BODY WAVE TRAVEL TIME STUDIES AND INFERENCES

V. G. KRISHNA, K. L. KAILA AND P. R. REDDY
National Geophysical Research Institute, Hyderabad 500007, India

ABSTRACT – *A variety of techniques are well developed for body wave travel times analysis and study of crustal and upper mantle velocity structure in India. P wave travel time curves determined from shallow earthquakes data in various directions from India reveal significant variations while S wave travel times show comparatively better agreement with respect to the world average JB travel time tables. Both P and S wave velocities in the uppermost mantle beneath the Indian subcontinent are relatively high (P velocity 8.2–8.4 km/s and S velocity 4.6–4.8 km/s) as compared to other regions of the Earth. Deep earthquakes travel times analysis in the Hindukush region also confirmed the relatively high P and S wave velocities in the upper mantle in this region. Velocity-depth models for the mantle beneath the Indian subcontinent inferred from P wave travel time curves reveal prominent discontinuities at average depths (below the crust) of 400, 650, 950, 1350 and 1900 km. These inferred velocity discontinuities in the mantle are also consistent with the discontinuous nature of P wave amplitude decay curves observed out to 98° distance. The prominent velocity discontinuities at 400 km and 650 km depths in the upper mantle transition zone are also well brought out by dT/d△ measurements at the GBA seismic array as well as deep earthquakes travel times analyses and velocity determinations at the depths of foci. These two discontinuities are probably associated with both compositional and phase changes in the transition zone. Modeling results of some anomalous travel time observations from deep focus earthquakes suggest that the phase transformations associated with the 400 km and 650 km velocity discontinuities may be relatively elevated by 80–150 km and 30–80 km respectively in the subducting lithospheric slabs.*

New models of the lithospheric velocity structure in the Indian shield obtained from explosion and earthquake seismological data consistently reveal prominent low velocity layers, with large velocity contrasts at their boundaries, both in the continental crust and the subcrustal lithosphere. These models suggest a rheological stratification of the continental lithosphere. Anomalously high uppermost mantle P wave velocities of up to 8.6–8.9 km/s and a higher than normal velocity gradient are also found in some regions, especially in the southeastern part, of the Indian shield. These high velocities and high velocity gradient are indicative of presence and/or continuation of elastic anisotropy in the continental upper mantle in this region.

INTRODUCTION

The most fundamental parameters concerning the physics of the Earth's interior are the velocities of seismic body waves, P and S. Travel times, amplitudes and periods of body waves form the necessary data set to determine the velocity-depth functions essentially for the following regions within the Earth:

- upper and lower crust,
- subcrustal LID, above the upper mantle low velocity zone (LVZ), considered to be the main part of the seismic lithosphere,
- upper mantle low velocity zone below the LID,
- region between LVZ and 400 km discontinuity,
- transition zone consisting of the 400 km and 650 km velocity discontinuities,
- the lower mantle.

While the existence of most of these subdivisions within the Earth has been recognized for quite some time, the increased quantity and quality of body waves data together with the development of modern data acquisition and processing techniques have progressively yielded more complicated but realistic models within various regions of the Earth. Observations of travel times of body waves are most numerous and there have also been a large number of studies in India utilizing them which provided valuable results concerning the seismic velocity structure beneath the Indian subcontinent.

The standard method of analysis consists of measuring travel times (T) of body waves produced by earthquakes and/or nuclear explosions (if available) as a function of epicentral distance (Δ), smoothing the data and fitting by a curve, estimating $dT/d\Delta$ as a function of Δ and inverting to obtain the velocity-depth function. The main factors that may contribute to the scatter in the travel times data are the errors in the hypocentral depths and origin times of earthquakes, the epicentral distances, the unknown velocity variations in the source and receiver regions and strong lateral velocity variations (if any) over the Δ range considered. Methods for body wave travel times interpretation based on the seismic ray theory are well developed[1]. For most regions within the Earth, velocity increases slowly and continuously as a function of depth. The resulting travel time curve in such a case is concave downward, the curvature decreasing with increasing distance. The amplitude of the arriving wave is also a slowly decreasing function of distance. A rapid increase of velocity at certain depth results in a triplication of the travel time curve. If the velocity increase is continuous and the velocity gradient discontinuous, the cusp at the far end of the second branch of travel time curve has large amplitudes. If both the velocity and velocity gradient are continuous, both the cusps are associated with large amplitudes. On the other hand, if there is a discontinuous decrease in velocity the travel time curve displays a shadow zone, i.e., a range of Δ where no waves arrive. However the cusp at which the new travel times branch starts has large amplitudes. If the velocity decrease is continuous, i.e., $(r/v)\ (dv/dr) \geqslant +1$, at any level no ray can bottom or have its deepest point at that level. The limits and the width of the shadow zone depend on the depth of focus. However, if the focus is below that level no shadow zone occurs. Further, if the decrease of V with increasing depth is only slight enough so that $(r/v)\ (dv/dr)$ remains less than $+1$ then also no shadow occurs. Techniques for calculating $T-\Delta$ curves for any velocity distribution including continuous and discontinuous increases and decreases of velocity with depth are also well developed[2]. It is quite evident that in addition to identifying various first as well as later arriving travel time branches, location of the cusps and amplitudes analyses of different phases provide crucial information on the velocity structure and the nature of various discontinuities at depths.

P AND S WAVE TRAVEL TIME CURVES AND THE MANTLE VELOCITY STRUCTURE

A large number of seismological studies in various regions of the Earth confirmed the presence of significant lateral velocity variations extending deep into the upper mantle. Consequently, the need to develop regional body wave travel time curves valid for different regions of the Earth was well recognized. Thus a research project on body wave travel time studies was initated during 1966 by the seismology group at the National Geophysical Research Institute, Hyderabad, with the main objectives to determine the regional body wave travel time curves and the seismic velocity structure of the mantle beneath the Indian subcontinent. For evaluating the travel time curves of P and S waves using observations from shallow earthquakes as well as nuclear explosions, a novel statistical method was developed[3,4] for multibranched curve fitting by weighting observations and iterative least squares fitting. In this method, the first approximation straight line fits and the standard deviations σ for each travel times branch are obtained on the basis of observations well separated from the cross-over regions between successive branches. By assuming that the errors in the travel time points are distributed according to normal law of errors and by multiplying the normal distribution function by $1/\sigma$, the normal probability curve for the travel time points is obtained which in turn is used for assigning weights to all the observation points over the entire distance range to fit each of the travel time branches. Thus by this method of weighting observations and using all the observation points for least squares fitting of each travel time segment, the possible bias in assigning data points to either of the successive branches, especially near their cross-over point, can safely be eliminated. This algorithm with iterative procedure can be run on high speed computers to obtain the slopes and time-intercepts of various travel time segments stabilized at the appropriate values.

P and S wave travel times recorded by Indian seismological observatories from shallow earthquakes and nuclear explosions up to 55° epicentral distance in the northernly azimuth from India have been studied[4,5] by using the above described statistical method. The P wave data in this direction revealed four travel time segments with abrupt velocity changes occurring around 19°, 22° and 33° epicentral distances (figure 1a). The four travel time segments yielded apparent velocities of 8.35 ± 0.02, 10.11 ± 0.06, 11.22 ± 0.07 and 13.59 ± 0.08 km/s. The S wave data revealed three travel time segments with velocities of 4.60 ± 0.01, 6.10 ± 0.04 and 7.63 ± 0.06 km/s, the apparent velocity changes occurring at 21° and 31° epicentral distances (figure 1b). The travel time residuals with respect to the

