# New 3D velocity model (mTAB3D) for absolute hypocenter location in southern Iberia and the westernmost Mediterranean.

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#### 12 **Key Points:**

13 • New 3D velocity model for southern Iberia and the westernmost Mediterranean.

- Relocation of hypocenters in the Trans-Alboran Shear Zone and seismotectonic analysis. 14
- Seismotectonic analysis of a continuous catalog in Eastern Betics Shear Zone, and the Al-15 • Hoceima seismic sequence (2016). 16

#### Abstract 17

The Trans-Alboran Shear Zone is one of the most seismically active areas in the westernmost 18 Mediterranean, where a wide variety of tectonic domains have developed within the context of 19 20 oblique convergence between Eurasia and Africa plates. In this region, earthquakes occur close to seismogenic structures, some of them large enough to cause damaging events. In addition, the 21 diversity of tectonic domains implies a lateral variation of seismic wave propagation, which 22 could affect the hypocenter reliability if not addressed during the location procedure. In this 23 work, we present mTAB3D, a new 3D P-wave velocity model that accounts for the lateral 24 heterogeneity of our study area. To test this model, we used arrival times from the Spanish 25 Seismic Network catalog and performed two non-linear absolute location inversions: the first 26 comprises all the seismicity detected during 2018-2022 in the Eastern Betics Shear Zone; the 27 second one consists of the earthquakes recorded during the Al-Hoceima seismic sequence 28 (2016). We compare our results against hypocenters computed with a 1D velocity model of the 29 region (mIGN1D) and observe that mTAB3D achieves better clustering near active structures 30 and lower epicentral uncertainties. Moreover, hypocenters obtained with mTAB3D show notable 31 reliability even in scenarios of a low azimuthal gap, such as the 2016 Al-Hoceima sequence. The 32 new catalogs computed with our model help us to infer possible genetic relations between 33 seismicity and source faults within our study area and can be used as an additional tool when 34

looking into prior seismic sequences. 35

#### **Plain Language Summary** 36

- 37 The convergence between Africa and Eurasia plates developed the Trans-Alboran Shear Zone,
- where earthquakes are quite frequent. Here, seismicity is controlled by the main active structures, 38

and some of them can trigger large earthquakes (M $\geq$ 6.0). The tectonic complexity of the study

40 area implies that seismic waves after an earthquake do not propagate equally in every direction,

41 which may produce mislocations when a laterally homogeneous model is used. Due to this, we

have developed a new 3D velocity model (mTAB3D) that accounts for this heterogeneity. We
 tested mTAB3D by locating earthquakes from two catalogs from the Spanish Seismic Network

tested mTAB3D by locating earthquakes from two catalogs from the Spanish Seismic Network
that occurred in our study area and compared the results to those obtained using a 1D model.

45 Broadly, our results show lower uncertainties and locations closer to the possible fault sources,

46 even in scenarios of unfavorable distribution of seismic stations. We conclude that mTAB3D can

47 be used to obtain reliable hypocenters for seismotectonic studies within the westernmost

48 Mediterranean.

# 49 **1 Introduction**

The need for a more precise location of earthquakes within areas with clear evidence of 50 51 recent active tectonics is critical, not only to improve tectonic interpretation but also for seismic hazard analysis. However, to achieve an accurate solution, we usually face some issues that 52 could hamper our results: (1) the number and spatial distribution of seismic stations, (2) the 53 54 number and uncertainty in the seismic wave phase arrivals, and (3) how suitable is the velocity model used in the hypocenter inversion (Husen & Hardebeck, 2010). Altogether, assessing the 55 hypocentral absolute location of earthquakes with the lowest possible uncertainty is the primary 56 goal of recent studies that review earthquake catalogs. Some works strive for better precision and 57 accuracy by relocating the earthquakes using new techniques or improved velocity models (Diehl 58 59 et al., 2021; Lomax & Savvaidis, 2022).

In the Iberian peninsula and its surroundings, the former task has been fulfilled in different regions by modeling the 3D variation of the seismic waves in the subsurface at multiple scales from local (Theunissen et al., 2018; Sánchez-Roldán et al., 2021) to regional (Moudnib et al., 2015; Lozano et al., 2020), or even greater scale (Arroucau et al., 2021). These models have allowed us to estimate the influence of lateral velocity variations over the earthquake location within the region of interest. Furthermore, this procedure is essential in studies that seek to associate earthquakes with specific tectonic sources.

The westernmost Mediterranean, and particularly the Alboran basin, is a tectonically 67 complex region characterized by a shallow (<30 km), low-moderate seismicity (Stich et al., 68 2003). However, there is evidence in the historical and instrumental record of large earthquakes 69 in this region along the Betic Cordillera, Alboran Sea, and Maghrebian margin: the 1518 Vera 70 earthquake (EMS-98 VIII-IX), 1804 and 1910 Adra earthquakes (EMS-98 intensity VIII-IX), 71 and the 1994 – 2004 Al-Hoceima earthquakes (Mw 5.9 and Mw 6.3 respectively) (Martínez-72 Solares & Mezcua, 2002; Biggs et al., 2006; Kariche et al., 2018). More recently, a Mw 6.4 73 struck the offshore area of Al-Hoceima on 2016/01/25 causing material damage and casualties 74 (Buforn et al., 2017; Gràcia et al., 2019). 75

The shallow seismicity (depth < 50 km) is related to the deformation caused by the slow Africa-Eurasia NW-SE convergence (Serpelloni et al., 2007; De Mets et al., 2015), with a rate of ~4-6 mm/yr. The regional active tectonics is characterized by the transcurrent fault systems active since at least late Tortonian times (7-9 Ma) (Bourgois et al., 1992; Comas et al., 1992; Woodside and Maldonado, 1992). In this context, we observe the Trans Alboran shear zone

81 (TASZ) (De Larouzière et al., 1988), and its northwards continuation onshore, the Eastern Betics

Shear Zone (EBSZ) (Bousquet, 1979; Silva et al., 1993). Both systems cut from SW to NE in the
 Alboran Basin and connect the Iberian and Maghrebian margins.

In this work, we present a new 3D velocity model that comprises the region bounded by 84 the southern Iberian margin, the Alboran basin, and the North African margin. After that, we test 85 the suitability of the model by relocating two earthquake datasets corresponding to two 86 87 subregions within the TASZ and the EBSZ: the first includes the seismicity registered during 2018-2022 in the Eastern Betics, and the second the earthquakes detected during the Al-Hoceima 88 2016 seismic sequence. The reliability of the model and relocations are evaluated by comparing 89 the parameters and uncertainties of the hypocenters to previous results computed with a 1D 90 velocity model (Mezcua and Martínez-Solares, 1983). Finally, a seismotectonic analysis of each 91 region is carried out based on the new hypocenters and how they may be related to nearby active 92 faults that could act as sources. 93

# 94 2 Geodynamic and tectonic setting

The Gibraltar Arc and Betic-Rif cordillera are placed between the African and Eurasian plates in the westernmost Mediterranean (Fig. 1). A slow convergence at 4~6 mm/yr between these two plates is responsible for the complex tectonic features in this region (Seton et al., 2012; Vissers and Meijer, 2012).

99 The major geological features of the Alpine Betic-Rif orogenic system are:

- The Internal zones that belong to the Alboran Domain, which also can be subdivided into three equivalent tectonic complexes (from bottom to top on the Betics/Rif system): a)
   Nevado-Filabride only in the Betics and inferred to be the edge of the South Iberian paleomargin; b) the Alpujarride/Sebtide and c) the Malaguide/Ghomaride (Balanyá & García-Dueñas, 1987; Galindo-Zaldívar et al., 1989; Chalouan & Michard, 1990; Jabaloy et al., 1993; Bouyabaouene et al., 1995; Booth-Rea et al., 2015).
- The External zones composed of Mesozoic-Miocene sedimentary rocks deposited over
   the Maghrebian (Prerif, Mesorif, and Intrarif) and South Iberian (Subbetic, and Prebetic)
   margins, and the Flysch units over them (Crespo-Blanc & Frizon de Lamotte, 2006).
- Neogene basins with Miocene to Pliocene infill (e.g.: Guadalquivir, Granada, or Guadix-Baza among others) (Viseras et al., 2005), or Plio-Quaternary sediments like the Algero-Balearic and Alboran basins (Gómez de la Peña et al., 2021). The Alboran basin is traditionally subdivided into the West Alboran basin (WAB), South Alboran basin (SAB), and East Alboran basin (EAB), where the WAB reaches the maximum sedimentary thickness (~8 km) (Fernández-Ibáñez and Soto, 2017).

