An Adriatic thrust fault of the 2021 seismic sequence estimated from precise earthquake locations with sP depth phases

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Key points

- Location of 70 M>=2.9 earthquakes the Italy-Croatia off-shore 2021 seismic sequence with sP converted phases.
- The use of sP converted phases in locating events strongly constrains depth of off-network earthquakes.
- High precision of the fault geometry with important implications on the Adriatic seismotectonics and hazard.

Abstract

An earthquake sequence occurred in the Central Adriatic region during March-June 2021. The sequence started on March 27 with a mainshock of Mw 5.2 at 13:47 UTC. No foreshock was observed before the mainshock. The sequence lasted about three months until the end of June 2021. About 200 seismic events were recorded by the regional seismic network, and 4 earthquakes have M⋝4.0. The March 27, 2021 earthquake is one of the strongest instrumental events that occurred in this area, bounded approximately by the Ancona-Zadar line to the north and the Gargano-Dubrovnik line to the south. The mainshock originated at a focal depth of 9.9 km. The seismicity spreads from the mainshock up-dip and down-dip along a NE dipping plane. Here we investigate the first−order geometry of the fault activated by this seismic sequence by using sP depth phases. We aim to significantly reduce the large uncertainty in hypocentral locations of the offshore earthquakes beneath the Adriatic Sea, an area that plays a fundamental role in geodynamics of the Mediterranean. The refined earthquake locations also allow us to make inferences on the seismotectonic context responsible for the seismicity, identifying this structure (here referred to as the Mid-Adriatic Fault, MAF) as a thrust fault NW-SE striking and ~45° NE-dipping. The use of depth-phase arrival times to constrain the off-network event locations is of particular interest to Italy due to both the peculiar shape of the peninsula and the extreme scarcity of seafloor stations whose cost and management are very expensive and complex. We present here the first attempt to apply this off-network location technique to the Italian off-shore seismicity with the aim of improving the hazard estimation of these hard-to-monitor regions.

Introduction

The Adriatic region is located in the Mediterranean Sea (Figure 1) that was part of the Tethyan margin during the Mesozoic times (Decourt et al., 1986; Dewey et al., 1989; Handy et al., 2010; Stampfli & Borel, 2002; Capitanio & Goes, 2006). The Adriatic microplate (D'Agostino, N. et al., 2008) is located between the

European and African major plates, and it has played a major role in the tectonic history of the central Mediterranean region. It is an NW-SE elongated continental block surrounded by the Alpine belt, the Dinaric-Hellenic systems, and the Apennines belt whose formation started after the continental collision between the European and African plates during ~40 Ma to ~30 Ma ago (e.g., Handy et al., 2010; Coward & Dietrich, 1989; Dal Piaz, 2001; Pfiffner, 2014; Schmid et al., 2004; Trümpy, 1960).

Many researchers assume that Adria moved as a single block, whereas other researchers, on the basis of seismic and geodetic investigations, suggest that it may have fragmented into two blocks that are currently rotating with respect to each other (Le Breton et al., 2016 and references therein). Indeed, seismic reflection profiling, GPS velocities and diffuse seismicity in the central area have been interpreted as evidence for the fragmentation of the Adriatic plate, with the northern part rotating independently from the southern part (D'Agostino et al., 2008; Sani et al., 2016), suggesting the complex structural setting of this region.

The seismicity in the central Adriatic Sea has been recorded by the improving seismic network, especially in recent decades. Nevertheless, the precise location of the Adriatic off-shore earthquakes was hampered in both historical and instrumental seismology times due to almost exclusive resentment along the coast with consequent poor documentation, and to the large gap in the distribution of seismic stations, respectively. Nevertheless, starting from the 1986-1990 seismic sequences (Console et al., 1993), the Adriatic region has been viewed from a different perspective, and investigation on its geodynamics had a new impulse. From the seismological point of view, however, the hypocenter location difficulty still remains.

The data reported in the current seismic catalogs, however, show remarkable seismic activity beneath the Adriatic Sea (Figure 1), with the mainshock magnitude comparable to those of the surrounding zones (ISIDe Working Group, 2007; Ivančić et al., 2018; CSEM/EMSC, Bossu et al., 2008). Since 1985, the ISIDe catalog lists 6 seismic events with M>4.5 that occurred in the central Adriatic region (40 km off-shore), four of them belonging to the Jabuka 2003 seismic sequence (Herak et al., 2005), confirming that the seismic potential of this area is significantly higher than that assumed until some time ago. Improving the event location is thus mandatory to better understand the relationship between earthquakes and the tectonic setting of this area.

The *sP* depth phases enable us to estimate more accurately the focal depths of these earthquakes with respect to only using P and S wave arrivals, even if their locations are outside of a seismic network (Umino et al., 1995; Zhao et al., 2002, 2007). For example, Umino et al. (1995) refined hypocentral locations of suboceanic events in the Tohoku forearc region using *sP* depth phase. As a result, they could show a more detailed double seismic zone in the Tohoku district. The definition of *sP* phase is as follows (e.g., Umino et al., 1995): "an upgoing S-wave that is subsequently reflected and converted to a P-wave at the top of the crust and finally reaches stations at the surface". Hence, due to the peculiar geometry of its ray path, a depth phase in earthquake location mimics the presence of a seismic station at the bouncing point on the local topography, more or less above the hypocenter (Zhao et al., 2002, 2007). The efficiency of the depth-phase arrival times in hypocenter locations resides in that the travel time difference between, for example, an *sP* phase and P-wave (sP − P time) mainly depends on the focal depth (Stein & Wiens, 1986; Umino et al., 1995) and on the seismic velocity structure. In the Adriatic area context, *sP* phases can hence give a strong contribution to improve the location of suboceanic events, therefore contributing to solving many existing controversies and open questions regarding present-day tectonics of the Adriatic region.

