Topic	Earthquake location at teleseismic distances from 3-component records (Tutorial with exercise by hand)
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Version	October 2002; **DOI: 10.2312/GFZ.NMSOP-2_EX_11.2**

1 Aim

This exercise and tutorial aims at making you familiar with the basic concept of locating seismic events by means of teleseismic records from single 3-component stations. Often the results are comparably good or even better than for uncalibrated single seismic arrays.

The exercise uses teleseismic events only although the procedure outlined below is the same for local seismic events. In the latter case local travel-time curves as in Exercise EX 11.1 have to be used for phase identification and distance determination. Note however that azimuth determinations for local events are less reliable when short-period records are used. They are much more influenced by local heterogeneities in the crust than teleseismic long-period or broadband records. Accordingly, particle motion might deviate significantly from linear polarization (see Chapter 2, Fig. 2.6) and the azimuth of wave approach for local events sometimes deviates more than 20° (+ 180°) from the backazimuth AZI towards the source (see Chapter 11, Fig. 11.23).

2 Data

The following data are used in the exercise:

- two 3-component earthquake records: a) Kirnos BB-displacement seismograms (Figure 2) and b) long-period (WWSSN-LP) seismograms (Figure 3);
- simplified differential body-wave travel-time curve (with respect to the P-wave first arrival) for the distance range 0° < D ≤ 100° (Figure 4) according to the classical Jeffreys-Bullen (1970) travel-time curves;
- IASP91 table (Kennett, 1991) of travel-time differences pP-P and sP-P, respectively, as a function of epicentral distance D (in degree) and source depth h (in km) (see Table 1);
- global map of epicenter distribution with isolines of epicentral distance D (in °) and principal directions of backazimuth AZI from station CLL (Germany).

3 Procedure

3.1 Assessment of the earthquakes distance and depth range, identification of essential phases, estimation of epicentral distance D and depth h

- Identification of the very first as well as of later secondary arrivals from teleseismic events in broadband or long-period filtered records. At least P and S have to be identified. P is the first arrival (up to about 100°). For teleseismic events (D > 20°) P has its largest amplitude in the vertical component. S is the first arriving shear wave, up to about 83°, and has its largest amplitudes in horizontal components. For larger distances SKS becomes the first arriving shear wave (see t-D curves in Figure 4 and record examples in Figures 10c, 12d, 14e and 15b of DS 11.2). Misinterpreting it as S might result in significant underestimation of the epicentral distance.

- Determination of epicentral distance D by using the travel-time difference t(S-P) according to travel-time tables (e.g., IASPEI91; Kennett 1991) or by fitting best a set of differential travel-time curves as in Figure 4 with the identified phases in the record. Note that the records and the t-D-curves must have the same time scale. In the distance range 20° < D < 85° the following *rule-of-thumb* allows to determine D with an error < 3°:

$$D\ [°] = [t(S\text{-}P)_{[min]} - 2]\times 10. \qquad (1)$$

- Note, that the travel-time difference t(S-P) but also the time difference between P or PKP (beyond 105°) with other secondary phases is influenced by the source depth h. Unrecognized significant source depth might result in underestimating D by several degrees. Accordingly, it is important to assess first whether an event was deep or shallow (i.e., probably within the crust).

- For a first rough discrimination between deep and shallow earthquakes one should compare the amplitudes of body waves with that of (dispersed!) surface waves. If the latter are well developed and significantly larger in amplitude than the earlier body waves, then the event can be considered a crustal earthquake. If, however, the long-period surface waves have much smaller amplitudes than the earlier body waves or are not recognizable at all, then the earthquake is surely deeper than 100 km.

- The identification of depth phases (see Chapter 2, Fig. 2.43) is difficult for shallow events, because then they follow within a few seconds to the primary P or S onset. One may then use travel-time curves or tables for surface focus (h = 0 km) or "normal depth" events (h = 33 km) for estimating the distance. In any event, if D >> h, the error in distance estimate is usually negligible.. They are crucial for improving hypocenter locations.

- However, in the case of relatively weak or absent surface waves one should look for depth phases! They are crucial for improving hypocenter locations (see discussion in section 11.5.4 of Chapter 11 and Figure 7 in IS 11.1). Examples for depth phases are given in DS 11.2, Figures 7b, 9a, 16b and in DS 11.3, Figures 3b-d and 5a. If depth phases such as pP and/or sP have been identified, h can be calculated rather reliably when the epicentral distance is roughly known. One may use for it either the differential travel-times pP-P or sP-P (see Table 2), or,if such tables are not at hand, roughly estimate h by another rule-of-thumb:

$$h\ [km] \approx 0.5\ t(pP\text{-}P)\ [s] \times n \qquad (2)$$

  with n = 7, or 8, or 9 for h < 100 km, 100–300 km, or…× **9** h > 300 km.
- Generally, when interpreting seismic records you should proceed as follows:

Take interest! Be curious! Ask questions!
to your seismic record

1.	**Is the event**	**NEAR** (D < 20°)	**or TELESEISMIC** (D > 20°)?
Criteria:			
• **Frequencies**	on SP records	**f ≥ 1 Hz**	**f ≤ 1 Hz**
• **Amplitudes**	on LP records	**not or weaker**	**large, also for later phases**
• **t(S-P)**		**< 3.5 min**	**> 3.5 min**
• **Record duration**		**< 20 min**	**> 20 min**
	(for magnitudes < 5; may be longer for strong earthquakes)		

2.	**Is the event**	**SHALLOW or**	**DEEP** (> 70 km)?
Criteria:			
• **Surface waves**	on LP records	**strong**	**weak or none**
• **Depth phases**	usually	**not clear**	**well separated and often clear**
• **Waveforms**	usually	**more complex**	**more impulsive**

3.	**Is the event**	**D < 100°**	**or**	**D > 100° ?**
Criteria:				
• **Surface wave max.**	after P arrival	**< 45 ± 5 min**	or	**> 45 ± 5 min** (Table 5 in DS 3.1)
• **Record duration**	on LP records	**< 1.5 hours**	or	**> 1.5 hours**
	(may be larger for very strong earthquakes)			

4. Is the first strong horizontal arrival		**S**	**or**	**SKS ?**
Criteria:				
• **Time difference to P**		**< 10 ± 0.5 min**		**≈ 10 ± 0.5 min**
• **Polarization**	large horiz. A	**in R and/or T**		**in R only**

Warning ! If the first strong horizontal arrival follows P after ≈ 10 ± 0.5 min it may be SKS. **Check polarization** (see 11.2.4.3 in Chapter 11). R and T are the radial and transverse horizontal components, respectively. Misinterpreting SKS as S may yield D estimates up to 20° too short. Look also for later multiple S arrivals (SP, SS, SSS) with better D control.

5. What are the first longitudinal and transverse onsets for D > 100° ?

Beyond 100° epicentral distance phase interpretation and distance determination from travel-time differences between secondary phases becomes more difficult. A long-period P may still arrive first, up to about almost 150°, yet with steadily decreasing amplitude and therefore recognizable only in records of strong earthquakes. But this P did not travel a direct mantle path, rather it has been diffracted around the core-mantle boundary. Therefore, it is termed Pdif (old nomenclature Pdiff; see Figs. 11.59 and 11.63 in Chapter 11). First onsets in SP records, however, are beyond 100° usually the later arriving PKiKP and PKPdf (Fig. 11.59), or, somewhat later PP. The latter is often the first strong longitudinal Z-component arrival in both SP, LP and BB records (see Figs. 11.60 and 11.63). The first strong arrivals on horizontal (R) components are PKS or SKS.

Misinterpretation of these first strong longitudinal and transverse wave arrivals as direct P and S, respectively, may result in epicentral distance estimates up to more than 70° too short! This, however, can be avoided by taking the criteria **3.** above into account. Also note, that the travel-time difference between PKPdf and PKS or SKS is (almost) independent of distance. Therefore, these first arriving P and S waves do not allow distance to be estimated from their onset-time difference. Rather look for later arriving multiple-reflected S waves such as SS, SSS, etc. They are usually well developed in this distance range on horizontal LP records, have a large slowness difference with respect to earlier arriving core phases and thus allow D to be estimated with an error of usually < 2°.

