The 1620 and 1644 Earthquakes in Alcoy and the Eastern Region of Spain

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Abstract

The 2 December 1620 earthquake, which caused considerable damage to the town of Alcoy in eastern Spain, and the seismic sequence of June 1644 in the region from Alcoy to the coast of the Mediterranean Sea are studied using contemporary sources. Focal parameters are determined for the 1620 shock and the three mainshocks of the 1644 sequence on 15, 19, and 26 June. The distribution of damage and casualties from the 1620 earthquake in Alcoy leads to the assignment of maximum intensities of VIII–IX. A solution is presented for problems concerning dates, locations, and sizes of the three largest shocks of the 1644 sequence given in previous catalogs and studies.

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Introduction

On 2 December 1620, a severe earthquake occurred in the town of Alcoy (Alicante province, eastern Spain), which caused considerable damage and many casualties. This earthquake was not an isolated event; 24 years later, in 1644, a series of earthquakes occurred in the same region from Alcoy to Gandía on the Mediterranean coast, some 60 km to the east. These two seismic events, although occurring nearby both spatially and temporally, had very different characteristics (Buforn and Udías, 2021). In the first case, in 1620, there was a large earthquake located in the town of Alcoy, followed by aftershocks for more than a month. In 1644, there was a sequence that lasted more than a month, with three larger shocks but none that can be identified as the mainshock. After this period of intense seismic activity, the region has been at low activity levels, except for an earthquake of magnitude 4.8 that occurred in 1945.

The eastern region of Spain, located from 3° W to 0.5° E and 37.5° N to 40° N (Fig. 1a), is characterized by medium-to-low seismic activity compared with other regions of the Iberian Peninsula. However, large earthquakes separated by long periods have occurred there. South of 38.5° N, seismic activity is more frequent, with some earthquakes in the historical period (before 1900; Fig. 1b, triangles; 1829 Torrevieja earthquake, $I_{max} = X$; Muñoz *et al.*, 1983), as well as in the instrumental period, causing much damage (2011 Lorca earthquake, $M_w = 5.1$; Martínez-Solares *et al.*, 2012; Fig. 1b, circles). North of 38.5° N, epicenters are concentrated near the coast (Fig. 1b). Historically, there have been some large earthquakes, such as that in 348 B.C., which destroyed the pre-Roman town of Sagunto; that in 1258, which caused much damage to the town of Onteniente (Buforn and Udías, 2020); that in 1396 in Tabernes de Valldigna; and that in 1748 in Montesa, which destroyed the monastery (Buforn *et al.*, 2015). In this region, in the instrumental period, there have been few large earthquakes; the largest was in Onteniente in 1945 ($M = 4.8$, $I_{max} = VII$), which was felt over a wide area (Rey Pastor, 1951). In modern times, continuous activity of moderate and small earthquakes is present, as shown in Figure 2, where the distribution of epicenters for 1980–2020 and $M_L \geq 2.5$ is shown. The largest seismic activity takes place to the south of 39° N, with epicenters distributed in the northeast–southwest direction, which may be correlated with the fault system known as Cadiz–Alicante, where some recent earthquake sequences have occurred in Bullas in 2005 and Lorca in 2011. North of 39° N, seismicity is lower, with epicenters distributed in the northwest–southeast direction. In the center of the region, seismic activity is practically null and increases west of 2.5° W. There are also epicenters located offshore both north and south of 39° N. Earthquakes in the region are at shallow depths of less than 40 km.

In this work, the parameters of the earthquakes of 1620 and 1644, especially the distribution of the intensities, are evaluated using all the available contemporary information of their damage and other effects. The main difficulties of studying historical seismicity in the Iberian Peninsula are that, in general, the information is very dispersed and access to original documents, which are often badly preserved, is difficult, and manuscripts have calligraphy that is difficult to read (Udías *et al.*, 2020). Another problem in evaluating intensities is that it is difficult to distinguish between the damage of the main earthquakes and their

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aftershocks. Often, buildings are affected by successive earthquakes, and it is doubtful to assign damage to a particular shock. Reports may not always assign the damage to the largest shock. This is especially difficult in seismic sequences, such as that of 1644, for which there was no mainshock.

The Alcoy 1620 Earthquake

The Alcoy earthquake of 2 December 1620 is reported in most catalogs of the Iberian Peninsula: Sánchez Navarro-Neumann (1921), Galbis Rodríguez (1932), Rey Pastor (1951), Munuera (1963), Fontseré and Iglesies (1971, which situates it between Alcoy and Navarrés), Mezcua and Solares-Martínez (1983), and Martínez-Solares and Mezcua (2002). Assigned values of intensity vary from VII–VIII (Martínez-Solares and Mezcua, 2002) to IX (Fontseré and Iglesies, 1971).

Contemporary documentation about this earthquake dated between 1620 and 1632, such as city council records and notarial acts (published and in manuscript form, Fig. 3), provides the first direct information about the occurrence and damage produced by the earthquake.

