Can we consider the 1951 Caviaga (northern Italy) earthquakes as non-induced events?

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Electronic Supplements:

- n. 5 Tables containing macroseismic and seismic phase data used in the present study to relocate the 1951 seismic events and the 1786 historical events, and the final location parameter sets
- n. 1 Text containing the estimates of stress variation due to unloading in the upper crust

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Introduction

On the night between May 15 and 16, 1951, two moderate earthquakes with estimated magnitudes of M 5.4 and 4.5 occurred in northern Italy, about 40 km southeast of Milan, close to the small town of Caviaga. They were recorded by several observatories worldwide, as reported by the International Seismological Summary (ISS) Bulletin. Despite the moderate magnitudes, these two events caught the attention of seismologists and have been studied in detail, in particular by Caloi et al. (1956), because they were close to Caviaga, in an area that was assumed to be aseismic. Moreover, their shallow hypocenters (*ca*. 5 km in Caloi et al., 1956) indicated a possible anthropogenic source, related to wells for gas withdrawal (Figure 1, Data and Resources).

In the absence of any further discussion or revision of the original study by Caloi et al. (1956), the Caviaga earthquakes have been included in several compilations of induced seismicity, and they have been generally accepted as cases of anthropogenic events (Grasso, 1992; Maury et al., 1992; Guha, 2000; Suckale, 2009; Klose, 2013; MINE Junior Research Group, 2014).

In particular, the two events are currently included in the catalog of anthropogenic events that was compiled by Klose (2013), as they formally match all of the required criteria to be classified as induced or triggered events. These criteria are: (a) description of the candidate earthquake in a scientific peer-reviewed article, or in conference proceedings or as an abstract; (b) characterization in terms of time of nucleation, dominant focal mechanism, geographic location, with uncertainty of depth and maximum observed seismic magnitude; (c) characterization of the human activity in terms of start/end time of operations, geographic location, depth in the earth crust, and mass changes in proximity to wells. The first criterion was satisfied by the report by Maury et al. (1992), in which the Caviaga events were mentioned: “In Italy, the production of gas from the Caviaga field caused an earthquake of magnitude 5.5 in 1951. Caloi et al. (1956) assumed, and Caloi was able to confirm in 1970 (Caloi, 1970), that the gas production was the main cause of the earthquake". For the two additional criteria, Caloi et al. (1956) studied the first motions of the main shock at 21 seismological stations, indicating that the earthquake was "...a violent outward thrust, in a solid angle with an axis strongly inclined towards NW". Supported by the shallow hypocentral location that they reported as 5 km in depth, as well as proximity of the events to wells, Caloi et al. (1956) suggested a correlation between the two seismic events and the gas extraction activities. Should this speculation be true, the first of these two events (estimated origin time May 15, 1951; 22:54 GMT) would be the strongest induced event that has ever occurred in Italy, the strongest in Europe related to extraction fields, and one of the major induced events anywhere in Europe (see Data and Resources, MINE project).

After 60 years it is possible to revisit this interpretation using improved computational techniques, the available high-resolution data, enriched historical catalogs, and a deeper understanding of the regional seismotectonic and crustal structure.

The focus of this study is the relocation of these two events with the use of modern hypocentral location methods, and the analysis of the historical seismicity of the area. A complete seismic source parameterization is out of the scope of this preliminary study. In the following we describe the regional geological setting and the gas reservoir characterization, introduce the context of historical seismicity, provide a description of the main shock relocation, discuss the uncertainties of the hypocentral parameters and estimate the variation of the stress field due to extraction activities. We consider this revision necessary to be able to discuss the possibility that these two events were not induced by human activity, as well as to improve the quality of the dataset for decision makers involved in risk evaluation.

Geological and tectonic setting

The area where the Caviaga earthquakes occurred is interesting from a tectonic point of view. It is located in the central to western part of the Po Plain, and lies exactly where the buried front of the Northern Apennines (in particular, the Emilia thrusts and folds) meets the most external Southern Alpine front (Figure 1). Both of these fronts are considered to be tectonically active and competing, with the Alpine part showing weaker activity (Bresciani and Perotti, 2014; Vannoli et al., 2014).

Shortening of the western Southern Alps in this area began in the early Oligocene to Messinian, whereas the Apennines shortening began in the middle-late Miocene to Pleistocene. At present, the tectonic evolution of the Adria foreland is controlled by both the diachronous chain segment activities and the coeval competition.

Geological sections that cross the Apennines-Alps meeting point exactly east and west of Caviaga indeed show the Apennines fold and thrust structures overlapping the already deformed Alpine Monocline (Figure 1 section 2; Pieri and Groppi, 1981; Cassano et al., 1986). Other similar images for the Adria foreland have been drawn by Fantoni and Franciosi (2010) and Boccaletti et al. (2011), and these have always been based on drillings and seismic data collected over more than 50 years of hydrocarbon exploration. The present-day deformation given by GPS measurements shows a shortening of 0.5 mm/yr to 1.0 mm/yr toward the north, due to the clockwise rotation of the Adria plate with respect to Eurasia, around a pole located in northwestern Italy, at latitude 45.2°N and longitude 8.0°E (Serpelloni et al., 2005).

Recent seismic activity is more frequent on the Apennines side. However, on the Alpine side, a few events with magnitudes up to 4 and deep hypocentral depth have been registered and located just north of the location of the Caviaga earthquakes (Figure 1; Table 1). Prevailing thrust or strike-slip sources characterize the northernmost segment of the Apennines belt (Figure 1).

Gas field characteristics

At the date of May 1951 two gas production licenses were active in the epicentral area: the Caviaga and the Ripalta license (Figure 3; UNMIG, see Data and Resources).

The natural gas field of Caviaga, about 40km SE of Milan, was discovered in 1944 and immediately showed enormous potentiality (Dami, 1952). At present it is still in production, even if in depletion phase. As at 2014 a total amount of 12,2 billion cubic meters (at standard temperature of 15°C and pressure of 101.325 Pa defined as Smc - Standard cubic meter) of natural gas has been produced (UNMIG, see Data and Resources).

The reservoir is located on top of an EW-oriented anticline, at a depth between 1300 and 1700 m below the ground level, into the lower Pliocene formation (LPl sensu Cassano et al. 1986, Figure 1), named “Strati di Caviaga” (AGIP Mineraria, 1959a), characterized by prevalent sand beds with thin intercalations of clayey facies. The reservoir is confined in a structural trap defined by a 179-430 m thick clayey-marly facies association on the top (middle Pliocene age) and by a folded and mineralized strata of the basal Pliocene on the bottom, with a maximum thickness of 210 m. The contact with the underneath Miocene marly-sandly formation (UM sensu Cassano et al. 1986, Figure 1) is transgressive type.

The gas extracted from the Caviaga field is defined as wet-gas and mainly comprises methane (97,7%, with an absolute weight of 0.7) and other heavy hydrocarbon gases industrially processed to obtain natural gasoline with a relative density (at 15° C) of 0.8 (AGIP Mineraria, 1959a). The gas dehydration was done through a solid-absorption plant (AGIP Mineraria, 1959a)

By the end of 1951, 701 million Smc of methane, 1824 mc of natural gasoline and 1676 mc of water had been extracted from 21 productive wells of a total of 32 drilled (AGIP Mineraria, 1959a; UNMIG, see Data and Resources). The Caviaga license included two well fields in 1951:

the Caviaga well field and the Cornegliano well field, a few kilometers westward from Caviaga. The Cornegliano well field went into production in 1952 (UNMIG, see Data and Resources).

The Ripalta gas field was located about 10 km NE of Caviaga. Discovered in 1949, extraction continued from 1950 to 1994, with a total gas production lower than 3.6 billion Smc (UNMIG, see Data and Resources). At the Ripalta field, the reservoir is located on top of an EW-oriented anticline, at a depth between 1415 and 1590 m below the ground level, into the basal part of lower Pliocene formation (LPl sensu Cassano et al. 1986, Figure 1). The reservoir rock is known as "Strati di Ripalta" (AGIP Mineraria, 1959b) and is characterized by prevalent sand beds with thin intercalations of clayey facies.

The reservoir is confined in a structural trap defined by a 523-653 m thick clayey-marly facies association on the top (lower-middle Pliocene age) and by Tortonian-lower Miocene marly formation (UM and MM sensu Cassano et al 1986, Figure 1) at the bottom, at least 800 m thick.

The contact between the Pliocene sandly formation and the underneath Miocene marly formation is transgressive (AGIP Mineraria, 1959b). The gas extracted was a wet-gas with a percentage of methane of 99% and the residual heavy hydrocarbon gases was industrially processed to obtain natural gasoline.

At the end of 1951, 312 million Smc of methane and about 38 mc of natural gasoline and 47 mc of water were extracted from 13 productive wells (AGIP Mineraria, 1959b) out of a total of 23 drilled (UNMIG, see Data and Resources).

No one of the wells sited in the Caviaga and Ripalta gas fields had ever been involved in fluid/water injection at the date of 1951 (UNMIG, see Data and Resources).

Historical seismicity

The region where the May 15-16, 1951, earthquakes occurred is characterized by infrequent seismicity. The map of historical seismicity (Figure 1, right panel; Rovida et al., 2011) shows that the 1951 events are not the only earthquakes to occur in this region. At least another event of the same strength ($M \geq 5.0$) occurred in 1786.

These 1951 earthquakes have been studied by several authors. The basic data currently included in the Italian Macroseismic Database (Locati, et al., 2011) were provided by a technical report (SGA, 2002) that was based on the parameterization of observations collected by the study of Caloi et al. (1956) and on an analysis of some journalistic correspondence. The information yielded by this technical report was reviewed for the present study, along with some journalistic correspondence and a register of macroseismic records that were received by the Central Office for Meteorology and Geodynamics. The updated distribution of the effects (Camassi, 2014; Figure 2; Table S1, Supplementary Material) shows a very large felt area that suggests a deep hypocenter, as for other well-known historical events in the Po Valley (1796, 1909 and 1983; Vannoli et al., 2014). The new macroseismic location of this epicenter is 1.5 km south of that given by the Italian Parametric Catalog (Rovida, et al., 2011), a few kilometers southeast of Caviaga, with estimated M_W 5.25 (Table 2; Figure 3).

