian plains and many valleys. Based on this fault pattern, the whole region can be characterised as a large-scale, "normal" fault system.

The M_w6.3 earthquake on March 3rd, 2021, that occurred in the Greek mainland, in the central part of the broader Aegean geodynamic context (Figures 1 and 2), was among the strongest recorded earthquakes in northern Thessaly. There is rare significant seismic activity during the 19th and early 20th century. Previous strong earthquakes are known mostly during the historical period (Figure 2a; Papazachos and Papazachou, 2003) which include many errors of location and/or magnitude (or they sometimes can be rather dubious). One strong earthquake was recorded prior to the 2021 sequence in March 1941 M_s 6.3 near Larissa (Figure 2a; Papazachos and Papazachou, 2003). The following strongest shock (M_w6.0) one day later occurred ca. 10 km WNW of the first one (Figure 2). They both were extensional faulting earthquakes produced by two adjacent NW-SE-striking, NE-dipping faults. The NE-SW oriented extension of the *P*-axis that was revealed by the moment tensor solutions of this sequence (Figure 2b) is incompatible with the roughly N-S orientation deduced by geological evidence of the other nearby, previously known, active faults (Figures 2a and 3b; e.g. Caputo and Pavlides, 1993). Both shocks were followed by intense aftershock

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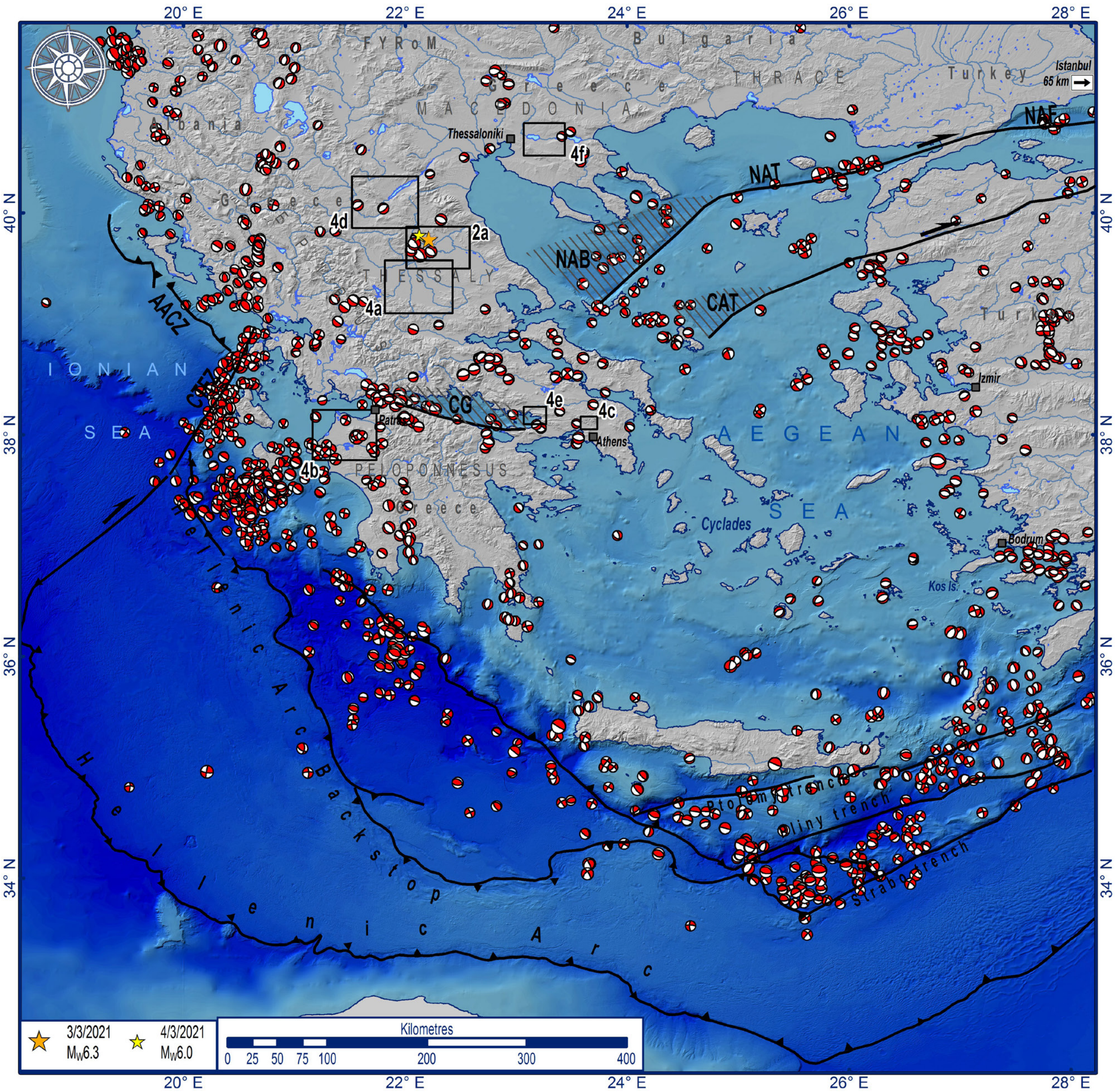

