

THE 1561 EARTHQUAKE(S) IN SOUTHERN ITALY: NEW INSIGHTS INTO A COMPLEX SEISMIC SEQUENCE

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In the summer of 1561, a strong seismic sequence struck southern Italy, then the Spanish-ruled Kingdom of Naples. Both the Italian seismological tradition and the latest catalogues locate it in the Vallo di Diano (Diano Valley), a low-seismicity intermontane basin 100 km south-east of Naples. We explore the hypothesis that current perception of the 1561 earthquake is distorted by the nature of the historical dataset from which its parameters have been assessed, and which mostly derive from a single - albeit very detailed - primary source. We present and discuss several previously unconsidered original accounts. Our results cast doubts on the traditional interpretation of the earthquake, which could have been either one Vallo di Diano mainshock or several strong earthquakes within a time/space window compact enough for contemporary viewers to perceive them as one. Unquestionably, there is much more to the 1561 earthquake(s) than previously appeared. We hope that this groundbreaking effort will rekindle the interest of the seismological community in this seismic episode, our knowledge of which is still far from complete.

Keywords: Historical seismicity, 1561 earthquakes, active faults, seismotectonics, Vallo di Diano, southern Italy

1. Introduction

Peninsular Italy is one of the most tectonically and seismically active regions of the central-western Mediterranean area. Almost all the strongest seismic events along the chain are generated by NW-SE normal faults (Fig. 1), which accommodate, on the whole, a NE-SW extension. The 1561 earthquake was located by the CPTI04 parametric catalogue (CPTI Working Group, 2004) in the Tyrrhenian side of the Apennine chain ($M_w=6.4$), and more precisely, in the Vallo di Diano (“Diano valley”, from an ancient name of the chief local town), where severe damage was reported by historical evidence first collected by Bonito (1691), Mercalli (1891) and Baratta (1901). This evidence was recently reassessed for the compilation of the CFTI (Boschi et al., 1995; 1997; 2000) and the NT4.1 (Camassi and Stucchi, 1997) parametric catalogues, by two independent research teams. Both studies of the 1561 earthquake (Boschi et al., 1995 and 2000; Camassi et al., 1997, unpublished) were based on a critical revision of

extant bibliography i.e., by and large, on the same set of sources; the CPTI04 catalogue adopted the parameters proposed by the published studies (Boschi et al., 1995 and 2000).

The 1561 event is the only strong earthquake on record in the Diano valley, an otherwise low-seismicity area. The historical evidence responsible for its location in the Diano valley comes from a single, albeit very detailed primary source, whose depiction of the 1561 earthquake effects could be partial or biased. To test this hypothesis, independent historical evidence is required; accordingly we collected several primary historical documents which had never been previously used in investigations of the 1561 earthquake. Taking into account the seismotectonic framework of the region, we explore the hypothesis that the 1561 earthquake was actually a complex seismic sequence that involved different, although conterminous, seismogenetic structures.

2. Overview of the Seismotectonics in the Area of the 1561 Earthquake

The Apennines are a fold-and-thrust belt chain that developed as a consequence of Africa-Adria-Europe relative plate-motion. The southern sector of the Apennine chain is basically a buried duplex system of Mesozoic-Tertiary carbonate thrust sheets overlain by a thick pile of rootless nappes derived from platform and basin depositional realms (Patacca and Scandone, 1989; Cinque et al., 1993). From 0.7-0.5 My ago, the southern Apennines have been affected by a NE-SW extension (Ward, 1994), with the largest deformations, the strongest earthquakes and the greatest evidence of active normal faulting concentrated mainly along the axial belt (Pantosti and Valensise, 1990; Galli and Galadini, 2003). Very little is known about most of the faults responsible for these earthquakes. Apart from the deep structural complexity of the inherited fold-and-thrust belt chain, the difficulties with the identification of active faults in the southern Apennines is mainly due to the high erodibility of the siliciclastic units that form the surface structure of the seismogenic belt, which does not allow the preservation of short-term, low-rate (<1 mm/yr) tectonic indicators (e.g., fault scarps). Thus, it is not by chance that the only paleoseismic investigations in this sector of the chain focus on the ~NW-SE faults that affect carbonate rocks. Among these, it is worth noting the Caggiano fault, a normal fault that partly faces the Diano valley and that was recently investigated by Galli et al. (2006) using three trenches, as discussed in the following paragraphs.

A number of $M > 6$ earthquakes have occurred in the southern Apennines over the last millennium, with the mesoseismic area of the 1561 earthquake falling between the earthquakes of 1466, 1694, 1857 and 1980 (all with $M_w \geq 6.5$; Fig. 1). The damage zones of these earthquakes partly overlap that of the 1561 earthquake. Apart from the 1980 event, seismogenic structures have not yet been convincingly associated with any surficial geological features.

Recent paleoseismological studies (D. Pantosti, pers. Comm.) suggest that the 1466 earthquake (not reported by the CPTI04; $M_w = 6.5$, according to Galli et al. 2006; see also Figliuolo and Marturano, 1996; Galli, 2003; Guidoboni and Comastri, 2005) could have been generated by segments of the Mount Marzano fault system, (MF in Fig. 2; Pantosti and Valensise, 1990; see Galli et al. 2006), which also produced the 1980 earthquake. The 1980 earthquake ($M_w = 6.9$; Fig. 3) occurred on a normal fault system (Westaway, 1996) comprising 3-5 $N310^\circ$ segments (mainshock and 20-s sub-

event), and an antithetic SW-dipping fault (40-s sub-event; Bernard and Zollo, 1989). The rupture nucleated at ~10 km depth (Amato and Selvaggi, 1993), causing ~35 km of discontinuous surface faulting along the Mount Marzano Fault System (Cinque et al., 1981; Westaway and Jackson, 1987; Pantosti and Valensise, 1990).

