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ADVANCED TECHNIQUES IN COMPUTATIONAL PHYSICS

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THE INVERSION OF SEISMIC WAVE DATA

by

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INVERSION FOR THE SLIP ON A FAULT (IRPINIA EARTHQUAKE)

(Adapted after Suhadolc et al., 1987; Harabaglia et al., 1987)

The Irpinia earthquake of the 23rd November 1980 (M_S=6.9) occurred in the southern Apennines, which killed over 3000 people and devastated an area of several thousand square kilometers, is, up to now, the best documented Italian seismic event. This earthquake provides a good opportunity for looking into the details of a complex normal faulting process.

The large scale features of this event are relatively well determined. The mainshock hypocenter and the aftershock distribution, as well as the focal mechanisms of the mainshock and of the overall process have been extensively studied (e.g. Del Pezzo et al., 1983; Bruestle and Mueller, 1983; Deschamps and King, 1984; Westaway and Jackson, 1987). The mechanism is characterized by dominant normal faulting, with one well constrained nodal plane, striking about N40W and dipping at about 60° (Fig. 1). Levelling data (Arca et al., 1983) confirmed this nodal plane as the fault plane. Moreover, Westaway and Jackson (1984) observed surface faulting segments striking NW. The other nodal plane is poorly constrained and the value and direction of the strike slip component varies according to different authors.

The complexity of the source (Fig. 2) is apparent even at teleseismic distances (e.g. Westaway and Jackson, 1987) and three main rupture episodes can be inferred from the analysis of far field P-wave arrivals. These three episodes show up neatly also in some of the near-field strong motion recordings (Berardi et al., 1981).

The complexity of this earthquake has been parametrized into some source models by different authors (Suhadolc et al., 1987; Westaway and Jackson, 1987; Bernard and Zollo, 1987a; 1987b) using in their analysis synthetic seismograms or synthetic S-wave polarizations. The obtained models, although different in some aspects, have many common features (see Figs. 3-5).

In order to verify the validity of some of the models proposed up to now, the vertical components of 7 stations of the ENEA-ENEL accelerographic network (Figs. 6-7) have been inverted for the slip along a system of faults. In order to do the inversion, the fault system has been discretized with a certain number of hypocentres (between 1000 and 2000). The synthetic seismograms from these point sources at the seven stations (Auletta, Bagnoli Irpino, Bisaccia, Brienza, Calitri, Rionero in Vulture, Sturno) have been computed using normal mode summation techniques (Panza, 1985; Panza and Suhadolc, 1987). Finally a linearized inversion method has been applied based on the conjugate gradient technique (e.g. Press et al., 1986).

Denoting the observed strong motion records at the i-th station with d_i, the synthetic accelerogram at the i-th station due to the j-th point source with a_{ij}, and its corresponding weight, which will be converted to slips on the fault, with w_j, the function that one has to minimize is given by

$$\Phi = \sum_i (d_i - \sum_j w_j a_{ij})^2$$

As a result of the minimization some negative weigths may be obtained - a physically unwanted feature implying slips in the direction opposite to that of the overall slip on the fault. In the case the negative weigths represent a big percentage of the total, the assumed initial rupturing model might be inadequate (Takeo, 1987). If only a small percentage of negative weigths is obtained, as in the majority of the following examples, a regularization technique is appliec. Starting from the obtained model some more iterations are performed adding to the minimization function the term

$$\Phi' = k \sum_i g(w_i)$$

where k is a properly selected constant and

$$g(w) = 0 \quad \text{fcr} \quad w \geq 0$$
$$g(w) = w^2 \quad \text{fcr} \quad w < 0.$$

As a result of such an inversion it has been possible to reproduce synthetically the observed waveforms for frequencies up to 1 Hz.

Two inversions have been performed, one on the model proposed by Suhadolc et al. (1987) - let us call it M1, the other on the model - call it M2 - adjusted from the one proposed by Bernard and Zollo (1987a).

The structural model used in the analysis (Fig. 8) is a modification of Model A proposed by Del Pezzo et al. (1983), who obtained it from the inversion of travel time data of local earthquakes. The model has been essentially modified in its upper 10 km, where constant velocity layers have been replaced by a gradient in the velocities. The S-wave velocity thus increases from 0.9 km/s at the surface to 3.3 km/s at the depth of 10 km. This gradient has been chosen to simulate the loading effect of the sediments which are present in several parts of the investigated area.

The fault system responsible of the main rupturing episode has been modelled by a set of microfaults (grid of point sources) positioned in a vertical plane to simulate the local geological setting as deduced from deep drilling wells (Mostardini and Merlini, 1986). For each point source the strike is oriented N140E and the dip is taken as 70°. The rake 340 proposed by Suhadolc et al. (1987) has been kept also fixed. This fault system model extends from the mainshock epicenter for about 45 km to the NW and for about 45 km to the SE. Near the southern tip a small extension of the fault system towards east is present (see Fig. 3).

Another problem, which does not allow to reduce further the space of possible solutions, is represented by the lack of an absolute time on the recorded data. The strong motion instruments deployed by ENEA-ENEL had only an internal clock and were activated when the acceleration exceeded a predetermined threshold. Thus a set of triggering times has to be assumed. One set - T1 - has been derived from matching at high frequencies (up to 10 Hz) the observed waveforms with the synthetic ones (Fig. 9), obtained through a direct trial-and-error approach by Suhadolc et al. (1987). The other set - T2 - is similar to the first one with the exception of the triggering time relative to the station of Brienza, where the triggering time based on model B by Bernard and Zollo (1987a), about 4 s later than what Suhadolc et al. (1987) propose, is taken.

The first inversion has been applied to the model M1 and the trigger times set T1. All the point sources have been initially given a unitary weigth. The rupture is assumed to spread out from the point source corresponding to the mainshock hypocenter with a velocity of 0.80 V_S, that is 80% of the S-wave velocity in the corresponding layer. The corresponding initial synthetic signal and the final synthetics obtained through the inversion, after 22 iterations, are given in Figs. 10 and 11, respectively. If one tries the same inversion assuming the trigger set T2, the iteration converges to a result which is not satisfactory for the Brienza station. A rupturing velocity of 0.70 V_S has been also tried, but the results were not as good as those obtained with the rupturing velocity 0.80 V_S.

Next the model M2 has been tried. In this model the fault to which the main shock belongs extends only a few km to the SE, the NW extension being the same as in model M1. To the south the model M2 is similar to M1 only in the first 8 km of depth, while below it consists of a low-angle fault (dip 20) extending to the NE for 10 km in a depth range 8-12 km. If the inversion is performed using the trigger set T2, the results are quite satisfactory (Fig. 12), while the trigger set T1 produces poor results.

The next step was the inversion of the complete recordings, including the event recorded after the first 40 s of recording. For this subevent the nucleation point of model B proposed by Bernard and Zollo (1987a) has been assumed. Moreover the fault system responsible for this late event has been assumed to be parallel to the principal fault system, but the dip of the point sources has been assumed to point towards SW with a value of 70°, the rake being assumed as 270 . The whole system of faults therefore models a graben-like structure. Assuming the trigger set T2 and the model M2 for what concerns the initial part of the recordings, the synthetic signals obtained through the inversion procedure (Fig. 13) are in very good accord with the data. The corresponding slips on the fault system are shown in Fig. 14.

The obtained results are of course non-unique, an example being the results obtained for the models M1/T1 and M2/T2. Further investigations are needed in the space of the initial models.

The main features obtained from the inversion are the big slips at shallow depths. It seems reasonable that the major features on the observed accelerograms are due to near-station, near-surface slips. In fact, high-frequency motion from more distant parts of the fault system are subject to stronger attenuation and wave interference. The same is true, for small epicentral distances and in the presence of thick sedimentary covers, for slips on the deep parts of the fault with repect to the near-surface ones.

To check this assumption an inversion has been performed on a fault system confined only to depths in the range 8 - 15 km. Moreover, only the rupture on the fault system extending from the main event hypocenter to the north and the stations surrounding it (Bagnoli Irpino, Bisaccia, Calitri and Sturno) have been considered. The synthetic waveforms resulting from this inversion are shown in Fig. 15. By comparing these waveforms with the observed ones, one can immediately see, that almost no similarity is present. Moreover, the amplitudes at the station of Sturno (STU) are very small with respect to those at the other stations, contrary to what is observed. The obtained slips on the faults show also a big percentage of negative values, a warning sign for an inadequate initial model.

