ANNALS OF GEOPHYSICS, VOL. 48, N. 6, December 2005

The role of instrumental *versus* macroseismic locations for earthquakes of the last century: a discussion based on the seismicity of the North-Western Apennines (Italy)

Stefano Solarino
INGV-CNT c/o Dipartimento Studio del Territorio e delle sue Risorse (DipTeRis),
Università degli Studi di Genova, Italy

Abstract
Many seismological observatories began to record and store seismic events in the early years of the twentieth century, contributing to the compilation of very valued databases of both phase pickings and waveforms. However, despite the availability of the instrumental data for some of the events of the last century, an instrumental location for these earthquakes is not always computed; moreover, when available, the macroseismic location is strongly preferred even if the number of points that have been used for it is low or the spatial distribution of the observations is not optimal or homogeneous. In this work I show how I computed an instrumental location for 19 events which occurred in the Garfagnana-Lunigiana region (Northern Tuscany, Italy) beginning from 1902. The location routine is based on a Joint Hypocentral Determination in which, starting from a group of master events, the systematic errors that may affect the data are summed up in the corrective factors complementing the velocity propagation model. All non-systematic errors are carefully checked and possibly discarded by going back to the original data, if necessary. The location is then performed using the classic approach of the inverse problem and solved iteratively. The obtained locations are then compared to those already available from other macroseismic studies with the aim to check the role to be attributed to the instrumental locations. The study shows that in most cases the locations match, in particular when considering the different significance of the location parameters, especially for the strongest events: the instrumental location provides the point where the rupture begins, while the macroseismic one is an estimate of the area where the earthquake possibly took place. This paper is not meant to discuss the importance and the necessity of macroseismic data; instead, the aim is to show that instrumental data can be used to obtain locations even for older seismic events, without any intention to define which location is better or more reliable.

Key words *historical seismicity – velocity propagation model – Joint Hypocentral Determination*

1. Introduction

In this paper I will show that when enough seismic recordings exist it is possible to compute an instrumental location of major earthquakes. The computation is carried out on an area of mid-high seismicity (Garfagnana, Northern Tuscany, box with dashes in fig. 3) and could be conducted on any other area of similar characteristics; the results are used for a discussion on the role of the instrumental data of historical earthquakes.

Mailing address: Dr. Stefano Solarino, INGV-CNT c/o Dipartimento Studio del Territorio e delle sue Risorse (DipTeRis), Università degli Studi di Genova, V.le Benedetto XV 5, 16132 Genova, Italy; e-mail: peter@dipteris.unige.it

Many efforts have been made in the recent past to recover the historical seismicity of the Italian Peninsula with the aim to distinguish hazardous areas through the appropriate algorithm. The goal of designing a map of hazard for the Italy has been an impressive incentive in recent decades and has led to the compilation of several parametric catalogues (Camassi and Stucchi, 1997; Gruppo di Lavoro CPTI, 1999; Boschi *et al.*, 2000; Gruppo di lavoro CPTI, 2004).

These catalogues differ for both period of coverage and number of events included, but they are especially distinct in the philosophy that guided their compilation. CFT (Boschi *et al.*, 2000) is based on macroseismic data and locations only, contains 605 seismic events selected on the basis of the minimum intensity threshold of VII and contains earthquakes which occurred in the period 461 B.C. to 1997. Conversely, NT4.1.1, (Camassi and Stucchi, 1997) contains all earthquakes exceeding $I_o=$ $=5/6$ or $M_s=4.0$ in the period 1000-1980, and this sums up to 2421 records. The compilation was then enlarged to cover the period 1981-1992. The catalogue is mainly based on macroseismic data, a few of which are novel, but it also contains several locations whose parameters have been previously published in other catalogues; the macroseismic data for these events are not always available. In particular, one catalogue that has been extensively used for merging data in NT4.1.1 is that published by Postpischl (1985), which also contained instrumental locations. NT4.1.1 is probably the most flexible and widely used historical catalogue in Italy and is thus adopted in this work as a reference. In this frame, it is especially important to emphasize that the records extracted from other catalogues and included in NT4.1.1 are indicated as CP: this code actually means that it is no straightforward to determine where the parameters come from (macroseismic or instrumental location) and especially that there is no direct information of the quality of these parameters. In the next paragraphs I will show that this lack biases the comparison, since more than 50% of the resulting instrumental locations that do not match with the existing ones are marked CP.

Finally, CPTI is the result of a joint project to merge and recompute part of the mismatching locations of the mentioned (CFT and NT) catalogues: it has been recently updated to version CPTI04 (Gruppo di Lavoro CPTI, 2004).

All these inventories cover almost the whole of human history and, being updated to very recent years, they overlap the period in which many seismological instruments were already operating. As an example, in fig. 1 I show the number of installed instruments *versus* years in the period 1900-1950 as derived from the results of the TROMOS (http://storing.ingv.it/tromos) project. The histogram does not show two important features: stations were almost homogeneously spread over the Italian Peninsula and a few of them never interrupted they recording activity, even if performed by updated and more modern instruments. Figure 3, even if only showing the position of the stations used in this work, gives a frame on the distribution of historical observatories. More information can be retrieved from the TROMOS web pages.

The existence of several seismic instruments provided good waveforms for the main earthquakes of the century; however, despite

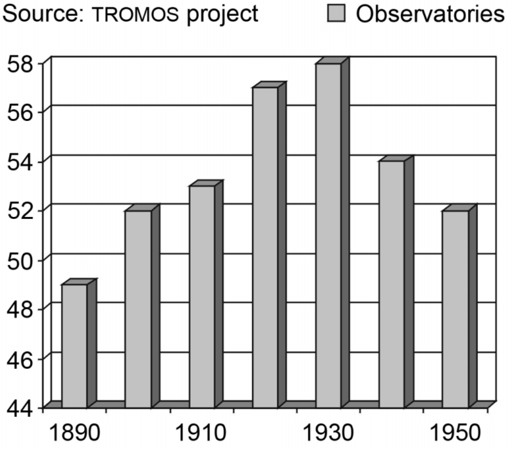

Fig. 1. Stations operating in Italy in the period 1900-1950 (source TROMOS). Since the project made an inventory of observatories established before 1940, the histogram is updated to that time. The last bars of the plot takes into account only the stations that still existed in 1950 and does not include those established in the decade 1940-1950.

the richness of the database, an instrumental location for these earthquakes is not always computed and when a macroseismic one is available it is strongly preferred, even when based on a poor and or not optimal distribution of the localities. In theory, it is more correct to input, in whatever computation, data obtained with the same means or obtained applying similar methodology, that is in this case to always use macroseismic data for homogeneity. But catalogues are already «biased» by a few instrumental locations as discussed above, so it does not seem so difficult to use alternative locations especially if they prove to be of acceptable quality. The study is not meant to discuss the acknowledged importance and the necessity of macroseismic location; instead, the aim is to show that instrumental data can be used to obtain locations even for older seismic events, without any intention to define which location is better or more reliable. In fact, throughout the paper the corresponding macroseismic locations will be used as a reference, and the discussion will be based on the differences between epicentral position rather than on quality of data and result.

