ANNALI DI GEOFISICA, VOL. XXXVI, N. 1, April 1993

Teleseismic observation of the November 23 1980, Irpinia earthquake

Domenico Giardini
Istituto Nazionale di Geofisica, Roma, Italia

Abstract
We review twelve years of source studies of the November 23 1980, Irpinia earthquake based on teleseismic data. Seismic data recorded at teleseismic distance for the Irpinia earthquake include a) polarities and amplitudes of first arrivals, b) digitized WWSSN records and c) digital GDSN waveforms. We review results and methods produced in ten years of research using analog and digital data and we present original modelling of long-period waveforms, to provide a description of the seismic source for these complex events. Different teleseismic datasets are in good agreement in providing a consistent image of the source structure comparing favourably with the higher definition reached by studies of local data. The November 23, 1980 event, as seen at teleseismic distances, was characterized by: a) a seismic moment of $(2.6 \pm 0.2) \times 10^{19}$ Nm, b) a source time function composed by a main shock followed by two smaller rupture episodes at about 18 and 38 seconds, with moment release distributed in the three episodes in percentages of approximately 60%, 25% and 15%, c) the depth of largest moment release is in the $(8 \div 13)$ km range, d) a focal mechanism with one fault plane dipping to NE (striking $(305 \div 330)°$ with an angle of $(53 \div 63)°$ and an almost pure dip-slip dislocation.

1. Introduction

The November 23 1980, Irpinia earthquake occurred at a turning point in modern seismology: the transition from analog to digital recording. The availability of data covering the whole seismic spectrum, recorded at teleseismic, regional and local distances, on analog and digital media, has made the 1980 Irpinia earthquake a test event to evaluate new algorithms, explore the resolution of different types of data and compare local and teleseismic analyses. The focus of this contribution is a comparative summary of the results obtained in twelve years of research using teleseismic data and an attempt to provide a homogeneous description of the November 23 1980 event, viewed at teleseismic distances.

The last twelve years have seen the deployment of digital seismic networks, the development of new methods of analysis and henceforth a better understanding of the seismic source. The first digital instruments were installed starting in 1977 as part of the IDA and GDSN networks, to improve and eventually replace the global existing distribution of high-quality, analog sensors WWSSN. The advent of broad-band regional digital networks is changing today the real-time investigation of significant earthquakes; in 1980 only a handful of digital stations were equipped with both short- and long-period channels, to be used in reconstructing the ground shaking over a broad range of frequencies. The source studies of the 1980 Irpinia earthquake reflect both the status of instrumental recording in 1980 and the methodological developments in the last decade.

It should be remarked that seismic waves at different frequencies view the seismic source in rather different ways. Arrival times measured on short-period traces image only the onset of the rupture, both in terms of location and geometry, which can be quite unrelated to the overall mechanism of a complex event, whereas seismic waves with periods longer than the event duration see the seismic source as an impulse and provide a global description of the whole source mechanism, bearing an easy interpretation only when the moment release maintains a constant fault geometry. Caution should be used in comparing results obtained at different frequencies, especially in the case of a complex event like the 1980 Irpinia earthquake. Indeed, all seismological efforts to parametrize the earthquake through one single parameter assume some characteristic spectral scaling law; in this case the scaling will not hold, leading to inconsistencies among parameters measuring different portions of the seismic spectrum and setting a true test for algorithms and methods.

2. Teleseismic observations in 1980

In 1980 teleseismic observations consisted of:

– arrival times, polarities and amplitudes of phases, mostly *P*, measured on analog instruments at short and long period and used for hypocentral location and determination of focal mechanism and magnitude;
– whole waveforms, including body and surface waves, recorded digitally or digitized from analog records; depending on the frequency range involved, they were used for moment tensor studies and to image the distribution of the seismic-source distribution in time and space.

Here we review the results according to the teleseismic data used (first arrivals, long-period waveforms, broad-band waveforms) and we derive original results to reduce the seismic-moment uncertainty. A summary of the focal mechanisms and source parameters published in the literature and obtained in this study is presented in fig. 1; for each solution we list the geometry of the fault plane, the seismic moment, the publication reference and the type of data used.

It is impossible, today as in 1980, to obtain a rapid and reliable characterization of a complex source process from analog records, since complete data from international agencies (ISC, NEIC, EMSC) will take months or years to become available and the process of collecting and digitizing WSSN records is even more lengthy; focal parameters for the Irpinia event, derived from the analysis of analog data, were published within a few years after the event (cf. fig. 1). Waveform modelling was a novelty in 1980 and has since evolved to the real-time routine procedure of today; new analyses of the 1980 Irpinia earthquake have been published over the last twelve years, following the development of more sophisticated modelling algorithms.

