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Revisiting the 1968 Belice valley (western Sicily) earthquake sequence

Domenico Di Giacomo[*,1], István Bondár[2]

(1) International Seismological Centre, Thatcham, UK
(2) Seismic Location Services, Lagos, Portugal

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Abstract

We revisit the earthquake sequence that struck the Belice valley (western Sicily) in January-February 1968. The sequence is characterized by several moderate earthquakes which occurred in close proximity in time and space, with the largest event recorded in the early hours of the 15th of January. To date we gathered the most comprehensive parametric data set of arrival times and surface wave magnitude (MS) readings in order to facilitate relocations and MS reassessments, respectively. The relocation results put the events in the middle-lower crust, with the hypocentres tightened compared to previous results. Our revised MS estimations for ten of the largest events of the sequence support a near-6 magnitude for the mainshock. We show that our MS results are in line with the information provided by the instrumental parametric data available, not just for the mainshock but also within the broader context of the entire sequence. Different from recent estimations, our results support a magnitude above 5.5 for the mainshock, but, at the same time, suggest that the mainshock magnitude value of 6.4 reported in various catalogues is overestimated.

Keywords: Belice valley; 1968 earthquake sequence; Parametric instrumental data; Relocation; Magnitude reassessment

1. Introduction

In January-February 1968 an intense seismic sequence occurred along the valley of the Belice river in western Sicily, resulting in widespread damage to several local communities (e.g., Azzaro et al., 2020; Guidoboni et al., 2019).

To date, this sequence includes the largest earthquakes instrumentally recorded in western Sicily, and, as such, it has been the subject of several studies[1], from early analyses by De Panfilis and Marcelli (1968), Marcelli and Pannocchia (1971), Bottari (1973) to recent reassessments by Orecchio et al. (2021) and Scarfì et al. (2025).

Only 24 events (arguably the largest) could be instrumentally located (e.g., International Seismological Centre, 2025a) out of the approximately 300 earthquakes (De Panfilis and Marcelli, 1968) detected at the time. As reported in Table 1, the sequence started (in an instrumental sense) with a moderate earthquake (short-period body-wave

1 A more comprehensive list of references studying the 1968 Belice valley sequence can be found at http://www.isc.ac.uk/cgi-bin/FormatBibprint.pl?evid=827285, last accessed November 2025.

magnitude mb = 5.2) at 12:28 (all times are in UTC) of January 14th and was followed by several earthquakes that culminated with the mainshock (magnitude estimations vary, as discussed later) 13.5 hours later, at 02:01 of January the 15th. The sequence then continued with events below magnitude 5 (except for two aftershocks on January 16th and 25th, reported with mb of about 5.1 in Table 1) until the beginning of March, when the last teleseismically recorded

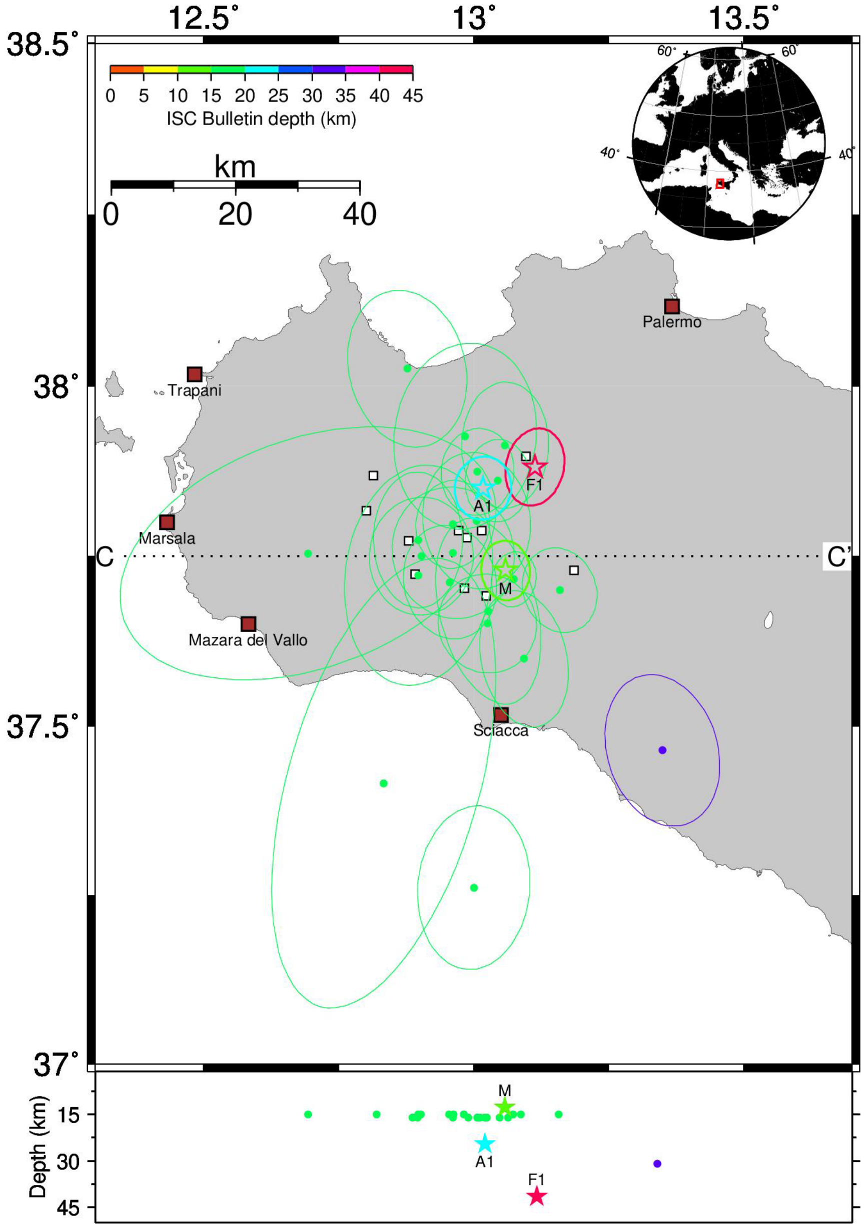

Figure 1. ISC Bulletin locations (Storchak et al., 2017; International Seismological Centre, 2025a) of the 1968 Belice valley sequence between 14 January and 4 March (24 earthquakes in total). Each epicentre (filled circle and star symbols) is shown with corresponding uncertainty (as computed by the ISC location algorithm, see Bondár and Storchak, 2011) and colour-coded by depth. Note that all events have depth fixed to a default grid value except the three largest ones, which are plotted with star symbols and labelled as F1 (largest foreshock), M (mainshock) and A1 (largest aftershock) and studied by Orecchio et al. (2021). The full details of the location parameters are listed in Table S1 in the Supplementary Material, whereas in Table 1 we only include parameters that are more relevant for the reader considering the results that will be discussed in later sections. The white squares are the localities listed in the Italian Macroseismic Database (Locati et al., 2022) with intensities of 8 and above for the mainshock (see Table S2 in the Supplementary Material). Selected main cities in western Sicily (brown squares) are shown for reference. The E-W dotted line at latitude 37.75° is the trace of the cross-section (C-C′ labels on the map) shown below the map.

earthquake occurred. Figure 1 shows the locations of the events in Table 1 as currently available in the bulletin of the International Seismological Centre (ISC, www.isc.ac.uk, Storchak et al., 2017; International Seismological Centre, 2025a).

Considering the capabilities of the local and international seismic network of the time (analogue instruments of various types, see, e.g., Kanamori (1988), Storchak et al., 2015) and the lack of stations in the local distance range (the closest seismic stations in the cities of Messina and Reggio Calabria are over 200 km distance from the epicentral area), it is not surprising that there is a large variation in the location (particularly in terms of depth) and magnitude estimations of the 1968 Belice valley earthquakes when comparing results from different authors and catalogues. For example, the first location analyses by De Panfillis and Marcelli (1968) as well as by Marcelli and Pannocchia (1971) provide depth estimates around 30 km, whereas Bottari (1973) proposes shallower depths, with several earthquakes below 12 km. More recently, Orecchio et al. (2021) obtained depth of 30-34 km from the moment tensor solutions of the three largest earthquakes and depths of 21 and 12 km from the Bayloc nonlinear hypocentre location method (Presti et al., 2004, 2008).

