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Source Geometry of Historical Events Retrieved by Synthetic Isoseismals

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Source geometry of historical events retrieved by synthetic isoseismals

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ABSTRACT

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The possibility of computing complete synthetic signals for laterally homogeneous structural models in an exact, efficient and computationally rapid way allows an investigation of the effects of given source and structural models on the macroseismic field. Synthetic isoseismals are computed by first adding vectorially, in the horizontal plane, the SH-wave and P-SV-wave displacement fields. The maximum zero-to-peak value of displacement is then calculated at points distributed in space in such a way that it is easy to contour the isolines automatically. This methodology, developed mainly in the point-source approximation and used to investigate the macroseismic field of some instrumentally recorded earthquakes, can also be applied to historical events.

Introduction

The macroseismic information obtained by the quantification of the effects and damage produced by an earthquake and represented by isoseismal lines is perhaps the oldest scientific tool for studying earthquakes (Mallet, 1862). Up to now, the intensity data have been processed using empirical formulas (Blake, 1941; Shebalin, 1959; Sponheuer, 1960) in order to deduce a rough estimate of the depth of the source and the attenuation laws (Anderson, 1978; Chandra, 1979). Shebalin (1972) was among the first to suggest that macroseismic data also contain information on the source geometry and the rupturing processes.

One of the first very simple methods to compute theoretical isoseismals was proposed by Ohta and Satoh (1980), who considered only a halfspace and direct rays. Moreover, they assumed the intensity to be proportional to the average slip on the fault. In such a way, both the orientation of the source and the propagation of seismic waves in more realistic media is neglected. It follows from such assumptions that non-circular isoseismals can only be explained by the spatial extension of the fault. Recently Chiaruttini and Siro (1991) proposed a method which takes into consideration only the S-wave radiation and the directivity effect. They do not consider either realistic media or the propagation of waves through them. To relate their theoretical kinematical function to observed isoseismals, they have to rely heavily on empirical laws relating, on the one hand, the theoretical kinematical function to observed peak ground acceleration (PGA) values, and on the other hand, PGA values to intensity data.

An initial application of synthetic seismograms to the study of observed isoseismals was presented by Panza and Cuscito (1982), who considered only

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SH waves. Recently Suhadolc et al. (1988a) have extended the methodology to the P-SV waves and therefore to the total field of motion. The synthetic isoseismals, constructed using complete synthetic seismograms, are defined by the equal value contours of the displacement field due to a point source. This choice, even if intensity is usually empirically related to acceleration (Trifunac and Brady, 1975; Murphy and O'Brien, 1977), is an appropriate one. In fact, for frequencies as high as 1 Hz, the shape of the isolines for displacement, velocity or acceleration is approximately the same and does not vary with frequency (Suhadolc et al., 1988a). For practical purposes, to give significant saving in computer time, the computations are usually performed with a cut-off frequency of 0.1 Hz. Another method for constructing synthetic isoseismals has recently been proposed by Zahradnik (1989). His algorithm, however, takes into account only the direct S wave and computes only the innermost isoseismal. The experience gained studying instrumentally recorded events (Suhadolc et al., 1988a; Panza et al., 1988) can be translated to the quantification of historical events for which the only quantitative data available are represented by macroseismic information.