The information that was available to Caloi et al. (1956) for the seismic history of Italy was limited to the seismological compilation of Baratta (1901), on which much of the information about the seismicity of the Italian territory was based until the 1980s. Caloi et al. (1956) refers in particular to the section "Topographic distribution of Italian earthquakes" which states (Baratta, 1901): "in the northern Italy seismicity map [...] Lodi and Lodigiano are not listed in any seismic area [...]". Baratta (1901) devoted a careful paragraph to the Lodi area, which in addition to casting doubt on the reality of an alleged earthquake that occurred in the year 290, only reported felt effects from distant earthquakes.

Although this area has certainly seen only low-to-moderate seismicity, it has been affected in the past by earthquakes that were located close to the 1951 earthquake. An important historical event was that of April 7, 1786 (M_W 5.5; Rovida et al., 2011), which was studied by Guidoboni et al. (2007) and was located very close to the area hit by the 1951 earthquakes. The update proposed by the present study (Figure 2; Table S2, Supplementary Material) locates this 1786 event a few kilometers southwest, and so very close to the locality of Caviaga, with an estimated M_W 5.33 (Table 2; Figure 3). This 1786 event, due to the wide felt area, also appears to have been a deep earthquake.

Another case that deserves to be considered in the reconstruction of the seismic history of this area is the earthquake of January 13, 1918. This was apparently a minor earthquake, and its parameters remain very uncertain. Its location is currently indicated 50 km far from the present area of interest (M_W 4.8; Rovida et al., 2011, Figure 1). In the parametric catalog by Postpischl (1985), this event was localized to a few kilometers from Caviaga, and it is interesting to note that in the collection of the Italian magnitude values compiled by Margottini et al. (1993), this earthquake was listed with an instrumental magnitude M_S 4.94, with the same location proposed by Postpischl (1985). Despite the difficulty of locating potentially deep earthquakes on the basis of macroseismic intensities, we hypothesize that a revision of the macroseismic dataset will also locate this earthquake in the vicinity of the area of Caviaga (Figure 3).

Careful consideration of historical and early instrumental seismicity thus leads to the conclusion that the area affected by the earthquakes of 1951 cannot be considered as aseismic.

Hypocentral location

The study of Caloi et al. (1956) presented several points that are open to discussion. First, the collection of seismographic data was very careful, but early analysis could not account for synchronization problems with the internal clocks of the stations. Secondly, in agreement with the general knowledge of the period, Caloi et al. (1956) considered an oversimplified velocity model of the Po Plain; Caloi et al. (1956) defined in their final summary: " […] a stratification of sediments more or less common to all Europe overlaying the Earth's crust which […] consists hence of three superimposed layers". Thirdly, as described previously, the historical seismicity of the area was nearly unknown, to the point that Caloi et al. (1956) stated that: "[…] the zone concerned is notoriously aseismic". In their final summary, Caloi et al. (1956) also declared that the most critical point of their study was the determination of the hypocentral depth. Of note, this is one of the most error-prone parameters even in modern seismology.

During the process of relocation of events that occurred tens of years ago, any source of error must be considered with particular attention. Uncertainties in earthquake location are generally ruled by two factors: measurement errors in the seismic arrival times and modeling errors of the calculated travel-times. For events that occurred in the early instrumental period (e.g. before the 1970s), the first class of error is definitely significant. In particular, when original seismograms are not available, measurement errors can be difficult to remove or reduce, and these come from a number of sources, which can include the signal-to-noise ratio, misidentification of seismic phases, poor quality synchronization, and unknown systematic delays in the internal clock of a station; indeed, they can even arise from banal circumstances, such as misprints in a transcription of daily bulletins. For these reasons, estimated Gaussian errors of the order of seconds are reasonable and acceptable in the study of such past events (Bondár et al., 2015; Sandron et al., 2014; Villaseñor and Engdahl, 2007). Modeling errors of calculated travel-times are dominated by the quality of the seismic velocity (or slowness) model that is used to calculate the ray paths and, of course, the theoretical travel-times. The *a-priori* velocity structure significantly controls the determination of the hypocenter (and in particular, the depth) mainly for regional and local events, because the seismic wave propagation is more affected by small-scale heterogeneities in the crust and upper mantle.

Dataset

The main source of arrival-time data for the 1951 Caviaga earthquakes is the monthly bulletin for May 1951 that was published by the International Seismological Summary (ISS, 1951; ISC, 2011). For the event of May 15, 1951, this bulletin included records from 79 observatories worldwide, and for the May 16 aftershock, records from 45 observatories worldwide.

With the aim to integrate and/or to check the available dataset, we collected coeval seismic station bulletins from different Euro-Mediterranean observatories . This was made possible thanks to the on-line bulletin databases that were constructed in the framework of the EUROSEISMOS project (Ferrari and Pino, 2003) and the ISC-GEM (International Seismological Centre - Global Earthquake Model; Storchak, et al., 2013), both of which are available through the INGV-SISMOS website (see Data and Resources; Michelini et al., 2005)

As the accuracy behind the timing reported in bulletins cannot be determined easily, the reliability of any station timing was checked using a comparison of the observed phases with the theoretical arrival times. We computed four different sets of expected arrival times using the AK135 velocity model (Kennett et al., 1995) and assuming fixed epicentral coordinates, which were deduced from the macroseismic epicenter (Rovida, et al., 2011) and different hypocentral depths (5, 40, 50, 60 km). The theoretical travel-times are compatible with observations for a hypocentral depth of 50 km. The observed arrival times were generally consistent with each other. In a few cases, these direct calculations allowed the correction of some macroscopic inconsistencies in the dataset of the phases, such as large clock bias, misidentification of the seismic phases, or typing mistakes. Indeed, when the time difference between the theoretical and observed arrival times at a station was constant, it is reasonable to infer that the gap was due to incorrect synchronization of the station clock. For the mainshock of May 15, 1951, this was the case for the seismic stations of L'vov (LVV, Poland) and Salò (SAL, Italy), for which we introduced a station delay time of 13.5 s and 10 s, respectively (Table S3, electronic supplement). In addition, the comparison with the theoretical arrival times allowed a complete redefinition of the phases associated with the onset data, according to the modern International Association of Seismology and Physics of the Earth's Interior IASPEI91 codification (Kennett and Engdahl, 1991).

The availability of original seismic station bulletins made it also possible to recover data that was affected by misprints. As an example, the ISS Bulletin reports an S-P difference of 12 s at the Durham station (DUR, UK) for the event of May 15, 1951, which is not compatible with an epicentral distance of about 1,320 km. Consultation of the original Bulletin from the British Observatory of Durham University highlighted a simple misprint in the manual process of re-writing of the observed arrival times, which reported the P-phase arrival at minute "59" instead of "57".

Finally, we collected a total of 12 original seismograms from the seismic stations of Bologna (BOL, Italy), Firenze (FIR, Italy), Messina (MES, Italy), Prato (PRT, Italy) and Timisoara (TIM, Romania), and we re-analyzed the picking of the phases. For the PRT and BOL stations, the new Sn-picking was used. These original arrival times from the ISS Bulletin and the corrections are listed in Table S3 (electronic supplement) for the May 15 event, and Table S4 (electronic supplement) for the May 16 event. The station codes and coordinates were extracted from the International Registry of Seismograph Stations (ISC, 2011).

Data processing and results

Seismic event location is a non-linear problem, and many algorithms and location programs have been developed over time to solve this. A hypocentral location and its uncertainties is only true in the framework of the applied criteria of the computation, and according to Schweitzer (2001) "… all estimated uncertainties must be considered in relation to other hypocenter solutions using the same model". On the basis of this consideration, we located the two seismic events of May 15-16, 1951, using two programs: HYPOINVERSE-2000 in its last version of hyp1.40 (Klein, 2014) and HYPOSAT (Schweitzer, 2001).

As for previous theoretical direct calculations, our reference model was the AK135 velocity model (Kennett et al., 1995). We used the HYPOINVERSE-2000 location algorithm with a view to modern standards of minimization of computational residuals, and therefore we used arrival-time data from 13 stations within a distance of about 400 km (13 P-phases and 5 S-phases; see Table S3, electronic supplement). For the main shock that occurred on May 15, 1951, at 22:54 GMT, we obtained a hypocentral solution at a depth of 32.42 ± 4.53 km, about 15 km northeast of Caviaga, with rms = 0.86 s (Figure 3; Table 3). The mean residual time (i.e., difference between observed and calculated arrival times) is 0.5 s for the P-phases and 0.9 s for the S-phases. For the aftershock of May 16, 1951, at 02:27 GMT, the epicenter solution is located about 6 km northeast of the first event, with a hypocentral depth of 13.71 ± 4.18 km, and mean rms = 0.70 s (Figure 3; Table 3).

It is worth noting that the rms travel-time residual provides a measure of the fit between the observed and theoretical travel-times, and therefore a small rms indicates a good fit with the data. However, the mere computational best fit strictly depends on the parameterization of the inverse problem, so we can expect a better fit with the data when considering a limited dataset. This mathematical trade-off usually reflects good consistency in the definition of the inversion in terms of the number of unknown parameters and observations. Nevertheless, the reliability of a seismic location as a physical problem cannot ignore other factors, such as azimuthal coverage, distances of the stations, velocity structure parameterization, and abundance of observations. This is the reason why we decided to test the hypocentral solutions obtained using another software, HYPOSAT (Schweitzer, 2001), which provides the opportunity to include not only the absolute onset data in the inversion, but also all of the travel-time differences between the phases observed at the same station. This possibility is particularly important for historical datasets that sometimes have errors in the absolute onset timing. Indeed, all travel-time differences are dependent on the epicentral distance, and not on the source time nor on systematic timing errors. For reflected phases, the travel-time difference for a direct phase is strongly influenced by the source depth. We used the CRUST 5.1 crustal model (Mooney et al., 1998) for the estimation of the station corrections with respect to the crustal structure below the station.