Figure 1. The major lithospheric-scale tectonic structures of the broader Aegean (after Barka and Kadinsky-Cade, 1988; Lallemant et al., 1994; Poulos et al., 1999; Şengör et al., 2005; Makris and Papoulia, 2012; Özbakır et al., 2013; Sakellariou et al., 2016). Abbreviations: AACZ = Apulia-Aegean Collision Zone, CTFZ = Cephalonia Transfer Fault Zone, CG = Corinth Gulf, NAF = North Anatolian Fault, NAT = North Aegean Trough, NAB = North Aegean Basin, CAT = Central Aegean Trough. Frames correspond to the map insets of Figures 2 and 5. The stars correspond to the two strong shocks of the 2021 sequence in northern Thessaly (as in Figure 2). Moment tensor solutions from RCMT catalogue (Pondrelli, 2002) for depths ≤ 40 km (crustal events).

activity, the spatiotemporal evolution of which showed the rupturing of two adjacent but induvial faults or segments. Joint analysis of seismic, SAR Interferometry, field geological and geodetic data for the spatial and temporal evolution of the mainshock rupture process revealed the main slip zone (Chatzipetros et al., 2021; Karakostas et al., 2021). The seismogenic sources are believed to be normal, unknown hidden faults within the crystalline Paleozoic basement of the Pelagonian geotectonic zone (Figure 2c), named Zarko blind fault.

Additionally, researchers have known that seismic waves are strongly amplified in deep sedimentary basins like those in the Larissa plain, the largest in Greece. This work, among others, also uncovers novel details