In particular, I introduce the basics of the method, I make a short description of the main problems encountered in assembling the data and finally I discuss and compare the obtained locations to try to find out which is the role of instrumental data for less recent earthquakes.

2. Towards an instrumental location: Joint Hypocentral Determination

The methodology applied in this work (Solarino *et al.*, 1996) has been extensively described in Solarino (2002). It is based on the concept that it is possible to account for all systematic errors that may interfere with the location of an earthquake by computing corrective factors in conjunction with the model used for locations; all non-systematic errors may instead be discarded by checking the single datum. For example, site effects or non perfect knowledge of the position of the instrument can be included in the correction factor, which will bias all data with the same importance, while a picking error can be avoided by a careful check of the single datum, especially if original waveforms are still available. This part of the work proves to be the most delicate, due to the difficulties in finding original seismic bulletins, digitized or on paper waveforms, original scripts by seismologists running the instruments. In a few cases data that would have represented a potential source of error were finally recovered by going back to the original seismogram.

One of the most important aspects in this frame is that of the time synchronization. It must be taken into account that the technology of clocks was very similar for all seismic observatories, although provided by different brands, as happens today. It is then reasonable to believe that the performances (and thus the errors) of these timing device were very similar. Data synchronized with these machineries can then be considered comparable.

It is also well known that in the early days of seismology scientists used mechanical clocks, the drift of which was corrected at established intervals using more sophisticated radio timing systems, and ensuring a more accurate absolute time. In case of major earthquakes, the phase picking was corrected to take into account the drift. Sometimes this correction was directly annotated on the seismogram, sometimes it was annotated apart, but in general the published and shared data was already corrected for the drift. However, in some cases, different phase pickings are found on diverse bulletins, perhaps reporting corrected and non-corrected data respectively: in such cases either it is possible to realize which is the correct timing or the reading must be discarded. Finally, since many location programs use *S-P* times, for this kind of data the correctness of absolute time does not really matter provided that no malfunctioning occurs during the recording of the event.

While random errors can be avoided by careful control of the data, systematic errors can be included in the computation by applying a Joint Hypocentral Determination (JHD thereinafter) technique, the aim of which, as stated above, is to sum up all errors in a corrective factor. As known, the JHD uses a master event to check the compatibility of its location with the rest of the data. In this case, the JHD technique has been based on a group of very recent and well located events that acted as masters in successive steps.

The starting point of the whole routine consisted in the computation of a very reliable velocity propagation model using a dataset of recent events (01/1999-12/2001, fig. 2); the computation of this propagation model, later indicated as «reference model», has been widely described by Ellsworth (1977) and Kissling (1988). The 1D model results from a combined, simultaneous inversion where the inverse problem is solved by the full inversion of the damped least squares matrix $A^TA+\lambda$. As the inverse problem is non-linear, the solution is obtained iteratively, where one iteration consists of solving both the complete forward problem and complete inverse problem once. VELEST (Kissling *et al.*, 1995), the code that performs the computation, can also be run in single event mode when only the location problem is carried out. In this case, an additional singular value decomposition of the symmetric matrix A^TA is performed to calculate the eigenvalues. As known, this way of treating the inverse problem provides supplementary information on the resolution: they will not be discussed in detail in this paper, but supplemental information can be found in Solarino (2002). At the end of the computation, different models with about the same residual variance and location precision can usually be obtained from the same data set. The model that coincides best with the surface geology and *a priori* information on the near-surface structure has to be chosen as the final model, and will be called «minimum» (Kis-

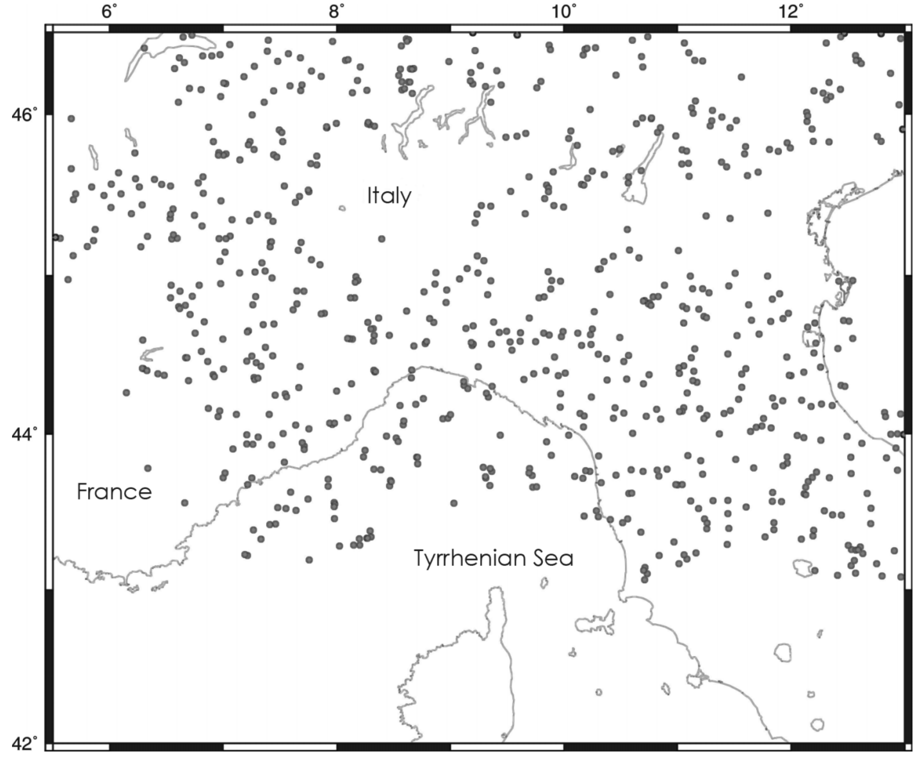

Fig. 2. Earthquakes used for the computation of the reference model applied in this work. They cover the period 1999-2001.