For the May 15, 1951, seismic event, we used 71 onsets (out of the 133 available) from 58 worldwide seismic stations, and 21 travel-time differences (Table S3, electronic supplement). The hypocentral depth is estimated at 34.66 ± 4.91 km (Table 3). The mean residual is 0.9 s for the onset phases, and 1.9 s for the travel-time differences. The rms obtained is 1.1 s.

For the May 16 event, we used 38 onsets (out of the 76 available) from 29 worldwide seismic stations, and 12 travel-time differences (Table S4, electronic supplement). The hypocentral depth is estimated at 20.34 ± 3.42 km (Table 3). The mean residual is 0.9 s for the onset phases, and 1.0 s for the travel-time differences. The rms obtained for this location is 1.0 s.

With reference to EPcrust model (Molinari and Morelli, 2011) the main shock on May 15th is located in the lower crust and the aftershock on May 16th is located in the upper crust or at the boundary upper/lower crust depending on the location code (HYPOINVERSE or HYPOSAT respectively).

As a double-check, we have calculated the event locations, and relative rms values, keeping fixed depths (Figure 4). For the first event the rms value obtained with a fixed depth of 5 km, that is the value of the hypocentral depth attributed by Caloi et al. (1956) to the event, is about twice the rms obtained for a location depth fixed to 32 km, that is the closer value to the one obtained in this work (Table 3). For the 16 May aftershock we obtained a similar trend, shifted to smaller values (Figure 4).

Discussion

We know that human activities can induce or trigger seismicity (Grasso, 1992; Suckale, 2009 and references herein; National Research Council, 2013). This is one of the most outstanding present-day points of discussion, considering the dramatic increases in seismicity rates in areas characterized by strong sub-soil use, with the occurrence of several M~5 events (National Resources Council, 2013; McGarr, 2014) in areas where historical and earlier instrumental seismicity rates were low. However, we also believe that there is the need for good, and sometimes revised, data to infer reliable conclusions about early events identified as induced. With this aim, we investigated the Caviaga earthquakes, with an initial focus on the parameters that can help determine whether these events were related to human activities.

One of the arguments of Caloi et al. (1956) to support the hypothesis of an induced or triggered earthquake is that these 1951 earthquakes occurred in an area thought to be aseismic. However, the revision of the historical seismicity around the Caviaga area, indeed in a context of very incomplete knowledge, shows that at least one seismic event with similar magnitude occurred on April 7, 1786, with an inferred location very close to the 1951 macroseismic epicenters (Figure 3). In addition, if solutions proposed by Postpischl (1985) and Margottini et al. (1993) are accepted, the January 13, 1918, earthquake was also located close to Caviaga. Overall, the tectonic setting, the present-day deformation, and the seismicity are typical of a region of low-to-moderate seismicity (Figure 1).

The information collected here was not available at the time of Caloi et al. (1956). Indeed, modern enriched historical catalogs and deeper understanding of the regional seismotectonics invalidate one of the basic assumptions made by Caloi et al. (1956), "… however, the studied area, at least in historical times, has always been considered aseismic" [p.93].

Our hypocentral relocation goes one step further, with new observational data and two different methods used to investigate both of the May 15-16 events. Our results indicate hypocentral depths greater than 5 km (Table 3). As discussed previously, precision in hypocentral location cannot be assured by a simple estimate of the rms misfit. The number of onsets and travel-time differences used and the azimuthal coverage provided during the computation are all parameters that must be taken into account. For these reasons, we consider the results obtained with HYPOSAT (Schweitzer, 2001) as the preferred solutions, despite the mathematically higher rms estimates.

All of our solutions indicate deep sources, in the range of 32-35 ±5 km for the May 15, 1951, event, and 14-20 ±4 km for the May 16 event, depending on the computational method (Table 3). The rms's of locations computed with HYPOINVERSE-2000 are approximatively half of the rms computed with a fixed hypocentral depth of 5 km (Figure 4), the value inferred by Caloi et al. (1956).

The conclusion that the 1951 Caviaga seismic events had deep hypocenters is also supported by the widespread distribution of macroseismic effects (Figure 2; Vannoli et al., 2014) and the observations of related elastic waves at teleseismic distances (i.e., the farthest recording station is Palomar, USA, at an azimuthal distance of 87.8°; Tables S3 and Table S4, electronic supplement).

At least 13 events have occurred since 1986 at depth greater than 10 km within a distance of 20 km around Lodi (Table 1), a further element which indicates that deep natural seismicity is not infrequent in this area.

Although shallow depth suggests that earthquakes are induced, one must also consider the possibility of deeper activated events, in particular whether the stress perturbation related to gas production could propagate to such large depths and eventually trigger a pre-existing natural stress on a fault at its critical failure threshold. For instance, significant sequences of events (M>5.5) at midcrustal depth were observed between 1976 and 1994 in Uzbekistan, in proximity and beneath the Gazli gas reservoirs and in France between 1974 and 1997 close to the Lacq field region (Suckale, 2009; Bardainne et al., 2008; Grasso, 1992; and references herein).

One source of stress change is the isostatic imbalance due to the removal of mass. We can calculate the distribution of stress change resulting from unloading by considering the cumulative volume V of gas extracted at the date of 1951(V~ 700 Mm^3, ρ =0.701 kg/m^3; Dami, 1952; AGIP Mineraria, 1959a). The total volume of water and gasoline extracted is low. These data refer to the end of the year 1951, hence they are reported in excess. Note that 700 Mm^3 is less than 5% of the total field production from 1944 to 2014 (see Data and Resources).

Following the classical approach suggested by Boussinesq (Boussinesq, 1885; Fung, 1965) the unloading corresponds to a stress change of ~1.7Pa at 35km depth and distance of about 20 km (see Supplementary Materials). The same estimation repeated for the volume of gas extracted at the Ripalta gas field gives a stress variation of ~0.75Pa at 35km depth and distance of 20km. Even considering a cumulative effect of changes of stress due to the exploitation of the two gas fields we obtain a value well below the threshold of 10kPa that is generally invoked for seismicity triggering (Stein & Lisowski, 1983; Reasenberg & Simpson, 1992; Hardebeck et al., 1998; Vidale et al., 1998; Stein, 1999).

Other sources of stress perturbation include variations in pore pressure and of poroelastic stress. A direct numerical model for the calculation of the stress disturbance related to poroelastic effects and their propagation through the whole crust is out of the scope of this work. Nevertheless, it is possible to note that (i) since the exploitation until 1951 corresponded to about 5% of the total production, it did not involve substantial changes in terms of volume and internal pressure of the two gas reservoirs (ii) several highly impermeable layers in the stratigraphic sequence define the structural traps where the reservoirs are confined (iii) the volume of crust under consideration is characterized by extreme heterogeneities, important vertical and horizontal discontinuities and the contact between Adria and Eurasia plates (Figure 1).

Given the relative proximity of the earthquake to gas wells, it is not possible to reach a definitive conclusion about the source mechanism for these events. However on the basis of these considerations, the hypothesis of hydraulic continuity, eventually responsible for the poroelastic effects propagation 35 km into the crustal layers, is not considered feasible.

Conclusions

The Caviaga earthquakes have been listed in the main catalogs of induced and triggered events relying on the location given by Caloi et al. (1956) and their speculations based on the knowledge of the time concerning the macroseismic history and tectonics of the area. This new analysis effectively invalidates earlier results that were used to identify the earthquake as induced. In particular this work focuses on (i) the relocation of both the events of May 15 and 16, 1951, pointing to deep (midcrustal) sources, (ii) the investigation on the historical seismicity of the area and the identification of past events through the study of their macroseismic effects, (iii) the observation of recent recorded seismicity, indicating that deep natural seismicity is not infrequent in the area under investigation, (iv) the neotectonics controlling the active contact between the

Apennines and the Italian Alps, (v) the evaluation of stress perturbation induced by gas production, a value which results well below the threshold generally invoked for seismicity triggering.

All these arguments call into question the chance that the Caviaga events were caused by human activities, rather sustaining the thesis of a tectonic source.

Data and Resources

All the following website have been last accessed on March 2015.

Catalogue of Italian Seismicity (CSI): http://csi.rm.ingv.it/.

CPT11 Parametric Catalogue of Italian Earthquakes: http://emidius.mi.ingv.it/CPTI11/

DBMI Italian Macroseismic Database: http://emidius.mi.ingv.it/DBMI11

Catalogue of Strong Earthquakes in Italy (461 B.C.–1997) and the Mediterranean Area (760 B.C.–1500): http://storing.ingv.it/cfti4med/.

Italian Centroid Moment Tensors (CMT) Dataset: http://www.bo.ingv.it/RCMT/Italydataset.html.

Italian Seismological Instrumental an Parametric Data-Base (ISIDE): http://iside.rm.ingv.it.

