J Geophys (1984) 54:183–194

Journal of Geophysics

Converted phases from the mantle transition zone observed at European stations

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Abstract. Converted phases from the mantle transition zone have been observed as precursors about 1 min before the main S-wave phases S, SKS and ScS in long-period records of the Gräfenberg array (GRF) and a few European WWSSN stations, at epicentral distances from 70–90°. The 23 earthquakes used were located along the west coast of America from Alaska to Ecuador, with a concentration of events in Central America, and in East Asia from the Aleutians through Japan to Sumatra. Relatively strong converted energy was observed for the American earthquakes, except for two events in the South Mexico/Guatemala region. The East Asian earthquakes produced significantly less precursor energy.

The interference of conversions from P to SV below the focus and from SV to P below the stations is studied with theoretical-seismogram calculations. Due to interference precursors are normally stronger on the horizontal-radial than on the vertical component; this is in agreement with the observations. In special cases with either maximum or minimum P radiation towards the station conversion takes place only on one side, and precursor observations can be related directly to structure either below the focus or the station. The data set includes such favorable cases.

The interpretation of observed precursors in terms of the fine structure in the conversion zone is difficult, even in favorable cases, because of the low resolving power of long-period converted phases. Nevertheless, the following conclusions can be drawn from the observations presented. Most of the precursor observations for the American events are compatible with typical models of the transition zone between upper and lower mantle, having two discontinuities at depths of about 400 and 670 km. Such a structure applies for western Europe and for the Caribbean Sea/Gulf of Mexico region, in the latter case with a possible local interruption by a smoother transition zone. A relatively smooth transition zone below East Asia from about Korea to the Sea of Okhotsk can also explain the lack of precursor energy for a few earthquakes in and close to Japan. These results indicate large-scale lateral variations in the sharpness of the mantle transition zone.

Key words: Converted phases – Transition zone between upper and lower mantle – Lateral variations – Synthetic seismograms – GRF broadband array

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Introduction

Petrological models of the earth's mantle postulate the world-wide existence of a zone between the upper and lower mantle at depths from 400–700 km, characterized by a two-stage phase transition from mainly olivine to its high-pressure spinel and post-spinel phases. Detailed seismological investigations of this depth range, using reflected and refracted waves from earthquakes and explosions, exist only in a few regions, e.g., in the western part of the United States (Helmberger and Engen, 1974; Burdick and Helmberger, 1978) and in Europe (King and Calcagnile, 1976; Given and Helmberger, 1980; Burdick, 1981; Rademacher et al., 1983). Converted waves offer another means to investigate this depth range (Vinnik, 1977; Faber and Müller, 1980; Baumgardt, 1981; Vinnik et al., 1983; Bock and Ha, 1984). In our previous paper (Faber and Müller, 1980) hereafter called paper I, we reported on a study of converted phases which are produced mainly by conversion from SV to P at the mantle transition zone. These phases appeared as precursors to S, ScS and SKS in long-period records, observed at North-American stations, of the Romanian earthquake of 1977 and of two Tonga-Fiji earthquakes. Epicentral distances ranged approximately from 70–95°, and the time difference between the converted phases and S or SKS was typically 40–60 s. Although the resolving power of long-period converted waves is limited, the observed precursor amplitudes required zones of pronounced velocity increase like those in the models, suggested by the above-mentioned studies of reflected and refracted waves.

The conversions studied in paper I have been abbreviated Sp, and they are produced below the stations (Fig. 1).

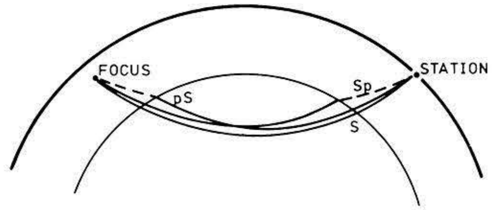

Fig. 1. Ray paths of the mantle S phase and of the corresponding converted phases Sp and pS, produced by a discontinuity. Similar conversions are connected with SKS and ScS

Other precursors to the main S phases, which are also of interest in the present paper, are produced below the focus by conversion from P to SV at the mantle transition zone. We call them pS for symmetry reasons; in this study P-to-S surface reflections at the focus for which this abbreviation is normally reserved are not mentioned. Which of the conversion types dominates, Sp or pS, depends mainly on the focal mechanism. Usually, i.e., for non-vanishing SV- *and* P-radiation in the direction of the stations, both types of conversions will be present, provided that structural contrasts are such that converted energy is generated. Calculations of theoretical seismograms (examples are presented later) show that in this case Sp and pS interfere by and large constructively on the horizontal-radial component and destructively on the vertical component. The usual case will therefore be that converted phases have larger amplitudes and are therefore easier identified in radial-component than in vertical-component seismograms; this is indeed what we find in the present investigation. The situation remains the same, if the SV radiation in the direction of Sp is weak or vanishes, i.e., if the precursors are mainly pS. Only if P-radiation in the direction of pS is weak, the precursors which then are mainly Sp will dominate on the vertical component. This happens when a station is located close to a P nodal plane, in which case SV radiation is often strong and provides for energetic Sp phases. The earthquakes studied in paper I were selected according to this special condition, and the data set of the present paper contains another example.

The interpretation of observed precursors in terms of the velocity structure in the mantle transition zone is complicated by the fact that usually source radiation is favorable for both Sp and pS generation, since then the structure both below the station and below the focus is involved. There are the two exceptions mentioned above:

The first is the case studied in paper I, i.e., weak or vanishing pS and strong Sp radiation. In this case the precursor information is related to the structure below the station; for instance, the amplitude ratio of conversions and the main S phases, measured on the vertical component, is diagnostic of the velocity contrasts in the transition zone below the station.

The second exception is the case of weak or vanishing Sp and strong pS radiation. This happens when the station is close to the P or T axis of the fault-plane solution. Then precursor information is mainly related to the structure below the focus. In this case the optimum observational quantity is the amplitude ratio of conversions and the P phase, since the source influence is minimized as in the first case. This amplitude ratio, taken on the radial component, is diagnostic of the velocity contrasts below the focus. If, in particular pS radiation is strong and there are very weak or missing converted phases on the radial component, this may indicate that for structural reasons weak or no conversion took place below the focus. Therefore, the study of S precursors at one station for earthquakes with strong pS radiation towards that station can give information on lateral variations of the velocity contrasts in the transition zone between upper and lower mantle.

For the present investigation we used mainly data of the broadband seismic array Gräfenberg (GRF) in the Federal Republic of Germany. The data of this array are especially suitable for our investigation for several reasons:

The GRF array is located at a distance of about 80° from regions of major earthquake activity (North and Central America, Aleutians to Indonesia).