However, it is probably in terms of magnitude that the largest variations are observed, particularly for the mainshock. Indeed, estimations span, among others, from an equivalent moment magnitude Mw of 6.4 (mean between macroseismic and instrumental magnitudes) in the "Catalogo Parametrico dei Terremoti Italiani" (CPTI v4.0, https://emidius.mi.ingv.it/CPTI15-DBMI15/, last accessed January 2026) by Rovida et al. (2020, 2022), in line with the estimation by North (1977), to a surface wave magnitude (MS) of 6.0 by the ISC and an Mw of 5.2 by Orecchio et al. (2021). Finally, in the most recent work by Scarfì et al. (2025), it is suggested for the mainshock an Mw of 5.7 to better fit the ground motion.

In this context we aim to reappraise the January-February 1968 Belice valley earthquakes by expanding the parametric data available in the ISC Bulletin (International Seismological Centre, 2025a) and including additional arrival times from the Bureau Central de l'Association Internationale de Sismologie (BCIS, 1968) as well as newly digitized surface wave data (Section 2) to facilitate relocation (Section 3) and magnitude reassessment (Section 4), respectively. Finally, we discuss our relocations and the robustness of the MS of the mainshock we propose here considering the overall reassessment of the sequence (Section 5).

2. Dataset

Here we describe the work done to improve the parametric data collection both in terms of arrival times (for relocation) and surface wave amplitude and periods (for MS reassessment). To the best of our knowledge, the parametric dataset we assembled for relocation and MS reassessment is the most comprehensive to date and is available in the Supplementary Material.

2.1 Arrival times

Our starting dataset for relocating the 1968 Belice valley earthquakes comes from the reviewed solutions of the ISC Bulletin (Storchak et al., 2017; International Seismological Centre, 2025a). As reported in Table S1, the number of stations (nsta) for each event available in the ISC Bulletin goes from as small as 7 to over 100 for the largest events (175, 250 and 184 for earthquake F1, M and A1, respectively), corresponding to over 2000 body-wave arrival times for the entire sequence.

Since one of our aims is to get the best possible depth estimates for the sequence, we checked the reidentified depth phases in the ISC Bulletin by consulting the station printed bulletins (Di Giacomo et al., 2015a, 2022; International Seismological Centre, 2025b) or the listing in the BCIS (1968). This led us to update the reported phase as PP, S or null for ten arrival times associated to five earthquakes. Although such screening of the depth phases had a minimal impact on the initial dataset, it was fundamental to indicate that for every earthquake in the sequence (except for the last one in Table 1) several arrival times in the BCIS (1968) were not included in the ISC Bulletin. We therefore digitized the BCIS arrival times (see Di Giacomo and Storchak, 2023) from stations that are missing in the ISC Bulletin and integrated them in the ISC Bulletin dataset. This task allowed us to add between 8 and 45 arrival times per event for a total of 520 arrival times (345 P, 35 Pn, 33 S, 30 Sn, etc.) from about 90 stations worldwide. We note that among the stations with more arrival times added from the BCIS (1968) there are several in France (e.g., station

Table 1. Main parameters of the 1968 Belice valley earthquakes listed in the online ISC Bulletin (International Seismological Centre, 2025a) at the time of writing (January 2026). The full details of the location parameters are listed in Table S1 in the Supplementary Material. Event labels for the three largest events depicted with star symbols in Fig. 1 are reported in brackets in the ISC event identifier (ISC_Evid) column. The column listing ISC magnitudes (mb and MS) includes the magnitude uncertainty (smad, see Bondár and Storchak, 2011) and the number of stations used (nsta). The last column reports the magnitude listed in the "Catalogo Parametrico dei Terremoti Italiani" (CPTI v4.0, https://emidius.mi.ingv.it/CPTI15-DBMI15/, last accessed January 2026) by Rovida et al. (2020, 2022). The full CPTI listing for the 1968 Belice valley sequence is in Table S3 of the Supplementary Material.

ISC_Evid	ISC origin time (UTC)	mb ISC (smad nsta) | MS ISC (smad nsta)	CTPI MwDef (ErMwDef)[2]
827263	1968-01-14 12:28:25	5.20 (0.15 5)	5.1 (0.24)
827266	1968-01-14 13:15:45	4.69 (0.20 8)	4.9 (0.24)
827270	1968-01-14 15:48:32	4.60 (0.27 11)	4.84 (0.17)
827284 (F1)	1968-01-15 01:33:05	5.04 (0.10 20)	5.37 (0.18)
827285 (M)	1968-01-15 02:01:06	5.45 (0.23 25) | 6.03 (0.04 5)	6.41 (0.09)
827290	1968-01-15 03:18:39	4.55 (0.18 8)	4.57 (0.22)
827299	1968-01-15 10:25:08		
827307	1968-01-15 13:42:04		5.53 (0.59)
827310	1968-01-15 14:59:45	4.72 (0.30 4)	4.79 (0.31)
827314	1968-01-15 17:31:52		
827317	1968-01-15 18:22:52		4.46 (0.45)
827323	1968-01-15 22:19:56	4.60 (0.33 5)	4.79 (0.26)
827324	1968-01-16 00:54:06		4.79 (0.26)
827327	1968-01-16 04:09:16		
827341	1968-01-16 13:10:31		4.57 (0.35)
827349 (A1)	1968-01-16 16:42:47	5.08 (0.27 21)	5.45 (0.15)
827506	1968-01-21 02:39:05	4.27 (0.34 4)	4.6 (0.25)
827639	1968-01-25 09:56:48	5.12 (0.23 21)	5.37 (0.15)
827640	1968-01-25 10:04:16	4.20 (0.02 3)	4.26 (0.27)
827649	1968-01-25 14:35:31	4.37 (0.14 5)	4.46 (0.24)
827673	1968-01-26 08:02:17	4.69 (0.23 9)	4.79 (0.22)
825792	1968-02-05 11:17:38	4.36 (0.14 5)	4.36 (0.23)
826109	1968-02-12 16:26:03	4.48 (0.02 5)	4.66 (0.19)
824648	1968-03-04 23:37:58		4.46 (0.45)

codes LMR, SPF, LRG, LBF, HAU, CDF, CDR, see International Seismological Centre, 2025c, for station details in the International Registry of Seismograph Stations, hereafter referred to as IR). We also added arrivals in BCIS for station MSI (Messina ING) as the ISC Bulletin only listed arrivals from station MES (Messina University, or its equivalent MES1). Figure S1 in the Supplementary Material shows the station distribution for each earthquake (stations with arrival times sourced from BCIS shown in blue). The station distribution for the key earthquakes F1, M and A1 is shown in Figs. S1d, S1e and S1p, respectively. The augmented dataset here introduced is used in the relocation of the events in Table 1, with results shown in Section 3.

2.2 Surface wave data

In ISC routine operations MS is computed by the ISC location algorithm (Bondár and Storchak, 2011) for earthquakes with depth ≤60 km when surface wave data (displacement amplitudes measured with periods between 10 and 60 seconds, on vertical and horizontal components) is available for at least three stations between 20° and 160° distance.

As reported in Table 1, only the mainshock has an MS in the ISC Bulletin. One reason for that is due to an early policy adopted by the ISC to exclude long period amplitude measurements up to 1970, whereas short-period amplitude measurements (e.g., as provided by stations belonging to the World-Wide Standardized Seismograph Network, WWSSN, Oliver and Murphy, 1971), were integral part of ISC operations (as a result, most of the events in Table 1 include mb from ISC). To mitigate such gap in data collection, the ISC has set out, in the context of the ISC-GEM Catalogue (Storchak et al., 2015), to digitize station readings from printed bulletins (Di Giacomo et al., 2015a) that contain surface wave amplitude and periods. As a result of the readings digitized for the ISC-GEM Catalogue and then used in the ISC rebuild project (Storchak et al., 2017), the mainshock is listed in the ISC Bulletin with an MS of 6.0 from five stations (IR station codes UPP, GRS, MOS, TAS, MAG).