3. Focal mechanisms

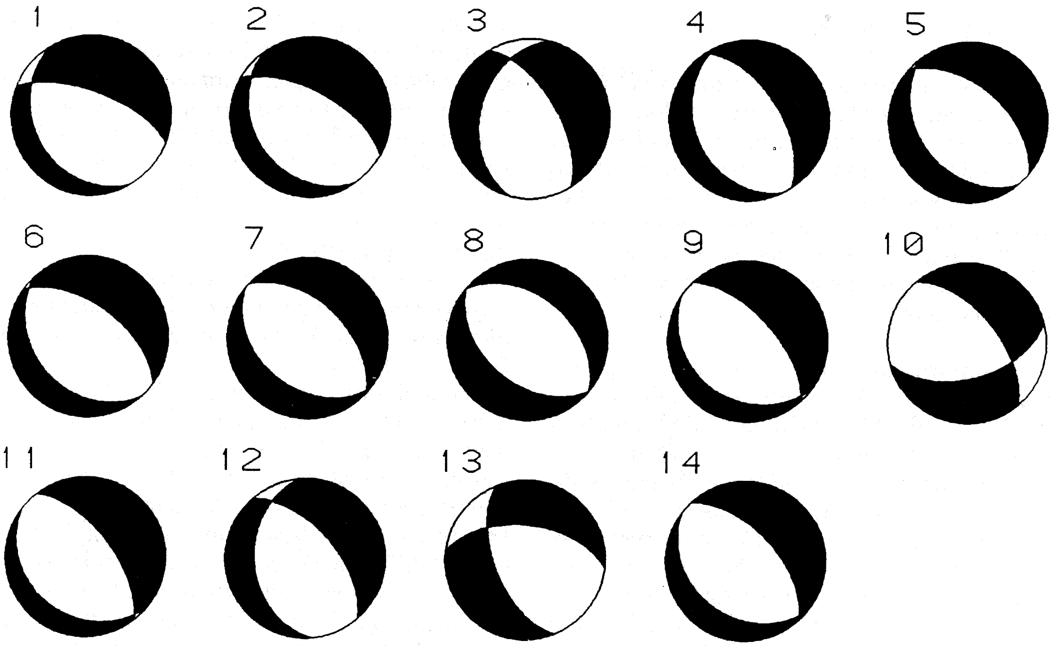
Focal mechanisms of the 1980 Irpinia earthquake have been obtained using:

1) polarities of *P*-waves measured on short-period instruments and reported by international agencies like the ISC (Gruppo di lavoro sismometria terremoto del 23.11.1980, 1981; Gasparini *et al.*, 1982, 1985; Del Pezzo *et al.*, 1983; Martini and Scarpa, 1983);
2) selected polarities from long-period WWSSN microfiches (Deschamps and King, 1983; Nakanishi and Kanamori, 1984; Westaway and Jackson, 1987).

While the WWSSN long-period readings were found to be very consistent, the ISC Bulletin data contain more than 30% of wrong polarity readings; a solution derived from selected ING and ISC Bulletin data (n. 3 in fig. 1) produces a focal mechanism similar but slightly rotated with respect to published solutions (n. 1-2). There is good agreement among focal mechanisms obtained from polarities (fig. 1; n. 1-3) and from combinations of polarities and other data (n. 9-10, 14). A noticeable exception is the mechanism of Deschamps and King (1983, 1984), characterized by a large trascurrent component; widely referenced in the literature, it relied on some key polarities later shown to be erroneous (Westaway and Jackson, 1987).

4. Magnitude

Estimates of magnitude for the 1980 Irpinia earthquake were issued by several observatories and international seismological agencies: among these, $m_b = 6.0$ and $M_S = 6.9$ (NEIC), $M_L = 6.5$ (ING), $M_L = 6.9$ (EMSC), $m_b = 6.0$ and $M_S = 6.8$ (ISC).