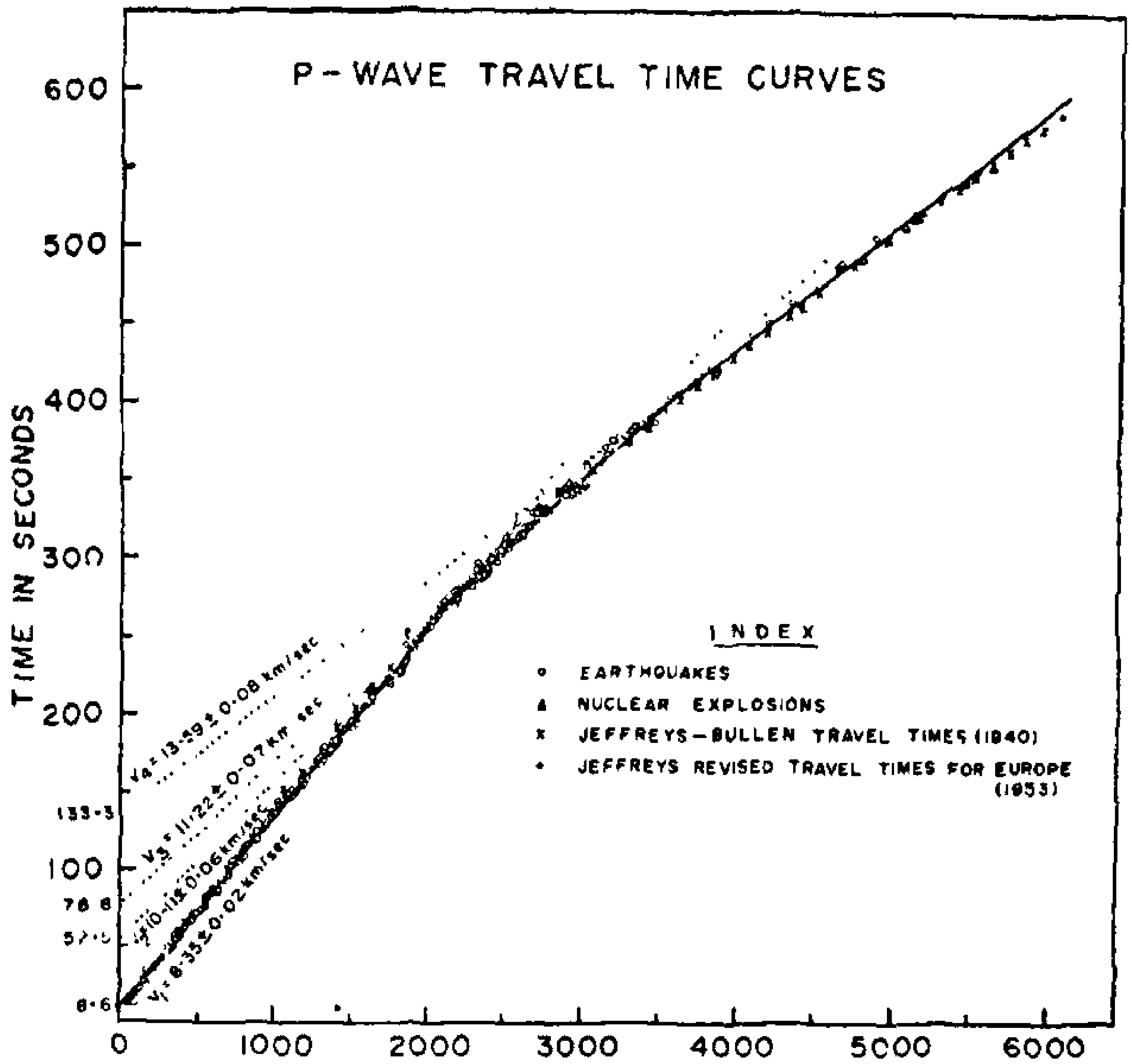

FIGURE 1(a) P wave travel time curves, for northern direction from India, determined from shallow earthquake data. Thick straight line segments are the weighted least square solutions. (Reproduced from ref. 4).

world average Jeffreys-Bullen (JB) travel time tables[6] [observed-JB times] for P waves in the northern direction from India are found to be mostly negative (-1 to -10 s) up to 19° epicentral distance and mostly positive ($+4$ s) for distances greater than 33°. The JB residuals for S waves in this direction are found to be mostly negative (up to -25 s) up to 20° epicentral distance and mostly positive (up to $+12$ s) for distances greater than 28°. The inferred upper mantle P wave velocity structure from the travel time studies[4] in the northern direction revealed three prominent velocity discontinuities at depths (below the crust) 380 ± 20, 580 ± 50 and 1000 ± 120 km with true velocities below the discontinuities 9.47 ± 0.06, 10.15 ± 0.07 and 11.40 ± 0.08 km/s respectively. The uppermost mantle P velocity in this direction is found to be 8.31 ± 0.02 km/s.

Similar studies were further extended[7] by using P and S wave travel times data from shallow earthquakes in the northeastern, southeastern, southern, southwestern and northwestern directions from India as recorded by Indian seismological observatories. The same statistical method of weighting observations has successfully been used to determine the P and S wave travel time curves, up to 70° epicentral distance range in the northeastern and southeastern directions and up to 90° distance range in the southern, southwestern and northwestern directions from India. An important result of this study is that in all the six directions the P and S wave velocities in the uppermost mantle beneath the Indian subcontinent are consistently higher [P velocities 8.20–8.43 km/s and S velocity 4.60 km/s] as compared to other regions of the Earth. Inferred velocity structures for the mantle in these regions reveal significant vertical and lateral variations with prominent discontinuities occurring at average depths (below the crust) of 400, 650, 950, 1350 and 1900 km. Table 1 summarizes the P wave velocity-depth models inferred[7] for the mantle beneath the Indian subcontinent in the six directions. The JB residuals for P waves for epicentral distances greater than 33 are found to be mostly negative (-3 to -4 s) in all the directions except in the northern direction from India. However, it was found that the S wave travel time curves in all the six directions from India show comparatively better agreement with the world average JB travel times.

In a later study[8], P wave travel times data from shallow earthquakes in the northeast Indian source region recorded at seismological observatories along

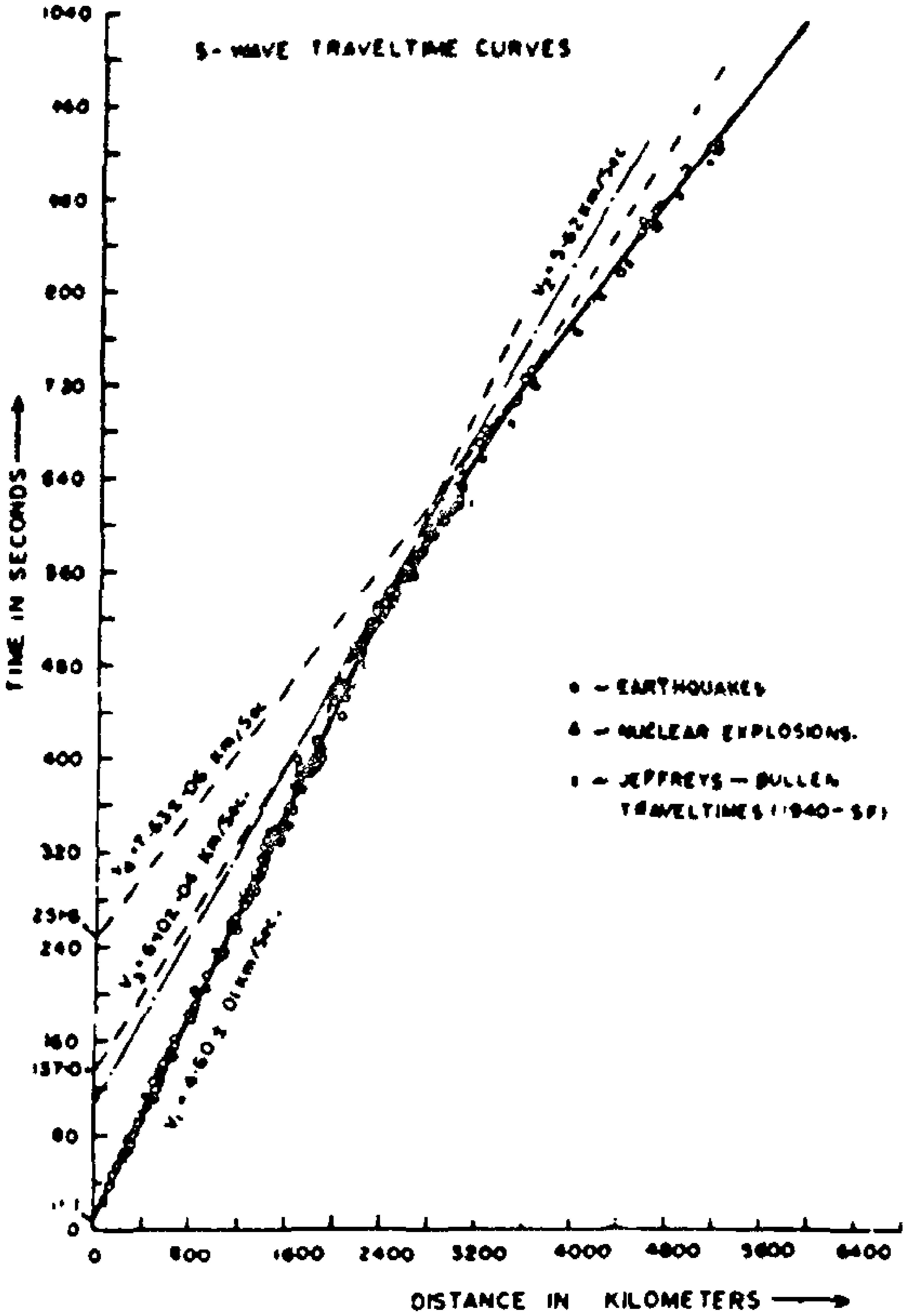

FIGURE 1(b) S wave travel time curves, for northern direction from India, determined from shallow earthquake data. Thick straight line segments are the second iteration weighted least square solutions. (Reproduced from ref. 5).

the southwestern and western directions across the peninsular shield and the northwestern direction across the Himalayas, are used for inferring the upper mantle velocity structure by a forward modeling technique. The travel time observations out to 30° epicentral distance revealed sharp changes in the apparent velocity at distances of about 19° and 24°. The inferred P velocity-depth functions, giving satisfactory fit to these travel time observations (figures 2a, b), reveal two prominent velocity discontinuities in the upper mantle at depths of 400–440 km and 640–680 km each associated with a 8%–10% velocity increase. No significant variations in the upper mantle velocity-depth models for the peninsular shield and the Himalayas have been found from this study.

DECAY RATE OF P WAVE AMPLITUDES FROM NUCLEAR EXPLOSIONS

The velocity discontinuities (first or second order) in the Earth's mantle, inferred from travel time studies of P and S waves from shallow earthquakes[4,5,7] are also well confirmed by a study[9] of P wave amplitudes decay rate with epicentral distance up to 98°. The P wave amplitudes versus distance data from a set of nuclear

Table 1. P wave velocity-depth models inferred for the mantle beneath the Indian subcontinent from shallow earthquake travel times data[7].