3.2 Estimation of backazimuth AZI

- Identify the proper direction of P-wave first motion in the three components Z, N, E. Make sure by exact time correlation that you really compare the same first half cycles in all three records! This is particularly important, if in one of the horizontal components the first onset is very weak or near to zero. Then one might be misled and associate the stronger amplitude of a later half cycle with the first motion in the other components and gets a wrong backazimuth.
- Determine the **direction of particle motion AZI** in different horizontal quadrants from the amplitudes of first motions in the horizontal component records according to the formula

$$\mathbf{AZI = arc\ tan\ (|\,A_E/A_N|\,)} \qquad (3)$$

- If seismograph components have been calibrated properly and avail of identical frequency responses (which is the case for the records used in the two exercises below) then one just calculates the ratio between measured trace amplitudes. However, as demonstrated in Figure 1, the direction AZI may either show **towards the epicenter,** in case the first motion in Z is down (-, dilatational; see blue record traces), or away from the epicenter in the direction of wave propagation if the first motion in Z is up (+, compressional; see red record trace). In the latter case, the backazimuth BAZ, measured clockwise from north towards the source epicenter as seen from the station) is BAZ = AZI + 180°.

- But the conversion from AZI into BAZ depends on the quadrant of particle motion and thus the polarity patterns in the three components. Table 1 guides you how to determine the quadrant of horizontal particle motion and then to calculate BAZ from measured AZI.

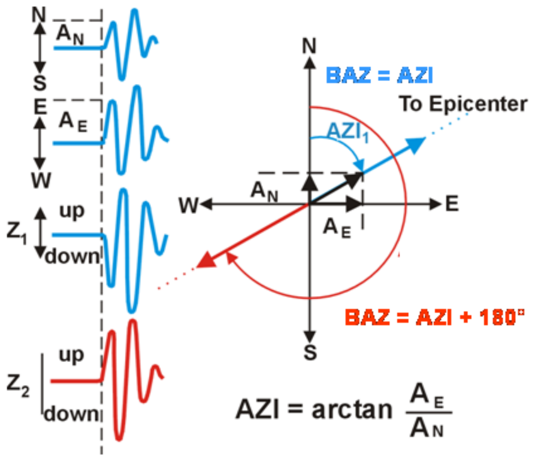


Figure 1 Synthetic example of P-wave first motions in 3-component records (left) from which the azimuth AZI (clockwise from north towards the direction of wave-propagation), respectively the backazimuth BAZ (clockwise from north towards the direction of the source as seen from the station) can be calculated.

Table 1 How to identify the quadrant of AZI measurement and to calculate BAZ from AZI.

Z	N-S	E-W	AZI	BAZ
–	+	+	1st quadrant	BAZ = AZI
–	–	+	2nd quadrant	BAZ = 180° - AZI
–	–	–	3rd quadrant	BAZ = 180° + AZI
–	+	–	4th quadrant	BAZ = 360° - AZI
+	+	+	1st quadrant	BAZ = 180° + AZI
+	–	+	2nd quadrant	BAZ = 360° - AZI
+	–	–	3rd quadrant	BAZ = AZI
+	+	–	4th quadrant	BAZ = 180° - AZI

- If this 180° ambiguity has been resolved by taking into account the P-wave vertical component first motion polarity then one may also calculate BAZ from horizontal component records of either later cycles of P with larger amplitudes or even by using the amplitude ratio in E/N from other later phases that are polarized in the vertical propagation plane such as PP, SKS, SP etc.

3.3 Event location using the estimated epicentral distance D and backazimuth BAZ

- You may use a sufficiently large globe (diameter about 0.5 to 1 m), mark there the position of your station and then use a bendable ruler with the same scale in degree as your globe and an azimuth dial to find your event location on the globe.
- Another possibility is that you get a regional (Figure 5) or global map projection (Figure 6) which shows isolines of equal azimuth and distance from your station. Such maps can nowadays easily be calculated and plotted for any station with known co-ordinates together with the seismicity pattern.

4 Data used for the exercise

- 3-component broadband displacement records of an earthquake plotted in Figure 2;
- 3-component long-period WWSSN records of an earthquake plotted in Figure 3;
- Simplified differential travel-time curve according to the Jeffreys-Bullen model for the distance range up to 100°;
- Regional map for Europe and the Mediterranean with earthquake epicenters and isolines of D and BAZ with respect to station MOX, Germany;
- World map with epicenters and isolines of D and BAZ from station CLL, Germany;
- Table 2 of travel-time differences pP-P and sP-P as a function of distance D and depth h according to the IASP91 travel-time tables (Kennett, 1991).

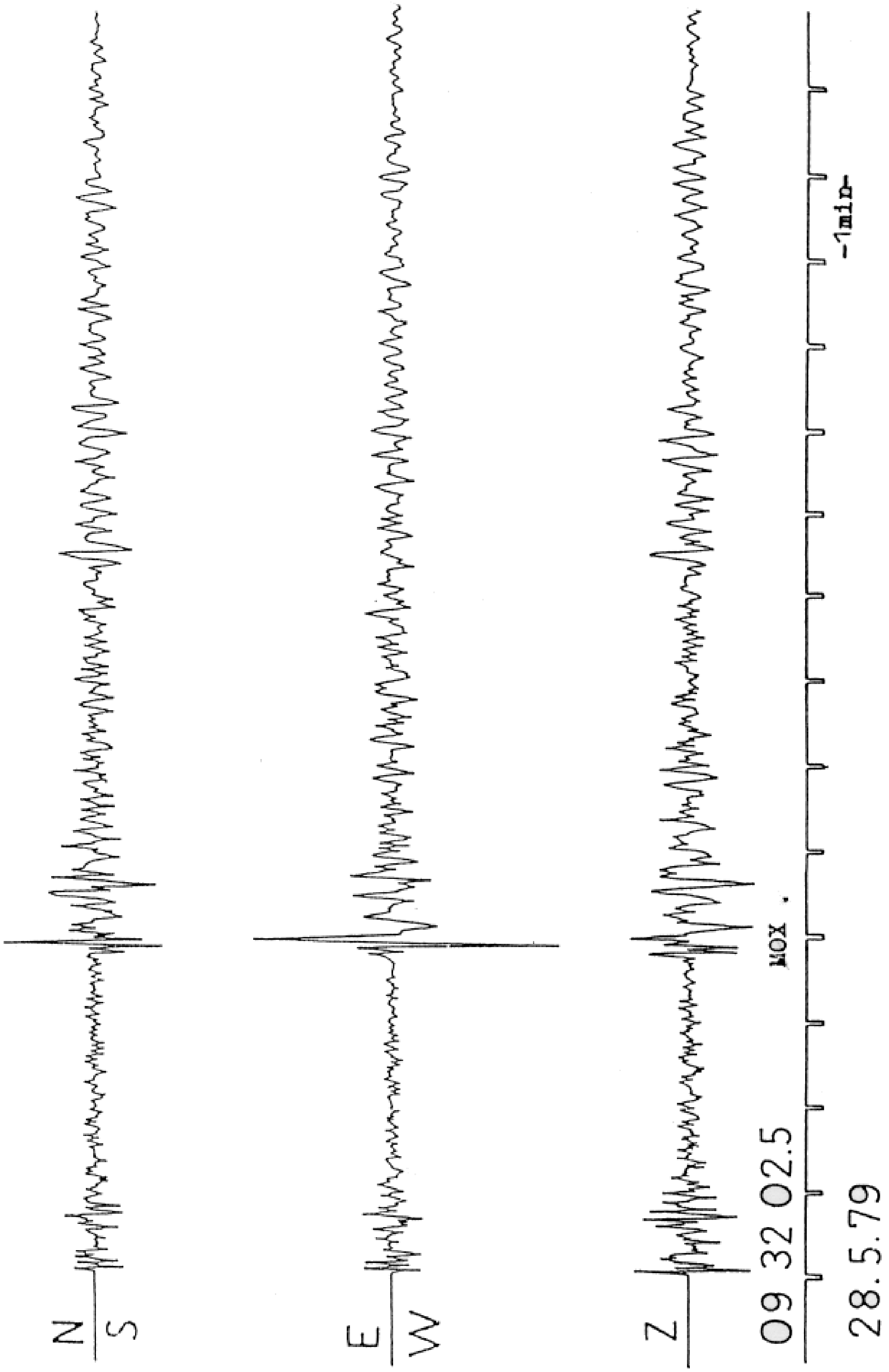


Figure 2 3-component record of a Kirnos BB-displacement seismograph at station MOX, Germany. For response see Fig. 3.11 in Chapter 3. Original time-scale of the analog record was 15 mm/minute. All components were properly calibrated and had identical magnification.