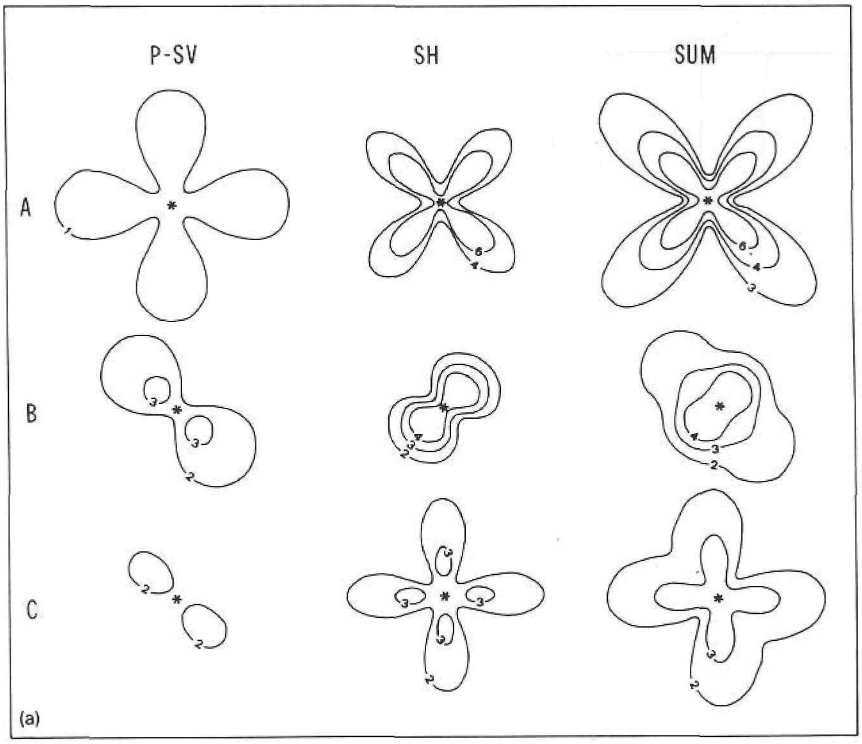
General considerations

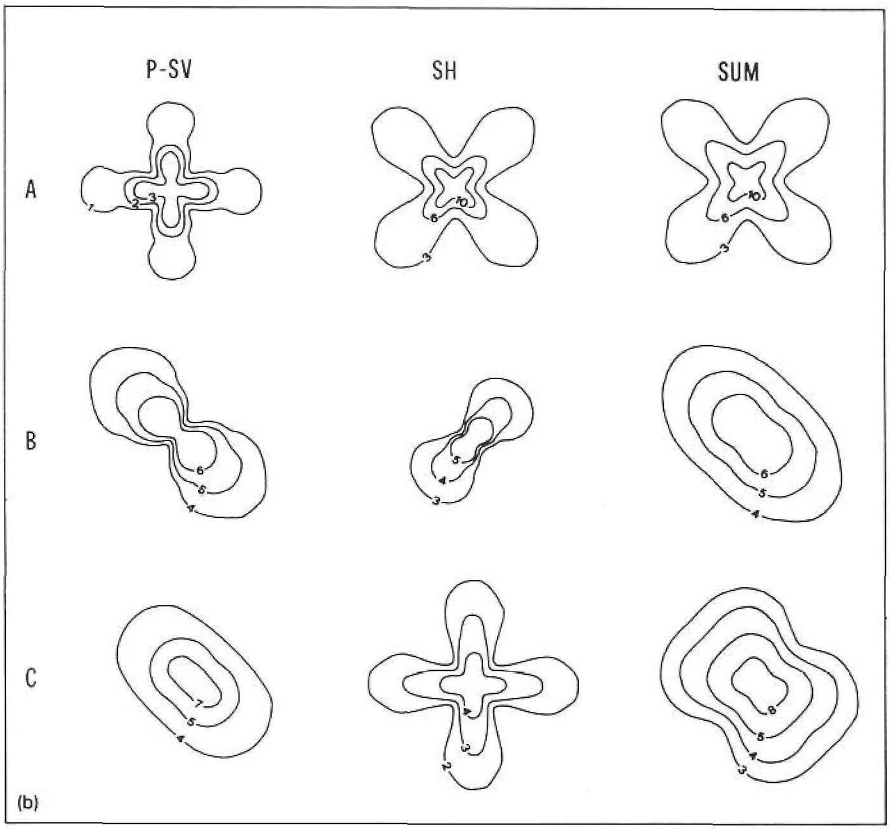
The theoretical isoseismals are constructed taking the vector sum of the radial and transverse components of displacement. The maximum zero-to-peak value of this quantity is used to represent the distribution in space of ground shaking. The synthetic seismograms are computed via the mode summation (Panza, 1985; Panza and Suhadolc, 1987; Florsch et al., in prep.) at points distributed in space in such a way that it is easy to contour the isolines automatically. The point sources are defined by the focal depth and by the three parameters that specify the fault-plane solution: strike, dip and rake.

To minimize the effect of source finiteness in space and time, we consider signals corresponding to a point source but with a cutoff frequency of 0.1 Hz, although the damage—and therefore the isoseismals—can in general be related to frequencies around 1 Hz. On the basis of our experience, for most structural models, the general shape of the theoretical isoseismals does not change significantly when the computational cutoff frequency is extended from 0.1 Hz to 1 Hz, provided the source extension is taken into account in the high frequency computation.

It is very useful to analyse the isoseismals corresponding to the three fundamental shear dislocations (Ben-Menahem and Singh, 1981, p. 186). An example for a hypocentral depth of 17 km and for a fault strike oriented 225°, is shown in Fig. 1(a). The structural model used to construct these isoseismals is FRIUL5B (Fig. 2(a)), a structure representative of the Friuli (northeast Italy) region. The SH-wave radiation prevails in the case of a vertical fault with a zero rake, and in the case of an inverse fault with a dip of 45°; the total horizontal displacement has four lobes in both cases. The efficiency in the radiation of P-SV and SH waves is about the same when the fault is vertical (rake 90°). In this case the total horizontal displacement field has two lobes and the elongation changes in going from the inner to the outer isoseismals. This last feature is quite often observed, an example being the isoseismals of the August 18, 1892 Pembroke (South Wales, UK) earthquake (Musson et al., 1984) shown in Fig. 3. Even if the isoseismals cannot be drawn out to sea, the data available on land clearly support the effect calculated theoretically; it is, therefore, possible to infer that a source of the dip-slip type is compatible with the obtained macroseismic field.

Fig. 1. Displacement fields (cm) corresponding to the three fundamental shear dislocations (Ben-Menahem and Singh, 1981) for a point source 17 km deep. Starting from the left, the first column represents the P-SV-wave displacement field, the second the SH, while the third represents the total horizontal displacement field. Each row corresponds to a different mechanism, from the top to the bottom: (A) dip 90°, rake 0°; (B) dip 90°, rake 90°; (C) dip 45°, rake 90°. The strike of the fault in all examples is 45° (0° is up, 90° to the right). Seismic moment = 10^{19} Nm. Cutoff frequency 0.1 Hz. (a) Structural model FRIUL5B (Suhadolc et al., 1988a) shown in Fig. 2(a). (b) Structural model IRPGRA1 (Suhadolc et al., 1988b), shown in Fig. 2(b).


P-SV
SH
SUM
A
B
C
(a)