The full information about location and characterization of wells for exploration and gas withdrawal is available on the website of the Italian Ministry of Economic Development - Directorate-General for mineral and energy resources:

List of exploration permits in force, http://unmig.sviluppoeconomico.gov.it/unmig/pozzi/pozzi.asp; Official information of Caviaga Gas Production License http://unmig.mise.gov.it/unmig/titoli/dettaglio.asp?cod=890; Official information of Ripalta Gas Production License http://unmig.mise.gov.it/unmig/titoli/dettaglio.asp?cod=2896; Production details on Caviaga Gas Fields http://unmig.sviluppoeconomico.gov.it/unmig/produzione/pluriennale/dettaglio.asp?cod=890&min=G; Production details on Ripalta Gas Fields http://unmig.sviluppoeconomico.gov.it/

unmig/produzione/pluriennale/dettaglio.asp?cod=10086&min=G; UNMIG, Min. Ind. Comm. Artig. (1997) http://unmig.mise.gov.it/deposito/titoli/decreti/890_19971020.pdf

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Seismic station Bulletins available through the INGV-SISMOS website https://sismos.ingv.it

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Figure captions

Figure 1. Top: Maps of the area of interest showing the tectonic setting and seismicity between 1981 and 2012 (ISIDe Working Group; CSI, Castello et al., 2006). Symbols in color indicate earthquakes (circles for M >2.0 and squares for M>4.5). Symbols are scaled with magnitude and colors accord to depth scale. Focal mechanisms are for seismicity with M >4.5 from 1977 to present (Pondrelli et al., 2006). Top-left inset: the black box is study area; the red dashed line marks the boundary of the Adria plate. Tectonic structures (red) and geological sections (light green lines) are extracted from Pieri and Groppi (1981) and Cassano et al. (1986). Top right map: blue stars indicate the original locations of the events of May 15 (15-Caloi) and 16 (16-Caloi) according to Caloi et al. (1956) and the epicenter of May 15 according to the ISS Bulletin (ISS); white open squares indicate

macroseismic epicenters from historical seismicity (Rovida et al., 2011); yellow circles show the distribution of Caviaga and Ripalta gas wells active at 1951 (Ministry of Economic Development, 2014). Bottom: two geological sections extracted from Pieri and Groppi (1981) and Cassano et al. (1986). Legend: Q, Quaternary; UPl: Upper Pliocene; LPl, Lower Pliocene; UM, Upper Miocene; MM, Middle Miocene; LM, Lower Miocene; PG, Paleocene; Mz, Mesozoic; MB, Magnetic Basement.

Figure 2. Distribution of the macroseismic effects (on the MCS scale) for the 1951 (left) and 1786 (right) earthquakes (Camassi, 2014; Tables S1 and S2, electronic supplements). F=Felt; D=damage to a single building. Insets: Study area.

Figure 3. Map showing the epicenters (stars) from the present study for the events of May 15 and 16, 1951. Computed with HYPOSAT: 15A, 16A. Computed with HYPOINVERSE-2000, version hyp1.4: 15B and 16B. White squares indicate historical data, with present-study macroseismic epicenters used for the 1786 and 1951 events. Location for 1918 is from Postpischl (1985). Symbols are scaled to the macroseismic magnitude. White circles are active wells before 1951.

Figure 4. Plot of the variation of the rms travel time residual as a function of hypocentral depth, obtained by fixed-depth inversions with the software HYPOINVERSE. Diamonds indicate results for fixed-depth location inversions for the event 15B (Figure 3). Reversed triangles give rms values as a function of depth for the event 16B (Figure 3).

Table 1. Locations of the events recorded in the last 30 years with hypocentral depth >10 km and within a distance of 20 km around Lodi (see also Figure 1; ISIDe Working Group, 2010). M_L: Richter or Local magnitude: md: distance magnitude.

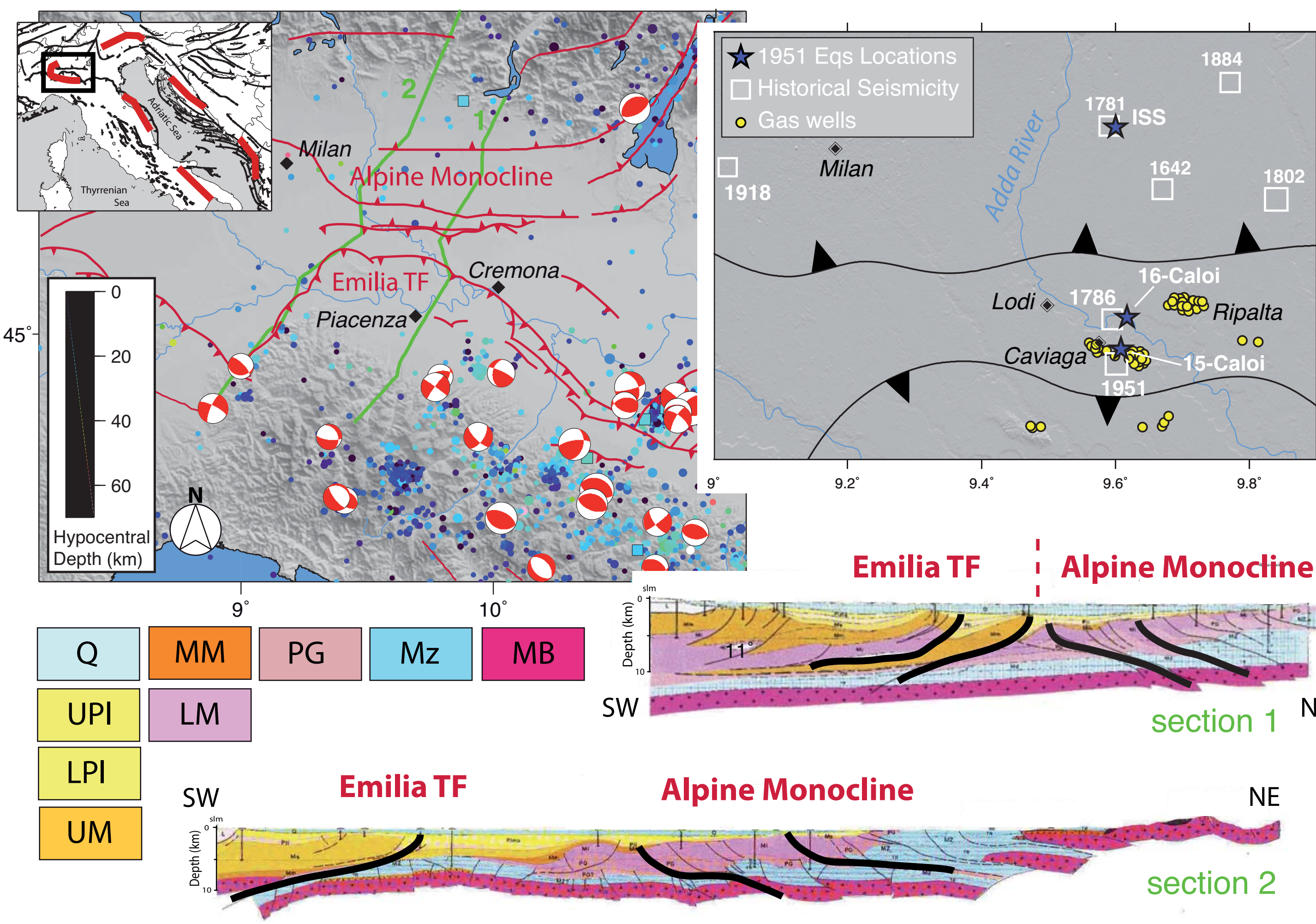
Date (yyyy-mm-dd)	Origin time (GMT)	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude
2013-08-09	22:47:47.540	45.369	9.41	34.4	2.2--ML
2011-09-10	23:14:49.890	45.481	9.372	47.0	2.4--ML
2011-09-06	21:46:54.760	45.409	9.392	35.6	2.3--ML
2010-07-30	19:05:41.880	45.445	9.392	33.5	2.3--ML
2007-09-17	18:43:47.710	45.411	9.378	34.8	2.8--ML
2004-12-03	14:28:26.100	45.34	9.425	14.2	1.9-- ML
2002-07-14	22:23:10.780	45.389	9.509	15.5	2.8--md
1999-12-26	00:54:04.180	45.481	9.453	15.8	2.3-- ML
1994-02-14	03:52:27.540	45.485	9.513	23.5	2.0--md
1993-02-09	18:49:43.540	45.363	9.303	21.1	2.0-- ML
1991-07-29	18:37:22.230	45.422	9.381	13.8	3.2-- ML
1986-09-27	08:58:49.120	45.156	9.388	14.4	2.4--md
1986-07-17	09:44:41.000	45.323	9.633	19.7	2.6--md

Table 2. New macroseismic parameters of the 1951 and 1786 earthquakes. M_W is the macroseismic moment magnitude and dM_W its uncertainty.

Date (yyyy-mm-dd)	**Time (GMT)**	**Np**	**I_{max} (degrees)**	**Latitude (°N)**	**Longitude (°E)**	**M**	**dM**
1951-05-15	22:54	174	6-7	45.234	9.603	5.25	0.07
1786-04-07	00:25	10	7-8	45.266	9.550	5.33	0.27

