

The Romanian Earthquake of August 30, 1986: A Study Based on GEOSCOPE Very Long-Period and Broadband Data

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Abstract—The Romanian earthquake of August 30, 1986 is the second largest intermediate depth event in this area since the worldwide deployment of digital instrumentation, and the first one since the installation of GEOSCOPE network. It offers the unique opportunity to document this well-known but poorly understood zone of deep continental seismicity using high quality teleseismic data in different frequency bands. The source is well constrained both from very-long period surface wave data observed on GEOSCOPE stations and, independently, from body wave modelling at various worldwide stations. The depth obtained is approximately 140 kilometers, the seismic moment, $0.8 \cdot 10^{27}$ dyne-cm and the mechanism from both data sets is very similar to that of the previous 1940 and 1977 Vrancea events, indicating that these events, although having occurred at noticeably different depths, are expressions of the same tectonic process. However, from the detailed study of the source using broadband data, it can be inferred that the source presents much less complexity than the 1977 event.

Key words: GEOSCOPE seismic data, Romania, focal mechanism, bodywave modelling, source process.

Introduction

On August 30, 1986 a magnitude $M_s \approx 6.9$ earthquake occurred at intermediate depth in the Southeast bend of the Carpathian arc. This region is well-known for its frequent intermediate depth seismic activity (CONSTANTINESCU *et al.*, 1966; TRIFU and ONCESCU, 1987) and, in fact, the Eastern Carpathians show many features of an island arc formed by the subduction of oceanic lithosphere in front of the Moldavian platform (BLEAHU *et al.*, 1973; RADULESCU and SANDULESCU, 1973). At present, this seismicity is however restricted to the Southeast corner of the arc, and why is this so is not yet fully understood. In the last fifty years, two other large shocks have occurred in this region, on November, 10, 1940 ($M_s \approx 7.4$) and on March 4, 1977 ($M_s \approx 7.6$) the famous Vrancea event which produced much damage in this area. The latter, as well as its aftershocks, have been extensively studied (e.g.,

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FUCHS *et al.*, 1979; MÜLLER *et al.*, 1978; TRIFU, 1981) and, in particular, it was found that the source was complex and consisted mainly of three shocks, the last of which was interpreted to be a stopping phase (MÜLLER *et al.*, 1978). This detailed study of the source was made possible by the availability of broadband digital data from the newly installed Graefenberg array in SW Germany (HARJES and SEIDL, 1978).

In the following study, we present briefly the major geologic and tectonic features of the Carpathian belt and the results of a study of the 1986 event, based mostly on presently available data from the GEOSCOPE network (ROMANOWICZ *et al.*, 1984), and compare them to those found for the 1977 Vrancea earthquake.

The Carpathian Arc

The Carpathian arc is one of the most striking features of the Alpine Chain. Located inside the Eurasian plate, there are some evidences that it was formed as the result of convergence of two intracontinental zones (RADULESCU and SANDULESCU, 1973). A geologic map is shown in Figure 1. In the outer part of the Carpathian arc, the Moldavian platform is considered to be the remanant continental part of a paleo plate whose oceanic lithosphere has been entirely subducted. In its inner part, the folded mountain arc has been created during the collision phase: the suture between the inner and the outer part of the arc is a defunct trench, mostly revealed by a strong negative Bouger anomaly (ROMAN, 1970). From this tectonic feature, towards the West, alkali-basaltic magmatic rocks constitute the last relics of Quaternary volcanism which was active during probable island arc formation; at the present time, it is completely extinct. Moreover, underneath the Transylvania and the Pannonian basins formed in the Upper Tertiary and Quaternary time respectively, positive Bouguer anomalies (ROMAN, 1970) and high average heat flow anomalies have been identified. These anomalies are, without any doubt, correlated with a thin substratum which is a consequence of crustal spreading due to the melting of part of the crust (BLEAHU *et al.*, 1973). In the West, the Pannonian basin, the larger of the two basins is attached to the Eurasian continent.