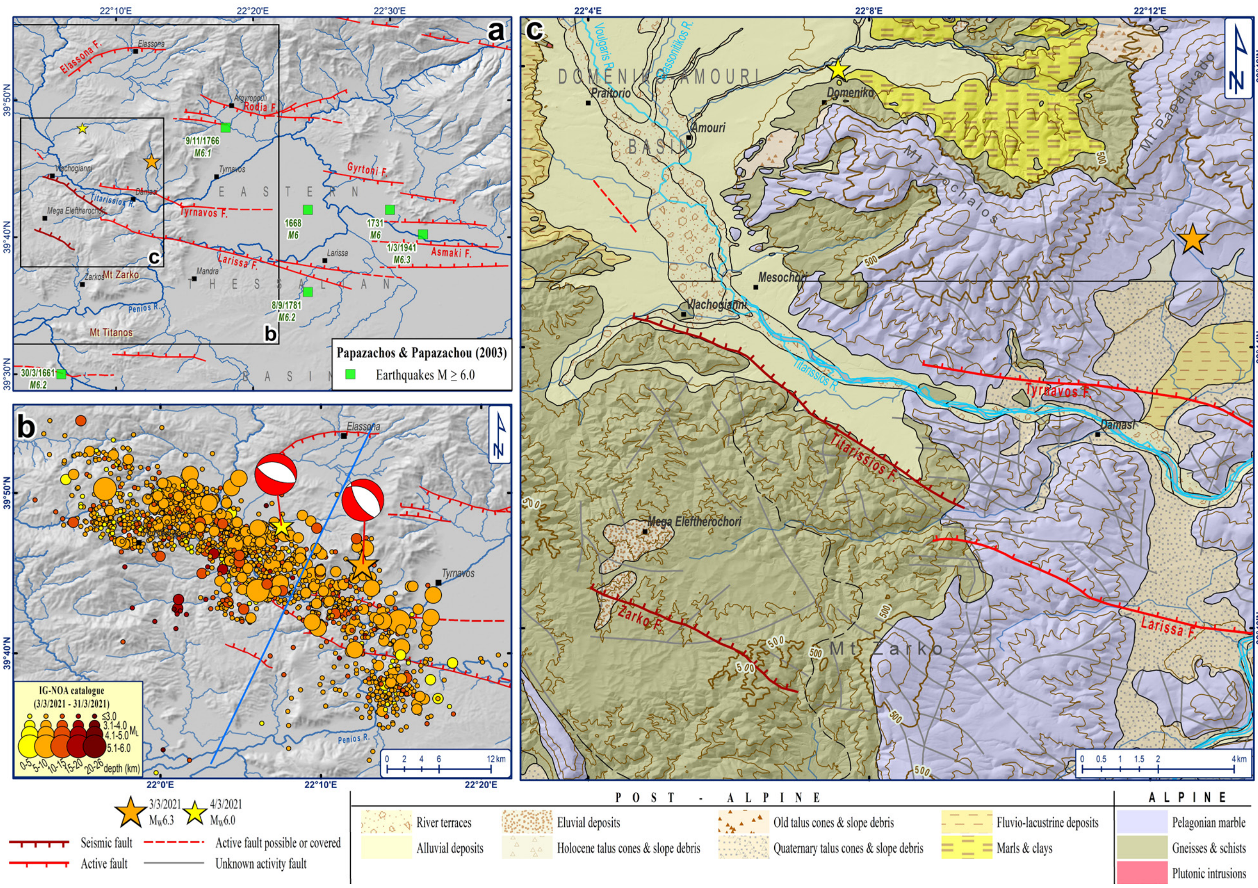

Figure 2. (a) The broader epicentral area of the Eastern Thessalian Basin with the major active tectonic features and the strong historically and instrumentally recorded earthquakes. Frames refer to insets. (b) Hypocentral distribution of the 2021 Tyrnavos-Elassona seismic sequence (IG-NOA's catalogue). Moment tensor solutions are also from IG-NOA. Blue line represents the profile path of Figure 4. (c) Geological map of the epicentral area (IGME, 1987; 1998). The old tectonic structures are delineated with light gray colour.

about the relationship between basin structure, covered by young sediments, as well as unknown faults and ground motion, which is useful for site-specific hazard assessments, because most of the population lives on plains near the side of the fault zones. The March 2021 earthquakes generated numerous secondary phenomena with vast areas of alluvial deposits, mainly along the river valleys, exhibiting spectacular liquefaction features. In this study, we refer to the faulting process of the 2021 North Thessaly earthquake, examining the mainshock's effect on the surrounding faults and their role in seismic hazard assessment (SHA).

2. Tectonic and geodynamic history

The earthquake area of northern Thessaly consists of crystalline rocks and metamorphosed Paleozoic and possibly pre-Paleozoic rocks of the Pelagonian zone, which are unconformably overlain by younger lacustrine and fluvial Neogene and Quaternary deposits (Figure 2c). The final configuration of the basement is an aggregate of multiple deformation phases. It has a more complex picture of tectonic deformation, as several tectonic events have affected its rocks (Kilias, 1995; Chatzipetros et al., 2021).

The latest alpine process that characterises the western part of the broader study area is the formation of the Cenozoic (Late Eocene to Late Miocene) Meso-Hellenic Trough (or Basin), a piggy-back basin developed during the eastward subduction of the external zones (e.g., Godfriaux, 1970; Doutsos et al., 1994; Ferrière et al., 2004; 2011; Kilias et al., 2015), or a strike-slip half-graben (Zelilidis et al., 2002), or a pull-apart basin (Vamvaka et al., 2006). The local NE-SW oriented extension of the trough is associated with NW-SE-trending, either normal or strike-slip faulting, not only along the trough's margins, but within its inner part as well (e.g., Ferrière et al., 2004; 2011; Vamvaka et al., 2006; Kilias et al., 2015).

Inherited structures in the relatively shallow and weak volume correspond to the suture zone between Internal and External Hellenides orogens (Kilias, 1995; Tolomei et al., 2021). The resulting cratons are relatively strong, but the remnants of ancient plate boundaries, as well as sutures and associated faults tend to be weaker. Since Middle Miocene, the earthquake broader area is being deformed under an extensional stress field (Figure 3). According to today's dominant knowledge, the extensional tectonic deformation occurred with two main phases: the first since the Late Miocene – Pliocene, until the Early Pleistocene, when the new plains were deformed, the extensional stress field (σ_3) had a NE–SW direction, causing the deformation of large normal fault zones of NW–SE strike (Figure 3a). These zones mark the eastern and western margins of Larisa plain.

Since the Middle Pleistocene, the geodynamics of the Aegean Region have been abruptly changed, with this change being characterised by a roughly longitudinal stretching direction. So, the second extension direction (σ_3) switched slightly to NNE–SSW, causing the formation during the middle to late Quaternary of younger faults of WNW–ESE strike (Figures 2a and 3). These faults define the northern margin of Larisa plain and formed long, complex grabens throughout central and northern Greece.

Typical active faults, based on geological criteria, are dipping to SSW, such as the Rodia and Gyrtoni faults, and they are generally delineating the boundary between the marginal formations to the north and the Larisa plain to the south (Figure 2a). Faults dipping to N and NNW, such as Tyrnavos, Larisa and Asmaki are antithetic to the abovementioned ones (Figure 2a). They are considered secondary structures in relation to the ones marking the northern Larisa plain boundary. Especially the Larissa fault is longer, possibly associated to the northwestern Titarissios fault, which runs along the southern slope of Titarissios valley, separating the alpine basement from the alluvial deposits (Figure 2c). Along the southern part of the Titarissios valley and near the southwestern margin of the Domeniko-Amouri basin, a buried fault system displacing Lower Pleistocene sediments has been tectonostratigraphically interpreted from a lignite-deposits investigation (Dimitriou and Giakoupis, 1998, after Galanakis et al., 2021). All aforementioned faults are of particular interest as they are considered active and are closer to the large population centres of the area, increasing thus the seismic hazard.