Seismotectonic setting of the Central Adriatic Sea

The Adriatic Sea is located in the Mediterranean region between the Italian and the Balkan peninsulas, and it is an elongated basin mostly shallow and semi-enclosed. The Southern Alpine, the Dinaric and the Apennine chains, the orogens surrounding the Adriatic basin, originated from the Cenozoic compressive regime following the extensional tectonics in the Triassic age of the Tethis. The Dinaric and Apennine fronts gradually migrated in a SW and a NE direction, respectively, toward the central axis of the Adriatic Sea (Channel et al., 1979). The Adriatic basin is over 800 km long and ~200 km wide (Figure 1) and can be divided into three areas, with increasing depth from the northwest to southeast, different topographic gradients and seismotectonics characteristics (Trincardi et al., 1996).

The northern Adriatic Sea, a shallow and flat shelf area, reaches an average bottom depth of ~35 m occupying the flooded seaward extension of the Po Plain representing the most extensive continental shelf of the entire Mediterranean Sea. It gently slopes down to ~100 m depth to a line between Pescara and Sibenik, where a slope leads to the central basin at depths of 140-150 m (Trincardi et al., 1996; van Straaten, 1970). The northern part of the basin is, by convention, bounded to the south by the transect approximately at 43.5°N.

The central Adriatic is up to 50 km wide. It shows an average depth of 130-150 m, but it is also characterized by the Mid-Adriatic Depression (MAD), which is a complex transverse depression, elongated in a NE-SW direction for ~125 km, between Sibenik (Croatia) and Pescara (Italy), reaching 240-270 m depths (see Figure 1). Seismic activity in the northern part is known for occurrences of relatively small earthquakes and occasional recording of moderate ones along the western coastline ($M < 5$).

Immediately to the south-east of the MAD, an alignment of structural highs (Mid-Adriatic Ridge, MAR, Finetti et al., 1987) extending to Palagruza, has been interpreted as the result of compressive tectonics of the external Apennines (Argnani & Frugoni, 1997; Scrocca, 2006, 2007) or Dinaric Chains (Finetti & Del Ben, 2005) or identified by some studies (Geletti et al., 2008; Grandic et al., 1997; Finetti & Del Ben, 2005) as a halo-kinetic structure deformation of the Burano sequence and of the older Triassic evaporites, connected to a regional compressive regime, which began in the pre-Pliocene. Some researchers (Argnani et al., 1991; Calamita et al., 2003) suggested that the compressive tectonics caused inversion of some pre-existing normal faults, while the contractional reactivation of pre-existing Mesozoic normal faults from the Paleogene along the Mid-Adriatic Ridge was suggested by Scisciani & Calamita (2009) and Gambini et al. (1997).

The central Adriatic Sea is separated from the southern area by a line, running from the Gargano Peninsula to the Croatian coast (the Gargano-Dubrovnik line). The southern area shows a wide depression of 1218 -1225 m deep.

According to the ISIDe Catalog (ISIDe Working Group, 2007), the Adriatic area exhibits moderate-to-strong seismicity (Figure 1). The central part is the most active of the Adriatic platform with $ML \geq 5.0$ events occurring in the last 30 years, suggesting that the seismic potential of the area is significantly higher than assumed in the past. Along the Central Adriatic coast, two main seismic sequences occurred. A first one occurred in 1987 with a Ml 5.0 characterized by a compressive fault solution. This was located very close to the Adriatic coast, in front of Porto San Giorgio (Riguzzi et al., 1989). A second one occurred in 2013, in the Conero offshore, with a Mw 4.9 mainshock also characterized by a compressive focal mechanism (http://terremoti.ingv.it/event/2367191). This was located at about 20 km from the city of Ancona. Regarding the Central Adriatic off-shore, the strongest earthquakes occurred in the open sea, with magnitudes up to

Mw5.4 belonging to the 2003 Jabuka seismic sequence, (Herak et al., 2005), the 1988 Palagruza seismic sequence, (Herak et al., 1996) and the 2021 seismic sequence analyzed in this paper. The focal mechanisms of these mainshocks, aligned along a NW-SE direction, are shown in Figure 1b.

The mainshock of the 2021 seismic sequence occurred about 20 km north of the Palagruza islands, 80 km from the Gargano promontory and about 40 km from the Croatian island of Lastovo. It was felt in many central-southern Italian regions, from Ancona to Foggia, and also in Central Dalmatia. Their epicenters lie in the open sea, about 100km to the SE of the 2003 Jabuka seismic sequence, and about 50 km to the NW of the 1988 Palagruza seismic sequence. Their hypocenters dip towards the northeast, similarly to the fault system identified on the available seismicity and reflection profiles in the area, placing the seismic sequence on the Dinaric front. The fault-plane solution of the mainshock based on the TDMT (Time Domain Moment Tensor) solution indicates faulting caused by a NE-SW directed tectonic pressure, on a reverse fault. The seismicity in the Croatian offshore near Jabuka Island should be linked to a NW-SE external thrust of the Dinaric Chain (Herak et al., 2005).

Data and Method

To analyze the seismic sequence in details, we selected 80 ML ≥ 2.9 earthquakes that occurred from 2021/03/27 to 2021/09/30, from the INGV catalog (http://terremoti.ingv.i) within 50 km around the epicenter of the mainshock (Mw 5.2) on March 27th 2021. We then downloaded the 3-component seismograms recorded at stations located within 300 km from the INGV bulletin hypocenter, by using the INGV EIDA node (Strollo et al., 2021 and references therein) INGV web services (http://terremoti.ingv.it/webservices_and_software). Finally, we visually analyzed the waveforms to identify P and S wave arrivals and at least one sP arrival.