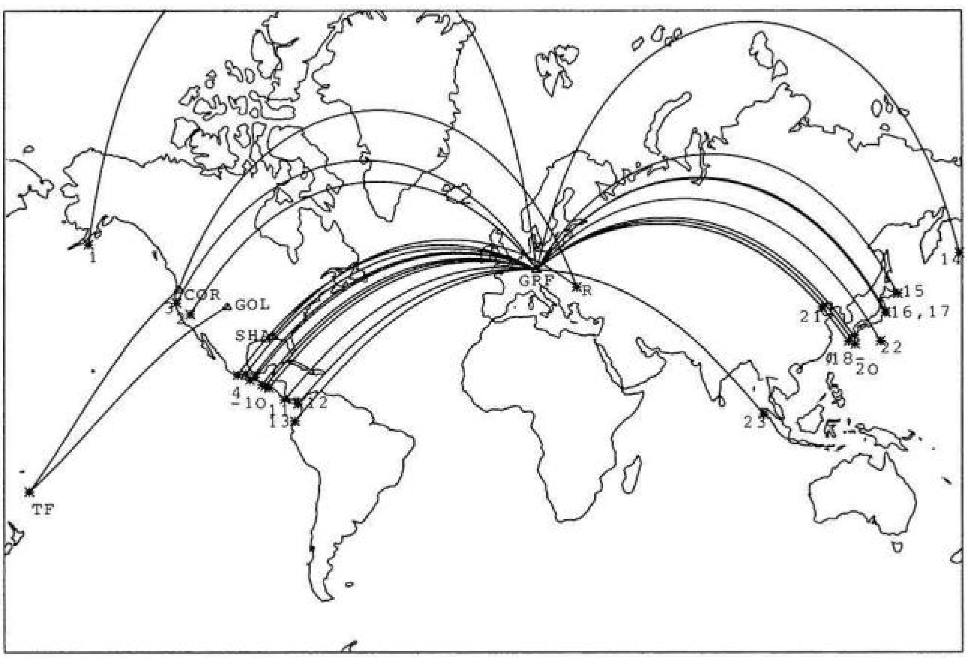

Fig. 2. Broadband-array station GRF and earthquakes of which S-wave precursors are investigated in this paper (event numbers as in Tables 1 and 2). Included are also earthquakes and stations that were used in an earlier study (Faber and Müller, 1980). TF denotes Tonga-Fiji earthquakes which were observed at WWSSN stations from COR to GOL; R is the Romanian earthquake of 1977, and the corresponding stations were located between COR and SHA. The lines which connect epicenters and stations are great-circle paths

Table 1. American earthquakes (focal coordinates according to USGS)

No.	Date	Origin time	Epicenter	Region	Focal depth (km)	Distance to GRF (deg)	P:S[b]	KONV:P on radial component
(1)	13 Feb 79	05:34:25.9	55.5 N 157.2 W	Alaska	33	74.8	1	0.7
(2)	25 May 80	16:33:44.7	37.6 N 118.8 W	California/Nevada	5	82.5	1	0.5
(3)	08 Nov 80	10:27:34.0	41.1 N 124.3 W	California	19	81.5	0.5	1
(4)	14 Mar 79[a]	11:07:16.3	17.8 N 101.3 W	Mexico	49	90.3	0.5	1
(5)	24 Oct 80	14:53:35.1	18.2 N 98.2 W	Mexico	72	88.3	0.5	1.3
(6)	29 Nov 78[a]	19:52:47.6	16.0 N 96.6 W	Oaxaca, Mexico	18	89.0	0.7	0.9
(7)	22 Jun 79[a]	06:30:54.3	17.0 N 94.6 W	Chiapas, Mexico	107	87.1	~0.1	–
(8)	06 Apr 82	19:56:53.4	14.3 N 92.1 W	Chiapas, Mexico	65	87.6	0.6	–
(9)	27 Oct 79	14:35:57.3	13.8 N 90.9 W	Guatemala	58	87.2	0.7	–
(10)	19 Jun 82	06:21:57.4	13.2 N 89.4 W	El Salvador	83	86.8	0.5	0.7
(11)	24 Aug 79	04:26:54.2	9.0 N 83.5 W	Costa Rica	40	86.3	0.9	0.5
(12)	11 Jul 76[a]	16:54:31.8	7.3 N 78.5 W	Panama	22	84.3	0.6	0.6
(13)	09 Apr 76[a]	07:08:47.0	0.8 N 79.8 W	Ecuador	9	90.1	0.8	1

The numbers in the first column correspond to the numbers in Figs. 2–4 and 6
[a] Fault-plane solutions are known (Fig. 8)
[b] P on vertical, S on radial component

Table 2. East Asian earthquakes (focal coordinates according to USGS)

No.	Date	Origin time	Epicenter	Region	Focal depth (km)	Distance to GRF (deg)	P:S[a]	KONV:P on radial component
(14)	19 Feb 77	22:34:04.1	53.6 N 170.0 E	Aleutians	33	75.6	2	0.3
(15)	23 Feb 80	05:51:03.2	43.5 N 146.8 E	Kuriles	44	79.3	~2	–
(16)	12 Jun 78	08:14:26.4	38.2 N 142.0 E	Japan	44	82.1	2	0.6
(17)	14 Jun 78	11:34:20.0	38.3 N 142.4 E	Japan	40	82.3	~3	–
(18)	23 May 78	07:50:28.2	31.1 N 130.1 E	Japan	161	83.1	~3	–
(19)	02 Jan 81	15:39:47.3	29.2 N 128.1 E	Ryukyu	242	83.6	4	–
(20)	14 Dec 76	16:06:44.4	28.3 N 130.7 E	Ryukyu	41	85.6	0.3	0.5
(21)	28 Jul 76	10:45:35.2	39.7 N 118.4 E	China	26	70.4	0.8	0.5
(22)	06 Sep 82	01:47:01.9	29.3 N 140.3 E	Izu-Bonin	167	89.3	1	–
(23)	20 Jun 76	20:53:13.4	3.4 N 96.3 E	Sumatra	33	84.3	~1	0.5

The numbers in the first column correspond to the numbers in Figs. 2 and 7
[a] P on vertical, S on radial component

Continuous digital recordings exist since 1976 and are easily available.

The broadband high-resolution digital data allow accurate numerical filtering and hence offer the possibility to compare this data set to previously investigated long-period WWSSN and SRO recordings and to treat it in the same way. All of the GRF records shown in this paper are WWSSN long-period simulations of the broadband data; in the broadband data themselves converted phases are less clearly identified. The locations of the earthquakes and of some stations mentioned in this paper as well as the great-circle paths connecting them are shown in Fig. 2. For conversion depths between 400 and 700 km the conversion sites have a distance of 10–13° from the stations (for Sp) and from the epicenters (for pS), respectively. Information on the 23 earthquakes studied is given in Tables 1 and 2.

Fault-plane solutions were available or could be constructed only for a few events (see Fig. 8). In the other cases we tried to obtain an idea about the location of GRF on the focal sphere from the amplitude ratio of P on the vertical component and S (in the sense of mantle S) on the radial component. P amplitudes are easily determined, but for S usually only a rough estimate can be found because of interference with SKS and ScS. The method therefore is a rather crude approximation. However, it showed quite clearly that for most of the American events GRF is located at some distance from both the P nodal planes and the P or T axis, implying precursor contributions both from Sp and pS. For several events in East Asia GRF is definitely closer to the P or T axis with the consequence that the precursors consist mainly of pS.