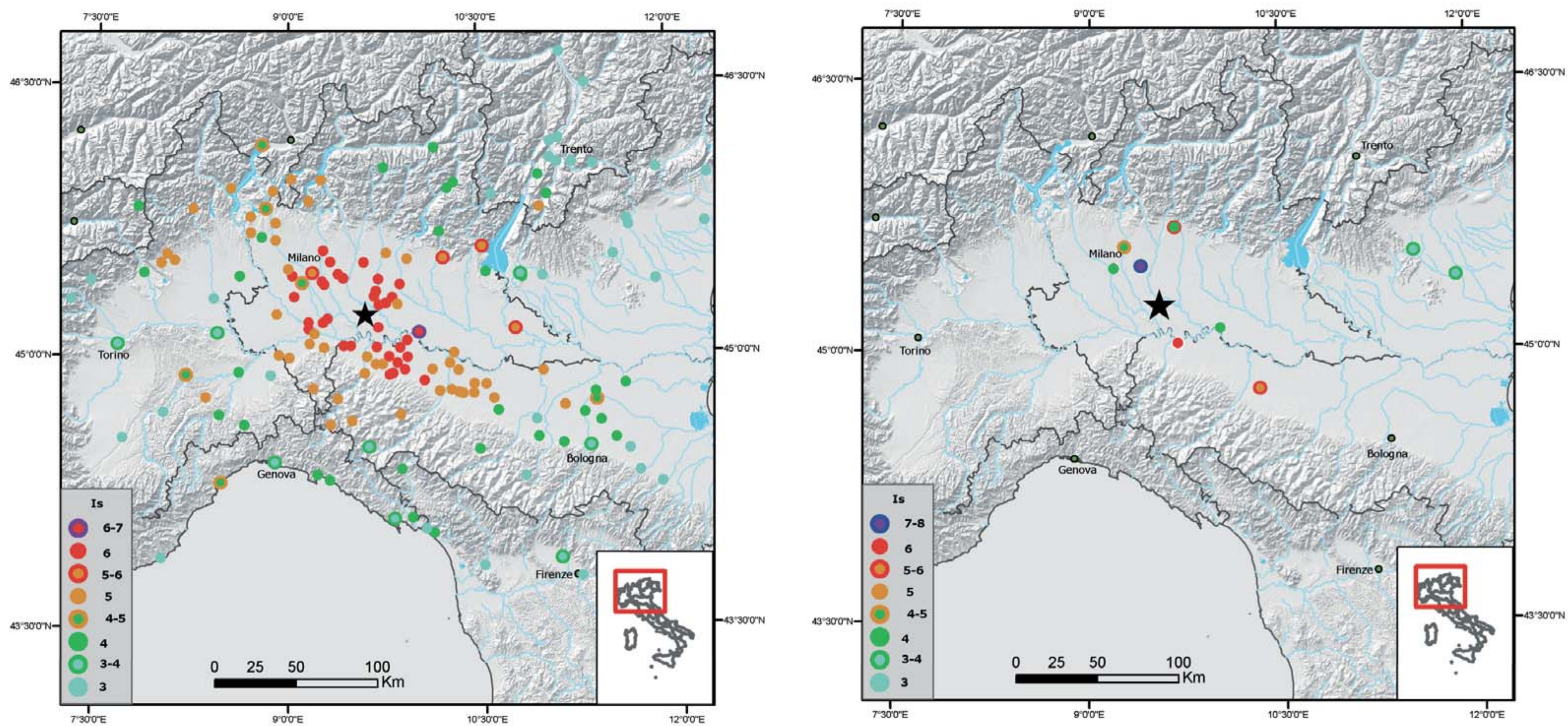
Table 3. Hypocentral parameters for the May 15 and 16, 1951, seismic events obtained in the present study using the HYPOSAT and HYPOINVERSE-2000 version hyp1.40 location codes. The complete parameter set for each location is reported in Table-S5 Supplementary Material.

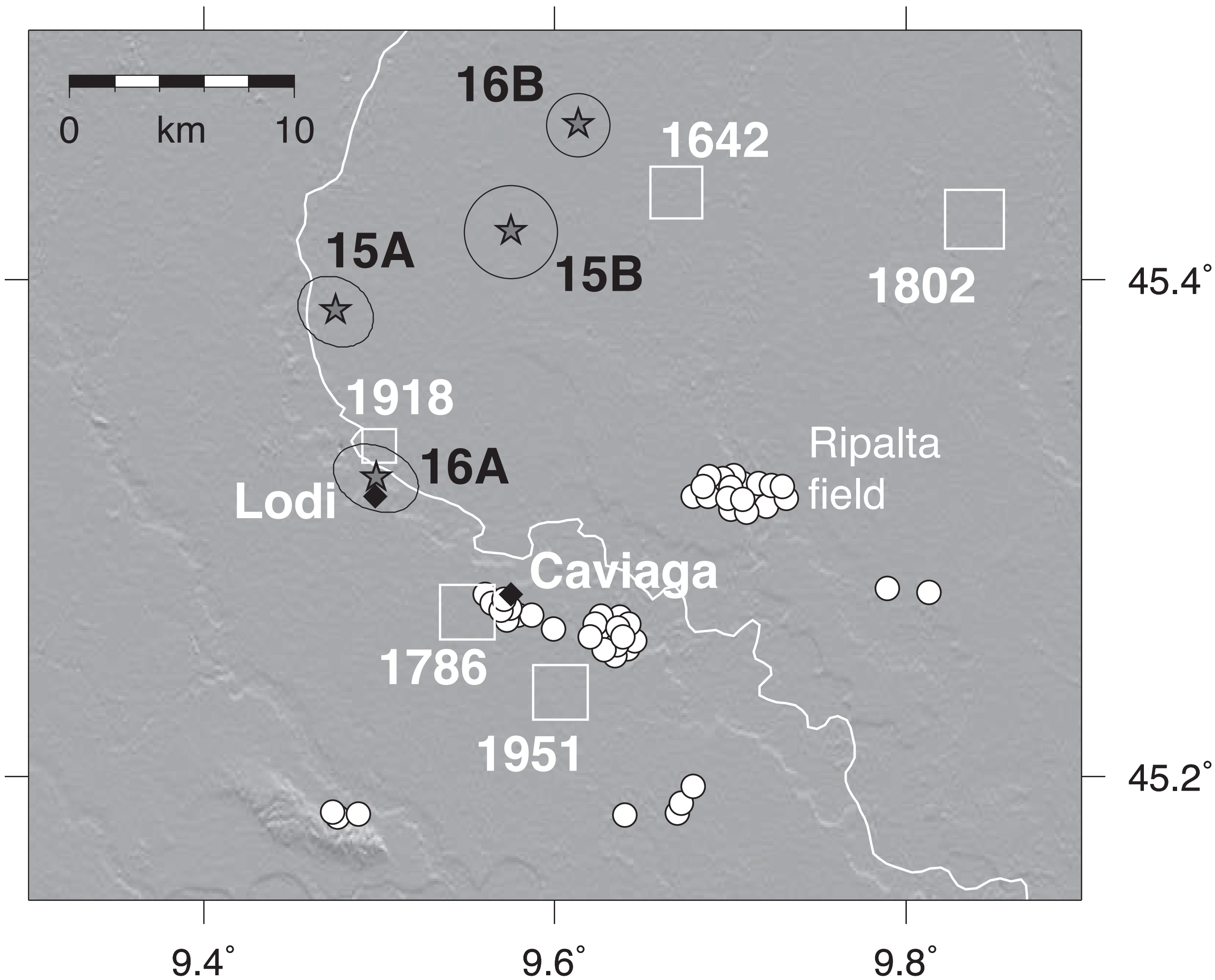
Parameter	**May 15, 1951**		**May 16, 1951**	
	HYPOSAT	**HYPOINVERSE**	**HYPOSAT**	**HYPOINVERSE**
Origin time (GMT)	22:54:29.92±0.36	22:54:29.75±0.39	02:27:00.73±0.46	02:27:00.82±0.48
Latitude (°N)	45.387±0.028	45.419	45.320±0.031	45.462
Longitude (°E)	9.475±0.036	9.575	9.498±0.052	9.613
Depth Z (km)	34.66±4.91	32.42±4.53	20.34±3.42	13.71±4.18
rms (s)	1.13	0.86	1.02	0.70



Adriatic Sea
Thyrrenian Sea
2
1
Milan
Alpine Monocline
Emilia TF
Cremona
Piacenza
45°
0
20
40
60
Hypocentral Depth (km)
N
9°
10°
1951 Eqs Locations
Historical Seismicity
Gas wells
1884
1781
ISS
1918
Milan
Adda River
1642
1802
16-Caloi
Lodi
1786
Ripalta
Caviaga
15-Caloi
1951
45.6°
45.4°
45.2°
9°
9.2°
9.4°
9.6°
9.8°
Q
MM
PG
Mz
MB
UPl
LM
LPl
UM
Emilia TF
Alpine Monocline
SW
NE
section 1
Depth (km)
Emilia TF
Alpine Monocline
SW
NE
section 2
Depth (km)

Figure 2


7°30'0"E
9°0'0"E
10°30'0"E
12°0'0"E
46°30'0"N
45°0'0"N
43°30'0"N
Trento
Milano
Torino
Genova
Bologna
Firenze
Is
6-7
6
5-6
5
4-5
4
3-4
3
0 25 50 100
Km
7-8


0
km
10
16B
1642
15A
15B
1802
45.4°
1918
Ripalta
field
16A
Lodi
Caviaga
1786
1951
45.2°
9.4°
9.6°
9.8°

