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The Montenegro, Yugoslavia, earthquake of April 15, 1979: source orientation and strength

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Long-period teleseismic P, S and Rayleigh waves and geologic considerations indicate that the Montenegro earthquake involved thrust faulting on a plane striking nearly parallel to the Adriatic coast and dipping ca. 15° toward the Yugoslav mainland. There is some support from modeling of body waves recorded on long-period WWSSN instruments for a focal depth of 22 km, but the possibility of a multiple source and the difficulty of matching some of the detailed characteristics of the P- and S-wave forms reduce our confidence in the determination of the depth. Fortunately, the source orientation and moment of the event are not sensitive functions of the depth. The long-period (256 s) moment was 4.6×10^{19} Nm (4.6×10^{26} dyne-cm). The moment obtained by fitting the first cycle of P and S waves recorded on WWSSN long-period instruments is about four times smaller. This increase of moment with period is consistent with spectral estimates of the moment from SH waves recorded at SRO and ASRO stations.

1. Introduction

The relative slip on fault planes, deduced from studies of the energy radiated by earthquakes, plays an important role in deciphering tectonic plate movements. The Montenegro earthquake of April 15, 1979, provides such information for a poorly understood part of the Mediterranean region (Fig. 1), an area of complex plate tectonics (McKenzie, 1972). The Montenegro earthquake is also of interest because it was recorded by more than 25 strong-motion instruments, and thus can be studied in unusual detail. It is not our purpose in this paper to make an exhaustive study of the

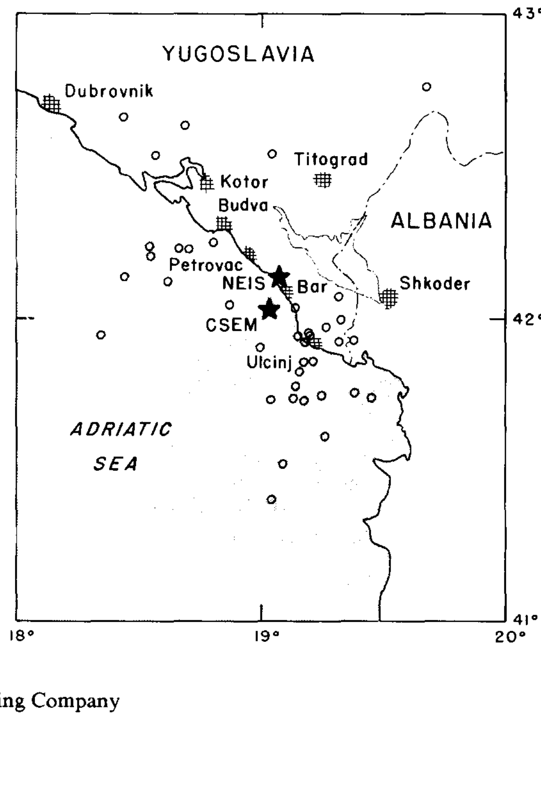

Fig. 1. Epicenters of main-shock (stars) and after-shocks (dots) of the Montenegro, Yugoslavia, earthquake of April 15, 1979. After-shock locations, taken from NEIS reports, for 1-day period after main-shock.

earthquake. Our goal is more modest: to present the focal mechanism and the seismic moment of the event. We will discuss, however, some characteristics of the body waves recorded at teleseismic distances that will be of importance in detailed modeling studies.

2. Main-shock and after-shock locations

The preliminary determination by the U.S. National Earthquake Information Service (NEIS) placed the epicenter of the earthquake at lat. 42°08′N, long. 19°04′E. The European–Mediterranean Seismological Centre at Strasbourg (CSEM) placed the epicenter at lat. 42°02′N, long. 19°02′E, a difference of 12 km from the NEIS location (Fig. 1). Most of the aftershocks occurring within 1 d of the main-shock fell into two groups, centered near Budva and Ulcinj, respectively. The noticeable lack of after-shock activity between Ulcinj and Budva persisted throughout the after-shock sequence. The after-shock distribution described here, taken from the NEIS locations, is generally consistent with locations reported by Nedeljkovic et al. (1979) for the first two days after the main event, except that they also located a number of events in Albania, east of Shkoder. It also agrees with the results of Console and Favali (1981), who used data from many European stations. The relation of the after-shocks to the rupture surface of the main-shock is not clear, although a working hypothesis consistent with the distribution of intensity and of strong ground motion is that the region between the two centers in after-shock activity represents the zone ruptured in the main-shock. Peak accelerations were high along a considerable length of the coast (0.4 g at Petrovac, Bar and Ulcinj) but decreased significantly inland (Anicic et al., 1980, Petrovski et al., 1980).

A focal depth of 17 km was assigned by CSEM, and Console and Favali (1981) find that the hypocentral depths of the aftershocks are generally less than 20 km. With the assumption that radiation is due to a single concentrated source, some support for a source depth of about 22 km comes from modeling the WWSSN long-period P and S waves, using the methods of Kanamori and Stewart (1976). The modeling results discussed later are not wholly satisfactory, however, and we do not assign much confidence to the focal depth. Fortunately, the focal depth has little effect on the source orientation or the moment determined from the first-half-cycle of the body waves.