Depth (km) below crust	True velocity (km/s)	Depth (km) below crust	True velocity (km/s)
Northern direction		**Southern direction**	
0	8.31	0	8.20
380 ± 20	9.47	376 ± 10	9.55
580 ± 50	10.15	756 ± 15	11.53
1000 ± 120	11.40	935 ± 20	11.72
		1227 ± 30	12.11
Northeastern direction		**Southeastern direction**	
0	8.33	0	8.43
430 ± 10	9.93	370 ± 10	9.51
630 ± 15	10.73	690 ± 20	11.35
840 ± 20	11 47	1020 ± 25	11.84
1180 ± 30	12.09	1220 ± 30	12.10
Northwestern direction		**Southwestern direction**	
0	8.40	0	8.20
592 ± 10	10.95	324 ± 10	9.18
863 ± 15	11.67	728 ± 15	11.49
1295 ± 20	12.30	948 ± 20	11.62
1412 ± 45	12.48	1395 ± 35	12.44
1875 ± 125	12.97	1864 ± 60	13.08

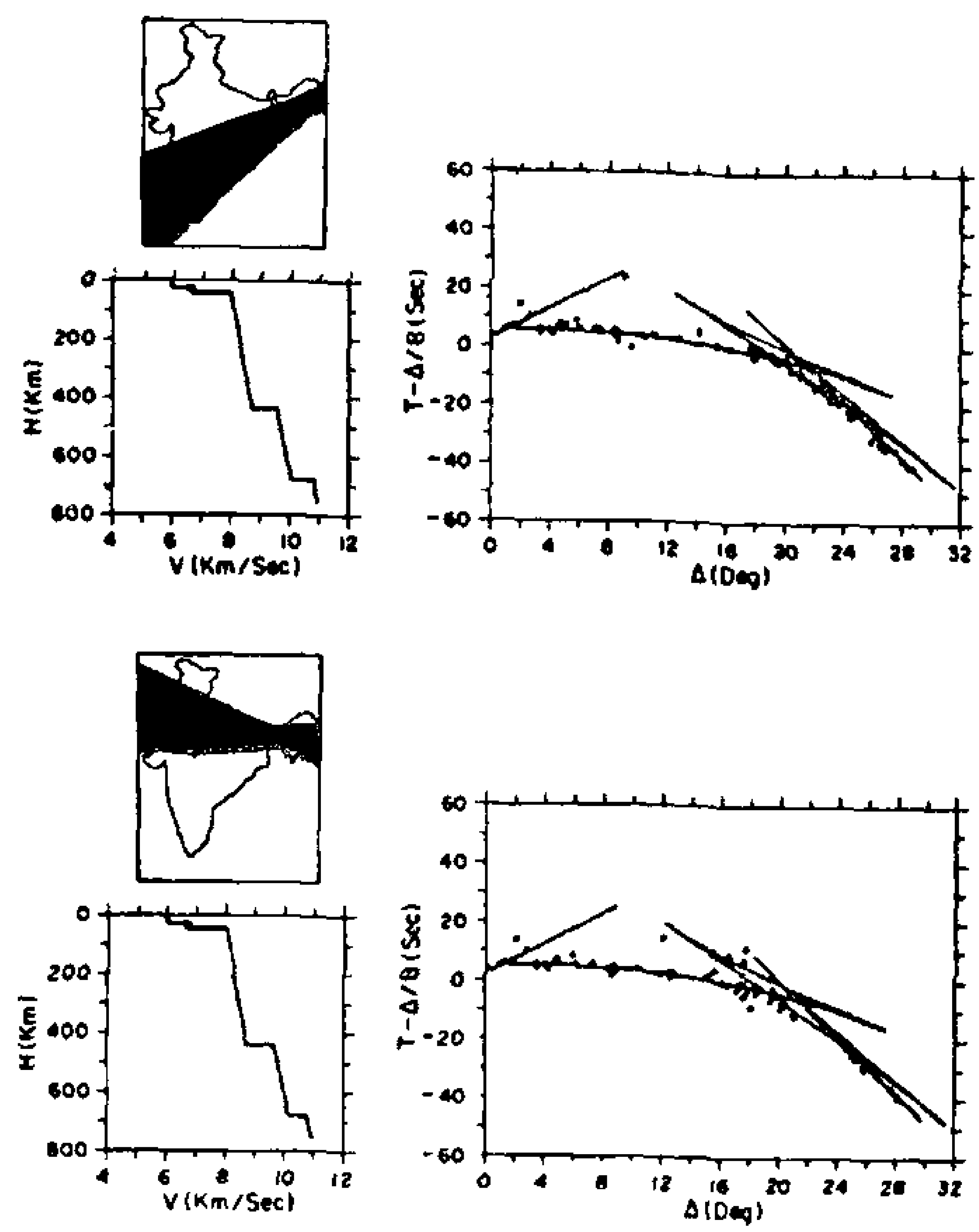

Figure 2(a) P wave travel time curves for the southwestern and western directions across the peninsular shield giving satisfactory fit to the travel time observations from the northeast Indian source region. The P velocity-depth functions inferred by forward modeling of travel time observations are also shown. (Reproduced from ref. 8).

explosions revealed that they are more consistent with discontinuous amplitude decay curves in various Δ ranges rather than a continuous curve over the entire Δ range. A reasonably good agreement is also found between the starting points of the discontinuous amplitude decay curves in different Δ ranges and the distances where the deep refracted phases from plausible velocity discontinuities in the mantle start appearing as first arrivals on the surface of the Earth (figure 3). The discontinuous nature of amplitude decay curves is also supported by another study[10] of the variation of $d^2T/d\Delta^2$ with distance Δ.

Upper mantle velocity structure from seismic array measurements

Seismic array measurements of slowness [$dT/d\Delta$] and apparent azimuths, together with application of signal processing techniques[11], appear to be more promising for determination of upper mantle velocity structure if the data is adequately available in the complete Δ range from the array. Because this method does not depend on absolute travel times, the inverted velocity-depth models are not seriously affected by possible errors in the travel time measurements caused by earthquake origin time errors.

The Gauribidanur medium aperture seismic array [GBA] in the south Indian shield provides good quality data suitable for deriving the upper mantle velocity structure. The data set of over 350 earthquakes, covering the epicentral distance range of 14°–36°, and the azimuthal range of 0°–360°, recorded at this array was processed[12] by adaptive processing technique on the first 36 s of the short period P wave trains. Four seismic zones defined by the following azimuthal ranges have been considered in the above study: ■ Himalayan (0°–90°), ■ Java trench (90°–180°), ■ Mid-oceanic ridge (180°–280°) ■ Hindukush (280°–360°). Processing of these data sets brought out not only the lateral variations in the upper mantle velocity structure but also provided locations of possible triplications on the upper mantle travel time branches which are crucial for inferring high velocity gradient zones and/or first-order discontinuities within the upper mantle. Because of the lack of observations for distances less than 14°, average Earth models[13,14] for the crust and the uppermost mantle were assumed and only the deeper structure was iteratively adjusted such that the theoretical travel time