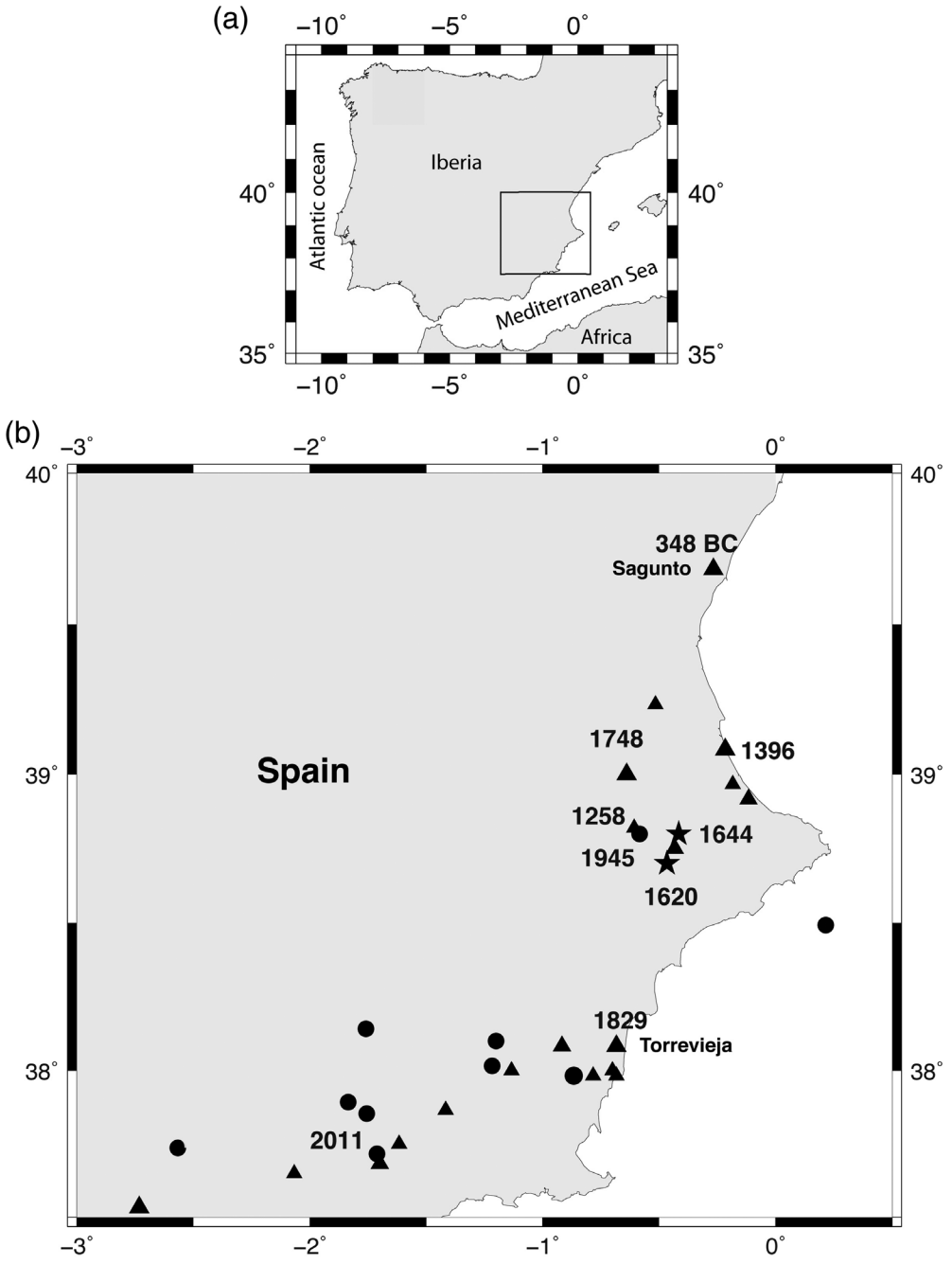

Figure 1. (a) Studied region marked by the square. (b) Larger earthquakes occurred in the studied region in the historical period (before 1900, triangles) and the instrumental period (circles), and the sizes of symbols are proportional to the intensity or magnitude. Stars correspond to the 1620 and 1644 epicenters of the Instituto Geográfico Nacional (IGN) catalog (see Data and Resources).

Main earthquake and aftershocks

All documents coincide with the date of the mainshock: 2 December 1620. Regarding the time of occurrence, there is ambiguity; times are given as 6 p.m. local time (GMT 18 hr; García Molero, 1621) and between 6 and 7 p.m. local time (18–19 hr GMT; Bravo, 1621), whereas less precise times are given as "after the evening prayers" (*después de las oraciones de las Ave Marías*), "after sunset" (Carbonell, 1668; Moya y Moya, 1922, document 2), and "at nightfall" (*al anochecer*; Moya y Moya, 1922, document 3). Castelló (2001) gives the time as felt in the town of Ibi near Alcoy at 5 p.m. local time, but this is clearly an error. The earthquake was followed by a sequence of aftershocks, some of them with a known hour of occurrence (Table 1). It has been reported that there were 33 aftershocks between 2 and 3 December (Abad, 1621; Carbonell, 1668). Among the aftershocks, some are mentioned in particular, for example, that of 14 December at 4–5 a.m. is said to have been "as large as the mainshock" (*tan grande como el principal*; Carbonell,

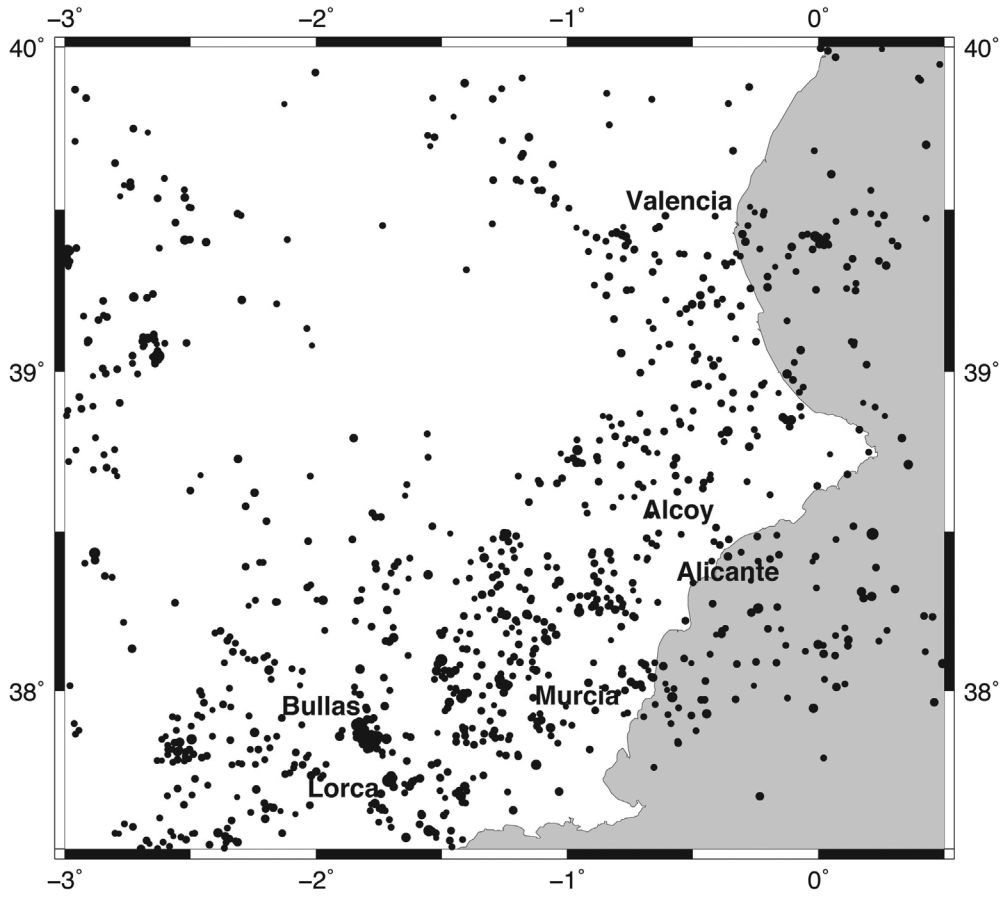

Figure 2. Distribution of epicenters for the period of 1980–2020 (M_L > 2.5) taken from the IGN (see Data and Resources).

1668); other aftershocks mentioned are 18 December from 3 to 4 a.m. (Carbonell, 1668; Moya y Moya, 1922), 25 December at approximately 6 p.m. (*Vísperas*; Carbonell, 1668; Moya y Moya, 1922), 6 January from 8 to 9 p.m., and 14 January at 1 a.m., 1621, which are all approximately the same intensity (Carbonell, 1668; Moya y Moya, 1922).

Damage distribution

Alcoy. Most of the information on the damage and casualties produced by the earthquake corresponds to the town of Alcoy, for which most of the damage and casualties took place. Alcoy, today an important city of 60,000 inhabitants, was a small town of 614 houses and 2763 inhabitants in 1620 (Dávila Linares, 1990). Minor damage is also reported in the village of Ibi, a short distance to the south, and in Alcoleja and Agres. In other nearby villages, the shock is reported to have been barely felt. Prior to this earthquake, a small earthquake in 1615 produced some damage to the main church of Alcoy.

Figure 4 shows on a contemporary map the places in Alcoy of which the main damage was produced. The Main Parish Church (*Iglesia Parroquial de Santa María*), which was built in the thirteenth century (Fig. 4, number 1), suffered great damage; the vault was cracked open, and a large part of it fell to the ground (Bravo, 1621; Carbonell, 1668). The church is reported to have suffered some damage in a previous small earthquake in 1615 that required some repair work in one arch (Archivo Municipal de Alcoy [AMA], 1615).

The Convent of Saint Augustine (*Convento de San Agustín*, Fig. 4, number 2)—a good building of cut stone (*era un Convento muy fuerte labrado de piedra*, García Molero, 1621) and considered the best building in the region (*Era el convento el mejor que había en aquellos Reynos,* Abad, 1621)—also suffered heavy damage, and its walls and arches fell to the ground. Three of the four heavy towers attached to the convent (**a**, in Fig. 4), which had walls of approximately 1 m thick (*siendo sus fuertes murallas de nueve palmos de grueso*, Abad 1621), also fell to the ground. The tower that was used as a sacristy with thick walls of approximately 2 m thickness (*tenía las paredes de ella veinte palmos*, Bravo, 1621) also fell to the ground. In particular, the choir was destroyed and fell, killing seven monks and wounding five who were there at the time.