3. Source orientation

The focal mechanism (Table I, Fig. 2) was obtained by a conventional analysis of the long-period records from World-wide Standardized Seismograph Network (WWSSN) and Seismic Research Observatory (SRO) stations and by an inversion of the spectra of Rayleigh waves at a period of 256 s obtained from 12 records, with good azimuthal coverage, from the IDA network (Kanamori and Given, 1981). The P-wave first motions and the S-wave polarization angles, measured from the first half-cycle of motion at stations for which there was linear correlation between the two horizontal components of motion, provide good constraints for one nodal plane (A in Fig. 2). The inversion of Rayleigh waves was made using either a double couple source or a moment tensor source. The inversion is in general ill-behaved for earthquakes within several tens of kilometers of the Earth's surface (Kanamori and Given, 1981). Because we believe the Montenegro event to be this shallow, the ill-conditioning of the double-couple inversion was removed by using plane A as a constraint. The plane B is the result of the inversion; the formal uncertainty in slip angle is $\pm 2°$.

In the moment tensor inversion, the ill-conditioning was removed by requiring that the faulting be either pure dip-slip on a plane dipping at 45° or pure strike-slip on a vertical plane. In this case the strike of the fault is not fixed. With these constraints, the inversion gave a pure dip-slip

TABLE I

Summary of focal mechanisms

Plane	Dip direction	Dip angle	Data used
A	211°	75°	P, S waves
B	38°	15°	256-s Rayleigh waves

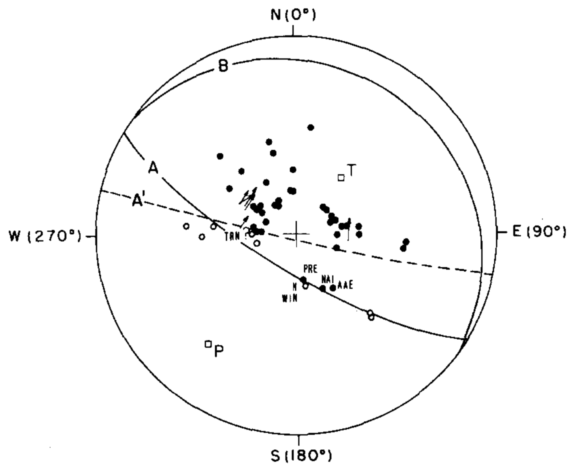

Fig. 2. P-wave focal mechanism solution (lower hemisphere, equal area projection): dots and circles are compressional and dilatational first motions, respectively; (N) a nodal first motion; (P, T) pressure and tension axes for the system of planes A, B; arrows are polarization vectors of S waves. Plane A′ is mentioned in the Discussion section. Seismograms from named stations are shown in Fig. 5.

TABLE II

Results of inversion of Rayleigh waves [a]

Fault parameter	Constraint	
	Double couple plane A fixed	Moment tensor [b] $M_{xz} = M_{xy} = 0$
Dip direction	211°	215°
Dip angle	75°	45°
Slip angle	88.3°	90°
Moment	4.6×10^{19} Nm	2.6×10^{19} Nm [c]

[a] Extended fault surface, 0–24-km depth.

[b] These constraints are equivalent to constraining the fault to be either pure dip-slip on a plane dipping at 45° or pure strike-slip on a vertical plane.

[c] Moment of minor double-couple 13% that of major double-couple.

motion with strike direction similar to that obtained for plane A from the P- and S-wave analysis (Table II). Although this solution is too restricted because of the strong constraints, it is in general consistent with the solution obtained by the double-couple inversion. The fault planes strike sub-parallel to the Adriatic coastline.