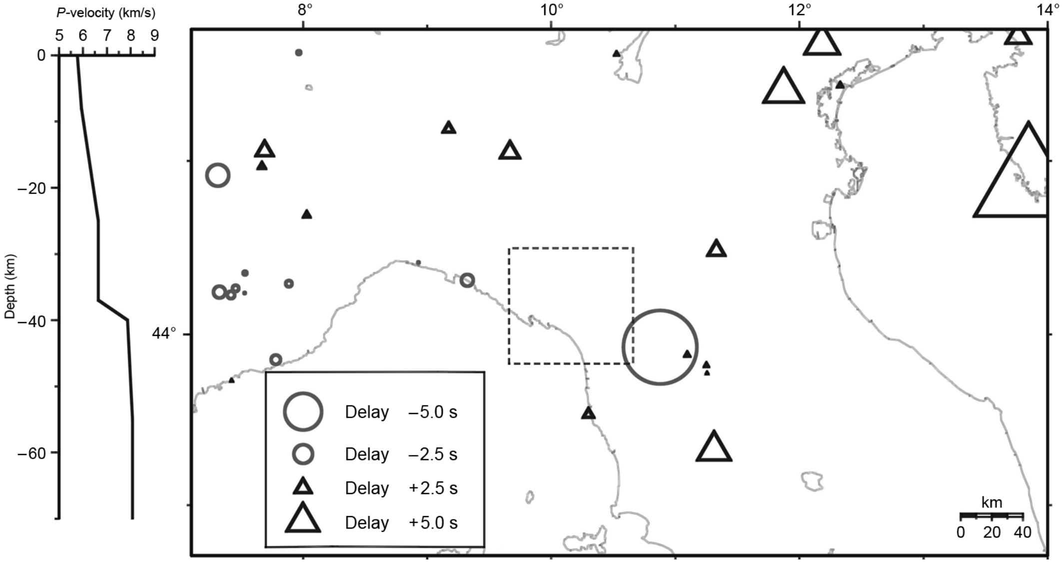

Fig. 3. Velocity propagation model (left panel) and position of stations used for this study. For each station, the correction factor is reported (circle for negative values, triangle for positive; size is proportional to the amount) as after the computation process resumed in table I. The distribution of delays is close to the optimal, being very nicely distinct the positive and negative areas (Kissling *et al*., 1995). The box with dashes shows the approximate extension of the Lunigiana-Garfagnana area.

Table I. Evolution of the computation of delays for the seismic observatories the readings of which are used in this work. At increasing steps the number of known stations corrections (in percentage with respect to the total number) expands, and even observatories that no longer operate can be taken into account.

Step	1973	1972	1968	1965	1961	1959	1951	1939	1934	1931	1928	1928	1927	1926	1921	1920	1902	1902
1	72%	75%	50%	40%	50%	50%	50%	40%	42%	62%	28%	20%	20%	40%	25%	20%	40%	40%
2	100%	100%	66%	60%	75%	75%	66%	40%	42%	62%	28%	20%	20%	40%	50%	33%	40%	40%
3	100%	100%	100%	100%	100%	75%	83%	40%	50%	62%	28%	20%	20%	40%	75%	33%	40%	40%
4	100%	100%	100%	100%	100%	100%	100%	40%	58%	62%	28%	20%	30%	40%	75%	33%	60%	40%
5	100%	100%	100%	100%	100%	100%	100%	100%	58%	62%	58%	20%	40%	60%	75%	44%	60%	40%
6	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	72%	40%	80%	100%	75%	66%	60%	40%
7	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	90%	100%	75%	77%	80%	60%

sling, 1988) to indicate that it provides minimum average (rms) values for all earthquakes used in the inversion. Additionally, relocation of known sources (shots, blasts) facilitates the choice of the best model and gives hints on its reliability.

The 1D model resulting from the computation with VELEST (fig. 3, left panel) is accompanied by *P* and *S* station corrections that are first calculated only for the stations that are still operating and that contributed to the location of the master events, while those relative to seismic observatories that are no longer operating or have run for a limited amount of time are adjoined and adjusted in the following steps. Basically, each step consists of a selection of older events, of the location with data for which station corrections are known and eventually of letting unknown station corrections free to float to compute relative delays. In detail, the latter operation consists in keeping the computed propagation model and fix the master locations (whose number is increased at each run with more events) and hence let the program compute, sum up and attribute delays to stations for which readings are present but have not been used for location (Kissling *et al.*, 1995). In practice, station corrections are always computed with respect to master events, and the number of known station corrections increases at each step, being computed also for older or no longer operating stations. Table I reports in a very schematic way the evolution of station delays the readings of which are included in each event discussed in this paper. At the beginning of the process, almost nothing is known for some events. The successive steps are used to compute the diverse station delays until a correct location can be made.

At the end of this routine, the model is complete with all station delays (fig. 3) and can be used for the location of the «historical» events of the Garfagnana area.

3. Data and results

Apart from the limitation of the availability of instrumental data, in theory no constraints act in selecting the data to be relocated. In practice there are several limitations that must be taken into account.

First, the events must be included in some other (macroseismic) catalogue for comparison. This is not going to be necessary in a future application, but it is of paramount importance to test the results, and cannot be neglected at this stage. Second, events must have at least 4 usable phase pickings that in some cases may mean 6 to 7 readings to be conservative enough to consider mistakes, picking errors and non-matching information. Third, there must exist more than one source for the data to cross-check the entries, as mentioned in the last paragraph. By combining all these aspects, it turned out that the best selection should take into account events which occurred later than 1900, that are included in the NT4.1.1 Catalogue (the most complete) and whose data are reported on two or more of the sources quoted in Appendix A. It is noteworthy that some of the references reported in Appendix A are compilations, and should then be comprehensive of all data available for an event as collected from the various bulletins and observatories. The careful cross checking between these compilations and some other original data showed that in a few cases the compilations contain inconsistencies and differences, and this is another important issue towards the use of more sources.

