Observed travel times for Multiply-reflected *ScS* waves from a deep-focus earthquake

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Ricevuto il 26 Agosto 1966

SUMMARY. — The deep-focus Argentinean earthquake of December 8 1962, generated multiply reflected *ScS* phases which were recorded very clearly at stations of the *IGY* and the *USC&GS* standardized worldwide networks and at Canadian stations. The data gathered from this earthquake for the multiply-reflected *ScS* and *sScS* were used to construct the travel times and to extend them to shorter epicentral distances. These new data brought to light an error in published travel times for the *2(ScS)* phase.

RIASSUNTO. — Il terremoto profondo avvenuto in Argentina l'8 Dicembre 1962, ha originato onde *ScS* riflesse più volte, che sono state registrate molto chiaramente dalle stazioni sismiche della rete mondiale standard dell'*IGY* e dell'*USC&GS* e dalle stazioni Canadesi.

I dati raccolti mediante lo studio di questo terremoto per le onde *ScS* e *sScS*, sono stati usati per costruire la curva dei tempi di tragitto ed estesi a distanze epicentrali più brevi.

Questi nuovi dati, inoltre, hanno messo in luce un errore relativo ai tempi di tragitto già pubblicati per le onde *2(ScS)*.

INTRODUCTION

Multiply-reflected *ScS* and their surface images from the December 8, 1962, deep-focus earthquake in Argentina were unusually well recorded by long-period seismographs at stations of the *IGY* and the *USC&GS* standardized network, and at Canadian stations. This investigation describes a study made on the identification of the multiply-reflected

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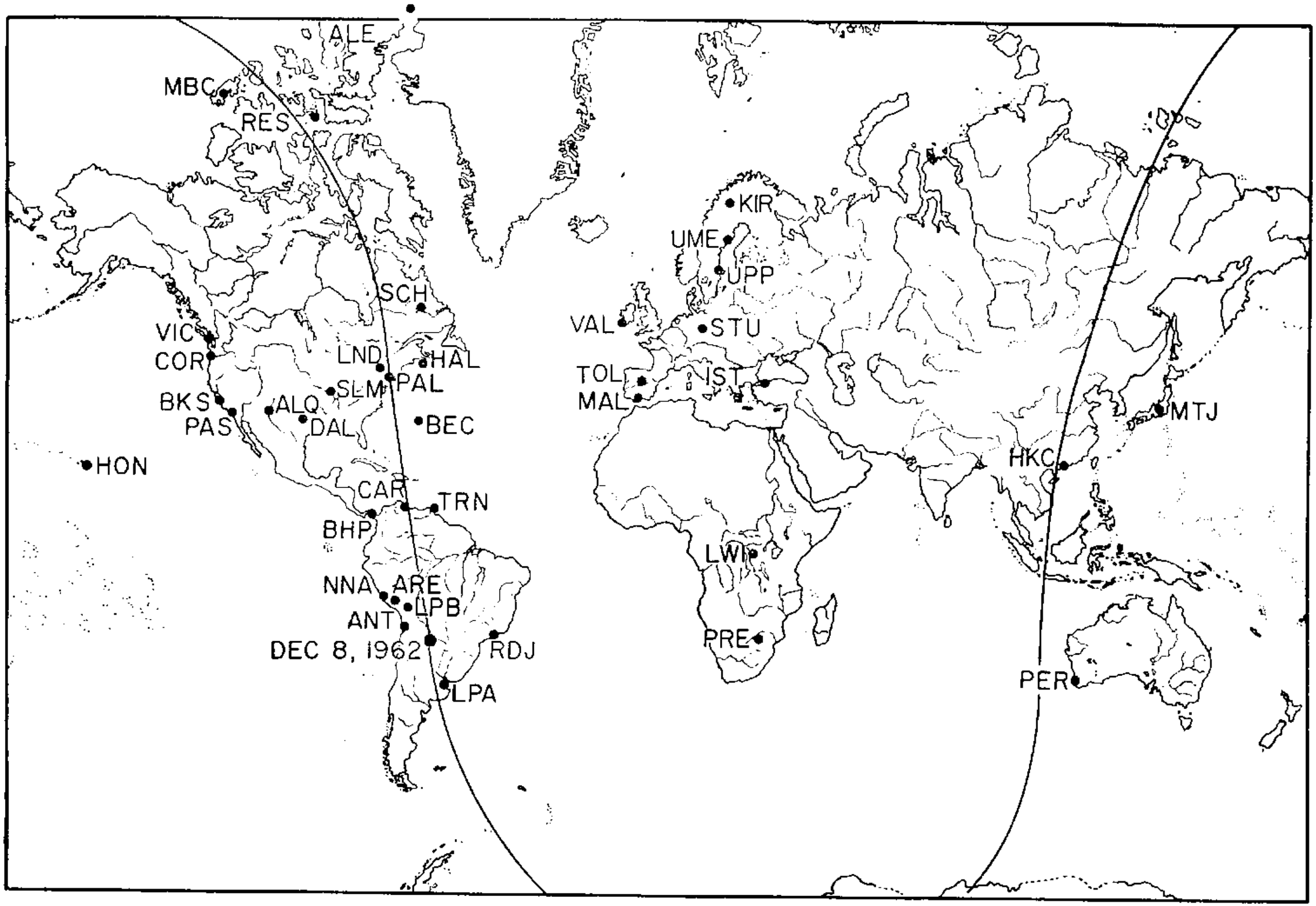