Since then, however, digitation work done to expand and improve the ISC-GEM Catalogue has continued, and MS readings from bulletins not considered before, particularly from European stations, have now been digitized. Therefore, surface wave data currently available is more comprehensive, and it includes enough readings for ten of the largest earthquakes of the Belice sequence, as summarized in Table 2. The surface wave readings available for these earthquakes allow us to reassess MS, as shown in Section 4.

Table 2. Summary of the MS readings now available for ten earthquakes of the 1968 Belice sequence. Station details are available in the IR. Codes reported in bold for the mainshock are for those stations with MS readings already available in the ISC Bulletin.

ISC_Evid	IR codes of the stations with MS readings
827263	CLL PRU KRA FUR
827266	VIE KRA TOL
827270	FUR MOX VIE CLL PRA UPP PRU KRA KIR TOL
827284 (F1)	FUR BRA MOX WAR UPP PRA VIE DUR KIR PRU APA NIE TOL
827285 (M)	WAR **GRS** BKR BUC **SIM** PRU FUR PRA **MOS** MOX RIV TLG ZAG* ERE **BRA DBN** KHO VIE RBN UZH SEM KAT DUR KIS **UPP** BEO **HRB** APA **TAS** KIR PUL KRA **MAG** NVL TOL TIK NIE RAC
827317	PRU MOX UPP CLL
827341	MOX PRU KIR
827349 (A1)	WAR BRA VIE PRU MOX PRA DUR UPP APA DBN CLL BEO KIR SRO FUR KRA HRB NIE TOL
827639	FUR ZAG* BRA PRU PRA KRA DUR APA DBN UPP MOX KIR BEO VIE CLL NIE TOL
827649	MOX CLL PRU

3. Relocations

Our objective for performing the relocation of the Belice valley sequence was to obtain more accurate locations and more reliable depth estimates for the events, as event depth can also affect magnitude estimates. To achieve this goal, we apply a two-step approach by relocating the events first with a single-event location algorithm to obtain a homogeneous bulletin that also includes the previously unreported BCIS arrivals, and then, using the results as input, relocate the events with a non-linear multiple-event location algorithm. This approach has already been successfully applied to the Caucasus region (Bondár et al., 2024).

To prepare for simultaneously locating the entire sequence with a multiple-event location algorithm, we relocate the events so that we can include the BCIS arrivals that were originally not in the ISC Bulletin. This relocation is performed with the *iLoc* (Bondár et al., 2015) single-event location algorithm, a development of the ISC locator (Bondár and Storchak, 2011). *iLoc* itself is further developed by adding new features, such as the use of back azimuth and slowness measurements together with arrival times in the location, as well as obtaining travel-time predictions from the global 3D crust and upper mantle model, Regional Seismic Travel Times (RSTT, Myers et al., 2010, Begnaud et al., 2021a, 2021b). Owing to the use of a 3D velocity model and accounting for correlated travel-time prediction errors that arise when ray paths from neighbouring stations traverse through unmodeled velocity structures, *iLoc* is well suited for improving locations for events recorded by severely unbalanced station networks such as ours, where there are hardly any stations to the South of the sequence.

Using the *iLoc* results as input, we continued locating events with *Bayesloc*, a non-linear multiple-event location algorithm (Myers et al., 2007, 2009), that solves the multiple-event location problem with Markov Chain Monte Carlo simulation to sample the joint probability distribution postulated by Bayes' theorem. The joint *a posteriori* distribution contains all multiple-event parameters (hypocentres, picking errors, travel-time predictions with corrections as well as phase labels) as a product of *a priori* estimates of hypocentres, phase labels, travel-time corrections and picking errors, and conditional probability distributions of travel-times and arrival times that are conditional on the hypocentres themselves, on the computed travel-times and their corrections, phase labels and their corresponding pick precisions.

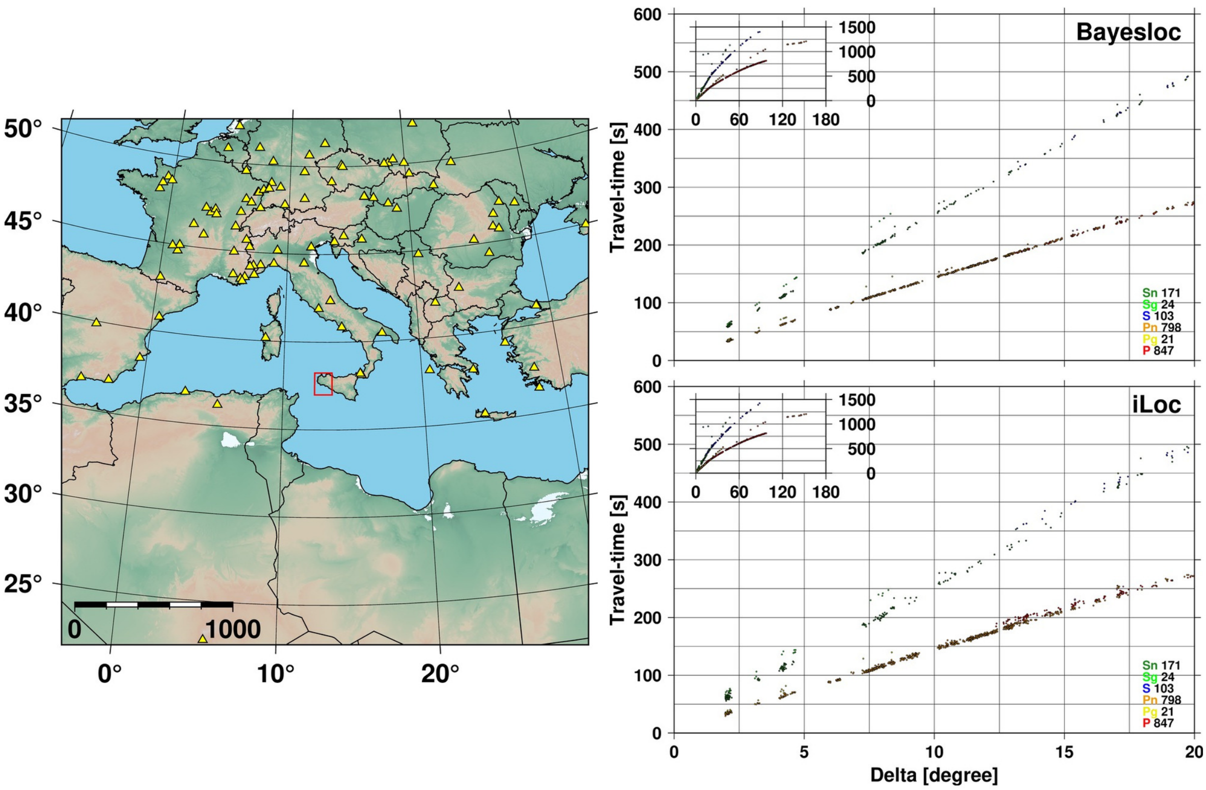

Figure 2. Map of the regional network used in the relocations and the observed travel-time curves in the a) *iLoc* and b) *Bayesloc* relocations. The insets on the top left show the travel times over the entire distance range. *Bayesloc* obtains better travel-time estimates by adjusting the slope and intersection for the travel-time curve of each phase.

During its iterations the algorithm takes into account the probability that a phase is incorrectly identified and allows for relabelling the phase. It also estimates path and phase specific corrections by adjusting the slope and shift of the travel-time curve for every phase. Figure 2 shows the travel-time curves for the *iLoc* locations and those obtained by *Bayesloc* after 10,000 iterations with 10 Markov chains.

By finding better travel-time estimates and correcting for phase identification errors, the algorithm behaves robustly against outliers, tightens the seismicity and improves the depth distribution and reduces location uncertainty estimates (e.g., Myers et al., 2011; Simmons et al., 2012; Gibbons et al., 2017; Schardong et al., 2021). Figure 3 shows that *Bayesloc* considerably tightened the Belice sequence locations, moved the largest events closer together, and most importantly, determined the depth of all events to be in the crust. In Section 5 we further discuss our relocation results with those from the recent literature.