From the last  $\sim$ 35 Ma, slab subduction and western migration and the placement of the 115 Alboran domain over the Maghrebian and Iberian paleomargins, are considered the main 116 117 processes driving the tectonic evolution of the westernmost Mediterranean (Royden, 1993; Faccena et al., 2014). Although this is still a matter of debate, some geodynamic models 118 involving mantle delamination (Calvert et al., 2000) with associated slab tearing (Booth-Rea et 119 120 al., 2007; Mancilla et al., 2015a) are proposed in this context of slab roll-back extension (Lonergan & White, 1997; Faccena et al., 2004; Spakman & Wortel, 2004) and possible 121 clockwise rotation in subduction orientation (Chertova et al., 2014; van Hinsbergen et al., 2014). 122 An NNW-oriented extension develops sedimentary basins in the region from the late Serravallian 123

- 124 to the late Tortonian. Later, since the late Miocene, a process of tectonic inversion causes an
- 125 NW-SE shortening, resulting in structures resembling "basin and range" morphology
- 126 (Weijermars, 1987; Montenat & d'Estevou, 1999; Meijninger & Vissers, 2006; Herrero-Barbero
- 127 et al., 2020), where the extensional basins have been deformed and cut off by the occurrence of
- 128 the TASZ and the EBSZ (De Larouzière, 1988).



129

The TASZ and EBSZ comprise a system of strike-slip and reverse faults oriented from 130 NNE-SSW to ENE-WSW, developed in that post-Miocene shortening stage and cut off from the 131 Maghrebian to the South Iberian margins across the Alboran Basin, affecting both the basement 132 and Neogene-Quaternary sediments of the area. According to GNSS data, the present-day 133 transpressive tectonic regime is driven by a NNW-SSE shortening (Argus et al., 2011; 134 Echeverria et al., 2013, Borque et al., 2019; Piña-Valdés et al., 2022), which is coherent with the 135 kinematics on the major faults within the TASZ and EBSZ, as evidenced by field data, seismic 136 137 profiles, or earthquake focal mechanisms (i.e., Stich et al., 2003, 2006; Giaconia et al., 2015; Martín et al., 2015; Moreno et al., 2016; Ferrater et al., 2017). Here, from south to north, the 138 main crustal faults are: the Nekor fault (NF; Leblanc & Olivier, 1984), Trougout fault (TF; 139 Lafosse et al., 2018), Al-Idrisi fault (AIF; Ammar et al., 2007), Alboran Ridge Front fault (ARF; 140 Ballesteros et al., 2008), Yusuf fault (YF; Mauffret et al., 1987), Carboneras fault (CbF; 141 Bousquet & Phillip, 1976), Palomares fault (PF; Völk, 1967), Alhama de Murcia fault (AMF; 142 143 Montenat, 1973), Carrascoy fault (CF; Silva, 1993) and Bajo Segura fault (BSF; Montenat,

144 1977). Some of these faults, especially those across the Alboran basin, act as boundaries between

145 different crustal domains (Gómez de la Peña et al., 2018) and constitute structured tectonic

blocks with a diffuse and minor to moderate seismic activity (Rodríguez-Escudero et al., 2014;

147 Grevemeyer et al., 2015). In this scenario, different studies have explored the possibility of large

149 ESBZ (Gómez-Novell, et al., 2020; Herrero-Barbero, et al., 2021).

# 150 **3 Materials and Methods**

As previously stated, Alboran and south Iberia regions have a complex structure due to 151 their complicated tectonic evolution. Thus, the suitability of the velocity model applied during 152 the relocation is crucial for obtaining well-constrained hypocenter solutions (Husen and 153 Hardebeck, 2010). Sometimes, relying on average seismic velocity models (1D models) could 154 bias or offset the results. Because of that, some studies propose the use of 3D models that 155 156 account for the lateral variation of velocity to tackle the mislocation of hypocenters caused by oversimplification of the crustal and mantle heterogeneities (Husen et al., 2003; Flanagan et al., 157 2007; Carannante et al., 2015; Matos et al., 2018; Theunissen et al., 2018; Lozano et al., 2020; 158

- 159 Diehl et al., 2021).
- 1603.1 mTABD3D: new regional 3D velocity model

In this paper, we present a 3D velocity model (hereafter mTAB3D) based on a

162 compilation of geophysical and geological data of the study area ( $6^{\circ}W/1^{\circ}E/35^{\circ}N/39^{\circ}N$ ) that

accounts for the most relevant structures and their influence on the lateral variation of P-wave

propagation, such as the two continental margins with different mountain ranges, or the mostimportant sedimentary basins (Fig. 2).

166 During the modeling process, data related to the composition and structure at depth were 167 used to model three regional surfaces:

Topography/bathymetry: Taken from topography (Amante, C. & B.W. Eakins, 2009;
 NOAA National Geophysical Data Center, 2009) and bathymetry (GEBCO Compilation
 Group, 2022) data.

Basement top: multichannel seismic reflection data (Rodríguez-Fernández et al., 2004; Medaouri et al., 2014; Haberland et al., 2017; Marín-Lechado et al., 2017; Martínez-García, et al., 2017; Gómez de la Peña et al., 2018; d'Acremont et al., 2020; Gómez de la Peña et al., 2021), and 2D gravity modeling profiles (Amores Lahidalga et al., 2002; García-Castellanos et al., 2002; Jiménez-Pintor et al., 2002; Sanz de Galdeano et al., 2007; Alfaro et al., 2008; Insua-Arévalo, 2008; Pedrera et al., 2020).

- Moho discontinuity: wide-angle seismic data (Booth-Rea et al., 2018; Gómez de la Peña et al., 2020), P-wave receiver function (Mancilla et al., 2015a; Mancilla & Díaz, 2015), deep seismic sounding (Díaz & Gallart, 2009), 2D gravity modeling profiles (Insua-Arévalo, 2008; Pedrera et al., 2020), joint gravity and thermal analysis (Carballo et al., 2015; Torne et al., 2015), and ambient noise tomography profiles (Palomeras et al., 2017). Where data density was insufficient, the CRUST1.0 crustal model was used (Laske et al., 2014)
- 183 (Laske et al., 2014).

To consider a realistic distribution of blocks in the uppermost part of the model, we use geological and tectonic maps of the study area (Marín-Lechado et al., 2017; Fernàndez et al., 2010: Clariana Caraía et al., 2021: Martín Sarrana et al., 2021: Matas & Martín Barra, 2021a;

186 2019; Clariana-García et al., 2021; Martín-Serrano et al., 2021; Matas & Martín-Parra, 2021a;

Matas & Martín-Parra, 2021b; Montes et al., 2021; Roldán et al., 2021; IGME, 2021). This
 procedure permits the inclusion of small bodies that may affect the location of the shallowest

earthquakes (e.g.: sedimentary basins). The summary of these data used to build mTAB3D is

190 available in Table S1.

Using the intersections and depth relations between those surfaces, we can model the 191 geometry of the main blocks following the same approach as Sánchez-Roldán et al. (2021). For 192 instance, we defined the sedimentary cover by subtracting the topography (or bathymetry) from 193 the basement top, and the basement is the volume within the basement top and the Moho 194 discontinuity. Everything above the topography/bathymetry will be air/water, while the mantle 195 will be below the modeled Moho surface. In addition, studies that identify changes in lithology 196 or geophysical properties (e.g.: Gómez de la Peña et al., 2018) allow us to subdivide the area into 197 different types of crust or crustal domains (i.e.: Iberian crust to the north, magmatic arc crust 198

199 below the EAB, or oceanic crust in the easternmost part of the model).