In the following we first discuss separately the events in America and those in East Asia. The main purpose of these sections is to present evidence for the existence or non-existence of converted phases. We also try to draw conclusions from the observations on the sharpness or smoothness of the mantle transition zone; structures with discontinuities or high velocity gradients (such as those in Fig. 9) are considered as representing a sharp transition zone, whereas a smooth transition zone would be characterized by continuous velocity-depth functions with only moderate gradients. The discussion of this question is qualitative, but based on experience following from synthetic-seismogram calculations as those in paper I. In a further section we present a few examples of such calculations. The main points here are to illustrate the relative importance

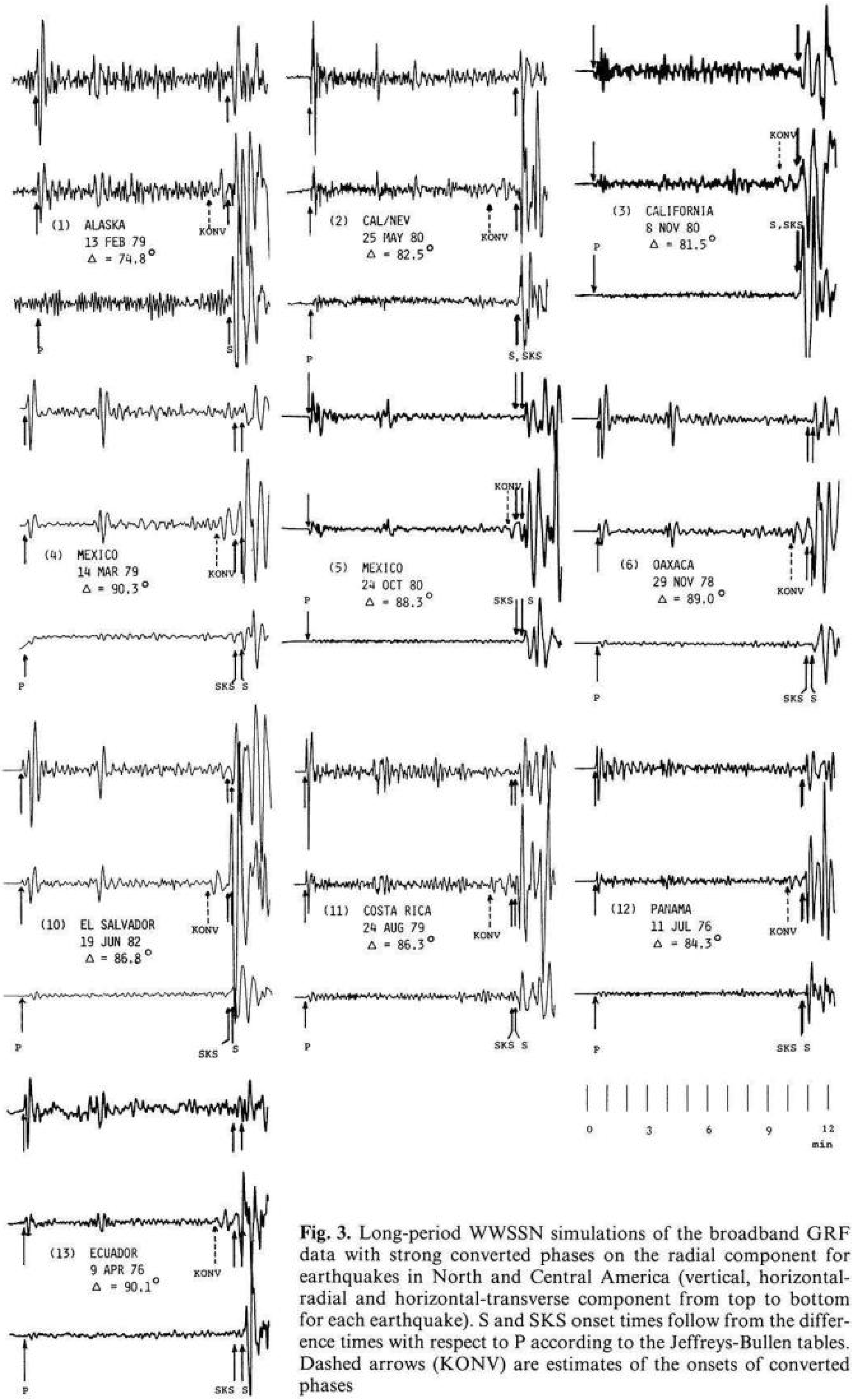

Fig. 3. Long-period WWSSN simulations of the broadband GRF data with strong converted phases on the radial component for earthquakes in North and Central America (vertical, horizontal-radial and horizontal-transverse component from top to bottom for each earthquake). S and SKS onset times follow from the difference times with respect to P according to the Jeffreys-Bullen tables. Dashed arrows (KONV) are estimates of the onsets of converted phases

of Sp and pS conversions, and to investigate the influence of the size of velocity jumps at mantle discontinuities on the conversions. At the end we summarize our view of the potential and limitations that converted S-wave precursors may have for studies of the mantle transition zone.

Data from American earthquakes

GRF long-period WWSSN simulations for the American earthquakes (Table 1) are reproduced in Figs. 3 and 4. For the majority of the events S precursors appear mainly on

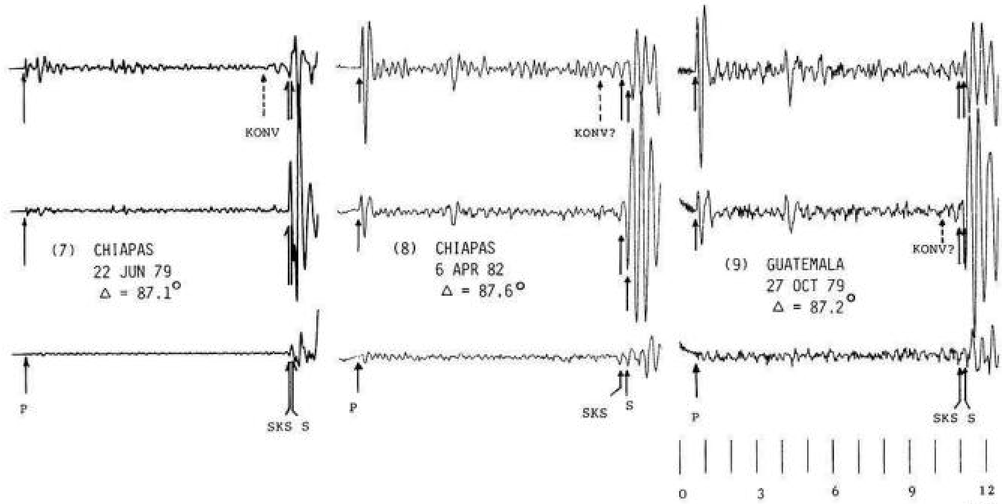

Fig. 4. The same as Fig. 3 for 3 Central American earthquakes. By contrast to Fig. 3, converted energy here is either very weak (events (8) and (9)) or restricted to the vertical component (event (7))

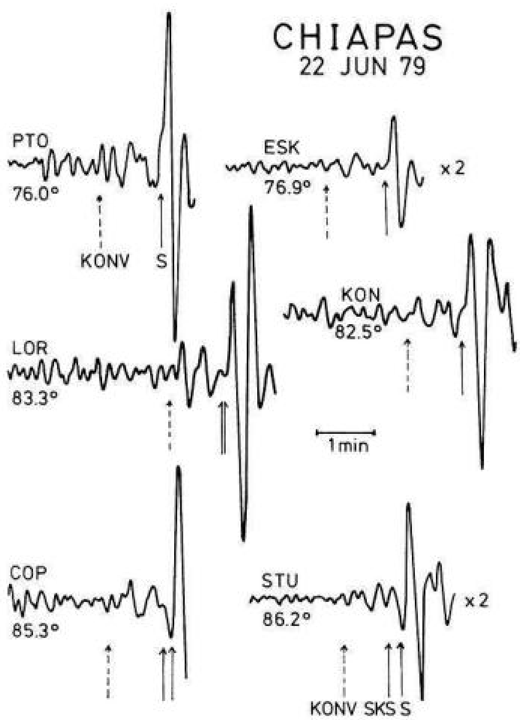

Fig. 5. Long-period WWSSN seismograms (vertical component) for event (7) at European stations. Amplitudes in the ESK and STU records have to be doubled; then all records have the same amplitude scale