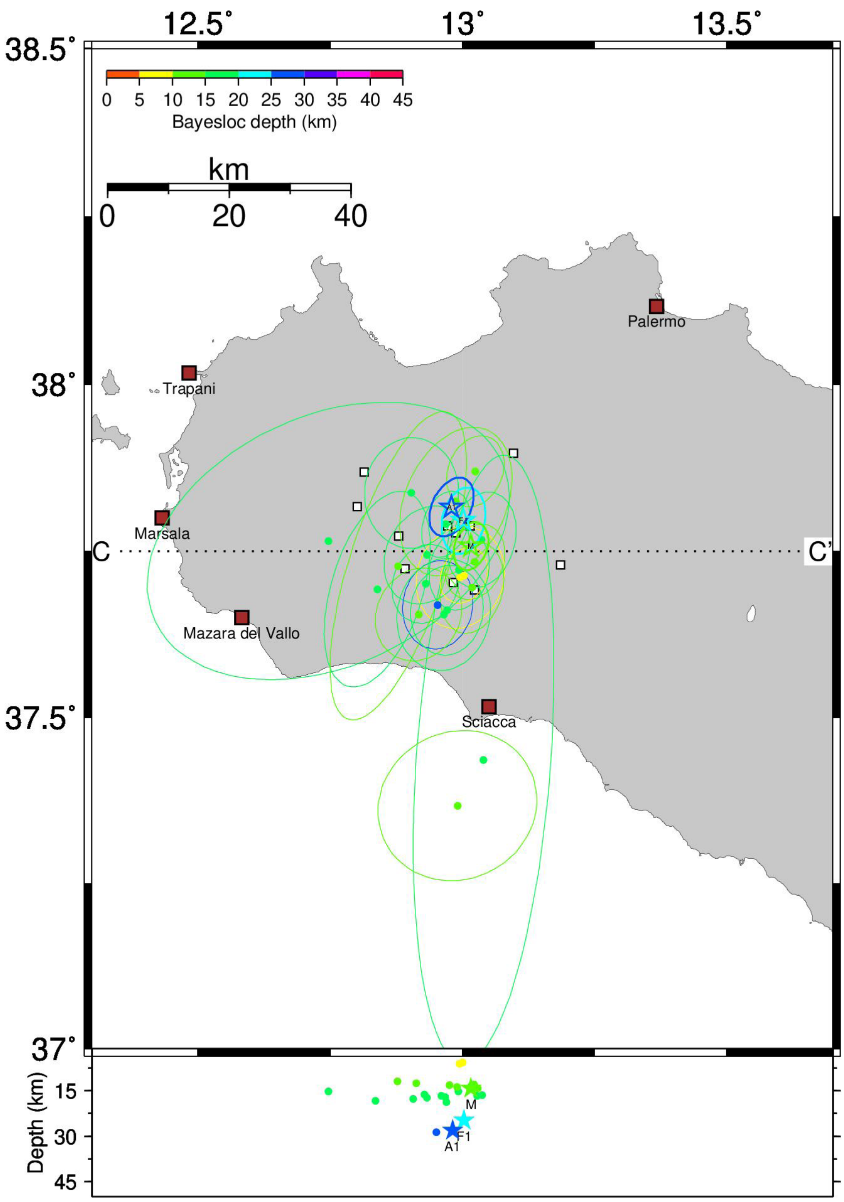

Figure 3. As in Fig. 1 but with locations obtained from *Bayesloc* and with the augmented dataset of arrival times.

4. Magnitude reassessment

Using the relocation results just discussed, we computed MS with the ISC location algorithm by fixing the depth as obtained in Section 3. Emphasis here is given to the MS results as they are largely new and bring important elements for the discussion of Section 5. The MS results are also available in the Supplementary Material in a dedicated file (Belice1968_MS_data.log) which mimics the format of the ISC MS dataset (Di Giacomo and Storchak, 2022). We do not provide a dedicated file for mb as the data is fully available in the ISC Bulletin, and we did not add mb related data for this work.

For the ten earthquakes for which we recomputed MS we applied the same expansion of period and distance ranges described in Di Giacomo et al. (2015b) and Di Giacomo and Storchak (2022). In short, instead of using the ISC standard distance and period range of 20°-160° and 10-60 s, respectively, we expand the minimum distance to 5° and minimum period to 5 s, in line with the broad-band MS computation recommended by IASPEI (2013). Such MS expansion is allowed for the data we have gathered as the MS measurements for the 1968 Belice sequence are not limited to strict amplitude measurements around 20 s, which are known to underestimate MS if used below 20° distance (Bormann et al., 2009, 2013). Furthermore, Di Giacomo and Storchak (2022) have shown the benefits of the MS expansion (in case of equivalent broad-band station measurements) as the event MS can be based on a larger number of stations and it can allow MS estimates for light (i.e., magnitude between 4 and 5) pre-digital earthquakes (as we can consider the case of the 1968 Belice valley earthquakes).

For the MS data we use here the shorter distance is 8.4° and 21 (out of about 250) surface wave measurements have period below 10 s (full details in the Supplementary Material). The MS results are summarized in Table 3.

The spatial distribution of the MS stations for the key earthquakes F1, M and A1 is shown in Fig. 4. The same type of plot for the other earthquakes with recomputed MS is available in Fig. S2, whereas Fig. S3 shows the mb station distribution.

The bulk of the MS stations (see also Fig. S2) are in Central, Eastern and Northern Europe, with additional contributions from stations TOL (Toledo, Spain), DUR (Durham, United Kingdom) and for the mainshock the former Soviet Union network (including station NVL in Antarctica) and RIV (Riverview College, Australia).

The MS for the mainshock is now based on 38 stations (instead of five as currently listed in the ISC Bulletin, see Table 1) and is 0.1 magnitude units (m.u.) smaller than in the ISC Bulletin. It also appears constrained well-enough considering the uncertainty of 0.18 m.u. We will discuss in more detail the MS of the mainshock in Section 5.

Table 3. Summary of the results for the 10 earthquakes for which we have been able to recompute MS. As in Table 1, inbrackets are listed the MS uncertainty (smad) and the number of stations used (nsta).

ISC_Evid	Recomputed MS (smad nsta)
827263	4.64 (0.14 4)
827266	4.99 (0.43 3)
827270	4.75 (0.08 10)
827284 (F1)	5.43 (0.12 13)
827285 (M)	5.93 (0.18 38)
827317	4.49 (0.20 4)
827341	4.24 (0.14 3)
827349 (A1)	5.56 (0.11 19)
827639	5.52 (0.12 17)
827649	4.42 (0.11 3)

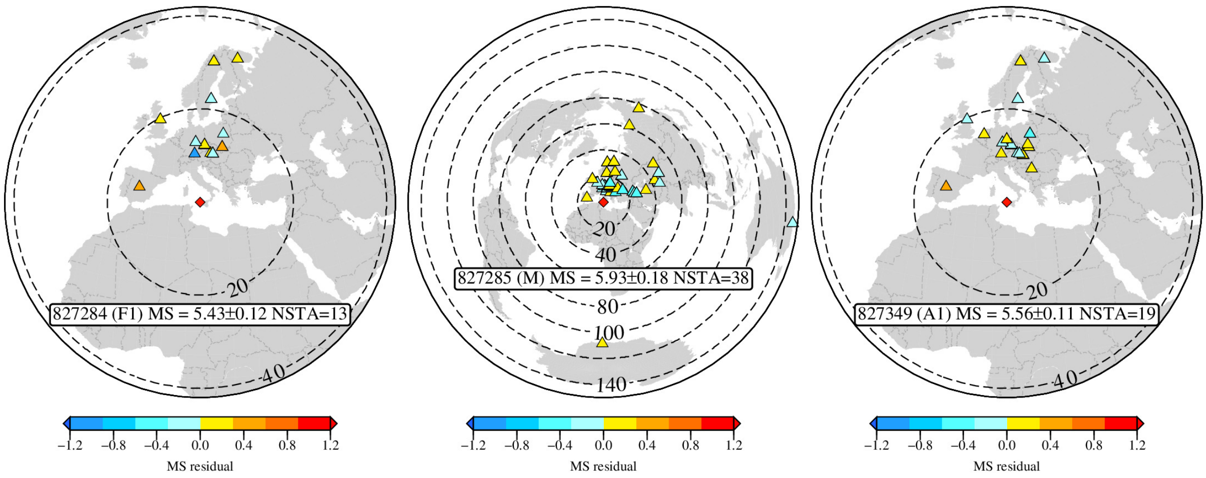

Figure 4. Distribution of the stations contributing to the MS reassessment for the key earthquakes F1 (left), M (middle) and A1 (right). Red diamonds are the earthquake epicentres, triangles are the stations colour coded by magnitude residuals. Text lists the ISC_Evid, the network MS and the corresponding uncertainty as well as the number of stations used. Note that only the mainshock has MS stations at distances above 40° (see also Fig. S2).