The initial selection of 56 seismic events (as extracted from NT4.1.1 for the area 43.6-44.6 and 9.1-10.5) was dramatically reduced to 30 when looking for the multiplicity of sources but the number dropped to 19 when considering the minimum number of readings required for locations upon careful selection of the blunder-free data (the compiled phase readings for these data are reported in Appendix B). Of course, this aspect diminishes the potential of the instrumental locations *versus* the macroseismic ones, it being possible in this case only for fewer than 40% of the events, and will be discussed in the final paragraph. The characteristics of the selected events are reported in table II (second column from left); their location properties are taken from the NT4.1.1 Catalogue.

After checking for data completeness on all available sources, events have been located applying VELEST in single event mode; the final locations are reported in table II together with the relevant location errors, while table III shows a comparison of the obtained locations with the original positions. The new locations are compared with the macroseismic ones in fig. 4, where it is possible to see at a glance how far the epicentres have been shifted: the vectors connecting each two points indicate the change in position from macroseismic to instrumental and show very different lengths for the diverse couples. The figure also shows that the original locations were sometimes very clustered (see for example events 08/1902, 1920, 1968, 1961, 1939).

The characteristics of the newly obtained locations are reported in table II: the depth, marked by bold characters, has been computed for more than 50% of the earthquakes. At first glance, the obtained distribution of earthquakes seems compatible with the knowledge of the recent seismicity of the area (Solarino *et al*., 2002) and with the proposed position for the main seismogenic structures of the area (*e.g.*, the Garfagnana-north fault, Valensise and Pantosti, 2001); moreover, the less clustered aspect of the seismicity seems less «artificial» than the macroseismic one.

The errors associated with the new locations (ERX, ERY, ERZ) are on average less than 5 km, and the overall RMS is sometimes less than 1 s. The usage of the standard errors in the hypo format may appear inadequate or incomplete to describe the uncertainties of the final locations and, as shown in Solarino (2002), could be substituted by a less compact form by showing the full resolution matrix or its diagonal elements.

However, at this stage the errors are only used to distinguish between locatable and non-locatable events and to give a rough idea about the final quality and reliability of the results and in such an attempt the standard errors are enough. Finally, the gap shows that for some events the station coverage is very good, while in a few cases it exceeds 200°.

The analysis of the differences between locations (table III, difference between latitudes and between longitudes in km) shows three different trends. There are seismic events (05/03/1902, 07/09/1920, 1931, 1939, 1951, 1959, 1972) for which the differences between the two location methods do not exceed 16 km for each coordi-

Table II. Index of the events relocated in this work. The list is the final result of a selection done in the area 43.6-44.6 and 9.1-10.5 after checking for multiplicity of data sources and minimum number of phase pickings (see text). The locations parameters of the second column are those of the NT4.1.1 (Camassi and Stucchi, 1997) Catalogue. The remaining columns are relative to instrumental locations and report the position, the depth and the errors associated to the locations. NC is used for depths that are not adequately constrained.

Date	Location as in NT4.1.1 Catalogue	Instrumental location	Depth	rms	ERX	ERY	ERZ	GAP
05/03/1902	44.10N, 10.46E	44.16N, 10.31E	NC	0.92	1.3	3.5	2.3	281
04/08/1902	44.20N, 10.20E	44.09N, 11.12E	NC	1.66	0.9	3.7	2.6	246
27/10/1914	44.05N, 10.45E	44.38N, 10.82E	4.5	0.65	4.4	4.8	3.3	115
07/09/1920	44.20N, 10.20E	44.25N, 10.14E	4.3	1.70	3.6	4.6	7.1	121
29/11/1921	44.50N, 9.80E	44.76N, 10.78E	NC	0.01	3.6	3.8	1.6	163
18/11/1926	44.30N, 10.00E	44.80N, 9.82E	NC	2.88	3.7	4.3	1.7	113
28/10/1927	44.53N, 9.53E	44.73N, 9.84E	11.7	1.80	3.1	3.1	4.4	81
20/07/1928	44.50N, 9.61E	44.72N, 10.06E	5.9	0.89	3.1	3.2	4.1	99
03/08/1928	44.20N, 10.20E	44.50N, 11.03E	16.6	1.31	3.5	2.9	3.9	132
25/01/1931	44.25N, 10.10E	44.28N, 10.02E	5.5	1.10	3.2	3.2	0.0	161
13/06/1934	44.48N, 9.80E	44.51N, 10.52E	NC	1.27	3.3	2.4	4.5	109
15/10/1939	44.16N, 10.23E	44.30N, 10.43E	42.2	1.40	4.2	4.2	3.1	143
12/08/1951	44.06N, 10.48E	44.09N, 10.56E	0.2	0.10	3.9	4.3	1.4	199
26/01/1959	44.50N, 9.50E	44.60N, 9.47E	NC	0.56	2.8	3.9	3.0	118
03/08/1961	44.20N, 10.20E	43.98N, 10.25E	37.6	1.28	3.5	4.1	3.6	157
09/11/1965	44.45N, 10.30E	44.43N, 10.74E	35.0	0.19	4.4	4.3	3.7	153
07/06/1968	44.10N, 10.20E	44.58N, 10.81E	21.4	0.15	3.5	4.2	0.6	221
25/10/1972	44.41N, 9.91E	44.39N, 9.84E	39.5	0.20	4.1	4.7	4.6	167
05/06/1973	44.51N, 9.56E	44.27N, 9.30E	NC	0.12	2.7	4.9	3.8	169

Table III. Absolute differences (in km) between the latitude and the longitude of the macroseismic and instrumental locations. Bold numbers are used when the differences exceeds 16 km for any of the values. The magnitude is taken from the NT4.1.1 Catalogue. The last column of the table displays the number of points of intensity available for the macroseismic location. CP indicates the events extracted from other catalogues: for these events no quality information can be derived.