It can be therefore concluded that the obtained results (Figs. 13 and 14), based on an initial model consistent with other independent geophysical observations (e.g. Bernard and Zollo, 1987a; Westaway and Jackson, 1987) and on the assumption of a constant rupturing velocity, certainly represent an acceptable solution for the rupturing process. The limitations to its validity are mainly due to the fact that the effects of lateral structural heterogeneities present in the area, have not been taken into account. Even if recently big advances have been made in the theoretical treatment of lateral inhomogeneities in surface wave propagation (Vaccari et al., 1987), one is still far away from knowing the three dimensional Earth structure of a certain area with the accuracy necessary for an inversion procedure like the one described above.

At the end let me just briefly give some typical execution times relative to what has been described above.

The computer on which the programs ran is an IBM 3090. The frequency response of a structural model is obtained in about 3000 s. Each seismogram is then obtained in about 5 s. An iteration of the inversion procedure requires on the average, about 300 s. A complete inversion procedure with about 10000 seismograms requires an execution time which ranges from about 5000 to about 20000 s. The memory requirements range from 50 to 200 Mbyte.

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FIGURE CAPTIONS

Fig. 1 - View of the Irpinia epicentral area. Aftershock epicenters, strong motion sites (dots), levelling path (thin line), surface fault trace (thick segments), main shock epicenter (star) and focal mechanisms are presented. From Bernard and Zollo, 1987a.

Fig. 2 - Evidence of source complexity. Top: Broad band vertical record inversion at teleseismic distances (79°). Bottom: east component of acceleration at MER (Mercato San Severino). From Bernard and Zollo, 1987a.

Fig. 3 - Rupture process according to Suhadolc et al. (1987).

Fig. 4 - Rupture process according to Westaway and Jackson (1987).

Fig. 5 - Rupture process according to Bernard and Zollo (1987).

Fig. 6 - Vertical components at six stations of the ENEA-ENEL accelerographic network.

Fig. 7 - Vertical components (filtered with a Gaussian filter having a cutoff frequency of 1 Hz) at seven stations of the ENEA-ENEL accelerographic network.

Fig. 8 - Structural model used in the inversion procedure.

Fig. 9 - High frequency waveform matching at station Sturno (from Suhadolc et al., 1987).

Fig. 10 - Initial synthetic signals used in the inversion (model M1/T1 - see text).

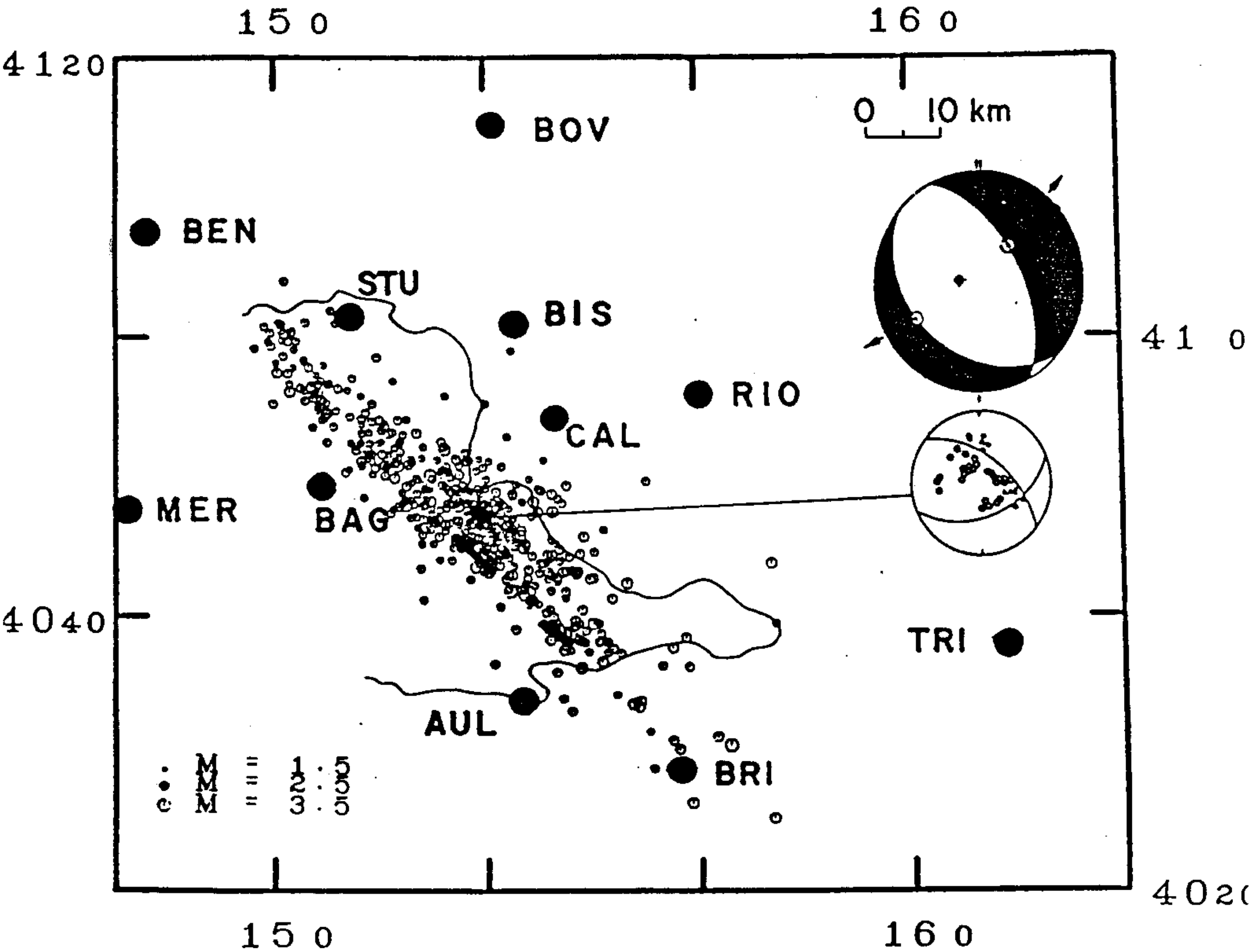
Fig. 11 - Final synthetic signals after 22 iterations (model M1/T1).

Fig. 12 - Final synthetic signals after 16 iterations (model M2/T2).

Fig. 13 - Final synthetic signals after 28 iterations (on three fault systems).

Fig. 14 - Distribution of the slips on the three fault systems producing the synthetic signals of Fig. 13.

Fig. 15 - Final synthetic signals in the case only a deep fault system is considered (see text).