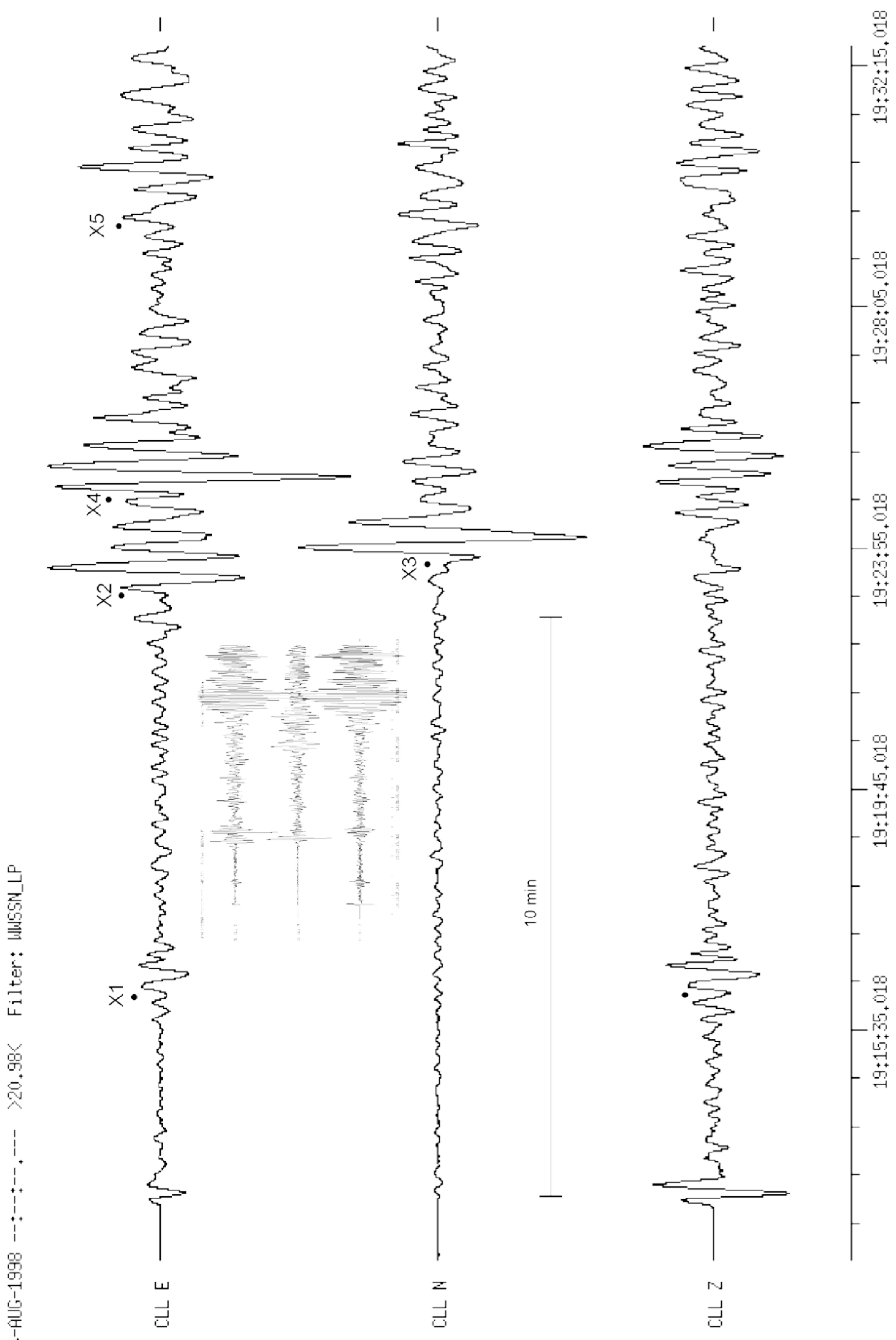


Figure 3 **A** long-period 3-component body-wave record section (WWSSN-LP simulation) of station CLL, Germany. **<u>Insert</u>:** Complete event record at compressed scale.

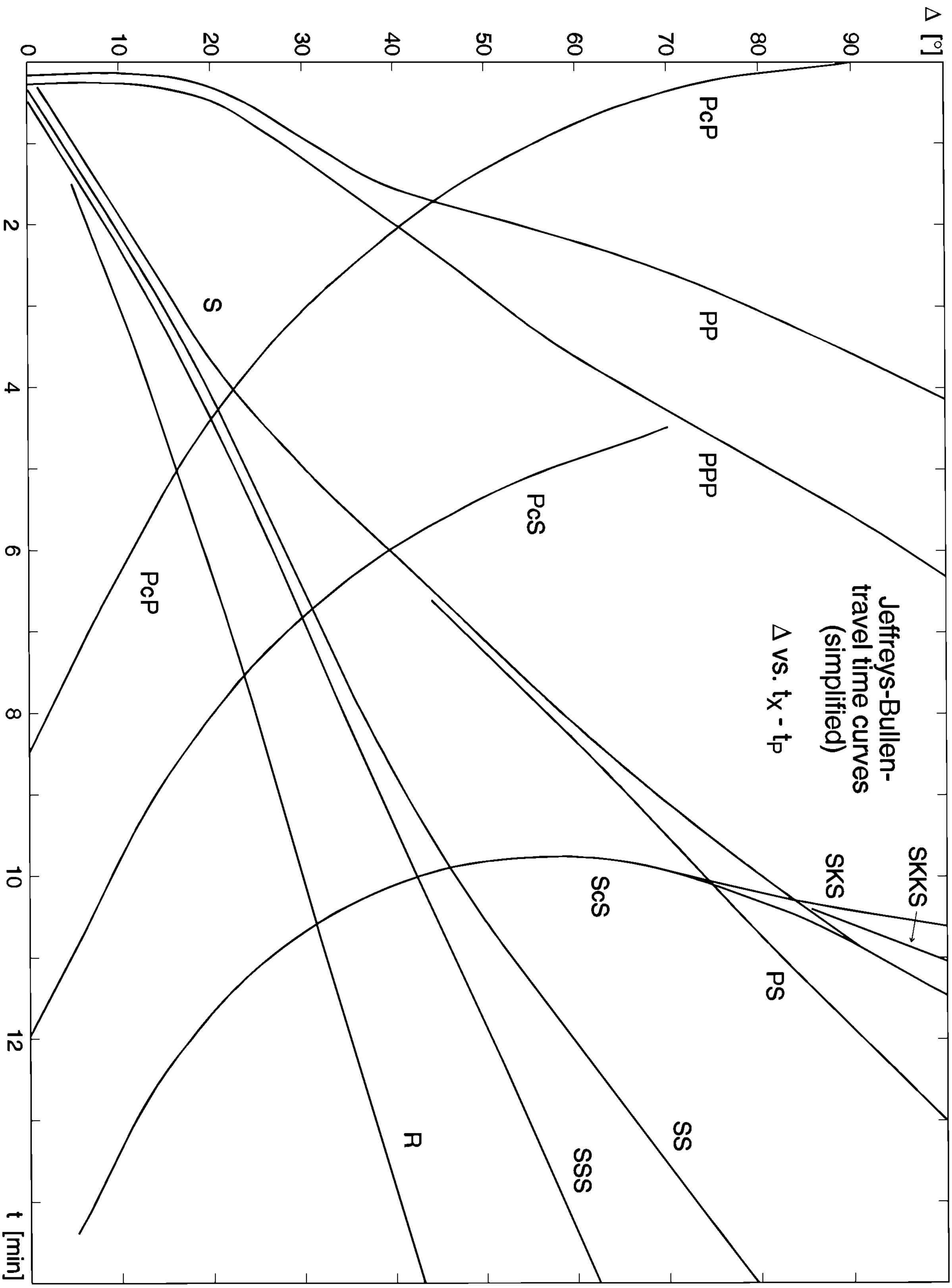


Figure 4 Simplified Jeffreys-Bullen differential travel-time curve in the distance range 0° < D ≤ 100°. Original time scale was 15 mm = 1 min.