The presence of (1) a trench, (2) a folded arc, (3) a magmatic arc, (4) a retroarc basin and (5) a continental margin sequence, reinforces the idea that the Carpathians have similar geologic and tectonic setting as circum-Pacific island arcs. However, there is no visible evidence of an oceanic lithosphere, a typical feature of island arc assemblages, ahead of the Moldavian platform. Nevertheless, the presence of a paleoslab underneath the northern part of the Carpathians was proposed by BLEAHU *et al.* (1973), on the basis of K_2O/SiO_2 ratio analysis: they suggest the presence of a southward-dipping Wadati-Benioff plane at depths of about 135 km to 165 km. From a seismotectonic point of view, the active seismicity in the Vrancea region is

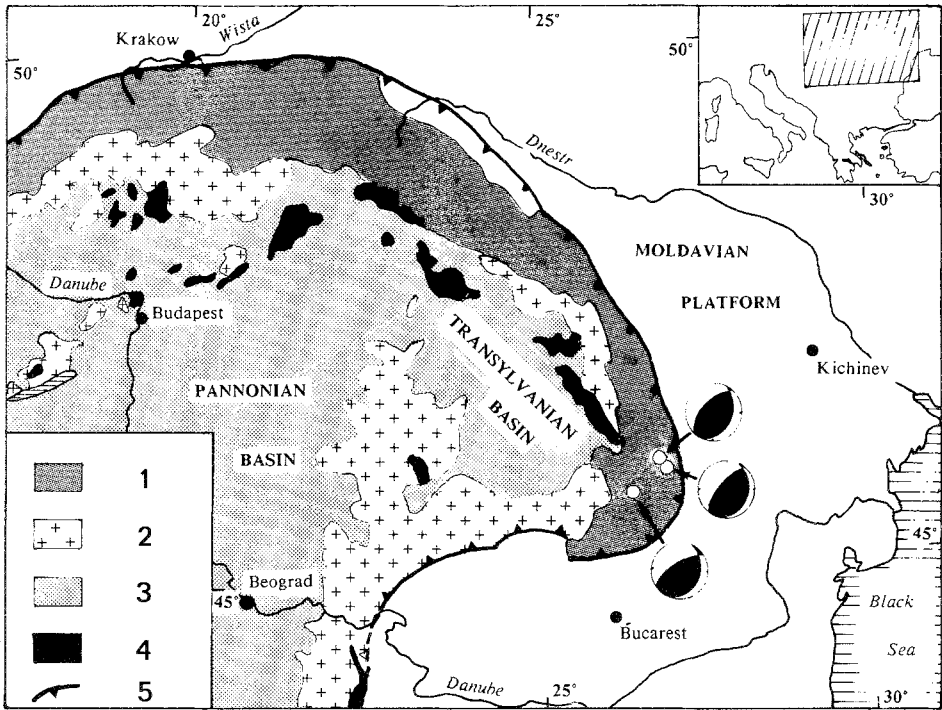


Figure 1

Geological sketch of the Carpathian arc from World Geological Atlas. 1 = folded arc, 2 = crystalline Mezozoic outcrops, 3 = Transcarpathian marginal basins, 4 = calc-alkaline magmatic arc, 5 = hypothetical arc trench limiting the inner from the outer part of the arc. Open circles are localization of 1940, 1977 and 1986 Romanian earthquakes with their respective focal mechanisms.

better correlated with a subducted plate, dipping towards the North-West. As we shall see below, the 1986 event confirms this last assumption.

Inversion of Mantle Wave Data

At the time of the 1986 event (Latitude = 45.55°N , longitude = 26.32°E , origin time = 21 h 28 mn 35.5 sec, NEIC), 14 GEOSCOPE stations were operational and recording continuously 3-component very-long period data at a rate of 0.1 sample per second. Five of those also had the capability to record broadband data at a rate of 5 sps.