The causative fault of the 1694 Irpinian earthquake ($M_w=6.9$; Fig. 4) is still not known, although the damage distribution is very similar to that of the 1980 earthquake. No surface rupture has been identified in any of the trenches dug across the Mount Marzano fault system.

A lively scientific debate is still open concerning the nature, location and trend of the structure responsible for the 1857 earthquake ($M_w=7$) (see Pantosti and Valensise, 1990; Benedetti et al., 1998; Cello et al., 2003). Two mainshocks apparently occurred within 3-4 min of each other (Baratta, 1901; Magri and Molin, 1979), causing heavy damage in the Diano and Agri valleys, with the first shock felt mainly in the northern part of this mesoseismic area (Branno et al., 1983; Fig. 2).

Finally, as mentioned above, recent paleoseismological studies along the Caggiano fault structure, placed south-east of the Mount Marzano fault (Galli and Bosi, 2003; Galli et al., 2006; Fig. 5), have revealed repeated surface faulting over the past 7 ky. The two most recent events are roughly datable to between the 1500's and the 1800's, AD (Fig. 5b). The Caggiano fault was accordingly suggested as the possible causative fault for the 1561 earthquake and/or for the northernmost 1857 shock. Moreover, the existence of an active structure at depth in the Caggiano fault hanging wall was demonstrated by the January 25, 1893, earthquake. This earthquake was located between the villages of Auletta and Pertosa, both of which were seriously damaged (Fig. 5), and was felt across a vast area of southern Italy (Fig. 6); the net NW-SE elongation of its mesoseismic area (Fig. 6) suggests fault orientation similar to that of the Caggiano fault.

3. Why Does Pacca's Description of the 1561 Earthquake Puzzle Us ?

The current view concerning the 1561 earthquake is that there were two primary shocks, on July 31 and August 19 (see Boschi et al., 2000; the CPTI04 lists only the latter, being a de-clustered catalogue). The July 31 event has a very poorly constrained macroseismic field, with heavy damage to the town of Buccino and no specific effects documented elsewhere, although it is said to have affected a large area. The macroseismic field of the 19 August event is better constrained: the highest intensity values occurred in the Diano valley, with severe damage reported in several sites of the Basilicata region and around (but not "in") Buccino (Fig. 7).

The August 19 dataset has been the basis for the assignment of the epicentre of this earthquake to the Diano valley (near Polla). This dataset, as with most of the 1561 historical dataset, was derived from a single source or rather from two different descriptions by a single author (Pacca, 1563; Pacca, 16th century). In this case "most" means 28 out of a total of 32 intensity data points (IDP) provided by the CFTI studies (Boschi et al., 1995; 1997; 2000), and 28 out of a total of 30 IDP provided by Monachesi and Stucchi (1997; i.e., the macroseismic database for the NT4.1 catalogue).

Pacca (b. 1534, d. 1587) was a Neapolitan writer and academician (Morelli, 1993; Castelli, 2003). His first, succinct description of the 1561 earthquake is included in a narrative of occurrences in

the Kingdom of Naples over the years 1557-1562, first published in 1563 as an addition to a multi-authored *Istoria del Regno di Napoli* (Pacca, 1563). The *Istoria*'s original author was Pandolfo Collenuccio (d. 1504), but the work was later extended to 1586 through successive additions by Mambrino Roseo (d. 1584), Pacca himself and Tommaso Costo (d. 1613). Owing to the vagaries of printers, Pacca's name does not appear in the main frontispiece of any of the several extant printings of the *Istoria*, but only in an easy-to-miss internal "sub-frontispiece". However, Pacca's part-authorship of the *Istoria* is reliably attested by later bibliographers (Soria, 1781; Minieri Riccio, 1844). Pacca also left a longer description of the 1561 earthquake in his *Discorso del terremoto* (Pacca, 16th century), an unpublished treatise on which he worked probably to the end of his life. Giuseppe Mercalli brought it to light in 1891 when he published a selection of its descriptions of 16th century earthquakes, (Mercalli, 1891).

Pacca's "short" description of the 1561 earthquake was written no later than 1563 (the year it was published), and possibly earlier; perhaps as early as late 1561. The "long" description is more detailed than the "short" one; this could mean that it relied on more extensive research and/or that it was written later, but no more precise dating is possible. What really matters, however, is that the "short" and "long" descriptions give rather different versions of the July 31 and August 19 events (Fig. 8), and we cannot know why Pacca altered his first version, and whether or not the latter should be considered more reliable than the former. The above-mentioned previous studies, which were both of a preliminary nature and part of a large-scale reviewing project, exploited as best they could the richest source readily available; considering these circumstances, a reasonable approach. Here, however, we focus on an in-depth investigation of the 1561 earthquake, including consideration of several original accounts that had never been taken into account before this study.

4. Looking for New Evidence about the 1561 Earthquake

Our search for original accounts of the 1561 earthquake was a "no-budget", expeditious one. Accordingly, we pooled together the findings of a few previous studies (Galli, 2003; Castelli 2003) and those by an ongoing study of 16th century newsletters (details in Camassi & Castelli, 2004; Castelli & Camassi, 2005). The resulting set of sources includes newsletters, notarial records, private memoirs, epigraphic sources and historiographical materials, the earliest of which were written no later than August 9, 1561, and the latest in the second half of the 17th century (Table 1). It must be stressed that – given the preliminary nature of the study – we purposely did not attempt to assay either of the main documentary complexes available for the history of southern Italy in the 16th century, namely the Archivio di Stato of Naples and the Archivo General of Simancas (Spain). Obviously, no study of the 1561 earthquake could aspire to call itself complete while these two tremendous record depositories remain unexplored. We hope that our present attempt will rekindle interest in the 1561 earthquake, and that an adequately-funded concerted effort can be set in motion.