The Monastery of Saint Francis (*Monasterio de San Francisco*, Fig. 4, number 6) also suffered very heavy damage, and the vault opened "like a pomegranate" (*quedó como una granada por todas partes abierto,* Abad, 1621). All the walls of the church and adjacent towers fell to the ground (*cayeron todos los muros de la iglesia con muchas torres de piedra que había en ella,* Bravo, 1621). The whole monastery remained uninhabitable. The Convent of the Holy Sepulcher (*Convento del Santo Sepulcro*, Fig. 4, number 3) suffered less damage, but it was reportedly in serious danger (*está en grande peligro*, Carbonell, 1668).

In addition to churches, houses and civil buildings also suffered heavy damage. There are reports of damage at the Algadines oven (*Horno de Algadines*, Fig. 4, number 4) and the oil mill (*Almacera*). The wall that surrounded the town suffered great damage; special mention is made of the new

(a)

RELACION
MVY VERDADERA DE
vn caſo muy eſpantoſo y laſtimoſo,
que en la villa de Alcoy Reyno de
Valencia ſucedio, Miercoles dos de
Diziembre deſte año paſſado
de 1620.

POR EL LICENCIADO ALONSO GAR
cia Molero natural de Granada, dirigida a el ſeñor don
Luys de Guzman y Vazquez, Corregidor de la di-
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(b)

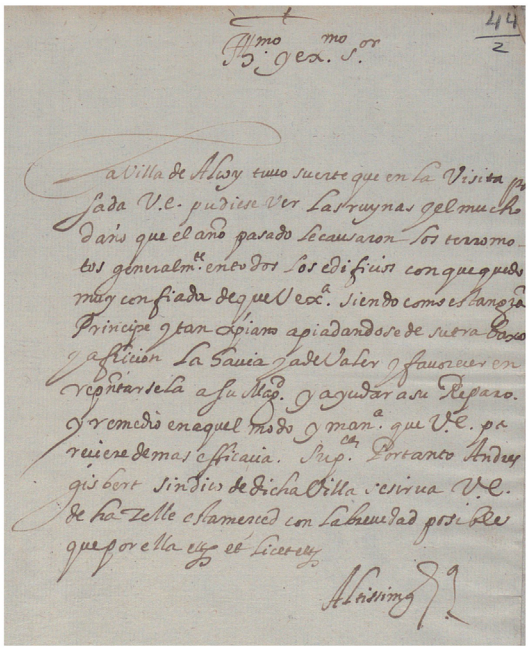
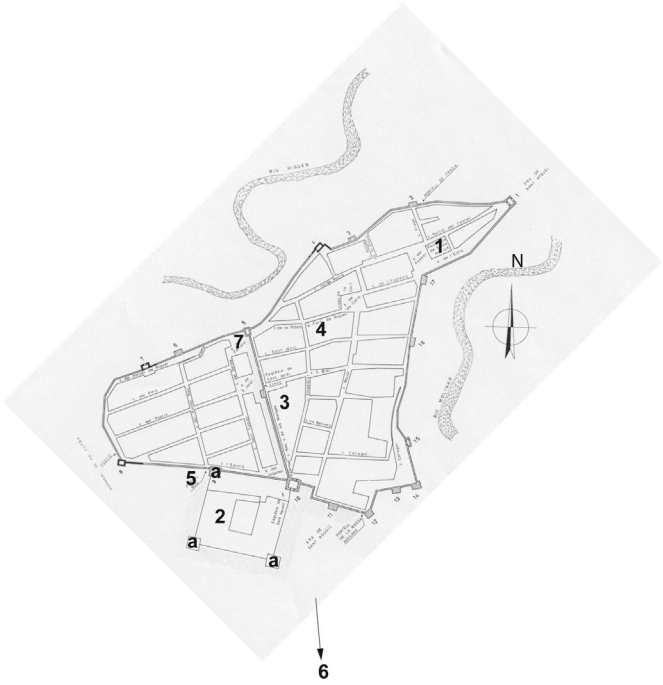


Figure 3. Examples of documents used. (a) Printed document (García Molero, 1621). (b) Manuscript: Letter of A. Gisbert describing the visit to the Spanish King (Archivo de la Corona de Aragón [ACA] 44/2, 1622). The color version of this figure is available only in the electronic edition.

doorway in the wall (*Portal Nuevo*, Fig. 4, number 5) and the doorway and tower of Saint George, which fell all the way to the river (*torre y portal de S. Jorge*, Fig. 4, number 7). Damage to private houses along some streets was reported, for example, of the street of *Borra*, the doorway to the valley of St. George, and other houses and parts of the walls, without specific places. Outside the town, at approximately 3 km (*a media legua del lugar*), the hermitage of Saint Anthony (*San Antonio*) was damaged. Damage was fairly uniform through the town (Fig. 4), and no special local ground effects were detected.

The earthquake also produced ground effects in the area of Cantagallet, approximately 1.4 km to the southeast of Alcoy,



1.- Main Church ; 2.-- St. Augustin convent; 3.- Holy Sepulchre convent

4.- Algadines; 5.- New gate ; 6.- St. Francis convent; 7.- St. George gate

Figure 4. Seventeenth century plan of the city of Alcoy (modified from Vicedo San Felipe, 1925).

with large ground cracks along a length between 8 and 16 km (between one and three leagues; Abad, 1621; Carbonell, 1668; Moya y Moya, 1922). Delgado *et al.* (2006) attribute these effects to the instability of hillsides in the area.

TABLE 1
The 1620 Alcoy Main Earthquake and Aftershocks

Date	Origin Time	Shock	Macroseismic Epicenter/I_{max}
2 December 1620	18	Mainshock	38.67° N, 0.48° W
	18–19		VIII–IX
	17 (Ibi)		
2–3 December		33 aftershocks	
14 December	4–5	Similar size as mainshock	
18 December	3–4		
25 December	18		
6 January 1621	20–21		
14 January	1		