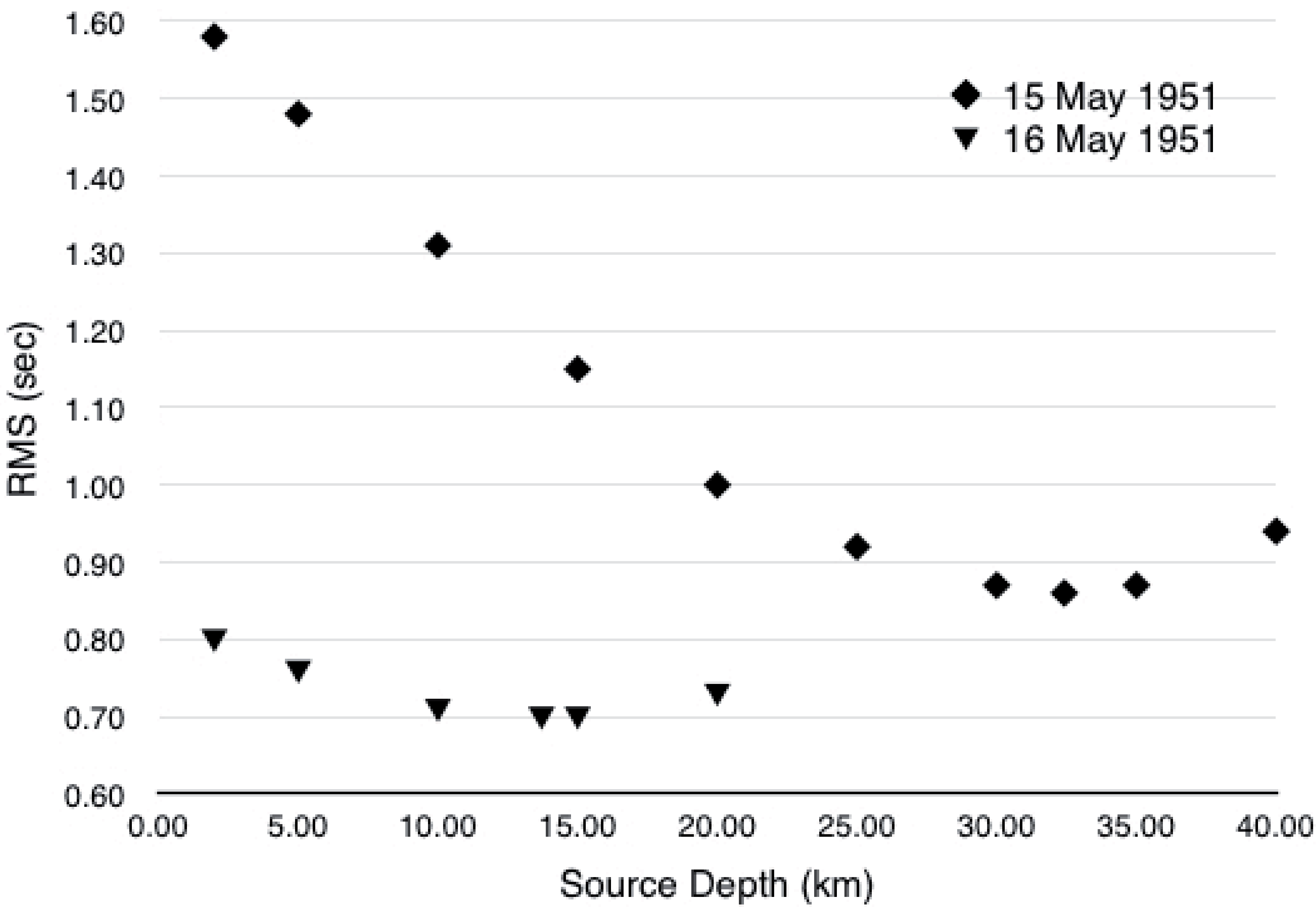

15 May 1951
16 May 1951
RMS (sec)
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Source Depth (km)

Table S1 - Macroseismic intensities of the May 15, 1951 earthquake (Camassi, 2014). SC = Special Cases: MS = Multiple settlement; SS = Small settlement; SB = Single Building. D = Damage to a single building; F = Felt.

Localities	SC	Lat	Lon	MCS Int
Cremona		45.136	10.024	6-7
Albuzzano		45.187	9.273	6
Caorso		45.049	9.874	6
Castel San Giovanni		45.059	9.433	6
Castelleone		45.296	9.764	6
Cernusco sul Naviglio		45.524	9.330	6
Ciriano		44.908	9.816	6
Coazzano		45.331	9.048	6
Codogno		45.161	9.705	6
Cortemaggiore		44.996	9.932	6
Crema		45.362	9.686	6
Cusago		45.446	9.032	6
Fidenza		44.866	10.061	6
Fiorenzuola d'Arda		44.928	9.911	6
Merlino		45.433	9.430	6
Monticelli d'Ongina		45.089	9.930	6
Montodine		45.286	9.709	6
Monza		45.584	9.274	6
Pavia		45.189	9.160	6
Piacenza		45.052	9.693	6
Pontenure		45.000	9.787	6
Roveleto		44.965	9.852	6
San Donato Milanese		45.414	9.266	6
San Giuliano Milanese		45.399	9.283	6
Sarmato		45.060	9.490	6

Sergnano		45.427	9.704	6
Settala		45.455	9.390	6
Soncino		45.399	9.874	6
Travacò Siccomario		45.153	9.160	6
Treviglio		45.521	9.593	6
Trigolo		45.329	9.814	6
Vistarino		45.209	9.307	6
Zappello		45.334	9.671	6
Brescia		45.544	10.214	5-6
Mantova		45.152	10.775	5-6
Milano		45.464	9.190	5-6
Salò		45.606	10.522	5-6
Turca di Sopra	SB	44.900	9.790	D
Macherio	SB	45.640	9.268	D
Bareggio		45.483	9.000	5
Bellagio		45.975	9.258	5
Biella		45.566	8.053	5
Bobbio		44.767	9.386	5
Borgo San Siro		45.235	8.911	5
Cadelbosco di Sopra		44.763	10.597	5
Canneto Pavese		45.050	9.280	5
Casei Gerola		45.006	8.927	5
Chiari		45.538	9.931	5
Concordia sulla Secchia		44.914	10.982	5
Crevalcore		44.722	11.147	5
Crosano		45.819	10.976	5
Cuasso al Monte		45.914	8.880	5
Faggeto Lario (Lemna)	MS	45.858	9.158	5
Ferriere		44.645	9.497	5
Gattatico		44.795	10.444	5
Golaso		44.679	9.873	5

Gorla Minore		45.642	8.902	5
Gossolengo		45.000	9.615	5
Lanzo d'Intelvi		45.980	9.020	5
Martinengo	SB	45.570	9.768	5
Mezzanino		45.125	9.205	5
Mongrando (Ceresane)	MS	45.518	8.007	5
Nizza Monferrato		44.774	8.360	5
Noceto		44.809	10.180	5
Ottone		44.623	9.332	5
Parma		44.801	10.329	5
Pinarolo Po		45.070	9.168	5
Podenzano		44.957	9.686	5
Poviglio		44.842	10.541	5
Rivergaro		44.907	9.598	5
San Giacomo		45.532	8.113	5
San Giorgio Piacentino		44.957	9.737	5
San Lazzaro Parmense		44.793	10.360	5
San Pancrazio Parmense		44.814	10.270	5
Sissa		44.961	10.259	5
Somma Lombardo		45.685	8.708	5
Soragna		44.928	10.124	5
Sorbolo		44.846	10.449	5
Soresina		45.288	9.855	5
Torricella del Pizzo		45.019	10.293	5
Torrile	MS	44.922	10.326	5
Varallo		45.816	8.254	5
Varano Borghi		45.774	8.704	5
Varzi		44.823	9.197	5
Venegono Inferiore		45.738	8.901	5
Verbania (Pallanza)	MS	45.928	8.552	5
Voghera		44.993	9.010	5

Asti		44.899	8.206	4-5
Buccinasco		45.408	9.108	4-5
Galliera	MS	44.751	11.393	4-5
Locarno		46.170	8.793	4-5
Savona		44.307	8.480	4-5
Varese		45.818	8.825	4-5
Acqui Terme		44.677	8.465	4
Alessandria		44.913	8.615	4
Aprica		46.152	10.150	4
Belforte Monferrato		44.623	8.662	4
Bentivoglio		44.634	11.423	4
Breno		45.957	10.303	4
Budrio		44.537	11.536	4
Castello d'Argile		44.681	11.296	4
Castelnuovo Rangone		44.549	10.939	4
Cavedine		45.994	10.972	4
Chiavari		44.317	9.322	4
Crespellano		44.514	11.129	4
Desenzano del Garda		45.464	10.547	4
Esine		45.925	10.253	4
Ferrara		44.836	11.618	4
Foppolo		46.043	9.751	4
Gallarate		45.659	8.793	4
Gardone Val Trompia		45.688	10.184	4
Gressoney-la-Trinité		45.829	7.823	4
Ivrea		45.462	7.875	4
Marola		44.484	10.485	4
Massa		44.025	10.123	4
Novara		45.446	8.623	4
Pontremoli		44.377	9.882	4
Rapallo		44.349	9.230	4

Reggio nell'Emilia		44.697	10.631	4
Rovereto		45.888	11.037	4
Sant'Agostino		44.793	11.385	4
Sarzana		44.111	9.961	4
Sona		45.433	10.832	4
Bedonia		44.503	9.629	3-4
Bologna		44.498	11.340	3-4
Casale Monferrato		45.132	8.450	3-4
Genova		44.419	8.898	3-4
La Spezia		44.105	9.819	3-4
Palazzolo		45.452	10.818	3-4
Prato		43.880	11.096	3-4
Torino		45.070	7.674	3-4
Ala di Stura		45.315	7.305	3
Alba		44.693	8.033	3
Bolzano		46.497	11.354	3
Cadine		46.087	11.065	3
Carrara		44.050	10.065	3
Condino		45.889	10.600	3
Crosara		45.708	11.675	3
Faenza		44.288	11.881	3
Fai della Paganella		46.178	11.069	3
Feltre		46.019	11.906	3
Firenze		43.777	11.249	3
Fossano		44.550	7.721	3
Imola		44.353	11.714	3
Imperia		43.885	8.027	3
Lancenigo		45.714	12.277	3
Locana		45.417	7.460	3
Lucca		43.843	10.505	3
Marostica		45.744	11.657	3

Medicina		44.477	11.639	3
Merano		46.671	11.162	3
Modena		44.647	10.925	3
Padova		45.407	11.876	3
Pavullo nel Frignano		44.334	10.834	3
Pergine Valsugana		46.062	11.238	3
Roncegno		46.051	11.410	3
San Michele all'Adige		46.194	11.135	3
Tortona		44.897	8.864	3
Trento		46.064	11.124	3
Vallombrosa		43.731	11.558	3
Vercelli		45.322	8.418	3
Verona		45.438	10.994	3
Vicenza		45.549	11.549	3
Vittorio Veneto		45.982	12.305	3
Albareto		44.447	9.701	F
Brunate		45.820	9.095	F
Celle Ligure		44.342	8.545	F
Como		45.810	9.084	F
Oropa [santuario]	SS	45.627	7.981	F
Saronno		45.628	9.034	F
Varazze		44.361	8.577	F
Venezia		45.438	12.335	F
Vizzola Ticino		45.625	8.697	F
Zambana Vecchia		46.157	11.072	F

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Table S2 – Macroseismic intensities of the April 7, 1786 earthquake.