Fig. 1. – Map showing location of epicenter, stations, and a great circle path through Palisades.

phases, and the construction of their travel-times as recorded on long-period instruments. The observations of the travel-times of the *2(ScS)* at shorter epicentral distances have permitted the extension of the travel-time curve for this phase down to an epicentral distance of 7°. Previously in the literature, the travel-time curve for *2(ScS)* has been given for an epicentral distance greater than 90°. The *n(ScS)* family of phases has been identified without any doubt by the presence of the *n(sScS)* phases on the recordings. Identification of phases traveling in the major circle path is shown. In the process of plotting the observed travel times of the *2(ScS)* phase, an error in the published travel-time curve for this phase has been found, for a depth of focus of 600 km.

INTERPRETATION OF THE DATA

The epicenter, origin time, and depth of focus for the December 8, 1962, earthquake were located by using Bolt's (1960) program for the 7090 *IBM* computer. One hundred fifty readings of impulsive *P* phases, 14 *pP* and 10 *PKP* readings, were used in the relocation. The pertinent data are listed in Table I.

Table I

Epicenter		*Origin Time (GMT)*	*Depth*	*Magnitude*	
		h m s	km		
25.8° *S*	63.4° *W*	21 27 22.2	620	7 *PAS*	*USC&GS*
25.78° *S*	62.15° *W*	21 27 18.0	580	6 3/4 *PAL*	

The data used in this study are from the stations shown in Figure 1. The solid line in this figure is a great circle path through Palisades, N.Y., and the station code identifying each of the stations corresponds to the three letter code assigned by the *USC&GS*. Readings of the phases which constitute the data were done from long-period recordings having a natural period of 30 sec and 100 sec for the seismometer and galvanometer, respectively.

Figure 2 shows a graphical description of the phases which have undergone four reflections at the core-mantle boundary, denoted as

4(ScS), through the minor circle path and recorded at *SCH*. Also in the same figure is shown a phase which travels through the major circle path and has been reflected three times at the core-mantle boundary, denoted as *3(ScS)*$^-$, and also recorded at the same station.