N	Fault plane		M_0 (10^{19} Nm)	Reference source	METHOD
	strike	*dip*			
1	290°	66°	–	Gruppo di lavoro Irpinia, 1981	Polarities
2	298°	64°	–	Gasparini *et al.*, 1982	Polarities
”	”	”	–	Del Pezzo *et al.*, 1983	Polarities
”	”	”	–	Martini e Scarpa, 1983	Polarities
”	”	”	–	Gasparini *et al.*, 1985	Polarities
3	328°	62°	–	this study	Polarities
4	328°	57°	3.0	Boschi *et al.*, 1981	CMT
5	310°	54°	2.4	Giardini *et al.*, 1984	CMT
6	305°	58°	2.4	Ekström *et al.*, 1987	CMT
7	312°	53°	2.7	Westaway and Jackson, 1987	CMT
8	309°	45°	2.8	Kanamori and Given, 1982	Surface waves
9	317°	63°	2.6	Nakanishi and Kanamori, 1984	Surface waves
10	320°	60°	2.0	Deschamps and King, 1983	Surface waves
11	317°	63°	2.6	this study	Surface waves
12	322°	63°	6-10	Brustle and Müller, 1983	Love waves
13	276°	54°	1.3	Sipkin, 1987	Body waves
14	317°	59°	2.1	Westaway and Jackson, 1987	Body waves

Fig. 1. Summary of focal mechanisms of the November 23 1980, Irpinia earthquake obtained from teleseismic observations. For each solution we list the fault plane, identified by independent evidence, the seismic moment, the publication reference and the data used or method of analysis. Solutions n. 1-3 were obtained by polarity data, n. 4-13 by inversion of long-period data and n. 14 by modelling body waves; n.9-10 and n. 14 also used polarities. Solution n. 2 is found in four sources in the literature. Solutions n. 3 and n. 11 were obtained in this study by direct inversion of raw ING-ISC polarity data (n. 3) and by modelling of surface waves (n. 11).

5. Long-period waveforms

A first indication of the complexity of the Irpinia event was inferred by the very long source duration (> 30 s) obtained in studies of surface wave and long-period body waves and confirmed by local registrations; conversely, only studies employing waves with periods much longer than 30-40 seconds see the source as impulsive.

Estimates of the moment tensor were obtained by inversion of:

1) surface waves (135-180 s) and long-period body waves (45-60 s), in different applications of the CMT method incorporating GDSN and IDA digital data (Boschi *et al.*, 1981; Giardini *et al.*, 1984; Ekström *et al.*, 1987) and WWSSN digitized data (Westaway and Jackson, 1987);

2) monochromatic (256 s) surface waves; in a first application the mechanism was constrained to be a pure normal fault, with a 45° dipping plane (Kanamori and Given, 1982); a second mechanism was obtained also with polarities of first arrivals (Nakanishi and Kanamori, 1984);

3) long-period body and surface waves (120-200 s) (this study);

4) regional Love waves (Brustle and Müller, 1983);

5) body waves (30-50 s) (Sipkin, 1987).

With few exceptions, the estimates of fault geometry and seismic moment are in good agreement (fig. 1; n. 4-13); the dip of one focal plane – identified to be the fault plane by the aftershock distribution – is in the $(53 \div 63)^\circ$ range and the strike in the $(305 \div 330)^\circ$ range; a seismic moment of $(2.4 \div 3.0) \times 10^{19}$ Nm is consistent with the majority of the results. The two estimates in obvious disagreement are flawed by procedural faults: the small moment of Sipkin (1987; $M_0 = 1.3 \times 10^{19}$ Nm) was produced by the inversion of waves with periods comparable with the source duration, while the calibration of regional Love waves is a procedure very sensitive to the structural model, and produces in this case a far too large seismic moment ($M_0 = (6 \div 10) \times 10^{19}$ Nm; Brustle and Müller, 1983).

We invert long-period body and surface waves to reduce the uncertainty on the seismic moment. We model 22 traces for 8 GDSN stations, all characterized by excellent signal-to-noise ratios and simple, uncontaminated surface-wave trains; we use six hours of data for each trace, including 3 or 4 consecutive orbits of Rayleigh and Love waves, filtered at periods longer than 100 seconds. Inversion for the six elements of the moment tensor is performed in a narrow frequency band ($(6 \div 8)$ mHz); the algorithm used is based on the generation of complete synthetic seismograms by summation of normal modes (details of the method are found in Giardini and Beranzoli, 1992).