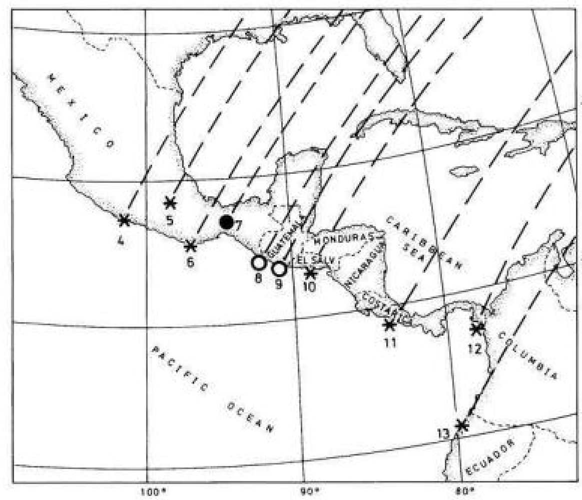

Fig. 6. Earthquakes in Central America with * strong converted phases at GRF mainly on the radial component, o no or very weak converted phases, although the P- and SV-radiation is similar to the radiation from the earthquakes marked by *, • converted phases on the vertical component only. The dashed lines are great-circle paths to GRF

the radial component (marked by KONV in Fig. 3). Three events are exceptions (Fig. 4): event (7) with converted energy only on the vertical component, and events (8) and (9) with only weak or no conversions at all. Precursors very similar to the strong arrivals for the Mexican events (4) and (6) were found in European WWSSN data, not shown here, from other events along the Mexican coast.

The P-to-S amplitude ratios of the American events, given in Table 1, are between 0.5 and 1, with the exception of event (7) which is discussed below separately. For events (6), (12) and (13), having ratios of 0.7, 0.6 and 0.8, fault-plane solutions are available (Fig. 8). GRF has a location in these mechanisms which is intermediate between a P nodal plane and the T axis. From the ratios of the other events we conclude that the situation here is similar. Hence, for all American events except (7) it appears that both conversion types were generated, Sp below the station and pS below the focus. In this case it is difficult to interpret the amplitude ratios of precursor and P phase, which are also given in Table 1, in terms of the velocity contrasts in the mantle transition zone either below the earthquake foci or below GRF. These ratios vary from 0.5–1.3 with a mean value of 0.9. The calculation of synthetic seismograms, described later, shows that ratios of about 1 can be reproduced by assuming both Sp and pS conversion in typical mantle models such as SP-1 of paper I (see Fig. 9). The data of Fig. 3 do not force us to deviate from such a model.

Event (7) is the only American event with an extreme P-to-S ratio, namely about 0.1, at GRF. The focal mechanism in Fig. 7b confirms this observation since only weak P-energy is expected to be radiated in the direction of Europe. The location of one of the P nodal planes relative to the European stations is similar to the location of one of the nodal planes of the 1977 Romanian earthquake relative to those American stations where we first observed converted phases, mainly on the vertical component (see paper I). Also in the GRF records of event (7) in Fig. 4 conversions are restricted to the vertical component. In both cases Sp is the dominant conversion type. Similar results follow from long-period records of several European WWSSN stations that we have studied in addition; their vertical-component seismograms are shown in Fig. 5. The conversion sites for event (7) are located below the eastern North Atlantic adjacent to Ireland and Great Britain.

The very weak converted energy prior to the S phases on the radial component for the two closely neighbored earthquakes (8) and (9) in the Chiapas/Guatemala region (Figs. 4 and 6) is a conspicuous observation. According to the P-to-SV amplitude ratios in the GRF records (Table 1), there seems to be no essential difference in P and SV radiation between these events and the neighboring events (4) to (6) and (10) to (13), which do have clear precursors on the radial component. There are two possible explanations for the gap in converted energy:

The converted waves from the mantle transition zone form a complex wavefield, because of conversion at two transitions or discontinuities and because each of the phases S, SKS and ScS generates precursory converted phases. Synthetic seismograms (e.g., those in Fig. 10) show that this interference causes considerable variations in waveform, with partially destructive interference in the distance range 83–90°. Epicentral distances of events (8) and (9) are between 87 and 88° and thus just in this distance range. An argument against this explanation is the existence of converted phases in records from close distances, e.g., for event (5) at 88.3°.

Reduced converted amplitudes could also be due to lateral variations within the mantle transition zone. In this case the velocity contrasts in this zone would be less pronounced at the conversion sites of pS about 10 to 13° from the epicenters of events (8) and (9), compared with the conversion sites of neighboring events. Then only the contribution of Sp to the precursors would be present, which according to the conclusions drawn above from event (7) does not vanish, and precursor amplitudes would be reduced on the radial component.

We consider the second explanation as somewhat more plausible than the first one, but before it can really be accepted the observations for events (8) and (9) should be confirmed by more events at about the same place.

Data from East Asian earthquakes

In Table 2 the parameters of 10 events in East Asia are compiled which are located at similar distances from GRF as the American earthquakes, and Fig. 7 shows their GRF records. A clear difference to the American events is that P arrivals are often much stronger relative to S than in Figs. 3 and 4. P-to-S amplitude ratios in Table 2 for the events (14) to (19) are greater than 1 and reach values up to 4; the station GRF seems to be located close to the P or T axis of their fault-plane solutions. This group of events will be called A in the following. The P-to-S ratios of the 3 events (21) to (23) (group B below) are between 0.7 and 1; the location of GRF in the fault-plane solutions must be similar as for the majority of the American events, i.e., somewhere between a P nodal plane and the P or T axis. Event (20) has a P-to-S ratio of about 0.3 which implies that GRF is relatively close to a P nodal plane.

In the case of group A events P energy is very high while SV energy is quite low. This leads to the conclusion that P is radiated close to the P or T axis and that also pS radiation is energetic; the difference in radiation angle between P and pS is about 20° for epicentral distances around 80°. In this case it is justified to assume that, if conversions are observed, they are mainly of pS type and that conclusions about the velocity structure below the foci can be drawn from them. There are only 2 or 3 positive identifications of conversions in this group of 6 events, marked by KONV in Fig. 7. No precursors worth mentioning exist in the investigated time interval of the radial-component records of events (15), (18) and (19). We assume that they are also practically free of conversions, since it seems to be rather improbable that converted energy totally vanishes due to destructive interference either among conversions themselves or with possible P-wave multiples. The interpretation of this observation is that velocity contrasts in the mantle transition zone below group A events are generally less pronounced than below the majority of the American events or below Europe.