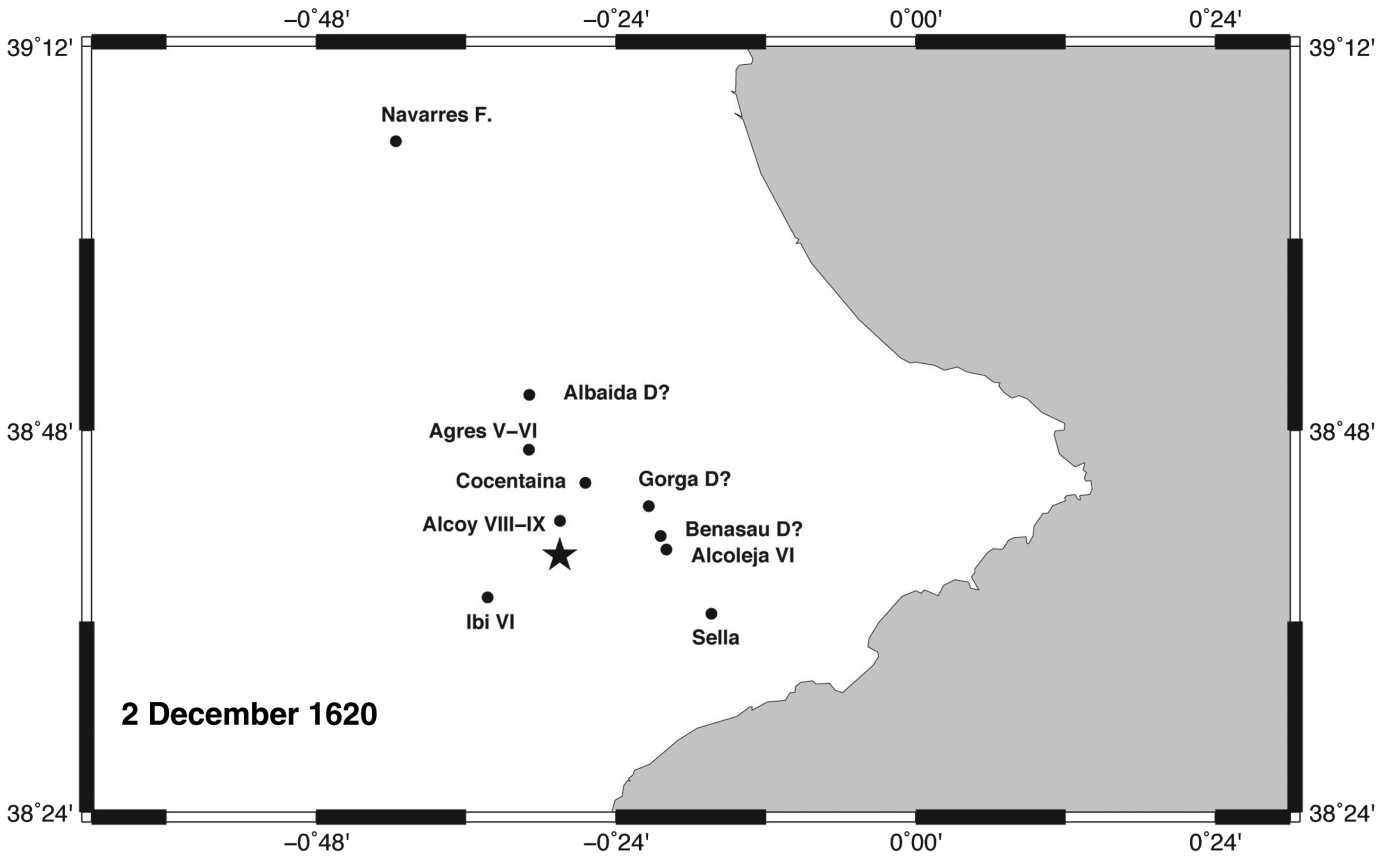


Figure 5. Intensity map for the 2 December 1620 earthquake. The star shows the macroseismic epicenter of this study. D? indicates sites with unidentified damage.

In summary, the damage was spread throughout the whole town (Fig. 4), affecting large buildings, such as those of churches and monasteries, towers and town walls, as well as private homes. The number of destroyed houses is estimated to be 380 of the 614 total (62%). The earthquake caused a large number of casualties, with 30 people dead and many wounded. Many of the wounded, described as *maltratados* (battered), *estropeados* (broken), and *descalabrados* (injured), may have possibly died afterward, thereby increasing the number of deaths. García Molero (1621) reports that the exact number of dead is not known as, when he writes, dead bodies were still being found under the ruins of the houses (*ir descubriendo cada día debajo de las ruinas cuerpos muertos*). Carbonell (1668) estimates that the total cost of the losses was 200,000 *ducados*. An estimation of the equivalent present value would be approximately 11 million euros.

Taking into account the reported damage in Alcoy, which affected all the large buildings, such as churches, monasteries, and convents, 62% of private homes that were destroyed, the number of casualties, the estimated economic cost of the damages, and the ground effects with large cracks, an intensity of VIII–IX in the European Macroseismic Scale (EMS-98, Grüntal, 1998) has been assigned. This value is similar to the one proposed by Rey Pastor (1951); Martínez-Solares and Mezcua (2002) assign a lower value to Alcoy, namely, VII–VIII, which was not in accord with the described damage; Fontseré and Iglesies (1971) propose an intensity of IX, but with an epicenter between Alcoy and Navarrés, which does not agree with the lack of information about damage in Navarrés and its long distance from Alcoy (Fig. 5).

Ibi. Ibi, which is a village located 10 km southwest of Alcoy (Fig. 5), is also reported to have suffered damage, although less so than Alcoy. Castelló (2001) reproduces the Notarial Protocol (*Protocolo Notarial*) written by Luis Pérez on 15 December 1620 (Archivo Histórico Municipal de Xixona [AHMX], 1620), which attests that the earthquake affected the whole village, causing damage to the principal arch of the Main Church with two of its stones falling to the ground and the Our Lady of the Rosary chapel being strongly cracked. Two hermitages (*Santa Lucía* and *San Vicente*) outside the village were also damaged by the earthquake. According to Castelló, inspections (*visuras*) were made by master masons (*maestros albañiles*) to evaluate the damage to a total of 30 houses, mostly in walls and chimneys. Four houses were considered to be at risk of collapse and were ordered to be uninhabited until their repair. In 1609, Ibi had approximately 300 houses (Bernabé Gil, 1986), and this number can be adjusted for 1620; therefore, 10% were damaged by the earthquake. A later document on 22 December 1620 (Castelló,

2001) reproduces an agreement of the village council, gives more details of the damage at the bell tower of the Main Church and to several houses, and proposes the rebuilding of the hermitage of Santa Lucia. There is no report of any casualties. According to the damage, the intensity at Ibi can be estimated as VI (EMS-98).

Other places. Bravo (1621) mentions that the earthquake was felt at Alcoleja (Fig. 5), which is located 12 km southeast of Alcoy. There is no indication of the time, but it is reported that shaking continued for an hour (*continuó dentro de una hora*), which can be interpreted as several aftershocks being felt within an hour after the earthquake. Damage to the church of Alcoleja that cracked open, and some parts of the roof fell to the ground (*La Esglesia de Alcolecha se badá*), is reported by Gascó Alonso (1886) using information from contemporary parish books. With this information, considering that Alcoleja is at approximately the same distance from Alcoy as Ibi but in the southeast direction, it has been assigned an intensity of VI (EMS-98). There is information about damage in Agres (Fig. 5)—a village located 9 km to the north-northwest of Alcoy (Reig Bodí, 2017). The church of St. Michael, which had already retained some damage in the 1615 earthquake, suffered special damage in the bell tower and roof, and needed repair; the intensity has been estimated as V–VI.

There is little information about damage in other places. Gascó Alonso (1886) reports that the earthquake was also felt in the villages of Gorga, Cocentaina, Benassau, and Albaida (Fig. 5), with some damage, but without giving any details (places with unspecified damage are marked with a D in Fig. 5). In Cocentaina, 7 km north–northeast of Alcoy, there was no damage, and the people went to help those of Alcoy (Carbonell, 1668). Finally, Bravo (1621) reports that the earthquake was also felt in Navarrés, 47 km north–northwest of Alcoy (Fig. 5), but with no resulting damage. Lack of information about damage in other small towns and villages near Alcoy may be explained by the fact that 1620 was only 11 years after the expulsion of the Moorish settlers (*moriscos*) in 1609, which resulted in an important depopulation of the region with a total abandonment of many farms (*alquerías*) and small villages and settlements.