From an analysis of first motions at regional

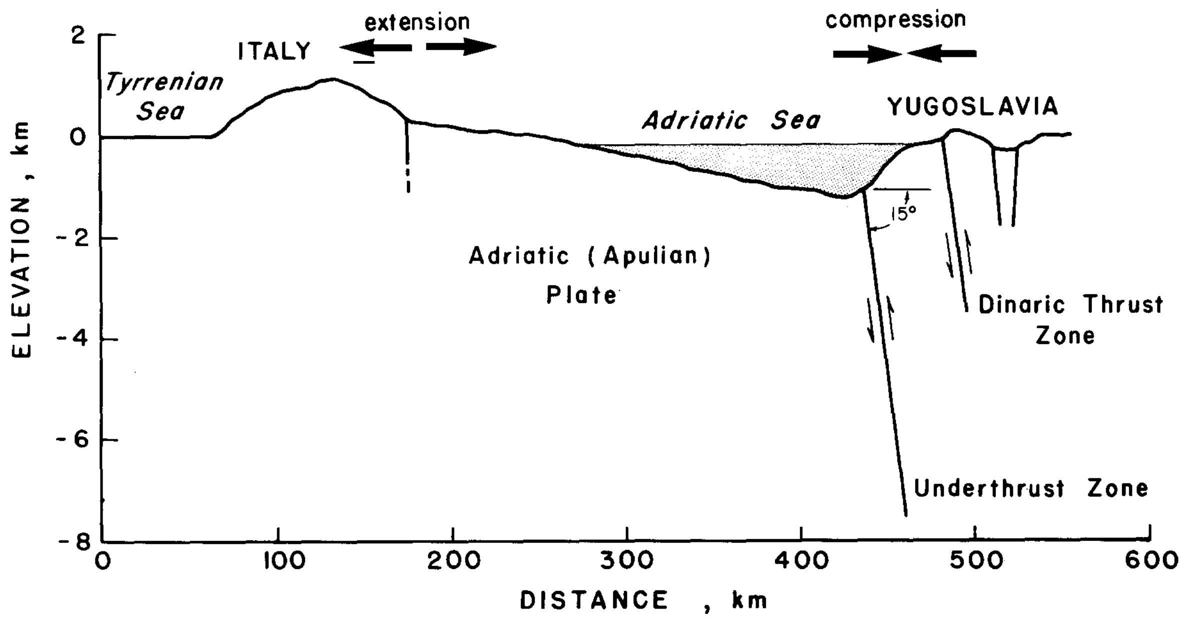

Fig. 3. Schematic southwest to northeast cross-section from Italy across the Adriatic Sea to Yugoslavia. The Montenegro earthquake probably occurred on the underthrust zone. The apparent steepness of the fault zones is an artifact of the vertical exaggeration (×30) of the cross-section. Actual dip is probably 15° or less.

distances (with 1500 km), Console and Favali (1981) have also found a fault plane with a NW–SE strike. The plane dips steeply (85°) to the northeast, however, and the slip on the plane has a significant component of right lateral motion. It appears from the stereographic projection shown in their paper that our solution agrees with their data if a few inconsistencies are allowed. Although not mentioned by Console and Favali, both the CSEM and the NEIS reported a foreshock 6 s before the mainshock. This may make it difficult to pick the first motion of the mainshock and might explain the inconsistencies.

The geology of the area favors plane B in Fig. 2 as the fault plane, with thrust of the Yugoslavian mainland over the Adriatic crustal block (Apulian plate of Lort, 1971). Geologic evidence for this interpretation is: (1) large-scale westerly and southwesterly thrusting in the Dinarides of Cretaceous limestones and Triassic and Jurassic ophiolites over Tertiary rocks along the Dinaric thrust zone (Fig. 3): (2) uplifted Holocene and Pleistocene(?) marine terrace deposits along the youthful Adriatic coast (Gachelin, 1977). Under-thrusting of the Adriatic block under the mainland may occur on the offshore fault shown as the boundary between the Adriatic and Dinaric masses (Sikoseka and Prosena, 1979). Thrust faulting on plane B is consistent with the tentative tectonic interpretation of McKenzie (1972) in which the Adriatic block converges on the European mainland with right-lateral thrusting motion. The distribution of