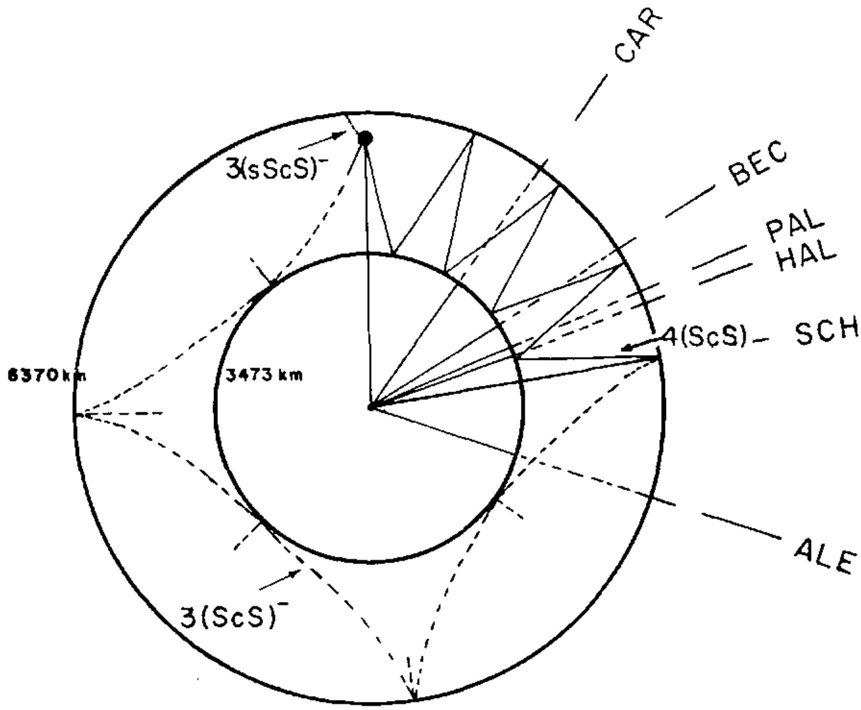

Fig. 2 – Graphical example of ray paths and notations used for the multiply-reflected phases which have traveled along the minor and major circle paths.

Figure 3 shows a tracing of the *E-W* component seismogram at *CAR*, with an epicentral distance of 36.24° and an azimuth from the station to the epicenter of 174.61°. The original recording was done on a recorder with a 30 mm/min. revolution rate. In this figure, the tracing has been reduced by a factor of four. The portion of this recording is between the arrival time of the *S* phase and approximately a minute after the arrival time of the *4(ScS)*. On the original seismogram, the peak-to-peak amplitude of the *ScS* phase is 357 mm. The *n(ScS)* and *n(sScS)* are indicated on the seismogram. The identification of the *n(ScS)* series has been made certain by the arrival of its surface images on the recordings.

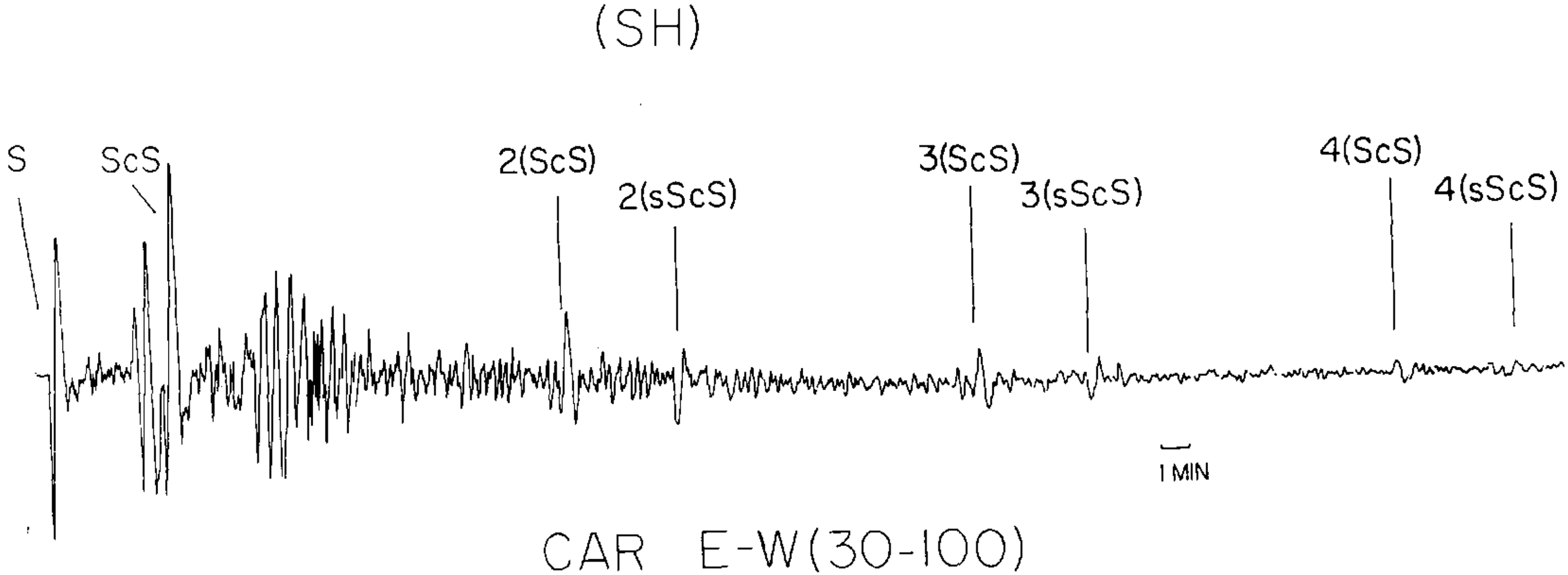

Fig. 3 – Seismogram from *CAR*, December 8, 1962, *E-W* long-period component.