200 We estimated the P-wave velocity of every type of block at each depth of the model

according to relations that consider rock properties, such as composition and density (i.e.:
Christensen & Mooney, 1995; Brocher, 2005) (Fig. S1A). We compared our estimations with

202 Christensen & Mooney, 1995; Brocher, 2005) (Fig. S1A). We compared our estimations with 203 previous results obtained in other studies of the region (i.e.: Grevemeyer et al., 2015; Mancilla &

Díaz, 2015). This procedure has two exceptions: velocities above topography/bathymetry, and

205 mantle blocks. We assigned a constant velocity of 1.5 km/s to those blocks that are above

topography/bathymetry. On the other hand, we estimated the mantle velocity interpolating from a

207 linear regression of the mantle velocity estimated in the ak135-F modified after Montagner and

Kennet (1995), and since that is a 1D average model, we do not account for the lateral

209 heterogeneity in the mantle (Fig. S1b).



Figure 2

210

The main features in the mTAB3D velocity model (Fig. 2), are the distribution and 211 relation among the different tectonic domains of the study area. For example, we modeled the 212 progressive eastwards thinning of Iberia (A-A' section in Fig. 2) or the break-off of the sub-213 Iberian (C-C' section in Fig.2) and Maghrebian (D-D' section in Fig.2.) subducted lithosphere 214 under the Eastern Betics (SE Iberia) and the Rif (northern Africa), respectively. Also, we 215 accounted for some areas in the Alboran Sea where sedimentary subbasins and basement 216 outcrops made contact (B-B' section in Fig. 2), which may be related to the presence of active 217 faults of the TASZ (e.g.: WAB and SAB limited by the Al-Idrisi fault, see Fig. 1). Lastly, from 218 this 3D layered distribution of blocks, we extract a grid with a maximum extent of 607x443x204 219 km<sup>3</sup>, and with nodes every 1x1x1 km<sup>3</sup> where we assign a specific P-wave velocity value. 220

221 3.2 Earthquake absolute location computation

To test the performance of the mTAB3D velocity model, we computed a relocation using a dataset of 1598 earthquakes detected in the EBSZ between 2018-2022. Those results were compared to the obtained after relocating the same dataset using the 1D velocity model from Mezcua and Martínez-Solares (1983) used in the Spanish Seismic Network for routine earthquake location, hereinafter, mIGN1D.

We retrieve arrival times recorded by the Spanish Seismic Network within the area 227 covered by the 3D velocity model (Fig. S2; IGN, 2020). Then, we use the Nonlinloc software 228 suite (NLL henceforth; Lomax et al., 2000). This software uses a non-linear location procedure 229 230 which provides a statistically optimal solution and a posterior uncertainty estimation, expressed as the probability density function (PDF), and allows the use of a 3D velocity model. First, 231 within the NLL suite, following a finite-differences, eikonal-equation algorithm (Podvin & 232 Lecomte, 1991), we compute the theoretical travel-times with the Grid2Time program. Then, for 233 the NLLoc program run, we adopted the equal differential-time (EDT) likelihood function in the 234 procedure (Zhou, 1994; Font et al., 2004), which is more robust where outliers are present in the 235 data. The Oct-Tree sampling algorithm (Lomax et al., 2000) estimates efficiently the maximum 236 likelihood hypocenter of the PDF, which will be the preferred solution in this work. The NLLoc 237 program allows us to calculate the 68% confidence ellipsoid from the PDF's, and thus we obtain 238 the horizontal and vertical uncertainties (errH and errZ, respectively) based on the axes of this 239 ellipsoid. Finally, after a first relocation, NLLoc estimates the average phase residuals in every 240 station, which may act as station corrections for a second run of NLLoc over the dataset to 241 compute more constrained solutions. This will be useful to reduce the contribution of any bias in 242 243 the relocation process. It should be noted that in this procedure we will keep the same software, configuration parameters, and arrival times. 244

245 We set another test to know if this model could be suitable to study past seismic sequences within a specific zone and limited duration. For that, we chose the Al-Hoceima 2016 246 seismic sequence with 540 earthquakes of M≥2.5, registered by the Spanish Seismic Network on 247 2016-01-21 and 2016-04-01 in the TASZ. The geographical location of this sequence allows us 248 to study the results that we should expect when relocating within an area close to the edge of our 249 model, which implies fewer arrival times in the computing procedure and could bias the 250 251 hypocenters. Here, we will also face the problem related to the distance to closer stations and their spatial distribution, which affects the quality of the solution, especially when assessing the 252 hypocenter depth (Lomax et al., 2014). 253

In this scenario, we perform an additional procedure to the relocation in NLL, similar to 254 the one explained in Lomax and Savvaidis (2022), which consists in computing the source-255 specific station term corrections (SSST) during the hypocentral relocation procedure using the 256 program Loc2SSST within the Nonlinloc suite. These SSSTs fluctuate in the 3D velocity model 257 and, during the iterative operation, the program generates specific files for every station and 258 259 phase that contain the time correction value at each node of the model. Despite the computational cost of this method, the advantage of this procedure lies in the possibility of running several 260 instances of Loc2SSST in parallel, which improves the time performance during runtime. 261 Besides, it offers stable and reliable hypocenters in a situation with fewer available stations in the 262 vicinity of the seismic sequence. 263

# 264 **4 Results**

# 265 4.1 EBSZ 2018-2022 catalog

The compiled catalog comprises 1598 earthquakes detected by the Spanish Seismic Network (IGN, 2022), with magnitudes ranging from 0.4-4.1, recorded between 2018-2022 in the southeastermost part of the Iberian peninsula. We have relocated all the events using two

different velocity models, the mTAB3D and the mIGN1D. We chose this spatiotemporal window

270 because this geographic area is prone to diffuse seismicity with casual seismic sequences, such

as the one that occurred in the Albudeite and Mula towns in 2018 (Fig. 3), with an Mw 4.1 mainshock.

Since mTAB3D only accounts for P-wave velocity, we applied a local constant  $V_P/V_S$ ratio of 1.73, obtained after plotting tS-tP arrival times at each station against tP absolute arrival times in a Wadati diagram (Fig. S3a). This  $V_P/V_S$  ratio is consistent with the value proposed in receiver function studies that use stations within our study area (Mancilla et al., 2015b).

The comparison of the hypocenter location between mIGN1D (Fig. 3a) and mTAB3D (Fig. 3b) shows subtle differences; however, we can observe some particularities. The first one is related to the depth distribution of hypocenters; in both cases, seismicity seldom exceeds 15 km in depth. Nevertheless, the percentage of hypocenters that converge around 0 km in mIGN1D nearly doubles the amount relocated by mTAB3D (Fig. 3).



Figure 3

282

283 Secondly, if we focus on epicentral distribution, hypocenters obtained with mTAB3D are slightly closer to the nearest faults (e.g.: PF, AMF, CF) (Fig. S4). In addition, mTAB3D gets a 284 better clustering of the events in some areas, such as the LTF. After normalizing the number of 285 epicenters per unit of area (Fig. 4), in this case, 10 km<sup>2</sup>, we obtain the main clusters after the 286 relocation. Results are similar between mTAB3D and mIGN1D in terms of events distribution, 287 although mIGN1D gets two small clusters to the west of PF in an area where mTAB3D does not 288 289 achieve enough density. However, the foremost difference lies in the evident cluster localized to the NE of the interest area, where most of the epicenters are related to a seismic sequence that 290 occurred in 2018 between CrF and AMF. Here, epicenter density is much higher after relocating 291 292 with mTAB3D.