Palaeoseismological studies in the area (Caputo et al., 2004, 2006; Tsodoulos et al., 2016) showed that there are several faults of low slip rate (up to 0.2 mm/year) and surface displacement of ca. 20–40 cm per event. Despite being slow faults (i.e. associated with long recurrence interval), they pose a significant risk due to the fact that they can produce events of up to approximately M6.5, based on their geological, geometrical and palaeoseismological

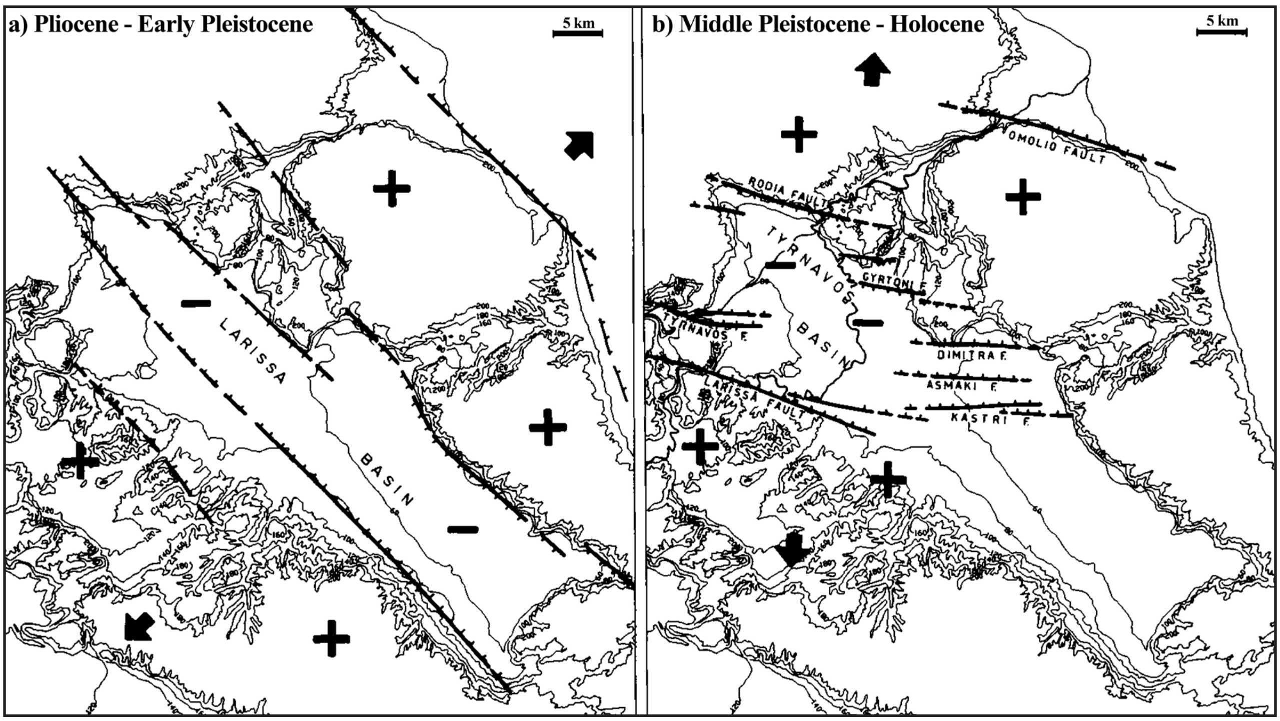

Figure 3. Simplified structural map of eastern Thessaly showing the major normal faults activated during the Pliocene-Lower Pleistocene (a) and Middle Pleistocene – Holocene (b) extensional regime. Arrows point the direction of the extensional stress field. "+" and "-" signs represent uplifted and depressed areas. After Caputo et al. (1994).

characteristics. A similar study about the slow-rate Milesi fault near the city of Athens was performed by Grützner et al. (2016).

3. The 2021 Tyrnavos-Elassona earthquake sequence

The seismic sequence that affected northern Thessaly in March 2021 perfectly reflects the above structural and seismotectonic complexities as far as the preliminary available focal mechanisms indicate nodal planes ranging between WNW-ESE and NW-SE.

According to Koukouvelas et al. (2021), the main shock may have initiated onto a fault segment laying to the continuation of Larissa fault and subparallel to the Tyrnavos fault segment (i.e. the prolongation of Titarissios fault). The lack of surface ruptures along with the characteristics of the aftershock distribution suggest a complex interplay between known active faults with surface expressions and unknown faults with lack of surface expression.

The results and conclusions of Ganas et al. (2021) indicate that the March 3rd, 2021 (M_w6.3) rupture occurred on a NE-dipping, intermediate-angle normal fault. The event of March 4th, 2021 (M_w6.0) occurred northwest along another WNW-ESE oriented fault. Nevertheless, seismic ruptures with lateral displacement were found in the field, in agreement with the modelled faults as blind structures.