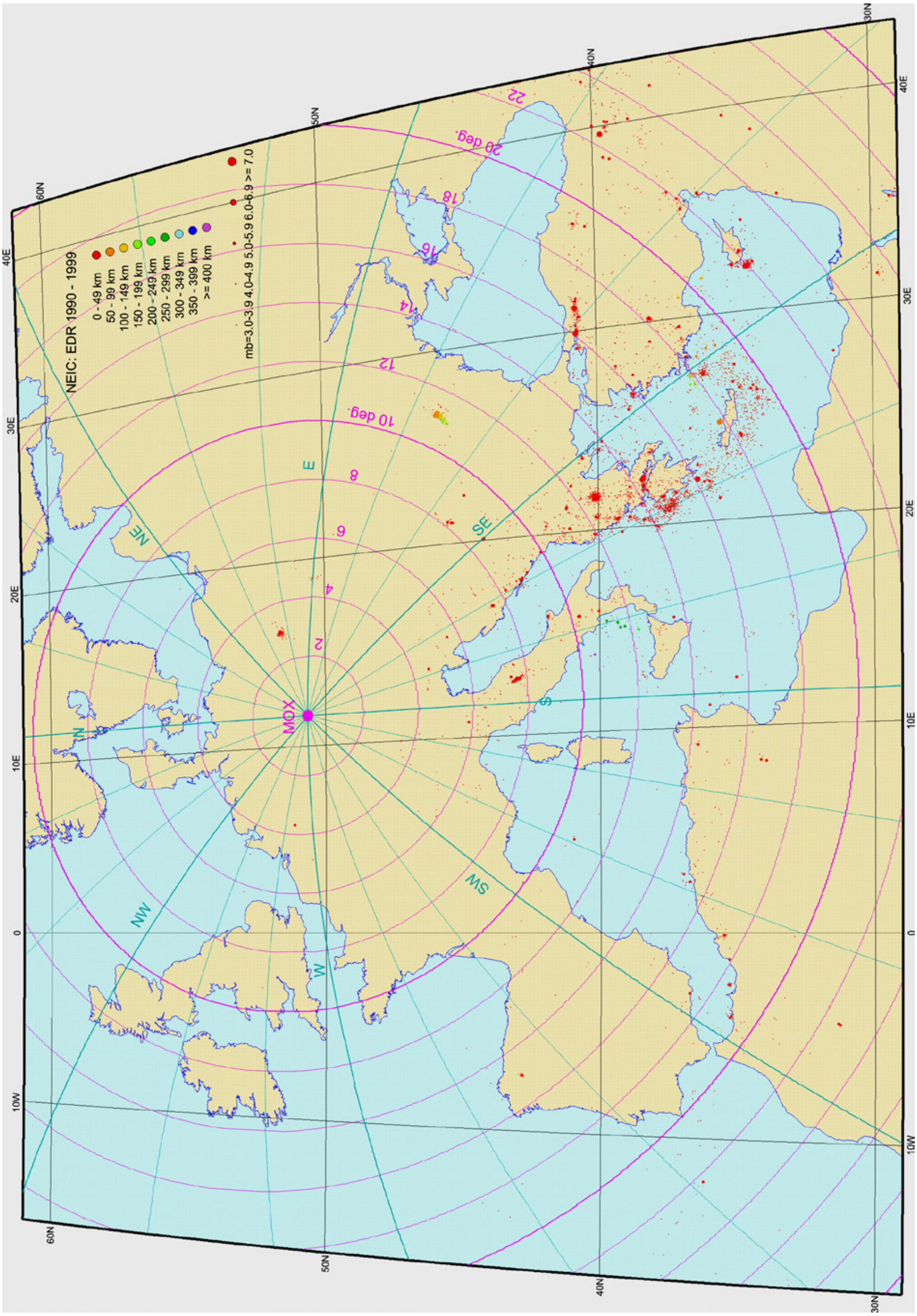


Figure 5 Regional map for Europe and the Mediterranean with earthquake epicenters and isolines of D and AZI with respect to station MOX, Germany.

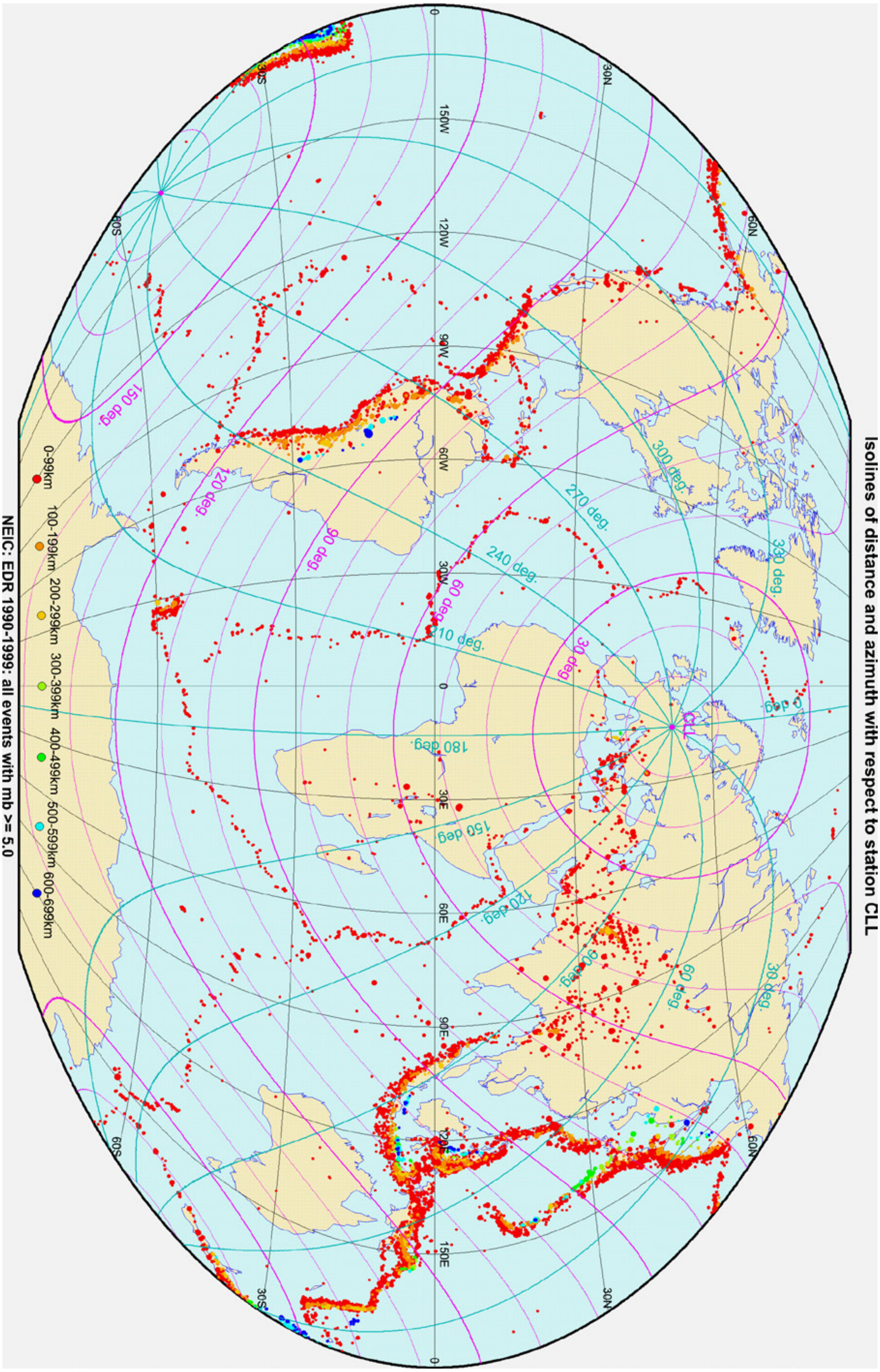


Figure 6 World map with epicenters and isolines of D and AZI fort station CLL, Germany.