P-SV
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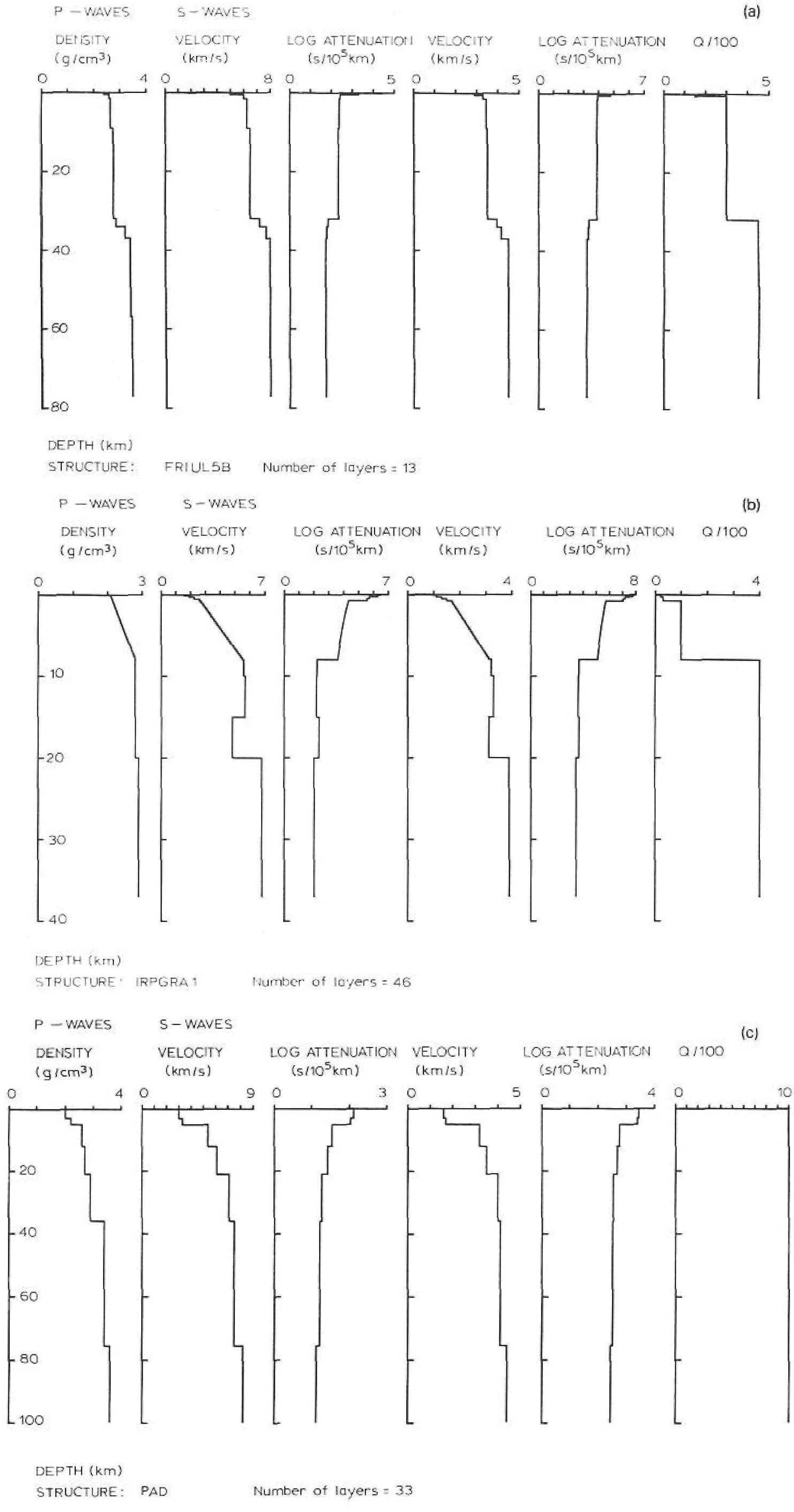
(a)
P — WAVES
S — WAVES
DENSITY (g/cm³)
VELOCITY (km/s)
LOG ATTENUATION (s/10⁵km)
VELOCITY (km/s)
LOG ATTENUATION (s/10⁵km)
Q/100
0 4
0 8
0 5
0 5
0 7
0 5
20
40
60
80
DEPTH (km)
STRUCTURE: FRIUL5B
Number of layers = 13
(b)
P — WAVES
S — WAVES
DENSITY (g/cm³)
VELOCITY (km/s)
LOG ATTENUATION (s/10⁵km)
VELOCITY (km/s)
LOG ATTENUATION (s/10⁵km)
Q/100
0 3
0 7
0 7
0 4
0 8
0 4
10
20
30
40
DEPTH (km)
STRUCTURE: IRPGRA1
Number of layers = 46
(c)
P — WAVES
S — WAVES
DENSITY (g/cm³)
VELOCITY (km/s)
LOG ATTENUATION (s/10⁵km)
VELOCITY (km/s)
LOG ATTENUATION (s/10⁵km)
Q/100
0 4
0 9
0 3
0 5
0 4
0 10
20
40
60
80
100
DEPTH (km)
STRUCTURE: PAD
Number of layers = 33

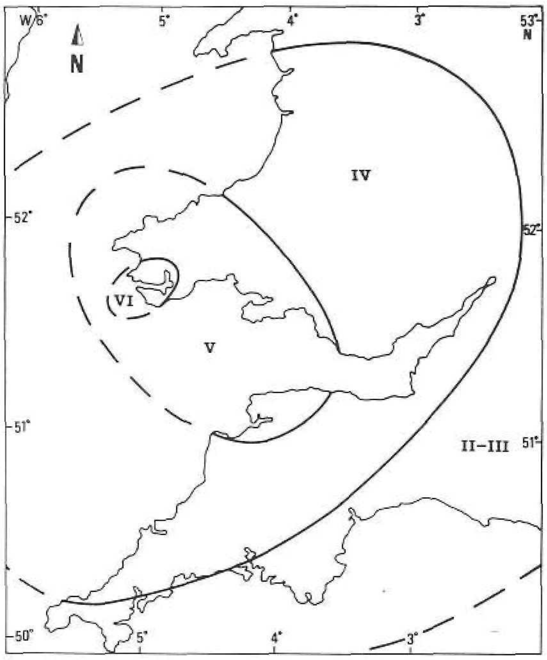

Fig. 3. Observed isoseismals of the August 18, 1892 Pembroke (South Wales, UK) earthquake (after Musson et al., 1984).