While P and S wave arrivals are present in a waveform, either visible or not, the sP onset can be either not present at all or not trivial to discriminate with respect to other possible reflections. Nevertheless, previous studies (Umino & Hasegawa, 1994; Umino et al., 1995; Gamage et al., 2009; Zhao et al., 2002, 2011; Huang and Zhao, 2013a,b; Liu et al., 2013a,b) have defined important guidelines to detect the sP phases. We thus build a workflow from standard P- and S-onset pickings to final hypocenter relocations that includes the necessary steps to identify sP-onsets. The first part of this workflow is based on two key points: the sP phase is a conversion from an up-dip S wave to a downdip P wave and thus its signal is typically stronger on the vertical component; on a record section with waveforms aligned on the P onsets, the sP-P differential time is nearly a constant with small variations related to the 3-D Earth structure. This latter feature is due to the fact that the up-dip part of the S ray, from the hypocenter to the surface topography, only depends on the real focal depth, while the second part, the P-ray from the reflection point at the surface to the receiver, especially beyond 90-150 km distance, is close to that of the direct P-wave. Thus, the sP delay at these distances is almost only due to the focal depth. Hence our first step, after manually identifying P and S wave onsets, is to produce a vertical-component waveform stacks aligned on the P-onsets identifying a group of stations where a possible sP wavelet is visible at an almost constant delay time from the P-onset (see Figure S1). Then, among them we chose no more than the two best visible ones. This choice, discussed in Zhao et al. (2011), is important because even just a single sP strongly helps to constrain the focal depth when locating the earthquake. Hence, using less reliable sP onsets would only add noise to the inverse problem.

The third important feature is that the particle motion of an sP phase is quite similar to that of a P wave. We thus performed the particle motion analysis on the identified possible sP wavelets and removed from the set those not responding to this feature (see Figure S2). A further check is performed on the sP-P travel time difference, plotting their distance-arrival times position against theoretical P and sP dromocronas calculated with the Pyrocko/cake (Heimann et al., 2017) tool in a mean layered 1-D velocity model extracted from the more recent 3-D P and S-wave velocity model by Magnoni et al. (2022) (see Figure S3). This step is a redundant check of reliability for the identified sP phases.

Finally, we use the on-purpose designed code by Zhao et al. (2007, 2011). This code is able to compute theoretical travel times and ray paths of P-wave, S-wave, Pn-wave refracted at the Moho interface, and sP-wave in a 1-D or 3-D velocity model. To keep our first approach to the Adriatic earthquakes as simple as possible, and to cope with the small local scale, we preferred to use a 1-D mean local velocity model based on a high-resolution large-scale regional model. To model the P- and S- wave refraction at the Moho, we introduced the latest Moho topography by Di Stefano et al. (2011). Finally, the conversion at the surface is usually controlled by the sediment thickness. Also this feature is modeled by the code of Zhao et al. (2007, 2011). Nevertheless, the Adriatic region in this specific sub-region, where the seismic sequence object of this paper occurred, has very thin sediments. We thus used, in our first approach, a constant layer of 0.1 km thick and a P-wave velocity (Vp) of 1.8 km/s and Vs of 0.6 km/s in the whole region to model the sedimentary layer, as an approximation based on a previous study (Giustiniani et al., 2020). More detailed information might be added in the future.

Results

We relocated 70 earthquakes of the March 2021 seismic sequence, for which we were able to reliably identify at least one sP onset. Figure S4 shows statistics on the hypocentral location uncertainty and intrinsic quality. It is worth reminding here that we did not pick arrivals at stations from the Dinaric side networks even when they are available. This was done on purpose to benchmark the location method against the "large" gap conditions for which it was designed and it is reflected by the gap distribution histogram reporting azimuthal gap >= 240°. Also, the distribution of the distance to the first station from the final epicenter is a consequence of its off-shore (off-network) position, leading to having no station above the hypocenter. The formal hypocentral errors are quite low with respect to the typical off-shore events, being generally smaller than 2-3 km, which is very close to the error of an event beneath a dense seismic network.

Figure S5 shows the origin time uncertainties versus longitude, latitude, and focal depth uncertainties. We here observe the classic trade-off between focal depth and origin time. However, it is important to note that the trade-off, usually much larger for the focal depth when locating off-network events, in this case is essentially isotropic in space, suggesting that the sP phase greatly helps reducing the hypocentral mislocation and uncertainties.

Figure 2 shows the number of sP observations per station against their positions on the map. Although we, on purpose, did not pick all the possible sP onsets but only the best ones, this was done for all the events. Thus, Figure 2 is quite representative of the stations where high quality sP phase was observed most of the times. The station IV MOCO, showing the highest number of observations, is located at a mean distance of ~170 km from the seismic sequence at an elevation of about 1 km o.s.l. Moreover, a relatively high number of sP phases is also observed at shorter epicentral distances along the same azimuth. Despite this evidence, our dataset is not large and statistically significant enough to assess the reason for a higher or lower sP visibility at specific sites.

Figure S6 shows the sP residuals for the whole dataset with respect to formal errors of the focal depth and epicentral location. This analysis shows no significant trend between these variables, especially with depth and related uncertainty, with the exception of the origin-time uncertainty, for which smaller errors seem to correspond to smaller sP residuals spreading. This result indicates that the use of sP phases helps to reduce the typically strong trade-off between focal depth and origin time as well as their uncertainties.

Discussion

Between March and September 2021, a total of 80 earthquakes (M >= 2.9) were recorded in the Central Adriatic Sea, within the Adria plate. The seismic sequence started with the mainshock on 27 March 2021 at 13:47:51, Mw5.2 INGV (Mw5.5 USGS; Mw5.4 Geofon). Figure 3 shows that the epicenters are located in a seismic active NW-SE area included between the 2003 Jabuka seismic sequence to the NW and the 1988 Palagruza seismic sequence to the SE. The distribution of the epicenters corresponds to the fault traces discussed in Ivancic et al. (2006), part of which is characterized by an inverse rupture mechanism. Despite the identification of the rupture mechanism, a clear image of the fault geometries throughout the whole area was difficult to recover based on the earthquake distribution with depth (Herak et al., 2005) because of difficulties in constraining hypocenter locations off-shore without close seismic stations. Conversely, using the sP phase to constrain the focal depth, and consequently latitude and longitude, as we did in the present work, results in a quite clear image of the geometry of the fault associated with the 2021 seismic sequence, which we call the *Mid-Adriatic Fault* (MAF) hereafter.