150
160
4120
410
4040
BOV
0 10 km
BEN
STU
BIS
RIO
CAL
MER
BAG
TRI
AUL
BRI
M = 1.5
M = 2.5
M = 3.5

FIG. 1

From BERNARD & ZOLLO, 1987

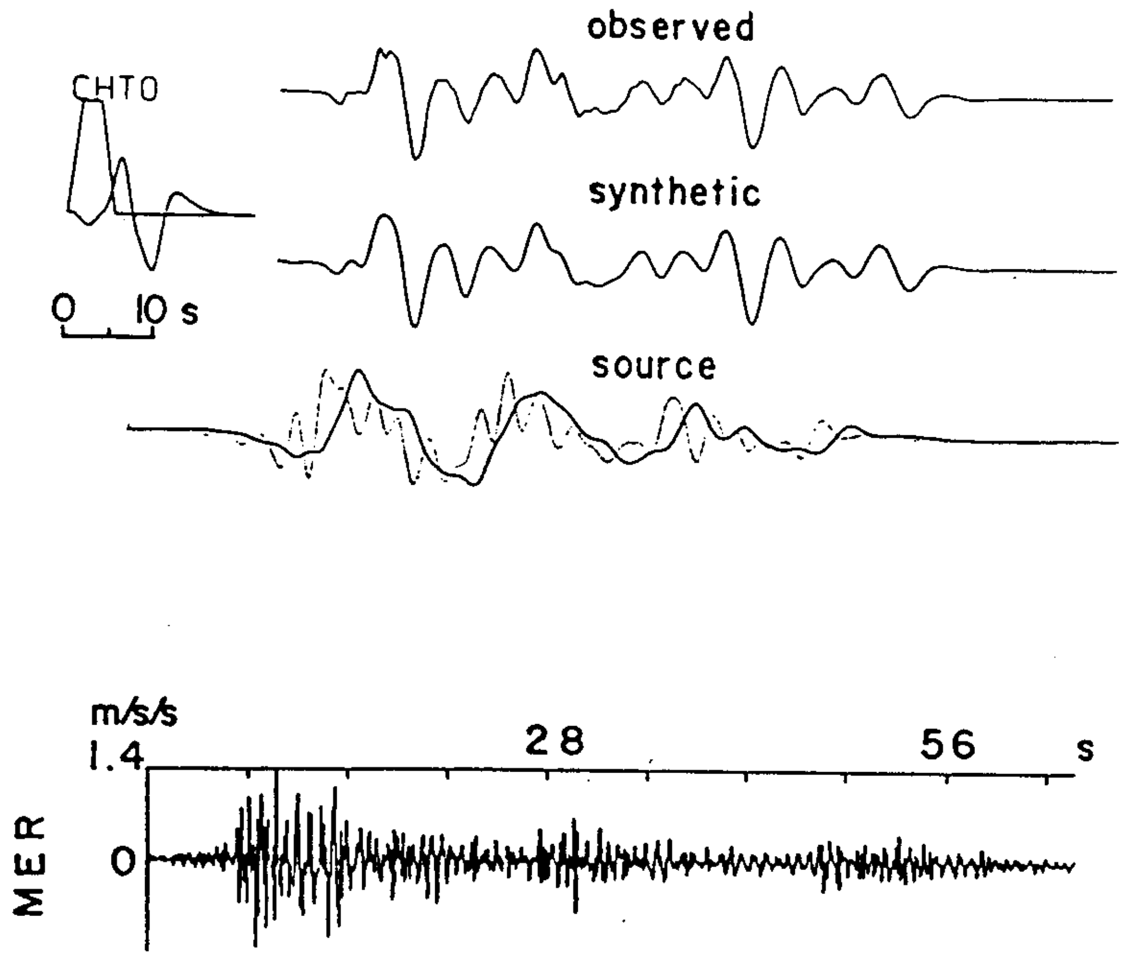


FIGURE 2

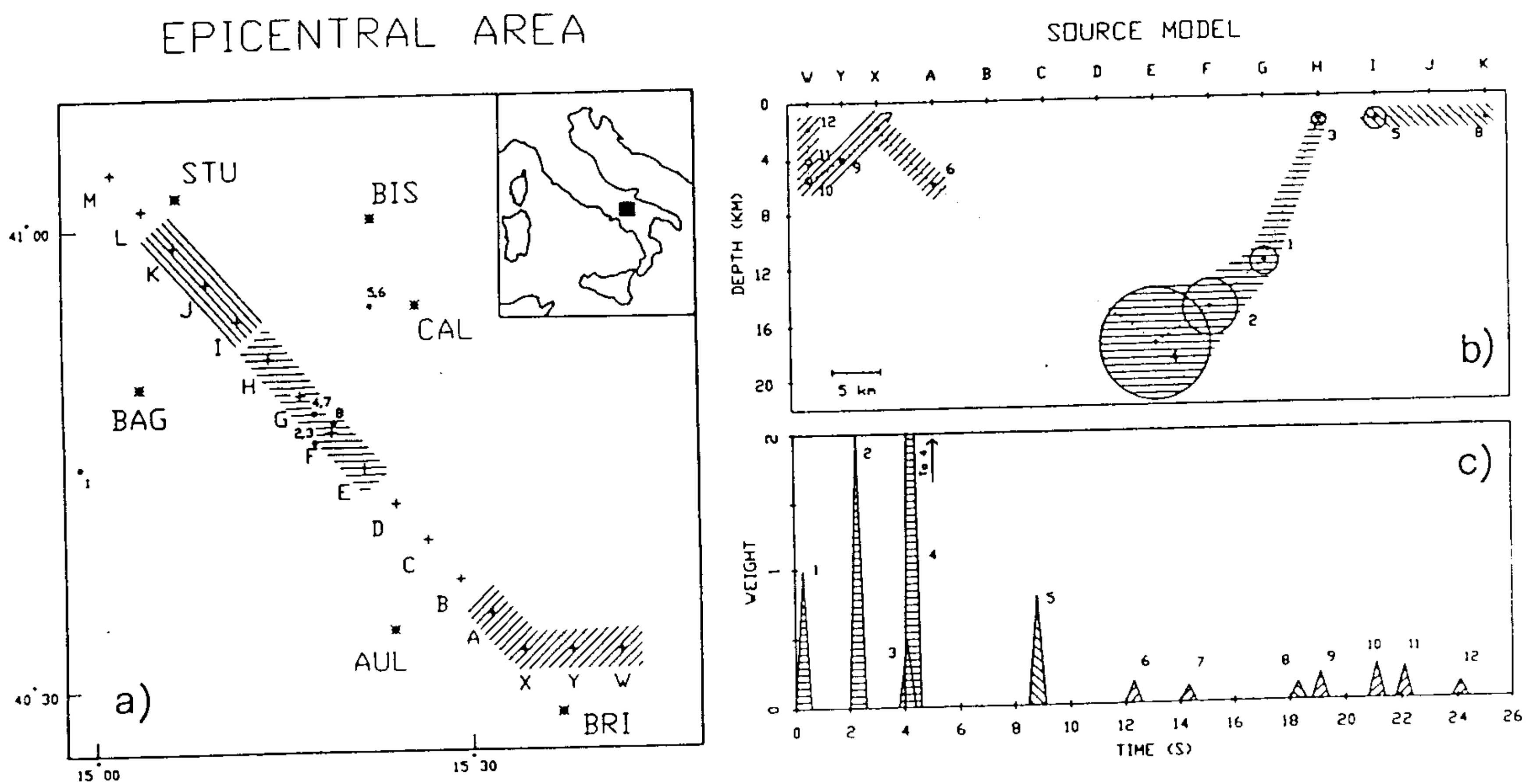

EPICENTRAL AREA
SOURCE MODEL
STU
BIS
CAL
BAG
AUL
BRI
a)
b)
c)
41°00
40°30
15°00
15°30
DEPTH (KM)
5 km
WEIGHT
TIME (S)

FIG. 3

V'ESTAWAY & JACKSON, 1987

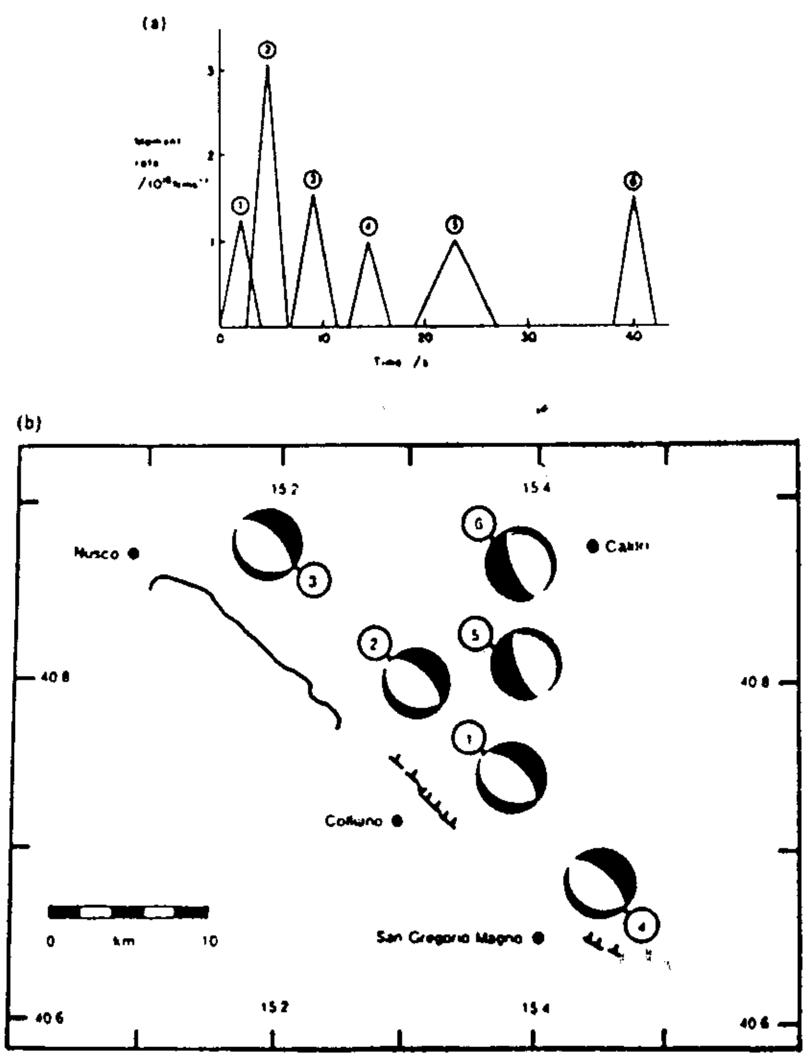


Figure 24. (a) Moment rate for the final, preferred, source model, incorporating six subevents. (b) Summary map of the final, preferred, source model, incorporating six subevents. The map shows the focal mechanism and the suggested position of faulting in each of these subevents.