If the isoseismals of the three fundamental shear dislocations are computed using a different structural model, the individual displacement field of P-SV and SH waves preserves the general shape, but, due to a variation in the relative amplitudes of the two wavefields, some of the features of the total displacement field—such as the change in the orientation of the outer with respect to the inner isoseismals—may be lost or changed. Figure 1(b) shows an example, the structural model being in this case IRPGRA1 (Fig. 2(b)), a structure characterized by a significant low-velocity sedimentary cover and representative of the Irpinia (Southern Italy) region. The other features discussed in the previous paragraph are unchanged, except for the total horizontal displacement field in the case of the 45° dip and 90° rake, which has changed from a four-lobed pattern to a two-lobed one.

The structural model influences the relative amplitudes of P-SV and SH fields and has, therefore, some effect on the shape of the isoseismals, but its influence is not as relevant as that due to the geometrical source parameters. According to the experience gained so far for a cutoff frequency of 0.1 Hz, the following results are obtained in the presence of a significant sedimentary cover: if the source is close to the bottom of the sedimentary cover, the SH field prevails, while if it is deeper, the P-SV field is dominant. The SH field seems to dominate as soon as the ratio $R = \beta_B/\beta_A$ is greater than 1.7, where β_A and β_B are, respectively, the average S-wave velocities—weighted with the thickness of each layer in the crust—below and above the source.

Applications to "instrumental" events

Detailed descriptions of several applications to real data can be found in the papers by Suhadolc et al. (1988a), Panza et al. (1988), Panza (1991), Suhadolc (1991) where it is shown that the source parameters, in particular the source depth, have a strong influence on the isoseismal shape. A summary of the most significant examples of modelling the observed macroseismic field of instrumentally recorded earthquakes is given here.

The $M_L = 4.9$ Parma earthquake (Ferulano, 1986) is located at the contact between the Northern Apennines and the Po Valley. The focal depth estimates, based on instrumental observations, vary between 30 and 40 km (International Seismological Centre (ISC) and U.S. National Earthquake Information Service (NEIS) bulletins; Craglietto et al., 1989). In the Northern Apennines the structural data (Pieri and Groppi, 1981; Castellarin et al., 1985) indicate that the overthrusts intersecting Mesozoic layers can be located at depths not exceeding 10–15 km. It is therefore reasonable to locate the fault responsible for the

Fig. 2. (a) Structural model FRIUL5B (Suhadolc et al., 1988a). It has been assumed that $Q_\alpha = 2.5\ Q_\beta$. (b) Structural model IRPGRA1 (Suhadolc et al., 1988b). It has been assumed that $Q_\alpha = 2.5\ Q_\beta$. (c) Structural model PAD (Craglietto et al., 1989). It has been assumed that $Q_\alpha = 2.5\ Q_\beta$.

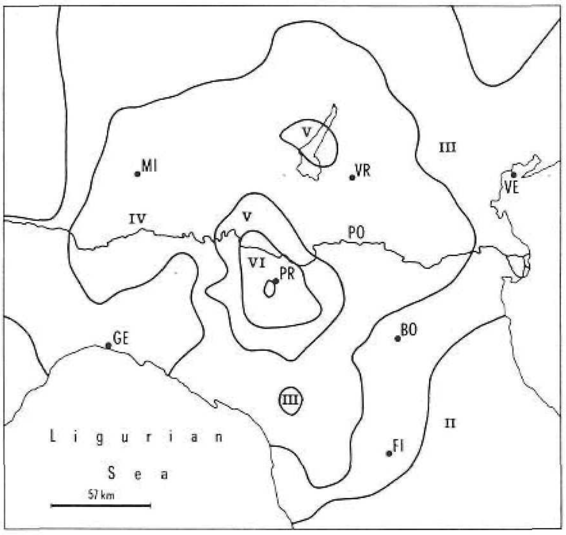

Fig. 4. Observed isoseismals of the November 9, 1983 Parma (Northern Italy) earthquake (after Margottini et al., 1984). The intensity values have been interpolated and the isoseismal lines drawn automatically. *MI* = Milano; *GE* = Genova; *PR* = Parma; *VR* = Verona; *BO* = Bologna; *FI* = Firenze; *VE* = Venezia.

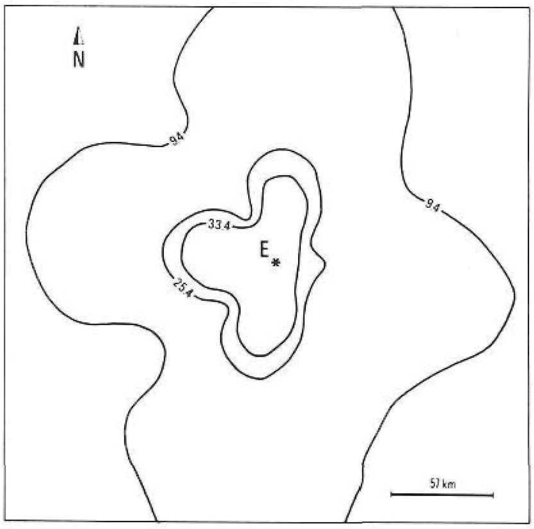

Fig. 5. Theoretical total displacement field (in units of 10^{-29} m) for a seismic moment $|M_0| = 10^{-7}$ Nm and a point source at 30 km depth modelling the November 9, 1983 Parma earthquake. Source and structural parameters in Table 1 and in Fig. 2(c).

1983 Parma earthquake in the crystalline basement. The macroseismic field of this earthquake has been determined by Margottini et al. (1984) and is shown in Fig. 4. The fault plane solution and the structural model (Fig. 2(c)), which have been used as input for the construction of the synthetic isoseismals, are taken from Craglietto et al. (1989). At the focal depth of 30 km, the resolution analysis with respect to variations of the dip angle permits the exclusion of values lower than 50°. The synthetic isoseismals corresponding to the input parameters of Table 1 are shown in Fig. 5. The concordance between synthetic and observed isoseismals remains satisfactory to a focal depth of 20 km, but for shallower sources there is no correspondence (Panza et al., 1987). The analysis of the macroseismic field therefore confirms the location of the event in the crystalline basement.