Table 2 Travel-time differences pP-P and sP-P as a function of distance D and depth h according to the IASP91 travel-time tables (Kennett, 1991).

pP-P	Depth of source [km]											
Δ	15.	35.	50.	100.	150.	200.	250.	300.	400.	500.	600.	700.
	s	s	s	s	s	s	s	s	s	s	s	s
2	3.6	7.5										
4	3.6	7.5										
6	3.6	7.5										
8	3.6	7.5										
10	3.6	7.6										
12	3.6	7.6	7.9									
14	3.6	7.6	8.0									
16	3.8	8.1	9.3	20.1	26.2							
18	4.0	8.5	10.1	16.2	25.9	32.6	38.8					
20	4.3	9.2	11.5	19.0	25.6	33.2	39.6	45.4				
22	4.3	9.3	11.7	19.4	26.9	34.4	41.7	48.4	59.9			
24	4.5	10.0	12.7	21.4	29.8	37.8	45.3	52.2	64.1	82.7		
26	4.6	10.0	12.8	22.1	31.3	40.2	48.7	55.8	68.2	83.4	93.4	
28	4.6	10.0	12.9	22.3	31.5	40.5	49.1	57.2	72.2	84.3	94.4	
30	4.6	10.1	12.9	22.4	31.7	40.8	49.4	57.7	72.9	85.2	95.6	
32	4.6	10.1	13.0	22.5	31.9	41.0	49.8	58.1	73.5	86.1	96.8	
34	4.6	10.1	13.0	22.6	32.1	41.3	50.1	58.5	74.1	87.0	98.1	
36	4.6	10.2	13.1	22.8	32.3	41.6	50.5	59.1	74.9	88.0	.99.4	
38	4.6	10.2	13.1	22.9	32.6	42.0	51.0	59.6	75.6	89.1	100.8	109.7
40	4.7	10.2	13.2	23.1	32.8	42.3	51.4	60.2	76.5	90.2	102.2	111.6
42	4.7	10.3	13.3	23.2	33.1	42.7	51.9	60.8	77.3	91.3	103.7	113.5
44	4.7	10.3	13.4	23.4	33.4	43.0	52.4	61.3	78.1	92.4	105.1	115.4
46	4.7	10.4	13.4	23.6	33.6	43.4	52.8	61.9	78.9	93.5	106.6	117.3
48	4.7	10.4	13.5	23.7	33.9	43.7	53.3	62.5	79.7	94.6	108.0	119.1
50	4.7	10.5	13.6	23.9	34.1	44.1	53.7	63.0	80.5	95.6	109.3	120.9
52	4.8	10.5	13.6	24.0	34.4	44.4	54.2	63.5	81.3	96.7	110.7	122.7
54	4.8	10.5	13.7	24.2	34.6	44.8	54.6	64.1	82.0	97.7	112.0	124.3
56	4.8	10.6	13.8	24.3	34.8	45.1	55.0	64.6	82.7	98.6	113.2	125.9
58	4.8	10.6	13.8	24.5	35.1	45.4	55.4	65.1	83.4	99.6	114.5	127.5
60	4.8	10.7	13.9	24.6	35.3	45.7	55.8	65.6	84.1	100.5	115.6	129.0
62	4.8	10.7	13.9	24.8	35.5	46.0	56.2	66.0	84.8	101.4	116.8	130.4
64	4.9	10.7	14.0	24.9	35.7	46.3	56.5	66.5	85.4	102.2	117.9	131.8
66	4.9	10.8	14.1	25.0	35.9	46.5	56.9	66.9	86.0	103.1	119.0	133.2
68	4.9	10.8	14.1	25.1	36.1	46.8	57.2	67.4	86.6	103.9	120.0	134.5
70	4.9	10.8	14.2	25.3	36.3	47.1	57.6	67.8	87.2	104.7	121.0	135.8
72	4.9	10.9	14.2	25.4	36.5	47.3	57.9	68.2	87.8	105.4	122.0	137.0
74	4.9	10.9	14.3	25.5	36.7	47.6	58.2	68.6	88.4	106.2	122.9	138.2
76	4.9	10.9	14.3	25.6	36.8	47.8	58.6	69.0	88.9	106.9	123.9	139.3
78	4.9	11.0	14.4	25.7	37.0	48.1	58.9	69.3	89.4	107.6	124.8	140.5
80	5.0	11.0	14.4	25.8	37.2	48.3	59.2	69.7	90.0	108.3	125.7	141.5
82	5.0	11.0	14.5	25.9	37.4	48.5	59.5	70.1	90.5	109.0	126.5	142.6
84	5.0	11.1	14.5	26.1	37.5	48.8	59.8	70.4	91.0	109.7	127.4	143.7
86	5.0	11.1	14.6	26.1	37.7	49.0	60.0	70.8	91.4	110.3	128.2	144.7
88	5.0	11.1	14.6	26.3	37.9	49.2	60.4	71.2	92.0	111.0	129.0	145.6
90	5.0	11.1	14.6	26.3	37.9	49.3	60.5	71.4	92.3	111.4	129.5	146.3
92	5.0	11.1	14.7	26.3	38.0	49.4	60.6	71.5	92.4	111.6	129.8	146.6
94	5.0	11.1	14.7	26.4	38.0	49.5	60.6	71.5	92.5	111.7	130.0	146.9
96	5.0	11.2	14.7	26.4	38.1	49.5	60.7	71.6	92.7	111.9	130.2	147.2
98	5.0	11.2	14.7	26.4	38.1	49.6	60.8	71.8	92.8	112.1	130.5	147.5
100	5.0	11.2	14.7	26.5	38.1	49.6	60.9	71.8	92.9	112.2	130.6	147.6

sP-P	Depth of source [km]											
Δ	15.	35.	50.	100.	150.	200.	250.	300.	400.	500.	600.	700.
	s	s	s	s	s	s	s	s	s	s	s	s
2	5.9	12.7	15.4	22.8	27.0	35.7						
4	5.9	12.7	15.5	24.4	32.4	40.0	46.9	53.1	63.7			
6	5.9	12.7	15.6	24.8	33.5	42.0	50.1	57.5	70.6	81.2	89.2	
8	5.9	12.7	15.6	25.0	34.3	43.5	52.4	60.8	75.8	88.6	98.5	106.0
10	5.9	12.7	15.7	25.3	35.1	45.0	54.6	63.7	80.6	95.1	106.6	115.9
12	5.9	12.8	15.7	25.7	36.3	46.7	57.0	66.7	86.0	101.4	114.0	125.3
14	5.9	12.8	15.8	26.8	38.0	49.0	59.8	70.5	91.4	107.7	121.3	134.6
16	6.0	13.1	16.7	28.6	40.4	52.4	64.4	75.9	97.2	114.1	130.3	143.9
18	6.1	13.4	17.2	30.5	43.6	56.5	69.0	80.9	103.0	121.7	139.3	153.3
20	6.3	13.9	18.1	31.9	45.5	58.9	72.0	84.6	108.5	129.6	148.2	162.8
22	6.4	14.0	18.2	32.2	46.0	59.9	73.8	87.3	113.0	135.2	155.5	171.4
24	6.6	14.5	19.0	34.0	48.6	63.0	77.1	90.7	116.5	139.1	159.6	177.1
26	6.6	14.5	19.0	34.1	49.0	63.7	78.1	92.1	118.8	142.4	163.5	181.3
28	6.6	14.6	19.1	34.2	49.2	64.0	78.5	92.5	119.3	143.0	164.9	184.0
30	6.6	14.6	19.1	34.3	49.3	64.1	78.7	92.8	119.7	143.6	165.7	185.1
32	6.6	14.6	19.2	34.4	49.4	64.3	78.9	93.1	120.2	144.2	166.5	186.2
34	6.6	14.6	19.2	34.5	49.6	64.5	79.2	93.4	120.7	144.9	167.4	187.3
36	6.6	14.7	19.3	34.6	49.8	64.8	79.5	93.8	121.2	145.6	168.3	188.5
38	6.6	14.7	19.3	34.7	49.9	65.0	79.8	94.2	121.8	146.4	169.3	189.8
40	6.7	14.7	19.4	34.8	50.1	65.3	80.2	94.6	122.4	147.2	170.3	191.1
42	6.7	14.8	19.4	34.9	50.3	65.6	80.5	95.1	122.9	148.0	171.3	192.3
44	6.7	14.8	19.5	35.0	50.5	65.8	80.8	95.5	123.5	148.7	172.3	193.6
46	6.7	14.8	19.5	35.2	50.7	66.1	81.2	95.9	124.1	149.5	173.3	194.8
48	6.7	14.9	19.6	35.3	50.9	66.3	81.5	96.3	124.7	150.3	174.3	196.0
50	6.7	14.9	19.6	35.4	51.1	66.6	81.8	96.7	125.2	151.0	175.2	197.2
52	6.7	14.9	19.7	35.5	51.3	66.8	82.2	97.1	125.8	151.8	176.1	198.3
54	6.7	15.0	19.7	35.6	51.4	67.1	82.5	97.5	126.3	152.5	177.0	199.5
56	6.8	15.0	19.8	35.7	51.6	67.3	82.8	97.8	126.8	153.2	177.9	200.6
58	6.8	15.0	19.8	35.8	51.8	67.6	83.1	98.2	127.4	153.8	178.8	201.6
60	6.8	15.0	19.9	36.0	51.9	67.8	83.4	98.6	127.8	154.5	179.6	202.6
62	6.8	15.1	19.9	36.1	52.1	68.0	83.6	98.9	128.3	155.1	180.4	203.6
64	6.8	15.1	20.0	36.2	52.3	68.2	83.9	99.2	128.8	155.7	181.2	204.6
66	6.8	15.1	20.0	36.3	52.4	68.4	84.2	99.6	129.3	156.3	182.0	205.5
68	6.8	15.2	20.1	36.3	52.6	68.6	84.4	99.9	129.7	156.9	182.7	206.5
70	6.8	15.2	20.1	36.4	52.7	68.8	84.7	100.2	130.1	157.5	183.4	207.4
72	6.8	15.2	20.1	36.5	52.8	69.0	84.9	100.5	130.6	158.1	184.1	208.2
74	6.9	15.2	20.2	36.6	53.0	69.2	85.2	100.8	131.0	158.6	184.8	209.1
76	6.9	15.3	20.2	36.7	53.1	69.4	85.4	101.1	131.4	159.1	185.5	209.9
78	6.9	15.3	20.3	36.8	53.3	69.6	85.7	101.4	131.8	159.7	186.2	210.7
80	6.9	15.3	20.3	36.9	53.4	69.8	85.9	101.7	132.2	160.2	186.8	211.5
82	6.9	15.3	20.3	37.0	53.5	69.9	86.1	101.9	132.6	160.7	187.4	212.3
84	6.9	15.3	20.4	37.0	53.6	70.1	86.3	102.2	132.9	161.2	188.0	213.0
86	6.9	15.4	20.4	37.1	53.8	70.3	86.5	102.5	133.3	161.7	188.7	213.8
88	6.9	15.4	20.4	37.2	53.9	70.5	86.8	102.8	133.7	162.2	189.2	214.5
90	6.9	15.4	20.5	37.2	54.0	70.5	86.9	102.9	133.9	162.4	189.5	214.8
92	6.9	15.4	20.5	37.3	54.0	70.6	86.9	103.0	134.0	162.5	189.7	215.0
94	6.9	15.4	20.5	37.3	54.0	70.6	87.0	103.0	134.0	162.6	189.9	215.3
96	6.9	15.4	20.5	37.3	54.1	70.7	87.1	103.1	134.2	162.8	190.1	215.5
98	6.9	15.4	20.5	37.3	54.1	70.7	87.1	103.2	134.3	162.9	190.2	215.7
100	6.9	15.4	20.5	37.3	54.1	70.7	87.2	103.2	134.3	163.0	190.3	215.7