4.1. Newsletters

Records 2, 3 and 6 of Table 1 are from newsletters (*Avvisi*), a typical 16th century source. They were produced in many European towns by professional “intelligencers” who collected the latest news from a mix of official and occasional sources and sent it to subscribing customers. *Avvisi* writers relied heavily on hearsay and their work needs to be carefully scrutinized to weed out mistakes, misspellings and outright lies. On the whole, however, *Avvisi* are a valuable source of information and well worth the effort needed.

Newsletters 2 (BAV, 1561a) and 3 (ASMo, 1561) of Table 1 are especially interesting because they shed new light on the July 31 event. Newsletter 2 (written in Rome on August 9, 1561, based on “news from Naples”) describes an undated shock (which must be that of July 31) as causing damage to “houses and palaces.” The buildings named are the Duomo (Cathedral), the St Lorenzo and St Agostino churches, and the nunnery of St Maria Regina Coeli, whose inmates had to seek shelter elsewhere (a detail which appears confirmed by Ceva Grimaldi, 1857, for the nunnery). According to the previously available dataset, the 1561 earthquake shocks did not cause any damage in Naples.

Newsletter 3 (written in Naples on August 9, 1561) gives a list of localities outside Naples that were damaged by the July 31 event. Some are individually named and easily identifiable, and there is reference to “four ‘castles’ [i.e. walled urban settlements] belonging to Signor Bernabò Caracciolo”. The Neapolitan nobleman bearing this name in 1561 was the Lord of four villages/small towns: Balvano, Sicignano, Ricigliano and Pietramala (Shamà & Dominici Battelli, 2003). It thus appears reasonable to identify them as the “*quattro castelli*” (four castles) of the *Avviso*. Balvano, Sicignano and Ricigliano are among the sites cited by Pacca (16th century) as damaged by the event of August 19. If our identification is acceptable, this would backdate the earliest instance of damage in Balvano, Sicignano and Ricigliano to July 31. Unfortunately we have been unable to identify “Pietramala.” There is a Pietramala in Tuscany and a former Pietramala, now Cleto, in Calabria, but neither appear likely to have been affected by the 1561 earthquake.

Newsletter 6 (BAV, 1561b) was written in Rome on September 9, 1561, and was based on “news from Naples.” This account simply states that “the earthquake does not cease to cause ruins in Basilicata” (a probable reference to the August 19 event, that according to Pacca [16th century] damaged several localities in Basilicata) and that “many houses collapsed in Salerno”, which is midway between Naples and the Diano valley. Judging from the private journal of the Bishop of Salerno, who in 1561 was away from his Diocese but did keep in regular touch, this last piece of news could be exaggerated. The Bishop’s journal is discussed at more length below.

4.2. Notarial records

Italian notaries are officers who are authorized to perform legal formalities, such as drawing up contracts and deeds, and the certifying their correctness and conformity to law. There are many situations in which notarial records can double up as accounts of earthquakes: for instance, if a notary was called to prepare a contract concerning business related to an earthquake, such as the restoration of a damaged building, or if the notary used an earthquake as a chronological reference. Notaries also sometimes chose to fill a blank space in their notebook with the account of an earthquake they had

personally witnessed or heard about. Table 1 includes examples of all of these instances. Record 1 of Table 1 is an eyewitness notarized deposition that gave a description of the July 31 event as it was felt by a group of people in the village square in Atripalda (ASAv, 1561); records 4, 7 and 8 mention single damaged buildings in Buccino (ASSa, 1561a-b); record 9 (ASSa, 1561c) is a memorandum that was probably written towards the end of 1561, by a notary of Atena Lucana (Diano valley) who described the earthquake sequence from its start on July 31, 1561, continuing to August 19, 1561 and on to the end of that year; this notary listed the localities damaged by the July 31 event, adding that the August 19 event increased the damage to all of the previously mentioned sites),

4.3. Private memoirs and historical chronicles

The earliest available private account of the 1561 earthquake is an entry in the journal of the Archbishop of Salerno (Seripando, 16th century). The Prelate was then in Trento (northern Italy), attending the ongoing ecumenical Council, but he kept in regular touch with the Salerno Diocese by post. On August 22, 1561, Archbishop Seripando recorded having just received news of an earthquake that had been felt recently in Salerno (on an unspecified day) and the collapse of a palace that occurred eight days later. The inland distance between Trento and Salerno is about 1,000 km; so assuming a daily cover of ~100 km for a fast courier on horseback, it would have taken at least a dozen days for this news to reach Trento. Therefore, the earthquake recorded in Seripando's journal must be either the July 31 event or another shock that occurred before August 19. A couple of shocks were recorded as felt in Avellino at the beginning of August 1561 by Bella Bona (1656), a local historian that extracted this detail from a notarial memorandum for which the original is now lost. A few more felt accounts of the 1561 earthquake were almost certainly written down by direct witnesses in Naples, Solofra, Benevento, and Avellino, although their precise dates of compilation cannot be ascertained; these accounts were included in books that were printed from a few years to a century after 1561 (Castaldo, 16th century, Maffei, 1564; Vipera, 1635).

4.4. Epigraphic records

Galli (2003) gives detailed information on epigraphic and archaeological evidence connected/likely to be connected with the 1561 earthquake. Here we give a brief summary of it (Fig. 9).

4.4.1. Epigraphs explicitly mentioning an "earthquake" (dated in/ around "1561" or undated)

Tito. A door lintel salvaged from a church destroyed in the 1980 earthquake bears an inscription attesting that the church had already collapsed in the earthquake of July 31 "1560" (Fig. 11a; Laurenzana, 1989). This is certainly a mistake of the carver, as Pacca (16th century) lists Tito among the sites damaged by the August 19, 1561 event. This record allows to backdate the start of damage in Tito to July 31, as confirmed by ASSa (1561c) too.