The isoseismals of the November 23, 1980 Irpinia event (Fig. 6) were synthesized by Suhadolc et al. (1988a) using only a few modes. The synthetic isoseismals obtained using all the modes in the considered frequency-phase velocity interval and the source parameters of Table 1 were obtained by Panza et al. (1987) and are shown in Fig. 7.

The elongation of the isoseismals along the axis of the Apenninic chain is neatly modelled and can be attributed to the source parameters of the point source used. The differences between the iso-

TABLE 1

Fault-plane solutions and references for the structural models used to construct synthetic isoseismals

Event	Strike (°)	Dip (°)	Rake (°)	Depth (km)	Structure
Parma, 1983	70	80	140	30	PAD (Fig. 2(c))
Irpinia, 1962	115	70	275	17.5	IRPGRA1 (Fig. 2(b))
Irpinia, 1980	320	70	275	6	IRPGRA1 (Fig. 2(b))
Friuli, 1976	280	30	115	7	FRIUL5B (Fig. 2(a))
Capitanata, 1627	310	45	90	20	IRPGRA1 (Fig. 2(b))

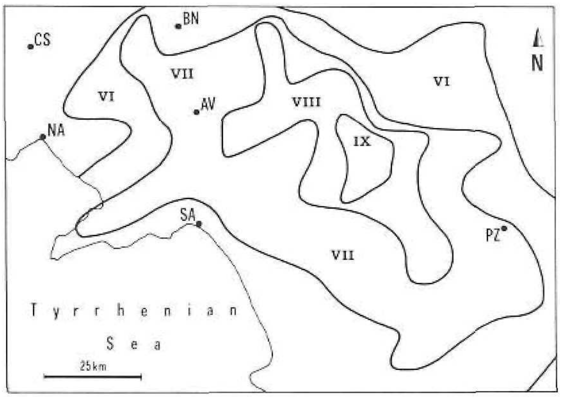

Fig. 6. Observed isoseismals of the November 23, 1980 Irpinia (Southern Italy) earthquake, MSK scale (after D. Postpischl, pers. commun., 1986). We have chosen to use as experimental data these isolines and not the ones, significantly smoothed, published by CNR (1985) to outline the importance of using, whenever possible, unsmoothed macroseismic fields. *AV* = Avellino; *BN* = Benevento; *CS* = Caserta; *NA* = Napoli; *SA* = Salerno; *PZ* = Potenza.

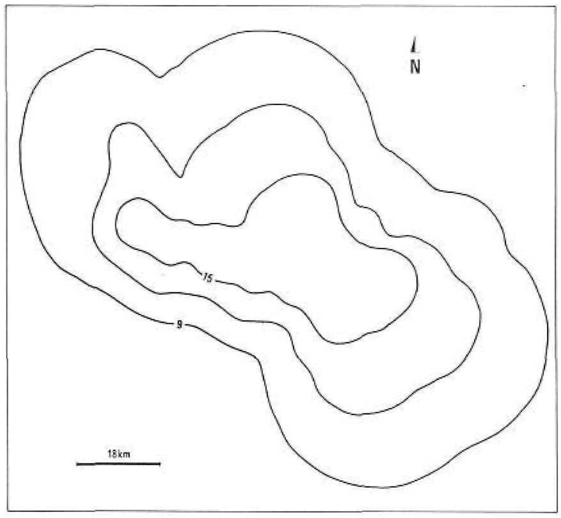

Fig. 8. Theoretical total displacement field (in units of 10–29 m) for six point sources (see Fig. 9) at 6 km depth, each with a seismic moment $|M_0| = 10^{-7}$ Nm, modelling the November 23, 1982 Irpinia earthquake. The structural model used in the computation is given in Fig. 2(b).

seismals of Fig. 7 and those obtained by Panza and Cuscito (1982) using only SH waves and a focal depth of 18 km are obviously due to the inclusion, in this paper, of the P-SV field. The main effect of the inclusion of the P-SV field is to partly "fill in" the "voids" present in the Panza and Cuscito (1982) solution, which are due to the nodal lines of the SH-wave radiation. Moreover, to obtain a radiation dominated by SH waves the focus has to be moved around 6 km. However, the overall pattern of the two solutions remains the same. Since the rupturing process of this earthquake is highly complex (Bernard and Zollo, 1989; Harabaglia et al., 1987), the introduction of spatially extended sources could be relevant. In any case, the example of Fig. 8 clearly shows that, with a cutoff frequency of 0.1 Hz, the spatial finiteness of the source (Fig. 9) introduces only minor effects superposed over those of the single point source.

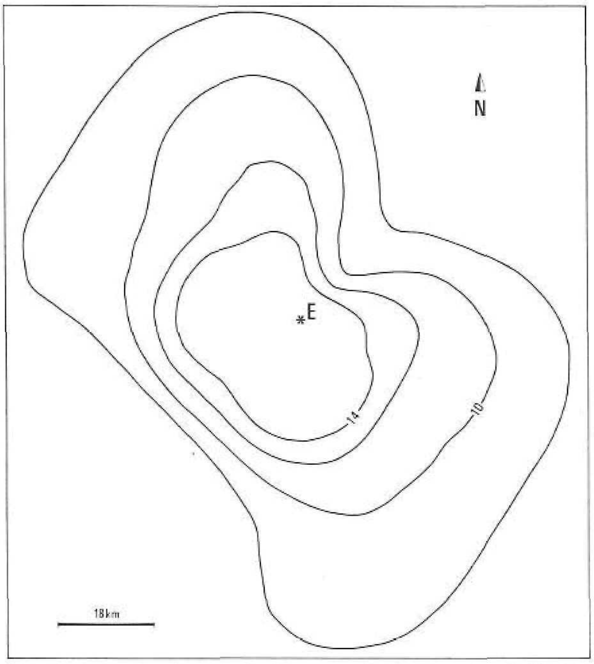

Fig. 7. Theoretical total displacement field (in units of 10–29 m) for a seismic moment $|M_0| = 10^{-7}$ Nm and a point source at 6 km depth modelling the November 23, 1980 Irpinia earthquake. Source and structural parameters in Table 1 and Fig. 2(b).