Among the newly obtained MS only ISC_Evid 827266 appears to be not well-constrained with an MS of 5.0 from only 3 stations and with an uncertainty of 0.43. Four earthquakes have MS > 5.0 and only these have MS stations beyond 20° distance. For the earthquakes for which we obtain MS ≤ 5.0 the contribution of the stations below 20° distance is fundamental, and it allows us to get MS for six earthquakes.

In general terms, the MS results appear to fit with the observational information we have at hand (e.g., how well an earthquake has been reported, as shown in Fig. S1) as well as the mb results. In Fig. 5 we show an updated magnitude timeline of the 1968 Belice valley earthquakes using both MS and mb. As already shown in previous works (e.g., De Panfilis and Marcelli, 1968; Orecchio et al., 2021), the sequence had three minor-to-moderate earthquakes on January the 14th and, about ten hours later, peaked in the early hours of the 15th with the mainshock (MS = 5.9, mb = 5.5), which was preceded 28 minutes earlier by a large foreshock (MS = 5.4, mb = 5.0). Smaller earthquakes continued until a large aftershock (MS = 5.6, mb = 5.1) occurred on the 16th of January. Another peak in the activity is observed on the 25th of January with the second largest aftershock (MS = 5.5, mb = 5.1), after which only minor earthquakes occurred. The updated magnitude information just described will help us in the discussion of next section.

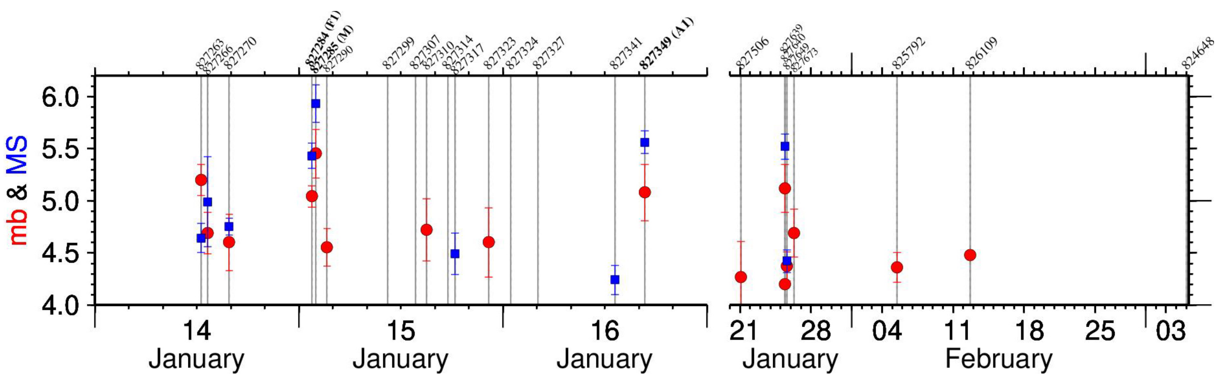

Figure 5. Magnitude timeline of the 1968 Belice valley earthquakes from our recomputed MS (blue symbols) and the mb from the ISC Bulletin (red symbols) with their corresponding uncertainties. Thin vertical grey lines depict the origin time, with the ISC_Evid (Table 1) on top is shown for guidance. The timeline is split in two parts: the first, on the left, shows earthquakes between the 14th and 17th of January 1968; the second, on the right, shows earthquakes between the 20th of January and 5th of March 1968.

5. Discussion

The small inter-event times of the 1968 Belice valley earthquakes pose a challenge for authors studying the sequence both from a macroseismic and instrumental point of view. Indeed, it is difficult to associate the impact of an individual earthquake (particularly for events in the pre-digital era) when several moderate events occur closely in time (see Azzaro et al., 2020). Similarly, from an instrumental point of view such a sequence would have created overlapping signals and required expert and meticulous analysis. Furthermore, the limitations of seismic network of the time (as mentioned earlier, the closest stations were over 200 km distance) contributed to the large discrepancies in location and magnitude estimations among different authors. By using an augmented parametric dataset for all Belice valley earthquakes in January-February 1968 and modern location techniques (i.e., starting from ISC locations and then refining with *iLoc* and *Bayesloc*), we reduced the uncertainties and obtained locations in the middle-lower crust with tightened hypocentres. Indeed, the largest outliers of the sequence are now closer to the largest events (F1, M, A1), which, in turn, are also much closer to each other (Fig. 3). Another important

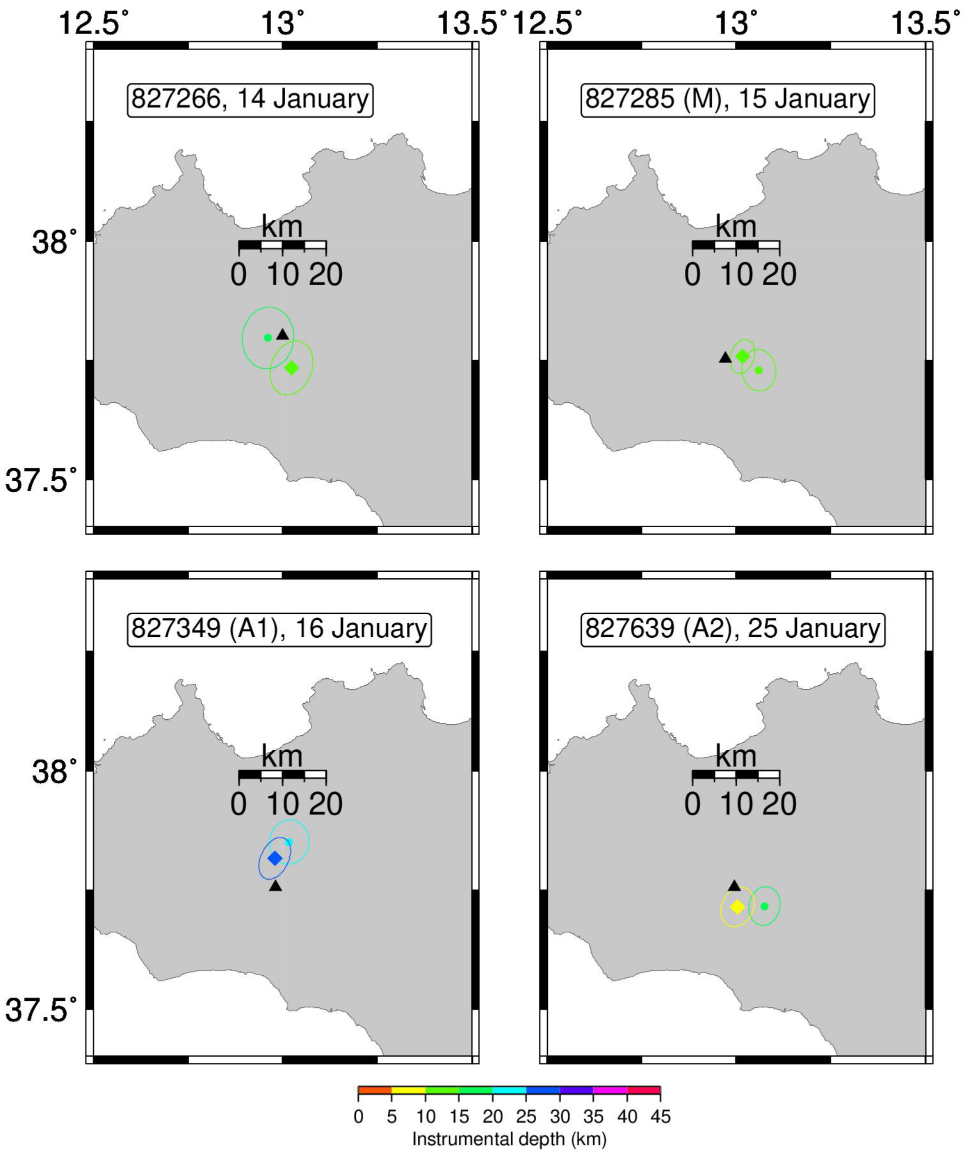

Figure 6. Instrumental locations from *Bayesloc* (diamonds, this study) ISCloc (circles, Bondár and Storchak, 2011) and macroseismic epicentres (black triangles, by Azzaro et al., 2020) for ISC_Evid = 827266 (top left, largest earthquake in our record that occurred on the 14th of January), main shock (M, top right), largest aftershocks (A1, bottom left) and second largest aftershock (A2). Instrumental location symbols as well as the corresponding error ellipses are colour-coded by depth.