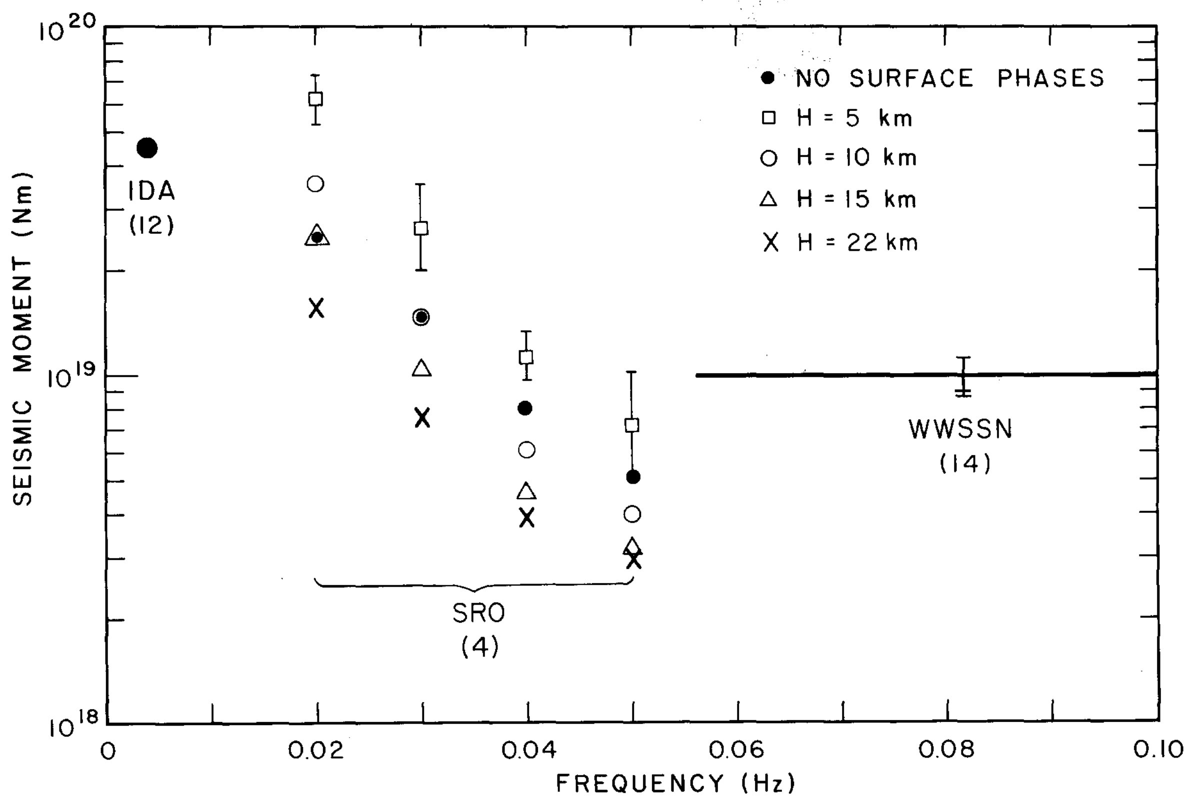

Fig. 4. Seismic-moment estimates. Number of records used in estimate in parentheses. Influence of source depth shown for SRO data. Bars are standard error of the means (shown for one source depth; errors for other points are similar). Logarithmic averages were used to compute means except for IDA estimate, based on an arithmetic mean. WWSSN estimates were based on first extreme of P- and S-wave arrivals with dominant periods about 10 and 20 s, respectively, and were only slightly affected by source depth. SRO estimates at each frequency were made assuming that the observed spectral level equalled the long-period spectral level. Corrections were made for instrument response, geometric spreading, radiation pattern, and attenuation ($t^*=4$).

the intensity and strong ground motion is consistent with the strike of the prospective fault planes (subparallel to the coast) but is of little help in determining on which plane the faulting took place.

4. Source strength

The strength of the earthquake can be measured by its magnitude and moment. The seismic moment (M_0) was estimated from 256 s Rayleigh waves recorded on the IDA network, S waves from the SRO stations, and P and SH waves recorded on the long-period instruments of the WWSSN (Fig. 4). M_0 estimates for the WWSSN data were obtained by scaling the synthetic seismograms to the initial part of the body-wave pulses. Frequency domain estimates of M_0 were obtained from SH pulses formed by rotating the SRO data. The increase of moment with period is quite large, although not without precedence (e.g. Reyes et al., 1979), and may be evidence for a complex source. Destructive interference in the radiation from a complex source would help explain the high-frequency trend toward low estimates of moment from SRO spectral data, compared to the WWSSN time-domain estimates. Considerable oscillation in moment estimates can be expected from spectra at higher frequencies. Clearly, the long-period Rayleigh-wave moment is a more meaningful measure of the overall strength of faulting than are the body-wave moments from waves of less than about a 33-s period.

The surface-wave magnitude published by the NEIS was 7.0 (Preliminary Det. Epicenters, No. 14-79). On examining the data, we find that this value may be biased to the high side by an abnormally large estimate from the South Pole station (SPA) of 7.6 and by a cluster of six stations in the narrow source-to-station azimuth range of 304–328° that gave values of M_s between 7.1 and 7.4. The remaining nine stations that reported surface wave measurements gave M_s equal to 6.8 or less. A weighted average based on these considerations would yield an M_s of about 6.6 or 6.7, which is consistent with the observed moment of about 10^{19} Nm at periods near 20 s (using the relation $\log M_0 = 1.5\,M_s + 9$, M_0 in Nm; Hanks and Kanamori, 1979).

5. Discussion

Although our major goals—finding the source-orientation and strength—have been accomplished, we would like to discuss some features of the WWSSN long-period body waves that are relevant to a more detailed description of the source. Figures 5 and 6 show P and S waves arranged by source-to-station azimuth.

Notice the strong phase indicated by the label '1' in both figures. It is most obvious for south to south-east source-to-station azimuths and follows the initial arrivals by ca. 20 s. No second arrivals due to earth structure are expected in this time and distance range. The conclusion is that the phase must be related to the source. The strong S-wave portion of the near-source accelerograms have a duration of no more than 10 s, thus ruling out a multiple event as the cause of the phase (unless it was produced by a slow earthquake that radiated little energy in the frequency band of the accelerograph). Another possibility is that it is a wave reflected from the free surface above the source. This puts the source depth close to 40 km. A difficulty with this explanation is that the phase does not appear on the S waves at northwestern azimuths (GEO, AAM, GDH, among others), even though the theoretical results predict that it should be as noticeable there as at the southerly azimuths (Fig. 7).

Another candidate for a source phase is labeled '2' in Fig. 5. This phase is most obvious at stations in the third column of the figure, but it can be picked out on most of the stations (although PcP is expected at approximately the same time for stations beyond about 80°). Again, the existence of this phase at distances from 37° (KBS) to 87° (DUG) requires that it come from the source region. The time after the first P-arrival of 8–10 s puts the depth at 22 km if the phase is a surface reflection. Theoretical seismograms from a point source at this depth fit a considerable portion of some of the S-waves (e.g. GDH in Fig. 7) quite well, but are not as successful at other stations