Figure 4 shows four vertical sections across the strike of the Mw 5.2 fault. The NW-SE cross-sections (Figure 4a,b) show a clear dip to the northeast. The mainshock is located approximately in the middle of the aftershock zone ranging from close to the bathymetry to ~15 km depth along the fault plane. Based on the hypocentral distribution, the fault shows a northeastward dip between ~35° and ~45° that is well within the range of moment tensor solutions determined by different institutions. The MAF runs parallel to the SW with respect to the Jabuka–Andrija fault and to the South Adriatic fault (see Ivancic et al., 2006; Kastelic et al., 2013) and along the NW-SE trending alignment of structural highs named Mid-Adriatic Ridge (MAR in Figure 3) (Finetti et al., 1987). We modeled the mean fault plane based on the 3-D earthquakes alignment. The gray box in Figure 3 and the gray line in Figure 4a,c represent the modeling result. Following this geometry we constrain the fault outcrop at the seafloor corresponding to a fault segment reported in the Map of Active faults by Ivancic et al., 2006 (and references therein), where it is shown with unknown sense of displacement.

The MAR appears to be a key feature in the seismotectonics of this area. It has been interpreted as a forebulge by De Alteriis (1995) or as the result of compressive tectonics of the external Apennine (Argnani & Frugoni, 1997; Scrocca, 2006, 2007) or Dinaric (Finetti & Del Ben, 2005) Chains. According to Grandic et al. (1999), the two main alignments of the MAR, the Palagruza High and the Jabuka Ridge, are caused by salt doming of Triassic evaporites. This halokinetic tectonics, still active, characterizes sectors where successive regional compressive regimes induced reduction of resistance to deformation, leading to preferential pathways for gas-rich fluids extrusion from the sedimentary sequences to the seafloor and shallow below the sea-bottom where these gas seepage shows up as pockmarks, mud volcanoes, and mud-carbonate mounds (Geletti et al., 2008). Our results indicate that the structure activated with the 2021 seismic sequence, is the one outcropping close to the Palagruza High where previous studies suggested halokinetic activity in the framework of compressive/transpressive tectonics interacting with the migration of gas-rich fluids. This confirms the correlation (Geletti et al., 2008; Geletti et al., 2020 and references therein) between such tectonics and the occurrence of relevant seismic events and related seismic sequences like that of Jabuka (ML 5.5, Herak et al., 2005) or the March 2021 seismic sequence reported here. Figure 4d is an "along-plane" down-dip section showing earthquakes located within +/- 3 km from the modeled fault plane. This plot represents the distribution of the located earthquakes on the fault plane and seems to show that the northernmost shallow part of the fault was not completely activated or is locked. However, this possibility should be further confirmed by extending the dataset in time and lowering the magnitude completeness.

Another important aspect of correctly mapping the faults responsible for the off-shore Adriatic events is related to the tsunami hazard. The Adriatic Sea has been struck several times in the past by tsunamis (Tinti et al., 2004; Maramai et al., 2019; see also Paulatto et al., 2007 for a complete review). Although the northwestern Adriatic Sea is particularly vulnerable due to the extremely shallow water, the central and southern parts are also exposed to such a risk as it is well documented in Stoppa et al. (2014) analyzing the 1627 M6.7 Frentana coast earthquake (~200 km west of the MAF, in the Abruzzi coastal region) and the related tsunami which destructive effects were historically testified. Stoppa et al. (2014) stressed this risk and expected the possibility of fast modeling of tsunami propagation in the eventuality that a moderate to strong earthquake would occur in the Adriatic coastal or off-shore area. Recently, INGV has built up a Tsunami Alert Center (CAT) which is part of the large worldwide community for tsunami monitoring and early warning (Selva et al., 2021 and references therein). Beyond the complexity of tsunami modeling, the probability analysis of wavefront propagation and the alert system itself are based on some criteria about the tsunamigenic potential, a relevant part of which is the focal depth of the earthquake source and the possible extension of the fault slip to the surface. Our analysis of the 2021 seismic sequence in this sense suggests that the MAF, though related to a moderate event with a magnitude smaller than the minimum M5.5 limit for the Decisional Matrices, might produce ruptures propagating to the seafloor increasing the already evidenced tsunamigenesis potentiality (Stoppa et al., 2014) of the Adriatic faults and in general of this seismically active large area.

Conclusions

The 2021 central Adriatic seismic sequence activated a segment of an active fault system located off-shore in the central Adriatic Sea along the axis of the Adria microplate that is involved in a double verging subduction environment. The tectonics of this area is determined by the migration of the outer thrusts of the Apennines and External Dinarides toward the northeast and southwest, respectively, generating a compressive regime which led to a complex system of NW-SE trending thrust, back-thrusts, and anticlines, and to important alignments of halokinetic structures and vertical uplifting. The analysis of the instrumental seismicity shows that the several faults identified with active-source seismology in the framework of petroleum and gas exploration in this area, are anything but seismically inactive or poorly active, despite the moderate magnitude of the stronger events, confirming the suggestion by Kastelic and Carafa (2012).

In the present work, we analyzed the seismograms recorded at in-land stations related to the earthquakes that occurred during March and September 2021 in the central Adriatic Sea, identifying a set of high-quality sP onsets that are added to the canonical P- and S-onsets. We then applied the method for off-shore earthquake location by Zhao et al. (2007, 2011). Despite the absence of close-to-epicenter stations, this approach allowed us to better constrain the hypocenter locations, especially the focal depths, and thus to more accurately associate the seismic sequence to a specific fault, also giving hints on its geometry.