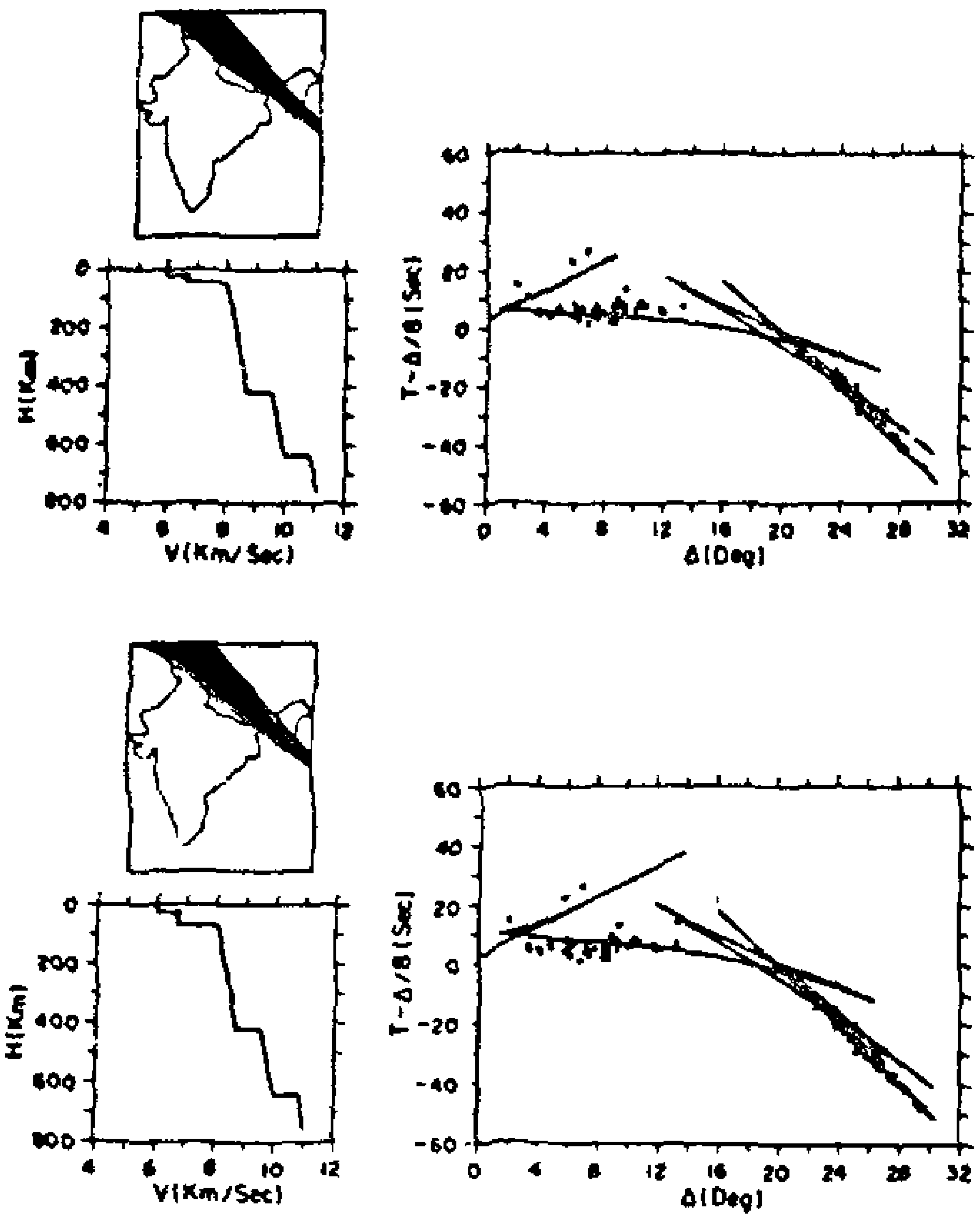

FIGURE 2(b) P wave travel time curves for the northwestern direction across the Himalayas giving satisfactory fit to the travel time observations from the northeast Indian source region. The P velocity-depth functions inferred by forward modelling of travel time observations are also shown. Note that the P travel times are delayed by 3-4 s in the distance range 9°–13° due to a relatively thick crust (about 70 km) beneath the high Himalayas and the Tibet plateau. (Reproduced from ref. 8).

branches corresponding to various layers well fit the observational points with appropriate slowness[12]. The velocity law assumed here for each layer was of the form $v = ar^{-b}$, where v is the velocity at radius r and a and b are constants. These two constants as well as the layer thickness were adjusted for each layer. The theoretical travel time branches and velocity models for the Himalayan region are shown in figure 4a. A summary of the velocity-depth models inferred from data in the four azimuthal ranges is given in table 2. The velocity model for the Hindukush region and the ray geometry for this model are shown in figure 4b. The following are the major features of the upper mantle velocity structure inferred from the array data study[12]:

- Evidence for a sudden increase in P wave apparent velocity near 18° distance corresponding to the 400 km discontinuity was obtained for all the regions (models RM1, RM2, RM3 and RM4). Sharp velocity gradients associated with the 650 km discontinuity were also found in all the regions except in the Himalayan region where this discontinuity is replaced by a very broad high velocity gradient zone. The maximum variation in the depths of the two discontinuities was ±15 km and the maximum uncertainty in the P wave velocity distribution at a particular depth other than the transition zones was approximately ±0.05 km/s, whereas within the transition zones it was ±0.15 km/s.
- Evidence was also found for a relatively thick low velocity/low Q layer along the oceanic paths as compared to the continental paths.

In another study[15], about 50 earthquakes recorded a the GBA seismic array in the distance range 35°–90° and about 200 earthquakes recorded at the Indian WWSSN stations at similar epicentral distances were used to obtain the seismic velocity structure of the lower mantle. Measurements of slowness and apparent azimuths were made from the short period P wave recordings. Analysis of this data set revealed no strong evidence for triplications in the travel time curves for the above range. It was inferred from this study that the P wave velocity increases continuously with a uniform gradient below 1000 km depth and is in close agreement with the JB model.

UPPER MANTLE VELOCITY STRUCTURE FROM P AND S WAVE TRAVEL TIME STUDIES OF DEEP EARTHQUAKES

Upper mantle P and S wave velocity-depth models can be obtained from travel time studies of deep earthquakes by determining velocities at the depths of foci of a large number of intermediate and deep focus earthquakes. This approach, although applicable to only those regions where deep focus earthquakes occur, however it yields more realistic velocity-depth models valid for the upper mantle beneath specific regions. A simple relationship exists[16] between the velocity V at the deepest point reached by an elastic wave through the Earth's interior and the apparent velocity V* at the epicentral distance Δ at which this wave arrives at the surface of the Earth. Application of this equation[17] to the ray which leaves the hypocenter of the shock at the depth h horizontally and arrives at the angular distance Δ* (in degress) on the surface of the Earth, where the travel time curve has its point of inflection and where the apparent velocity has its minimum value V^*, gives the relationship $V = V^*(r_0 - h)/r_0$ h being the focal depth of the earthquake, r_0 the radius of the Earth and V the true velocity at that depth. Therefore, if the focal depths are sufficiently accurate and there are good number of P and S wave arrival times over a small distance range in

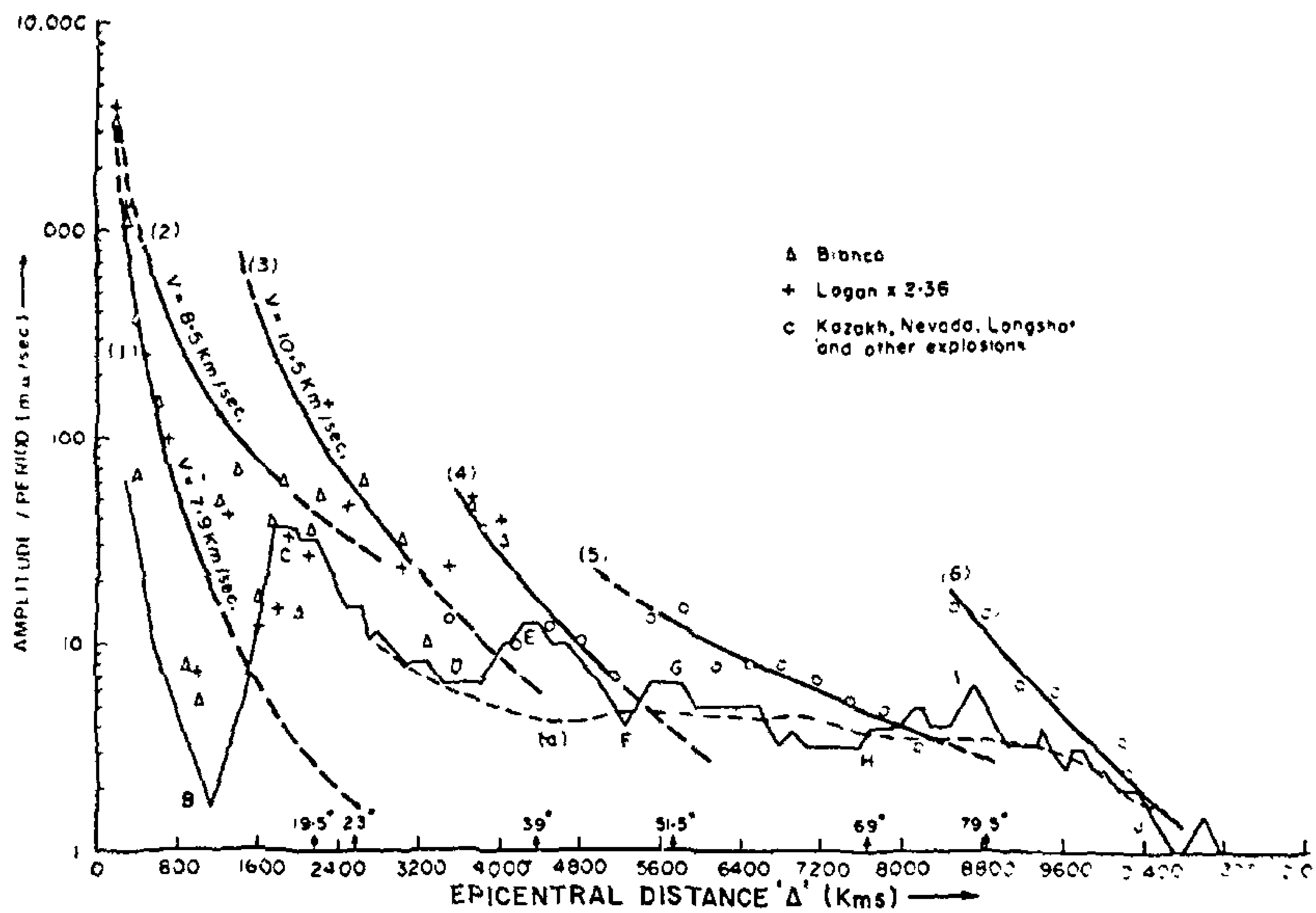

FIGURE 3 Discontinuous curves 1 to 6 showing decay rate of amplitude/period versus distance based on nuclear explosions data. Continuous thick curves are the least square fits to the observational data and the dashed lines are the extrapolations. The continuous decay curve ABCDEFGHIJ is the Gutenberg-Richter vertical amplitude curve. Small vertical arrows marked on the distance axis represent the epicentral distances at which the various deeply refracted phases appear as first arrivals on the surface of the Earth, according to a typical set of travel time curves. (Reproduced from ref. 9).

the vicinity of the inflection point Δ^*, the velocities can be determined at the depths of foci by this method[18] by measuring the apparent velocity V^* at Δ^*. However this method not only requires some first approximation value of the $dT/d\Delta$ appropriate to the focal depth under study, the location of the inflection point is also crucial and measurement of $dT/d\Delta$ at that point is likely to be erroneous due to the graphical approach of this method[18].