Polla. On the façade of the Villano palace, a 1590 inscription records the completed restoration of the town, previously destroyed by an undated earthquake (Fig. 11b). This is likely to be the 1561 earthquake, as Pacca (1563; 16th century) list Polla among the affected localities.

Sant'Angelo dei Lombardi. In the Franciscan convent a 1779 inscription records its destruction by an undated earthquake and subsequent reconstruction by Felice Peretti, the local *Regens studiorum* (Head of Studies) and later Pope Sixtus V (1585-1590). Peretti, who was never actually *Regens studiorum* in Sant'Angelo dei Lombardi, was nonetheless the General Superior of the Franciscan Order in 1566-1568. In that capacity he personally inspected several Franciscan houses of the Kingdom of Naples and could have ordered the restoration (I.L. Gatti, personal communication). If things went really so, the earthquake involved could have been that of 1561.

Buccino. On the façade of St. Maria Soldicta (a church destroyed in the 1980 earthquake) a 19th century inscription mentions the 1561 and 1857 earthquakes as responsible for previous collapses of the building. Recent archaeological findings in the mediaeval castle (Galli, 2003) reveal a collapse of the drawbridge machinery room, dated *circa* mid-16th century (from shards of pottery found sealed under the rubble, A. Lagi, personal communication) and possibly related to the 1561 earthquake.

4.4.2. Epigraphs not explicitly mentioning an earthquake

Viggiano. In the church of St. Benedetto, the date “1561” is carved on a door lintel. None of the available sources mention Viggiano as involved in the 1561 earthquake.

Laurenzana. On the façade of the St. Maria church an inscription records the 1583 restoration of the building, then near collapse for unspecified causes.

Marsico Nuovo. On the façade of the St. Gianuario church an inscription records the 1591 restoration of the building.

Torella dei Lombardi. An inscription on a bell in the St. Maria del Perillo church records that it was recast in 1599 after having crashed to the ground on an unspecified date between 1553 and 1599. This episode hints at a collapse of the bell-tower, for which the 1561 earthquake could have been responsible; ASMo (1561) lists Torella dei L. among the places affected by the July 31, 1561, event.

5. Using the New Dataset to Piece Together the 1561 Seismic Sequence

The new dataset includes several original sources that can be used to piece out the extension of the macroseismic fields of the July 31 and August 19 events, and a few intermediate shocks. According to the new dataset, the July 31 macroseismic field looks like the one described by Pacca (1563), rather than the one by Pacca (16th century). The resulting image is consistent with the hypothesis of an “Irpinian” earthquake that was strong enough to cause some damage in Naples, and severe damage in Basilicata and as far as the Diano valley. As for the August 19 event, the only available detailed description of its effects remains that of Pacca (16th century). Other sources either simply note that the July 31 event was followed by further shocks (undated), or at most that on August 19 “*further damage*” occurred in the same area that had already affected by the July 31 event (ASSa, 1561a; Pacca, 1563). However, the description by Pacca (16th century) is too detailed for the August 19 event to be dismissed as a mere aftershock of an “Irpinian” earthquake. All the more so as there is unquestionably some evidence of seismic activity in the Diano valley in 1561; ASSa (1561c): a memorandum by a local notary, mentions tremors that were felt, possibly in Atena Lucana and its surroundings, until the

end of 1561; Pacca (16th century) records minor seismic events in the Diano Valley in 1562 and 1563. The shock of August 19, 1561, could thus have triggered a local seismic sequence in the Diano Valley, in an area already afflicted by the non-local earthquake of July 31. The combined effect could have appeared to be a major catastrophe to the “*trustworthy witnesses*” mentioned by Pacca (16th century).

Examining the 1561 damage distribution from a strictly geographical point of view (i.e., without consideration of the timing of events that caused damage), one notes a concentration of high intensities around Vietri sul Mare (Is=IX MCS).

In southern Italy there are two small towns named Vietri. Along the Tyrrhenian coastline, between Amalfi and Salerno, there is “Vietri sul Mare” (V. “on the sea”); within the Apennines, some 100 kms inland, there is “Vietri di Potenza”. The suffixes “sul Mare” and “di Potenza” are fairly recent additions to their name, made after the unification of Italy (late 19th century) for the sake of administrative clarity. In older times, confusion between the two Vietri must have been common.

Pacca (16th century) listed a “Vietri” among the localities affected by the August 19, 1561 event, explicitly explaining that it was “a castle positioned between Amalfi and Salerno” (i.e. Vietri sul Mare). However, all other localities which Pacca mentioned side by side with “Vietri” are placed well within the Apennines, some even quite close to present-day Vietri di Potenza. Remarking on this point, all past studies of the 1561 earthquake - from Mercalli (1891), to Boschi et al. (2000) to Castelli (2003) – assumed that Pacca must have made a mistake and that he really meant to cite “Vietri di Potenza”, rather than “Vietri sul Mare”. This was a justifiable assumption, on the basis of the then available evidence but the availability of a wider set of original accounts leads us to a new assessment of the “Vietri vs Vietri” question. On one hand, the involvement of Vietri di Potenza in the 1561 earthquake is unequivocally attested by ASSa (1561c), a notarial memorandum that includes “Vietri” in a group of Apenninic localities affected by the July 31 event. On the other, ASMo (1561), BAV (1561b) and Seripando (16th century) name no less than three localities positioned in close proximity to Vietri sul Mare (Cava dei Tirreni, Nocera and Salerno), as affected by earthquakes from July 31 to late August 1561. This leads us to believe that when Pacca (16th century) named Vietri “between Amalfi and Salerno” as an earthquake-affected locality, he was not completely wrong after all but rather that he was conflating the two Vietris into one. It is quite likely that Vietri sul Mare experienced the same shocks that affected nearby Cava dei Tirreni, Nocera and Salerno. On the other hand, it is much less likely is one and the same earthquake could have affected both Vietri di Potenza and Vietri sul Mare to the extent described by the sources.