Our results suggest that the 2021 central Adriatic seismic sequence occurred along a NE-dipping fault, that we call MAF. This fault was already identified by seismic exploration studies though with “unknown vergence direction” (Ivančić et al., 2006; Ivančić et al., 2018). This fault segment is located parallel with and in between the 2003 Jabuka and the 1988 Palagruza seismic sequences to the northwest and southeast, respectively, in an area previously not showing high-rate seismicity. The TDMT (Time Domain Moment Tensor) associated with the 2021 mainshock shows a thrust-fault mechanism. Our results show that the sequence activated the MAF from close to the surface to a depth of about 20 km, with the mainshock approximately located in the middle of the sequence zone. Despite the high accuracy of the hypocentral locations, we constrained the dip angle within a range of 35-45°, which is compatible with a thrust fault and with the range of the moment tensor analysis by several seismic monitoring agencies, but has some difference from the TDMT that is slightly higher. The hypocentral distribution revealed by this study is in very good agreement with the MAF trace at surface, and both of its position and strike are close to the uprising halokinetic structure location, confirming the correlation between the geological feature and seismic activity in the central Adriatic crust. A precise identification of the geometry of the active faults responsible for moderate to possibly strong earthquakes under the Adriatic Sea is relevant also for studying the tsunamigenic potential of the seismic sources in coastal areas that are prone to tsunami-related damages. We also believe that our results are very promising for the determination of a more accurate map of the off-shore seismicity in Italy. Our next step will be to further improve the accuracy of the hypocentral locations by adding more detailed a priori information on the local 1-D, or even 3-D, crustal velocity models, and on the sedimentary cover. Moreover, we will progressively apply the method of sP identification and earthquake location to as many as possible off-shore seismic sequences that occurred in the Adriatic, Ionian, and Tyrrhenian seas, with the aim of making this approach as routinely used as possible in Italy.

Data and Resources

The waveforms analyzed in this article are available through the EIDA webservices (https://www.orfeus-eu.org/data/eida/webservices/); the hypocenter locations discussed in the present paper and shown in Figure 3 and Figure 4 is available as Supplemental Material in the form of a “Comma Separated Values (csv)” file.

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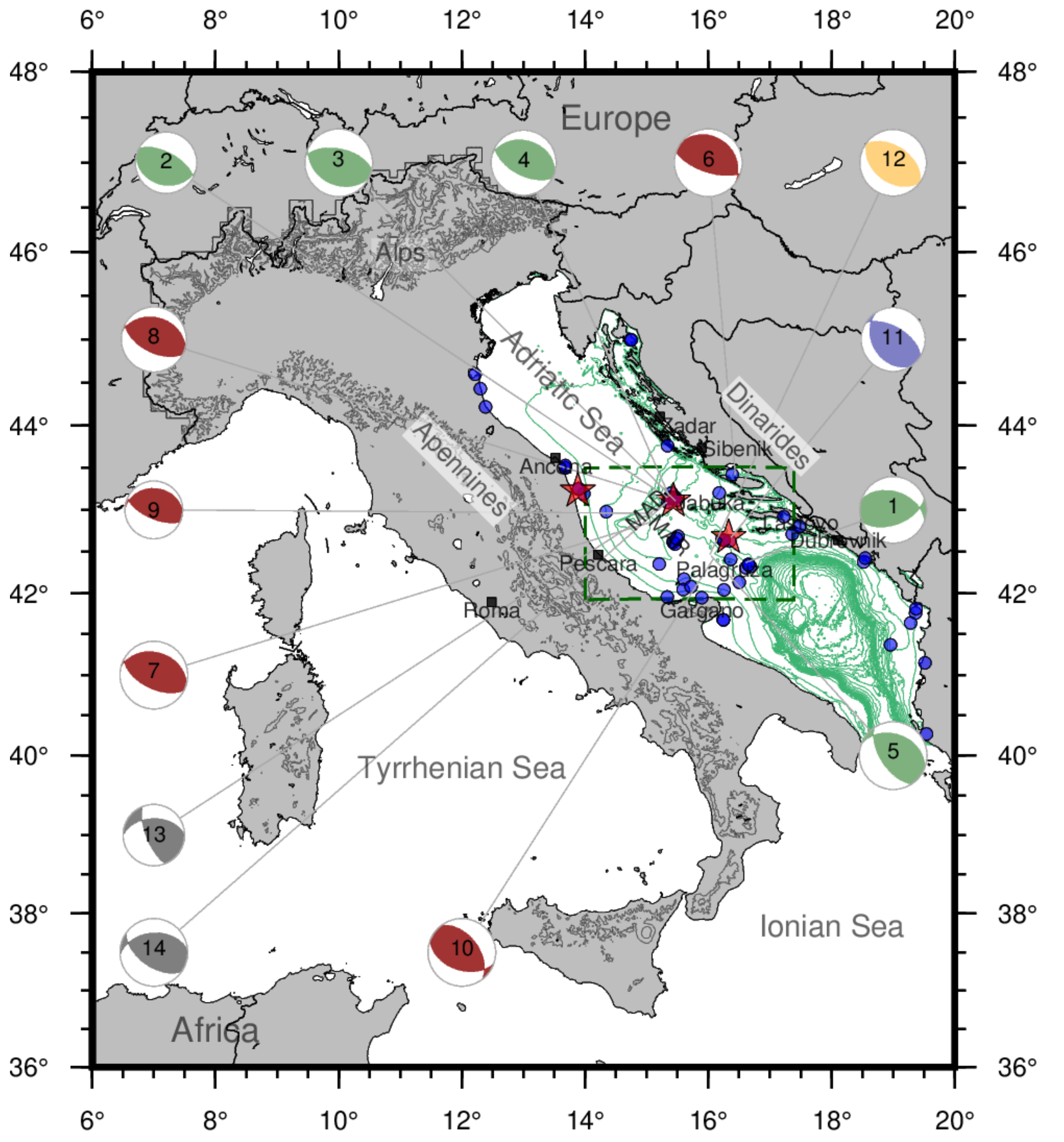
- **Figure 2**. Distribution of seismic stations (dark-red triangles) used in this study. The size of the triangles is proportional to the number of observed sP arrivals. The red star is the Mw 5.2 March 27, 2021 earthquake epicenter; gray and green contour lines are 750m/1500m a.s.l. topography and bathymetry every 50m b.s.l. respectively.
- **Figure 3**. Map of the central Adriatic area. Dark blue and purple stars denote events M > 4 and M > 5, respectively, from Latorre et al. (2021) and Iside (2021). Red lines denote active faults (Ivancic et al., 2006). MAR: the Mid Adriatic Ridge (Finetti et al., 1987) or the Central Adriatic Deformation Belt (Argnani & Frugoni, 1997). MAD: the Meso-Adriatic Depression (Geletti et al., 2008 and references therein). Dark green contours are bathymetric isolines every 20 m depth. Red star and black open circles are the 2021 mainshock (Mw 5.2) and its aftershocks, respectively, located by this study. The gray dashed box and the orange dashed line represent the modeled fault plane projection and its surface trace with triangles in the dip direction. Three black dashed lines (1, 2, 3) denote locations of the vertical cross-sections shown in Figure 4.
- **Figure 4**. **(a-c)** Vertical cross-sections showing hypocentral distributions along the three profiles shown in Figure 3. Open circles denote M < 5 earthquakes, whereas the red/orange star denotes the mainshock (Mw 5.2) on March 27, 2021. The gray dashed line denotes the mean modeled 35° dipping plane. **(d)** Hypocentral distribution of the earthquakes within 3 km from the modeled dipping plane as shown in (a-c).