We first determined centroidal source parameters using very-long period fundamental mode Rayleigh wave data at 9 selected GEOSCOPE stations (AGD, CAY, CRZ, KIP, PAF, PPT, RER, SCZ, WFM). The locations of these stations with respect to the epicenter are shown in Figure 2. The method is a two-step moment

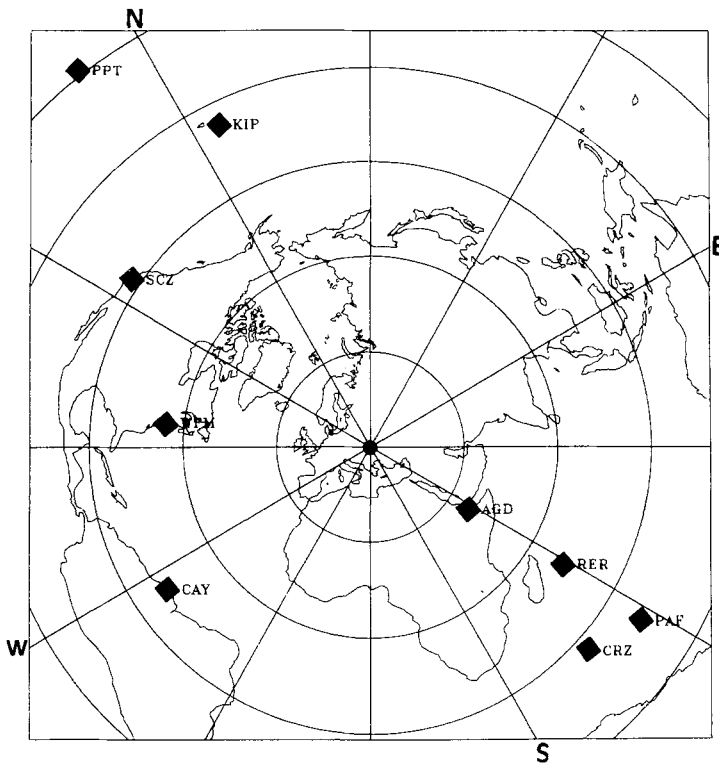


Figure 2

Distribution of GEOSCOPE stations used in a very-long period inversion for source parameters with respect to the epicenter.

tensor inversion in the frequency domain as proposed by ROMANOWICZ and GUILLEMANT (1984) and ROMANOWICZ and MONFRET (1986). In a first step, the source duration is determined with a directional part for sufficiently large enough earthquakes (MONFRET and ROMANOWICZ, 1986). In the second step, we determine centroidal depth and moment tensor. The Romanian earthquake is not large enough to generate a resolvable directivity effect on very-long period data, the source time determined therefore is a measure of the source process time.

Figure 3a shows the residuals versus half source time curves obtained for various earth models used for propagation corrections. Only first arriving trains R1 and R2 are considered (MONFRET and ROMANOWICZ, 1986) because, less perturbed than the other trains during propagation through the heterogeneous earth, they give more exact information concerning the source. In the second step, we determine the centroidal depth and moment tensor. The corresponding residuals versus depth curves are shown in Figure 3b. The results are summarized in Table 1. The centroidal depth agrees with that reported by NEIC (132 km) and places this event somewhat deeper but well aligned along the suspected subducted slab, with the Vancrea 1940 event ($h \approx 133$ km) and the 1977 one ($h \approx 100$ km).