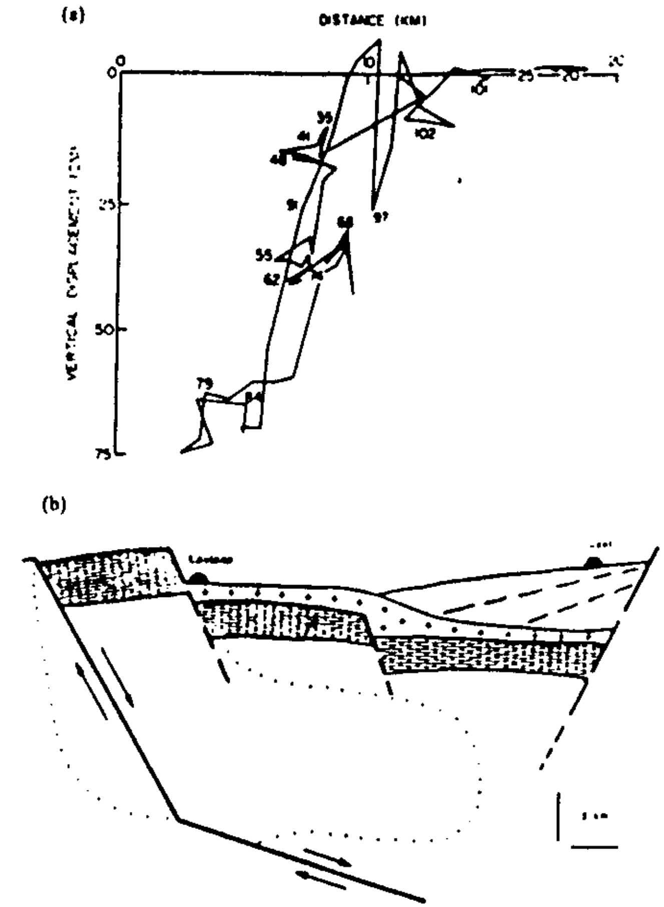


Figure 25. (Above and opposite.) (a) Elevation changes in the hanging wall observed through relevelling by Arca *et al.* (1983), in a section striking at N 43° E. The projection of the Monte Marzano segment of surface faulting is 2 km SW of the origin. Note that ground elevation changes are only observed less than 15 km NE of the surface faulting. Fig. 4 of Arca *et al.* (1983). (b) Section orientated SW–NE across the area in which faulting occurred in the mainshock, indicating the suggested relationship between slip in both early and late mainshock ruptures, and deformation due to aftershocks. Information on the structural geology of the area is simplified from Ippolito *et al* (1974) and from Ortolani & Torre (1981). It is based on borehole logs and on interpretation of shallow seismic reflection profiles shot for hydrocarbon exploration. Mesozoic limestone is indicated by brickwork shading, 'flysch' by crosses and Pliocene deposits of the Calrano basin by stipple. The area containing aftershocks is outlined by fine dots, and is based on Fig. 23(b). (c) Position of the levelling line (L) for which ground elevation changes have been modelled by Arca *et al.* (1983) and Crosson *et al.* (1986), in relation to the Monte Marzano (M) and Monti Picentini (P) segments of faulting, to the Sele Valley (V), and to the NE-striking fault (F) suggested by Crosson *et al.* (1986) as the source of the 40 s subevent. Benchmark numbers along the levelling line are from Arca *et al.* (1983).

FIG. 4

BERNARD
& ZOLLO,
1987

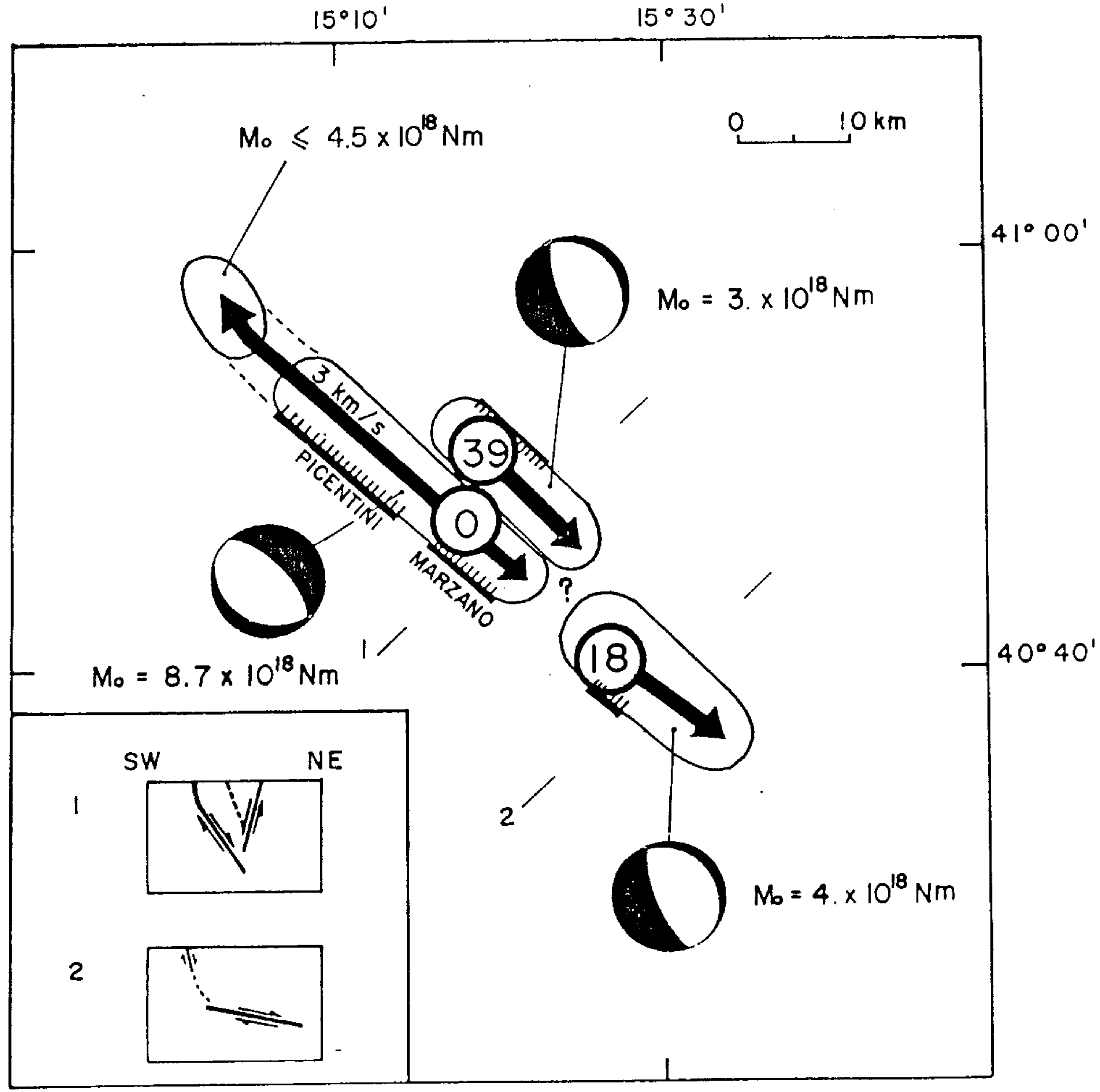
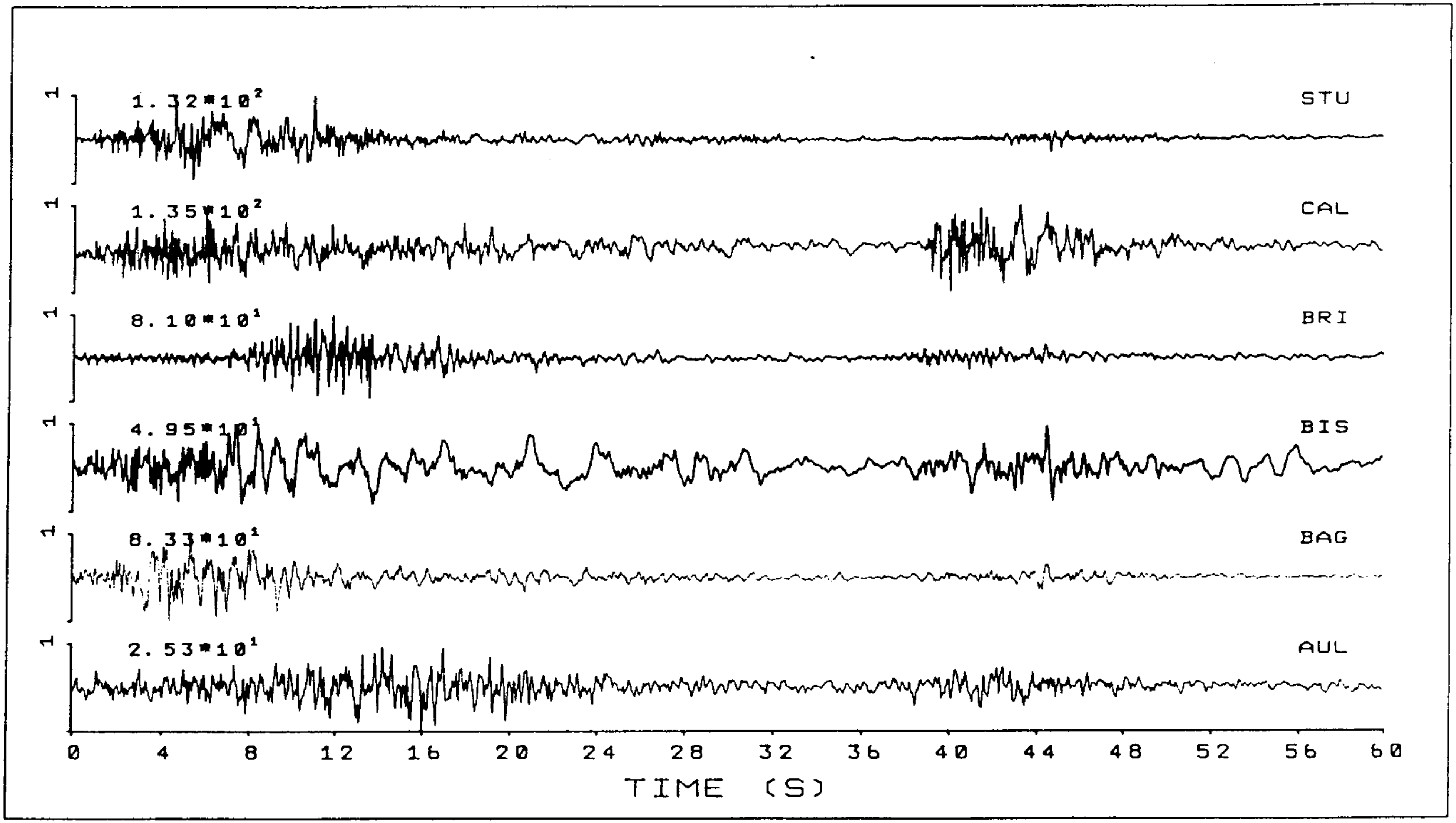