Event (20) is similar to the American event (7) concerning the P-to-S amplitude ratio; if converted phases were generated, they would have been mainly of Sp type and show up on the vertical component. The conversion site for Sp is located below western Russia. However, the precursor of event (20) is less safely identified as a conversion than the precursor of event (7) (see Fig. 4), since for event (20) there is no such significant frequency change from the P coda to the precursor as for event (7).

In the case of group B events radiation conditions were about the same as for most American events which generated strong conversions; however, no really strong precursors are observed in the records of group B events. For events (21) and (23) which produced precursor energy it cannot be decided whether the weakness of this energy is due to lack of conversion below the focus or below GRF. The apparent lack of precursors for event (22) points to lack of conversion both below the focus and below GRF. Lack of conversion below the focus is consistent with the result for group A events.

The East Asian earthquakes appear to allow the general conclusion that from the Chinese Sea southwest of Korea over northeast China to the Sea of Okhotsk (see Fig. 2) there exists a relatively smooth transition from the upper to the lower mantle.

Amplitude investigations

Theoretical seismograms have been calculated with the reflectivity method in order to obtain a more quantitative idea about the velocity contrasts at the depths in the mantle transition zone where conversion occurs. Another purpose was to investigate how large the proportion of Sp and pS energy in the converted phases is. Methodical details of such calculations have been described in paper I and will

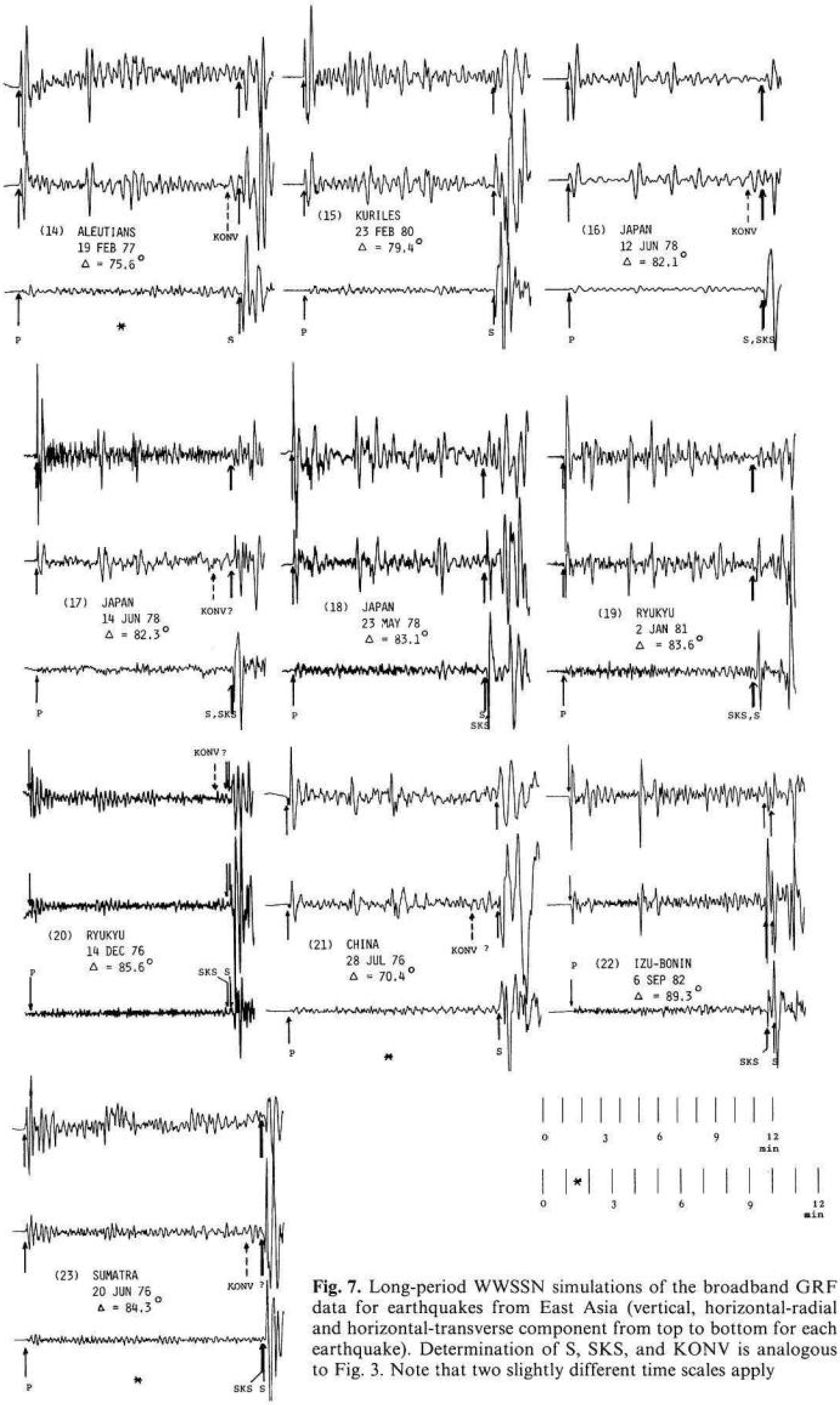

Fig. 7. Long-period WWSSN simulations of the broadband GRF data for earthquakes from East Asia (vertical, horizontal-radial and horizontal-transverse component from top to bottom for each earthquake). Determination of S, SKS, and KONV is analogous to Fig. 3. Note that two slightly different time scales apply

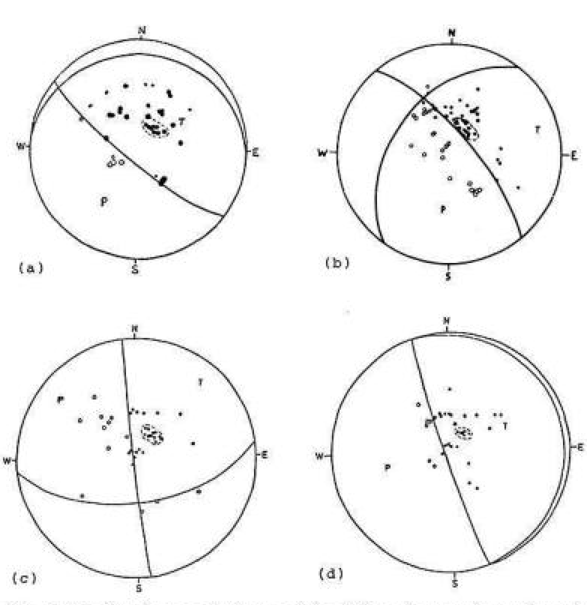

Fig. 8. Fault-plane solutions of the following earthquakes: (a) event (6): Oaxaca, NOV 29, 1978 (Stewart et al., 1981), (b) event (7): Chiapas, JUN 22, 1979, (c) event (12): Panama, JUL 11, 1976, and (d) event (13): Ecuador, APR 9, 1976. The fault-plane solution of the Mexican earthquake of MAR 14, 1979 (event (4) in Table 1) is nearly identical with (a) (Chael and Stewart, 1982). GRF is located roughly in the middle of the European stations which are encircled by a dashed line