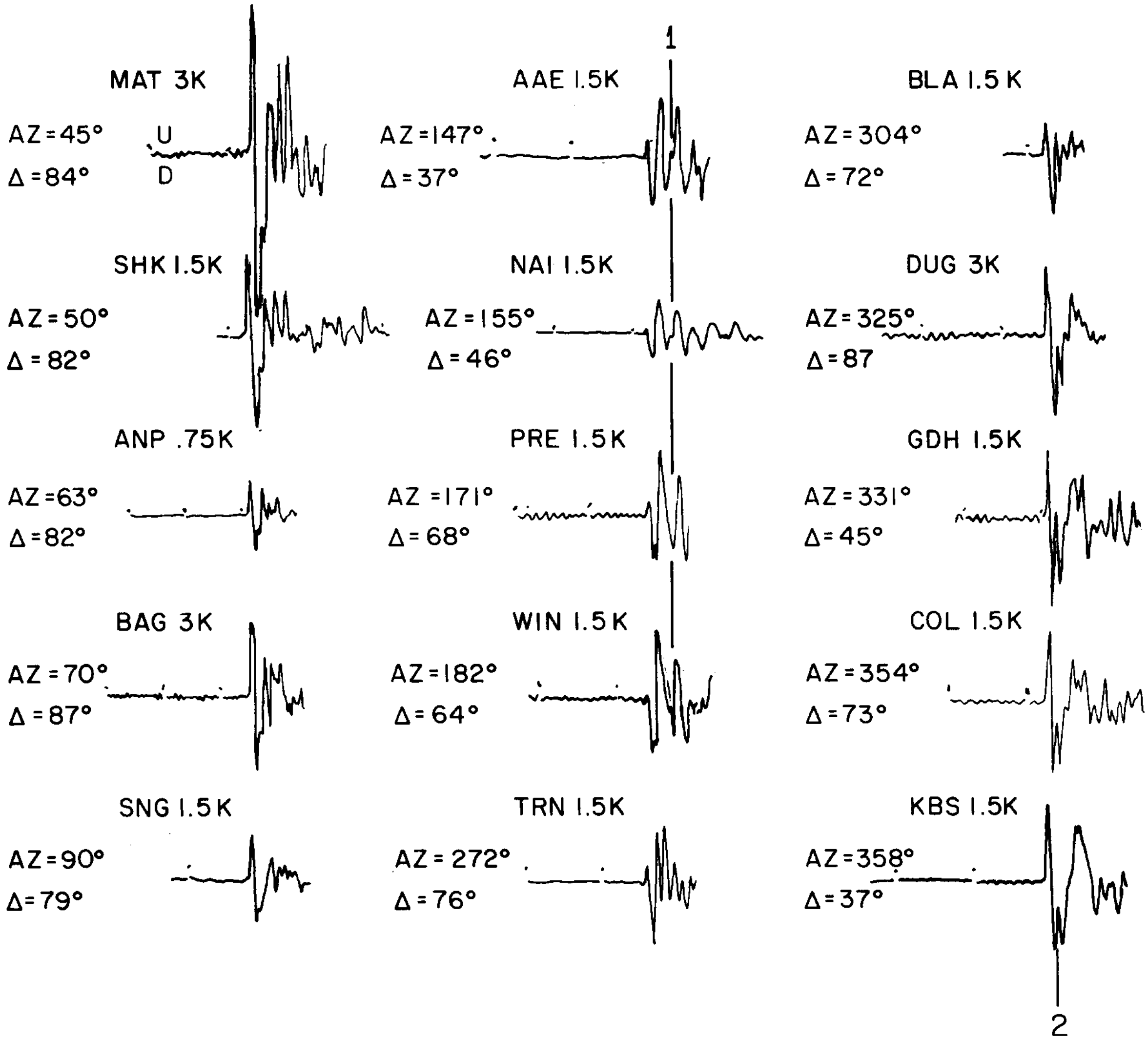

Fig. 5. Tracings of P waves arranged according to source-to-station azimuth (AZ). The magnification follows the station abbreviation. Phases 1 and 2 are discussed in the text.

(WIN, Fig. 7). The fit of the synthetic records to the P waves is quite poor, however (Fig. 8). Consider GDH, which shows the phase very clearly. The model using the preferred source orientation (pure thrusting on plane A in Fig. 2) shows only an inflection point at the appropriate time. With this fault orientation both pP and sP have negative signs and thus force the motion in the downward direction. pP is close to a node, however, and it is possible to change its sign by using plane A′ in Fig. 2. The sP phase dominates, however, even for the most extreme rake angles allowed by the first motions, and therefore it is not possible to make the downward motion return as rapidly as the observations demand (and even if it were possible, the obvious nodal character of the first motion at stations in the middle column of Fig. 5 rules out plane A′).