refinement regards the depth of F1, where we obtain a free-depth of 24.7 km that is much more consistent with the overall depth features of the sequence than the ISCloc free-depth of 41.4 km currently listed in the ISC Bulletin. In Fig. 6 we compare our *Bayesloc* relocations with those from ISCloc as well as the macroseismic locations by Azzaro et al. (2020) for the largest earthquake of the 14th of January (ISC_Evid = 827266), M, A1 and the second largest aftershock of the sequence which occurred on the 25th of January (ISC_Evid = 827639, hereafter rereferred to as A2). The *Bayesloc* locations differ between 5 and 9 km with those from ISCloc, and between 4 and 7 km with the macroseismic ones of Azzaro et al. (2020). Except for the 14th of January earthquake (ISC_Evid = 827266), the relocations obtained in this work move closer to the macroseismic epicentres. A direct comparison with the epicentres by Orecchio et al. (2021) is not straightforward as their full relocation details are not available, but visual comparisons suggest location differences in line with those shown in Fig. 6. However, we can compare the depths of the largest events: our *Bayesloc* depth results of 24.7 km, 14.1 km and 28 km for F1, M and A1, respectively, are consistent with the depth estimations of 21, 12 and 21 km by Orecchio et al. (2021).

Regarding magnitude, we assembled a much more comprehensive MS dataset for the sequence and based our MS on an unprecedented number of stations. The most critical magnitude reassessment regards the foreshock (F1) and mainshock (M), which are separated by about 28 minutes. From the parametric data we gathered from printed bulletins to compute MS we found no obvious misinterpretation of the surface wave trains belonging to earthquake F1 and M. Since they are co-located, 28 minutes appear to have been long enough to measure surface wave amplitude and periods for both events, as summarized in Fig. 7. We also note that 13 MS stations (FUR, VIE, BRA, PRU, PRA, NIE, MOX, TOL, WAR, DUR, UPP, KIR, APA, see data in the Supplementary Material) are in common to F1 and M, and their mutual station MS differences averages at 0.5 m.u. In our experience it is unlikely that several of such observatories would misinterpret the readings of the surface waves of these two events. Furthermore, some of these

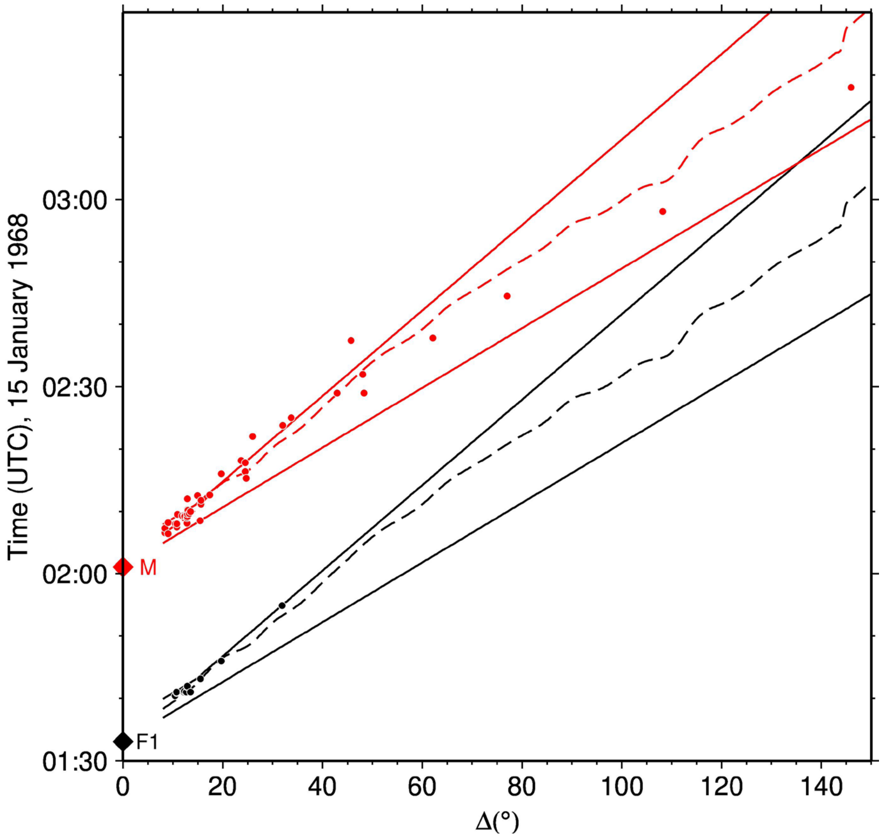

Figure 7. Surface wave arrival times vs distance for the foreshock (F1, black circles) and the mainshock (M, red circles). The black and red diamonds depict the origin time of F1 and M, respectively, the solid curves (black for F1, red for M) represent the time range where we expect to observe surface waves based on empirical data from the ISC Bulletin (for distances below 20° such curves are not well constrained, but the observations here are within range for both events for stations at shorter distances), whereas the dashed curves (black for F1, red for M) are the expected times of the Airy phase of Rayleigh waves according to Gorbunova and Kondorskaya (1977).

Table 4. Extract of the printed bulletins from long-term observatories for earthquake F1 and M. The bulletins screenshots reported here, as well as of other stations mentioned in the main text, can be found in the ISC Electronic Archive of Printed Station/Network Bulletins (Di Giacomo et al., 2022; International Seismological Centre, 2025d). Also note that the surface wave arrival times from the Uppsala bulletin (stations UPP, KIR) are not given, hence also not plotted in Fig. 5.

Bulletin	Screenshots for F1 and M
Prague	JAN15 01 33 04.1 Sicily 37.89 N 13.08 E, 44km, m 5.1 ISC KHC eiP 01 35 45, D 11.2 PRU eiPC. 01 35 55 (1.2s 87mu), e 38 30, Lm 41 (LH: 10s 26u), M 5.5, D 12.1 PRA eP 01 35 56, Lm 41.2 (LH: 10.5s 29u, LV: 10s 16u), M 5.6, D12.2 JAN15 02 01 04.1 Sicily 37.78N 13.03 E, 3km, m 5.4 ISC KHC eiP 02 03 48 (1.2s 188mu), D 11.3 PRU eP 02 04 00 (1.5s 262mu), ei 05 50, eiS 06 16, Lm 09.4 (LH: 12s 77u, LV: 12s 19u), M 5.9, D 12.2 PRA eP 02 04 05, Lm 09.2 (LH: 11.5s 53u, LV: 12s 36u), M 6.0,D 12.3
Moxa	15. eP 01 36 04.5 Sicily 37.93 N 13.14 E i 36 07 H = 01 33 02.7 h = normal MAG=5.1 ei 36 09.5 D = 12.8 Az = 355.6 (USCGS) LmH 41.9 PV2:1.1s 125.0nm LmV 42.0 LmH:11s 22.4 um LmV:13s 11.1 um MLH=5.5 15. eP 02 04 09 Sicily 37.95 N 13.12 E +iP 04 10 H = 02 01 08.5 h = normal MAG=5.4 iPL B 04 11.5 D = 12.7 Az = 355.7 (USCGS) ei 04 23 PV2:1.2s 61.2nm PV3:1.2s 143.0nm eS C 06 33 PV4:1.2s 354.0nm eS B 06 46 LmH:13s 75.0 um LmV:13s 37.1 um LmH 09.6 MLH=5.9 LmV 10.3 24
Uppsala	15 Up iP 01 37 54.1 i 01 37 55.8 iS 01 41 49 i 01 41 59 i 01 42 17 micr sec P N 0.5 4 P Z' 0.2 1.3 Mx E 11 18 Mx N 11 15 Mx Z 9.0 15 D = 2450 km = 22°. Ki iP 01 39 10.6 i 01 39 22.2 micr sec P Z' 0.6 1.4 Mx E 12 18 Mx N 4.3 12 Mx Z 6.9 16 Sicily (h = 30 km). m = 5.7, M = 5.5 (Up,Ki). 15 Up iP1 02 06 01.9 C iP2 02 06 04.9 iS 02 10 05 micr sec P2 N 1.2 4 P2 Z 1.5 4 P2 Z' 0.4 0.8 S E 8.6 13 S N 13 13 Mx E 61 19 Mx N 42 16 Mx Z 37 16 D = 2450 km = 22°. Ki iP1 02 07 17.3 iP2 02 07 20.8 iS 02 12 15 i 02 17 17 micr sec P2 Z' 1.5 1.4 S E 2.2 9 S N 2.5 8 Mx E 47 18 Mx N 15 15 Mx Z 23 15 D = 3350 km = 30°. Sicily (h = 30 km). m = 6.0, M = 6.3 (Up,Ki). Multiple P; average P2 - P1 = 3.8 sec.