Examples of waveform modelling are shown in fig. 2, in time and frequency domain. Data are well reproduced in amplitude and phase with a seismic moment of 2.6×10^{19} Nm; the best double-couple solution is shown in fig. 1 (n. 11). In agreement with these results, a re-examination of the CMT waveform fitting of Giardini *et al.* (1984) shows that, although the synthetic traces provided a good fit to the data, the predicted amplitude was somewhat smaller than the observed one, indicating that the seismic-moment value of 2.4×10^{19} Nm, obtained there, was sligthly underestimated.

For the Irpinia event the uncertainty on the seismic moment can be sensibly reduced, taking into account the good independent control on the source geometry provided by the aftershock distribution, the inversion of geodetic data and the geological evidence.

If we constrain the source geometry and measure the variance reduction obtained by different values of the seismic moment, we effectively evaluate the uncertainty associated with the seismic moment; in fig. 3 we plot as a function of seismic moment the variance achieved by different moment tensor solutions proportional to the preferred solution obtained from the inversion of long-period waveforms (n. 11 in fig. 1); the seismic moment is estimated to be $M_0 = (2.6 \pm 0.2) \times 10^{19}$ Nm. This value is not affected by the relatively small uncertainty in focal geometry (cf. fig. 1).

6. Broad-band waveforms

We seek to image the slip distribution in space

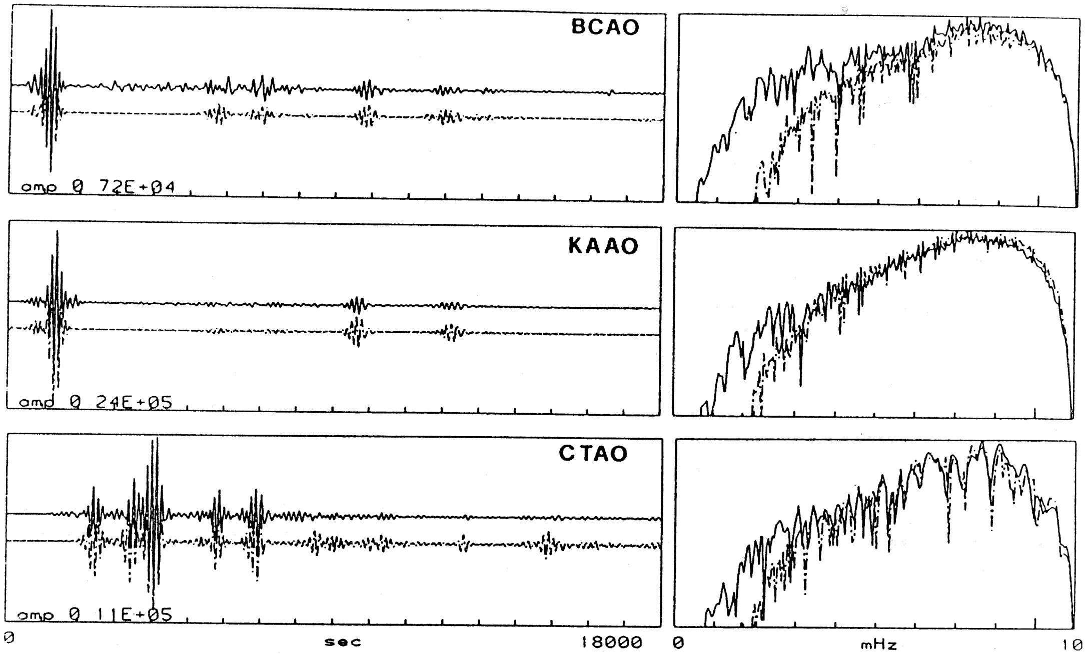


Fig. 2. Modelling of long-period waveforms for the inversion of the moment tensor. Three traces out of 22 used in the inversion are shown for GDSN stations BCAO (Central Africa), KAAO (Afghanistan) and CTAO (Australia). Time traces are in the left panels (amplitudes are in counts); the corresponding frequency spectra are on the right (data traces are above, synthetic seismograms below). 6 hours of long-period record are selected for each station, filtered at periods longer than 100 s. The frequency window used in the inversion is between 6 and 8 mHz.

and time; the analysis of teleseismic body waves, with characteristic periods of a few seconds, allows the determination of important properties of the seismic source through the deconvolution of *P* and *S* displacement pulses (*e.g.*, Ekström, 1989); more details on the seismic source would be obtained by inclusion of high-frequency data recorded at local distances.