ASMo (1561), BAV (1561b) and Seripando (16th century) mention damage in Vietri sul Mare, Cava dei Tirreni, Nocera and Salerno that cannot be attributed to an earthquake generated by the Mount Marzano-Caggiano structures, or by any of the neighbouring seismogenic structures (i.e. those of the Ofanto and Agri valleys). For one thing, there is no evidence that in 1561 there were any effects in dozens of localities midway between these structures and Vietri sul Mare, and where an earthquake generated by the above-mentioned structures would have caused heavier damage than in Vietri sul Mare itself. Moreover, the intensity that was reached in this Vietri by the 1561 earthquake (IX MCS) was much higher than the VI MCS intensity due to the 1694, 1857, and 1980 earthquakes, which were all stronger than the 1561 earthquake. One can thus not attribute the high intensity in 1561 to local

from Calabria to the Umbria-Marches, including the 1703, central Italy sequence (Galli et al., 2005) and the 1783 Calabrian sequence (Jacques et al., 2001; Galli and Bosi, 2002).

The Caggiano fault is itself complex, with two main segments separated by a right step accommodated by the Mount San Giacomo and Timpe faults, each approximately 10 km in length (Fig 5.; Galli et al., 2006). A third segment, the Polla fault overlaps the latter, bordering the northern Vallo di Diano slopes (PF in Fig. 10). Macroseismic observations suggest that the July 31 occurred on this fault system, but given the imprecision of the data one cannot determine whether this earthquake was a single event or a complex rupture involving events separated by seconds or even hours.

If the July 31 and August 19 earthquakes occurred on the Caggiano fault and in the Ofanto valley respectively, the sites placed between the two source zones would have experienced strong shaking twice, or even oftener, within 20 days. This is indeed what appears to have happened: Buccino was explicitly quoted by Pacca (16th century) and De Raimo (15th-16th century) as being “struck twice by the earthquake within one month,” while Tito, Polla, Sicignano and nearby places appear to have been severely damaged by the July 31 event before being destroyed or nearly destroyed in the August 19 event (ASMo, 1561).

Considering all the remaining questions regarding this complex sequence, and with the exception of a local triggered Vietri sul Mare event, one cannot identify detailed source zones for all of the principal events of the 1561 sequence, or even be sure how many distinct ruptures occurred. The newly considered historical sources do, however, further elucidate the seismotectonics and earthquake history of this part of the Apennines. The combined synthesis of archival and field data is, we suggest, the most powerful tool to understand past and potential future earthquake sources.

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8. References

8.1. Primary sources

- 1561
- a) ASAv [Archivio di Stato, Avellino], Notai, Atripalda, Notary Pietro Antonio De Masi, B 296, folios not numbered.
 - b) ASMo [Archivio di Stato, Modena], 1561, Archivio segreto Estense, Cancelleria, Estero, Avvisi e notizie dall'estero, Rome, August 9, 1561.
 - c) ASSa [Archivio di Stato, Salerno], 1561a, Protocolli notarili Salerno, Notary Tommaso Anguillara, B 588, f. 254.

- d) ASSa, Protocolli notarili Salerno, Notary Antonio de Tisbia, B 580, f. 66-69.
- e) ASSa, Protocolli notarili Salerno, Notary Donato Sabuco, B 7/1, folios not numbered.
- f) BAV [Biblioteca Apostolica Vaticana], 1561a, MS Urb. Lat 1039, Naples, August 9, 1561, f. 294r.
- g) BAV, 1561b, MS Urb. Lat 1039, Naples, 6 September 1561, folios not numbered.

Seripando, G., 16th century, *Giornale dal 1513 al 1562*, MS IX.C.42: Biblioteca Nazionale "Vittorio Emanuele III", Napoli, Italy.

- 1563 Pacca, C. [1563] *Della seconda parte del compendio dell'istoria del Regno di Napoli, il Settimo libro del Dottor Colanello Pacca Napoletano*. In: P. Collenuccio et al., *Compendio dell'istoria del regno di Napoli di m[esser] Pandolfo Collenuccio da Pesaro con la giunta delle cose notabili successe per tutto l'anno MDLXII*: Napoli, Gio[vanni] Maria Scotto.
- 1564 Maffei, G.C. [1564] *Scala naturale overo Fantasia dolcissima di Gio[van] Camillo Maffei da Solofra, intorno alle cose occulte, e desiderate nella filosofia*: Venetia, Gio[vanni] Varisco e Compagni.
- 16th cent. Castaldo, A., 16th century, *Dell'istoria di notar Antonino Castaldo*, in Gravier, G., ed., *Raccolta di tutti i piu rinomati scrittori dell'istoria generale del Regno di Napoli*, v. 6: Napoli, Gravier, 1769-1777.
 Pacca, N.A., 16th century, *Discorso del terremoto*, MS 7/A3: Società Napoletana di Storia Patria, Fondo sismico, Napoli, Italy.
 Raimo, L.sr., and Raimo, L. jr., *Annales de Raimo sive Brevis historia rerum in regno Neapolitano gestarum* (1197-1486), in L.A. Muratori, ed., *Rerum Italicarum Scriptores*, v. 23: Milano, Societas Palatina, 1733.
- 1635 Vipera, M. [1635]. *Chronologia Episcoporum, et Archiepiscoporum Metropolitanae Ecclesiae Beneventanae quorum extat memoriae*: Napoli, D. Montanari.
- 1656 Bella Bona, S. [1656] *Raguagli della città d'Avellino*: Trani, Lorenzo Valerij.