Galanakis et al. (2021) documented a series of primary (?) ground ruptures accompanied by extensive liquefaction phenomena in the Titarissios valley, roughly parallel to the river, and aligned along the buried faults detected from the borehole interpretation of Dimitriou and Giakoupis (1998).

On the other hand, the interferometric analyses (Pavlides et al., 2021; Chatzipetros et al., 2021; Galanakis et al., 2021; Ganas et al., 2021; Karakostas et al., 2021 and Tolomei et al., 2021) suggest that the activation of a NW-SE trending, approximately 20 km long normal fault (i.e. the Zarko fault) for the March 3rd, 2021 (M_w6.3) mainshock seismogenic source lies further to the south within the basement crystalline rocks. Based also on a joint analysis with seismological data and field observations, the causative Zarko fault is deemed to be a NW-SE trending and NE-dipping at a relatively moderate angle (approximately 35° to 36°). Small surface ruptures reactivated on older alpine faults have been measured with an average dip angle of 50° (Chatzipetros et al., 2021). Its dip angle is in good agreement with the attitudes of bedrock detachment faults that were caused by the collapse of the Pelagonian orogen (Chatzipetros et al., 2021). A possible deeper ramp-flat geometry of the detachment faults is considered. This is of particular importance, as it is a nontypical behaviour of an older, inherited alpine structure with no surface expression (Karakostas et al., 2021; Chatzipetros et al., 2021). The second and third events occurred within the NW extension segment of the same fault zone. The 2021 doublet ruptured previously unmapped fault segments with the majority of slip in the two main shocks.

4. More questions, fewer answers

Each earthquake with its peculiarities adds new data, experience and concerns in our knowledge. The March 2021 Tyrnavos-Elassona earthquake sequence in central Greece raises significant new problems in dealing with seismic risk, concerning fault as seismogenic source (Chatzipetros et al., 2021). Although there is little evidence for historic seismicity along the minor faults or fault segments that turned up capable of hosting damaging (M_w ≥ 6.0) earthquakes, they exhibit a similar faulting style along with the neighbouring mapped faults in Thessaly plain and surroundings. They appear rupturing members of a fault system that bounds the western margin of the eastern Thessaly basin, composing an extensional fault population alike in other areas in back arc Aegean region (Karakostas et al., 2021).

The small earthquakes indicate the presence of preexisting faults and weak zones susceptible to rupture. This seismic effect signifies that Mw ≥ 6.0 earthquakes can occur on relatively minor fault systems throughout the Greek territory and that often these minor fault zones have not been well identified. As the crust responds to the stress accumulation imposed by the surrounding plates motion, like the Aegean broader region, intraplate deformation occurs and is focused in these minor weak zones. Additionally, one more conclusion is that earthquakes of this magnitude can cause substantial ground motions, especially in plains with young and soft sediments, resulting in significant damage to constructions that were not built according to the current building code standards (Karakostas et al., 2021).

This earthquake raises new concerns and challenges, revising some established views, such as the status of active stress trends, the direction of active tectonic structures, the existence of a seismogenic fault in a mountainous volume of crystalline rocks without typical geomorphological expression or minor fault systems and the role of blind faults to Seismic Hazard Assessment.

4.1. Is the 2021 earthquake sequence related to a detachment fault?

According to the published data about the 2021 northern Thessaly seismic sequence, it is obvious that two sets of primary coseismic ground deformation phenomena occurred: the northern one follows the geomorphological path of the Titarissios valley with the NW-SE-striking, NE-dipping ruptures within the valley's fillings; the southern one is detected in the intermontane gneiss and schist alpine basement, which is also supported by the published interferometric images. Then the following question arises: how do these two sets connect to each other?

The most rationale hypothesis is the occurrence of a low-angle detachment fault lying at depth with a NE dip direction. The northern set of ruptures represents a vertical, upward splay of the detachment. The southern set could be either a splay or the frontal exposure of the detachment. This setting is not met for the first time in Greece. Aftershock distributions of the 1995 Kozani-Grevena earthquake depicted two parallel synthetic splays, one the Paleochori fault to the north, the rupture of which emerged on the surface, and the shallower-dipping Deskati fault to the south, whose rupture was constrained at depth (Chiarabba and Selvaggi, 1997; Hatzfeld et al., 1997). It is worth mentioning that there was a third partially reactivated fault, an inherited old E-W-striking strike-slip fault that slipped as an antithetic normal structure. The other example is the well-known and well-studied Corinth Gulf, where a deep, ca. N-dipping low-angle detachment fault branches into several parallel steeper faults towards the surface with simultaneous activity (Rigo et al., 1996; Hatzfeld et al., 2000).