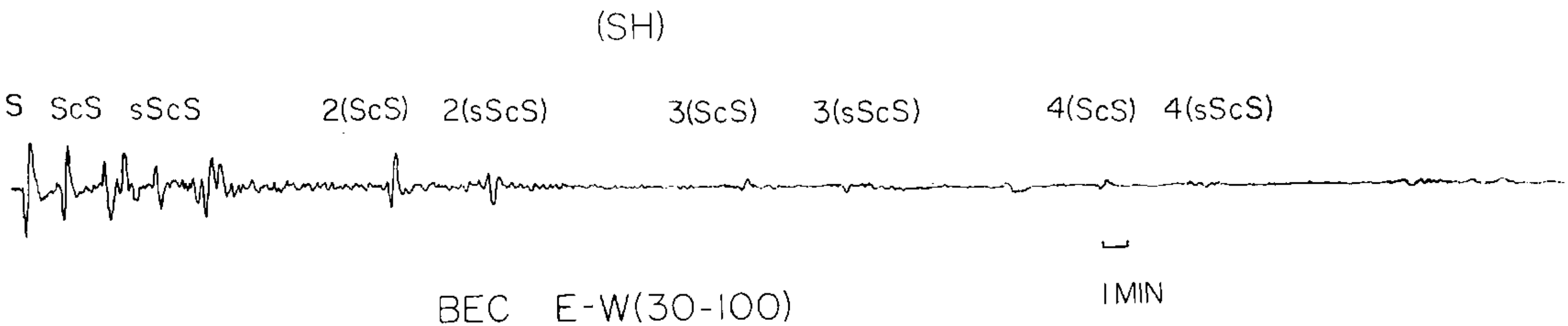

Fig. 4 – Seismogram from *BEC*, December 8, 1962, *E-W* long-period component.

Another typical seismogram tracing is shown in Figure 4. This figure is the *E-W* component at *BEC* with an epicentral distance of 57.86° and an azimuth of 178.6° and shows an especially clear recording of the *n(ScS)* and the *n(sScS)* series. On this record, the two series are indicated from *n* = 1 to an order 4; however, at the end portion of this seismogram, the *5(ScS)* can be seen very clearly. This phase was also well recorded at stations close to the epicenter, but there was difficulty in picking its arrival time since the background noise is high in that portion of the seismogram. On inspection of the *N-S* component seismogram, the horizontally polarized shear phases are very small in amplitude, and in the vertical component these phases were not discernible.

Figure 5 shows a composite of seismograms for nine stations. Eight are due North of the epicenter, and the ninth is due East. These recordings were made on long-period instruments; the *E-W* component is the one shown in this figure. Unfortunately, the variation of speed in the revolution of the drum is different for some of these stations; some have a 15 mm/min. and others 30 mm/min. revolution rate. When reduction was done on each of the seismograms in this composite figure, a one-to-one correspondence was lost. The picture length is made up of four parts put together, which can be seen in the breaking of the time axis. This fact also has introduced distortion, and because of these distortions, no attempt is made to draw a travel-time curve which connect one phase with another for a given series. The *ANT*, *BAA*, and *ARE* seismograms were omitted in this figure since their locations are too close to the time axis. The *RDJ*, *CAR*, *BEC* are tracings of the originals, and the *PAL*, *HAL*, *SCH*, *VIC*, *RES*, and *ALE* are reduced pictures of the original seismograms at these stations. The time axis is in minutes, with an interval of 2 minutes, and the distance axis is in degrees.

Travel-time curves.

The seismograms obtained from 38 of the *IGY*, *USC&GS*, and the Canadian stations were read (see Figure 1) and a total of 23 station records were used in the final gathering of the data which is used to construct the travel-time curves for the multiply-reflected phases. To interpret the phases on the recordings, the travel times of impulsive phases were picked, tabulated, and plotted. These readings were done on all three