FIG. 5



1.32*10²
STU
1.35*10²
CAL
8.10*10¹
BRI
4.95*10¹
BIS
8.33*10¹
BAG
2.53*10¹
AUL
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60
TIME (S)

FIG. 6

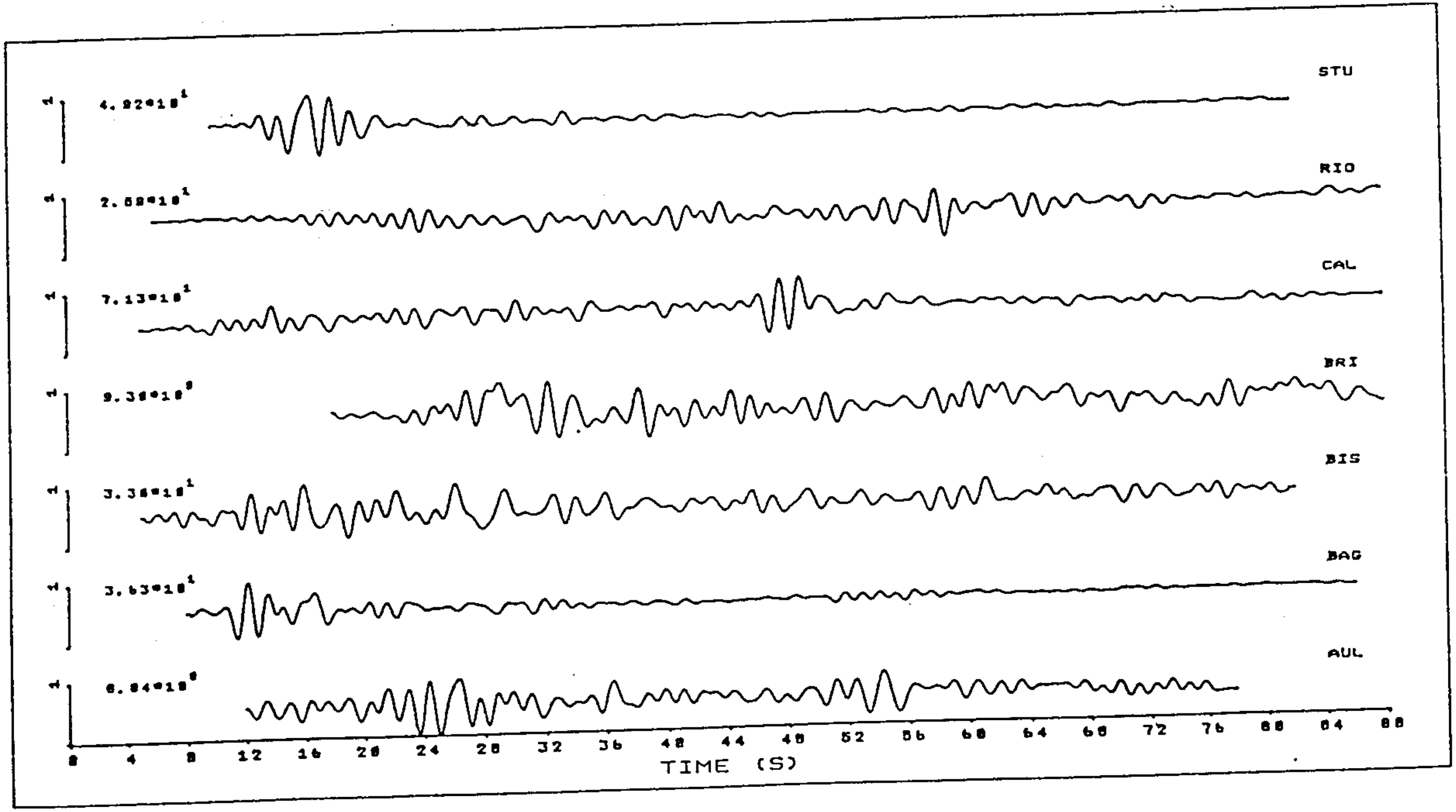
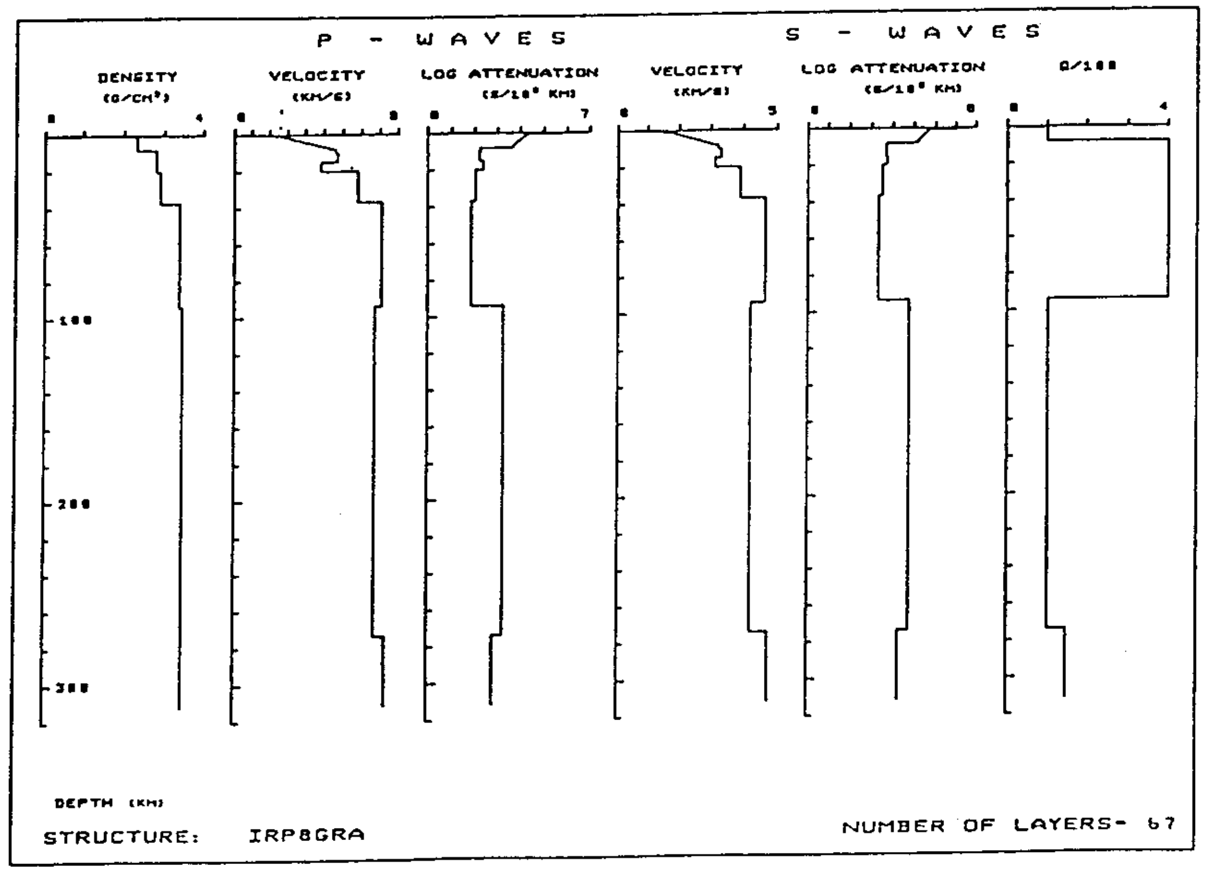