The August 21, 1962 Irpinia event has its epicentre slightly shifted northwards with respect to the 1980 earthquake. Its macroseismic field (Fig. 10) is nevertheless clearly elongated perpendicularly to the axis of the Apennines. In their study of the 1980 Irpinia event, Suhadolc et al. (1988a) have demonstrated that the ratio between the amplitudes of the SH waves and the horizontal component of the P-SV ones strongly depends on the depth of the source and on the elastic properties

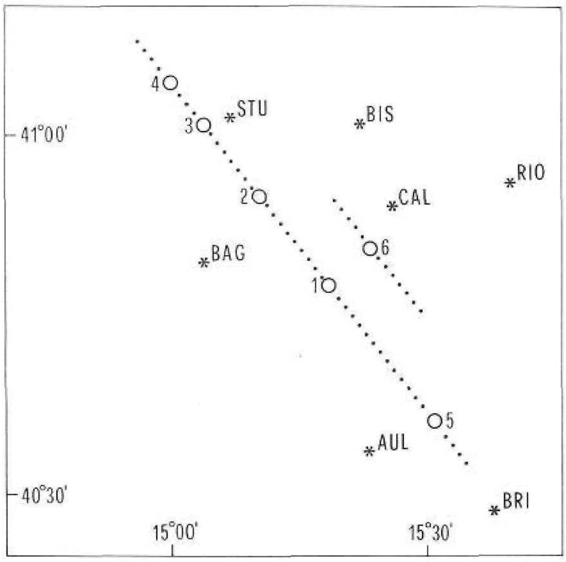

Fig. 9. Epicentral area of the November 23, 1980 Irpinia earthquake. Stars denote the accelerometric stations: Sturno (*STU*), Rionero in Vulture (*RIO*), Calitri (*CAL*), Brienza (*BRI*), Bisaccia (*BIS*), Bagnoli Irpino (*BAG*) and Auletta (*AUL*). The dotted lines indicate the surface projections of the faults of the model (Harabaglia et al., 1987). The open circles denote the positions of the six point sources, whose theoretical isoseismals were used to construct the synthetic isoseismals of Fig. 8. The fault plane orientation and relative strength of the single point sources are the following (number of point source, relative strength, strike, dip and rake): 1, 0.6, 320°, 70°, 275°; 2, 0.8, 320°, 70°, 275°; 3, 1.0, 340°, 90°, 270°; 4, 0.7, 360°, 90°, 270°; 5, 0.7, 320°, 70°, 275°; 6, 0.6, 110°, 70°, 275°.

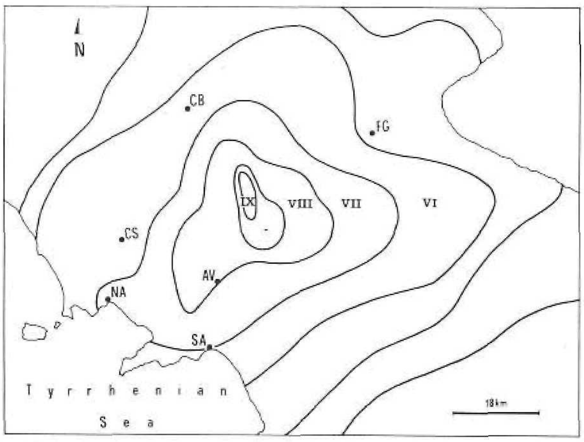

Fig. 10. Observed isoseismals of the August 21, 1962 Irpinia (Southern Italy) earthquake (after CNR, 1985). *NA* = Napoli; *SA* = Salerno; *CS* = Caserta; *AV* = Avellino; *CB* = Campobasso; *FG* = Foggia.

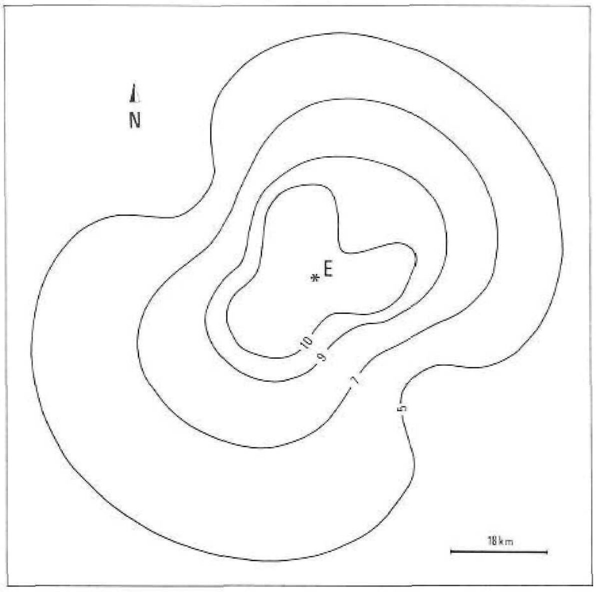

Fig. 11. Theoretical total displacement field (in units of 10^{-29} m) for a seismic moment $|M_0| = 10^{-7}$ Nm and a point source at 17.5 km depth modelling the August 21, 1962 Irpinia earthquake. Source and structural parameters in Table 1 and in Fig. 2(b).

near the hypocentre. If the source is placed near the bottom of the superficial low-velocity layers, the SH waves are dominant with respect to the P-SV ones and, therefore, isoseismals elongated along the Apenninic chain are obtained; otherwise, P-SV waves dominate SH ones and the macroseismic field has an elongation perpendicular to the Apenninic chain. It is therefore evident that the isoseismals of the 1962 Irpinia event can be easily explained by an earthquake having the same source geometry as the 1980 one, but with a focal depth greater than 10 km. A better fit between the isoseismals of highest intensity is reached (Fig. 11) if the strike of the fault is rotated by 180° (Table 1).