293

#### 4.2 Al-Hoceima 2016 seismic sequence

The Al-Hoiceima series (2016) starts with an Mw 5.0 foreshock on 2016-01-21 in the 295 South Alboran Sea, followed by an Mw 6.3 mainshock that occurred on 2016-01-25 (Buforn et 296 al., 2017). This earthquake was highly felt in Al-Hoceima (northern Morocco) and other nearby 297 cities causing several injuries and damaging buildings and infrastructures. At large distances, 298 such as in southern Iberia, people felt it with intensity IV (IGN, 2016). The sequence comprises 299 300 >2400 earthquakes until June 2016, but we selected a subset of 540 earthquakes with M≥2.5 detected by the Spanish Seismic Network between January 21st 2016 and April 1st 2016, the 301 period of the main activity. Following the same method used in the analysis of the EBSZ 2018-302 303 2022 catalog, we obtained a VP/VS ratio of 1.74 (Fig. S3b). For this relocation of the catalog, we proceeded similarly to the workflow explained in Lomax & Savvaidis (2022) for the NLL-SSST 304 hypocenter inversion. Table 1 shows the parameters to specify the criteria for the event location 305 in every iteration of the procedure. The weighted mean of rms was calculated repeatedly 306 considering the previous parameters and a shrinking spatial smoothing, D, starting at 4 km and 307 finishing at 1 km after the last run. 308

Table 1

rms	no. readings	gap	P-arrival rms	S-arrival rms	len3
1.0 s	25	180°	1.0 s	2.0 s	10.0 km

309





The absolute locations of the seismic sequence following the NLL-SSST procedure show that most of the epicenters tend to shift eastwards, close to the AIF area, in contrast with mIGN1D, which keeps the seismicity westwards from the traces of the main faults (Fig. 5). Regarding the depth distribution, our results indicate that seismicity ranges mostly from 0 km to 16 km and drastically decreases below this point. This is not observed in the mIGN1D results because many hypocenters converge around 0 km. The southernmost hypocenters computed with this 1D velocity model are systematically located at 30 km, which does not happen in the







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Both relocations have three main clusters (Figs. 5 & 6), but there are differences in their distribution and density. For example, epicenters obtained using the mIGN1D show a sparse

- distribution and density. For example, epicenters obtained using the interverb show a sparse distribution of seismicity when compared with the results using the mTAB3D, which achieves a
- higher density of hypocenters (Fig. 6). The northern cluster (number 3 in Fig. 6) that occurs
- around March is mainly located on the trace of AIF, while the same seismicity shifts to the east,

- between AIF and South Alboran Ridge (SAR), when localized with the mTAB3D (Figs. 5 & 6).
- The southernmost cluster's area (number 1 in Fig. 6) extends beyond the JF surface trace in
- 327 mIGN1D results, in contrast, the results obtained with mTAB3D show that the same earthquakes
- are mostly confined to the northwest of the fault trace (Figs. 5 & 6). Regarding the depth
- distribution of the clusters, mTAB3D located these three clusters progressively deeper from
- north to south (latitude depth cross section in Fig. 5b).

# 331 **5 Discussion**

As described in the previous section, the results of the hypocentral relocation vary greatly depending on the velocity model used. However, we need to understand how reliable the absolute locations from each model are. For this purpose, we used the covariance matrix calculated by Nonlinloc from the PDF obtained in the relocation. From this covariance matrix, we computed the vertical uncertainty (errZ) and a horizontal uncertainty ellipse, both with a 68

- 337 % confidence level. From this ellipse, the horizontal uncertainty (errH) is assessed after
- calculating the geometric mean between the horizontal semi-minor and semi-major axes. Both
- 339 vertical and horizontal values are given in kilometers.
- 340 5.1 Uncertainty analysis of a continuous catalog in the EBSZ
- In the case concerning the absolute location of a catalog in the area of EBSZ between
- 342 2018-2022, we divided the results into four levels of quality according to the number of arrivals
- used during the inversion for each hypocenter (A: Num. arrivals  $\ge 40$ ; B:  $20 \le$  Num. arrivals  $\le 344$  40; C:  $10 \le$  Num. arrivals  $\le 20$ ; D: Num. Arrivals  $\le 10$ ).
  - Table 2

	$Q_A = 63$		Q_B	= 253	$Q_C = 620$		$Q_D = 662$	
	errH	errZ	errH	errZ	errH	errZ	errH	errZ
mIGN1D	0.99	1.10	1.36	1.58	1.99	2.62	15.37	11.11
mTAB3D	0.94	1.32	1.28	1.92	1.79	2.63	13.67	9.81

The calculated average horizontal uncertainty (errH) for the four subsets (A to D) is always lower in mTAB3D than in mIGN1D (Table 1). Nevertheless, the mIGN1D performs better than the mTAB3D vertical error (errZ) except for the lowest quality subset.

348 It is worth noting that, even though mIGN1D's depth solutions may seem more reliable in general, we found that the number of hypocenters that converges at 0 km double the mTAB3D 349 catalog (histograms in Fig. 3). In addition, mTAB3D achieves a lower errH and epicentral 350 location tends to be closer to active structures in the area, at least for the main clusters (Fig. 4 351 and Fig. S4). Hypocenters computed with mIGN1D generally show worse constrained locations 352 when confronted against the same earthquake located with mTAB3D, especially for those events 353 relocated using few arrival times (Q D subset in Table 2), which usually are related to low-354 magnitude earthquakes and involve the most common type of seismicity in the region of EBSZ. 355 Comparing uncertainties earthquake by earthquake and plotting the results in a histogram, we see 356 that mTAB3D solutions are more reliable on average (Fig. S5). 357

The observed dissimilarity between relocations obtained using both velocity models could be related to the over-simplification committed by the mIGN1D when considering the velocity structure of the EBSZ. This structural zone limits two different crust domains composed

361 of geological units with contrasting properties (e.g.: sedimentary basins or volcanic rocks) (De

Larouzière et al., 1988) that could affect the wave propagation and, hence, influence the arrival 362 times at stations (Thurber, 1992). Applying station corrections computed by Nonlinloc partially 363 solves this issue for mIGN1D. Nevertheless, those corrections refer only to near-surface velocity 364 variations under the stations (Husen and Hardebeck, 2010), which could be a drawback when 365 relocating hypocenters within tectonically complex regions. In contrast, mTAB3D takes into 366 account this complexity and, thus, the obtained location of the hypocenters may be more reliable 367 to carry out the seismotectonic analyses in EBSZ. Seismicity in this area is mainly restricted to 368 the first 12-15 km of crust (García-Mayordomo, 2005) and shows a scattered distribution (Stich 369 et al., 2003); however, our results show that earthquakes and small seismic sequences are closer 370 to faults that bound basement blocks and sedimentary basins. The Guadalentín Valley, for 371 example, is bounded to the northwest by AMF and to the southeast by PF, LTF, and CF (Fig. 3). 372 Different geological studies have identified some of these faults as the source for some of the 373 most relevant seismic sequences both in the instrumental and historical records (López-Comino 374 et al., 2012; Insua-Arévalo et al., 2015; Martín-Banda et al., 2021; Martínez-Díaz et al., 2012, 375 2018). The hypocenters computed with mTAB3D distinguish a small sequence close to the LTF 376 and several epicenters along AMF and CF traces. This distribution is consistent with the 377 hypothesis of greater earthquake density around rigid and fractured basement blocks, uplifted on 378 the hanging wall of active faults (i.e.: CF, AMF, LTF). In contrast, the Guadalentín Valley, the 379 basin area in between the active faults (Figs. 1 and 3), shows lower seismicity density probably 380 381 due to its different rheological behavior (Rodríguez-Escudero et al., 2020; Alonso-Henar et al., 2021). 382