Localities	Lat	Lon	MCS Int
Liscate	45.481	9.407	7-8
Piacenza	45.052	9.693	6
Crema	45.694	9.670	5-6
Parma	44.801	10.329	5-6
Monza	45.584	9.274	4-5
Bergamo	45.694	9.670	4
Cremona	45.136	10.024	4
Milano	45.464	9.190	4
Vicenza	45.549	11.549	3-4
Padova	45.407	11.876	3-4

Table S3 - List of onset times and associated phases read on ISS 1951 bulletin (original) and modified by this study (modified) for the May 15, 1951 seismic event. Station codes are taken from the International Registry of Seismograph Stations (ISC, 2011). Onsets marked by a "*" have been used by HYPOSAT code (Schweitzer, 2001) and those marked by a "§" by HYPOINVERSE-2000 code (Klein, 2014).

	Original		Modified		
Station Code	**Phase**	**Onset time**	**Phase**	**Onset time**	**Used**
ABE	P	23 00 53.0	Pn	23 00 53.0	
ABE	S	23 02 15.0	Sn	23 02 15.0	
ALG	P	22 56 55.0	Pn	22 56 55.0	
ALI	P	22 57 07.0	Pn	22 57 07.0	
ALI	S	22 59 33.0	Sn	22 59 33.0	
ALM	P	22 57 31.0	Pn	22 57 31.0	
ALM	S	22 59 44.0	Sn	22 59 44.0	
BAS	P	22 55 09.0	Pn	22 55 09.0	*,§
BAS	Pg?	22 55 20.0	sPn	22 55 20.0	*
BES	P	22 57 17.0	Pn	22 57 17.0	
BGY	P	22 56 20.0	Pn	22 56 20.0	*
BGY	S	22 58 20.0	Sn	22 58 20.0	*
BOL	P	22 54 56.0	Pn	22 54 56.0	*,§
BOL	S	22 55 20.0	Sn	22 55 20.0	§
BOR	P	22 59 52.0	P	22 59 52.0	
BUD	P	22 56 11.0	Pn	22 56 11.0	*
BUD	S	22 57 26.0	Sn	22 57 26.0	*
CFF	P	22 55 36.0	Pn	22 55 36.0	*
CHU	P	22 54 56.0	Pn	22 54 56.0	

CHU	S	22 55 09.0	Sn	22 55 09.0	
CLC	P	23 07 08.0	P	23 07 08.0	*
COP	P	22 57 18.0	Pn	22 57 18.0	
CRT	P	22 57 29.0	Pn	22 57 29.0	*
CRT	S	22 59 42.0	Sn	22 59 42.0	
DBN	P	22 56 40.0	Pn	22 56 40.0	
DBN	S	22 57 46.0	Sn	22 57 46.0	
DUB	P	22 57 32.0	Pn	22 57 32.0	*
DUB	S	22 59 45.0	Sn	22 59 45.0	
DUR	P	22 59 13.0	Pn	22 57 13.0	*
DUR	S	22 59 25.0	Sn	22 59 25.0	*
EBR	P	22 56 24.0	Pn	22 56 24.0	*
EBR	S	22 58 24.0	Sn	22 58 24.0	*
FIR	P	22 55 02.0	Pn	22 55 02.0	*,§
FIR	S	22 55 24.0	Sn	22 55 24.0	*
FLO	P	23 05 34.0	P	23 05 34.0	*
FRE	P	23 07 08.0	P	23 07 08.0	*
HEL	P	23 03 00.0	P	23 03 00.0	
HEL	S	23 04 25.0	S	23 04 25.0	
HRB	P	22 56 04.0	Pn	22 56 04.0	*
HRB	S	22 57 11.0	Sn	22 57 11.0	
HRV	P	23 04 02.0	P	23 04 02.0	
ISK	P	22 57 56.0	Pn	22 57 56.0	*
ISK	S	23 02 39.0	Sn	23 02 39.0	
JEN	P	22 56 01.0	Pn	22 56 01.0	*
JEN	S	22 57 04.0	Sn	22 57 04.0	*
JRS	P	22 56 43.0	Pn	22 56 43.0	
JRS	S	22 58 12.0	Sn	22 58 12.0	*

KAL	P	22 56 42.0	sPg	22 56 42.0	
KAL	S	22 57 21.0	Sn	22 57 21.0	*
KEW	P	22 56 39.0	Pn	22 56 39.0	
KEW	S	22 58 14.0	Sn	22 58 14.0	*
KIM	P	23 06 13.0	P	23 06 13.0	
KRL	P	22 55 30.0	Pn	22 55 30.0	
KRL	S	22 56 20.0	Sn	22 56 20.0	
KSA	P	22 59 38.0	P	22 59 38.0	
KSA	S	23 03 36.0	S	23 03 36.0	
LVV	P	22 57 15.0	Pn	22 57 01.5	*
LVV	S	22 59 14.0	Sn	22 59 00.5	*
MAL	P	22 57 30.0	Pn	22 57 30.0	
MAL	S	23 00 55.0	Sn	23 00 55.0	
MES	P	22 56 30.0	Pn	22 56 30.0	*
MES	S	22 58 12.0	Sn	22 58 12.0	
MIN	P	23 06 57.0	P	23 06 57.0	*
MOS	P	22 59 17.0	P	22 59 17.0	
MOS	S	23 02 58.0	S	23 02 58.0	
MRG	P	23 04 51.0	P	23 04 51.0	*
MSS	P	22 55 13.0	Pn	22 55 13.0	*,§
MSS	S	22 56 00.0	Sn	22 56 00.0	*
NEU	P	22 55 08.0	Pn	22 55 08.0	*,§
NEU	S	22 55 35.0	Sn	22 55 35.0	*,§
OTT	P	23 04 12.0	P	23 04 12.0	*
PAD	P	22 54 56.0	Pn	22 54 56.0	*,§
PAR	P	22 55 55.0	Pn	22 55 55.0	*
PAR	S	22 56 59.0	Sn	22 56 59.0	*
PAS	P	23 07 15.0	P	23 07 15.0	*

PAV	P	22 54 38.0	Pn	22 54 38.0	*,§
PAV	S	22 54 44.0	Sn	22 54 44.0	*,§
PDC	P	22 54 46.0	Pn	22 54 46.0	
PDC	S	22 55 32.0	Sn	22 55 32.0	*
PLM	P	23 07 16.0	P	23 07 16.0	*
POT	P	22 56 54.0	Pn	22 56 54.0	
POT	S	22 57 36.0	Sn	22 57 36.0	*
PRA	P	22 55 55.0	Pn	22 55 55.0	*
PRA	S	22 56 59.0	Sn	22 56 59.0	*
PRE	P	23 05 53.0	P	23 05 53.0	*
PRT	P	22 55 00.0	Pn	22 55 00.0	*,§
PRT	S	22 55 35.0	Sn	22 55 23.0	*,§
PUL	P	22 59 04.0	P	22 59 04.0	
PUL	S	23 02 28.0	S	23 02 28.0	
RAC	P	22 56 35.0	Pn	22 56 35.0	
RAC	S	22 57 47.0	Sn	22 57 47.0	
RAV	P	22 55 08.0	Pn	22 55 08.0	*,§
RAV	S	22 55 33.0	Sn	22 55 33.0	*
REN	P	23 06 58.0	P	23 06 58.0	*
RES	P	23 03 23.0	P	23 03 23.0	*
ROM	P	22 55 30.0	Pn	22 55 30.0	*,§
ROM	S	22 56 14.0	Sn	22 56 14.0	*
RVR	P	23 07 13.0	P	23 07 13.0	*
SAL	P	22 54 53.0	Pn	22 54 43.0	*
SAL	S	22 55 06.0	Sn	22 54 56.0	*
SEA	P	23 06 27.0	P	23 06 27.0	*
SHF	P	23 04 01.0	P	23 04 01.0	
SLM	P	23 05 32.0	P	23 05 32.0	

SLM	S	23 13 53.0	S	23 13 53.0	
SOF	P	22 56 54.0	Pn	22 56 54.0	*
SOF	S	22 59 18.0	Sn	22 59 18.0	
STR	P	22 55 21.0	Pn	22 55 21.0	*,§
STR	S	22 55 58.0	Sn	22 55 58.0	*
STU	P	22 55 20.0	Pn	22 55 20.0	*,§
STU	S	22 55 56.0	Sn	22 55 56.0	*
TAM	P	22 59 28.0	P	22 59 28.0	*
TAM	S	23 03 37.0	S	23 03 37.0	*
TAR	P	22 56 14.0	Pn	22 56 14.0	*
TAR	S	22 57 34.0	Sn	22 57 34.0	*
TIM	P	22 56 29.0	Pn	22 56 29.0	*
TIM	S	22 58 57.0	Sn	22 57 45.0	
TIN	P	23 07 05.0	P	23 07 05.0	*
TOL	P	22 57 10.0	Pn	22 57 10.0	*
TOL	S	22 59 32.0	Sn	22 59 32.0	
TRS	P	22 55 16.0	Pn	22 55 16.0	*
TRS	S	22 56 05.0	Sn	22 56 05.0	
UPP	P	22 58 08.0	P	22 58 08.0	*
UPP	S	23 01 03.0	S	23 01 03.0	
UZH	P	22 56 41.0	Pn	22 56 41.0	*
UZH	S	22 58 27.0	Sn	22 58 27.0	*
VIE	P	22 55 50.0	Pn	22 55 50.0	*
VIE	S	22 56 54.0	Sn	22 56 54.0	*
WES	P	23 04 04.0	P	23 04 04.0	*
WIT	P	22 56 23.0	Pn	22 56 23.0	
WIT	S	22 58 05.0	Sn	22 58 05.0	
YAL	P	22 58 30.0	P	22 58 30.0	*

ZUL	P	22 55 04.0	Pn	22 55 04.0	*,§
ZUL	S	22 55 29.0	Sn	22 55 29.0	*,§

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Klein, F. W. (2014). User's Guide to HYPOINVERSE-2000, a Fortran Program to Solve for Earthquake Locations and Magnitudes, in Open File Report, 02/171 revised June 2014, USGS, Menlo Park CA (USA), 148.