STU
RIO
CAL
BRI
BIS
BAG
AUL
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88
TIME (S)

FIG. 7



P - WAVES
S - WAVES
DENSITY (G/CM³)
VELOCITY (KM/S)
LOG ATTENUATION (E/10⁶ KM)
VELOCITY (KM/S)
LOG ATTENUATION (E/10⁶ KM)
Q/100
0
4
8
7
5
100
200
300
DEPTH (KM)
STRUCTURE: IRP8GRA
NUMBER OF LAYERS- 67

FIG. 8

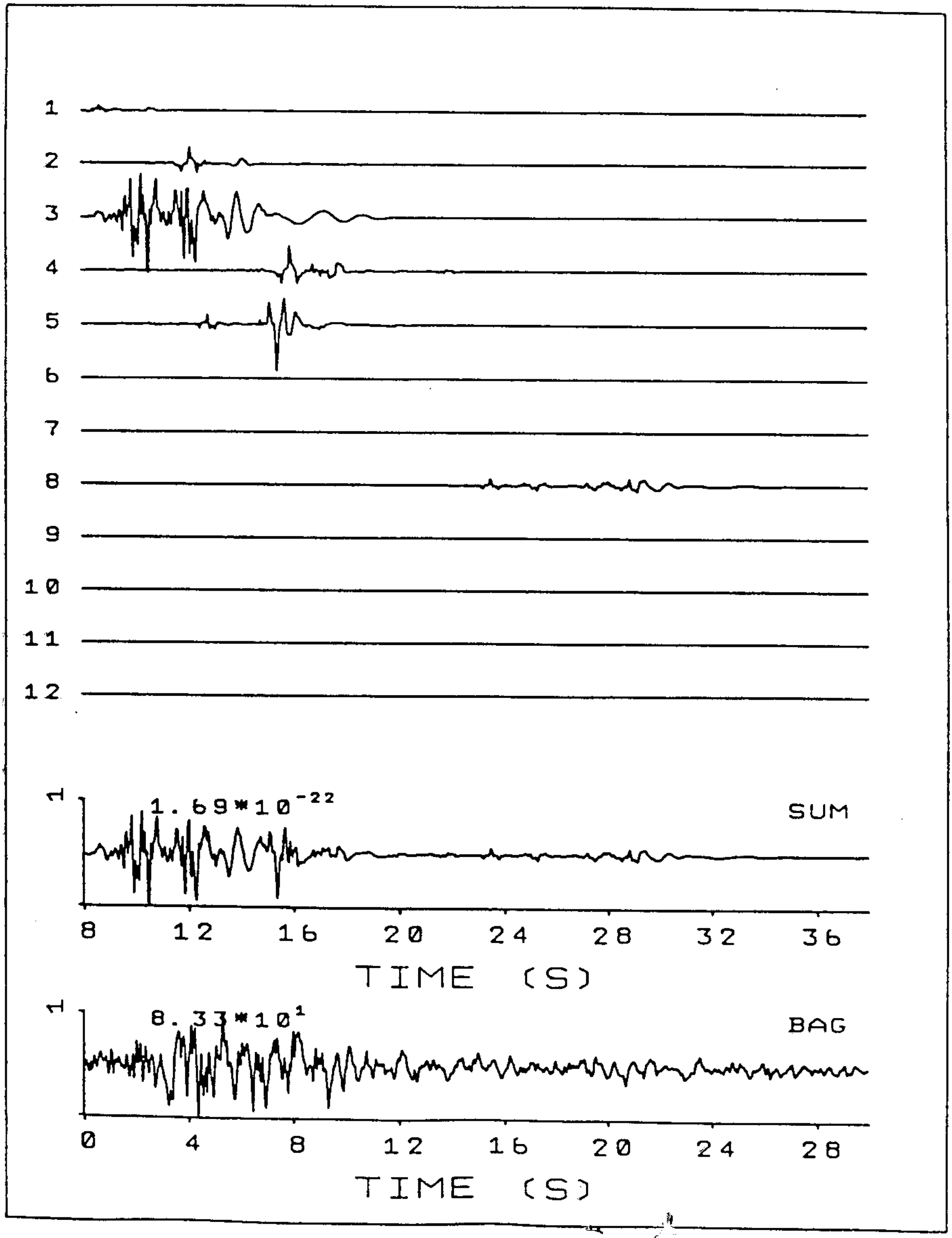

1
2
3
4
5
6
7
8
9
10
11
12
1
1.69*10^-22
SUM
8
12
16
20
24
28
32
36
TIME (S)
1
8.33*10^1
BAG
0
4
8
12
16
20
24
28
TIME (S)