383 Concerning the earthquakes that are unlike to be caused by large-scale faults in the area and appear far from them, some studies deduce that these events, which can occur in any place, 384 are triggered due to the high density of small-scale faults within the major tectonic blocks under 385 a transpressional regime (Echeverria et al., 2013; Rodríguez-Escudero et al., 2014). For example, 386 the 2018 seismic sequence in the Mula-Archena subbasin is located between the CrF and the 387 AMF but apparently unrelated to a clear source (Fig. 4). Focusing on this sequence, we observe 388 389 that the closest faults are Mula-Archena fault (MAF) and Tollos-Rodeos fault (TRF) (Fig. 7a). These NE-SW faults are assumed to dip steeply, and given their length, inferred from local 390 cartography (Silva et al., 1996; Martínez-Díaz, 1999), they could reach the depth where the 391 sequence occurs (~10-12 km). However, MAF and TRF orientation is not coherent with the 392 cloud's shape, which infers a plane dipping northwards. The focal mechanism obtained from the 393 moment tensor solution computed by the Spanish Seismic Network also shows E-W nodal plane 394 dipping northwards, and the depth of the centroid is similar to the one of the denser clustering 395 (Fig. 7b). There are minor E-W (N80°E to N110°E) subvertical faults in the area affecting the 396 sedimentary cover (blue lines in Fig. 7a) and showing reverse and left-lateral strike-slip 397 kinematics, which could act as possible linkages between major SE-NE faults (Martínez-Díaz, 398 1999). Although the behavior and geometry of these faults in depth are not well known, Herrero-399 Barbero et al. (2020), after the reinterpretation of seismic profiles in the area of the Mula-400 Archena subbasin, suggest the presence of some faults with highly dipping angles that would 401 402 mainly affect pre-Messinian formations at the bottom of the basin. These faults are interpreted with normal kinematics, but they could have been reactivated as reverse faults under the 403 transpressional regime that started in the late Miocene, as has also been inferred from the AMF 404 activity (Meijninger and Vissers, 2006; Herrero-Barbero et al., 2020). In this situation, the 405 basement units would be highly fractured due to a network of short-scale faults, which could also 406 limit the maximum magnitude of an earthquake in a seismic sequence (Leonard, 2010). Thus, 407

408 these faults could accommodate part of the deformation in the area and eventually may trigger





410

411 5.2 Uncertainty analysis of Al-Hoceima 2016 seismic sequence

This seismic sequence exemplifies how 1D velocity models may distort the findings, 412 causing the epicenter to shift away from the inferred source fault (Thurber, 1992; Husen and 413 Hardebeck, 2010). Epicenters computed with the mIGN1D velocity model following the NLL-414 SSST procedure are scattered and placed west of the AIF (Fig. 4), the fault that may have 415 produced the event (Gràcia et al., 2019). Besides, there is a high percentage of hypocenters that 416 converge around 0 km. This could suggest that this model does not resolve properly the 417 uppermost velocities in the area and does not account for variations caused by geological units 418 419 like sedimentary basins.

420 Regarding the reliability of the results obtained using mTAB3D, we got the values of the 68% confidence ellipsoid to represent the uncertainty of the hypocentral location (Table 3), as 421 previously described for the continuous catalog of EBSZ. Due to the lower number of stations 422 around the area where the Al-Hoceima 2016 seismic sequence occurred (some of the broadband 423 stations and accelerometers were deployed after the sequence), we modified the quality criteria 424 to divide the catalog into different subsets (A: No. arrivals  $\geq$  30; B: 20  $\leq$  No. arrivals  $\leq$  30; C: 15 425  $\leq$  No. arrivals  $\leq$  20; D: No. arrivals < 15). This time, the comparison of the uncertainties shows 426 427 that mTAB3D achieves more reliable locations given the lower values for both errH and errZ in every quality subset (Table 3, Fig. S6). So, since mTAB3D shows better constrained hypocenters 428 and improves the clustering among events, even in this situation of high azimuthal gap and large 429 distances to the seismic stations, we decided to use these results to analyze the seismic sequence 430 within the complex tectonic setting of the Alboran basin. 431

Table 3

	$Q_A = 78$		Q_B	= 262	$Q_C = 101$		$Q_D = 99$	
	errH	errZ	errH	errZ	errH	errZ	errH	errZ
mIGN1D	4.71	9.94	5.60	12.64	6.75	15.61	10.13	18.03
mTAB3D	3.99	9.87	4.09	10.89	4.99	13.13	7.26	15.38

Our results suggest that the Mw 6.3 mainquake of this sequence occurred slightly south 432 to a right-stepping bend of the AIF (Fig. 5). After a finite source modeling, Stich et al. (2020) 433 434 observe that the rupture propagates asymmetrically from the nucleation zone: southwards, following the fault trace (N10°E), with a maximum length of ~8 km (which is similar to the 435 distance to the southernmost cluster after our relocation); northwards, the rupture is ~13 km 436 437 following the orientation of the double restraining belt (N40°E). Here, we also found some relocated aftershocks aligned between the two branches of the restraining bend. Several studies 438 show how intricate geometries could influence earthquake rupture (i.e.: Oglesby & May, 2012; 439 Howarth et al., 2021). Compressive step-overs may act as barriers impeding the rupture 440 propagation (Elliot, et al., 2015). However, the rupture can go further when the stress drops 441 drastically, in our case, at the northeasternmost end of the primary fault segment where the 442 rupture nucleates (Oglesby, 2008), inducing a stress increase and nucleation of the rupture in the 443 N40°E strand of AIF, which may be the case for the Mw 6.3 mainquake, as we could infer from 444

the slip distribution scenarios from Stich et al. (2020).



446

As previously explained, the seismicity related to this sequence appears to be grouped 447 448 into three main clusters (Figs. 5 and 8a). Two of those clusters follow AIF's trace but finish 449 abruptly where this fault intersects the TB (Fig. 8b and 8c). In this area, Gràcia et al. (2019) 450 interpreted the presence of flower structures with folds and minor sub-vertical faults that converge in depth, and proposed that the structure may be related to the regional transpressional 451 kinematic setting. On the other hand, in the area between AIF and SAR (Fig. 8d), where the 452 other cluster lies, Gràcia et al. (2019) describe folds and reverse faults. Additionally, the focal 453 454 mechanisms computed by Buforn et al. (2017) can be grouped into two sets of kinematics depending on the area: those dominated by strike-slip component are more frequent in the 455

clusters on the AIF trace (Figs. 8a-c), whereas those showing reverse faulting are more common
in the western tip of the Alboran Ridge, close to the other epicenter grouping (Figs. 8a and 8d).

This difference in the structures observed in the subsurface and how the dominant 458 kinematics varies between zones support the idea of slip partitioning as the main controlling 459 factor for the evolution of this sequence (Gràcia et al., 2019; Stich et al., 2020). In this case, 460 461 seismicity starts in the Al-Idrisi fault zone, where its left-lateral slip accommodates part of the deformation. Stress transfer to the NE could reactivate faults in the area of SAR, triggering a 462 sequence of aftershocks where thrusting is the most common mechanism due to the favorable 463 orientation of those reverse faults according to the regional shortening (Serpelloni et al., 2007; 464 Martínez-García et al., 2017). After the relocation, we achieved better clustering around those 465 regions, even discriminating between two subsets in the Al-Idrisi fault zone. The average depth 466 of those clusters does not exceed 15 km (Figs. 5b-d), which is in accordance with the crustal 467 thickness estimates obtained from geophysical studies (i.e.: Palomeras et al., 2017; Gómez de la 468 Peña et al., 2018) that image a fairly thin crust where the seismogenic zone would be constrained 469 in the first 20 km (Grevemeyer et al., 2015; Gómez de la Peña et al., 2022). 470

471

5.3 Limiting factors and future work to consider after the location procedure

We have presented two examples of relocations carried out in different scenarios. In the 472 first one, we have a nearly ideal case where the stations are evenly distributed, in addition to not 473 being so far from the areas of seismic activity (Fig. 3). Under these circumstances, the type of 474 velocity model (1D vs. 3D) seems to act as a remarkable factor only when referring to the 475 476 location errors of the events classified in the low-quality dataset, as we have shown previously (Table 2). However, it is interesting to consider the lateral variation of P-wave velocity when we 477 study areas where active structures occur as boundaries between highly contrasting lithologies, 478 and hence, different physical properties that may affect the wave propagation. Although station 479 delays partly compensate for this effect when we computed the relocation with a 1D model, 480 sometimes it is not enough to rely only on the seismic network quality if we try to establish 481 which zones show higher activity or when we need to avoid biased locations. In these situations, 482 3D models could help us to obtain constrained solutions. 483