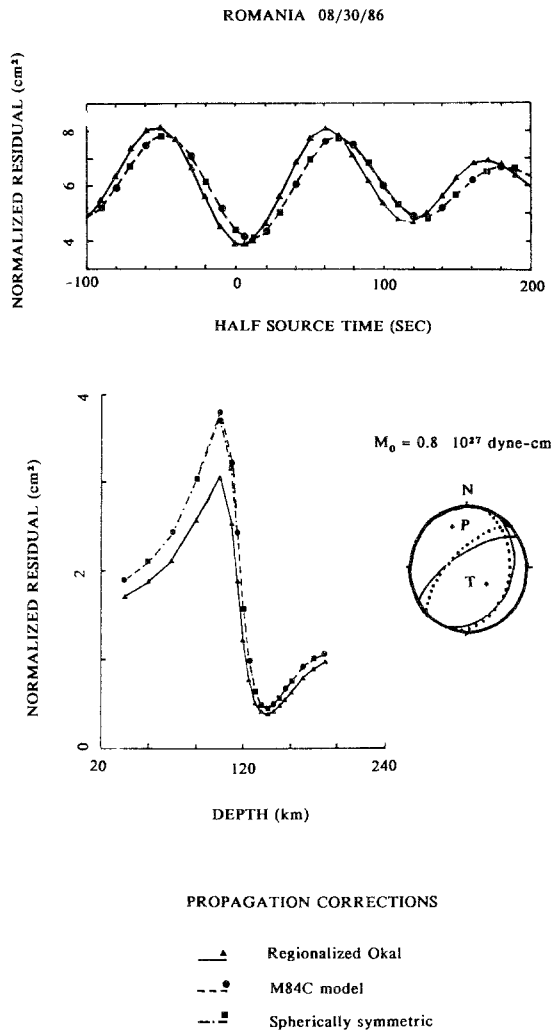


Figure 3

Rayleigh wave inversion based on 9 GEOSCOPE stations. At the top, normalized residuals versus half source time curves for several earth models giving a half source time of 10 sec from the Rayleigh waves moment tensor inversion (1st step). At the bottom, residuals versus depth curves and source mechanism and moment obtained in the second step of the inversion.

Figure 4 shows a SE-NW section of the seismicity ($3 < M_L < 5.5$) recorded in Vancrea region from October 1980 to September 1982 (ONCESCU, 1984), on which we have plotted the 1940, 1977 and 1986 main shocks. As we can observe, most of the earthquakes are located either near the surface or at intermediate depth. Most of those events seem to be distributed along the same planar body which is consistent with a descending slab, dipping towards the North-West. Moreover there appears a well defined gap between 50 km and 70 km of depth; this lack of

Table 1

Source parameters for the Romanian event of 08/30/1986 as determined by analysis of mantle wave and body wave data and compared to the 1940 and 1977 events

1986 event	Body waves	Mantle waves
Depth (km)	140	135–140
τ (sec)	4–6	≈ 10
M_0 (dyne-cm)	$0.6 \cdot 10^{27}$	$0.8 \cdot 10^{27}$
strike ($^\circ$)	225	226
dip ($^\circ$)	68	64
slip ($^\circ$)	105	107
	1940 event	1977 event
Depth (km)	133	100
strike ($^\circ$)	221	220
dip ($^\circ$)	51	69
slip ($^\circ$)	102	99

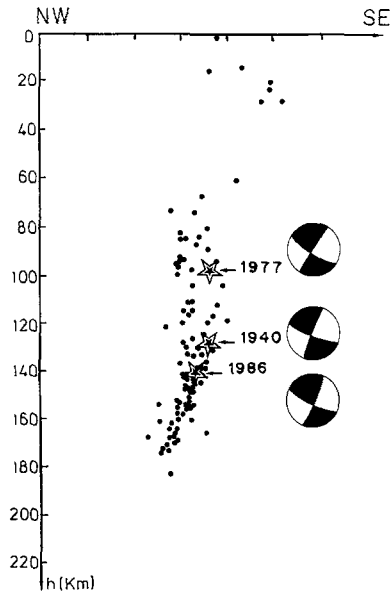


Figure 4

Projection of hypocenters on a SE-NW vertical plane (after ONESCU, 1984). Horizontal scale is the same as vertical one. Stars indicate the three major events which occurred in the area during the last forty years. The 1986 event is the deepest. Focal mechanism for the 1940 event is from CONSTANTINESCU *et al.* (1966), for the 1977 event from MÜLLER *et al.* (1978) and for the 1986 event from this study. The focal mechanisms are projected on the section plane.

seismicity could be connected with a shear between the shallow and deep part of the plate (FUCHS *et al.*, 1979; ROYDEN *et al.*, 1983) although this interpretation has recently been questioned (PURCARU and SPENCE, 1988). Focal mechanisms of the 1940, 1977 and 1986 main shocks (Figure 4), are very likely related to the same tectonic process, producing a very consistent mechanism. Therefore, there is some seismological evidence, confirmed by the 1986 event, towards the presence of a paleo-slab underneath the east corner of the Carpathian arc at depths greater than 50 km.

First Motion Data and P-Wave Modelling

Body wave data were available from WWSSN, GDSN, NARS and GEOSCOPE networks. The numerous and azimuthally well distributed first arrivals around the epicenter allowed us to determine an accurate focal mechanism, source depth as well as source time function, by waveform modelling of the three first body phases P , pP and sP .