stations represent some of the most consistent and reliable organizations of the time in observational seismology. Examples from three prominent institutes are shown in Table 4 with excerpts from their bulletins, both for F1 and M.

Our MS results for earthquakes F1, M and A1 are significantly larger than the Mw by Orecchio et al. (2021), who obtained 5.0 for F1 and A1, 5.2 for M from moment tensor inversion of digitized waveforms (stations COP, DBN, TOL, TRI, IST for all three earthquakes, plus ESK for F1 and M, PTO for F1, BUC and JER for A1). The only stations in common between our MS network and the stations used by Orecchio et al. (2021) are TOL (F1, M, A1), DBN (M, A1) and BUC (A1). The other stations used by Orecchio et al. (2021) are small contributors or absent in the ISC MS dataset (Di Giacomo and Storchak, 2022). Future studies using original seismograms will hopefully include a larger number of stations from Central and Eastern Europe, backbone of the MS networks used here.

Figure 8 shows the distribution of mb and MS for earthquakes with Mw = 5.2 in the Global Centroid Moment Tensor project (GCMT, https://www.globalcmt.org/, Dziewonski et al., 1981; Ekström et al., 2012), and, whilst the mb = 5.45 for the mainshock, even if unusual, may coexist with an Mw = 5.2, the MS = 5.9 appears to be difficult to reconcile In addition, using the mb to Mw conversion relationships by Scordilis (2006, equation 22), Lolli et al. (2015, equations 15 and 17) and Di Giacomo et al. (2015b, equation 2), an mb = 5.45 leads to Mw estimations between 5.6 and 5.8. We argue that the parametric instrumental information at hand favours a mainshock with magnitude between 5.5 and 6, as discussed in the following.

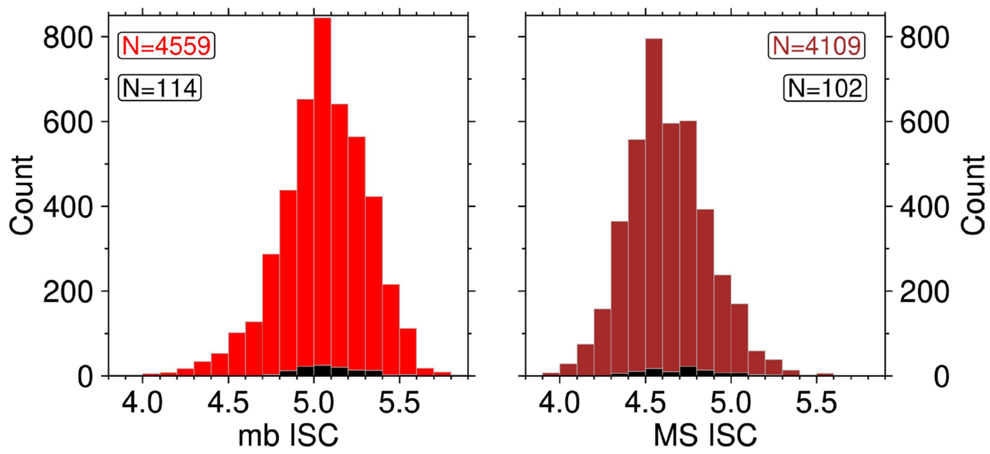

Figure 8. Distribution of ISC mb (left) and MS (right) for shallow earthquakes (depth ≤60 km) between 1980 and 2022 with Mw = 5.2 from the Global Centroid Moment Tensor project (GCMT, https://www.globalcmt.org/, Dziewonski et al., 1981; Ekström et al., 2012). The sub-set distributions shown in black are for earthquakes in the Euro-Mediterranean area, up to 20° degrees distance from the 1968 Belice valley earthquakes. Total numbers of data points shown in corresponding insets. The ISC magnitudes considered here have uncertainty ≤0.3 and are obtained from at least 10 stations.

First, we notice that larger earthquakes tend to be reported by a larger number of teleseismic stations (Δ ≥ 28°), as already depicted in Figs. 4 and S2 for the MS stations as well in Figs. S1 and S3 for the arrival-times and mb stations, respectively. Considering the teleseismic stations contributing with arrival times, Fig. 9 shows the number of teleseismic stations versus MS both the 1968 Belice sequence as well as other earthquakes with mb(ISC) ≥ 4.2 that occurred within 20° distance from the Belice epicentral area between June 1967 and June 1968 (i.e., approximately six months before and after the 1968 Belice valley sequence, so that the reporting network to the ISC can be considered comparable between the two sets of earthquakes). Figure S4 shows the same plot for mb. Although the number of earthquakes is not large, the 1968 Belice earthquakes fall well within the general trend of the Euro-Mediterranean earthquakes that occurred around the same time (i.e., the largest Belice earthquakes, if with smaller MS results consistent with Mw of 5.0 and 5.2, would be anomalously placed below the general trend observed for MS ≥ 5.0).

Similarly, the contribution from station RIV to the MS computation for the Belice mainshock favours a magnitude above 5.5. Station RIV, established in 1909, has been one of the most consistent stations in the southern hemisphere to report instrumental data for earthquakes worldwide and a fundamental station in the ISC MS dataset (Di Giacomo and

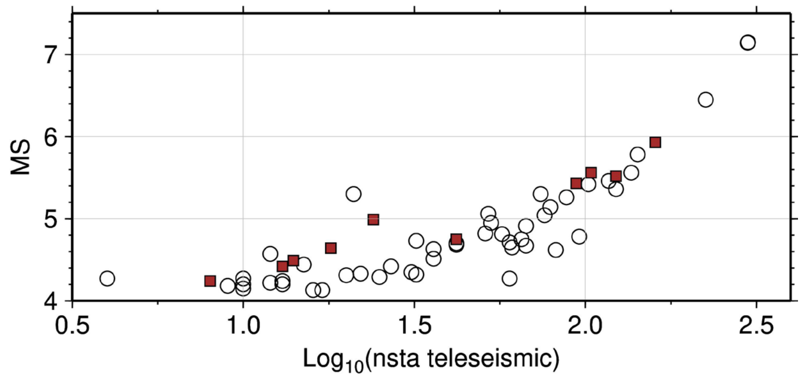

Figure 9. Log_{10} (number of teleseismic stations, $\Delta \geq 28°$) versus MS for the 1968 Belice valley earthquakes (brown squares) and earthquakes between June 1967 and June 1968 that occurred within 20° distance from the Belice epicentral area (empty circles).

Storchak, 2022). Figure 10 shows the earthquakes in 1967 and 1968 with recomputed MS that include RIV instrumental data, either arrival times and/or MS measurements. Interestingly, for earthquakes the Euro-Mediterranean area and continental Asia the MS contribution from RIV only occurs for MS around 6 and above. As a result, this also favours a magnitude above 5.5 as it would be difficult to justify MS measurements from RIV otherwise.