Focal parameters

Based on the mentioned instensity distribution, a macroseismic epicenter is proposed to the south of Alcoy (star in Fig. 5) equidistant from Ibi and Alcoleja, with coordinates of 38.67° N, 0.48° W; this is somewhat different from those of the Catalog of the Instituto Geográfico Nacional (IGN), namely, 38.700° N, 0.4667° W, which corresponds to the town of Alcoy. Regarding the depth of the focus, it is probable that it was quite shallow because of the concentration of the damage in Alcoy. The maximum intensity of the earthquake corresponds to that of Alcoy (VIII–IX, EMS-98). Delgado *et al.* (2006), from the intensity values, assigned a magnitude of 4.9 (m_b) and 4.6 (M_s) to the earthquake. This is based on only three values of intensity, which does not substantiate the result. In our opinion, for historical earthquakes, it is preferable not to give magnitude values (much less with a precision of one decimal), because they depend on the magnitude–intensity relation used and the values of intensities that already have large margins of error, as in the present case between VIII and IX (Udías *et al.*, 2020). The similarity between the damage in Alcoleja and Ibi may indicate that the mechanism of the earthquake could be that of a bilateral fracture with an origin at Alcoy propagating in the east–northeast (Alcoleja) and west–southwest (Ibi) directions.

The 1644 Seismic Sequence

The region surrounding Alcoy remained in seismic calm after the end of the aftershocks of the 2 December 1620 earthquake, which lasted until the end of January 1621. In June 1644, new earthquakes began to take place, which lasted until the middle of July. This second period of activity had important differences from the 1620 earthquake and its aftershocks. There was no mainshock, and earthquakes that lasted approximately 1 month, three that were larger sizes, were distributed over a larger area of approximately 30 km east–west, from Alcoy to Gandía on the coast, and approximately 12 km north–south (Fig. 6). Information about these earthquakes is less abundant than for the 1620 shock, and documents are more dispersed. Their presence in seismic catalogs is also highly varied, and some are reported in 1645. The first catalog is that of Galbis Rodríguez (1932), giving only the year 1644 for a large earthquake (*de gran violencia*) in Alcoy and adding several earthquakes in Alcoy, Concentaina, and Planes in 1645, without giving dates. Rey Pastor (1951) lists an earthquake in 1644 (without date) of intensity V and 40 others in 1645 in Alcoy and Concentaina (Fig. 5) with intensities of VIII–IX without any details. Munuera (1963) lists an earthquake in 1644 and another in 1645 in Alcoy, without dates or intensities. The catalog of Fontseré and Iglesies (1971) repeats the information of Galbis Rodríguez (1932). Mezcua and Martínez-Solares (1983) list an earthquake of intensity IX in 1645 in Alcoy. Finally, Martínez-Solares and Mezcua (2002) include four earthquakes with the same epicenter in Muro de Alcoy, also referred to as Muro (38°48' N. 0°25' W) in June 1644 (15 June at 23 hr, with intensities of IV–V; 16 June at 3 hr, with an intensity of V; 19 June at 16 hr, with an intensity of V, and another the same day at 18 hr). In conclusion, the information about these earthquakes in the catalogs is very dispersed and contradictory, requiring a detailed analysis of contemporary sources.

First, according to contemporary documents, there were no earthquakes in the region in 1645 but only in 1644. Several contemporary documents have been found about the seismic sequence of 1644. Based on this documentation, it can be concluded that the 1644 seismic sequence extended for approximately a month, beginning in the middle of June to the middle of July, with some days of high activity (*mas de 33 réplicas*, more than 33 aftershocks, Villalmazo, 1985). The

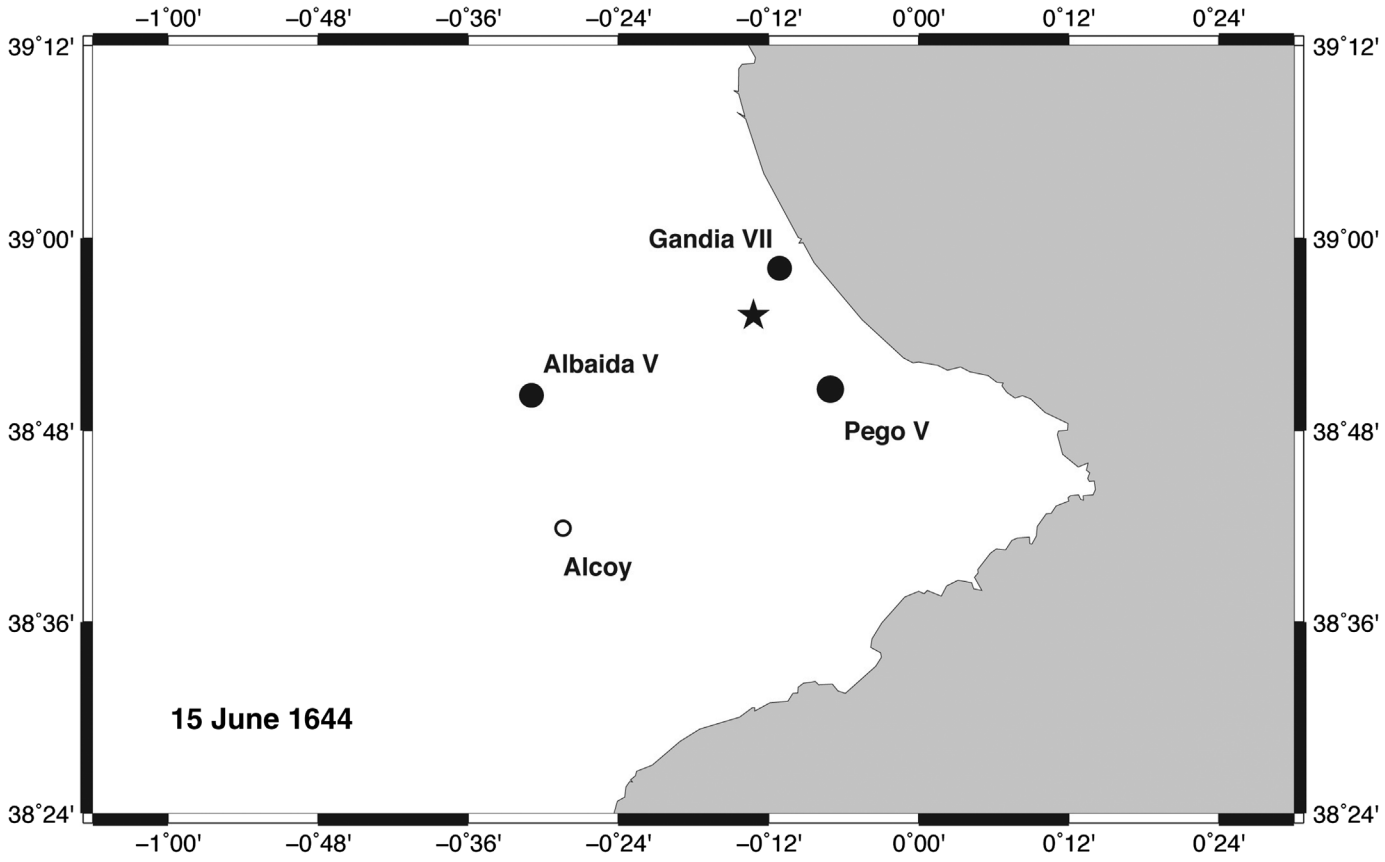


Figure 6. Intensity map for the 15 June 1644 earthquake. The star shows the macroseismic epicenter of this study. The white circle shows the town of Alcoy.

most important earthquakes of the sequence occurred on 15, 19, and 26 June.