The first motion P -wave data as well as results of modelling of the P -wave group for available vertical component records are shown in Figure 5 for long period stations and Figure 6 for broadband stations. On the broadband records (Figure 6) the three phases P , pP and sP are very well identified because of the intermediate focal depth ($h \simeq 140$ km) and the simple source time process. As the mean velocity model is well-known in this region, the source depth is well constrained at 140 km and confirms the result obtained at very long period. The others pulses observed on records from North American stations are mainly PcP , $pPcP$ and $sPcP$ phases.

Once focal depth determination has been completed, the waveform modelling was performed by classical trial and error procedure: source duration and focal mechanism were adjusted to fit the data. The NW dipping plane is very well constrained, in particular by first motions at North American stations (WFM, GEOSCOPE broadband record and RSNT, RSSD, RSON and RSNY, intermediate period records) and station FDF (Fort-de-France, Martinique, WWSSN response) but also by the pP polarity at WWSSN stations HKC and HYB (although P and sP phases are saturated) which happen to be on each side of the nodal plane for pP . The cluster of dilatations at smaller distances in the NW quadrant corresponds to European stations (mainly NARS stations, NOLET and VLAAR, 1982); the second cluster at larger distances corresponds to North American stations, which recorded clear nodal first arrivals. The SE dipping plane is not as well constrained from the amplitude ratio of P and pP . The best fitting source time function is a triangle of 6 seconds duration. The starting solution for the body wave modelling was that of the 1977 Vancrea event and the orientation of the nodal planes was modified to improve the fit. The moments obtained at each station (Figure 5) agree very well with the mantle wave results, as do the other source parameters, listed in Table 1,

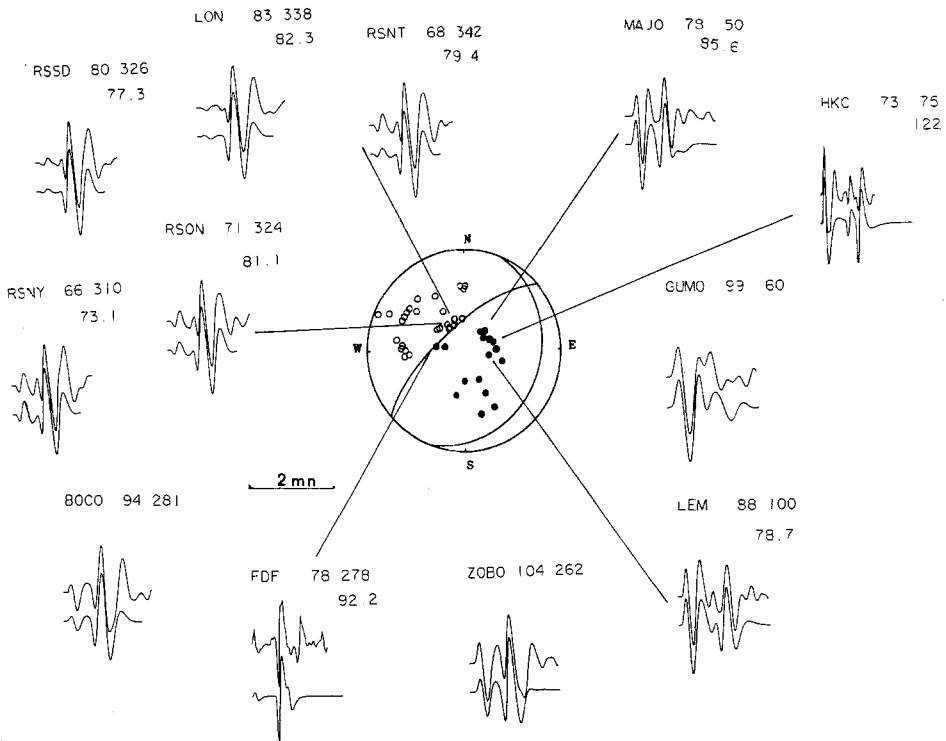


Figure 5

First motion data and *P*-wave modelling at several WWSSN and GDSN long period stations. Focal parameters used are listed in Table 1. Upper trace is the observed one. For each station, we give epicentral distance and azimuth in degrees and the estimate of seismic moment is in units of 10^{25} dyne-cm, and is given when direct *P*-wave is observed.