The May 6, 1976 Friuli earthquake ($M_S = 6.5$) occurred at the contact between the Southern Alps and the Friuli Plain of Quaternary sediments. The focal depth of this event has been established as at about 9 km (ISC, NEIC and CSEM bulletins; Cipar, 1980). For the fault plane parameters, most authors agree on a thrust-fault mechanism with a compressive axis oriented in a NNW–SSE direction (Console, 1976; Ebblin, 1976; Mueller, 1977; Cipar, 1980; Lyon-Caen, 1980; Stoll, 1980; Zonno

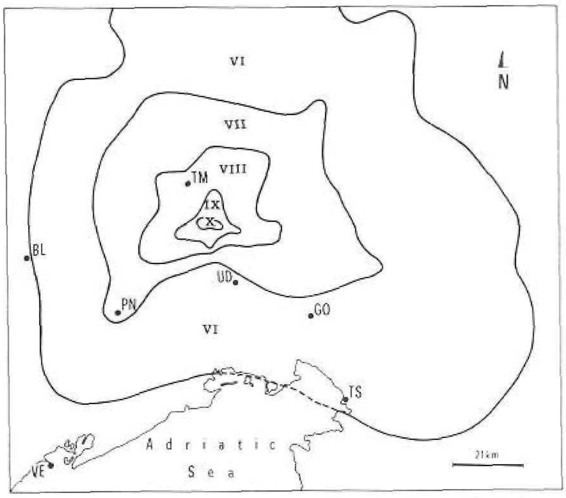

Fig. 12. Observed isoseismals of the May 6, 1976 Friuli earthquake, MSK scale (after Giorgetti, 1976). *VE* = Venezia; *BL* = Belluno; *PN* = Pordenone; *TM* = Tolmezzo; *UD* = Udine; *GO* = Gorizia; *TS* = Trieste.

and Kind, 1984; Barbano et al., 1985). The structural model used to compute the synthetic isoseismals, shown in Fig. 2(a), is taken from Suhadolc et al. (1988b). They have shown that even by keeping the focal depth fixed, the synthetic isoseismals may be very different, when varying the fault parameters in the range allowed by the

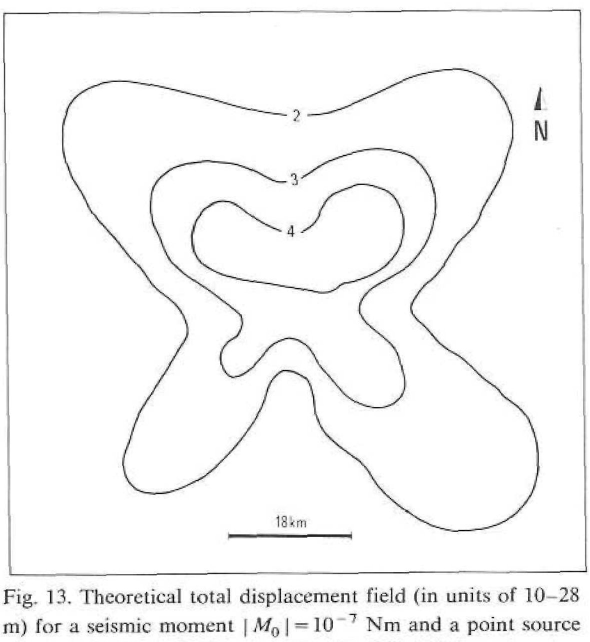

Fig. 13. Theoretical total displacement field (in units of 10–28 m) for a seismic moment $|M_0| = 10^{-7}$ Nm and a point source at 7 km depth modelling the May 6, 1976 Friuli earthquake. Source and structural parameters in Table 1 and in Fig. 2(a).

fault-plane solutions. For example, the isoseismals computed with the parameters: strike 225°, dip 10°, rake 60° (Mueller, 1977), are characterized by a two-lobed pattern, in total disagreement with the observed isoseismals (Fig. 12). Variations of the strike and rake, keeping the NNW–SSE orientation of the axis of maximum compression and the dip at 10°, do not produce satisfactory results. Increasing the dip to 30°, on the other hand, allows the generation of isoseismals which have a four-lobed pattern. At this stage an increase of the strike leads to a satisfactory agreement between the observed and the theoretical (Fig. 13) isoseismals. The lobes in the SE and SW direction, the strong intensity attenuation towards the south and the absence of nodes in the northern part have been successfully reproduced synthetically. The fault-plane parameters used to construct Fig. 13, reported in Table 1, are in excellent agreement with the ones proposed by Cipar (1981) on the basis of teleseismic data.

Application to historical events

The isoseismals of the July–September 1627 earthquake in Northern Capitanata (southeastern Italy) are shown in Fig. 14. Their symmetrical shape resembles one of those obtained in the case of the elementary moment tensors (mechanism C of Fig. 1(b)). In fact, if one computes the isoseismals of a pure thrust event 15 km deep, having

Fig. 14. Observed isoseismals of the July–September 1627 Northern Capitanata (Southern Italy) earthquake (after CNR, 1985).

a strike of 310° and a dip of 45° (Fig. 15), the accord with the data is very good. As a first approximation, the structural model used in the computation has been assumed to be that adopted for the modelling of the 1980 Irpinia earthquake (Fig. 2b). On the basis of this, one can associate the 1627 event in Capitanata with dip-slip faults in the region (Ciaranfi et al., 1983) and not with strike-slip faults evidenced in the Gargano area (Finetti, 1981). The shape of the isoseismals does not change significantly if the focal depth is brought to 20 km.