Figures



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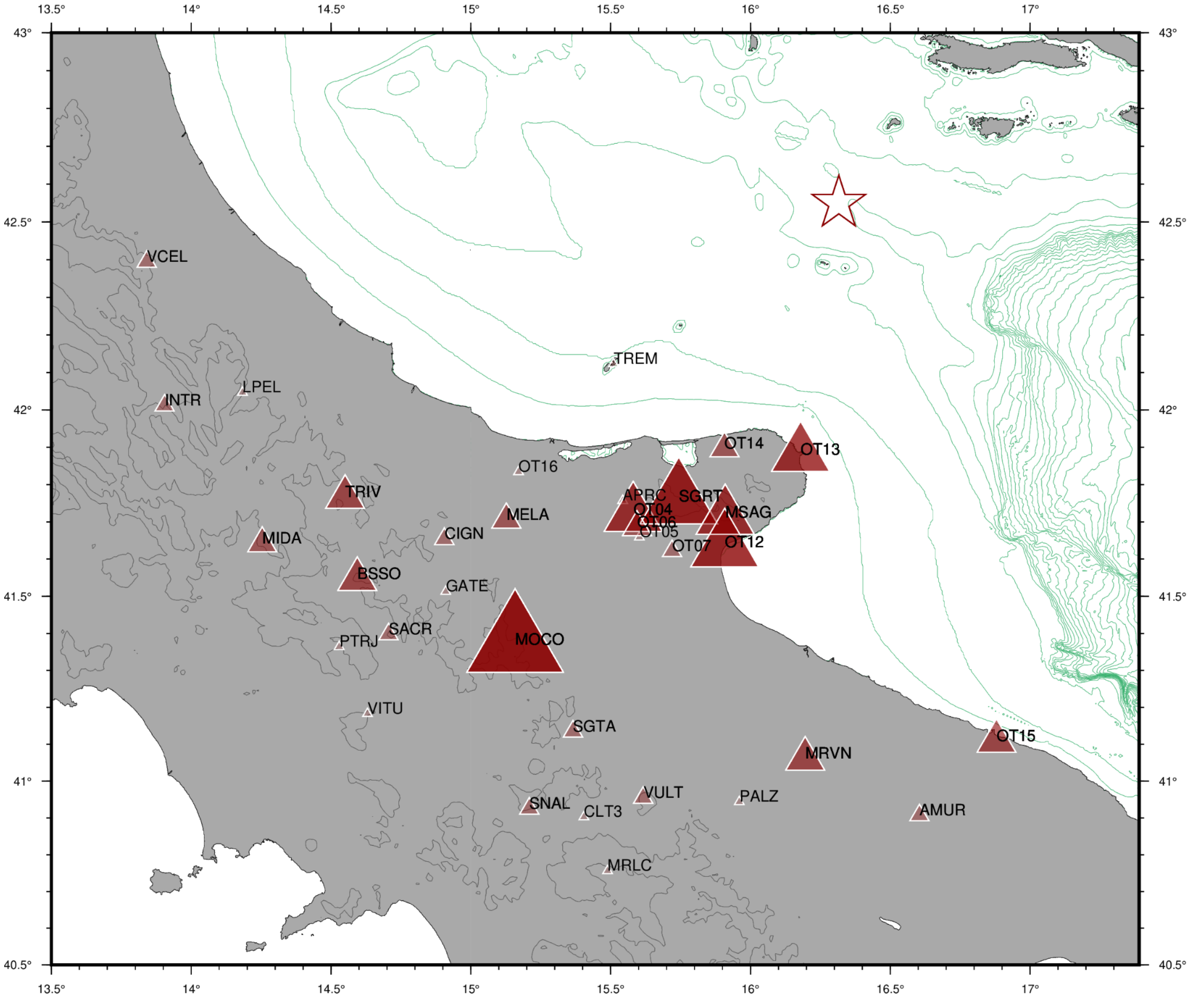
Mw 5.0, 3: 2003-03-29 Mw 5.5, 4: 2004-11-25 Mw 5.3, 5: 2021-03-27 Mw 5.5, 6: 1990-11-27 Mw 5.5, 7: 2003-03-29 Mw 5.5, 8: 2004-11-25 Mw 5.3, 9: 2004-12-03 Mw 4.7, 10: 2021-03-27 Mw 5.5, 11: 2021-03-27 Mw 5.2, 12: 2021-03-27 Mw 5.4, 13: 2003/03/27 Mw 5.0, 14: 2003/03/29 Mw 5.5; green contours are the Adriatic bathymetry every 50m; gray contours are the Italian topography at 750m and 1500m a.s.l.; the green dashed box is the target area of Figure 3.