In the second relocation, the seismicity appears confined to an area close to the 484 southernmost boundary of mTAB3D. Due to the unfavorable distribution of stations for this 485 sequence, we observe that the accuracy obtained by mIGN1D and mTAB3D is worse, especially 486 for the vertical uncertainty (Table 3). However, we noted that choosing between 1D or 3D 487 models could imply an important decision that may affect our results even in this adverse setting 488 (Figure S7 in Supplementary Material). Waves traveling longer distances could propagate across 489 different units that somewhat influence their path, leading to higher uncertainties. The Al-490 Hoceima sequence illustrates how we may reduce possible biased solutions when the velocity 491 model comprises important boundaries, such as the Al-Idrisi fault between two crustal domains. 492

Although mTAB3D shows how 3D velocity models improve the hypocenter location in complex tectonic areas, there are other fields where these models may be applied. For example, physics-based simulations include 3D velocity models in the workflow for computing ground motion predictions (Bradley, 2019; De la Puente et al., 2020). The historical and instrumental catalogs demonstrate that the westernmost Mediterranean is prone to damaging earthquakes, and mTAB3D may become an additional tool for obtaining ground-shaking maps, which are crucial for seismic hazard analysis and engineering studies. Lastly, the number and frequency of works 500 carried out in our study area allow us to incorporate more data into this model to enhance its 501 resolution and quality.

#### 502 5 Conclusions

Reliable earthquake absolute locations are crucial for seismotectonic studies in complex 503 tectonic areas. The westernmost Mediterranean region, due to its complicated geological history, 504 includes domains with variable geometries and properties that may affect wave propagation once 505 506 an earthquake occurs. In this context, we gathered data from previous studies at local and regional scales to build a P-wave velocity model (mTAB3D) consisting of a 3D grid that 507 accounts for the lateral heterogeneity in our study area. Our model is divided into several blocks 508 to represent the most characteristic bodies in the region (air/water, sedimentary basins, 509 basements of different natures, and upper mantle). Despite the presence of areas, usually situated 510 at the edges of the grid, where the scarcity or low resolution of data sources could produce a 511 priori uncertainties in the resolved geometries, we are confident that the mTAB3D is reliable and 512 realistic enough to reflect significant features such as the crustal thinning in the West Alboran 513

Basin, and the structures that bound various crustal domains, both onshore and offshore.

515 We tested the performance of this model by relocating two seismic catalogs: the first is a 516 continuous dataset recorded between 2018-2022 in the EBSZ, and the second comprises arrival

517 times recorded during the Al-Hoceima seismic sequence in 2016. We compared each relocation

- against a catalog built after relocating with a 1D velocity model (mIGN1D) using the same
- 519 dataset and following the same procedure. For the EBSZ catalog, we observed lower
- 520 uncertainties in mTAB3D than in mIGN1D when resolving the epicentral location. The
- 521 difference between results is especially emphasized when comparing errH and errZ in the subsets
- of low-magnitude earthquakes recorded by a few stations. In the case of the Al-Hoceima
   sequence, we applied the recent NLL-SSST method (Lomax & Savvaidis, 2022) and, although
- hypocenters lie close to the southernmost border where the wider azimuthal gap may influence
- the reliability, mTAB3D achieved the lowest uncertainty in every subset of quality and allowed
- 526 us to discriminate different clusters. In both catalogs, the new hypocenters correlate reasonably
- 527 well with the active faults present in both studied areas or enhance the seismic clusters.

Accordingly, mTAB3D may provide stronger hypocentral locations that may result in a quality improvement for seismotectonic studies. Finally, although we applied this model to recent seismicity, it can be valuable for studies focused on prior series where poorly constrained velocity models lead to unfavorable or biased locations. This methodology may be implemented when re-interpreting some past earthquakes and, thus, to a better understanding of southern lberia and the westernmost Mediterranean seismogenic processes.

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541 Investing in your future".

## 542 **Open Research**

543 Earthquake phase arrival seismic stations dataset was accessed through the Spanish

- 544 Seismic Network (<u>https://www.ign.es/web/ign/portal/sis-catalogo-terremotos</u>). Focal
- 545 mechanisms were obtained from the Spanish Seismic Network seismic moment tensor catalog
- 546 (https://www.ign.es/web/ign/portal/tensor-momento-sismico/-/tensor-momento-
- 547 <u>sismico/getExplotacion</u>, last accessed December 2022). Main active faults traces are from QAFI
- v.4. (<u>http://info.igme.es/qafi/</u>, last accessed December 2022). Geophysical Information System
- available from Instituto Geológico y Minero (IGME) avalilable at <u>http://info.igme.es/SIGEOF/</u>
- 550 (last accessed December 2017). Nonlinloc software can be accessed through its GitHub
- 551 repository (<u>https://github.com/alomax/NonLinLoc</u>). Figures and maps were built using the
- 552 Generic Mapping Tools software (Wessel et al., 2019). This manuscript was written using
- 553 LibreOffice Writer (<u>https://www.libreoffice.org</u>, last accessed February 2023). Supplementary
- material for this article includes tables and text with the summary of data used and the procedure
- to build mTAB3D. Raw grid files and metadata of mTAB3D model in under internal review for
- being released in a public repository.

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1044 **Figure 1**. Tectonic and geological setting of the westernmost Mediterranean (IGME, 2021). The

rectangle within the regional map in the inset represents the area that covers mTAB3D. Two gray

arrows represent the convergence direction between Iberia and Africa (Serpelloni et al., 2007).

The main faults (red lines) are from QAFI v.4. Database (IGME, 2022). BSF: Bajo Segura fault;
CrF: Crevillente fault; AMF: Alhama de Murcia fault; PF: Palomares fault; CbF: Carboneras

- 1048 CrF: Crevillente fault; AMF: Alhama de Murcia fault; PF: Palomares fault; CbF: Carboneras
- 1049 fault; YF: Yusuf fault; AIF: Al-Idrisi fault; WAB: West Alboran Basin; EAB: East Alboran Basin;
- 1050 SAB: South Alboran Basin.
- 1051 **Figure 2**. Map showing the distribution of data sources for building mTAB3D. The dashed
- 1052 rectangle frames mark the area covered in the model presented in Sánchez-Roldán et al. (2021).
- 1053 The depth cross sections depict the depth and lateral velocity variation of mTAB3D.

1054 **Figure 3**. Absolute earthquake locations obtained with mIGN (a) and mTAB3D (b). Red

- 1055 triangles represent broad-band stations and accelerometers from the Spanish Seismic Network.
- 1056 The dashed square in Figure 3b shows the location of the Mula-Archena seismic sequence in
- 1057 2018. The dashed red lines in the cross sections mark the 15 km depth. CrF: Crevillente fault,
- 1058 AMF: Alhama de Murcia fault; CF: Carrascoy fault; LTF: Los Tollos fault; PF: Palomares fault.
- 1059 **Figure 4**. Maps showing the density of epicenters after relocations with mIGN1D (a) and
- 1060 mTAB3D (b). The scale bar represents the normalized number of epicenters per unit of area (10
- $1061 \text{ km}^2$ ), and the map only shows those areas with density greater or equal to 5 epicenters /  $10 \text{km}^2$ .