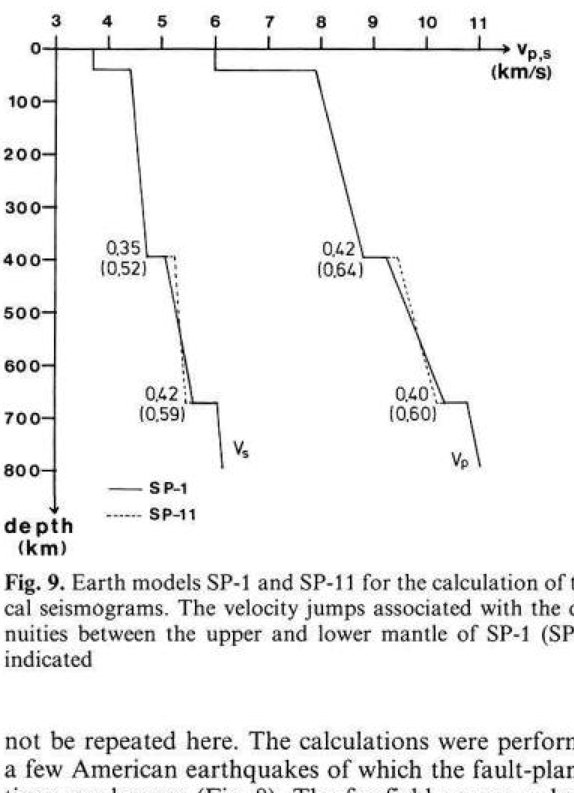

Fig. 9. Earth models SP-1 and SP-11 for the calculation of theoretical seismograms. The velocity jumps associated with the discontinuities between the upper and lower mantle of SP-1 (SP-11) are indicated

not be repeated here. The calculations were performed for a few American earthquakes of which the fault-plane solutions are known (Fig. 8). The far-field source pulse in the calculations was one sine oscillation with smooth beginning and end, having a dominant period of 30 s for event (6), 25 s for event (7) and 20 s for the others. This type of source pulse gave reasonable agreement between theoretical and observed P and S phases in the cases studied; more detailed modelling, including a moment function and an instrument response, was not necessary. The mantle velocity model used is primarily SP-1 of paper I (see Fig. 9), and conversion was assumed to take place at the first-order discontinuities at the depths 395 and 670 km. A modification of this model, SP-11, having more pronounced velocity contrasts, was also investigated.

Relative importance of Sp and pS conversions

Figure 10 shows synthetic seismograms for event (6) at Oaxaca, Mexico, along a profile in the direction of Europe. The seismograms include the main SV phases S, ScS, SKS and SKKS as well as their surface reflections at the focus and besides these the conversions pS from below the focus (seismograms on top), the conversions Sp from below the stations (center) and both conversion types (bottom). pS is much stronger on the radial than on the vertical component (top), in agreement with what one expects for an S wave. Sp is somewhat stronger on the vertical than on the radial component (center); this is also expected because Sp is a P wave. Both results are independent of the focal mechanism. The polarizations of pS and Sp are largely the same on the radial component and opposite on the vertical component, at least for shallow earthquakes with only little travel-time differences between pS and Sp. Thus, when both conversions are superposed there is by and large constructive interference on the radial and destructive interference on the vertical component, with the result that the precursors dominate on the radial component (bottom of Fig. 10). The superposition of pS and Sp depends on the orientation of the focal mechanism; calculations for other orientations than in Fig. 10, but with similarly strong P and SV radiation in the direction of the receivers, show that precursors *usually* dominate on the radial component. This result explains our observation that in a study of many earthquakes at one station conversions are more often identified on the radial than on the vertical component.

The contribution of both pS and Sp to the precursors in the normal case means that their interpretation with respect to velocity structure is difficult, because one can hardly discriminate between the influence of source and station structure and thus will obtain only an average model. The two exceptions have already been mentioned in the introduction: (1) pS radiation close to a P nodal plane and additionally sufficient SV radiation, i.e., dominance of Sp, and (2) Sp radiation close to the P or T axis, i.e., dominance of pS. Which situation is present, the normal case or (1) or (2), can be derived from the fault-plane solution of an event or, as shown in this paper, estimated from the P-to-S amplitude ratio in the record under investigation for converted phases.

Comparison of observed and theoretical seismograms

As discussed earlier, event (7) at Chiapas, Mexico, produced mainly Sp precursors (Figs. 4 and 5). Hence, conversion took place essentially below the eastern North-Atlantic and western Europe. We have modelled this case in a synthetic-seismogram calculation. Figure 11 shows on the left a suite of theoretical vertical-component seismograms between 75 and 90° along a profile with azimuth 30°, representative of Europe. On the right the observed seismograms of European WWSSN stations are reproduced from Fig. 5, and synthetic seismograms for the corresponding distance range are superposed. The theoretical precursors match the obser-