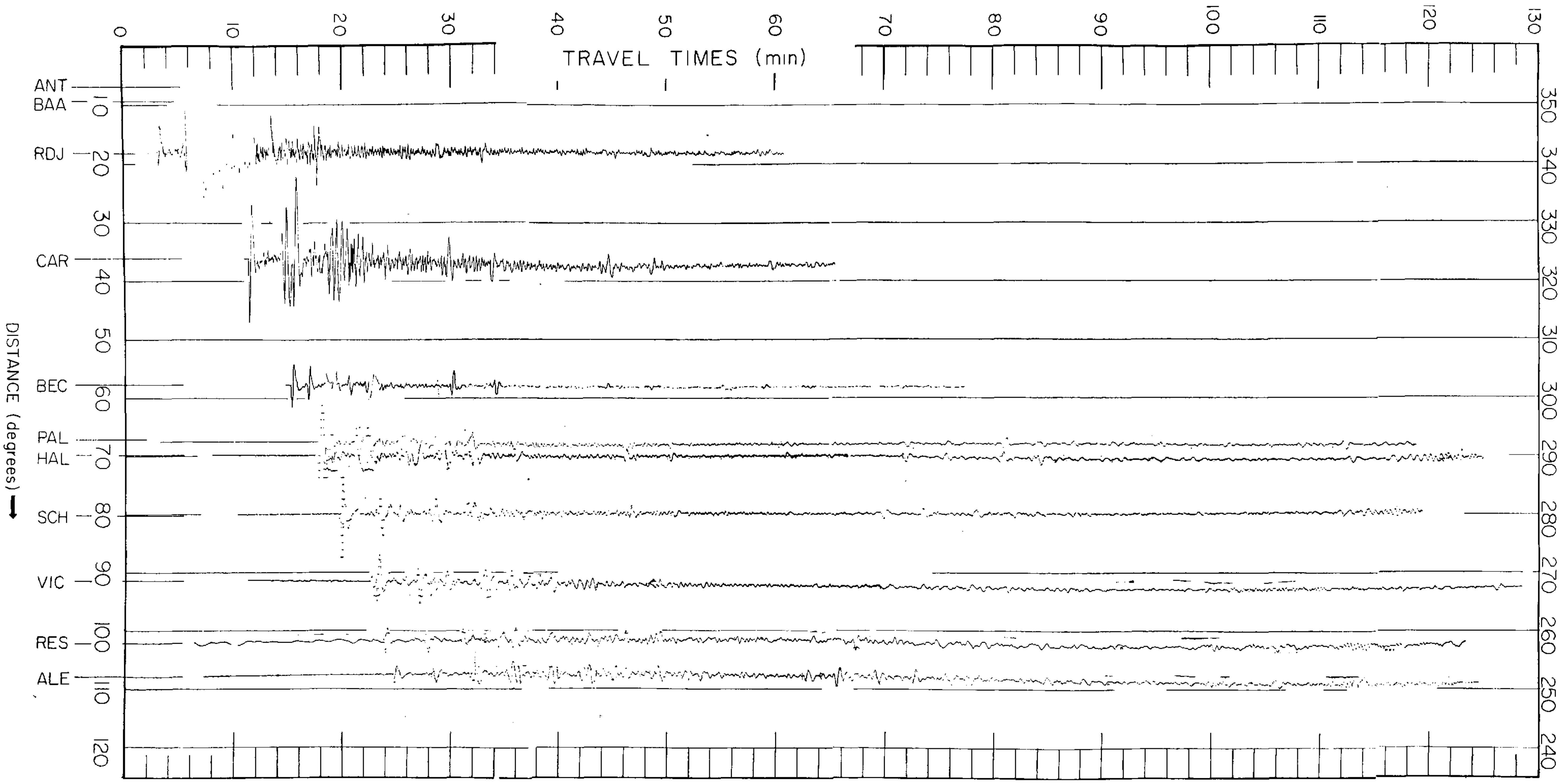

Fig. 5 – Time-distance composite picture, with seismograms from nine stations of the December 8, 1962, deep-focus earthquake. Time in minutes; distance in degrees.