first indication of a rather simple source process. All this may explain why our solution, which is well constrained from the VLP data (to at most $\pm 5^\circ$ in each angle) is in good agreement with the CMT (Harvard) solution, which also uses surface wave data (among others), and less so with the PDE and moment tensor solutions of the USGS monthly bulletins (slip of about 70° instead of 105°), which rely only on body waves from a mediocre, station distribution. We note, in Figures 5 and 6, that, although the whole *P*-wave group is well modelled at most stations, we have not been able to model correctly the *sP* arrival time or amplitude at station RER (broadband record). We suggest that this may be due to either (and most probably) the important heterogeneity of structure near the source in the direction of the take-off angle of this phase, associated with the hypothetical subducted slab, or to a downward propagation of the rupture zone along the faulting plane. The orientation of the dipping plane defined by the seismicity suggests that the fault plane is the NW dipping one, for which parameters are given in Table 1.

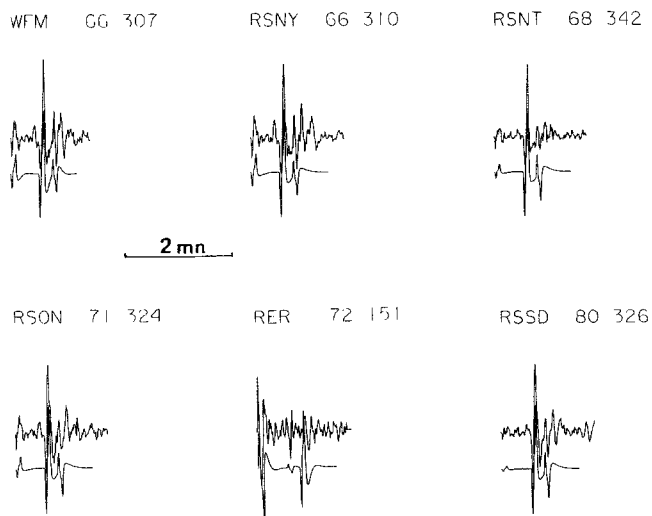


Figure 6

Modelling of some broadband and intermediate period *P*-wave records. Focal parameters are the same as in Figure 3. Epicentral distance and azimuth are given for each station.

Broadband GEOSCOPE Data: A More Detailed View of the Source

MÜLLER *et al.* (1978) have shown that broadband data are very useful for studying the different stages of the source process. For the 1977 event, they clearly displayed the subdivision of the main shock into three rupture phases. Figure 7 shows the vertical broadband records and associated *P*-wave spectra at 6 broadband stations located at the epicentral distances appropriate for this type of study: five of them are located in America and the other one RER, in La Réunion (Indian Ocean). All of these spectra are corrected for instrument response, attenuation and radiation of the dominant phase (i.e., *P* for RER and *pP* for North American stations). The corner frequency agrees well with a source duration of 5–10 seconds. The mean seismic moment is around $0.6 \cdot 10^{27}$ dyne-cm except for RER, where we have already pointed out an unexpected attenuation of the *sP* phase. This value is lower than the value determined by long period *P*-wave modelling; it could be explained by the approximation made on the radiation pattern.

We have inverted these records for the source time function using a deconvolution method presented in BEZZEGHOUD *et al.* (1986) adapted from that originally proposed by KIKUCHI and KANAMORI (1982). The observed seismogram is assumed to be a combination of elementary source impulses which occur at different delay times. The source time duration is the sum of these delays and the size of the impulses sketches the source shape.