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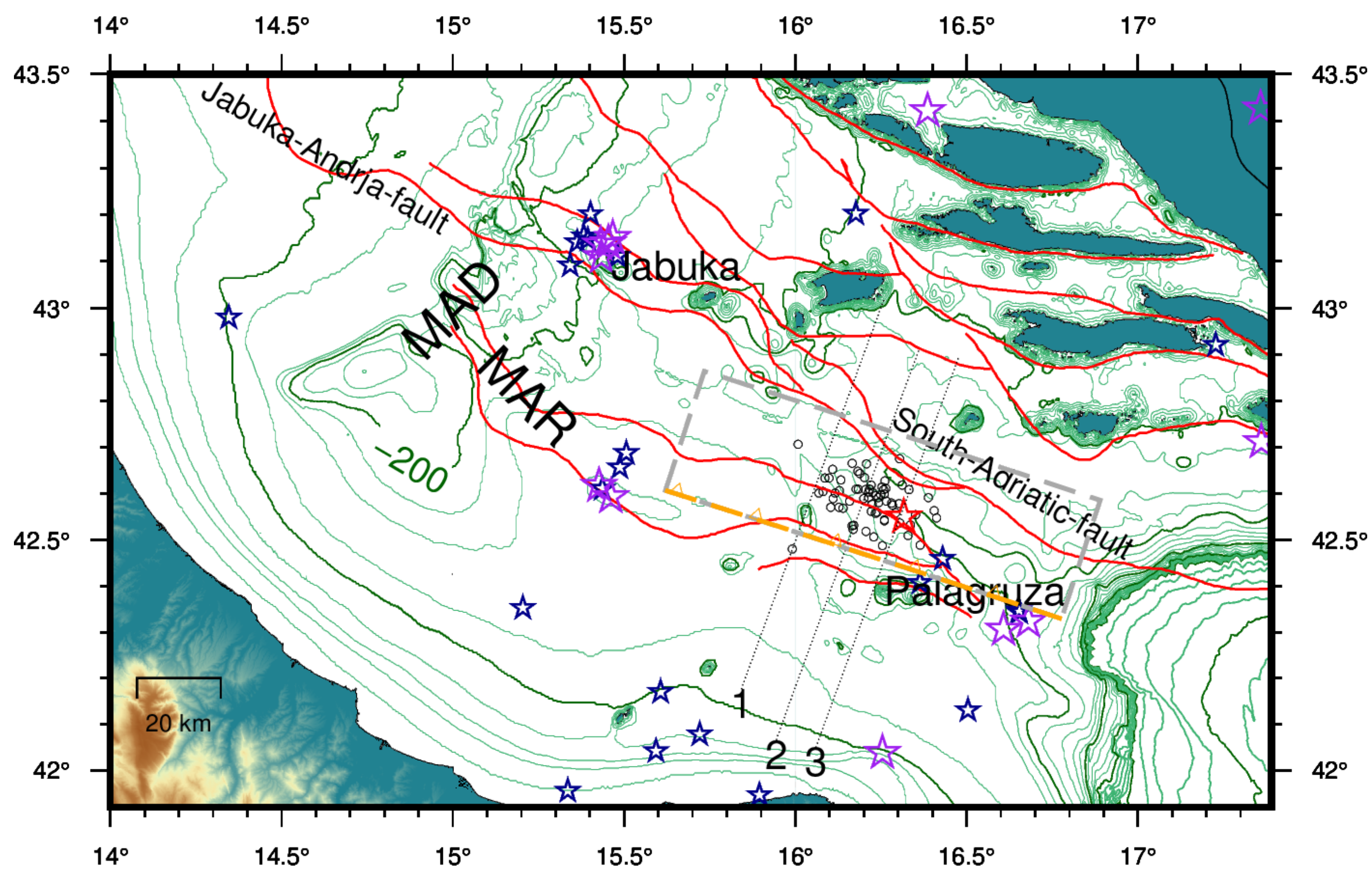