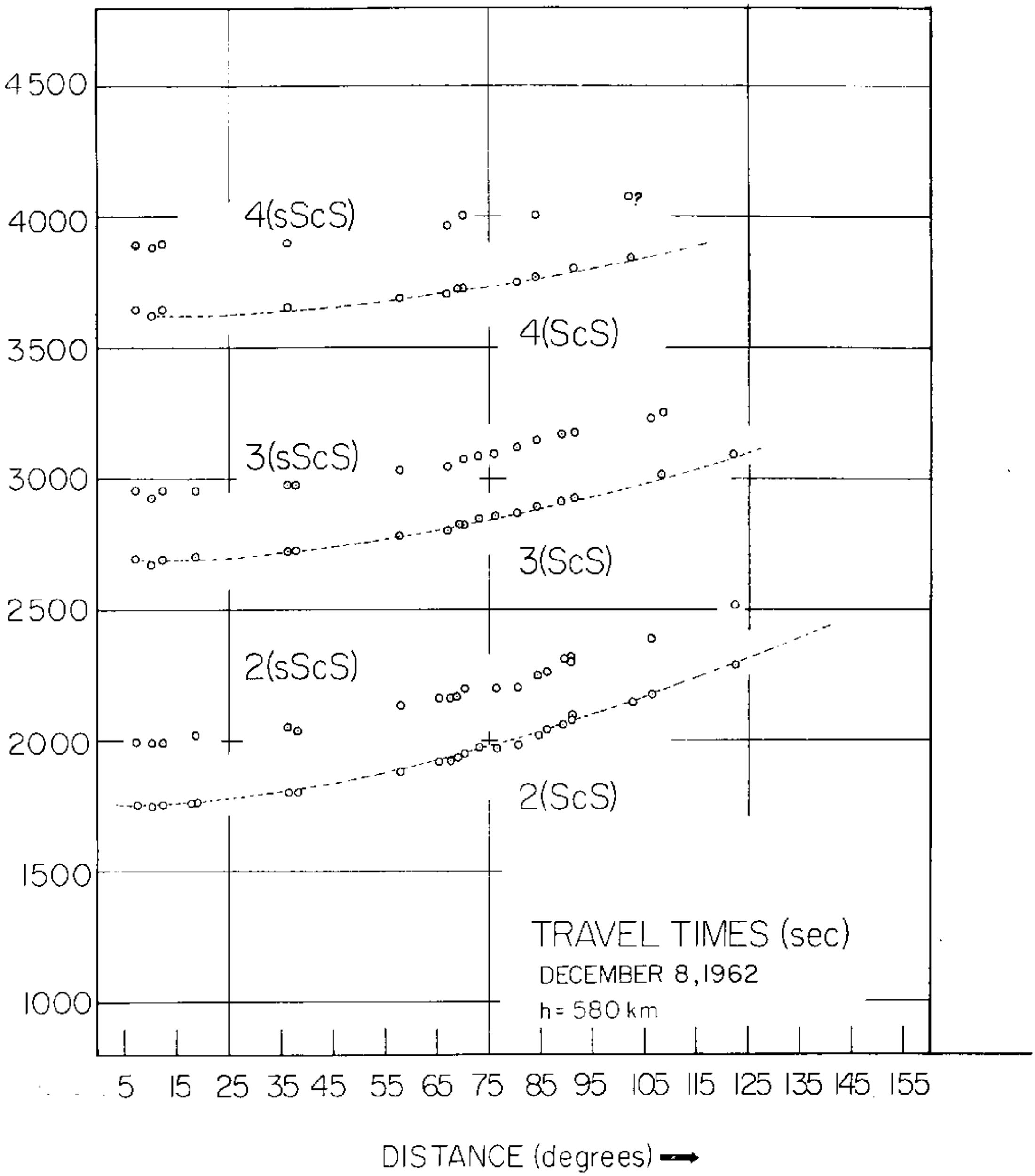

Fig. 6 – Observed travel times for the $n(ScS)$ and the $n(sScS)$ series. Time in seconds; distance in degrees.

components. After identification of the phases was certain, ellipticity corrections were applied to each of the readings. Figure 6 shows the travel times for the $n(ScS)$ and $n(sScS)$ series obtained from the deep-