5 Tasks

To run the exercise by hand you should first produce two paper copies of the records to be analyzed (Figures 2 and 3, respectively) and a transparent overlay copy of the differential travel-time curve in Figure 4 and. All copies should be made so as to have identical time scale.

5.1 Event record No. 1 (Figure 2)

5.1.1 Assess, whether the source was shallow (< 70 km) or deep (Look for surface waves!)

- Shallow source?
- Deep source?

5.1.2 Look for possible depth phases. Are there any clear depth phases?

- Yes?
- No?
- Comments on the possible depth range of the EQ if you suspect pP and/or sP to arrive in the complex wave group after P?

5.1.3 If you do not find any clear depth phases use the differential travel-time curve in Figure 4 (which is for surface foci), and try to identify the principal phases in the vertical and horizontal component record.

- Which phases you have identified?
- Give reasons for your interpretation?

5.1.4 a) Measure the time difference t(S-P), b) estimate the epicentral distance D by using Equation (1) and c) by matching t(S-P) with the t-D curve of Figure 4.

a) t(S-P) =
b) D = ……°
c) D = ……°

5.1.5 Determine a) the quadrant of P-wave first motion horizontal particle motion, b) AZI from the amplitude ratio $|A_E/A_N|$ using Equation (1), and c) calculate BAZ taking into account the relationships between AZI , quadrant and BAZ in Table 1.

a) Quadrant =
b) AZI (MOX) =……°
c) BAZ(MOX) = …...°

5.1.6 Locate the epicenter on the map given in Figure 5 and name the source region.

- Source region?
- Discussion?

5.2 **Event record No. 2** (Figure 3)

5.2.1 Assess, whether the event was shallow (< 70 km) or deep by looking for possible surface waves in the full record, which is inserted at strongly compressed time scale.

- Shallow event?
- Deep event?

5.2.2 Look for possible depth phases. Are there any clear depth phases?

- Yes?
- No?
- Comments?

5.2.3 Measure the time difference (in min) between the P-wave first arrival and the five marked onsets of stronger secondary wave arrivals in the records. Write down the time differences Xi-P (in min) in the order of their appearance.

- X1-P = , X2-P = , X3-P = , X4-P = , X5-P = ?

5.2.4 In order to match these travel-time differences with the differential t-D curve in Fig. 4 plot them with the same time scale as your overlay on the edge of a sheet of paper. Then place the P-wave onset mark on distance scale and move it there along until you match the onset marks of the later onsets with relevant travel-time curves in Figure 4. a) Read the distance D (in °) related to this best fit with as many as possible of your onset marks and b) identify the related phases and write their names on the onsets!

a) D (CLL) = ...°,

b) X1 = , X2 = , X3 = , X4 = , X5 =

- Comments, which support your phase interpretations ?

5.2.5 Determine a) the quadrant of particle motion, b) AZI and c) BAZ as in task 4.1.5.

a) Quadrant =
b) AZI (CLL) = ... °
c) BAZ(CLL) = ... °

5.2.6 Locate the event as in task 5.1.6 by using Figure 6

- Name of source region/country?

6 Solutions

Note: Your estimates for the travel-time differences should be within about 0.2 min, for D within 2° and for the backazimuth AZI within about 5° of the solutions given below. They were derived by hand by the authors of this tutorial exercise, following the outlined procedures. The solutions given below are numbered according to the tasks in section 5.

Event No. 1:

5.1.1
The earthquake is deeper than 70 km because no long-period and dispersive surface waves have been recorded.

5.1.2
On this record with low time resolution it is difficult the recognize for sure depth phases. However, they might arrive within the complex wave group that follows within about 40 s after the P onset. The ISC calculated a hypocenter depth h = 111 km and an epicentral distance D = 20.24° for station MOX. According to the IASP91 (Kennett, 1991) differential travel-time table for depth phases pP should then arrive about 21 s and sP about 35 s after P.

pP-P — Depth of source [km]

Δ	15.	35.	50.	100. 111	150.	200.	250.	300.	400.	500.	600.	700.
	s	s	s	s	s	s	s	s	s	s	s	s
2	3.6	7.5										
4	3.6	7.5										
6	3.6	7.5										
8	3.6	7.5										
10	3.6	7.6										
12	3.6	7.6	7.9									
14	3.6	7.6	8.0									
16	3.8	8.1	9.3	20.1	26.2							
18	4.0	8.5	10.1	16.2	25.9	32.6	38.8					
20	4.3	9.2	11.5	19.0 21s	25.6	33.2	39.6	45.4				
22	4.3	9.3	11.7	19.4	26.9	34.4	41.7	48.4	59.9			
24	4.5	10.0	12.7	21.4	29.8	37.8	45.3	52.2	64.1	82.7		
26	4.6	10.0	12.8	22.1	31.3	40.2	48.7	55.8	68.2	83.4	93.4	

sP-P — Depth of source [km]