Date	M_s/I_x	Diff. $(I_a - I_o)$, km	Notes
05/03/1902	5.0/7	7–12	76
04/08/1902	5.0/7	**11–72**	CP
27/10/1914	5.8/7	**37–29**	588
07/09/1920	6.5/10	6–4	454
29/11/1921	4.6/5	**30–77**	10
18/11/1926	4.2/5.5	**55–14**	CP
28/10/1927	4.8/6	**22–24**	39
20/07/1928	3.7/6	**25–35**	13
03/08/1928	4.2/5.5	**34–80**	CP
25/01/1931	4.0/6	4–6	CP
13/06/1934	4.9/6	**8–56**	29
15/10/1939	4.9/7	16–15	56
12/08/1951	4.5/5.5	3–6	18
26/01/1959	4.2/5.5	12–2	CP
03/08/1961	4.4/6	**24–4**	CP
09/11/1965	4.8/5	**1–34**	13
07/06/1968	4.3/NR	**53–48**	? DB
25/10/1972	4.7/5	3–6	186
05/06/1973	4.4/4	**26–20**	CP

nate. The choice of this reference value is somewhat arbitrary, but it represents a good compromise between the errors associated with the instrumental location and the uncertainty associated with the macroseismic one. It is then reasonable to say that the two locations match, if one considers that the instrumental location gives the point of rupture while the macroseismic one is more an average of the area the rupture started from. This statement is especially true for events exceeding *M* 5.5 (Gasperini and Ferrari, 2000), but the most widely shared definition of the macroseismic epicenter («the baricentre of the area featuring the maximum effects», Gasperini and Ferrari, 2000) involves a similar bias for all magnitude levels, though of course in proportion to them, since the maximum effects may depend upon several factors (site effects, wrong or inaccurate description, distribution of the localities).

On average, the number of points used for the macroseismic locations of these events is large, say greater than 30, except for a couple of them that directly come from other sources (CP).

A second group contains events that do not match: their differences not only exceed 16 km in one or both coordinates, but at least for one can be up to 80 km, which cannot be simply explained by the diverse meaning of the location parameters. These are the 08/1902, 1921, 1926, 1927, 07/1928, 08/1928, 1934, 1961, 1965, 1968, 1973 events. Almost all of them have been taken from other catalogues (CP), while those based on macroseismic observations have been located with 10 (1921), 13 (1928), 13 (1965), 29 (1934) and 39 (1927) localities. This second group is probably much more difficult to locate using macroseismic data with the currently available information; on average they have a lower magnitude (down to 3.7). Moreover, the original catalogue which contained those for which macroseismic data are not available (CP) was probably not accurate enough.

It is important to emphasize that, if the locations proposed in this work are reliable, some of these earthquakes actually occurred far from where they have been positioned, and this may have an impact on the microzonation and hazard computation. I discuss for example the event which occurred in 1934. Its original location has been obtained using 29 macroseismic observations (Monachesi and Stucchi, 1997), which is rather a good number, positioned as in fig. 5. It is evident that there is a very uneven distribution of localities and that they are especially lacking on the eastern side, which can have biased the macroseismic location (grey star) towards the western area. Conversely, the instrumental location (black star in the figure) moves the epicenter to the north-east, that is in the same direction where macroseismic data are most lacking. If I accept that the macroseismic location may be biased by the poor coverage on the eastern side and I take into account the location errors of the instrumental determination, all this would render plausible a shift of the lo-

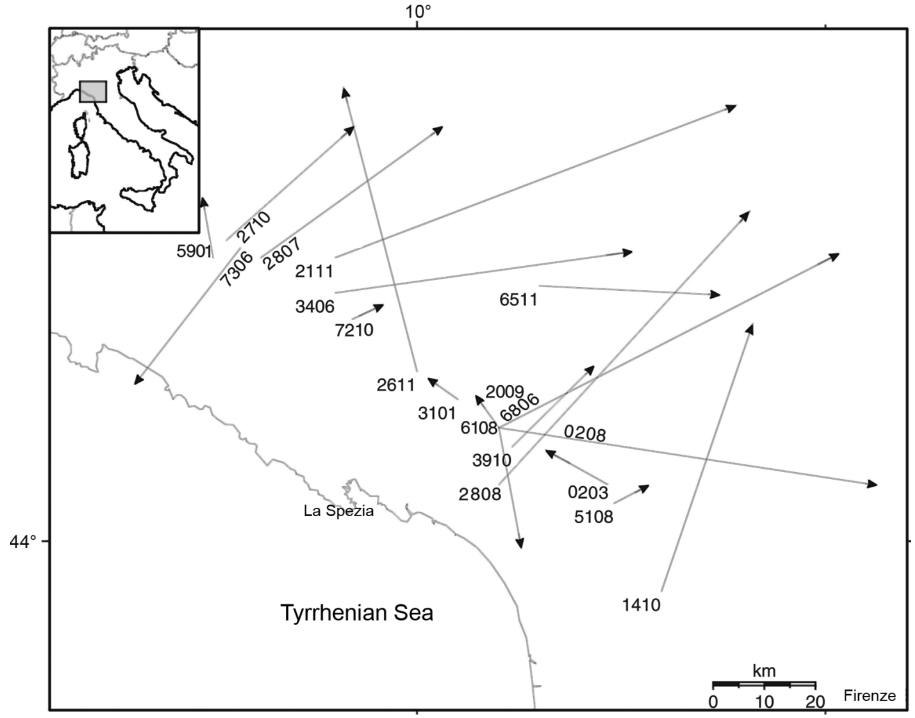

Fig. 4. Vectors connecting the original macroseismic location with the instrumental one as obtained in this work.

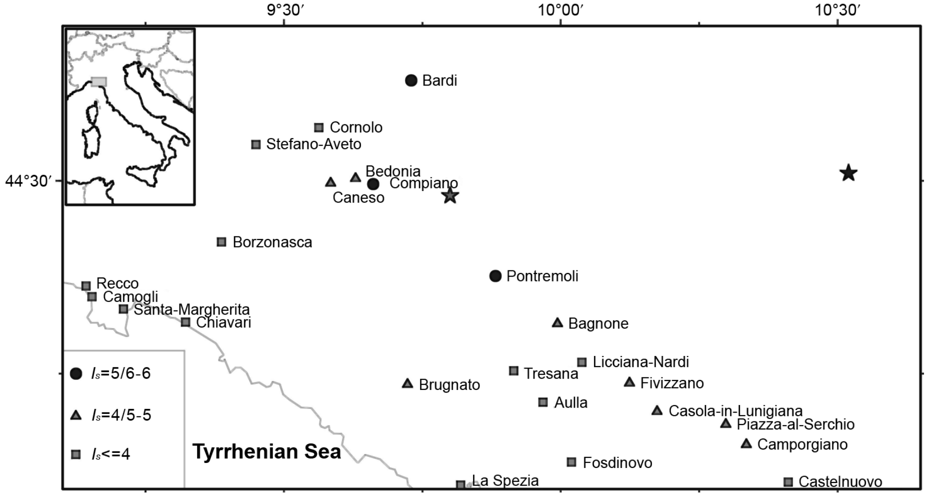

Fig. 5. intensities for the 1934 event (DOM, Monachesi and Stucchi, 1997). The grey star shows the macroseismic location, the black one marks the instrumental one proposed in this study.

cation of the earthquake towards the east, that would mean on the other side of the watershed of the Apennines.