The above described method of determining the velocities at the depths of foci was further significantly improved[19] by developing an analytical approach to determine the apparent velocity in the inflection point region, rather than strictly at the inflection point, thus eliminating the uncertainties associated with the graphical approach. For a deep focus earthquake data, $dT/d\Delta$ $(=p)$ has a maximum value at the inflection point. It thus follows that $T=p\Delta+a$, where a is a constant. Therefore, in the neighbourhood of the inflection point Δ^* (say from Δ_1 to Δ_2), p can be considered to be constant. In this analytical method[19], the travel times data between the lower limit Δ_1 and the upper limit Δ_2 are fitted by a least squares straight line with its slope equal to p and the time-intercept a. It has also been found that the properties of rapid variation of p value towards smaller Δ and a large magnitude variation of a value towards larger Δ, relative to the values around the inflection point Δ^*, can effectively be used to well determine the Δ_1 and Δ_2 limits to define the range of approximately constant p value in the neighbourhood of Δ^*. To a first approximation it can be shown that $1/T \simeq 1/p\Delta$. Thus the point where rapid deviation of travel time points occurs (due to the rapid variation of p value towards smaller Δ range) from the straight line fit (of slope $1/p$) to a plot of $1/T$ versus $1/\Delta$ defines the lower limit Δ_1 and the reciprocal of the slope gives a first approximation p value (figure 5a). It can also be shown that $(T-p\Delta)/T \simeq a/p\Delta$. Therefore the plot of $(T-p\Delta)/T$ versus $1/p\Delta$, using the first approximation p value, shows rapid deviation of travel time points from the straight line fit (due to the rapid variation of a value towards larger Δ range) at the point

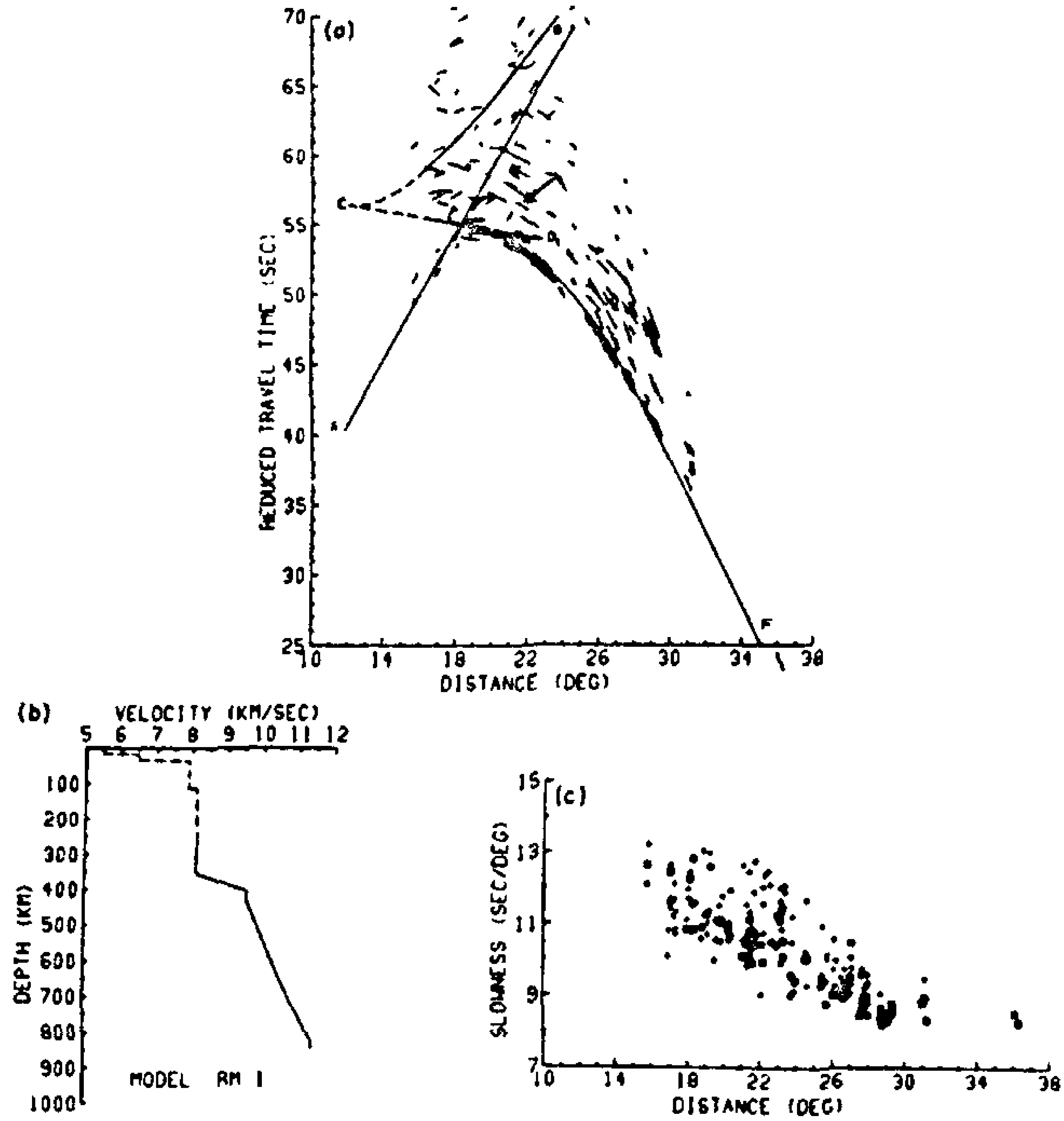

FIGURE 4(a) Array data set for the Himalayan region: (a) Reduced travel time graph with reduction velocity 10.0 km/s and the observed data. AB, BC, CD and EF are the theoretical travel time branches. Each line segment represents the slope at that point. First as well as later arrivals are also shown. (b) Velocity model RM1 inferred for the Himalayan region. (c) Observed slowness data versus distance, first as well as later arrivals, are also shown. (Reproduced from ref. 12).

corresponding to the upper limit Δ_2. Both the limits Δ_1 and Δ_2 can also be iteratively refined (figure 5a). The travel times data between the lower and upper limits can be linearly fitted by least squares technique to determine the p value (reciprocal of the apparent velocity V^*) appropriate to the focal depth h. The true velocity V can be obtained by using the relation $V = V^*[r_0 - h]/r_0$ where r_0 is the radius of the Earth. By determining the velocities at various focal depths by this analytical method[19], the velocity-depth model valid for the upper mantle in a specific region can be obtained. It should be mentioned here that the accuracy of determination of $dT/d\Delta$ and consequently of the velocities at depths, by this analytical method is often comparable to the accuracy obtainable from seismic array measurements. Because in both the methods, the $dT/d\Delta$ determination is independent of origin times of the earthquakes. Further a relatively large number of travel time observations, often available between the Δ_1 and Δ_2 limits, may overweigh the accuracy attainable by seismic array measurements where the distances in the array are more accurately known. Unlike in the array data analysis, the velocity-depth model of the upper mantle obtained from velocity determinations at several depths of foci by the analytical method[19] would be more realistic and particularly valid for the region under study.

This analytical method was successfully applied[20,21] to the Hindukush seismic region by using 51 deep earthquakes and the upper mantle P and S wave velocity depth models were obtained to a depth of 310 km (figure 5b). The velocity-depth models in this

Table 2. P wave velocity-depth models in continental and oceanic regions around India inferred from GBA seismic array measurements[12].

Depth (km)	Velocity (km/s)	Depth (km)	Velocity (km/s)
Himalayan region (Model RM1)		Hindukush region (Model RM4)	
0	5.50	0	5.50
15	5.50	15	5.50
15	6.50	15	6.50
33	6.50	33	6.50
33	7.90	33	7.90
113	7.90	113	7.90
113	8.13	113	8.13
354	8.13	362	8.13
404	9.55	412	9.67
434	9.55	545	9.67
825	11.34	644	10.84
847	11.34	678	10.84
		822	11.12
Java trench region (Model RM2)		Mid-oceanic ridge (Model RM3)	
0	5.07	0	5.07
1	5.07	1	5.07
1	6.70	1	6.70
5	6.70	5	6.70
5	7.80	5	7.80
95	7.90	95	7.90
175	8.00	175	8.00
175	7.75	175	7.75
352	7.75	332	7.75
427	9.85	407	9.69
574	9.85	599	9.69
705	11.08	638	10.75
725	11.08	860	11.29
819	11.18	872	11.30

region reveal a P velocity of 8.24 km/s at 55 km depth which increases linearly to 8.54 km/s at 220 km depth. At this depth of 220 km, there is a decrease in the velocity gradient and the P velocity reaches 8.62 km/s at 310 km depth. The S velocity in this region is however found to increase linearly from 4.61 km/s at 70 km to 4.77 km/s at 280 km depth with no indication of a decrease in the velocity gradient. Both the P and S wave velocities in the Hindukush region are found to be considerably higher than those in various other regions of the Earth. Subsequently, the *P* and *S* wave travel times data of deep earthquakes in the Western Pacific island arc–marginal sea regions as well as in the Mediterranean region have also been analyzed by the analytical method[19] described earlier and the upper mantle velocity structures are obtained in various regions[22–30]. These studies provided the first-order models of the upper mantle velocity structure, which were not earlier available in most of the deep earthquake regions of the Earth. Further the velocity models are also found more useful for determining earthquake source locations in some of those regions[31]. Another significant result of these studies is that the 400 km and 600 km velocity discontinuities in the upper mantle are directly brought out by the velocity-depth data obtained from deep earthquakes travel times. Modeling and interpretation of *P* and *S* wave travel time observations[32] which are anomalously late, produced by 36 deep earthquakes, as reflections from these two major velocity discontinuities in the mantle surrounding the inclined deep seismic zones revealed that the depths of phase transformations corresponding to the 400 km and 650 km velocity discontinuities are relatively elevated, by as much as 80–150 km and 30–80 km respectively, in the subducting lithospheric slabs.