Earthquake on 15 June

The first reported earthquake of the sequence occurred in the late hours (23 hr) of 14 June and was felt in Pego and Gandía (Fig. 6) without damage (Martí Sanz, 1930). The following day, 15 June, at 23 hr, a larger earthquake occurred, which affected the areas of Albaida, Pego, and Gandía and was followed by aftershocks during some days—the largest on 16 June at 3 hr a.m. (Martí Sanz, 1930; Sucías Aparicio, 1890–1915; Villalmazo, 1985; Sastre Ferrando *et al.*, 1979). According to the only contemporary document by Fr. Miguel Torró, prior to the Franciscan convent of Albaida (Villalmazo, 1985), the earthquake of 15 June at 23 hr was the largest earthquake that caused panic in Albaida. In Gandía, damage reported is that of walls and fences falling and much generic damage (*muchos daños*) in most houses, some of them cracking (*consentidas*; Martí Sanz, 1930); an intensity of VII has been assigned. In Albaida and Pego, the earthquake was felt by most people, giving an intensity of V. From these data, a macroseismic

TABLE 2
Largest Earthquakes of the 1644 Seismic Sequence

Date	Origin Time	Shocks	Macroseismic Epicenter/I_{max}
15 June	23 hr	Large earthquake	38.85° N, 0.22° W
			VII
19 June	16 hr	Earthquakes during more than 8 days	38.82° N, 0.45° W
		Some days more than 33 aftershocks	VII
26 June	19:30 hr		38.82° N, 0.3° W
			VIII–IX

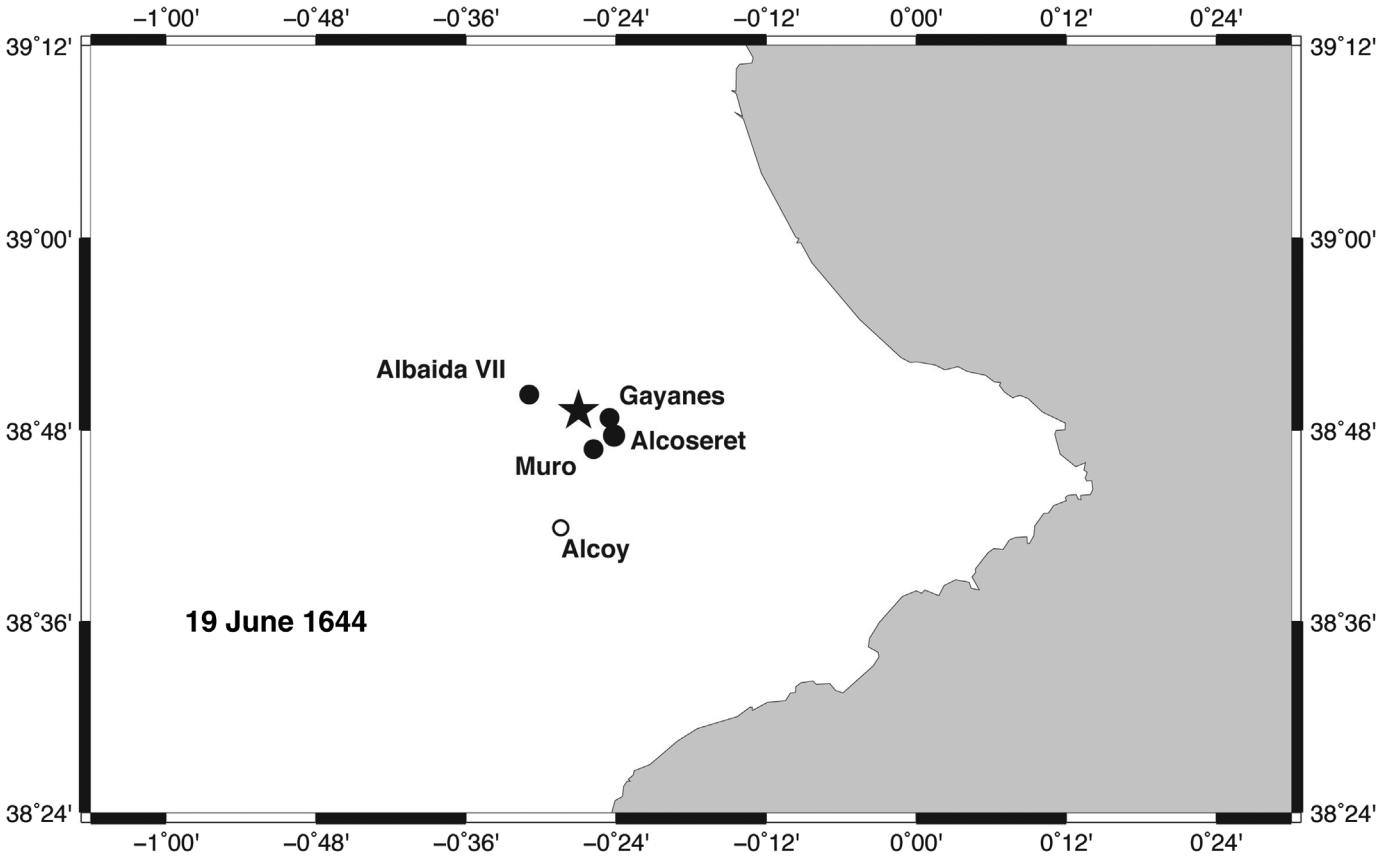


Figure 7. Intensity map for the 19 June 1644 earthquake. The star shows the macroseismic epicenter of this study. The white circle shows the town of Alcoy.

epicenter is proposed near Gandía at 38.85° N, 0.22° W (star in Fig. 6 and Table 2), which is located to the east of that proposed by Martínez-Solares and Mezcua (2002).

Earthquake on 19 June

The following earthquake occurred on 19 June at 16 hr and affected the villages of Albaida, Gayanes, Alcoseret, and Muro (Fig. 7). More damage was suffered in Albaida and is reported by Fr. Torró (Villalmazo, 1985; Sucías Aparicio, 1890–1915), who reports that the whole church was shaken, a cross on a spire fell, and the vaults cracked (*de la tierra que caía de las bóvedas de la iglesia*, dust falling from the vaults), and some houses fell to the ground in the village. An intensity of VII has been assigned to Albaida. Important damage was suffered in Gayanes and Alcoseret (*quedaron asolados*, were devastated; Fig. 7), as well as in Muro (special damage in Sella, a farmstead of Muro), for which several houses fell and there was damage to the church (Sucías Aparicio, 1890–1915, p. 23; Villalmazo, 1985). With this information, the maximum intensity of VII can be assigned to the earthquake on 19 June and a macroseismic epicenter near Albaida at 38.82° N, 0.45° W (Table 2, a black star in Fig. 7), very near the epicenter proposed by the catalog of IGN for the four earthquakes.

Earthquake on 26 June

The largest earthquake of the sequence produced damage over an area of approximately 42 km × 47 km, from the Monastery of Valldigna to the north, to Guadalest to the south, and from Oliva, Gandía, and Denia on the coast to the east, to Planes and Muro to the west (Fig. 8a,b). However, there is a confusion about the date. Most sources, such as Sucías Aparicio (1890–1915) and Soler i Struch (1980), date it to 26 June at 17 hr (*El terratremol que hi va haver a les cinc del vespre del diumenge dia 26 de Juny de l'any 1644*; the earthquake that happened in the 5 hr of the afternoon of the Sunday of 26 June 1644). 26 June in the afternoon is also reported by Tosca (1715; *el dia 26 de junio del año 1644 por la tarde*). An Act of the Council of Muro of 1644 dates it to 26 (*del terremoto que fue en esta Universitat a 26 del mes de Juny 1644*; of the earthquake that was in this farmstead on 26 June 1844). However, Sastre Ferrando *et al.* (1979), based on a notarial act of 27 June 1644, dated the earthquake on 21 June at approximately 19 hr (*cuando llegó el día 21 de dicho mes, a la que el sol se ponía:* on day 21 of the said month at sunset), but this may be due to a transcription error of the notarial act. Another date, 22 June, is reported by Margarit (1758) in a document about the church of Guadalest, which mentions the damage produced by the earthquake that destroyed the castle of Guadalest. This information of the date of 22 June given a hundred a hundred years later