The third group is made up of one event only (1914): its location consistently differs from the macroseismic one but, the latter being obtained by more than 500 localities, it is reasonable to believe that instrumental data are not able to constrain the solution adequately. This is shown by both the location errors associated with this hypocenter (they are among the highest) and by the resolution matrix (not reported), whose diagonal elements are very far from optimal (0.9604, 0.9584, 0.9525 and 0.8055 respectively for origin time, X, Y and Z coordinates).

The presented analysis, although not exhaustive, gives a rough estimate of the potential and limitations of both data and method and thus represents a good starting point for the discussion on the function of instrumental locations.

4. Discussion

The obtained instrumental locations proved to be very similar, in many cases, to those proposed using macroseismic data. Moreover, it is always possible to define how reliable they are by looking at the associated location errors (within the limitations that these errors may introduce) or at the resolution matrices, and finally they may provide information on the depth of the events, which cannot be easily derived with macroseismic data, although several methodologies have been proposed to infer depth from intensity observations. Provided thus that, under particular conditions, it is possible to obtain an instrumental location for older earthquakes, it is important to define the limits of their usage, that is to define what their role is.

It is evident that instrumental locations cannot substitute macroseismic locations as they do not completely overlap the recent part of the parametric catalogues: instrumental data are largely available only since the sixties, while as stated above they lack for the first decades of the twentieth century, except for very large earthquakes. But instrumental data give a much better chance to distinguish different events in seismic sequences, which is not required in the macroseismic database (it is selected to avoid clusters that would bias many of the applications which it is used for) but may be helpful in other studies (seismic cycles, seismotectonics and so on). For example, the event of September 1920 was preceded the day before by an important shock that is not included in the published macroseimic catalogues but was recorded by many seismographic stations: how did this first shock affect the macroseismic observations of the following large event? Could this important event be neglected when studying the way energy is released in the area? In this frame, it is very important to have at least a rough estimate of the depth of the earthquake, which can emerge, sometimes with severe limitations, from instrumental locations. In fact several methods have been proposed to infer depth from the attenuation of macroseismic data, but seldom are they applied and in no Italian macroseismic catalogue is depth reported.

At the moment, the usage of instrumental data for the mentioned purposes is limited by the fact that seismic bulletins and waveforms for historical events are not in digital format, but this will soon change thanks to national (SISMOS, Michelini and the INGV SISMOS Group, 2004) and international (EUROSISMOS, Ferrari and Pino, 2004) projects that aim at compiling information for both instruments and seismic recordings.

The correct role of the instrumental locations is then to support and complement the macroseismic data and, in the few cases in which the macroseismic data are poor, to be used instead, provided that the instrumental data have been carefully checked. This should not sound too odd since at the moment the most widely used parametric catalogue already contains a small percentage of instrumental locations, and adding a few more events or some more information could only improve it.

Acknowledgements

An anonymous reviewer and Fabrizio Bernardi provided very constructive comments. Graziano Ferrari shared his precious knowledge of the older instruments and observatories. He also gave me very good hints on the older data.

I owe special thanks to Alberto Ansaloni who provided very important information about the Observatory of Chiavari and let me thumb through the many bulletins, journals and scientific reports archived there.

This work is financed by the Istituto Nazionale di Geofisica e Vulcanologia and by the Dipartimento per la Protezione Civile within the DPC2004-06 research activity, under the S2 project.

Appendix A.

List of some of the reference sources used in this work. Not all the bulletins were published for the whole century. Some of them were compilations of comprehensive data, some were simply listing the data of a single observatory (*e.g.,* Venezia, Quarto Castello). Finally, some other were merged in more complete compilations. Good references in this sense can be found in the TROMOS Project.

Published by	Title	Notes
Regio Ufficio Centrale di Meteorologia e Geofisica, Microsismi, Fascicolo I	Bolletino sismico	Comprehensive compilation of data from many national observatories
Regio Ufficio Centrale di Meteorologia e Geofisica, Macrosismi, Fascicolo II	Bollettino sismico	Comprehensive compilation of data from many observatories
Union Geodesique et Geophysique Internationale, Bureau Central seismologique de Strasbourg	Bulletin du mois	Comprehensive compilation of data from many observatories
Raffaello Stiattesi, Osservatorio di Quarto Castello (Firenze)	Spoglio delle osservazioni sismiche	Contains data from Observatory alone
Atti del Reale Istituto Veneto di Scienze, Lettere ed Arti	Osservazioni sismografiche dell'Istituto di Fisica della Regia Università di Padova	Contains data from Observatory alone
Regio Ufficio Centrale di Meteorologia e Geofisica	Notizie sui terremoti osservati in Italia	Comments and data on the seismic activity at a national scale
Int. Union of Geodesy and Geophysics, the British Ass. Seismological Committee, the University of Oxford	The international Seismological Summary observatories	Comprehensive compilation of data from many
Caloi P., Medi E., Istituto Nazionale di Geofisica	Bollettino sismico mensile	Comprehensive compilation of data from many observatories
Caloi P., Pannocchia G., Rosini E.	Registrazioni sismiche data in Roma	Contains from Observatory alone

Published by	Title	Notes
International Seismological Centre	Bulletin	Comprehensive compilation of data from many foreign and national observatories
International Seismological Centre, Thatcham, U.K.	On-line Bulletin, http://www.isc.ac.uk/Bull	Covers the whole century
Osservatorio Geofisico del Seminario Patriarcale di Venezia (formerly Osservatorio Meteorologico e Geodinamico)	Bollettino Mensile (1920, 1927, 1934)	Bulletins were not published throughout the period of operation (1817-1938)

Appendix B.