The teleseismic data available to model the source of the November 23 1980, event are: i) digitized long-period records of about 20 WWSSN stations, with a frequency content extending to periods of a few seconds, and ii) broad-band displacement reconstructed from deconvolved short- and long-period channels from 4 GDSN stations. In fact, because of hardware limitations the first generation of digital instruments recorded band-passed signal and the analysis of broad-band displacement had to be performed through digital reconstruction. Figure 4 displays the characteristic instrument responses for a) an analog WWSSN, b) the SP-SRO sensor of the GDSN and c) the LP-SRO instrument; an example of reconstruction of the vertical broad-band *P*-wave displacement pulse, by deconvolution of *SP* and *LP* channels, is shown in fig. 5 for station ANMO.

The characteristic source time function of the Irpinia event is composed by three episodes, at distances of approximately 18 and 38 seconds, of decreasing amplitude, as it has been derived both through forward modelling of long-period body waves (Westaway and Jackson, 1987) and from inversion of broad-band displacement (Palombo *et al.*, 1989). Figure 6 compares the source time functions obtained by the different methods; the solutions are very similar and apparent discrepancies among different results reflect methodological differences. The algorithm of Bezzeghoud (1987) does not enforce a positivity con-

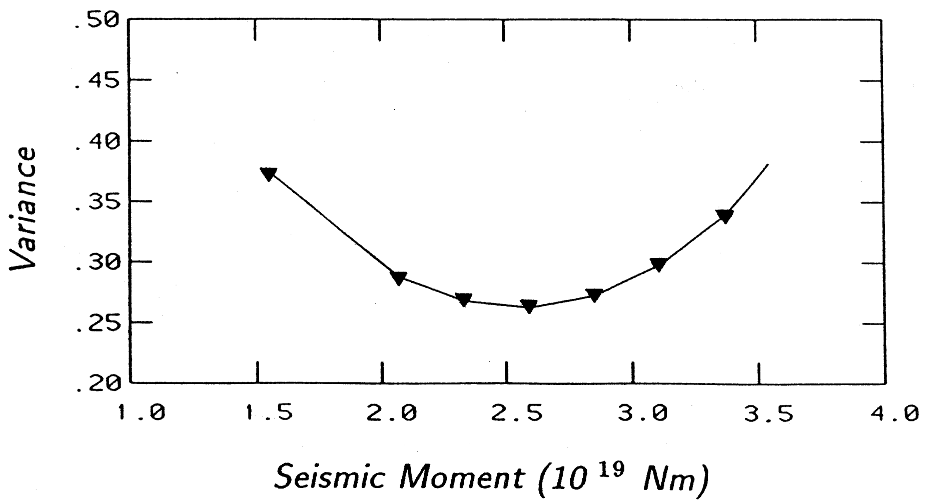


Fig. 3. Normalized variance (defined as the ratio of the variance to the norm of the data vector) obtained by different moment tensor solutions proportional to the preferred solution retrieved by inversion of long-period body and surface waves (n. 11 in fig. 1). The seismic moment is estimated to be $M_0 = (2.6 \pm 0.2) \times 10^{19}$ Nm.

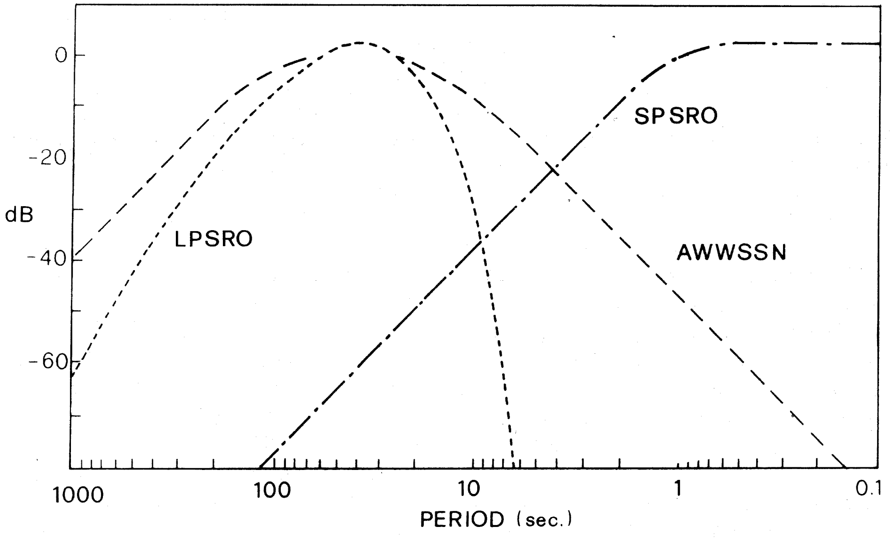


Fig. 4. Intrument response in velocity for a) an analog WWSSN, b) the SP-SRO sensor of the GDSN and c) the LP-SRO instrument. A normalized logarithmic dB scale is used.