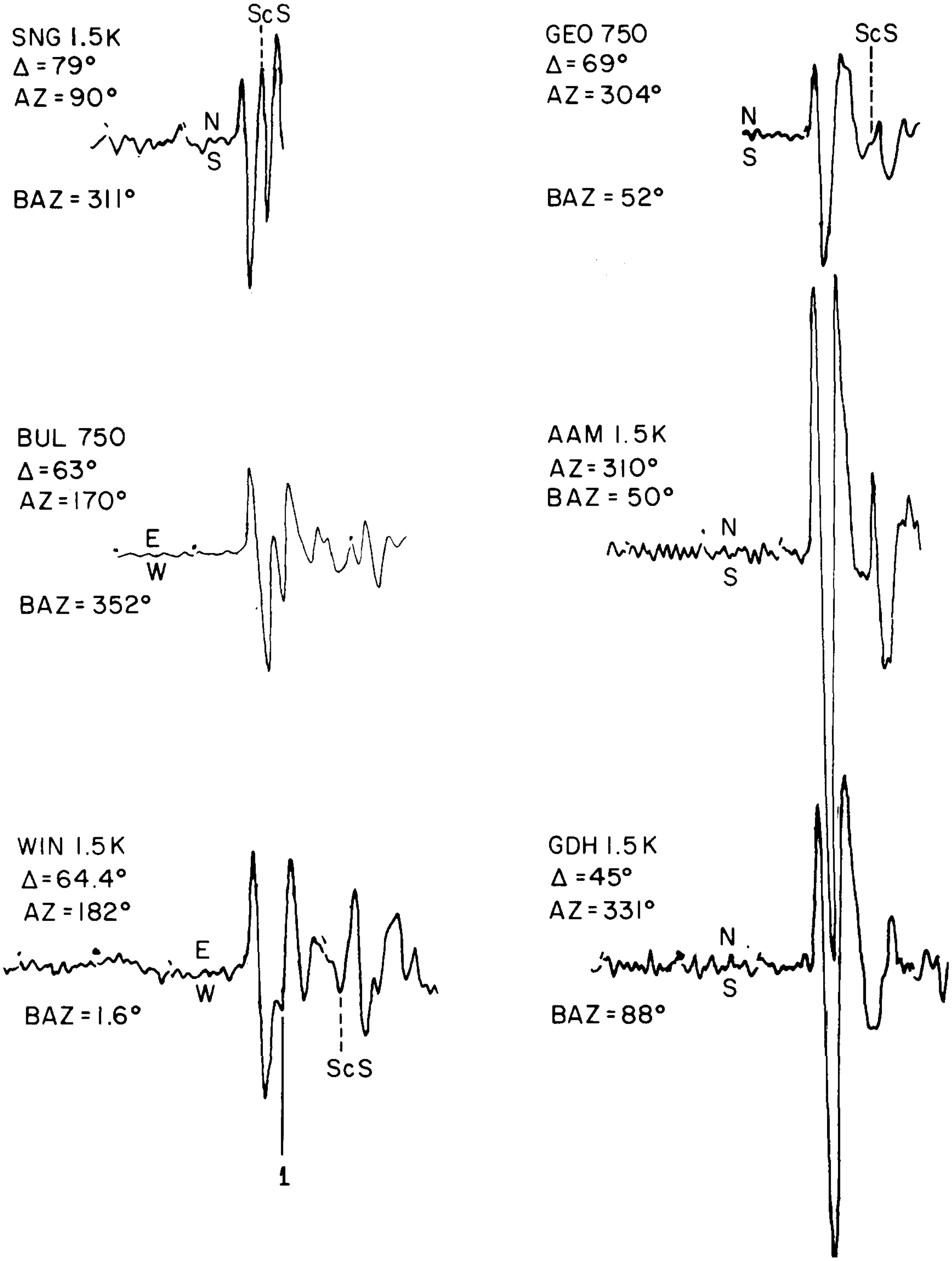

Fig. 6. Tracings of S waves arranged by source-to-station azimuth (AZ). The station-to-source (back) azimuth is given by BAZ. The S waves are predominately SH, being either naturally polarized into the transverse direction or having a transverse polarization, as seen by correlating both horizontal components (not shown).