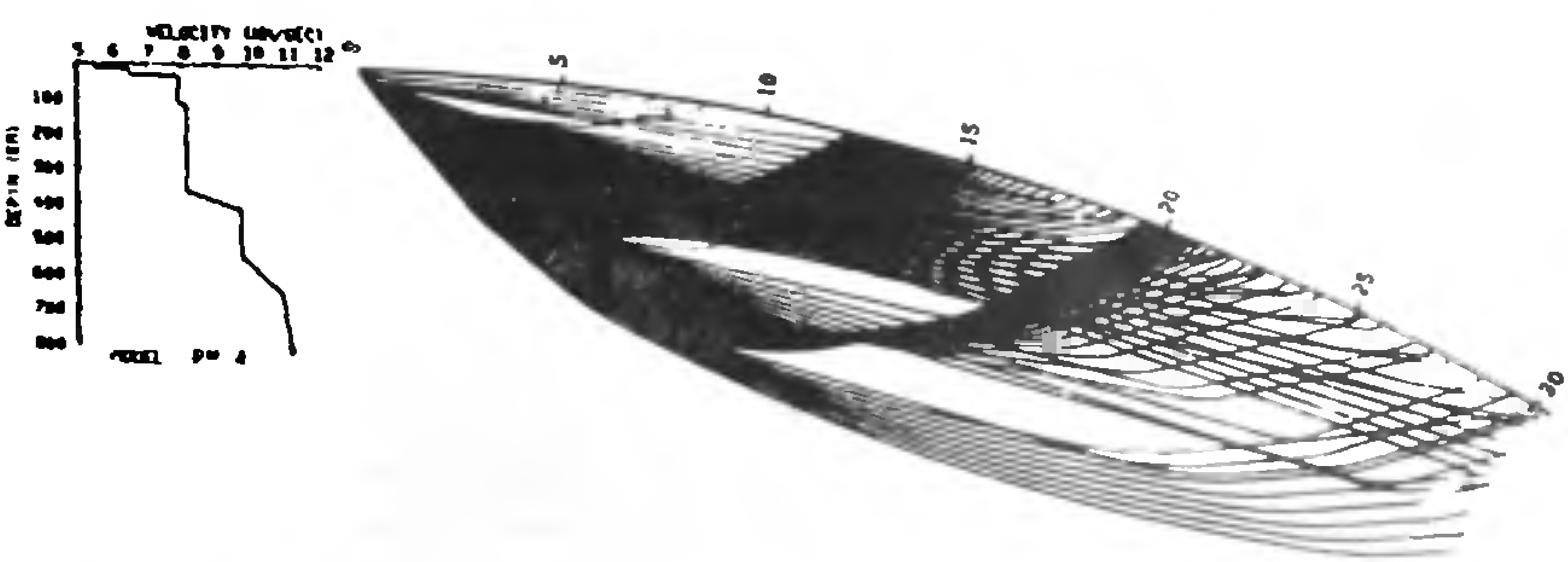

Figure 4(b) Velocity model RM4 and the ray geometry as obtained from earthquakes occurring in the Hindukush and surrounding regions. (Reproduced from ref. 12).

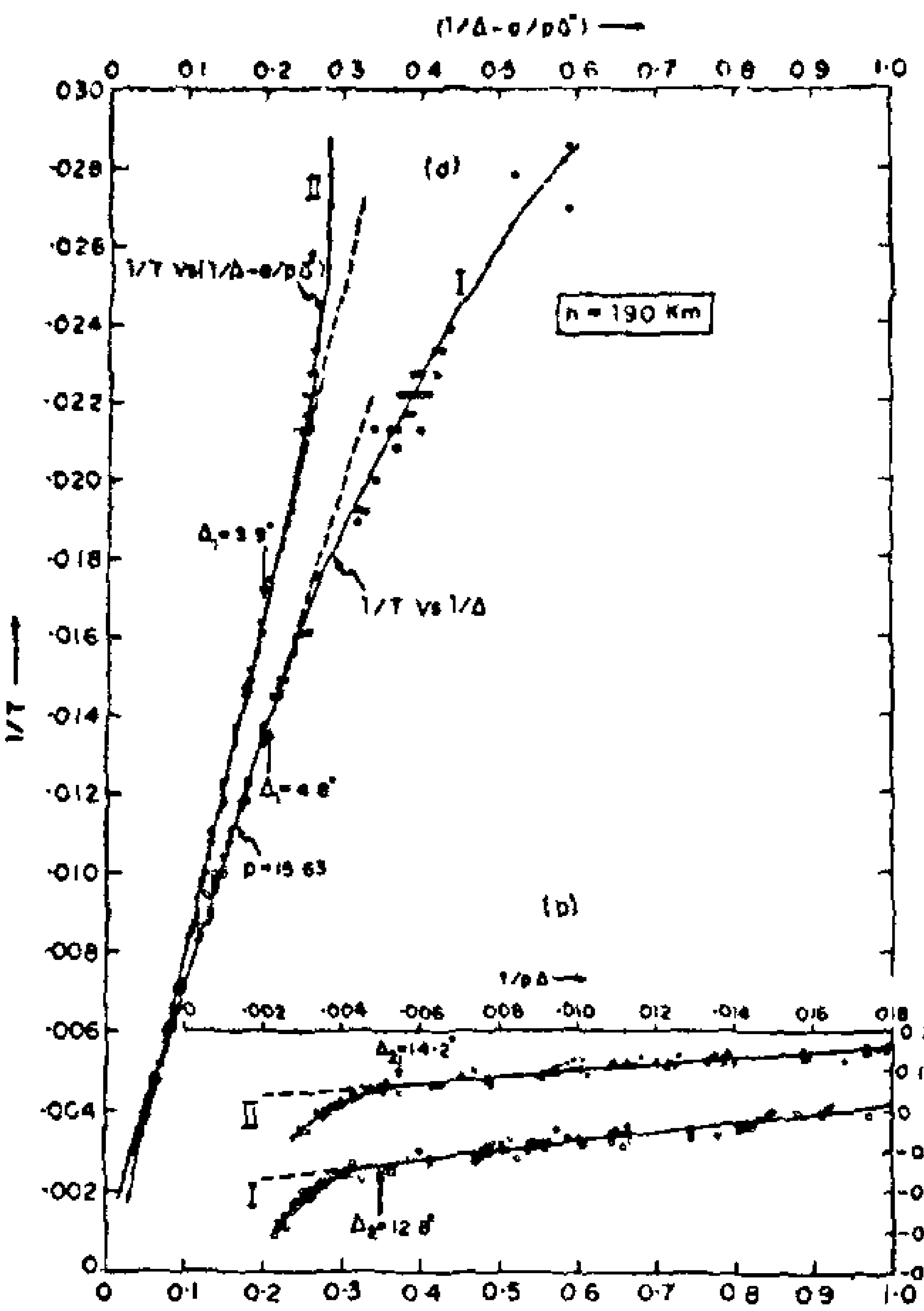

FIGURE 5(a) Travel time curves for P waves plotted in various mathematical forms for determining the limits Δ_1 and Δ_2 for a deep earthquake data set of focal depth 190 km. The plots are shown for I and II iterations. In these plots T is in sec and Δ in deg. (Reproduced from ref. 19).