straint and the resulting source time function (fig. 6a)) shows also episodes of negative moment release; by subtracting a curved negative baseline we obtain the same shape of Palombo *et al.* (1989; fig. 6b)). The solution by Westaway and Jackson (1987; fig. 6c)) is obtained by forward modelling and is more episodic; the first four pulses of the source time function, however, combine to reproduce quite precisely the shape of the first main episode in the other two studies.

The waveform modelling and the source time function obtained by Palombo *et al.* (1989) are shown in fig. 7, with the location on the focal mechanism of the stations used in the inversion

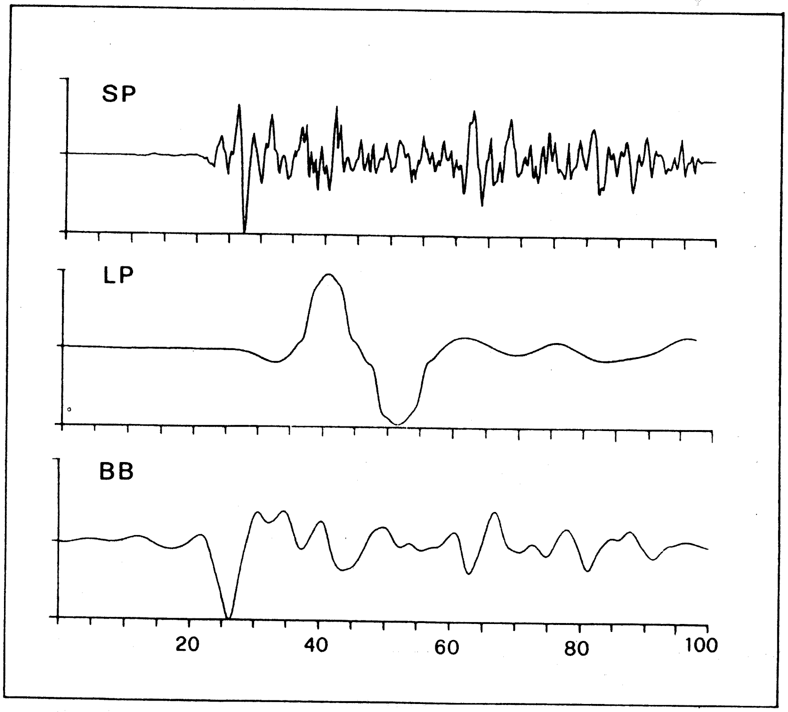


Fig. 5. Reconstruction of broad-band P displacement pulse (BB) at GDSN station ANMO by deconvolution of SP and LP channels. Vertical scales are equalized.

and the fit between broad-band P pulses and synthetics. This analysis constrains the depth of the main shock to $(8 \div 13)$ km; inversions performed at different depths consistently show that the source time function degrades at depths exceeding 15 km, setting a lower limit for the release of seismic moment.

The estimate of seismic moment derived by broad-band modelling of GDSN records is $M_0 = 2.4 \times 10^{19}$ Nm (fig. 7), consistent with the estimates from surface waves (cf. fig. 1), while the seismic moment obtained by WWSSN waves is somewhat smaller ($M_0 = 2.1 \times 10^{19}$ Nm; Westaway and Jackson, 1987; n. 14 in fig. 1). As shown by all models in fig. 6, the seismic-moment release is distributed in percentages of approximately 60%, 25% and 15% among the three main episodes.

Attempts have been made to exploit the resolution of teleseismic waveform modelling to resolve the finer structure of the first subevent and to discriminate different fault geometries for the three main episodes (Westaway and Jackson, 1987); however, the stability of these results needs further validation.

7. Conclusions

The quality of the teleseismic analyses of the November 23 1980, Irpinia earthquake is almost unmatched for any modern earthquake, owing to the availability of analog and digital data of good quality and to the application of different algorithms. Descriptions of the seismic source obtained with different teleseismic data are in good agreement, leaving few doubts on the source structure as seen at teleseismic distances and comparing favourably with the definition reached by studies of local data.