The recent sequence of Tyrnavos-Elassona possibly imitated the two above cases, using two slip paths along two branches: the largest amount of slip followed a southern branch, or the prolongation of the deeper low-angle fault towards the surface, causing the small surface displacements within the gneiss and schist and the distinctive maximum deformation in the InSAR images (Figure 4). A small amount of slip possibly took a different path, through steeper faults, such as the ones discovered by Dimitriou and Giakoupis (1998), creating the systematic NW-SE-striking ground fissures (secondary surface rupture as named by DePolo et al., 1991) and producing the extensive damages in the nearby constructions.

4.2. Other 'surprising' earthquakes in mainland Greece

Much to the surprise of many, the phenomenon of activation in an earthquake or a seismic sequence of two different directions has been observed in southern Thessaly (Karditsa-Sophades earthquake of 1954, M_S7.0), as well as other areas of the Greek mainland, such as the 1978, Thessaloniki M_S6.5, and the 1981, Kaparelli M_S6.4 events (see Pavlides, 1993) (Figure 5). From the perspective of unmapped activated faults, the May 13th, 1995, Kozani-Grevena M_w6.6, the September 7th, 1999, Athens M_w5.9, and the June 8th, 2008, Andravida-Movri M_w6.4 earthquakes (Figure 5) were unexpected events produced by previously unknown faults. Concerning the latter, the element of surprise is not constrained only to the lack of any historic rupturing evidence; it is also its NE-SW-striking, right-lateral strike-slip rupturing mechanism, as determined by focal mechanisms and several minor, secondary ground fissures (synthetic, antithetic, Riedel shears), which emplaces a large shear zone between the almost N-S oriented extensional stress field of the Gulf of Corinth to the east and the roughly E-W oriented compressional stress field of the Hellenic Arc to the west. With the rupture never reaching the surface (blind faulting), the 2008 Andravida-Movri earthquake left no morphological marks on the already subdued relief. Taking into account that even if a past earthquake reached the surface, the horizontal slip of the fault could only have created negligible deformation susceptible to erosion. This means that this particular fault can only be indirectly detected and mapped by high-resolution, good quality geophysical data in combination with geological interpretation. A similar case is the 1995 Kozani earthquake which ruptured within a subdued relief with no particular geomorphic marks, in contrast with the adjacent Servia fault, bearing a well-formed tectonic scarp with polished free-faces on Mesozoic limestone with slickenlines, which demonstrated no slip. The 1995 rupture preferred a less prominent path than the well imposed Servia fault. These complexities, combined with a lack of

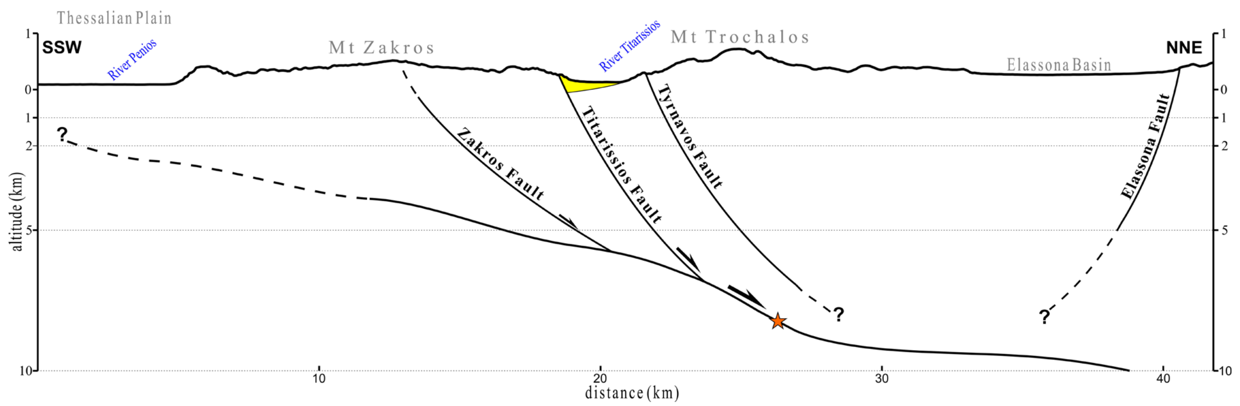

Figure 4. Schematic explanatory profile (see Figure 2b for path) crossing the major seismic (Zarko and Titarissios) and active (Tyrnavos and Elassona) faults (modified after Chatzipetros et al., 2021). The scale is 1:1 for depths below 0 and 2:1 for altitudes above 0 (exaggerated). The emergence of the detachment is unknown. The dashed fault line of Zarko fault implies that the fault remained hidden without forming any distinctive relief (see main text for discussion). The red star is the hypocentre of the mainshock projected on the profile.