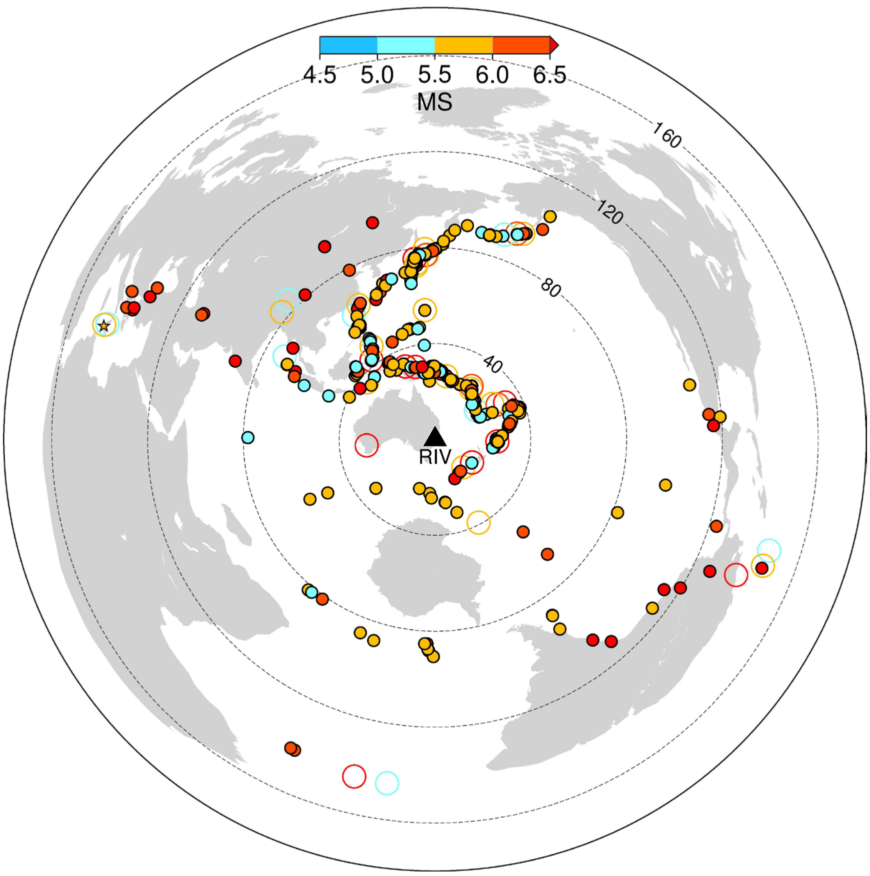

Figure 10. Earthquakes in 1967-1968 where instrumental data from station RIV is available and the event MS has been recomputed during the ISC-GEM Catalogue work. The solid and empty circles are the events where RIV contributes with or without MS measurements, respectively. The 1968 Belice valley mainshock is depicted with a filled star. The RIV reading the Belice mainshock can be found at http://www.isc.ac.uk/printedStnBulletins/Bulletins_scans/Australia/Riverview/Seism_Bull_1968_Riverview.pdf (reading No. 40).

We also note that the second largest aftershock of the sequence (A2) has an MS = 5.52 ± 0.12 (nsta = 17), very similar to earthquake A1 (MS = 5.56 ± 0.11, nsta = 19). Differently for the case of F1 and M, however, MS results for both A1 and A2 are not affected by close significant earthquakes that could have biased MS measurements. In this context, it is consistent that the magnitudes for F1, A1 and A2 (mb of 5.0-5.1 and MS of 5.4-5.6) are smaller than for M (mb = 5.5 and MS = 5.9). Furthermore, considering all earthquakes of the sequence (Fig. 5), a significantly smaller MS (e.g., by 0.5 m.u.) for the mainshock would require a comparable shift towards smaller MS for the other Belice events. Such a shift, however, would not fit in the broader instrumental information available (e.g., Figs. 9 and 10). Considering the global distribution of MS(ISC) = 5.9 between 1980 and 2020, an Mw(GCMT) around 6.0 should be expected, although smaller and larger values are possible, as shown in Fig. 11. The mb = 5.45 for the mainshock, however, is slightly smaller than expected for an MS(ISC) = 5.9. As a result, we do not rule out that a degree of contamination from the F1 coda into the M signal may have occurred (as pointed out by Orecchio et al., 2021), which could lead to a slight overestimation of MS for the mainshock. Therefore, we speculate that the MS = 5.9 obtained here for the Belice mainshock should be considered as an upper bound, and that catalogues used for seismic hazard analysis or other studies should not use the magnitude value of 6.4 as listed, e.g., currently in the CPTI (in its equivalent moment magnitude) or in previous versions of the ISC-GEM Catalogue (up to Version 9 released in 2021) that adopted the estimation by North (1977). In this context, our MS for the mainshock fits with the Mw of 5.7 suggested by Scarfì et al. (2025) based on ground motion simulations.

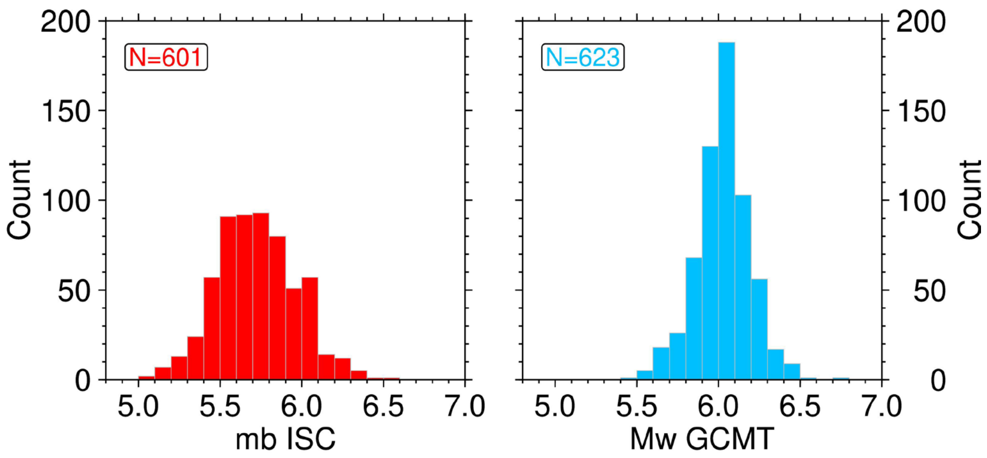

Figure 11. Distribution of ISC mb (left) and Mw GCMT (right) for shallow earthquakes (depth ≤60 km) between 1980 and 2022 with ISC MS = 5.9. Total numbers of data points shown in corresponding insets. As for Fig. 7, the ISC magnitudes considered here have uncertainty ≤0.3 and are obtained from at least 10 stations.

6. Conclusions

The 1968 Belice valley earthquakes that struck western Sicily in January-February 1968 are the most significant events in the region since instrumental recordings began. To date, we put together the most comprehensive parametric data set of arrival times by complementing the content of the ISC Bulletin with the arrival times in the BCIS. This augmented dataset and the combined use of advanced location techniques (*iLoc* + *Bayesloc*) allowed us to robustly locate the events in the middle-lower crust and better cluster the entire sequence, particularly the hypocentres of the largest events (F1, M and A1). Our relocations are consistent with recent instrumental relocations by Orecchio et al. (2021), particularly in terms of depths, as well as with the macroseismic locations of Azzaro et al. (2020), with which our relocations differ between 4 and 7 km for the largest earthquakes that occurred on the 14^{th}, 15^{th}, 16^{th} and 25^{th} of January. The magnitude reassessment has been done by processing the MS data digitized from printed bulletins and allowed us to compute MS for ten of the largest earthquakes of the sequence. The MS reassessment of the mainshock led as to an MS = 5.9 from 38 stations. We have shown that our MS reassessment for the mainshock, as well as the foreshocks and aftershocks, is consistent with the mutual variations of mb and reporting network. Hence our findings support a near-6 magnitude for the mainshock.

Data availability statement. Data used in this work is available in the Supplementary Material. The core part of the dataset used here comes from the online ISC Bulletin (International Seismological Centre, 2025a).

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*CORRESPONDING AUTHOR: Domenico DI GIACOMO,
International Seismological Centre, Thatcham, UK
e-mail: domenico@isc.ac.uk