This example shows how powerful the macroseismic information of historical events can be for retrieving a possible fault-plane solution. The method in its present state does not allow a systematic inversion. However, once a good accord has been obtained between observed and synthetic isoseismals by the direct approach, the fault-plane solution obtained allows the use of historical data in seismotectonic studies. If different historical events with similar isoseismals occurred in the same region, it is reasonable to infer not only similar rupturing mechanisms, but also comparable focal depths. This seems to be the case in the September 8, 1694 Campania Lucania earthquake,

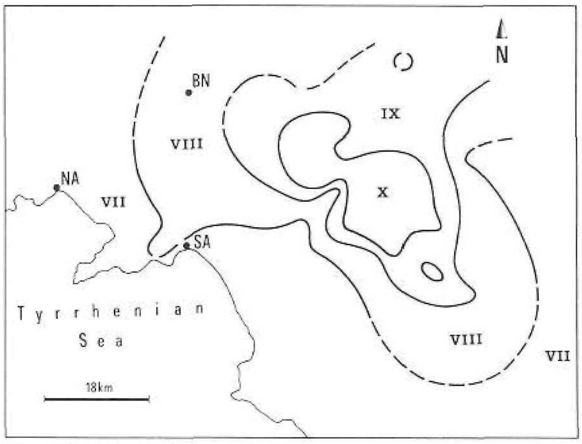

Fig. 16. Observed isoseismals of the September 8, 1694 Campania–Lucania (Southern Italy) earthquake (after CNR, 1985).

whose isoseismal shape (Fig. 16) closely resembles that of the 1980 Irpinia event (Fig. 6).

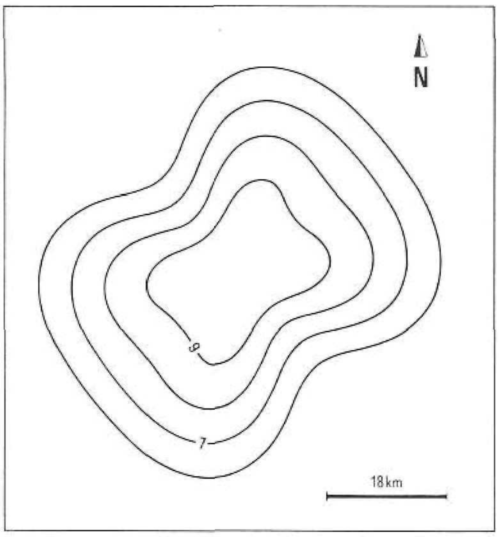

Fig. 15. Theoretical total displacement field (in units of 10^{-29} m) for a seismic moment $|M_0| = 10^{-7}$ Nm and a point source at 20 km depth modelling the July–September 1627 Northern Capitanata (Southern Italy) earthquake. Source and structural parameters in Table 1 and in Fig. 2(b).

Conclusions

The method proposed by Panza and Cuscito (1982) and Suhadolc et al. (1988a) has been used to reproduce the main features of the observed isoseismals of several earthquakes. Since laterally homogeneous structures are used in the modelling, the main conclusion that can be drawn is that some relevant features of the observed isoseismals are due only to the radiation pattern in the time domain of the earthquake source. Our results appear to be very sensitive to the source depth when the structural model contains a relevant sedimentary cover. Nevertheless, as already shown by Panza and Cuscito (1982), it can be said that the main difference between the theoretical and observed isoseismals can be reasonably associated with local effects and not with large-scale lateral variations. The influence of the fault-plane parameters and, in particular, of the focal depth has to be removed, if macroseismic data are to be used for the definition of attenuation laws and local responses to seismic shaking.

To apply this method, it is essential to use the original data on the spatial distribution of the macroseismic intensities; or at least, the isoseismals used in the comparison with the synthetic ones should not be smoothed, since this operation might significantly alter the information contained in the original data.

The method can be applied to the study of historical earthquakes in order to find their possible fault-plane solutions. The information obtained in such a way can be extremely helpful in the study and mitigation of seismic risk, and in understanding the tectonic setting of a region, allowing the use of historical data for seismotectonic studies and not just for the definition of seismicity. The possibility offered by the use of synthetic isoseismals strongly requires the definition of an as yet lacking, commonly accepted procedure with which to define seismic intensity on the basis of historical documents (e.g., Gutdeutsch et al., 1987).

The method described in this paper seems to be well suited to the analysis of historical events. In Southern Italy, the isoseismal shape of the 1627 Northern Capitanata earthquake allows this event to be associated with dip-slip and not transcurrent faults in the area. It has been also shown that the macroseismic fields of the 1694, 1962 and 1980 Irpinia events are consistent with a similar fault mechanism. Moreover the different isoseismal shape of the 1962 event can be explained by a source deeper (more than about 12 km) than those of the other two events.

From the values of displacement which characterize the isoseismal lines, and the seismic moment of the different earthquakes determined by various authors, or deduced for historical earthquakes by empirical relations (Karnik, 1969; Caputo and Console, 1980), it is possible to estimate, using the point source approximation, the ground motion displacement in relation to single intensity values. With an intensity of VII, displacements of the order of 0.5 cm can be associated, and with an intensity of VIII, displacements of the order of 2 cm. Finally, intensities IX and X seem to be characterized by displacements as large as 5 cm and 10 cm, respectively.

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