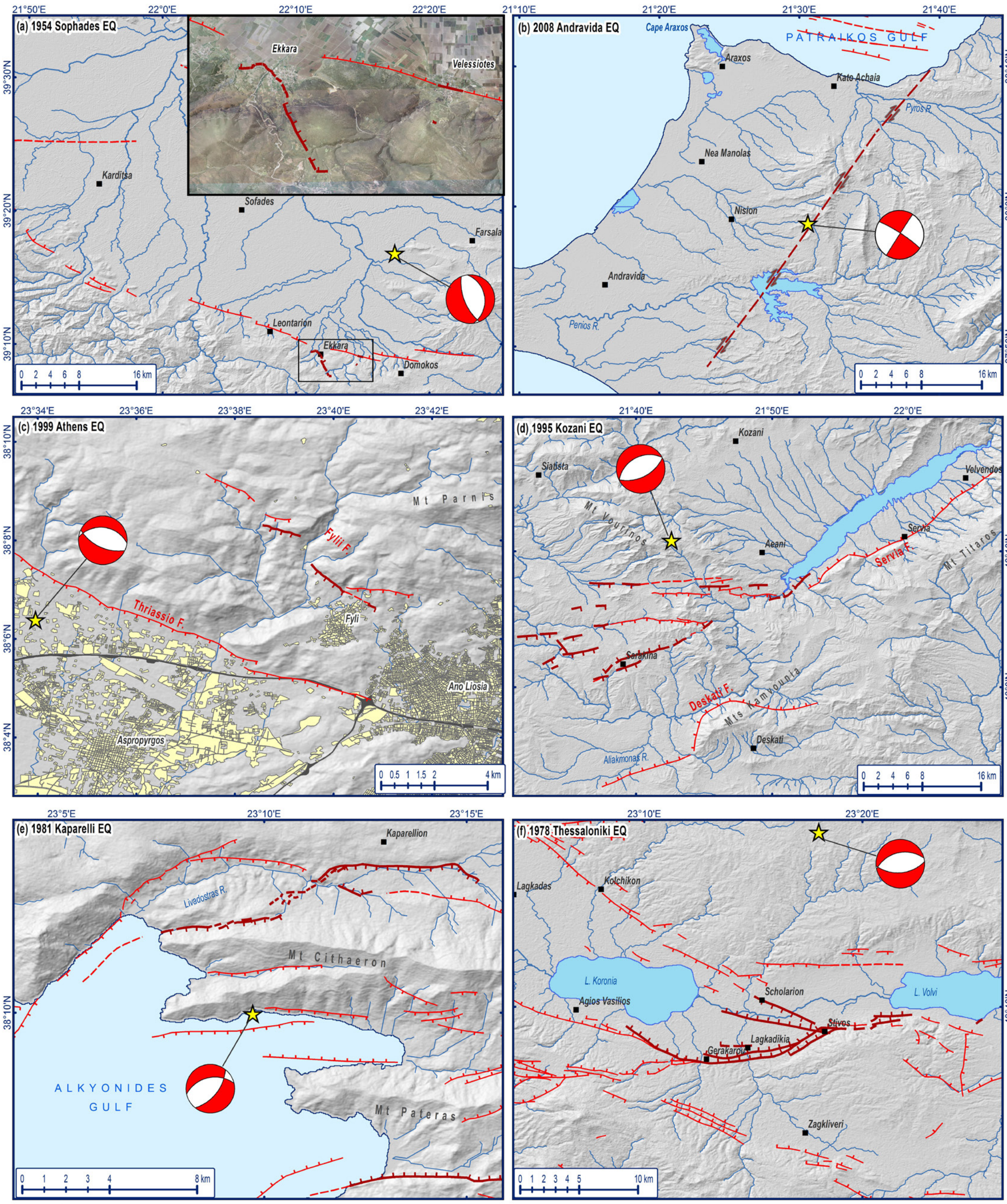

Figure 5. Seismotectonic maps of the earthquakes discussed in the text (the position of each map inset is shown in Figure 1). (a) The April 30th, 1954, Sophades earthquake showed coseismic ruptures (inset from the Hellenic Cadastral photomosaic) in a more NW-SE direction (Papastamatiou and Mouyiaris, 1986; Pavlides, 1993; Palyvos et al., 2010) than the E-W-striking srecognised faults in the area. (b) The 'blind', pure strike-slip, NE-SW-striking fault that produced the June 8th, 2008 Andravida-Movri earthquake. (c) The September 7th, 1999, Athens earthquake occurred by a previously unknown fault and had a minor surficial rupturing. Due to its proximity to the metropolitan city of Athens (the urban fabric is shown with yellowish polygons), the damages were rather significant. (d) A complex ground rupture pattern after the May 13th, 1995, Kozani-Grevena earthquake which was also associated with partial reactivation of adjacent faults. (e) The March 4th, 1981, Kaparelli earthquake was the 3rd strongest shock of the Alkyonides sequence. The coseismic ruptures did not remain along a straight line but followed different paths due to local geological conditions. (f) The complex coseismic rupture pattern of the June 20th, 1978, Thessaloniki earthquake and its connection with the NW-SE-trending alpine structures. Earthquake epicentres: (a) Papazachos and Papazachou (1993), (b, d, f) IG-NOA catalogue, (c) Papadimitriou et al. (2002), (e) Jackson et al. (1982). Focal mechanisms: (a) McKenzie (1972), (b) Regional Centroid Moment Tensor (RCMT) catalogue (Pondrelli, 2002), (c) Louvari and Kiratzi (2001), (d) Kiratzi and Louvari (2003), (e) Ekstrom and England (1989) and EMMA catalogue (Vannucci and Gasperini, 2004), (f) Braunmiller and Nabelek (1996). Fault symbols as in Figure 2.

geological and seismic data close to the source, make it challenging for scientists to pinpoint the finer details of the radiated seismic energy.