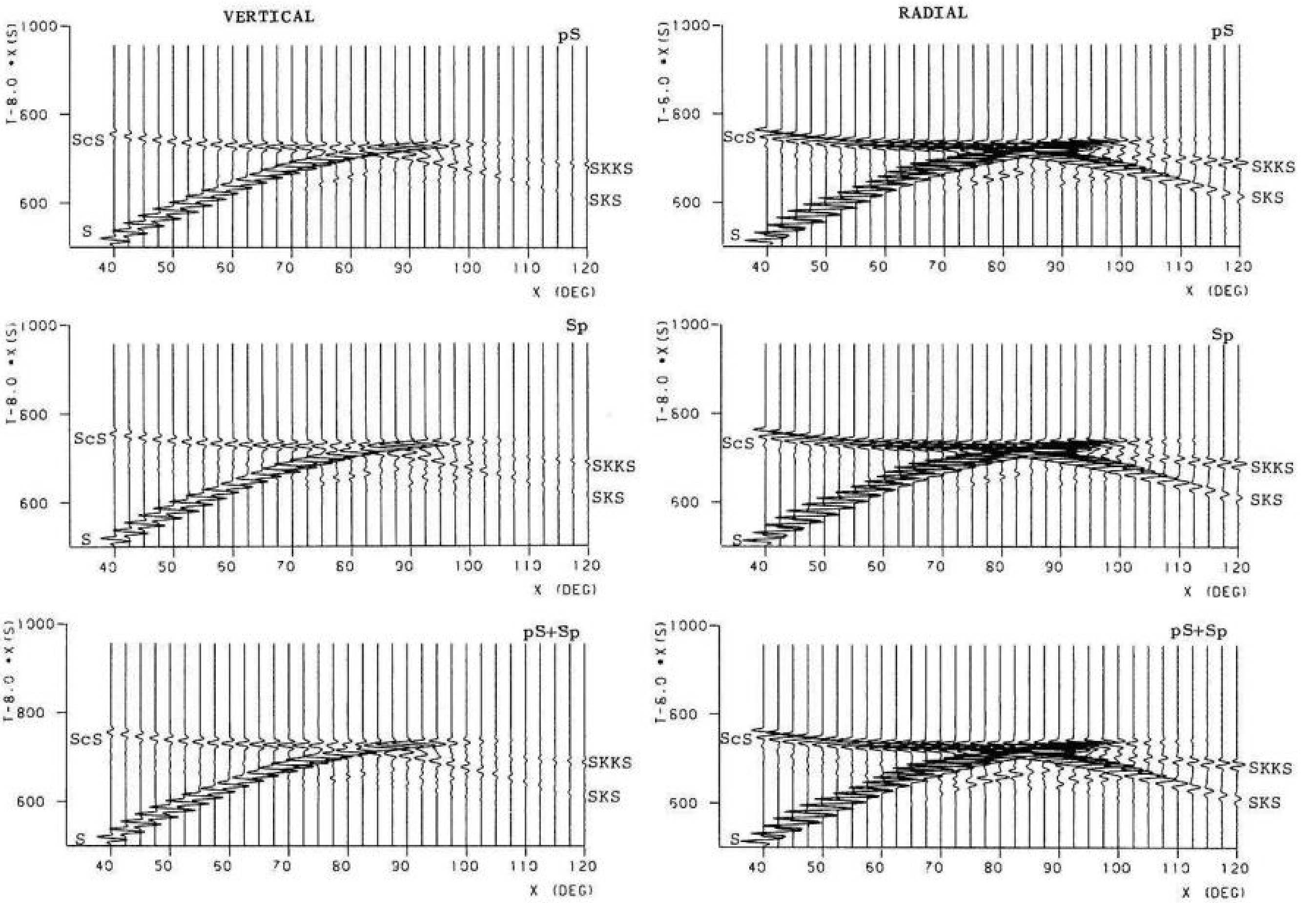

Fig. 10. Theoretical SV-wave seismograms, including precursors, for the Oaxaca earthquake and a profile through Europe. Earth model SP-1 was used, and no correction for absorption was applied. The precursors, appearing mainly between 70 and 100° before S and SKS, are produced by the discontinuities at depths of 395 and 670 km below the focus (pS) and below the station (Sp)

vations usually only in part, the extreme cases being station LOR with good agreement and station STU with less similarity in the waveform. However, if only precursor amplitudes are compared there is quite good agreement of theory and observation. We consider this as evidence for a mantle transition zone below the eastern North-Atlantic and western Europe similar to the transition zone of model SP-1.

Absorption has not been taken into account in the calculation for Fig. 11, since the Sp precursors and the main S phases have similar ray paths in the lower mantle and the difference in attenuation in the upper mantle would entail a reduction of the S, SKS and ScS amplitudes by roughly 10% with respect to Sp; this would not alter the conclusions drawn from Fig. 11.

Another comparison of observed and theoretical records, this time for station GRF, is shown in Fig. 12 for the events (6) (Oaxaca, Mexico), (12) (Panama) and (13) (Ecuador). Both radial- and vertical-component seismograms are included; the following discussion will be restricted to the radial components. Theoretical P- and S-wave seismograms were computed separately and superposed afterwards with the same amplitude scale. Anelastic attenuation was taken into account, using the dissipation times $t_p^* = 1$ s and $t_s^* = 5$ s (Anderson and Hart, 1978; Burdick, 1978). The amplitudes of observed and theoretical seismograms were matched for the P phases. Assuming only pS conversions below the foci in model SP-1, precursors are too weak for all 3 events. Including in addition Sp conversions below GRF increases the amplitudes on the radial component and brings the amplitude ratios of converted phases and P to about the values in Table 1. The same can be achieved by assuming pS conversions only, but at velocity contrasts which are about 50% larger than in SP-1; pS-conversions for a corresponding model (SP-11 in Fig. 9) have been included in Fig. 12 for the Oaxaca event. We emphasize that this has been done only for illustrative purposes. The more realistic interpretation is the assumption of conversion both below the foci and below GRF in models such as SP-1, since this also explains the precursor observations for event (7) which have been discussed before. From all this we conclude that SP-1 is a reasonable model for both conversion regions, i.e., under most of the Caribbean and the Gulf of Mexico and under western Europe.

A somewhat problematic aspect of the 3 events presented in Fig. 12 is that their theoretical S-to-P amplitude ratios are about twice the observed ratios. Most probably this is due to inadequate modelling of S waves relative to P; it may be due to incorrect assumptions about absorption or due to deviations between actual P and S radiation at

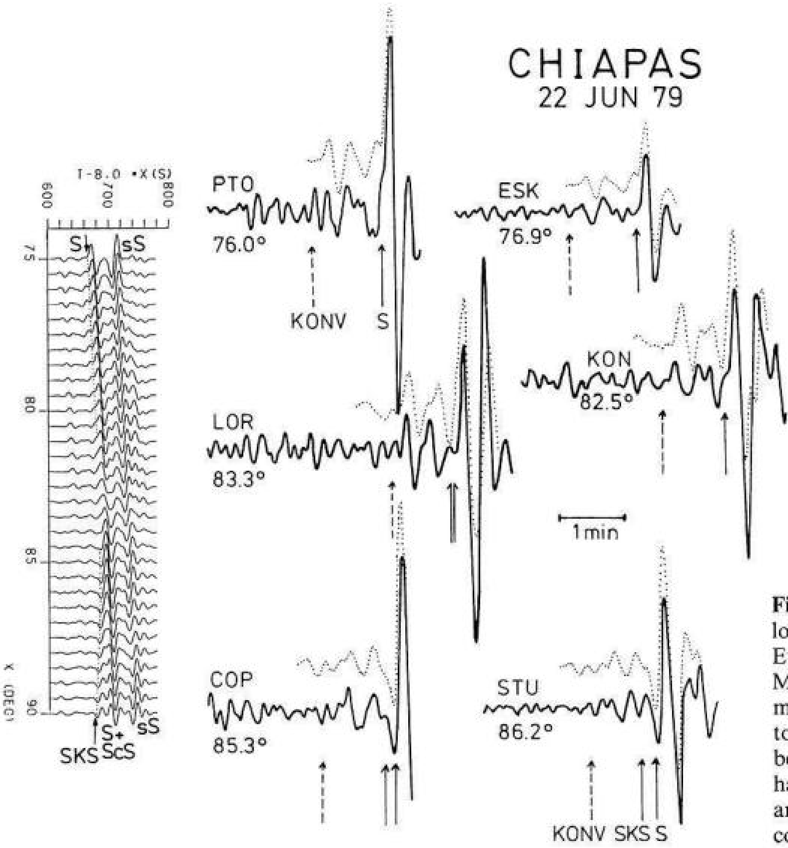

Fig. 11. Comparison of observed and theoretical long-period seismograms (vertical component) for European WWSSN stations and event (7) (Chiapas, Mexico). The theoretical seismograms were calculated for model SP-1 and include only Sp conversions as precursors to S and SKS. For comparison with the observations the best-fitting theoretical seismogram close to each station has been taken from the section on the left, and amplitudes were fitted in the S or S+SKS wavegroup. No correction for absorption was applied

the foci on the one hand and radiation from a double-couple source on the other, e.g., as a consequence of rupture propagation. This inadequate S-wave modelling, although not really understood, can approximately be corrected for by reducing the theoretical S-wave amplitudes in Fig. 12 to the level of the observations and a corresponding reduction of the Sp conversions by about the same factor, ~ 0.5 in the present case. The factor is about the same, since the paths of S and Sp are similar from the focus to the conversion zone below the station. After this correction the amplitudes of theoretical pS+Sp precursors would be reduced slightly compared to those plotted in Fig. 12, but this would not alter the conclusions drawn above about the velocity contrasts at the transition zone between the upper and lower mantle.

Discussion

On the background of the data studied in this paper and in paper I we evaluate the potential and limitations of investigations of the mantle transition zone with converted phases preceding S-waves as follows.