FIG. 9

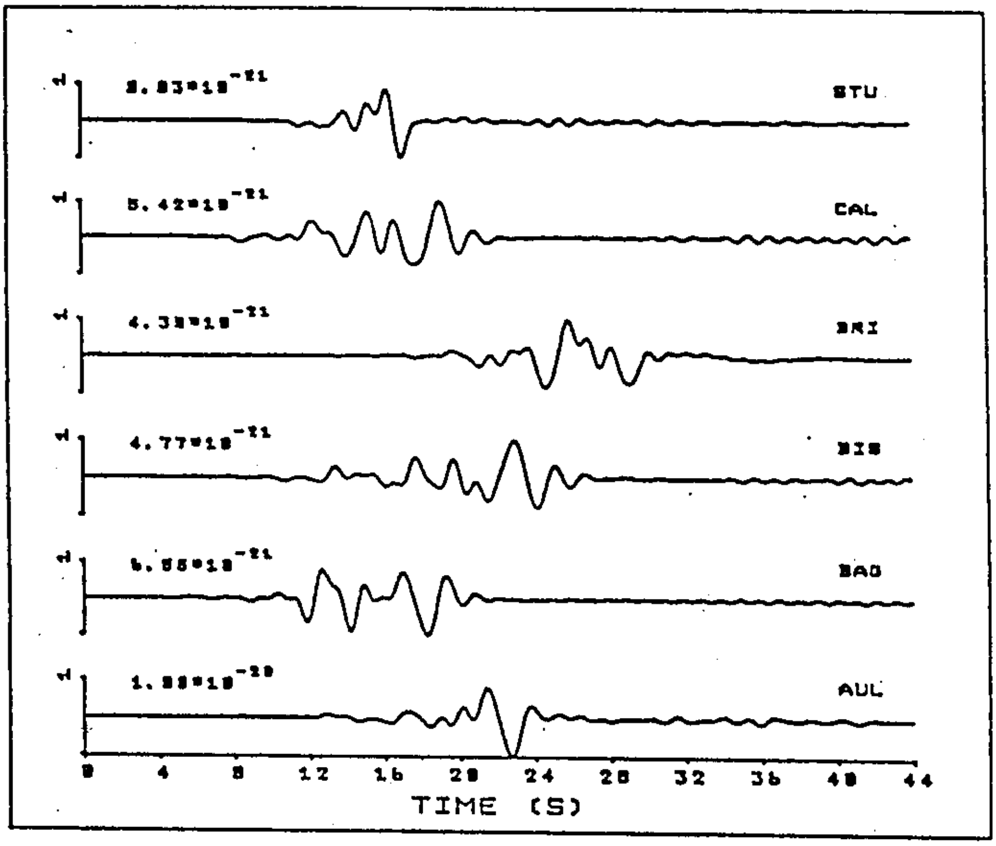


FIG. 10

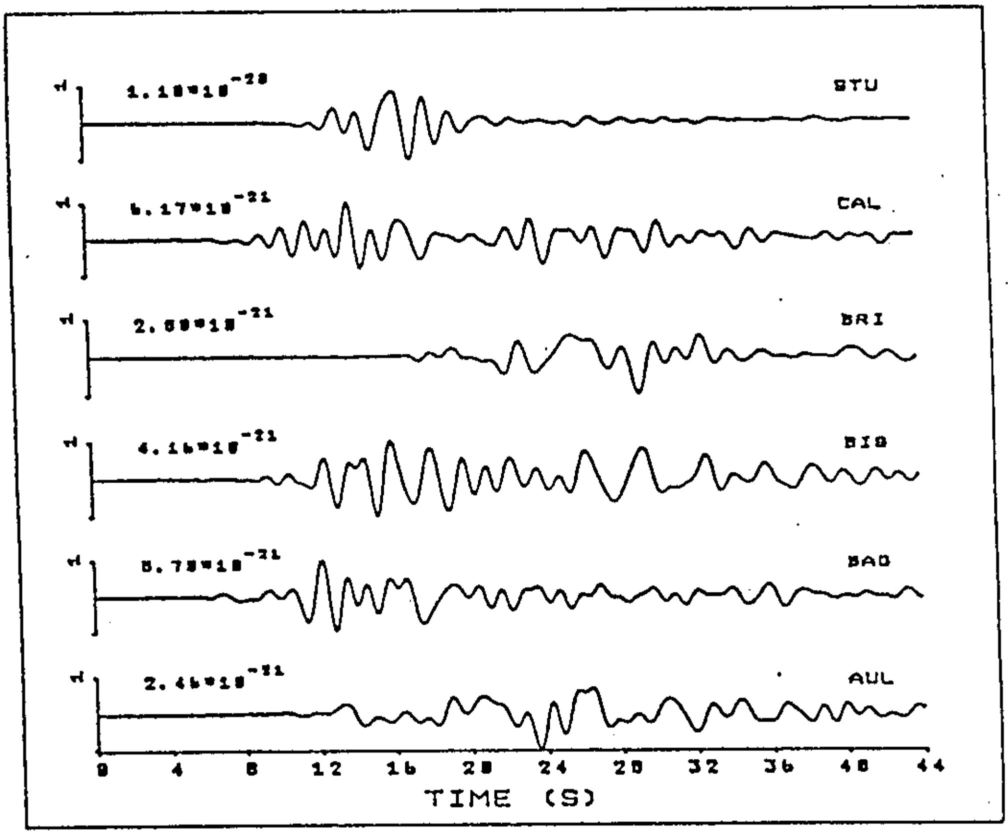


FIG. 11

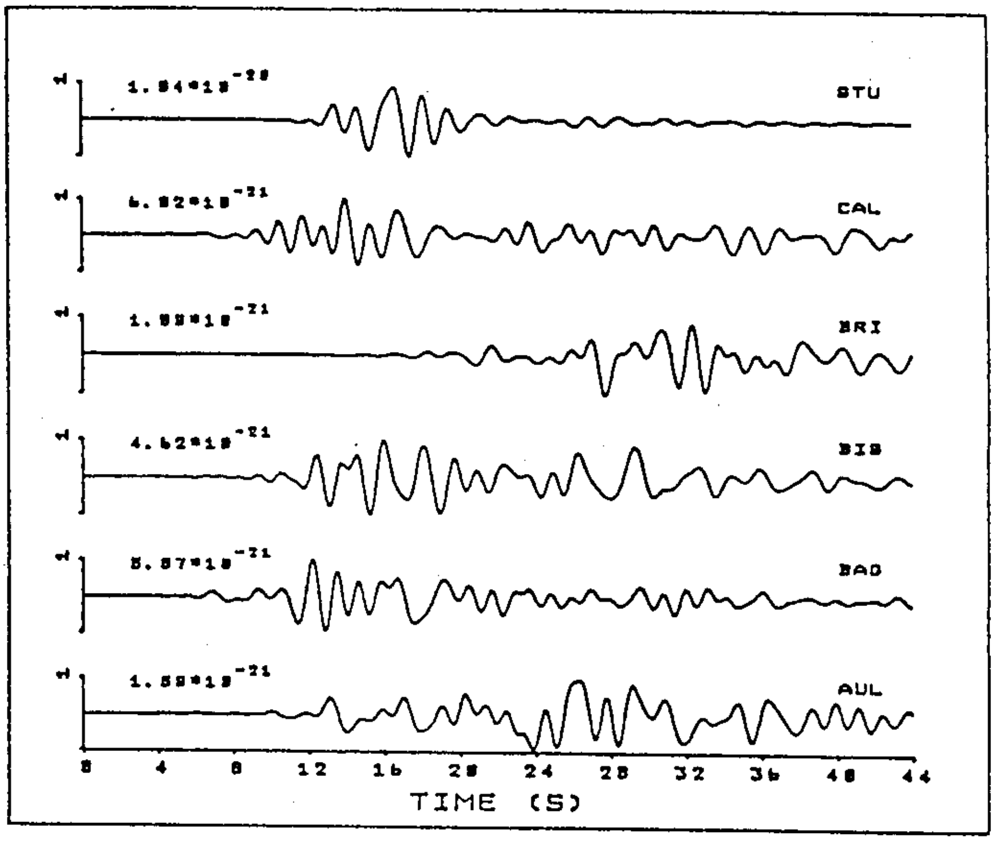
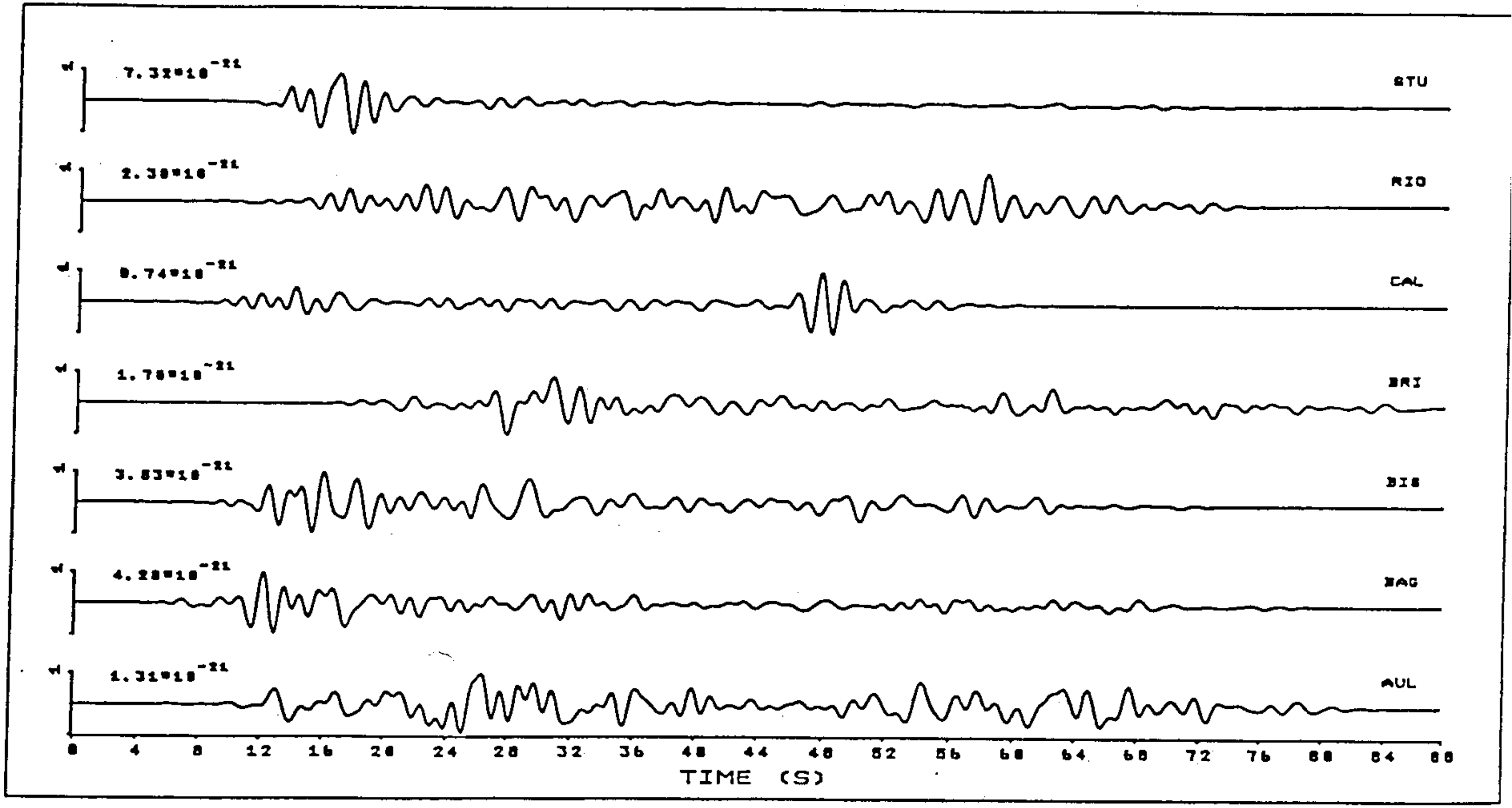