8.2. General

- Priestley, M. N. J and Calvi, G. M. [1991] "Towards a capacity — Design assessment procedure for reinforced concrete frames," *Earthquake Spectra* **7**(3), 413–437.
- Amato, A., and Selvaggi, G. [1993] "Aftershock location and P-velocity structure in the epicentral region of the 1980 Irpinia earthquake," *Annali di Geofisica*, **36**, 3-15.
- Baratta, M. [1893] "Sul terremoto Lucano del 25 gennaio 1893" *Annali dell'Ufficio Centrale di Meteorologia e Geodinamica*, **14**(1), 47-56.
- Baratta, M. [1901] *I terremoti d'Italia, Saggio di storia, geografia e bibliografia sismica italiana*, Torino, Fratelli Bocca Ed., 950 pp..
- Benedetti, L., Tapponier, P., King, G., and Piccardi, L. [1998] "Surface rupture of the 1857 southern Italian earthquake" *Terra Nova*, **10**, 206-210.
- Bernard, P., and Zollo, A. [1989] "The Irpinia, Italy, 1980 earthquake, detailed analysis of a complex normal faulting" *Journal of Geophysical Research*, **94**, 1631-1647.
- Boschi, E., Pantosti, D., Slejko, D., Stucchi, M., and Valensise, G. eds. [1993] "Irpinia dieci anni dopo. Special Issue" *Annali di Geofisica*, **36**, 1-351.
- Boschi, E., Ferrari, G., Gasperini, P., Guidoboni, E., Smriglio, G., and Valensise, G., eds. [1995] *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1980*, Bologna, ING-SGA, 970 pp..
- Boschi, E., Guidoboni, E., Ferrari, G., Valensise, G., and Gasperini, P., eds. [1997] *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1990*, Bologna, ING-SGA, 644 pp.
- Boschi, E., Guidoboni, E., Ferrari, G., Mariotti, D., Valensise, G., and Gasperini, P., eds. [2000] "Catalogue of Strong Italian Earthquakes from 461 B.C. to 1997. Version 3 of the Catalogo dei forti terremoti in Italia" *Annals of Geophysics*, **43**, 609-868.
- Branno, A., Esposito, E., Marturano, A., Porfido, S., and Rinaldis, [1983] "Studio su base macrosismica del terremoto della Basilicata del 16 dicembre 1857" *Bollettino della Società Naturalistica di Napoli*, **92**, 249-338.

- Camassi, R., and Castelli, V. [2004] "Looking for "new" earthquake data in the 17th-18th c. European "newssellers" network" *Journal of Earthquake Engineering*, **8**, 335-359.
- Camassi, R., and Stucchi, M. (Eds) [1997] *NT4.1- a parametric catalogue of damaging earthquakes in the Italian area (release NT4.1.1)*, GNDT-CNR open file report, Milano, 93 pp. available also on internet at <http://emidius.mi.ingv.it/NT/CONSNT.html>.
- Castelli, V. [2003] "Strong earthquakes included "by chance" in Italian catalogues, single cases or a hint of more?" *Annals of Geophysics*, **46**, 1247-1263.
- Castelli, V., and Camassi, R. [2005] "The shadow-zone of major Italian seismicity. Notes on the perception of lesser damaging earthquakes by 17th-18th c. journalistic sources" *Journal of Earthquake Engineering*, **9**, 333-348.
- Cello, G., Tondi, E., Micarelli, L., and Mattioni, L. [2003] "Active tectonics and earthquake sources in the epicentral area of the 1857 Basilicata earthquake, (southern Italy)" *Journal of Geodynamics*, **36**, 37-50.
- Ceva Grimaldi, F. [1857] *Della fondazione della città di Napoli dal tempo della sua fondazione sino al presente, memorie storiche*: Napoli, stamperia e calcografia Vico Freddo a Pignasecca 15, lxxviii+806 pp.
- Cinque, A., Lambiase, S., and Sgrosso, I. [1981] Su due faglie nell'alta valle del Sele legate al terremoto del 23.11.1981" *Rendiconti della Società Geologica*, **4**, 127-129.
- Cinque A., Patacca E., Scandone P., and Tozzi M. [1993]. Quaternary kinematic evolution of the Southern Apennines. Relationships between surface geological features and deep lithospheric structures, *Annali di Geofisica*, **36**, 249-260.
- CPTI Working Group, 1999] *Catalogo Parametrico dei Terremoti Italiani*, Bologna, ING - GNDT - SGA - SSN, 92 pp.
- CPTI Working Group, 2004] *Catalogo Parametrico dei Terremoti Italiani (versione 2004, CPTI04)*, Internet website INGV Sezione di Milano, <http://emidius.mi.ingv.it/CPTI/> (last revision 27 May 2004)
- Ferrari, G. (Ed.), [2004] *Viaggio nelle aree del terremoto del 16 dicembre 1857*, SGA, Bologna, vol. I, 500 pp; vol. II 516 pp.
- Figliuolo, B., and Marturano, A. [1996] "Il terremoto del 1466" *Rassegna Storica Salernitana*, **25**, 93-109.
- Galli, P. [2003] "Two poorly known earthquakes of southern Campania" Dipartimento della Protezione Civile-Servizio Sismico Italiano, RT/SSN/03/01, 1-22.
- Galli P., and Bosi V. [2002] "Paleoseismology along the Cittanova fault. Implications for seismotectonics and earthquake recurrence in Calabria (southern Italy)", *J. of Geophys. Res.*, **107**, B3, 10.1029/2001JB000234, 1/1-19.
- Galli, P., and Bosi, V. [2003] "Analisi paleosismologiche lungo la faglia di Caggiano, Monti della Maddalena, Sa" Riassunti estesi delle comunicazioni, Convegno Nazionale Gruppo Nazionale di Geofisica della Terra Solida, **22**, 106-108.
- Galli, P., Bosi, V, Piscitelli, S., Giocoli A., and Scionti V. [2006] "Late Holocene earthquakes in southern Apennines: paleoseismology of the Caggiano fault", *Int. J. Earth Sci. (Geol. Rundsch.)*, DOI 10.1007/s00531-005-0066-2, **95**, 855-870.
- Galli, P., and Galadini, F. [2003] "Disruptive earthquakes revealed by faulted archaeological relics in Samnium, Molise (southern Italy)" *Geophysical Research Letters*, **30**, 10.1029/2002GL016456, 70/1-4.
- Galli, P., Galadini F., and Calzoni F. [2005] "Surface faulting in Norcia (central Italy): a "paleoseismological perspective", *Tectonophysics*, **403**, 117-130.
- Gasparini, P. [2002] "The Boxer program, release 3.02 available at: <http://ibogfs.df.unibo.it/user2/paolo/www/boxer/boxer.html>.
- Guidoboni, E., and Comastri, A. [2005] *Catalogue of earthquake and tsunamis in the Mediterranean area from the 11th to the 15th century*, Istituto Nazionale di Geofisica e Vulcanologia, Rome-Bologna, 1037 pp.
- Jacques, E., Monaco C., Tapponnier P., Tortorici T. and Winter T. [2001] "Faulting and earthquake triggering during the 1783 Calabria seismic sequence, *Geophys. J. Int.*, **147**, 499-516.
- Laurenzana, N. [1989] *Tito. Storia, vicende, personaggi, usi e costumi, fede*, Cassola, Editore Moro, 286 pp.
- Magri, G., and Molin, D. [1979] "Attività macrosismica in Basilicata, Campania e Puglia dal 1847 al 1861" *CNEN, RT/AMB*, **79**, 5.
- Mercalli, G. [1891] "I terremoti napoletani del XVI secolo ed un manoscritto inedito di Cola Aniello Pacca", *Bollettino della Società Geografica Italiana*, **10(2)**, 349-372.
- Minieri Riccio, C. [1844] *Memorie storiche degli scrittori nati nel regno di Napoli*, Napoli, 414 pp.
- Monachesi G., and Stucchi M. [1997] DOM4.1, an intensity database of damaging earthquakes in the Italian area, <http://emidius.mi.ingv.it/DOM/>.
- Morelli, S. [1993] "Una fonte inedita per lo studio della sismologia storica, il Discorso del Terremoto di Cola Aniello Pacca (1563)" *Rassegna Storica Salernitana*, **10**, 247-259.
- Nostro C., Cocco M., and Belardinelli M. [1997] "Static stress changes in extensional regimes: an application to Southern Apennines (Italy), *Bull. Seismol. Soc. Am.*, **87**, 234-248.
- Nostro, C., Stein, R., Cocco, M., Belardinelli, M., and Marzocchi, W. [1998] "Two-way coupling between Vesuvius eruptions and southern Apennine earthquakes, Italy, by elastic stress transfer" *J. of Geophys. Res.*, **103**, 24487-24504.