Δ	15.	35.	50.	100.	150.	200.	250.	300.	400.	500.	600.	700.
	s	s	s	s	s	s	s	s	s	s	s	s
2	5.9	12.7	15.4	22.8	27.0	35.7						
4	5.9	12.7	15.5	24.4	32.4	40.0	46.9	53.1	63.7			
6	5.9	12.7	15.6	24.8	33.5	42.0	50.1	57.5	70.6	81.2	89.2	
8	5.9	12.7	15.6	25.0	34.3	43.5	52.4	60.8	75.8	88.6	98.5	106.0
10	5.9	12.7	15.7	25.3	35.1	45.0	54.6	63.7	80.6	95.1	106.6	115.9
12	5.9	12.8	15.7	25.7	36.3	46.7	57.0	66.7	86.0	101.4	114.0	125.3
14	5.9	12.8	15.8	26.8	38.0	49.0	59.8	70.5	91.4	107.7	121.3	134.6
16	6.0	13.1	16.7	28.6	40.4	52.4	64.4	75.9	97.2	114.1	130.3	143.9
18	6.1	13.4	17.2	30.5	43.6	56.5	69.0	80.9	103.0	121.7	139.3	153.3
20	6.3	13.9	18.1	31.9 35s	45.5	58.9	72.0	84.6	108.5	129.6	148.2	162.8
22	6.4	14.0	18.2	32.2	46.0	59.9	73.8	87.3	113.0	135.2	155.5	171.4
24	6.6	14.5	19.0	34.0	48.6	63.0	77.1	90.7	116.5	139.1	159.6	177.1

Accordingly, the first two sharp recognizable onsets after P on the Z component record are most likely the depth phases pP and sP (see Figure 7), not PP and PPP, as plotted in the simplified J-B-differential t-D curves of Figure 4. According to more recent travel-time models such as IASP91 (see DS 2.1) PP and PPP will appear only for D ≥ 30°.

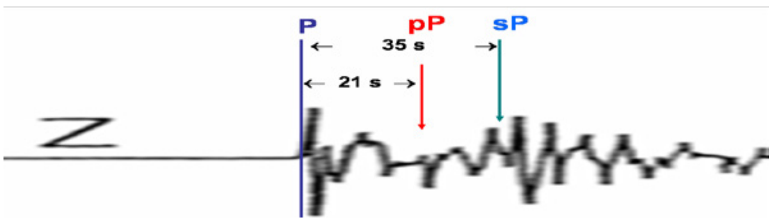


Figure 7 Cutout of the vertical component record in Figure 2, stretched in time-scale. This allows better recognition of the depth phase onsets pP and sP at the expected arrival times after P for an earthquake at 111 km depth (as calculated by the ISC).

5.1.3
You should have identified at least P on the Z component, the S wave as the largest onset on the E component, and SS (with longer period than S) on the N component.

5.1.4
The results are shown in Figures 8 and 9. Note that the ISC calculated for MOX, based on the global network location, D = 20.24°.

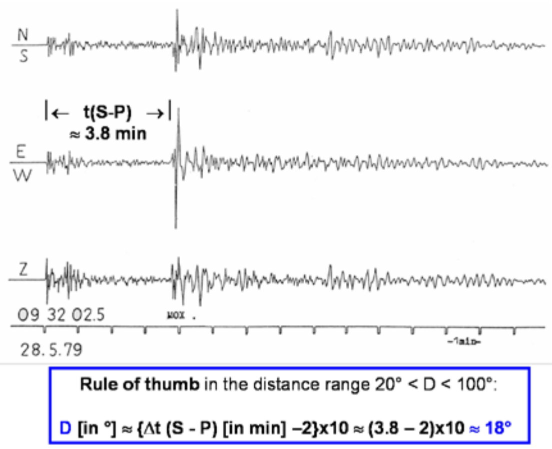


Figure 8

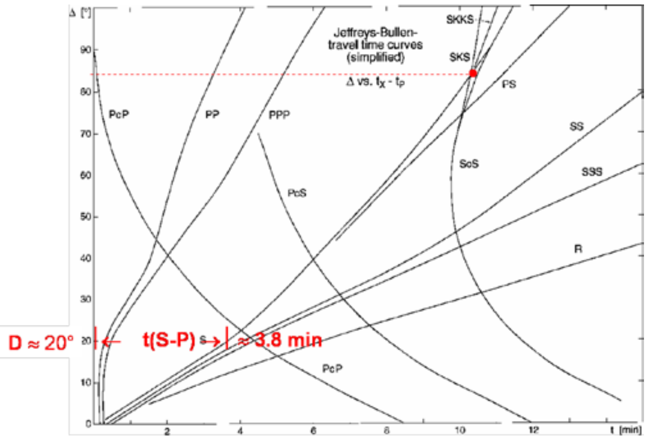


Figure 9

5.1.5
a) 2nd quadrant of P-wave first particle motion;
b) AZI(MOX) = **arc tan (| A_E/A_N|)** ≈ arctan (4/3) ≈ 53°
c) BAZ ≈ 125° .

5.1.6
Using the results from 5.1.4 and 5.1.5 (Figure 9) together with the map in Figure 5 the earthquake was located in the coastal area of **southern Turkey.** Locating a sub-crustal earthquake there makes sense, because the African Plate is sub-ducted underneath southern Turkey. Figure 10 shows the excellent agreement of the single station 3-component broadband solution with the global network solution of the ISC. **The two epicenter positions differ by only about 0.7°**!

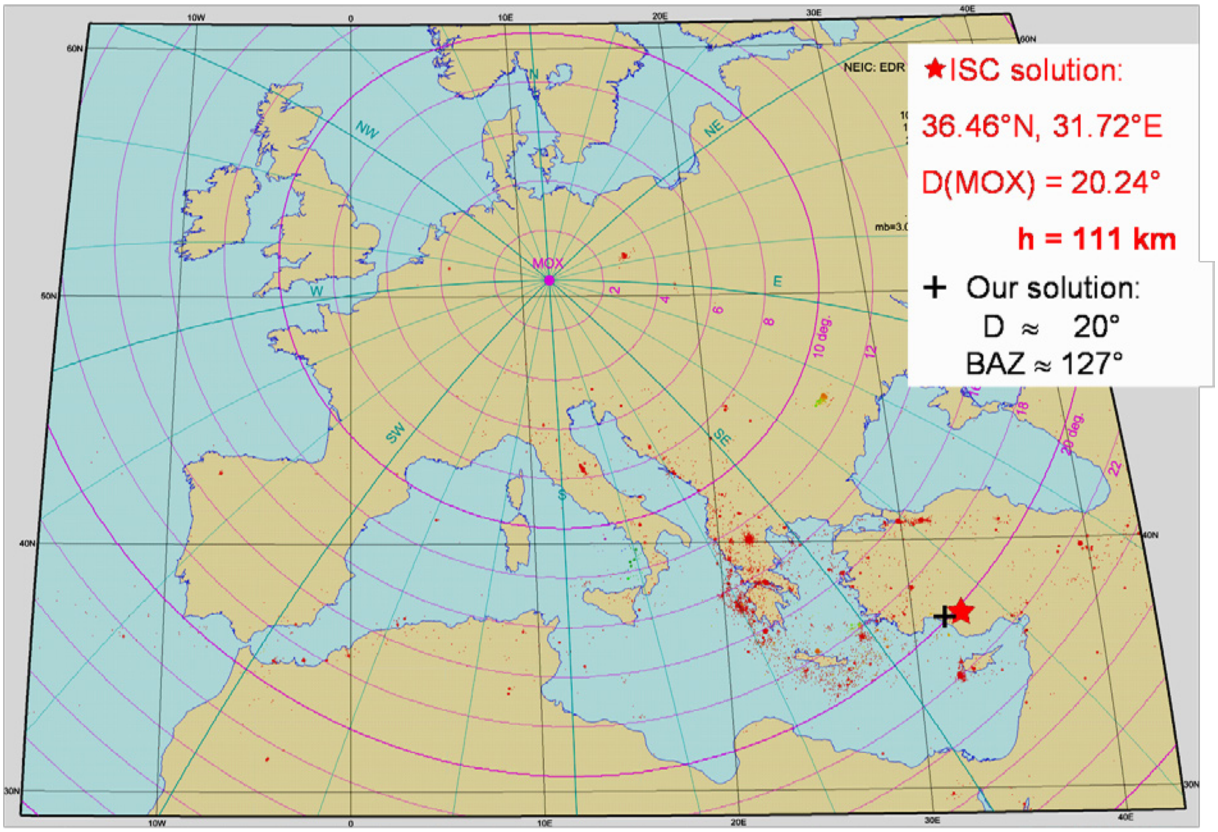


Figure 10

Event No. 2:

5.2.1
Shallow teleseismic earthquake with strong surface waves (see insert of Figure 3; A_{max} after about 37 min).

5.2.2
No depth phases recognizable in the LP records (NEIC reported for this earthquake a hypocenter depth of h = 19 km).