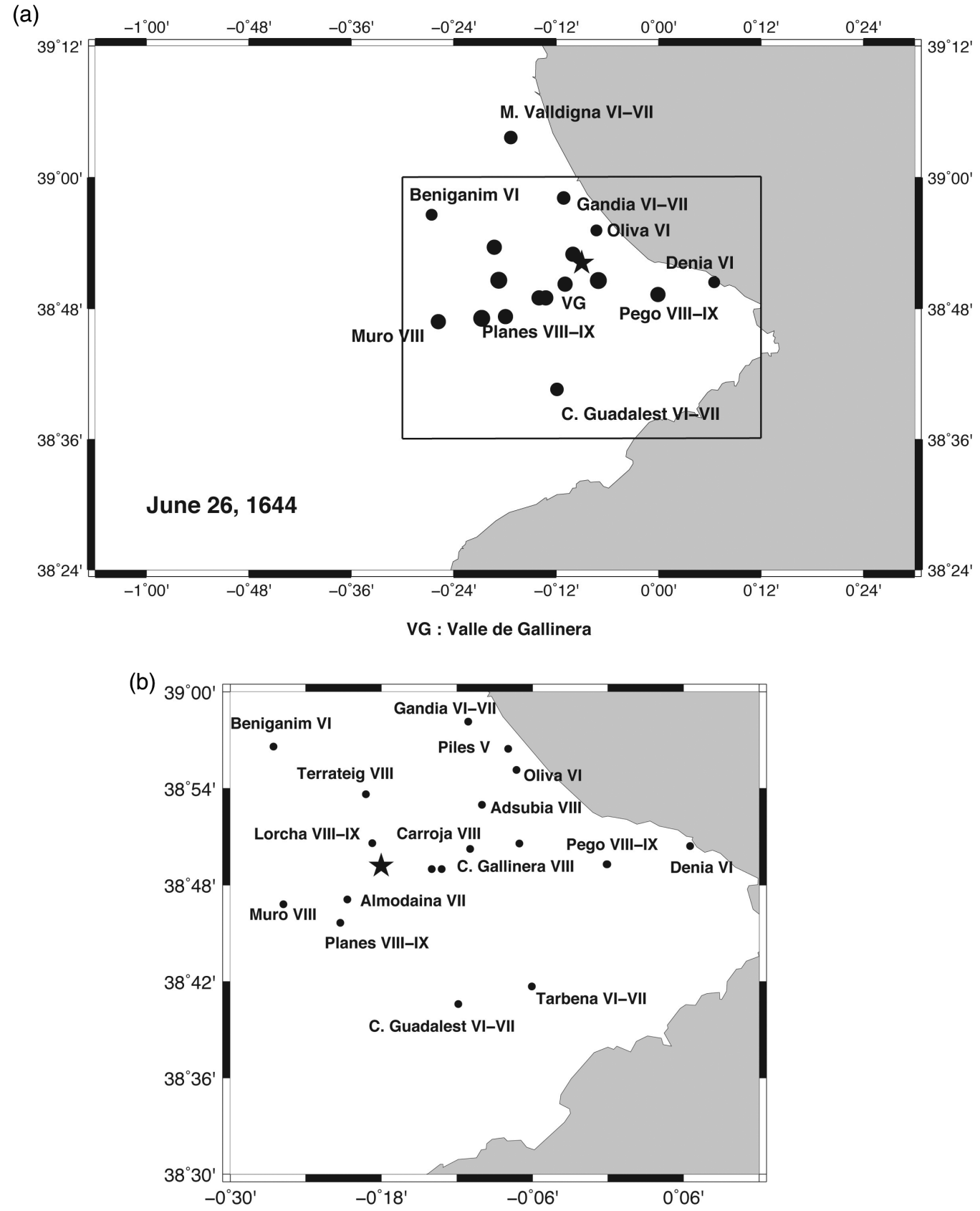


Figure 8. (a) Intensity map for the 26 June 1644 earthquake. The star shows the macroseismic epicenter of this study. (b) Intensity map for the area with the most damage in the 26 June 1644 earthquake (square in panel a). The star shows the macroseismic epicenter of this study.

may be due to date confusion. The agreement of several sources (Actes del Consell de Muro, 1644; Tosca, 1715) allows us to conclude that the earthquake took place on 26 June rather than on 21 June, as proposed by Sastre Ferrando *et al.* (1979). Momblanch y Gonzálbez (1959) presents additional written evidence for the earthquake that suggests that it happened after the feast of Saint John (24 June), not before.

Most of the greatest damage of the 26 June shock occurred in the area known as the Valley of Gallinera (Valle de Gallinera; Fig. 8a,b), where there was a castle, a Franciscan monastery (founded in 1611), several towns, villages, and farmhouses, and former Moorish farmsteads. A great part of the Castle of Gallinera fell to the ground, and the monastery suffered grave damage. Part of the church of Adsubia also fell to the ground, and widespread important damage was suffered in the village of Lorcha (Fig. 8a,b) and some farmsteads of the Valley of Gallinera. An intensity of VIII is assigned to the Valley of Gallinera. In Lorcha, all the houses of the village were entirely destroyed, and approximately ten persons died (intensity = VIII–IX; Sastre Ferrando *et al.*, 1979). The village of Planes (Fig. 8a,b), west of the Valley of Gallinera, also suffered heavy damage. In the village of Almodaina, near Planes, the earthquake demolished three houses and three people died. Heavy damage was also suffered in Catamarruch—a farmstead in Planes (I = VIII). Pego (Fig. 8a,b) was one of the towns with more damage; people are said to have been very frightened (*espanta molt la gent*), a wall of the city hall was cracked, and parts of the town walls and towers fell. The damage to the church is specified in an act of the town council (*Acta del Consell*) of 27 June informing the Archbishop that the bell tower and all chapels were cracked (*esta cruxida*); half of the vault fell to the ground, and the church was so damaged that people were afraid to enter it (*consumida de tal manera que se causa temor entrar en aquella*). In another document, a letter to the Duke of Gandía of 20 July asking for funds for its reconstruction, it is said that the church was greatly demolished (*está en grande manera derruyda*). Given this information, intensity of VIII–IX is assigned to Pego.

In Muro (Fig. 8a,b), the bell tower, vault, and several chapels of the Parish Church, a very solid building (*el más sólido de sus edificios*), collapsed (Momblanch y Gonzálbez, 1959; Actes del Consell de Muro, 1644). As many as 40 private houses also fell (Cavanilles, 1797; Sastre Ferrando *et al.*, 1979). It has been assigned an intensity of VIII. More towards north at Terrateig (Fig. 8b), 30 houses fell, leaving only three standing, and in Beniganim, farther to the north (Fig. 8b), the earthquake caused damage to the church (Tosca, 1715; Sastre Ferrando *et al.*, 1979). An intensity of VIII has been assigned to Terrateig and VI to Beniganim. Special damage is reported to have been caused by the earthquake to the Monastery of Valldigna (Fig. 8a), destroying two towers, and the damage is estimated as more than 20,000 *ducados* (equivalent to approximately 1 million euros; intensity of VI–VII). In Denia, the church of the Monastery was cracked, which is the same damage that occurred at the monastery in Oliva. In Gandía, the tower of Saint Nicholas fell to the ground, killing four people. Intensities have been assigned to Denia and Oliva (VI) and Gandía (VI–VII; Fig. 8a,b). To the south, the earthquake destroyed the castle of Guadalest (Fig. 8a,b), with one person dead and one wounded (VI–VII; Figueras Pacheco, 1919), and to the southeast, in Tárberna, many houses fell (VI–VII; Fig. 8b). The earthquake was felt in the city of Valencia (73 km to the north of Pego).