Converted-wave precursors are definitely observed in the long-period WWSSN or SRO frequency band at epicentral distances between 70 and 100°. Identification is often rather easy, easier at least than identification of other conversion types, e.g., long- or short-period P-to-S and S-to-P conversions in the coda of P, delayed with regard to P by several seconds to about 1 min (Vinnik 1977; Vinnik et al. 1983; Bock and Ha, 1984). In these cases one needs statistical arguments to discriminate between conversions and P arrivals due to continuing focal activity. However, *undisturbed* identification of S precursors as converted phases is also a rare case; usually the P-wave coda, including surface multiples, has not yet completely decayed in the time interval with conversions. The corresponding interference can be severe.

The interpretation of converted phases is rather complicated. Because of the different main body-wave phases which produce conversions and because of the structural details of the mantle transition zone, a complicated interference pattern of conversions arises which can only be interpreted with the aid of synthetic seismograms; the application of plane-wave transmission coefficients is not sufficient. Mostly it is also necessary to correct the synthetic seismograms for the influence of absorption. Hence, some knowledge about Q structure is required. Of course, employing synthetic seismograms is not a guarantee in itself for a unique interpretation of precursor observations which depend on a rather large number of structure and source parameters. Depending on the focal mechanism the precursors are a superposition of pS conversions below the focus and Sp conversions below the station. If both conversion types are present, modelling will normally give only an average structure for the mantle transition zone below the focus and the station. Only in the exceptional cases, where one of the two conversion types dominates clearly, a conclusion about one of the two structures is possible. It is worthwhile searching for these particular cases. In this context it is not always necessary to collect worldwide data for construction of a fault-plane solution. Sometimes the P-to-S amplitude ratio in the seismograms of a single station gives a sufficiently clear indication of the station's location in the fault-plane solution.

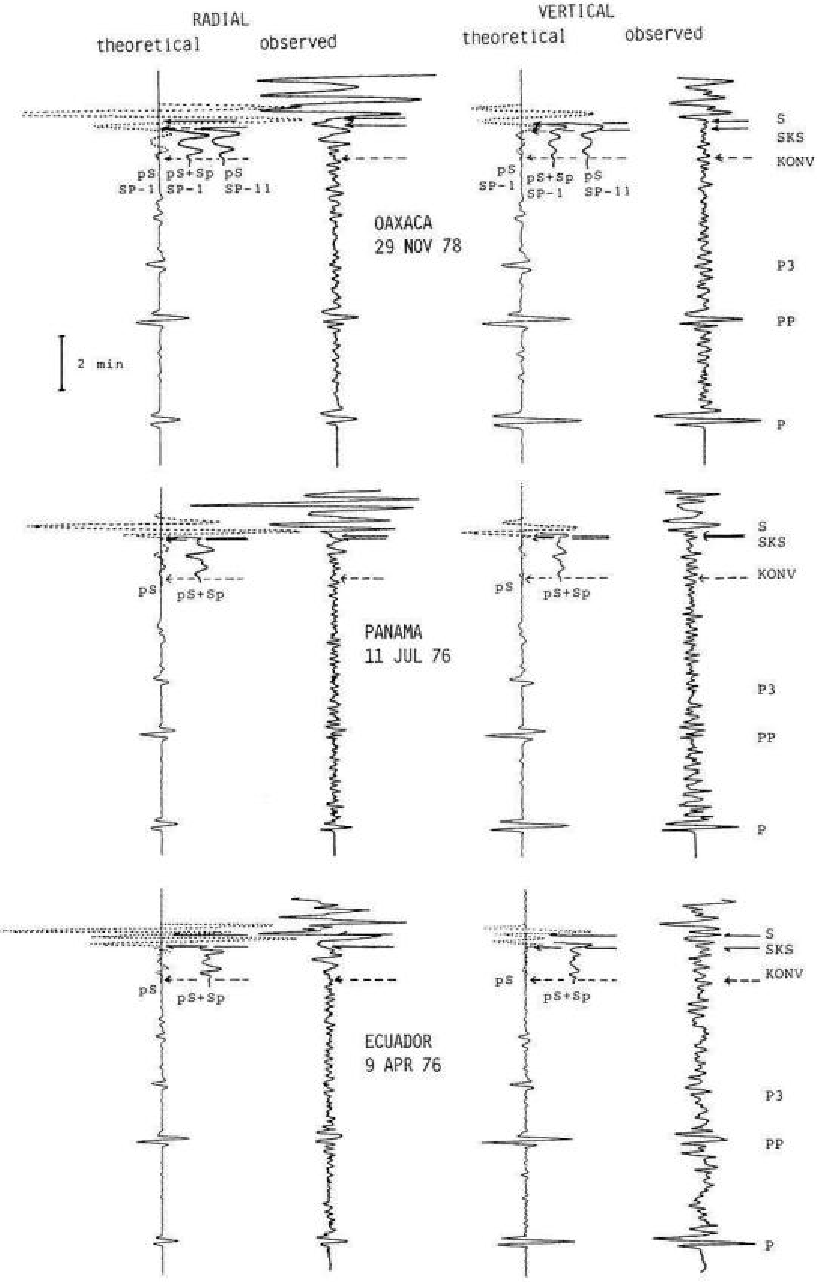

Fig. 12. Theoretical seismograms for GRF and comparison with simulated long-period WWSSN records: earthquakes of Oaxaca (top), Panama (center) and Ecuador (bottom). Calculation of P-wave seismograms, including P (plus surface reflections) and its surface multiples, and superposition of SV-wave seismograms, including S, ScS, SKS (plus surface reflections) and the precursor phases. Earth model SP-1 was used, for the Oaxaca earthquake additionally model SP-11. Correction for absorption by convolution with dissipation operators ($t_p^* = 1$ s, $t_s^* = 5$ s). The amplitudes from the first maximum to the first minimum of P in theoretical and observed seismograms were plotted at equal size

The resolving power of long-period converted phases is limited, i.e., it is not possible to infer from them the fine structure of the velocity-depth function in the conversion zone. For instance, it was reported in paper I that the conversion at a transition of thickness d is as effective as conversion at a discontinuity, provided that the velocity contrasts are the same and the dominent S wavelength is larger than about 0.5 d to 0.7 d. The present investigation seems to indicate that converted phases can better be used for the study of gross lateral variations in the structure of the mantle transition zone, a subject that is currently also addressed by surface-wave and free-oscillation investigations (Masters et al., 1982). It appears that we have detected a significant and widespread deviation from the more normal structure, as represented, e.g., by model SP-1 in Fig. 8; below the margin of the Eurasian plate from about Korea to the Sea of Okhotsk the velocity-depth functions seem to be considerably smoother. Lateral variations within the structure of the mantle transition zone of a more local character seem to exist between the Caribbean Sea and the Gulf of Mexico. Further studies with data from the increasing number of digital seismograph stations could serve to verify, supplement and extend our results.

Acknowledgments. This work was financed by the Deutsche Forschungsgemeinschaft. The computations were carried out at the computing center, University of Frankfurt. We thank Eric Chael for sending us WWSSN seismogram copies for several Mexican earthquakes. Helmut Aichele, Günter Bock, Wolfgang Brüstle, Rainer Kind and Jörg Schlittenhardt read the manuscript and made valuable comments. We are grateful to Ingrid Hörnchen for typing and retyping the manuscript and to Willi Mahler for drafting several figures.

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Received September 2, 1983; Revised February 23, 1984
Accepted February 23, 1984