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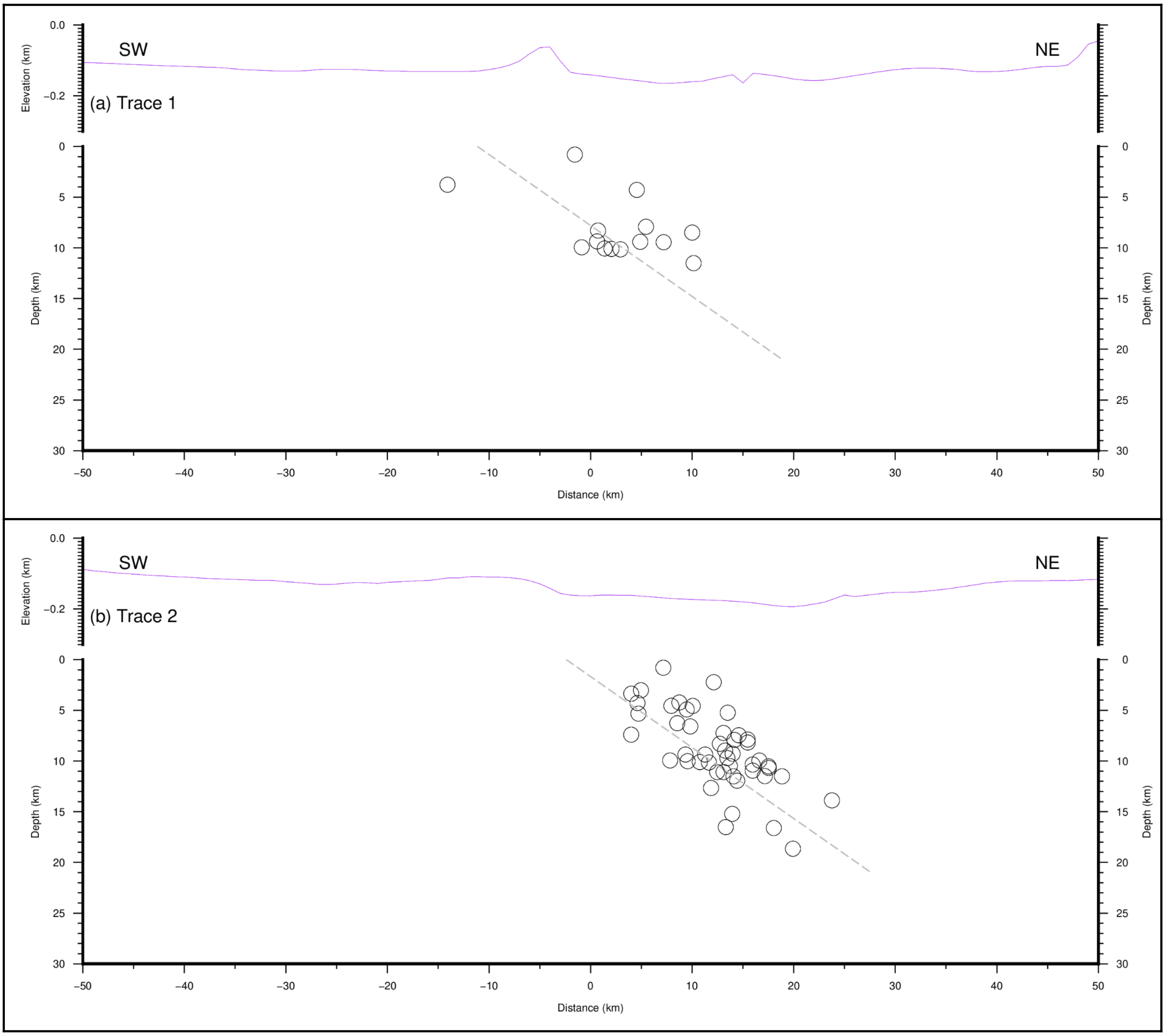
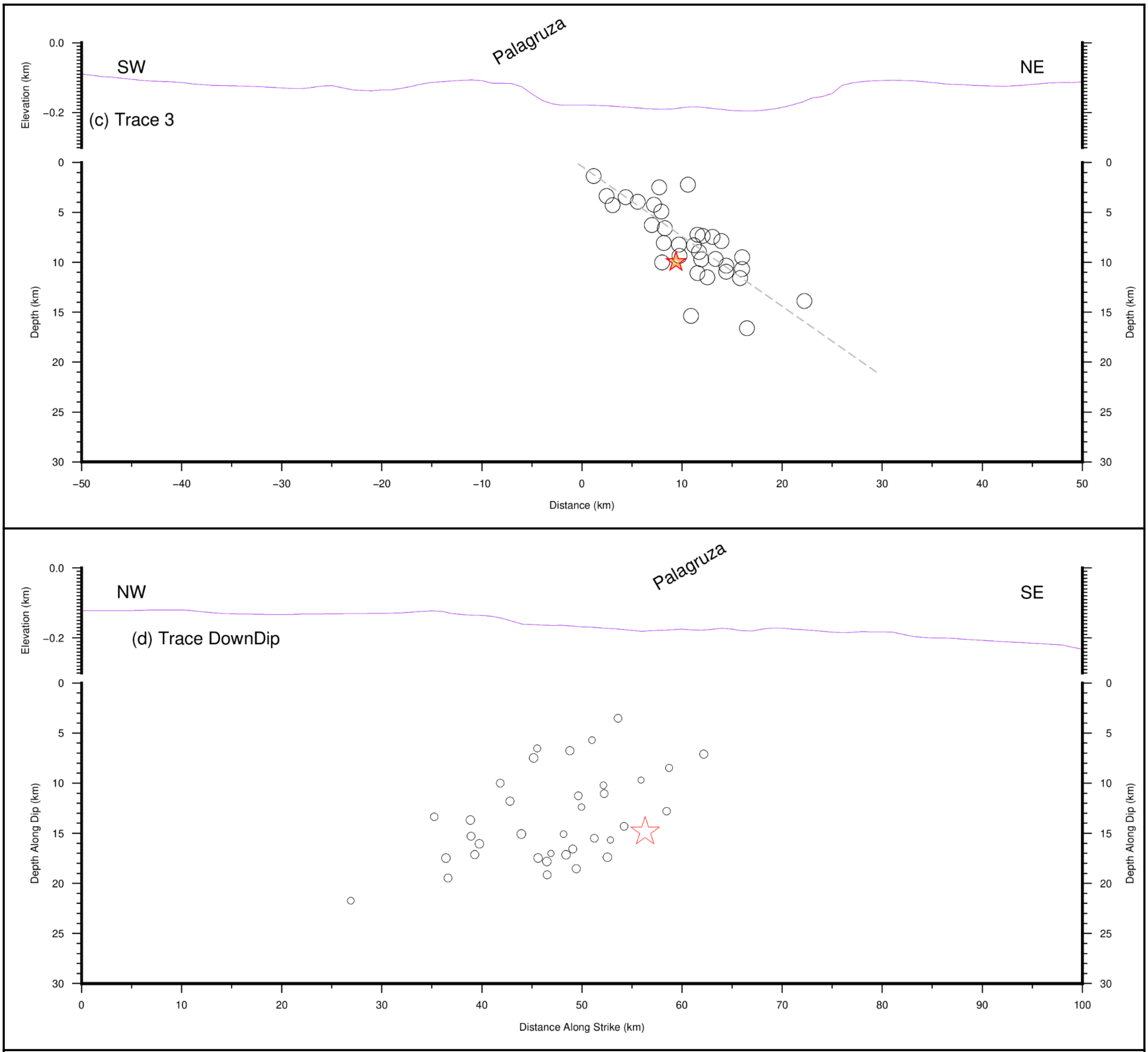


SW
NE
(a) Trace 1
Elevation (km)
0.0
−0.2
Depth (km)
0
5
10
15
20
25
30
−50
−40
−30
−20
−10
0
10
20
30
40
50
Distance (km)
SW
NE
(b) Trace 2
Elevation (km)
Depth (km)
Distance (km)



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