The principal source parameters are:

– the seismic moment is $(2.6 \pm 0.2) \times 10^{19}$ Nm,

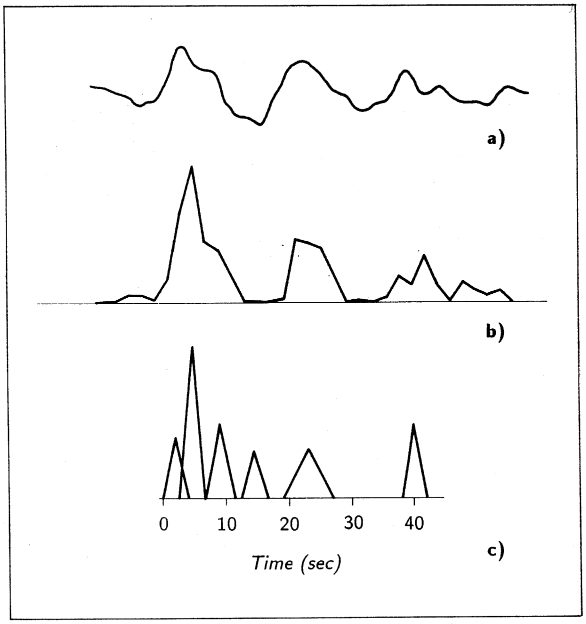


Fig. 6. Source time functions obtained by a) Bezzeghoud (1987), b) Palombo *et al.* (1989) and c) Westaway and Jackson (1987). Vertical scales are equalized.

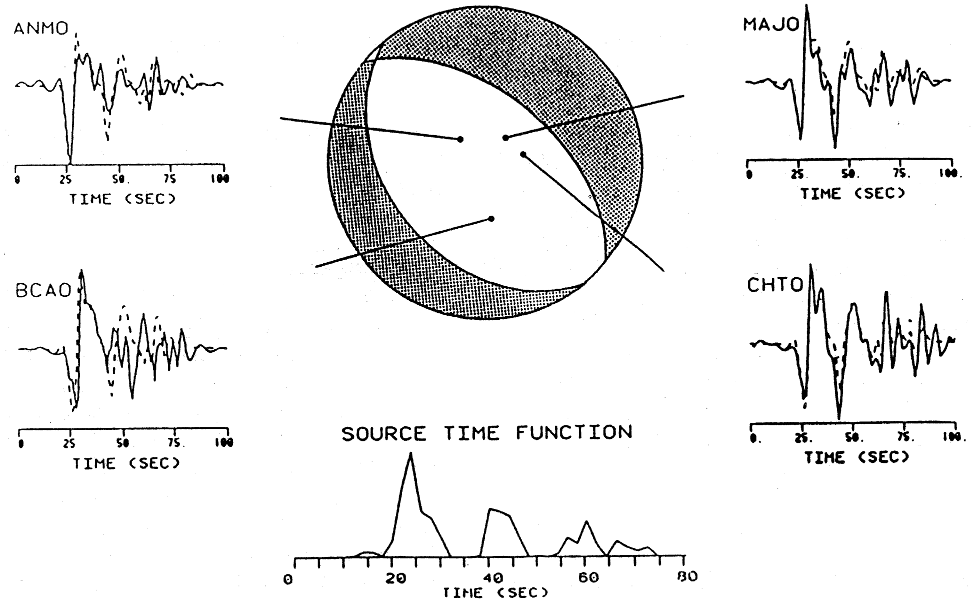


Fig. 7. Source time function obtained by Palombo *et al.* (1989) from broad-band *P*-wave displacement, reconstructed from deconvolved *SP* and *LP* vertical records of stations ANMO, BCAO, MAJO and CHTO. The focal mechanism is also shown, with the location on the focal sphere of the stations used in the inversion. The source time function exhibits the characteristic three episodes of decreasing amplitude; the total seismic moment is 2.4 × 10^{19} Nm.

– the source time function shows three main episodes at distances of about 18 and 38 seconds; moment release is distributed in the three episodes in percentages of approximately 60%, 25% and 15%,

– the depth of largest moment release is in the (8÷13) km range,

– the focal mechanism has one plane dipping (53÷63)° and striking (305÷330)°, with an almost pure dip-slip motion.

It is encouraging to know that the results obtained in twelve years of teleseismic analyses can now be retrieved in real time with the new telemetered broad-band stations, and that the Irpinia earthquake has contributed to set the new standards of seismology.

Acknowledgements

I am grateful to Prof. E. Boschi for his continuous encouragement and support. I thank D. Riposati for helping with the figures.