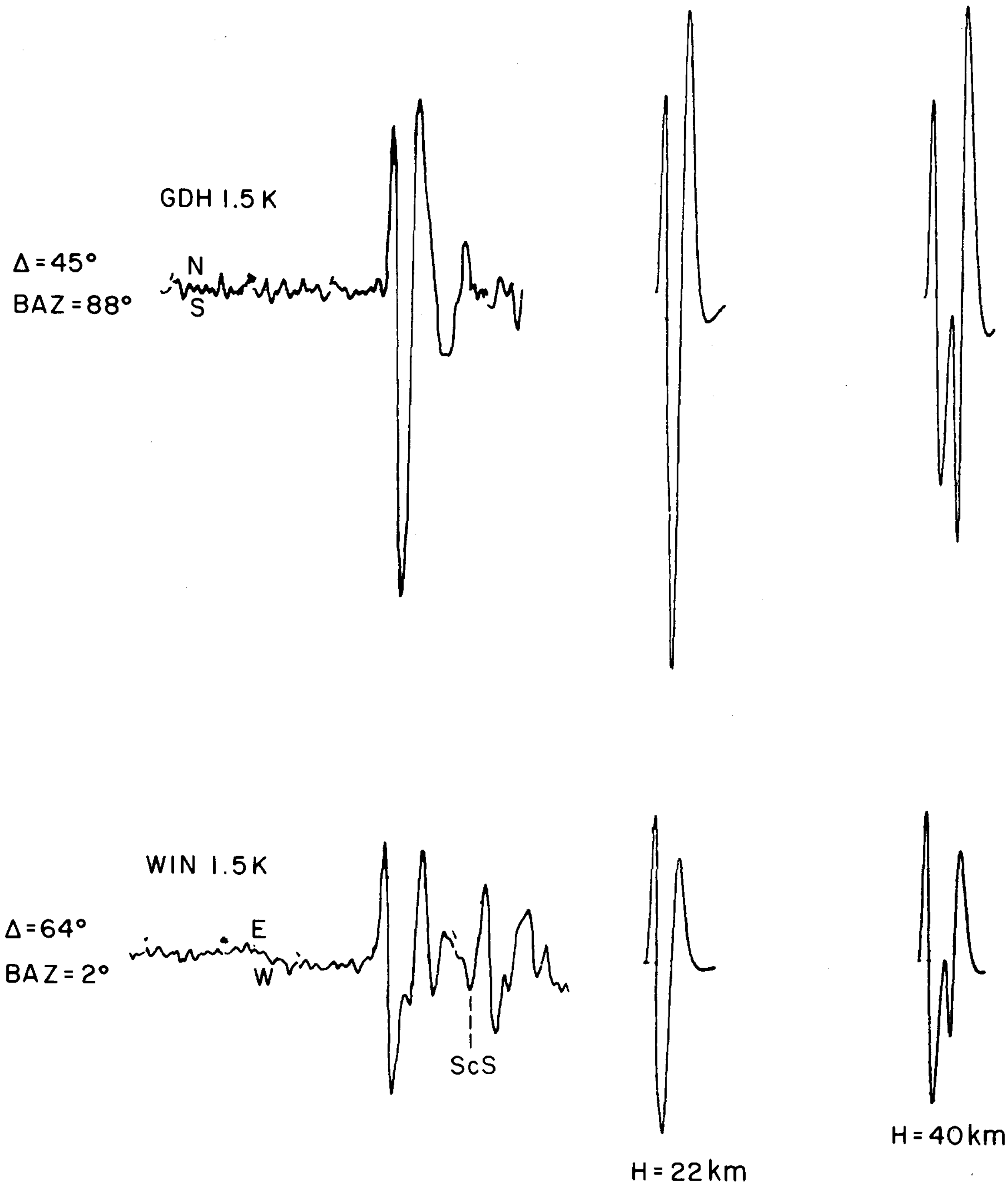

Fig. 7. Observed and theoretical S waves from a point-source model located at the depth indicated. All theoretical calculations assumed $t^*=4$ and a moment of 1.0×10^{19} Nm. The theory and data are plotted to the same scale. The derivative of the source time-function was approximated by a trapezoid with durations of 0.5 and 4.0 s for the shoulders and central section, respectively. A rake angle of 90° (pure thrust) was used for plane A of figure 2.