Data used in this work in hypo-tape format. Readings with weight 4 and 5 have not been used due to different listing in diverse bulletins and/or data sources; for convenience, they are listed anyway.

```
GIAC  P 5  2  3  5  7    556.00
QUCA  P 0  2  3  5  7    635.00
ROCC  P 0  2  3  5  7    757.00
TRI   P 0  2  3  5  7    708.00
FXIM  P 0  2  3  5  7    636.00
PADO  P 0  2  3  5  7    658.00

ROMA  P 0  2  8     4223750.00
QUCA  P 0  2  8     4223628.00
ROCC  P 0  2  8     4223741.00
TRI   P 0  2  8     4223670.00
FXIM  P 0  2  8     4223627.00
SIEN  P 5  2  8     4223740.00

CHIA  P 0   141027   92236.00
FXIM  P 0   141027   92236.00
PADO  P 0   141027   92247.00
ROCC  P 0   141027   92259.00
MONC  P 0   141027   92265.00
DOMO  P 5   141027   92257.00
MCI   P 0   141027   92273.00

PADO  P 5 20  9  7    55557.00          79.00 S 5
FXIM  P 0 20  9  7    55556.00
ROCC  P 0 20  9  7    55592.00
CHIA  P 0 20  9  7    55552.00
LIVO  P 5 20  9  7    55592.00
```

```
DOMO  P  5  20  9  7      55580.00
MONC  P  0  20  9  7      55581.00         110.00 S 0
VENE  P  0  20  9  7      55578.00
SIEN  P  0  20  9  7      55578.00
MCI   P  0  20  9  7      55650.00

PADO  P  0   21112912      445.00           62.00 S 0
POLA  P  0   21112912      496.00
FXIM  P  0   21112912      440.00
CHIA  P  0   21112912      440.00

MONC  P  0     261118225795.00             114.0 S 0
PADO  P  0     261118225791.00             116.0 S 0
FXIM  P  0     261118225715.00
PIAC  P  0     261118225760.00
LIVO  P  5     261118225864.00              74.00 S 0

MONC  P  0     271028214942.00              66.00 S 0
PADO  P  0     271028214945.00              70.00 S 0
FXIM  P  0     271028214940.00
ROCC  P  0     271028214968.00
VENE  P  0     271028214957.00              84.00 S 0
TREV  P  0     271028214959.00              85.00 S 0
PIAC  P  0     271028214922.00
LIVO  P  4     2710282149  5.00             20.00 S 4
ROMA  P  0     271028214982.00             132.0 S 0
DOMO  P  0     271028214990.00
```

```
CHIA   P  0      271028214920.00

PADO   P  0  28      720195353.00        75.00 S 0
PIAC   P  0  28      720195330.00
ROCC   P  0  28      720195383.00        142.0 S 0
TREV   P  0  28      720195363.00        84.00 S 0
MONC   P  0  28      720195365.00        82.00 S 0
CHIA   P  5  28      720195310.00
FXIM   P  0  28      720195343.00
LIVO   P  4  28      720195370.00

PADO   P  0  28  8     3231049.00        75.00 S 0
PIAC   P  0  28  8     3231048.00
ROCC   P  0  28  8      323983.00
TREV   P  0  28  8     3231060.00        100.0 S 0
LIVO   P  0  28  8      323970.00
FXIM   P  0  28  8      323998.00
MONC   P  0  28  8     3231053.00        89.00 S 0

TREV   P  0  31      125104854.00        74.00 S 0
PAVI   P  0  31      125104834.00
PIAC   P  0  31      125104832.00
PRT    P  0  31      125104830.00
FXIM   P  0  31      125104831.00
LIVO   P  5  31      125104870.00        60.00 S 5
ZUR    P  0  31      125104870.00        108.0 S 0
NEUC   P  0  31      125104868.00        109.0 S 0

TREV   P  0  34   613  9    657.00        85.00 S 0
PADO   P  0  34   613  9    652.00        74.00 S 0
TRI    P  0  34   613  9    670.70        86.30 S 0
VENE   P  0  34   613  9    659.00        79.00 S 0
PAVI   P  0  34   613  9    652.00
PIAC   P  0  34   613  9    637.00
PRT    P  0  34   613  9    638.50        52.00 S 0
LIVO   P  0  34   613  9    642.00        55.00 S 0
FXIM   P  0  34   613  9    638.50
SIEN   P  0  34   613  9    646.00
ROMA   P  0  34   613  9    672.00        119.0 S 0

RCU    P  0    39101515     573.30        107.0 S 0
MONC   P  0    39101515     559.00        84.00 S 0
TRI    P  0    39101515     571.00        105.0 S 0
CHUR   P  0    39101515     570.00        114.0 S 0
PRT    P  0    39101515     539.60        46.80 S 0

PRT    P  0  51      812211948.00         57.00 S 0
BOLO   P  0  51      812211955.00         67.00 S 0
PAVI   P  0  51      812211969.50         91.40 S 0
SALO   P  0  51      812211969.00         90.30 S 0
ROMA   P  0  51      812211987.50         125.4 S 0
TRI    P  0  51      812211985.00         134.0 S 0

PAVI   P  0  59 126        53556.60         68.80 S 0
OROP   P  0  59 126        53568.00         89.00 S 0
BOLO   P  0  59 126        53569.00         93.00 S 0
RMP    P  5  59 126        53742.00
PRT    P  0  59 126        53568.80         88.20 S 0
FXIM   P  0  59 126        53570.00         96.00 S 0
MONA   P  0  59 126        53573.50
TRI    P  0  59 126        53590.00         140.0 S 0
CHUR   P  0  59 126        53581.40
BAS    P  0  59 126        53590.40

FXIM   P  0  61  8       3102645.70         63.00 S 0
PRT    P  0  61  8       3102652.20         56.40 S 0
PADO   P  0  61  8       3102670.00         106.0 S 0
PAVI   P  0  61  8       3102680.00         100.0 S 0
RMP    P  5  61  8       3102741.30
MONA   P  0  61  8       3102668.00         114.0 S 0
CHUR   P  0  61  8       3102680.80         111.4 S 0
RSL    P  5  61  8       3102684.00         122.0 S 5
LJU    P  5  61  8       3102692.00         148.3 S 5
TRI    P  5  61  8       3102745.00

BOLO   P  0  6511        9153512.00         24.00 S 0
PAVI   P  0  6511        9153523.00         42.00 S 0
PADO   P  0  6511        9153526.00         47.00 S 0
RCU    P  0  6511        9153545.00         75.00 S 0

PAVI   P  0  68  6  7      93468.00         83.50 S 0
PADO   P  0  68  6  7      93469.00         90.00 S 0
RCU    P  0  68  6  7      93496.00
AQU    P  0  68  6  7      93496.00
RMP    P  0  68  6  7      93497.50
GENO   P  0  68  6  7      93464.00         78.00 S 0
STV    P  0  68  6  7      93483.20        105.50 S 0
ROB    P  0  68  6  7      93477.00         98.00 S 0
CUN    P  0  68  6  7      93482.00        105.00 S 0
TRI    P  0  68  6  7      93486.00
LJU    P  0  68  6  7      93495.00
```

```
FUR    P 0 68 6 7   93542.00

PAVI   P 0   721025215631.00        45.00 S 0
BOLO   P 0   721025215634.00        49.00 S 0
TNO    P 0   721025215639.40
GENO   P 1   721025215625.68        35.18 S 0
ALBA   P 1   721025215635.98
ROB    P 0   721025215635.23        51.73 S 0
SRX    P 0   721025215638.53        57.53 S 0
CUN    P 0   721025215639.53        59.53 S 0
VERN   P 0   721025215638.93
ROA    P 0   721025215640.03
ENR    P 0   721025215640.43
STV    P 0   721025215641.03        62.23 S 0
PNI    P 0   721025215641.68        63.43 S 0
CHIA   P 1   721025215620.00        25.00 S 0
LNS    P 2   721025215646.10
SPF    P 0   721025215649.50
LMR    P 0   721025215652.50
```

```
RSL    P 0   721025215652.51
LRG    P 0   721025215653.20
TRI    P 0   721025215656.80
RMP    P 0   721025215663.50
LJU    P 0   721025215666.50
FUR    P 0   721025215670.00
BAS    P 0   721025215664.00

PRT    P 0 73 6    5134752.60        70.20 S 0
RMP    P 0 73 6    5134784.00        122.0 S 0
GENO   P 2 73 6    5134727.90        39.60 S 1
ROB    P 0 73 6    5134745.00        61.50 S 0
SRX    P 1 73 6    5134747.30        67.50 S 0
CUN    P 0 73 6    5134750.00        69.40 S 0
STV    P 0 73 6    5134752.00        74.50 S 2
PNI    P 0 73 6    5134753.00        77.50 S 3
ZUR    P 0 73 6    5134774.10
TRI    P 0 73 6    5134772.10
LMR    P 0 73 6    5134762.60
```