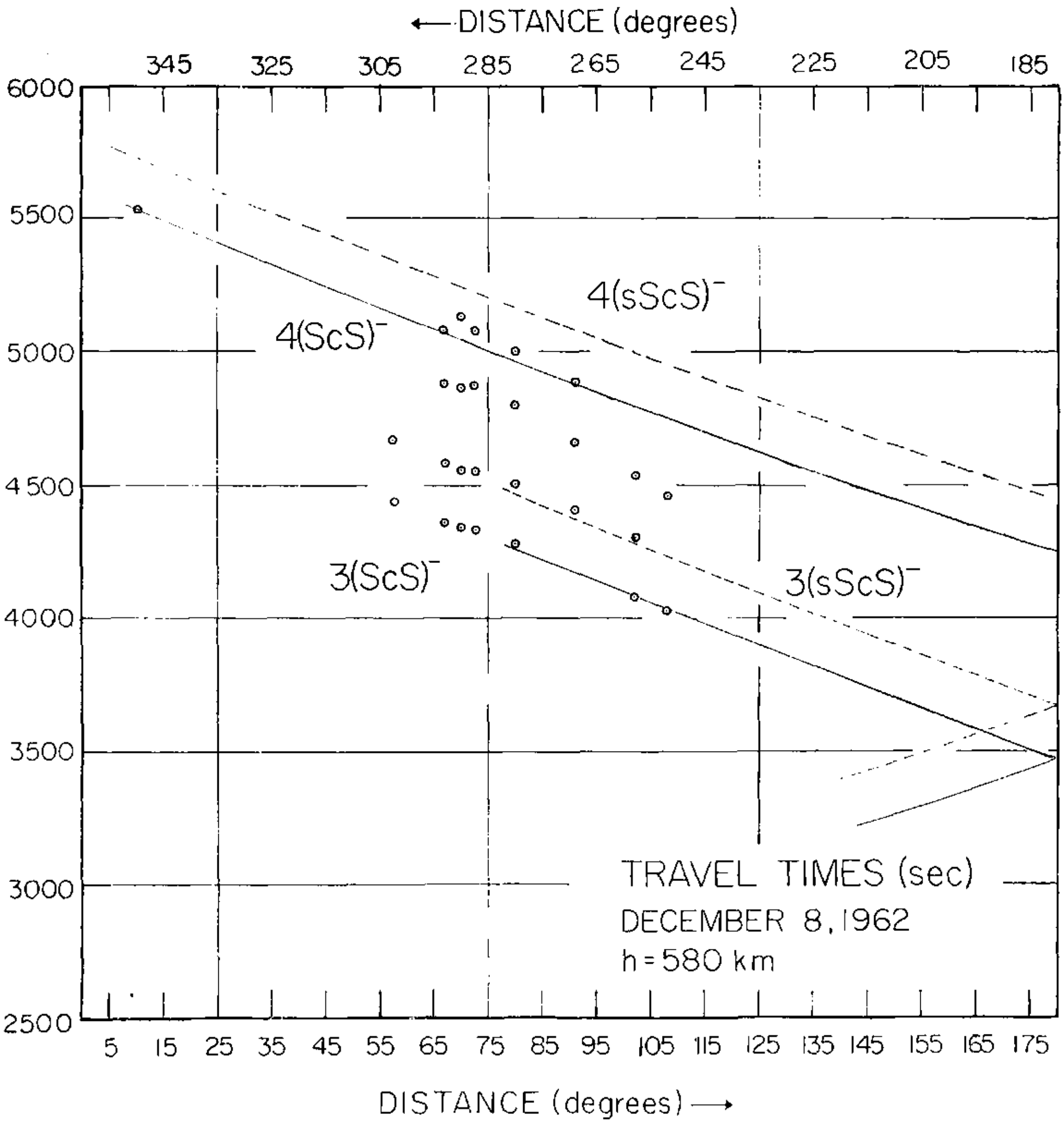

Fig. 7 – Observed travel times for the $3(ScS)^-$ and $3(sScS)^-$ phases. Time in seconds; distance in degrees.