It is worth mentioning that the seismic history in some of the case study areas (Kozani, Athens and probably Andravida) is not always adequate for estimating the seismic hazard. In more particular, the Kozani broader area was considered as rigid aseismic block or low seismicity region (Voidomatis, 1989; Papazachos, 1990), and the broader area of the metropolitan city of Athens was also considered as one of low seismic activity, given that important historical or instrumental seismic records were missing (Papadimitriou et al., 2002; Pavlides et al., 2002). The importance of the methodology and sources of information used for assessing seismic hazard is quantified and well discussed by Caputo et al. (2015).

Identifying the weak zones and the associated earthquake patterns is one of the goals of current and future seismic deployments. The goal of future attempts is to generate improved 3D images of the faults beneath the surface, especially those without surficial features and geomorphic marks. High resolution geophysical tomographies (data) are needed. With a denser array of seismic sensors, new research could also more accurately locate future earthquakes, which will help scientists determine the hazard in specific regions. It is such an important issue for geoscientists and engineers, to know what we are up against to, and to model what could happen if we do have to face a strong earthquake.

Additionally, there are hidden active faults that lie very close or within a broad distributed zone throughout towns and cities like Larissa or megacities like Athens (earthquake of 1999), İzmir, İstanbul and most cities along the North Anatolia Fault segments, where is potential for ground displacements beneath the downtown corridor where high-rise buildings either have been or will be constructed in the future.

The recent earthquake's proximity to, sometimes densely, inhabited areas, like the 2017 Kos-Bodrum M_w6.4 earthquake, occurred offshore between the Kos Island in Greece and Bodrum town on the Turkish coast (e.g., Karasözen et al., 2018; Sboras et al., 2020), the 2020 Samos M_w7.0 earthquake, occurred again offshore and caused extensive damage in İzmir (e.g., Akinci et al., 2021; Sboras et al., this volume), and the 2021, Tyrnavos-Elassona M_w6.3 earthquake, just 15 km away from Larissa with major impact in local villages, are extremely valuable for the seismic hazard community. All these recently emerging data can be a crucial input in active fault databases aiming at contributing to the SHA, to simulate the ground motions and consequently enhance the building codes. Using this experience and knowledge, the scientific community can be more suspicious and develop further multidisciplinary investigations, the engineers can improve new building designs and fortify the old constructions, and the state (in terms of administration, security corps and public services) with the citizens and can be better prepared for a new seismic crisis.

5. Concluding remarks

The experience of the March 2021 Tyrnavos-Elassona earthquake sequence, added to the knowledge of past surprising events and combined with the ever-increasing new knowledge from the scientific community worldwide, rose new problems that require rational answers, such as:

When and how do old, nonpreferably oriented to the modern stress field, faults rupture? How does rupture propagate, both horizontally and upwards, and how does it affect adjacent new, or old, faults (triggering effects on inherited structures)? How is the morphology affected, or in other words, when do normal faults occur along the margins of obvious geomorphological depressions (e.g., basins, valleys, etc.) and when do they occur in unexpected locations (e.g., mountainous areas)? Which are the best stand-alone or combined methods for detecting and recognising faults that are well hidden, either by natural processes or human interventions?

Any answer to any of the above questions can crucially contribute to a twofold hazard estimation: the ground motion simulation as deduced from deterministic seismic hazard assessment (DSHA), and the surface faulting hazard (Guerrieri et al., 2015) or surface fault rupture hazard (Boncio et al., 2012), a crucial assessment for building and infrastructure design considering that a possible fault displacement could damage the foundations of any technical construction. The estimation of both types of hazards is vital for places where the risk is high, such as critical facilities and/or urban areas. Hence, a special attention is needed to be given (i) on the role of inherited structures in seismogenesis deviating from standard rules, especially blind faults in mountains without any morphotectonic feature, and (ii) on the unknown hidden active faults and their role in SHA, especially close or under the modern urban areas and along lifelines.

New methodologies and scientific tools are needed to identify the weak zones and the associated earthquake patterns.

Acknowledgements

We would like to thank guest editor Hasan Sözbilir for his well-intended fruitful comments, as well as the two anonymous reviewers who greatly enhanced the manuscript. Editor Orhan Tatar is also thanked for his moral support during the fast-track preparation of this paper.

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