As the three arrivals of the *P*-wave group are well separated, we can try to retrieve the source time function corresponding to each phase; each solution then

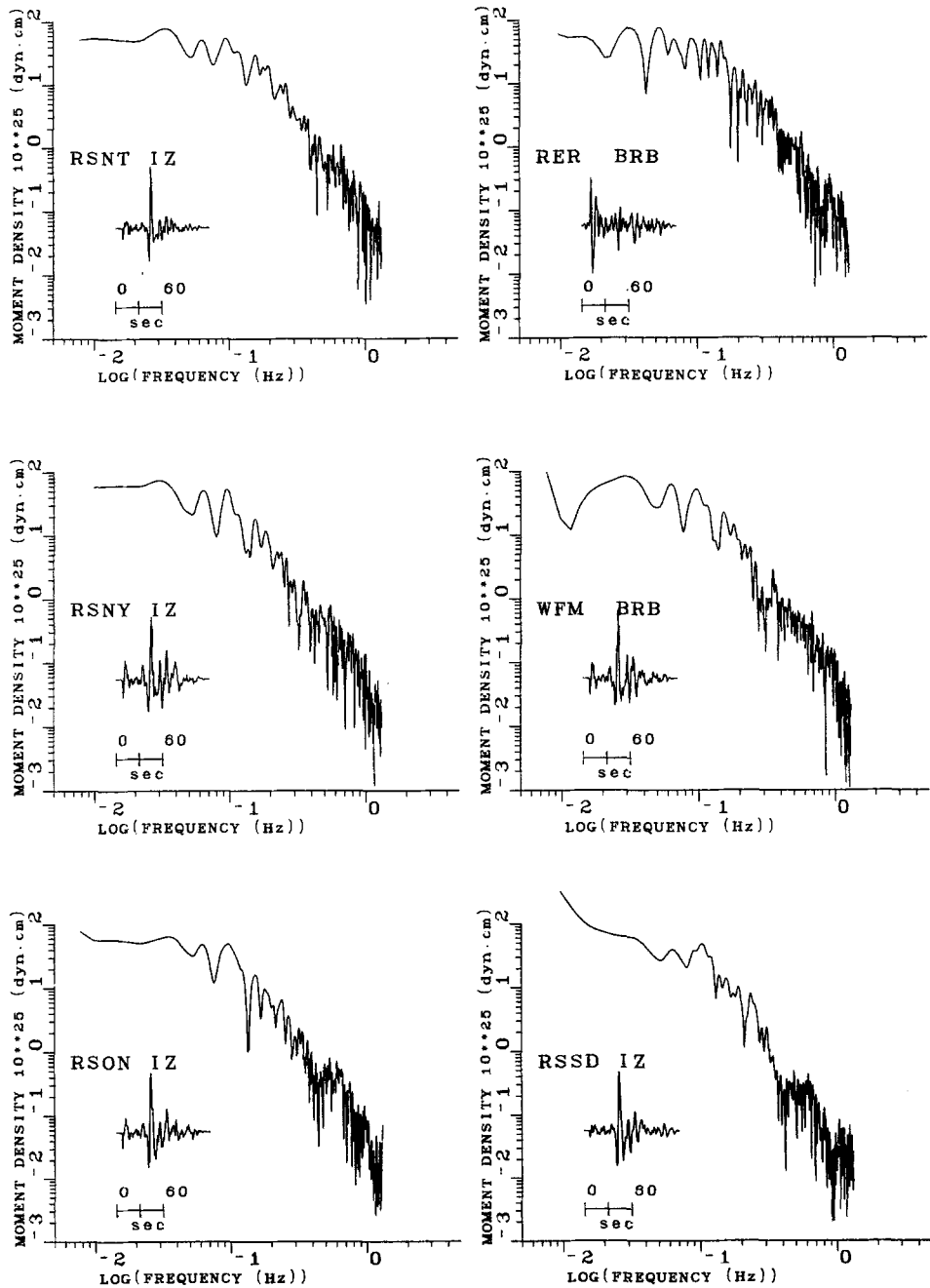


Figure 7

P-wave group. Vertical broadband records and corresponding spectra at GEOSCOPE broadband stations WFM (MIT, USA) and RER (La Réunion obs.) and at RSTN stations: RSNT, RSSD, RSON and RSNY. Long period constant, corner frequency and theoretical decay at high frequency are also given.