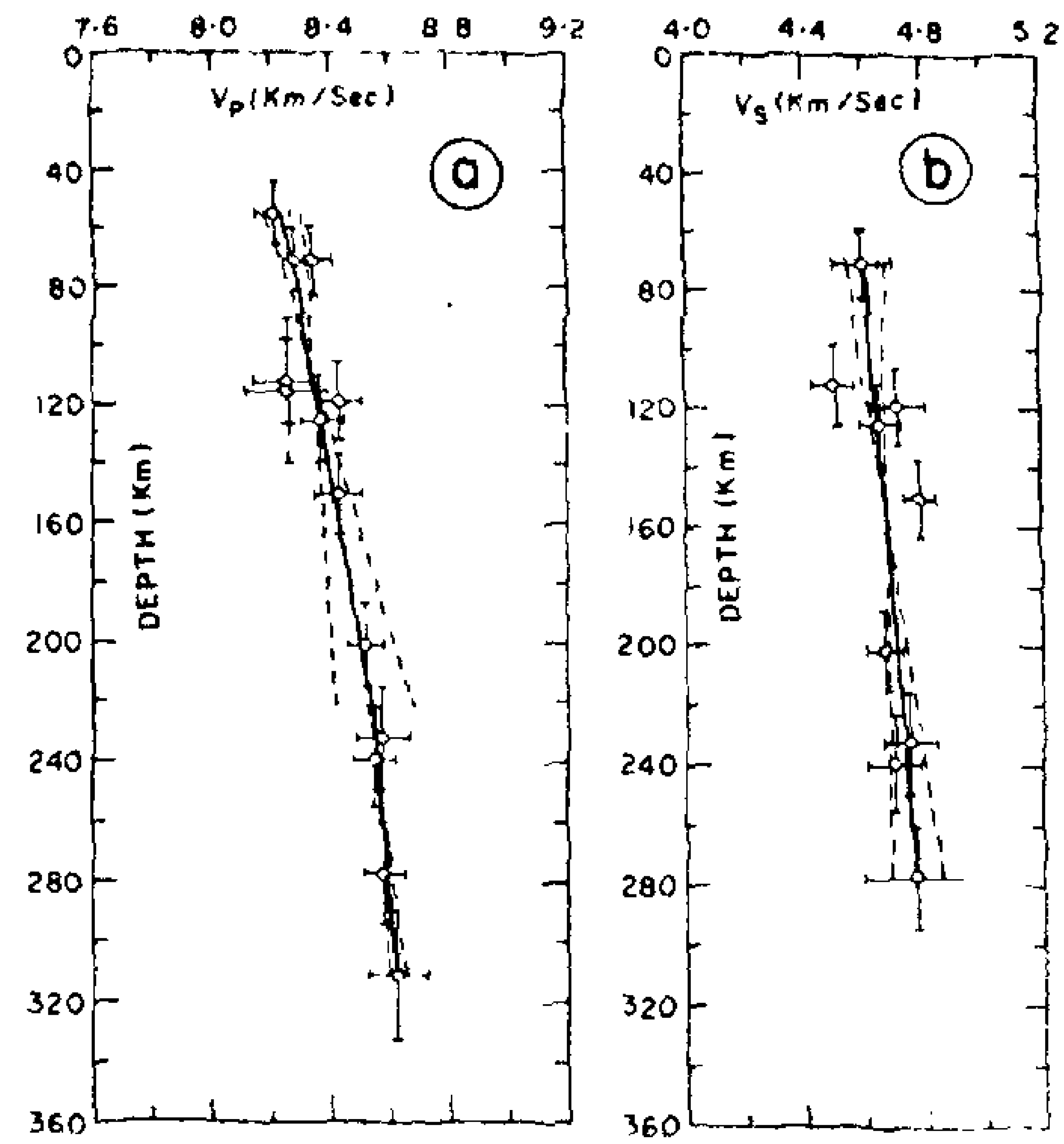

FIGURE 5(b) Refined velocity-depth plots (a) for P waves and (b) for S waves data in the Hindukush region. The velocities at redetermined depths are obtained by the analytical method[19]. Thick continuous lines are the least square fits to the velocity-depth points and the broken lines show the 95% confidence limits of the slopes. Truncated horizontal bars represent the standard deviations of the velocity values and vertical bars represent the standard errors of the redetermined focal depths. (Reproduced from ref. 21).

NATURE OF THE VELOCITY DISCONTINUITIES IN THE UPPER MANTLE

Seismologically observed velocity discontinuities in the Earth's mantle are generally considered to be associated with phase and/or chemical changes at the corresponding depths. Especially, the two major velocity discontinuities occurring at 400 km and 650 km depths in the upper mantle are associated with changes in elastic properties accompanying the phase transitions of olivine to spinel and spinel to post-spinel transformations respectively[33]. At depths of 300–350 km, $MgSiO_3$ Pyroxene transforms to a new garnet structure while near 400 km $(Mg,Fe)_2SiO_4$ olivine transforms to its polymorph of the β-structure. These transformations involve 8%–10% density increase and are considered to be mainly responsible for the major velocity discontinuity near 400 km depth (also widely known as the 20° discontinuity). At 500–550 km depth the β-phase transforms to a true spinel (γ) structure accompanied by only a 2% density increase which may not always produce a prominent velocity discontinuity that can be resolved by the seismological data. In a study[34] on the nature of the 400 km discontinuity in the Earth's mantle it was found that the velocity changes across this discontinuity as obtained from most of the seismological studies are consistently smaller [8%–10%], and only about a half in percentage magnitude of the velocity changes expected from experimental results[35] which generally gave in the range of 15%–20% for the α–γ and α–β phase transformations in the olivine. This discrepancy was found[34] to be essentially a result of considering the 400 km discontinuity as only a phase change in the olivine component of the upper mantle and it was suggested that probably an increase of Fayalite content in the olivine might explain the relatively small velocity changes across the discontinuity observed seismologically. It was inferred on the basis of this study[34] that the 400 km discontinuity in the upper mantle is both a phase and a chemical boundary. Rapid increases of velocity below the 650 km depth have been attributed to the transformation of the spinel and garnet phases into more densely packed states. The major velocity discontinuity occurring near 650 km depth is generally associated with the spinel to a post-spinel phase transformation in the $[Mg,Fe]_2SiO_4$ component of the upper mantle[33]. It was suggested that this discontinuity is caused by the disproportionation of $[Mg,Fe]_2SiO_4$ into a mixture of oxides [Mg,Fe]O and SiO_2 stishovite while some associated chemical change is also proposed[36]. Thus the 650 km discontinuity in the upper mantle is also considered both a phase and a chemical boundary.

STRUCTURE OF THE CRUSTAL AND SUBCRUSTAL LITHOSPHERE IN THE INDIAN SHIELD FROM EARTHQUAKE AND EXPLOSION SEISMIC OBSERVATIONS

Several attempts[37–40] were made to evaluate the crustal structure in India by travel times analyses of earthquake generated crustal and uppermost mantle phases Pg, P* and Pn as well as Sg, S* and S_n, well before the more definitive deep seismic sounding (DSS) experiments[41] by large explosions were undertaken. The crustal structure in the Himalayan foothills area was determined[37] by statistically analyzing the travel times of Pg, P* and Pn phases from shallow earthquakes in the Himalayas. The effect of a 6 ± 1 km thick sedimentary layer of average P velocity 2.7 km/s (delineated by a 15 km long seismic refraction profile in the Punjab foothills), was carefully taken into account for evaluating the crustal structure with the granitic layer thickness 8 ± 5 km, Pg velocity 6.2 ± 0.1 km/s; basaltic layer thickness 14 ± 7 km, P* velocity 6.9 ± 0.1 km/s; uppermost mantle Pn velocity 8.2 ± 0.1 km/s, giving a total crustal thickness of 28 ± 8 km. It is evident from the above study that the crustal structure determinations based on earthquake travel times data alone do not provide reliable models, although the range of velocities in various layers may be obtainable within reasonable error limits. Other studies[38–40] of crustal structure in the Indian shield region revealed the velocities of crustal phases as follows: Pg 5.6 – 5.7 km/s, P* 6.4 – 6.5 km/s, Pn 8.0 – 8.2 km/s, Sg 3.5 – 3.7 km/s S* 4.0–4.1 km/s and Sn 4.6 – 4.7 km/s.

Anomalously high P velocities of the order of 8.8 – 9.0 km/s in the uppermost mantle were earlier reported[42] from a study of the Bhadrachalam earthquake sequence of 1969 as well as other events recorded at the GBA seismic array in the distance range 225 – 525 km. Such high P velocities of 8.6 – 8.8 km/s and a correspondingly high S velocity of about 4.8 km/s in the uppermost mantle are also found for the Indian shield in a recent study[43] of travel time observations from earthquakes along the east coast in the Ongole region. The errors in these relatively high P and S velocities, determined for the uppermost mantle, are estimated to be within ± 0.05 km/s. DSS studies[44] along the Kavali-Udipi profile have also confirmed the relatively high Pn velocity of 8.6 km/s in the Indian shield. The most consistent and well accepted interpretation of such anomalously high Pn velocities and a higher than normal velocity gradient is the presence and/or continuation of elastic anisotropy in the continental upper mantle[45]. However, the travel times data both from earthquakes[39,43] on the west coast as well as the DSS observations[46] in the Koyna region revealed the Pn velocities in the range of 8.25–8.35 km/s.

Explosion seismic observations on long-range refraction profiles by a dense deployment of digital recorders, about 5 km apart, out to 500 km or more provide the crucial data for modeling the fine structure of the subcrustal lithosphere. These experiments, which are yet to be accomplished in India, have already been conducted along a number of profiles in the USSR, Western Europe and the United States. The results obtained from these studies reveal more complicated models of the structure of the continental subcrustal lithosphere that depart drastically from the classical models revealing only a gentle increase of velocities below the Moho. The most significant results on the structure of the continental subcrustal lithosphere are:

- occurrence of low velocity layers (LVL) at shallow depths below the Moho with large velocity contrasts at their boundaries
- observations of unexpectedly high P wave velocities of up to 8.6–8.9 km/s and high velocity gradients above the LVL at relatively shallow depths below the Moho.