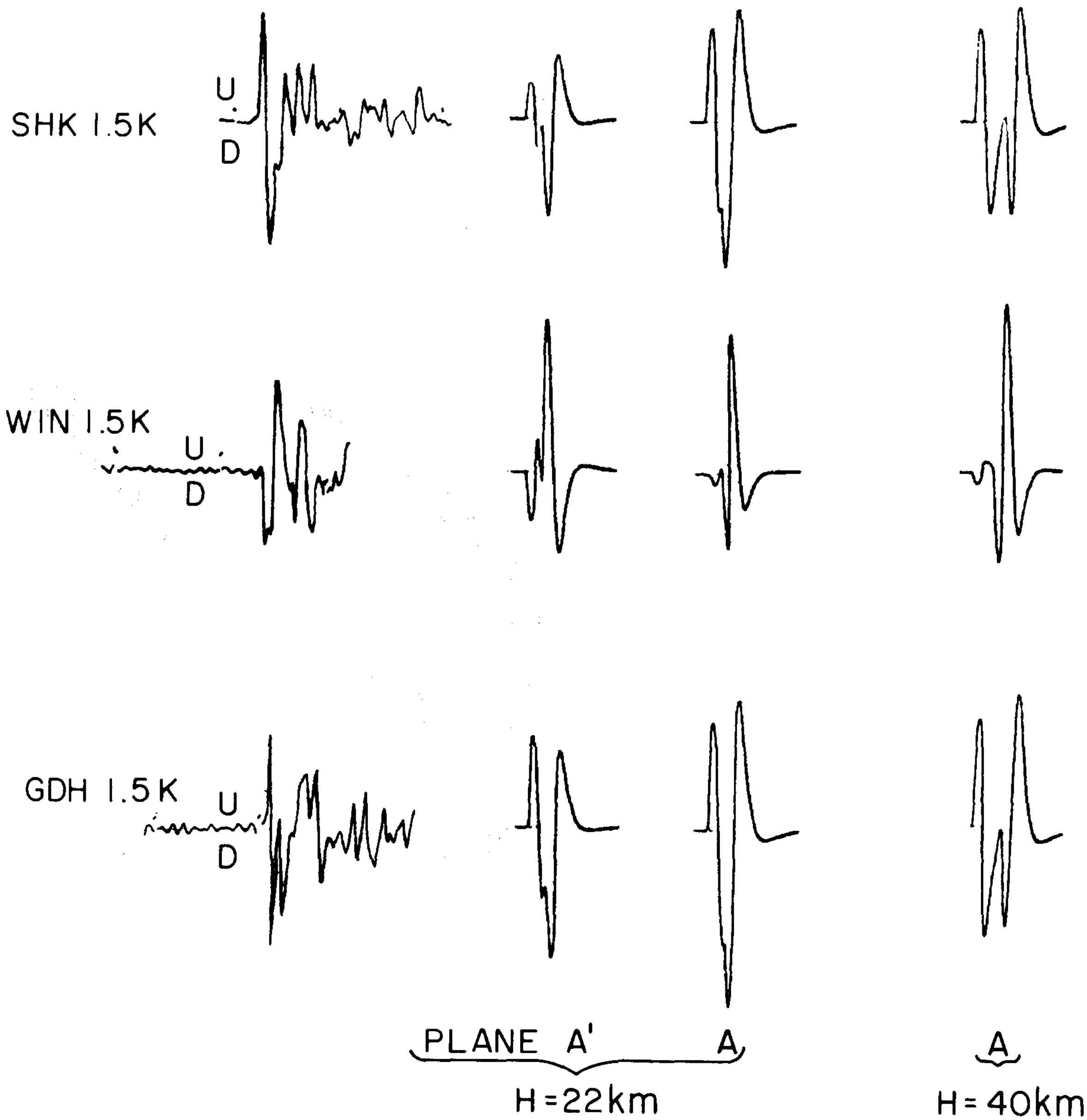

Fig. 8. Observed- and theoretical-P waves, as in Fig. 7 except a rake angle of 50° (left-lateral, thrust) was used on plane A′ and $t^* = 1$.

What we are left with is clear observational evidence for several phases coming from the source region, but with conflicting and inconsistent interpretations if a simple, point-source model is used. It may be possible to explain the observations by invoking an extended-source model, dipping layers, a complex earthquake, and surface reflections, but such a study is beyond the scope of this paper. The comparison of data and synthetic motions shown in Figs. 7 and 8, however, does support the claim made earlier that the moment estimated from the initial part of the body-wave pulses is not a sensitive function of source depth or orientation. The comparison also shows that the moments estimated from both P and S waves are consistent.

6. Summary and conclusion

In conclusion, we have found that the Montenegro, Yugoslavia, earthquake of April 15, 1979, ruptured along a shallowly dipping plane striking more or less parallel with the coastline, with predominately thrust motion. The earthquake is consistent with McKenzie's (1972) hypothesis of the convergence of the Adriatic block and the European mainland. The seismic moment was found to increase with period, with 250-s Rayleigh waves giving a moment of 4.0×10^{19} Nm. Inconsistencies were found in attempting to predict obvious source-related phases with simple, point-source models. This and the related frequency-dependent moment determinations may indicate that the source was relatively complex. If so, it is possible that the inferred orientation and strength may depend on the period of the waves used in the interpretation. In particular, it may have been improper to use P-wave first motions to constrain the fault plane used in the inversion of 256-s Rayleigh waves. Inverting the long-period Rayleigh waves under various assumptions regarding fault planes and source depths, however, support the overall conclusions of this study.

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References

Anicic, D., Berz, G., Boore, D., Bouwkamp, J., Hakenbeck, U., McGuire, R., Sims, J. and Wieczorek, G., 1980. Reconnaissance report: Montenegro, Yugoslavia earthquake April 15, 1979 (R.B. Matthiesen, coordinator), Earthq. Engineering Res. Inst., Berkeley, Calif.

Console, R. and Favali, P., 1981. Study of the Montenegro earthquake sequence (March–July 1979). Bull. Seismol. Soc. Am., 71: 1233–1248.

Gachelin, C., 1977. Neotectonique et geomorphologie du Montenegro littoral. Mediteranee, 31: 19–37.

Hanks, T.C. and Kanamori, H., 1979. A moment magnitude scale. J. Geophys. Res., 84: 2348–2350.

Kanamori, H. and Given, J.W., 1981. Use of long-period surface waves for fast determination of earthquake-source parameters. Phys. Earth Planet. Inter., 27: 8–31.

Kanamori, H. and Stewart, G., 1976. Mode of the strain release along the Gibbs fracture zone, mid-Atlantic ridge. Phys. Earth Planet. Inter., 11: 312–332.

Lort, J.M., 1971. The tectonics of the eastern Mediterranean: A geophysical review. Rev. Geophys. Space Phys., 9: 189–216.

McKenzie, D., 1972. Active tectonics of the Mediterranean region. Geophys. J. R. Astron. Soc., 30: 109–185.

Nedeljkovic, S., Krstanovic, M., Kovacevica, V., Knezevic, V. and Radovanovic, I., 1979. Analysis of instrumental earthquake data obtained from seismological stations at Belgrad, Titograd, Valandovo, Ohrid and Skopje. Karakteristike Zemljotresa od 15.04.1979.GOD. Seizmol. Zovod SR Srbije –Beograd, Seizmol. Stamica SR Crne Gore–Titograd, pp. 163–185 (in Serbian).

Petrovski, D., Naumovski, N., Zelenovic, V. and Stamatovska, S., 1980. Strong-motion accelerograms, digital and plotted data. V.II-uncorrected data, Part E, accelerograms IIE55–IIE68. Inst. Eqk. Engr. Engr. Seis., Univ. "Kiril and Metodij", Skopje, Yugoslavia.

Reyes, A., Brune, J.N. and Lomnitz, C., 1979. Source mechanism and aftershock study of the Colima, Mexico earthquake of January 30, 1973. Bull. Seismol. Soc. Am., 69: 1819–1840.

Sikoseka, B. and Prosena, D., 1979. The attempt of the defining of focus position of the earthquake of April 15, 1979, on the Montenegro coast, according to the existing seismological and geophysical data. Karakteristike Zemljotresa od 15.04.1979.GOD. Seizmol. Zavod SR Srbije–Beograd, Seizmol. Stamica SR Crne Gore–Titograd, pp. 279–310 (In Serbian).