- Pantosti, D., and Valensise, G. [1990] "Faulting mechanism and complexity of the November 23, 1980 Campania-Basilicata earthquake" *J. of Geophys. Res.*, **95**, 15319-15342.
- Patacca, E., and Scandone P. [1989] "Post-Tortonian mountain building in the Apennines: the role of the passive sinking of a relic lithospheric slab, In: Boriani A., Bonafede M., Piccardo G.B. e Vai G.B. (eds.), *The Lithosphere in Italy: Advance in Earth Science Research*, , Accademia Nazionale dei Lincei, Rome, 157-176.
- Postpischl, D., ed. [1985] Catalogo dei terremoti italiani dall'anno 1000 al 1980, *Quaderni della Ricerca Scientifica*, **114** (2B), 239 pp.
- Shamà, D., and Dominici Battelli A. [2005] "*Caracciolo Pisquizi, Duchi di Sicignano*" Internet website "Genealogie delle dinastie nobili italiane" <http://www.sardimpex.com> (version 10 January 2005; consulted 17 March 2005).
- Soria, F. [1781] *Memorie storico critiche degli scrittori napoletani*, Napoli, 684 pp.
- Spina, V., Galli P., Tondi E., Mazzoli S., and Cello G. [2007] "Quaternary fault segmentation and interaction in the epicentral area of the 1561 earthquake (Mw=6.4), Vallo di Diano, southern Apennines, Italy, *Tectonophysics*, in press.
- Ward, S. [1994] "Constraints on the seismotectonics of the central Mediterranean from very long baseline interferometry, *Geophys. J. Int.*, **117**, 441-452.
- Westaway, R. [1996] "Fault rupture geometry for the 1980 Irpinia earthquake, a working hypothesis" *Annali di Geofisica*, **36**, 51-69.
- Westaway, R., and Jackson, J.A. [1987] "The earthquake of 1980 November 23 in Campania-Basilicata (southern Italy)" *Geophys. J. Astron. Soc.*, **90**, 375-443.

Table 1 – Original records for the 1561 earthquake available to date. 1-24: written from August 1561 to ~100 years after; 25-27: written more than 100 years after 1561; A-B: records possibly dealing with earthquake effects without explicitly mentioning them.

Table 2 – Apparent chronological sequence of the now-available 1561 earthquake data. Although fairly confusing from a seismogenetic point of view, it includes information that derives from news that reached the sources with different days of delay.

Table 3 – Intensities evaluated for the proposed 1561 shocks. Only the intensities of the Vietri sul Mare sub-event are given separately because of the difficulty in discriminating the effects caused on the Apennine villages by the different events that occurred between July 31 and August 19, 1561. Grey-shaded localities were not reported in Boschi et al. (2000). (MCS, Mercalli-Cancani-Sieberg scale)

Figure 1 – Distribution of major earthquakes ($M \geq 6$; mod. after CPTI04) along southern Italy (black lines, primary seismogenic faults, mainly bounding intermontane Pleistocene basins; NAA, SAA, buried front of the northern and southern Apennine thrust and folds Arc, respectively). The main earthquakes in the investigated area are labelled.