Based on this information, a macroseismic epicenter was determined for the earthquake on 26 June, located between Lorcha and Planes at coordinates 38.82° N, 0.3° W (Table 2 and Fig. 8b, star). This earthquake was the largest of the whole sequence, with a total of 19 deaths and maximum intensity of VIII–IX, which affected a large area of approximately 48 km in the east–west direction from Denia to Muro (Fig. 8b). A problem in the evaluation of the intensities for this earthquake at the end of the sequence may be that buildings could have been already damaged by previous earthquakes of the sequence, and the assigned intensities are thus overvalued.

Conclusion

Contemporary documents have provided information about the occurrence of the earthquakes of 1620 and 1644 in the eastern region of Spain. Figure 9 and Tables 1 and 2 show the four macroseismic epicenters proposed here for these shocks. These geographical coordinates correspond to the site with the most damage and cannot be directly compared to those obtained for instrumental epicenters.

The Alcoy earthquake of 2 December 1620 is that of the largest maximum intensities, namely, VIII–IX. It was followed by a sequence of aftershocks for approximately 1 month and affected an area of approximately 35 km in length in the northeast–southwest direction. It can be interpreted as produced by a bilateral fracture with a center at Alcoy—the town that suffered the most damage and where 30 people died. Regarding the 1644 sequence, according to the available information, three earthquakes are identified as the largest of the sequence, that is, those of the 15, 19, and 26 June, and macroseismic epicenters and the maximum intensities are assigned to them. The earthquakes on 15 and 19 June have the same maximum intensity (I_{max} = VII)—the first with the epicenter near Gandía and the second near Albaida (Fig. 9 and Table 2). The 26 June earthquake, in the last part of the sequence, took place at the center of the area and is the largest of the sequence, with strong damage and 19 deaths (I_{max} = VIII–IX). It is then incorrect to consider the 19 June earthquake as the largest of the sequence, as is done by Martínez-Solares and Mezcua (2002) and the present IGN catalog, which ignores the 26 June shock. Another problem for the 1644 sequence is the difficulty in evaluating the damage on 26 June, because the buildings may have been affected by smaller previous earthquakes. The sequence of 1644 can be explained as being produced by a

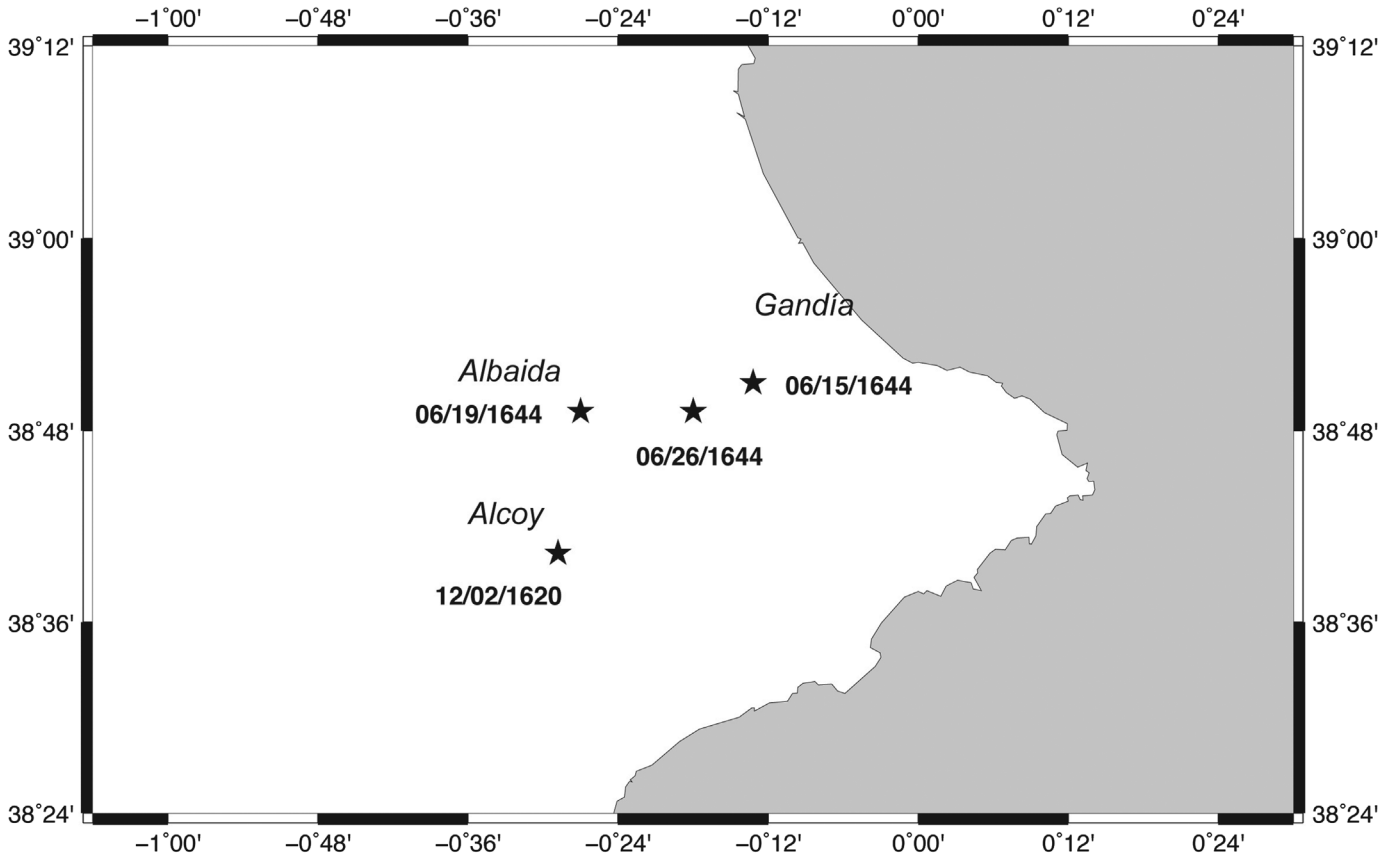


Figure 9. Macroseismic epicenters (stars) for the 1620 earthquake and the three largest shocks of the 1644 sequence.

system of faults in the east-northeast–west-southwest direction and located to the northeast of the fault proposed for the 1620 shock. In this case, there is not a single rupture, but several ruptures that begin at the eastern end near Gandía (15 June) continue in the most western part in Albaida (19 June) and finish in the central part in the Valley of Gallinera with the 26 June shock.

From the time of the studied earthquakes, the region has been seismically calm, with no large earthquakes, except for one of magnitude 4.8 in 1945. However, the 1620 and 1644 earthquakes show that the region is of potentially moderate seismic risk. Alcoy is now an important city of 60,000 inhabitants, and the area has recently experienced important industrial and residential and tourist development. The villages affected by the earthquakes in the seventeenth century are now flourishing developed towns. The repetition of these earthquakes would certainly cause very important damage and possible casualties.

Data and Resources

All historical documents used (printed documents, manuscripts, letters, etc.) are available online at the Instituto Geográfico Nacional (IGN, http://www.ign.es/web/ign/portal/libros-digitales/terremoto-alcoy). Historical and instrumental seismic data can be found in the IGN online catalog (https://www.ign.es/web/ign/portal/sis-catalogo-terremotos and https://www.ign.es/web/ign/portal/sis-area-sismicidad). All websites were last accessed in December 2021.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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