Schweitzer, J. (2001). HYPOSAT – An enhanced routine to locate seismic events, Pure and Applied Geophysics, 158, 277–289.

Table S4 - List of onset times and associated phases from ISS 1951 bulletin (original) and modified by this study (modified) related to the May 16, 1951 seismic event. Station codes are taken from the International Registry of Seismograph Stations (ISC, 2011). Onsets marked by a "*" have been used by HYPOSAT code (Schweitzer, 2001) and those marked by a "§" by HYPOINVERSE-2000 code (Klein, 2014).

	Original		**Modified**		
Station Code	**Phase**	**Onset time**	**Phase**	**Onset time**	**Used**
ALG	P	02 29 26.0	Pn	02 29 26.0	
ALG	S	02 35 28.0	PcP	02 35 28.0	
ALM	P	02 29 50.0	Pn	02 29 50.0	
ALM	S	02 32 02.0	sSn	02 32 02.0	
BAS	P	02 27 41.0	Pn	02 27 41.0	*,§
BAS	S	02 28 09.0	Sn	02 28 09.0	*
BES	P	02 27 48.0	Pn	02 27 48.0	*
BOL	P	02 27 29.0	Pn	02 27 29.0	*,§
BOL	S	02 27 50.0	Sn	02 27 50.0	*,§
BUD	P	02 29 16.0	Pn	02 29 16.0	
BUD	S	02 30 37.0	Sn	02 30 37.0	
CHU	S	02 27 46.0	Sn	02 27 46.0	*
CHU	P	02 27 28.0	Pn	02 27 28.0	*
CLC	P	02 39 39.0	P	02 39 39.0	*
DBN	P	02 30 27.0	Pn	02 30 27.0	
DUB	P	02 30 03.0	Pn	02 30 03.0	*
DUB	S	02 32 17.0	Sn	02 32 17.0	
FIR	P	02 27 34.0	Pb	02 27 34.0	*,§
FIR	S	02 28 10.0	Sn	02 28 10.0	
ISK	P	02 30 35.0	sPn	02 30 35.0	*
JEN	P	02 28 33.0	sPn	02 28 33.0	*

JEN	S	02 29 26.0	Sn	02 29 26.0	
KAL	P	02 29 33.0	Pn	02 29 33.0	
KAL	S	02 30 20.0	Sn	02 30 20.0	
KEW	P	02 29 10.0	Pn	02 29 10.0	
KEW	P	02 30 10.0	sPg	02 30 10.0	
KRL	P	02 28 02.0	pPn	02 28 02.0	*
KRL	S	02 28 54.0	Sb	02 28 54.0	
MES	P	02 28 58.0	Pn	02 28 58.0	
MIN	P	02 39 29.0	P	02 39 29.0	*
MSS	P	02 27 45.0	Pn	02 27 45.0	*,§
MSS	S	02 28 30.0	SnSn	02 28 30.0	*
NEU	P	02 27 40.0	Pn	02 27 40.0	*,§
NEU	S	02 28 09.0	Sn	02 28 09.0	*,§
PAD	P	02 27 28.0	Pn	02 27 28.0	*,§
PAD	S	02 28 00.0	Sn	02 28 00.0	
PAR	P	02 28 26.0	Pn	02 28 26.0	*
PAR	S	02 29 40.0	sSn	02 29 40.0	*
PAV	P	02 27 09.0	Pb	02 27 09.0	*,§
PAV	S	02 27 15.0	Sb	02 27 15.0	*,§
PLM	P	02 39 49.0	P	02 39 49.0	*
POT	P	02 29 42.0	Pn	02 29 42.0	
POT	S	02 30 00.0	Sn	02 30 00.0	
PRA	P	02 28 26.0	Pn	02 28 26.0	*
PRA	S	02 29 32.0	Sn	02 29 32.0	*
PRT	P	02 27 33.0	Pb	02 27 33.0	*,§
PRT	S	02 28 08.0	SnSn	02 28 08.0	*
RAC	P	02 29 44.0	sPg	02 29 44.0	
RAC	S	02 30 14.0	Sn	02 30 14.0	*

RAV	P	02 27 40.0	Pn	02 27 40.0	*,§
RAV	S	02 28 08.0	Sn	02 28 08.0	*,§
REN	P	02 39 30.0	P	02 39 30.0	*
ROM	P	02 28 19.0	sPb	02 28 19.0	*
ROM	S	02 29 07.0	Sn	02 29 07.0	
RVR	P	02 39 46.0	P	02 39 46.0	*
SAL	P	02 27 24.0	Pn	02 27 24.0	
SAL	S	02 27 37.0	Sn	02 27 37.0	
STR	P	02 27 54.0	Pn	02 27 54.0	*,§
STR	S	02 28 31.0	Sn	02 28 31.0	
STU	P	02 27 52.0	Pn	02 27 52.0	*,§
STU	S	02 28 32.0	Sn	02 28 32.0	*
TAM	P	02 32 01.0	P	02 32 01.0	*
TAM	S	02 36 12.0	pS	02 36 12.0	
TAR	P	02 28 46.0	Pn	02 28 46.0	*
TAR	S	02 30 06.0	Sn	02 30 06.0	
TIN	P	02 39 37.0	P	02 39 37.0	*
TOL	P	02 29 40.0	Pn	02 29 40.0	*
TOL	S	02 32 05.0	Sn	02 32 05.0	
TRS	P	02 27 46.0	Pn	02 27 46.0	*,§
TRS	S	02 28 38.0	Sn	02 28 38.0	
VIE	P	02 28 23.0	Pn	02 28 23.0	*
VIE	S	02 29 25.0	Sn	02 29 25.0	*
WIT	P	02 28 58.0	Pn	02 28 58.0	
WIT	S	02 29 44.0	Sn	02 29 44.0	
ZUL	P	02 27 35.0	Pn	02 27 35.0	*,§
ZUL	S	02 28 03.0	Sn	02 28 03.0	*,§

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Klein, F. W. (2014). User's Guide to HYPOINVERSE-2000, a Fortran Program to Solve for Earthquake Locations and Magnitudes, in Open File Report, 02/171 revised June 2014, USGS, Menlo Park CA (USA), 148.

Schweitzer, J. (2001). HYPOSAT – An enhanced routine to locate seismic events, Pure and Applied Geophysics, 158, 277–289.

Table S5 - Complete parameter set for each location. For each parameter x, Δx indicates the associated uncertainty.

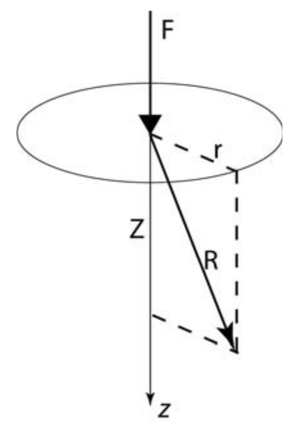
Parameter	May 15, 1951		May 16, 1951	
	HYPOSAT	**HYPOINVERSE**	**HYPOSAT**	**HYPOINVERSE**
Source time T0 (GMT)	22:54:29.92	22:54:29.75	02:27:00.73	02:27:00.82
ΔT0 (s)	0.36	0.39	0.46	0.48
Latitude (°N)	45.387	45.419	45.320	45.462
ΔLatitude (°)	0.028	-	0.031	-
Longitude (°E)	9.475	9.575	9.498	9.613
ΔLongitude (°)	0.036	-	0.052	-
Depth Z (km)	34.66	32.42	20.34	13.71
ΔZ (km)	4.91	4.53	3.42	4.18
Vp/Vs	1.80	variable	1.79	variable
Δ(Vp/Vs)	0.01	-	0.01	-
Max Epicentral Error Ellipse (km)	3.58	4.39	3.95	2.94
Min Epicentral Error Ellipse (km)	2.90	-	2.82	-
Epicentral Error Ellipse Azimuth (°)	126.9	-	115.1	-
rms (s)	1.13	0.86	1.02	0.70
N° onset	71	18	38	18
N° travel-time differences	21	-	12	-
Azimuthal gap (°)	36.9	89	63.5	84

Vertical Point Load at the Surface

Equations for the stress and strain induced in a homogeneous, isotropic, linearly elastic halfspace, with a plane horizontal surface, by a point load **F** perpendicular to the surface and acting at the surface was firstly solved by Boussinesq (1885).

Assumed that the Poisson's ratio is 0.5, the equations for the principal stresses reduce to simple forms (Fung, 1965).

In particular for most pratical analyses of the settlement behavior of soils, it is assumed that the volume of the soil is controlled exclusively by the vertical stress, σ_z:



$$\sigma_z = \frac{3Fz^3}{2\pi R^5}$$

In the present study the force F is due to the removal of the gas mass:

$V = 7 \cdot 10^8 \text{ m}^3$

$\rho = 0.701 \text{ kg/m}^3$

$z = 32 \cdot 10^3 \text{ m}$

$R = 35 \cdot 10^3 \text{ m}$

$F = m \cdot g = V\rho g = 7 \cdot 10^8 \cdot 0.701 \cdot 9.81 = 4.8 \cdot 10^9 \text{ kg} \cdot \text{m/s}$

$\sigma_z = 1.4 \text{ Pa}$

In spherical coordinates, the only non vanishing stress component is σ_{RR}

$$\sigma_{RR} = \frac{3Fz}{2\pi R^3}$$

$\sigma_{RR} = 1.7 \text{ Pa}$

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Boussinesq M.J., (1885) Application des potentiels à l'étude de l'équilibre et du mouvement des solides élastiques, principalement au calcul des deformations et des pressions que produisent, dans ces solides, des efforts quelconques exercés sur und petite partie de leur surface ou de leur intérieur; memoire suivi de notes étendues sur divers points de physique mathématique et d'analyse, Paris, Gauthier-Villars. (in French)

Fung Y.C. (1965) Foundations of Solid Mechanics, Prentice-Hall Int. Inc., London, pp. 198-202.