5.2.3
X1-P ≈ 3.65 min, X2-P ≈ 10.5 min, X3-P ≈ 11.3 min, X4-P ≈ 12.2 min, X5-P ≈ 17 min

5.2.4
- **D(CLL) ≈ 93°** ± 1° for the best match of the travel-time differences given under 5.2.3 with the with the travel-time curve shown in Figure 4. NEIC-PDE gives for station CLL 92.6°.
- The identified phases, which match best the travel-time differences to P given under 5.2.3 are: X1 = **PP**, X2 = **SKS**, X3 = **S**, X4 = **PS/SP**, X5 = **SS**

- Both SKS and PS are strongest in the horizontal component E where also P has its largest (radial) horizontal amplitude. At about the time of the PS arrival in N there appears also in Z a clear energy arrival (SP⬇). S arrives later than SKS and is strongest in the N (transverse) component only.

The summary results are plotted in Figure 11.

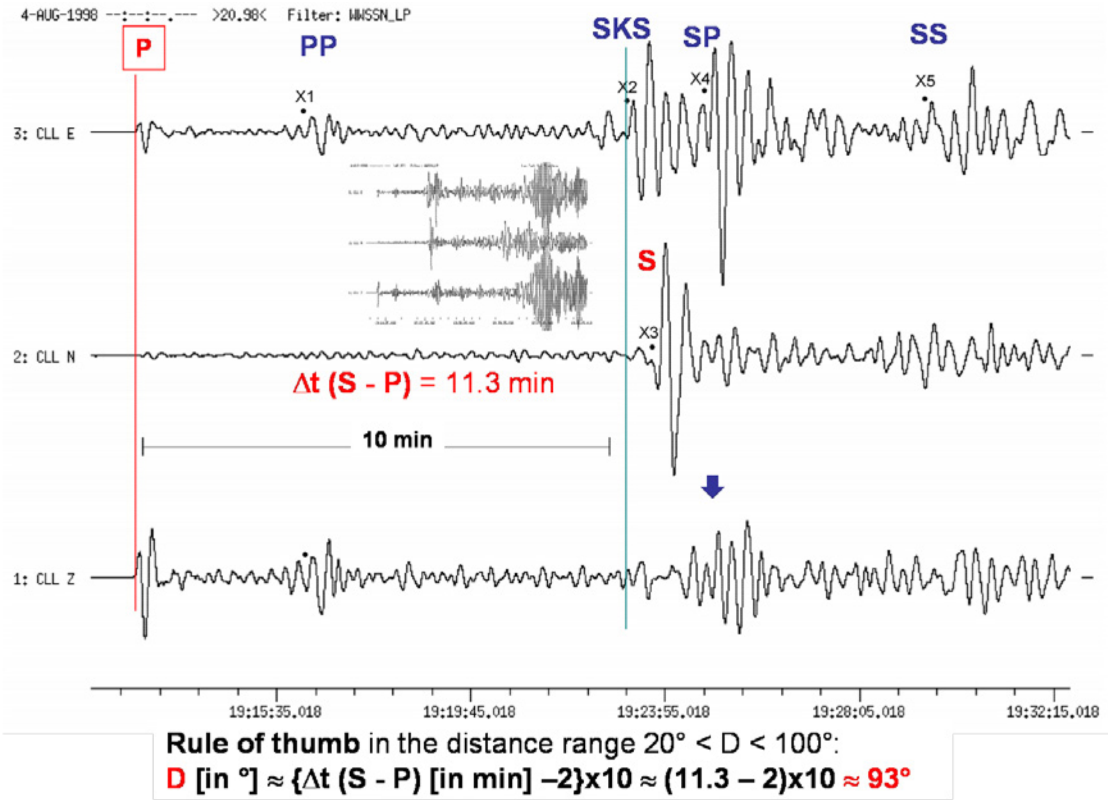


Figure 11

5.2.5

a) Quadrant ? Transition from 1st to 2nd because of large eastward P-wave motion; first motion in N-S component not measurable

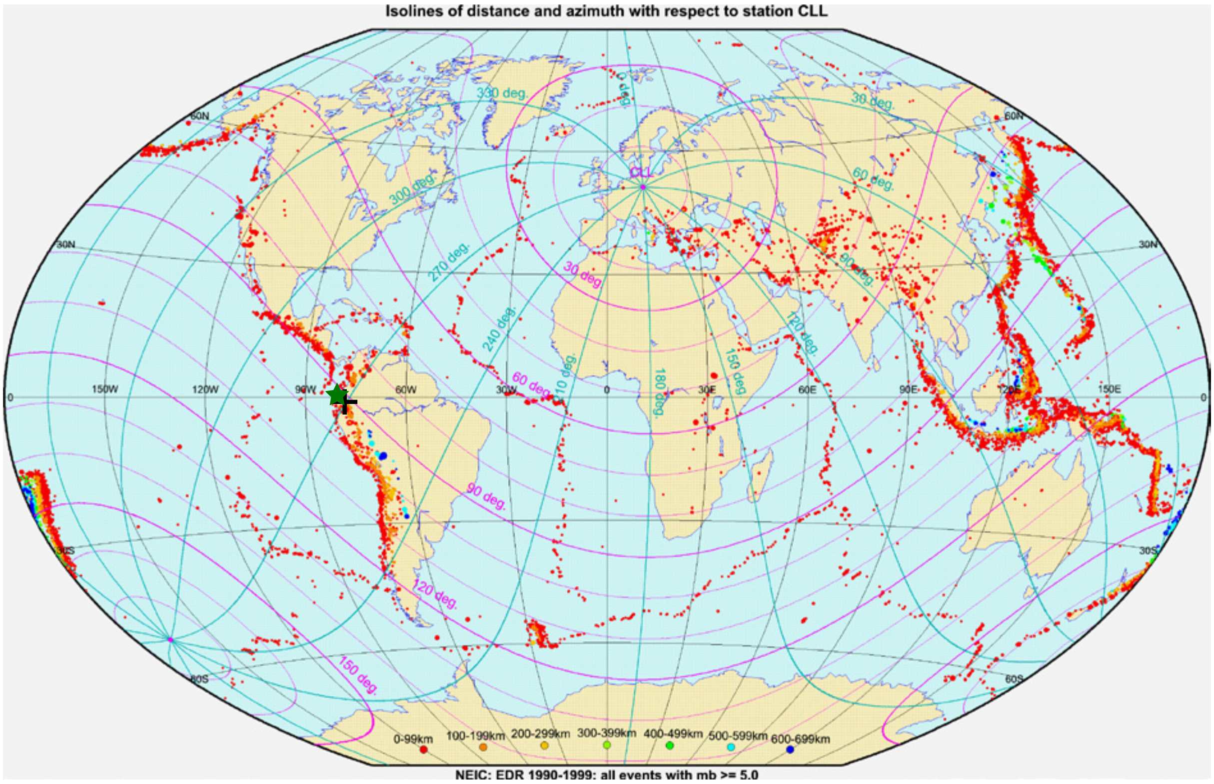
b) AZI (CLL) ≈. 90°

c) BAZ(CLL) ≈ 270° because + first motion in Z and E relates to a source in the W.

Comment: Recognizable P-wave upward (+) motion in the N component begins only more than 6 s later than in the Z component, thus being related to the strong downward (-) P-wave motion! Therefore, the azimuth might be a few degrees further north. In fact, NEIC-PDE gives for CLL AZI = 272.3°.

5.2.6

Using the map in Figure 6 for station CLL the source is located near **Ecuador.** NEIC-PDE gives as epicenter coordinates 0.59°S and 80.39°W, i.e., near coast of Ecuador. The difference between these two locations is < 3° (see Figure 12) and would be even less, if the week N-S first motion could have been resolved by appropriate interactive amplitude scaling.



+ CLL solution ⇒ **Ecuador, D ≈ 93°, BAZ ≈ 270° + a few degrees N?**

★ NEIC solution: **Ecuador**, 0.59°S, 80.39° W; D(CLL) = 92.6°, BAZ(CLL) = 272.3°

Figure 12

Acknowledgment

Figures 2 and 4 as well as Table 2 had been compiled by W. Strauch and K. Wylegalla for an earlier version of this exercise.

References

Jeffreys, H., and Bullen, K. E. (1940, 1948, 1958, 1967, and 1970). Seismological Tables. British Association for the Advancement of Science, *Gray Milne Trust*, London, 50 pp.

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