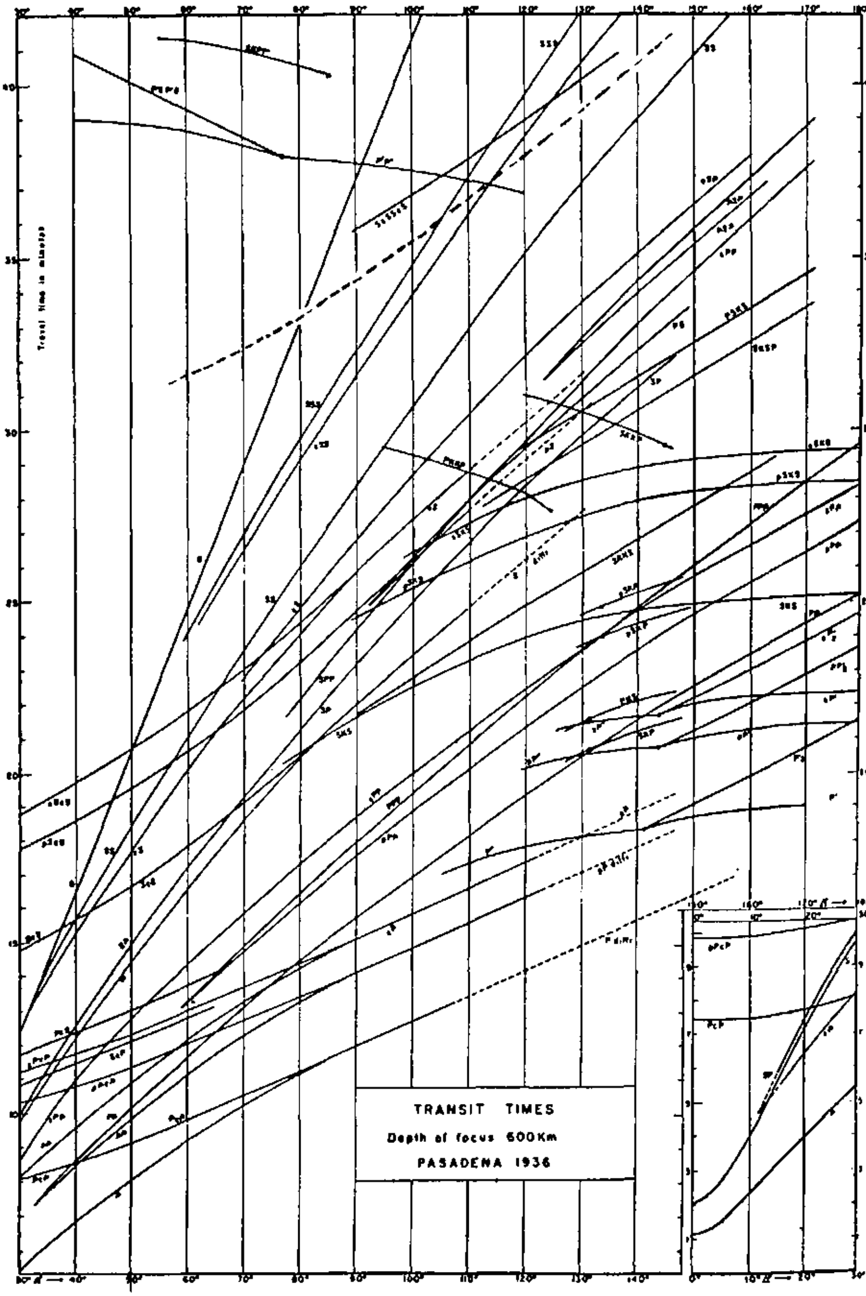

Fig. 8 – Travel-time curves (after Richter). The dash-line travel-time curve corresponds to the correct curve for the *2(ScS)* phase.

focus earthquake of December 8, 1962. Time is given in seconds and distance in degrees. The criterion used in the identification of the *n*(*ScS*) series is that of the presence of its surface images on the recordings (see Figures 3, 4, and 5).

The dashed curves in this figure correspond to the travel times for *2*(*ScS*), *3*(*ScS*), and *4*(*ScS*) for a depth of focus of 580 km. Some of the observed points on these curves were checked against the Jeffreys and Bullen tables (1948), using the times of *ScS* for a surface foci and the corresponding depth allowances. At first, Gutenberg and Richter travel-time curves for $h = 600$ km were used; however, the observed travel times from this earthquake at epicentral distances of 90° to approximately 125° were earlier than the times given by their curves. In this figure, the *n*(*ScS*) and the *n*(*sScS*) series are plotted up to order $n = 4$. The identification of order $n = 5$ was possible in many of the records, but the scatter of the data readings was large; hence, these readings were omitted. The recently installed long-period instruments by the *USC&GS* in South America made possible the gathering of the data at close epicentral distances, and hence, the extension of the travel time observations of the *2*(*ScS*) down to an epicentral distance of 7°.

In Figure 7 are shown the travel times of some of the phases which have arrived through the major circle path. The solid lines correspond to the travel-time curves for the $3(ScS)^-$, and the $4(ScS)^-$, and the dashed lines to their corresponding surface images. The observations of the earlier arrivals in this figure fit those of the $3(ScS)^-$ and the latter ones fit those of their surface image. After the arrival times of the $3(sScS)^-$, there are a number of observations which do not fit the $4(ScS)^-$ travel-time curve, and the latter arrivals scatter very much, so one cannot identify, with certainty, these phases as being of the $4(ScS)^-$ series. These phases in question are clearly recorded on some of the seismograms (see Figure 5) with amplitudes larger than those phases which have arrived through the minor circle path.

Figure 8 shows the travel-time curves given in Richter's book, "Elementary Seismology", on page 684, and on it a dashed travel-time curve has been drawn which corresponds to the correct travel-time curve for the *2*(*ScS*) phase obtained in this study. The travel-time curve published earlier by Gutenberg and Richter (1937) for the same phase, for a depth of focus of 600 km, should be redrawn as the dashed travel-time curve shown in Figures 6 and 8.

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