**Figure 5**. Absolute earthquake locations obtained with mIGN (a) and mTAB3D (b) following the NLL-SSST procedure. The pink circles show the location of the three principal clusters, and the

pink star depicts the Mw 6.3 mainquake of the sequence. The dashed red lines in the cross

sections mark the 16 km depth. Red triangles represent broad-band stations and accelerometers

1066 from the Spanish Seismic Network. SAR: South Alboran Ridge; AIF: Al-Idrisi fault; TB: Tofiño-

1067 Xauen Bank; JF: Trougout fault; NF: Nekor fault.

1068 **Figure 6**. Maps showing the density of epicenters after relocations with mIGN1D (a) and

- 1069 mTAB3D (b). The pink circles show the location of the three principal clusters. The scale bar
- 1070 represents the normalized number of epicenters per unit of area ( $10 \text{ km}^2$ ), and the map only
- 1071 shows those areas with density greater or equal to 5 epicenters  $/ 10 \text{km}^2$  (contour lines every 10 1072 events).
  - 1073 **Figure 7**. Detail map of the Mula-Archena seismic sequence during 2018 (Fig. 3b). (a):

1074 Epicentral distribution, as well as some faults and tectonic units. Black dashed lines delimit the

1075 hypocenters that are projected in the a-a' section. (b): Projected section (a-a') of the relocated

1076 hypocenters. The heatmap shows the density of events normalized to the number of events per 10

1077 km<sup>2</sup> (contour lines every 10 events). The dashed line indicates the inferred boundary between the

basement (pink) and sedimentary rocks (yellow). Focal mechanism of the Mw 3.9 mainshockfrom the moment tensor catalog of the Spanish Seismic Network (see Open Research section).

10/9 Ifom the moment tensor catalog of the Spanish Seismic Network (see Open Research section). 1080 LBF: Los Baños fault; MAF: Mula-Archena fault; TRF: Tollos-Rodeos fault; BqF: Barqueros

1081 fault; AMF: Alhama de Murcia fault.

Figure 8. Detail map of the Al-Hoceima seismic sequence during 2016 (Fig. 4). (a): Epicentral
 distribution and heatmap showing the areas with highest density of earthquakes. On the right

- 1084 panels, we include three depth sections projected across the principal clusters (6b, 6c, and 6d).
- 1085 The heatmaps show the density of events normalized to the number of events per  $10 \text{ km}^2$
- 1086 (contour lines every 10 events). Focal mechanisms from Buforn et al. (2017) plotted at their
- original location. SAR: South Alboran Ridge; AIF: Al-Idrisi fault; TB: Tofiño-Xauen Bank; JF:
   Trougout fault.
- **Table 1.** Criteria for event location in NLL-SSST. Here, we show the residuals' root mean square, *t*he minimum number of readings, the maximum azimuthal gap, the P-arrival and S-
- 1091 arrival rms and the ellipsoid major semi-axis length.
- Table 2. Uncertainty values grouped in four subsets according to the number of arrivals used in
   the relocation for mIGN and mTAB3D (values in kilometers).
- **Table 3.** Uncertainty values grouped in four subsets according to the number of arrivals used in
   the relocation for mIGN and mTAB3D (values in kilometers).

1	Earth and Space Science
2	Supporting Information for
3 4	New 3D velocity model (mTAB3D) for absolute hypocenter location in southern Iberia and the westernmost Mediterranean.
5 6	José Luis Sánchez-Roldán <sup>1</sup> , José A. Álvarez-Gómez <sup>1</sup> , José J. Martínez-Díaz <sup>1,2</sup> , Paula Herrero- Barbero <sup>3</sup> , Hector Perea <sup>4</sup> , Juan V. Cantavella <sup>5</sup> , and Lucía Lozano <sup>5</sup>
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12	
13 14	Contents of this file
15 16 17	Text S1 Figures S1 to S7 Table S1
19	Additional Supporting Information (Files uploaded separately)
20 21	Captions for Files S1 to S8
22	
23	Introduction
24 25 26 27	Text S1 explains all the steps carried out to make the 3-D P-wave model (mTAB3D). Figures with information about the 3D-velocity model presented in this work (Fig. S1), the seismic stations used for the relocation (Fig. S2), VP/VS ratio (Figs. S3 & S5), and uncertainties (Figs. S4 & S6). Figure S4 shows additional information related to the Eastern Betics Shear Zone

- 27 & S6). Figure S4 shows additional information related to the Eastern Betics Shear Zone
   28 relocation, and Figure S7 compares different relocations for large earthquakes of the Al
- 29 Hoceima seismic sequence. Table S1 summarizes the data used for building the 3-D P-wave
- 30 local model (mTAB3D). Finally, Files S1 to S8 have the hypocentral solutions information of
- 31 every relocation computed in this study.

## 32 **Text S1.**

The following lines explain how to model the structures and lateral heterogeneities in our study area to build the 3D P-wave velocity model. However, these steps can be replicated and used in other areas to obtain new 3D velocity models. We recommend using some GIS tools during the procedure.

37

38 Firstly, we gather every data related to the distribution and geometries of the tectonic 39 units and structures within our study area. The most relevant works will be those that define, 40 with enough resolution, the boundaries of sedimentary basins, basement surfaces, or the 41 Moho. Also, the works that image boundaries between structures with contrasting properties, 42 such as the case of sedimentary basins and basements bounded by faults. In Table S1 we show 43 the data sources used in this work. To avoid possible boundary effects due to the outwards 44 lack of data, we suggest setting a smaller model size, which will help to build the model using 45 areas with similar data density. For example, although we gathered enough data to build a 46 model within the approximate extension west: -7°, east: 2°, south: 34.5° and north: 40°, we 47 finally cut our model extension to west: -6°, east: 1°, south: 35° and north: 39°.

48

49 After gathering the data, we group them depending on the category or subject of study 50 to calculate the surfaces used in later steps. For example, we grouped those points that show 51 values of the Moho depth into a specific category, those related to the basement top into 52 another one, etc. Next, we obtain a 3D mesh (similar to a DTM) interpolating among points of 53 the same category to create a surface (e.g.: Moho boundary, basement top, etc.). We chose the 54 nearest neighbor interpolation method to make every 3D mesh. Then, we intersect these 3D 55 meshes against horizontal layers separated every 1 km. We do this to extract the slice 56 shapefiles every 1 km with the contour lines of that surface, which refers to the depth at which 57 we found each surface of interest.

58

59 After completing all the slices, we cut them to their final maximum extension. Then, we 60 calculate the intersection of the different surfaces at the same depth to define the geometry of 61 the modeled units. For example, we make the geometry of a sedimentary basin by the 62 intersection of the basement top surface and the topography surface (or bathymetry if it is an 63 offshore sedimentary basin). This procedure is repeated slice by slice until we have completed 64 every depth layer in our model. After this, we will obtain a set of shapefiles (as many as the 65 desired depth of our model), where every shapefile is divided into different planar geometries. 66 This division depends on the number of tectonic units at every depth layer. Readers should 67 note that the model will be more complicated at the first depth layers since the data density is 68 higher. The data availability will decrease progressively downwards, leading to less complex 69 geometries.

70

We must estimate the P-wave velocity and its evolution in depth. This procedure implies a bibliographic review of the geologic composition and rheology of the type and features of rocks within the tectonic units of our study area. After this, if we know the average composition of the tectonic units, we can evaluate the P-wave velocity from empirical relations (Christensen & Mooney, 1995; Brocher, 2005) based on the density variation in depth. With these relations, we create individual velocity profiles (in km/s) for each tectonic unit in our model (Fig. S1).

78

After completing all the slices at every depth layer and all the velocity profiles, we select tectonic units within each slice shapefile and assign it its corresponding velocity value based on its particular profile estimated previously. As a result, we will obtain a slice shapefile divided into different units, where every tectonic unit will have a value that refers to the specific P-wave velocity at the depth of the slice.

84

85 When we complete the previous procedure for every depth slice, we sample each slice 86 shapefile following a 1 km interval (both on the x-axis and y-axis). We will obtain points that 87 will be extracted and saved in a text file with the following columns: "X", "Y", "Z" and "VP". The 88 "X" and "Y" columns refer to the longitude and latitude coordinates (in degrees), respectively, 89 the "Z" to the depth (in km) and the "VP" to the P-wave velocity at that point (in km/s). With 90 that, we will create several files equal to the number of depth slices of our model, where each 91 file contains the corresponding 3D coordinates and velocity value.

92

We will convert the coordinates from geographic to cartesian units. For this, we find the center point of the slice defined in the text file and set its geographic coordinates (longitude, latitude) to 0. For example, the center point of our model is longitude: -2.5° and latitude: 37°, so we need to change that to longitude: 0 and latitude: 0. Positive values will be located upwards and to the right, so the lower left corner of the slice would be X: -305 and Y: -221.