corresponds to a different view of the rupture process. At present, we can extract the source time function in three directions only: from P and pP waves at WFM, RSNY, RSON and RSNT, and from P -wave at RER (Figure 8). At North American stations, the sP could not be separated from the $pPcP$ wave and at RER, the excitation of pP and sP is not large enough to obtain any resolution on the time function. The source duration varies from 4 to 6 seconds. In directions of maximum amplitude (pP at WFM, RSON, RSNY, P at RER), the source has a triangular shape, larger at WFM, with little evidence of complexity. On the contrary, the P -wave recorded in the NW direction leaves the source in a direction very near that of the fault plane; the source time function inferred from these records has a trapezoidal shape with evidence for a second, narrow but distinct pulse. This difference of duration between source functions in two directions of observation could be explained by a well developed stopping phase as already found for the 1977 event by MÜLLER *et al.* (1978) and an upward propagation in the vertical direction along the fault plane; but the resolving power of P -wave source time functions is too small to resolve properly the rupture propagation for this event which involves a fault area of about $25 \times 33 \text{ km}^2$ as suggested by the aftershock distribution (TRIFU and ONCESCU, 1987). Nevertheless, the relative position of the main shock with respect to the distribution in depth of aftershocks

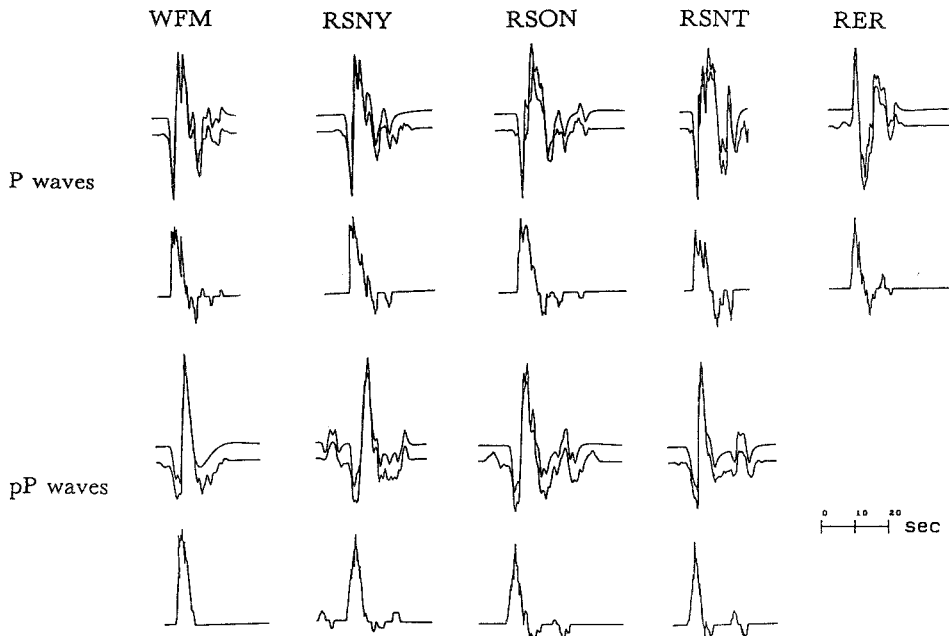


Figure 8

Comparison of synthetic and observed waveforms, and, on the line immediately below each waveform, corresponding source time functions. Top: P -wave; bottom: pP -waves. The top trace is the synthetic waveform.

rather suggests a downward propagation of the rupture and this problem could be further addressed by studying S-wave relative amplitude and source time functions even if the attenuation along this ray is more important.

Conclusion

In the example of the event of August 30, 1986, we have demonstrated that, using data from a relatively small number of high quality digital stations distributed worldwide, it is now possible to determine in a short time (DESCHAMPS *et al.*, 1986) source parameters for large events in such an area as the Vancrea region, a continental zone of unexplained intermediate depth seismicity. The source parameters obtained by long period surface wave inversion on the one hand, and bodywave modelling on the other are in good agreement, indicating a rather simple source process, as confirmed by closer inspection of broadband records. Contrary to the previous 1977 event, which has a very similar mechanism, there is no evidence of a complex rupture, and the source is somewhat deeper.

Because of the size of this event, very-long period data were not efficient to detect a directivity effect. Moreover, broadband *P*-wave modelling does not give an accurate estimation of the direction of source propagation. Aftershock distribution and the small relative amplitude of the *sP* phase at station RER suggest a downward rupture propagation whereas the source duration inferred from *P* and *pP*-waves implies an upward propagation. Further studies should be undertaken with broadband *S*-waves to clarify this contradictory point.

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