Figure 2 – Highest intensity datapoint distribution (HIDD) for the 1466 ($I_s=6-10$ MCS; Galli et al., 2006) and 1857 ($I_s=6.5-11$ MCS; Boschi et al., 2000; partial view) earthquakes. Symbol size is proportional to site intensity (I_s). Black lines are the known primary active faults (teeth on downthrown side. UF, Ufita fault; MF, Mt. Marzano fault system; CF, Caggiano fault). Galli et al. (2006) hypothesizes the partial rupture of the MF and CF in the 1466 and 1857 earthquakes, respectively.

Figure 3 – Highest intensity datapoint distribution for the 1980 earthquake ($I_s=6.5-10.5$ MCS; Monachesi and Stucchi, 1997). MF is the Mount Marzano fault system, which was responsible for the earthquake. It is worth noting that the earthquake had a NW directivity, as can be deduced by the HIDD.

Figure 4 – Highest intensity datapoint distribution for the 1694 earthquake ($I_s=6.5-11$; mod. after Boschi et al., 2000). Black lines are the known primary active faults in the area (teeth on downthrown side. UF, Ufita fault; MF, Mount Marzano fault system; MAF, Mount Mattina-Atella fault; TF, Teora fault). The seismogenic structure of this catastrophic earthquake is still unknown. Galli et al. (2006) hypothesize that the rupture might have occurred along the Ufita, Teora and Mount Mattina-Atella faults. Note that the 1694 HIDD includes those of 1466 and 1980.

Figure 5 – Shaded relief image of the northern Maddalena mountains, facing the Vallo di Diano. MSGF is the post-last-glacial-maximum Mount San Giacomo fault (arrows indicate bedrock fault scarp in inset A), which continues SW with the Timpe fault (TF). According to paleoseismological analyses (i.e., inset B; from Galli et al., 2006), the last ruptures of this fault system (E4 and E5) occurred during/ after the Little Ice Age (1200-1800 AD), being consistent with both the 1561 and 1857 fault ruptures.

Figure 6 – “Snap-shot” of the 1893 earthquake according to Baratta (1893, modified). The net NW-SE elongation of the “*area isosismica forte*” (strong isoseismic area, in legend) should account for the trend in the seismogenic structure. Baratta himself thought that this earthquake was “probably a repetition of the one that in 1561” damaged the Basilicata region, and which was caused by the same “seismic centre”.

Figure 7 – Geographic distribution of the sites affected by the 1561 earthquake (according to Boschi et al., 2000): the information on most affected sites was supplied by Pacca (16th century) only. Black symbols are those reported as hit by the July 31 shock.

Figure 8 – Pacca’s “changing opinions”. Panel A summarizes the first report of Pacca (1563; F=felt, D=damage, H=heavily), that is: (1561.07.31) Neapolitan Kingdom (F), Principato province and Basilicata province (HF/D?), Balvano, Tito, Piperno, San Licandro, Polla, Vallo di Diano area (HD). (1561.08.19): Naples (F), Principato province and Basilicata province (HD); in the above: 584 dead, 551 ruined buildings. Panel B summarizes the second report of Pacca (16th century), that is: (1561.07.31) Neapolitan Kingdom (F), Principato province, Basilicata province and Terra di Lavoro province (HF/D?), Buccino (HD). (1561.08.19): Naples (F), Atella, Atena, Avigliano, Balvano, Bella, Caggiano, Calitri, Muro, Ottati, Palo, Pantoliano, Picerno, Pignola, Polla, Potenza, Sant’Angelo, Sant’Arsenio, San Fele, San Giacomo, San Licandro, San Pietro, San Ruffo, Sala, Sicignano, Tito, Vietri (D/HD).

Figure 9 – Location of epigraphic evidence certainly or possibly connected to the 1561 earthquake (Galli, 2003). A, Tito, (formerly in the local Congrega). Note in the last row: “tota corrui a terremotu ultimo die 1560” (i.e., mistake for 1561). B, Polla; front of Palazzo Villani. Note in the 2nd row: “oppido motu terre concusso...”, and in the last: “...AD MDXC” (i.e., 1590, meaning that they took 30 years to restore the castle!).

Figure 10 – Intensity datapoint distribution of the July-August 1561 sequence according to the present study (see Table 3). The dashed ellipses include the possible mesoseismic areas of the different shocks. The one around Naples could be related to an eruption (and local earthquake) of Vesuvio (BAV, 1561a), the effects of which were cumulative with those of the other earthquakes of the sequence. The earthquake around Vietri sul Mare should be connected to a local (or offshore) epicentre, and not to the Apennine faults, since no other localities between the coast and the chain were damaged. The two ellipses between Campania and Basilicata hypothetically show the mesoseismic areas of the two mainshocks generated by the Caggiano fault (south) and by a subset of the Ofanto Valley seismogenic structures (fault names: see previous figure legends. PF, Polla fault.). Note that the epicentre of the 1893 earthquake matches the Caggiano fault plane.

Figure 11 – Induced stress in the southern 1561 earthquake region, due to slip on the Mount San Giacomo (a) and Timpe (b) faults (MSGF and TF in Fig. 5, respectively). Results are shown in terms of the Coulomb Failure Stress (CFS; faults optimally oriented for re-shear with respect to the remote stress field). Layer at 10 km of depth. Fault dip 65°; slip 0.4 m. Coefficient of friction of the layer 0.70; pore-pressure factor, 0.38; Skempton’s coefficient, 0.50. In our hypothesis, the rupture on July 31 of the Mount San Giacomo fault increased the stress in the crust volume to the southeast, “charging” the Timpe fault, which ruptured 19 days after (or *vice versa*).