98

99 Finally, we can merge all the text converted text files and then compute .hdr and .buf

files that we will need to calculate the travel times at each station using Grid2Time withinNonlinloc.





**Figure S1**. P-wave velocity profiles calculated for every crustal domain (a) and the mantle (b).





- 113 **Figure S2.** Elevation map of the study region showing the seismic stations used in this work
- 114 and their distribution (IGN, 2020). Red triangles: broad-band stations; purple triangles:
- 115 accelerometers.





116 Figure S3. Wadati diagram comparing t<sub>s</sub>-t<sub>P</sub> values against t<sub>P</sub> absolute for earthquakes in the



#### 117

124 **Figure S4**. EBSZ 2018-2022 relocation results after using mIGN1D and mTAB3D. a, c: maps

125 showing the number and distribution of the hypocenters located closer than or at 1 km of the

- 126 traces of the main faults (black contours around the red lines). b, d: Density maps of the same
- 127 epicenters. The scale bar represents the normalized number of epicenters per unit of area (10
- 128 km<sup>2</sup>), and the map only shows those areas with density greater or equal to 2 epicenters /
- 129 10km<sup>2</sup>. CrF: Crevillente fault, AMF: Alhama de Murcia fault; CR: Carrascoy fault; LTF: Los Tollos
- 130 fault; PF: Palomares fault.





126

- 131 **Figure S5**. Histograms comparing errH (a) and errZ (b) earthquake by earthquake for Eastern
- 132 Betics Shear Zone relocation. Values are obtained after subtracting mIGN1D uncertainty from
- 133 mTAB3D uncertainty, thus negative values (blue color) imply that, for a specific earthquake, the
- result obtained using mIGN1D is worse than the one computed with mTAB3D, and vice-versa when
- 135 referring to positive values (orange color). Black dashed line marks the error mean value.





137 Figure S6. Histograms comparing errH (a) and errZ (b) earthquake by earthquake for Al Hocecima

138 seismic sequence relocation. Values are obtained after subtracting mIGN1D uncertainty from

139 mTAB3D uncertainty, thus negative values (blue color) imply that, for a specific earthquake, the

result obtained using mIGN1D is worse than the one computed with mTAB3D, and vice-versa when

141 referring to positive values (orange color). Black dashed line marks the error mean value.

138



- 139 **Figure S7**. Maps comparing the results after relocating the earthquakes of the Al-Hoceima seismic
- sequence with Mw>3.9 using different velocity models. (A) Hypocenters from Buforn et al. (2017)
- 141 and 3D velocity model from El Moudnib et al. (2015). (B) Hypocenters from Gràcia et al. (2019) and
- 142 local 1D velocity model from Grevemeyer et al. (2015). (C) Results presented in this study using
- 143 mTAB3D. We can observe variations in hypocenter location and clustering. For example, results
- 144 from Buforn et al. (2017) tend to locate very shallow earthquakes (<2 km in depth) in a cluster close
- 145 to the AIF compressive step-over, whereas hypocenters from Gràcia et al. (2019) and our results are
- 146 shifted to the east. Additionally, Gràcia et al. achieve a high clustering in this area between AIF and
- 147 SAR. Results from Buforn et al. (2017) and this study show hypocenters around the southernmost
- 148 end of AIF. However, hypocenters from Gràcia et al. (2019) are scattered around this zone and
- shifted southwards. While hypocenters from Buforn et al. (2017) and this study are restricted to the
- 150 first ~20 km in depth, Gràcia et al. (2019) results show the wider depth range (from 2 km to 32 km)
- and high clustering around 5 km that seems to be related to a possible boundary within the 1D
- 152 velocity model from Grevemeyer et al. (2015).
- 153
- 154

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Surface	Data	Source		
Air/Watar	Topography	NOAA National Geophysical Data Center (2009)		
All/ Water	Bathymetry	GEBCO Compilation Group (2022)		
	Seismic reflection profiles	Chevron and Enadimsa ( <u>http://info.igme.es/SIGEOF/</u> ) Medaouri et al. (2014) Marín-Lechado et al. (2017) Martínez-García, et al. (2017) Gómez de la Peña et al. (2018) d'Acremont et al. (2020) Gómez de la Peña et al. (2021)		
		Amores Lahidalga et al. (2002)		
Neogene sedimentary	Gravity anomaly maps	García-Castellanos et al. (2002)		
basins		Jiménez-Pintor et al. (2002)		
		Rodríguez-Fernández et al. (2004)		
		Sanz de Galdeano et al. (2007)		
		Alfaro et al. (2008)		
		Haberland et al. (2017)		
		IGME (2017)		
		Clariana-García et al. (2021)		
		Marín-Lechado et al. (2017)		
	Geological mapping	Martín-Serrano et al. (2021)		
Basement (External/Internal zones	from IGME	Montes et al. (2021)		
and cover units)		Roldán et al. (2021)		
	Dessions for the	Mancilla et al. (2015)		
	studies	Mancilla and Díaz (2015)		

		Carballo et al. (2015)	
	Deep seismic profiles	Díaz and Gallart (2009)	
		Booth-Rea et al. (2018)	
		Gómez de la Peña et al. (2018)	
		d'Acremont et al. (2020)	
Crustal thickness (Moho topography)	Receiver functions	Mancilla et al. (2015)	
() () () () () () () () () () () () () (	Ambient noise	Palomeras et al. (2017)	
	Heat flow	Torne et al. (2015)	
		Fernàndez et al. (1998)	
		Insua-Arévalo (2008)	
	Gravity modeling	Pedrera et al. (2020)	

156 **Table S1.** Summary of the data used to build the 3-D P-wave velocity model mTAB3D. For each

157 layer we divide the table according the type of data and the source. Note that some sources

158 may appear more than once given that they were used for assessing two or more layers.

159

- 160
- 161
- 162 **Files**
- 163

164 We provide the eight files with the absolute locations and the uncertainty parameters

- 165 (extracted from the 68% confidence ellipse of the PDF's) obtained after performing the
- 166 relocation using mIGN1D and mTAB3D. The absolute location files follow this format:
- 167 origin\_time(YYYY-mm-ddTDD:HH:MM) longitude(°) latitude(°) depth(km) magnitude(mbLg)
- 168 origin\_time: Hypocenter's origin time after the relocation.
- longitude: Hypocenter's longitude in decimal degrees after the relocation.
- latitude: Hypocenter's latitude in decimal degrees after the relocation.
- depth: Hypocenter's depth in kilometers.
- magnitude: Hypocenter's magnitude (mbLg) computed by the Spanish Seismic Network.
   The files with the uncertainty values:
- horizontal uncertainty(km) vertical uncertainty(km) rms(s) no arrivals
- horizontal\_uncertainty: Obtained after computing the geometrical mean between the
- 176 horizontal semi-minor and semi-major axes of the 68% confidence ellipse in kilometers.
- vertical\_uncertainty: Vertical semi-axis of the 68% confidence ellipse.
- rms: root-mean-square of residuals at maximum likelihood or expectation hypocenter.
- no\_arrivals: number of readings used for the absolute location.
- 180
- 181 **File S1**. File\_S1.dat: Eastern Betics Shear Zone catalog's absolute locations with mIGN1D.
- 182 **File S2**. File\_S2.dat: Eastern Betics Shear Zone catalog's statistics with mIGN1D.
- 183 **File S3**. File\_S3.dat: Eastern Betics Shear Zone catalog's absolute locations with mTAB3D.
- 184 **File S4**. File\_S4.dat: Eastern Betics Shear Zone catalog's statistics with mTAB3D.
- 185 **File S5**. File\_S5.dat: Al Hoceima 2016 catalog's absolute locations with mIGN1D.
- 186 **File S6**. File\_S6.dat: Al Hoceima 2016 catalog's statistics with mIGN1D.
- 187 **File S7**. File\_S7.dat: Al Hoceima 2016 catalog's absolute locations with mTAB3D.
- 188 **File S8**. File\_S8.dat: Al Hoceima 2016 catalog's statistics with mTAB3D.
- 189