FIG. 12



7.32*10^-21
STU
2.38*10^-21
RIO
0.74*10^-21
CAL
1.78*10^-21
BRI
3.83*10^-21
BIS
4.28*10^-21
1.31*10^-21
AUL
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88
TIME (S)

FIG. 13

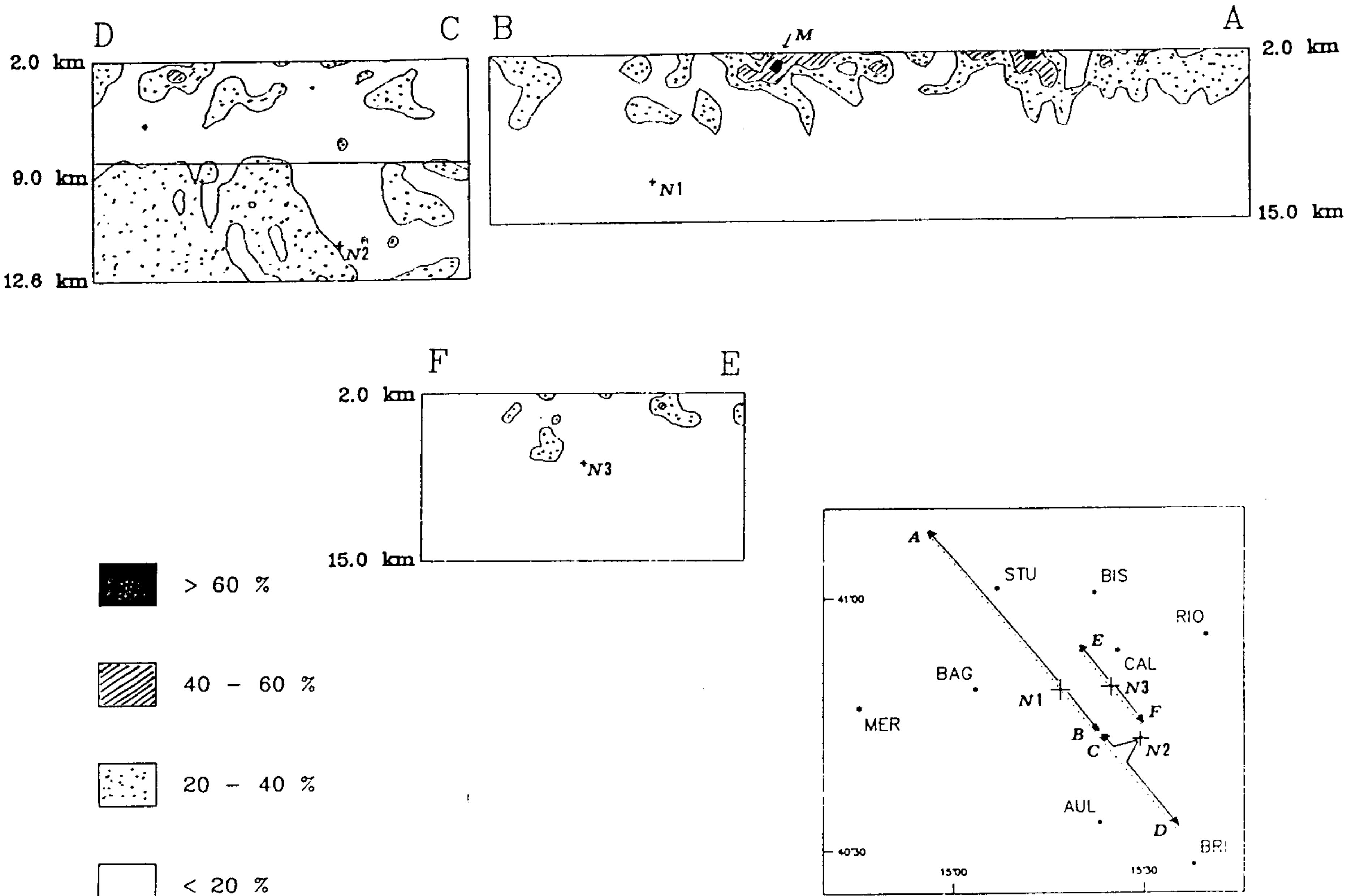
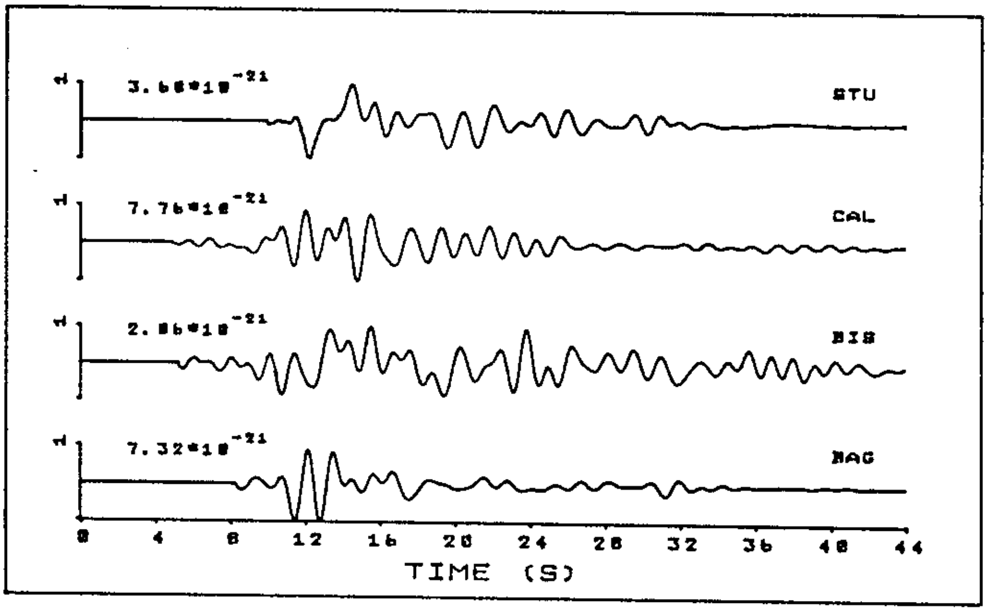

D
C
B
A
M
2.0 km
9.0 km
12.6 km
N2
N1
15.0 km
F
E
N3
> 60 %
40 - 60 %
20 - 40 %
< 20 %
STU
BIS
RIO
BAG
CAL
MER
AUL
BRI
41°00
40°30
15°00
15°30

FIG. 14



3.60*10^-21
STU
7.76*10^-21
CAL
2.06*10^-21
BIS
7.32*10^-21
BAG
0 4 8 12 16 20 24 28 32 36 40 44
TIME (S)

FIG. 15