REFERENCES

Boschi, E., E. Guidoboni, G. Ferrari, D. Mariotti, G. Valensise and P. Gasperini (Editors) (2000): Catalogue of strong italian earthquakes from 461 B.C. to 1997, *Ann. Geofis.*, **43** (4), pp. 268 (with CD-ROM).

Camassi R. and M. Stucchi (1997): *NT4.1.1 a Parametric Catalogue of Damaging Earthquakes in the Italian Area* (GNDT, CNR), pp. 66.

Ellsworth, W.L. (1977): Three dimensional structure of the crust and mantle beneath the island of Hawaii, *Ph.D. Thesis* (Massachusetts Institute of Technology), pp. 327.

Gasperini, P. and G. Ferrari (2000): Deriving numerical estimates from descriptive information: the computation of earthquake parameters, *Ann. Geofis.*, **43**.(4), 729-746.

Ferrari, G. and N.A. Pino (2004): eurosismos 2002-2004 a project for saving and studying historical seismograms in the Euro-Mediterranean area, in *XXIX General Assembly of the European Seismological Commission, Abstracts*, p. 74.

Gruppo di Lavoro CPTI (1999): *Catalogo Parametrico dei Terremoti Italiani* (ING,GNDT, SGA, SSN), (Ed. Compositori, Bologna), pp. 92.

Gruppo di Lavoro CPTI (2004): *Catalogo Parametrico dei Terremoti Italiani, Versione 2004* (CPTI04), (INGV, Bologna), (on line: http://www.emidius.mi.ingv.it/CPTI/)

Kissling, E. (1988): Geotomography with local earthquake data, *Rev. Geophys.*, **26**, 659-698.

Kissling, E., S. Solarino and M. Cattaneo (1995): Improved seismic velocity reference model from local earthquake data in Northwestern Italy, *Terra Nova*, **7**, 528-534.

Michelini, A. and the INGV SISMOS Group (2004): Current developments in the INGV SISMOS project, in *XXIX General Assembly of the European Seismological Commission, Abstracts*, p. 76.

Monachesi, G. and M. Stucchi (1997): *DOM4.1, an Intensity Database of Damaging Earthquakes in the Italian Area* (Web update 2000, on line: http://emidius.mi.ingv.it/DOM/).

Postpischl, D. (1985): Catalogo dei terremoti Italiani dall'anno 1000 all'anno 1980, *Quad. Ric. Sci.*, **114** (2B), pp. 239.

Solarino, S. (2002): The September 7, 1920 earthquake in Lunigiana-Garfagnana (Tuscany, Italy): can instrumental data provide a reliable location?, in *Proceedings of the XXVIII General Assembly of ESC* (CD-ROM).

Solarino, S., D.P. Hill and W.L. Ellsworth (1996): Eastern California seismicity beginning from 1927 and its relation to the post-1980 unrest in Long Valley Caldera, California, in *Agu Fall Meeting, Book of abstracts*, p. 206.

Solarino, S., G. Ferretti and C. Eva (2002): New insights on the seismicity of the Lunigiana-Garfagnana area (Tuscany, Italy), *J. Seismol.*, **6**, 141-152.

Valensise, G. and D. Pantosti (2001): Database of potential sources for earthquakes larger than *M* 5.5 in Italy, *Ann. Geofis.*, **44** (suppl. to no. 4), pp.180 (with CD-ROM).

(received January 18, 2005;
accepted May 6, 2005)