REFERENCES

BEZZEGHOUD, M. (1987): Inversion et analyse spectrale des ondes *P*, Thèse de Doctorat, Université de Paris VII.

BOSCHI, E., F. MULARGIA, E. MANTOVANI, M. BONAFEDE, A.M. DZIEWONSKI and J.H. WOODHOUSE (1981): The Irpinia earthquake of November 23, 1980, *EOS Transactions A.G.U.*, **62**, 330.

BRUSTLE, W. and G. MÜLLER (1983): Moment and duration of shallow earthquakes from Love-wave modeling for regional distances, *Phys. Earth Planet. Inter.*, **32**, 312-324.

DEL PEZZO, E., G. IANNACCONE, M. MARTINI and R. SCARPA (1983): The 23 November 1980 Southern Italy earthquake, *Bull. Seismol. Soc. Am.*, **73**, 187-200.

DESCHAMPS, A. and G.C.P. KING (1983): The Campania-Lucania (Southern Italy) earthquake of November 23, 1980, *Earth Planet. Sci. Lett.*, **62**, 296-304.

DESCHAMPS, A. and G.C.P. KING (1984): Aftershocks of the Campania-Lucania (Italy) earthquake of 23 November 1980, *Bull. Seismol. Soc. Am.*, **74**, 2483-2517.

EKSTRÖM, G. (1989): A very broad band inversion method for the recovery of earthquake source parameters, *Tectonophysics*, **166**, 73-100.

EKSTRÖM, G., A.M. DZIEWONSKI and J.H. WOODHOUSE (1987): Centroid-moment tensor solutions for the 51 IASPEI selected earthquakes, 1980-1984, *Phys. Earth Planet. Inter.*, **47**, 62-66.

GASPARINI, C., G. IANNACCONE, P. SCANDONE and R. SCARPA (1982): Seismotectonics of the Calabrian arc, *Tectonophysics*, **84**, 267-286.

GASPARINI, C., G. IANNACCONE and R. SCARPA (1985): Fault-plane solutions and seismicity of the Italian peninsula, *Tectonophysics*, **117**, 59-78.

GIARDINI, D. and L. BERANZOLI (1992): Waveform modelling of the May 20, 1990 Sudan earthquake, *Tectonophysics*, **209**, 105-114.

GIARDINI, D., A.M. DZIEWONSKI, J.H. WOODHOUSE and E. BOSCHI (1984): Systematic analysis of the seismicity of the Mediterranean region using the centroid-moment tensor method, in *The O.G.S. Silver Anniversary Volume, Trieste, 1984*, edited by A. BRAMBATI and D. SLEJKO, pp. 121-142.

Gruppo di lavoro sismometria terremoto del 23.11.1980 (1981): Il terremoto campano del 23.11.1980: elaborazione dei dati sismometrici, *Rend. Soc. Geol. It.*, **4**, 427-450.

KANAMORI, H. and J.W. GIVEN (1982): Use of long-period surface waves for rapid determination of earthquake source parameters. 2. Preliminary determination of source mechanisms of large earthquakes ($M_S \geq 6.5$) in 1980, *Phys. Earth Planet. Inter.*, **30**, 260-268.

MARTINI, M. and R. SCARPA (1983): Earthquakes in Italy in the last century, in *Earthquakes, Observation, Theory and Interpretation*, edited by H. KANAMORI and E. BOSCHI, *LXXXV Corso, Varenna*, pp. 479-492.

NAKANISHI, I. and H. KANAMORI (1984): Source mechanisms of twenty-six large shallow earthquakes ($M_S \geq 6.5$) during 1980 from *P*-wave first motion and long-period Rayleigh wave data, *Bull. Seismol. Soc. Am.*, **74**, 805-818.

PALOMBO, B., L. BERANZOLI and D. GIARDINI (1989): Tecniche di inversione per i parametri della sorgente sismica da sismogrammi a larga banda, in *Atti VIII Convegno Annuale G.N.G.T.S., Roma* (in press).

SIPKIN, S. A. (1987): Moment tensor solutions estimated using optimal filter theory for 51 selected earthquakes, 1980-1984, *Phys. Earth Planet. Inter.*, **47**, 67-79.

WESTAWAY, R. and J. JACKSON (1987): The earthquake of 1980 November 23 in Campania-Basilicata (Southern Italy), *Geophys. J. R. Astron. Soc.*, **90**, 375-443.