An important latest study[47,48], by modeling of travel times and amplitudes of explosion seismic observations in the Koyna region, provided for the first time a detailed model of the P velocity structure of the Indian continental subcrustal lithosphere (figure 6). Modeling of both travel times and amplitudes of refracted and later arriving reflected phases considerably reduces the range of plausible models that may equally well fit the travel time observations alone. Comparison of synthetic seismograms, for a range of velocity models, with the observed seismic record section in the Koyna region revealed a subcrustal P velocity model with alternating LVL separated by a thin high velocity layer[47,48]. Consistent velocity models of the subcrustal lithosphere have also been obtained by modeling of shallow earthquake travel time observations[43] out to 800 km (figure 7a,b). While the high P velocities and a higher than normal velocity gradient in the uppermost mantle are observed from earthquake data on the east coast,

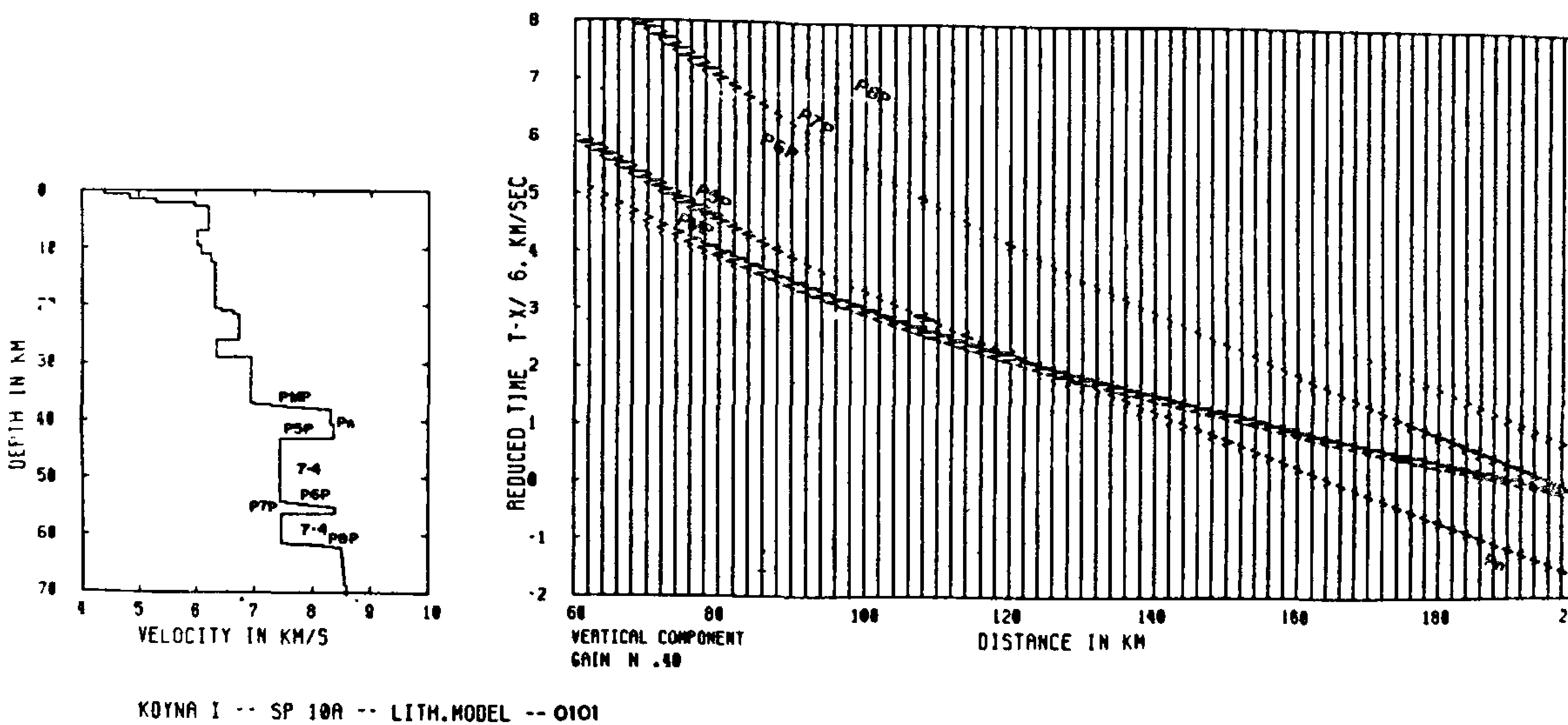

FIGURE 6 Record section of synthetic seismograms [normalized] computed for the subcrustal phases by using the litho-spheric P wave velocity model inferred for the Koyna region. Note the presence of prominent LVL in the crustal and subcrustal sections of the lithosphere in this region. (Reproduced from ref. 46–48).

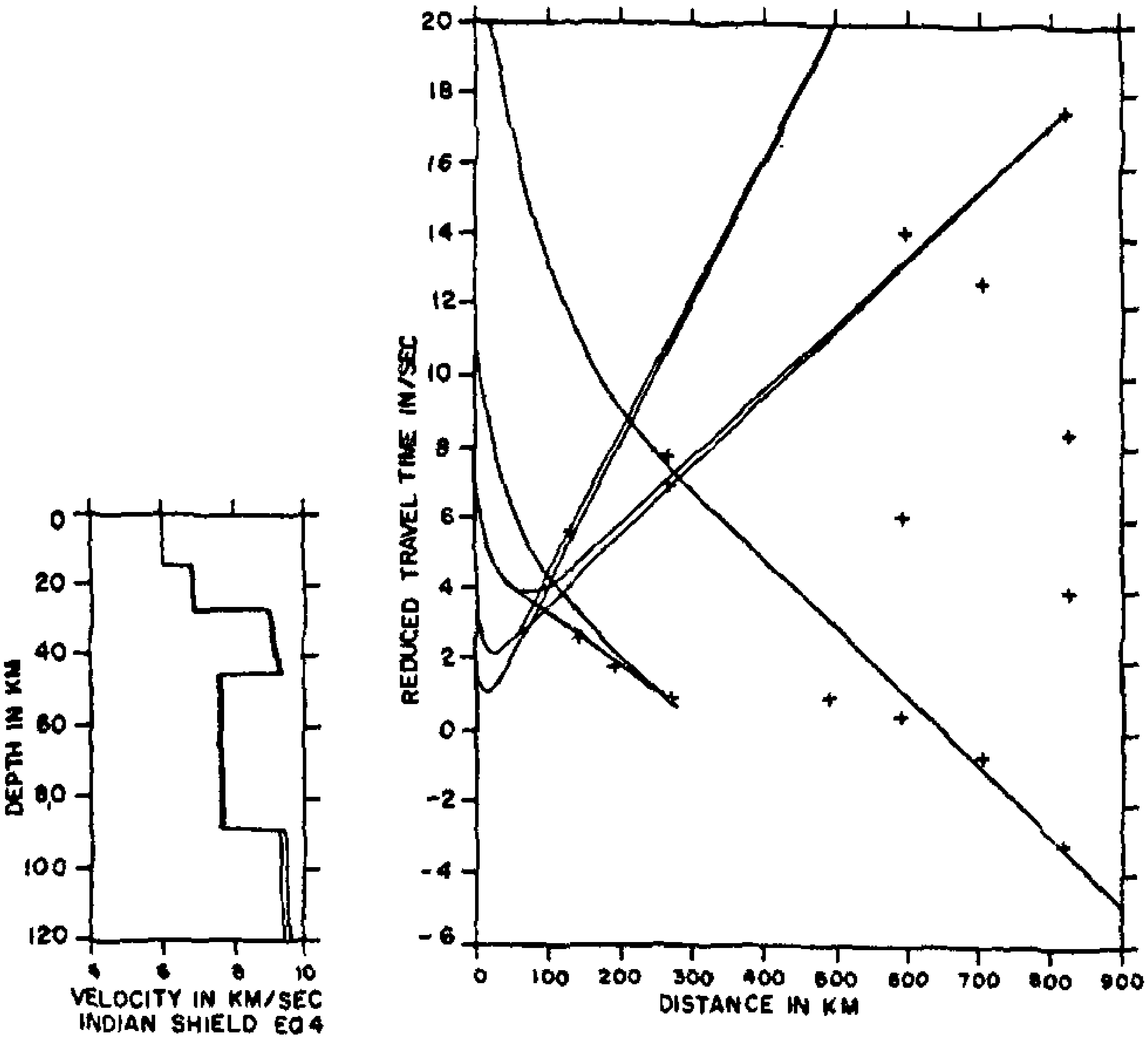

FIGURE 7(a) P wave travel time observations, plotted with reduction velocity 8.0 km/s, from a shallow earthquake in the Ongole region on the east coast, recorded by stations towards the western direction. The travel time curves, giving satisfactory fit to the observations, computed by using the inferred velocity-depth function, are also shown. Note the anomalously high P wave velocity and a higher than normal velocity gradient below the Moho and a prominent LVL in the subcrustal lithosphere in this region. (Reproduced from ref. 43).

the presence of alternating LVL in the depth ranges 40–54 km and 62–85 km are well inferred from data both on the east and the west coast (figures 6,7). By synthetic seismograms modeling[46] of DSS record sections in the Koyna region, LVL are also inferred both in the upper and the lower crust. The upper crustal LVL with its top at 6–7 km depth is found to be consistent with the depth distribution of seismicity, which is concentrated at 4–5 km depth, in the Koyna region. The occurrence of prominent LVL in the crustal and the subcrustal sections suggest rheological stratification of the continental lithosphere in the Indian shield[47,48]. Considering these interesting first results, it is highly desirable to undertake detailed explosion seismic long-range refrac-

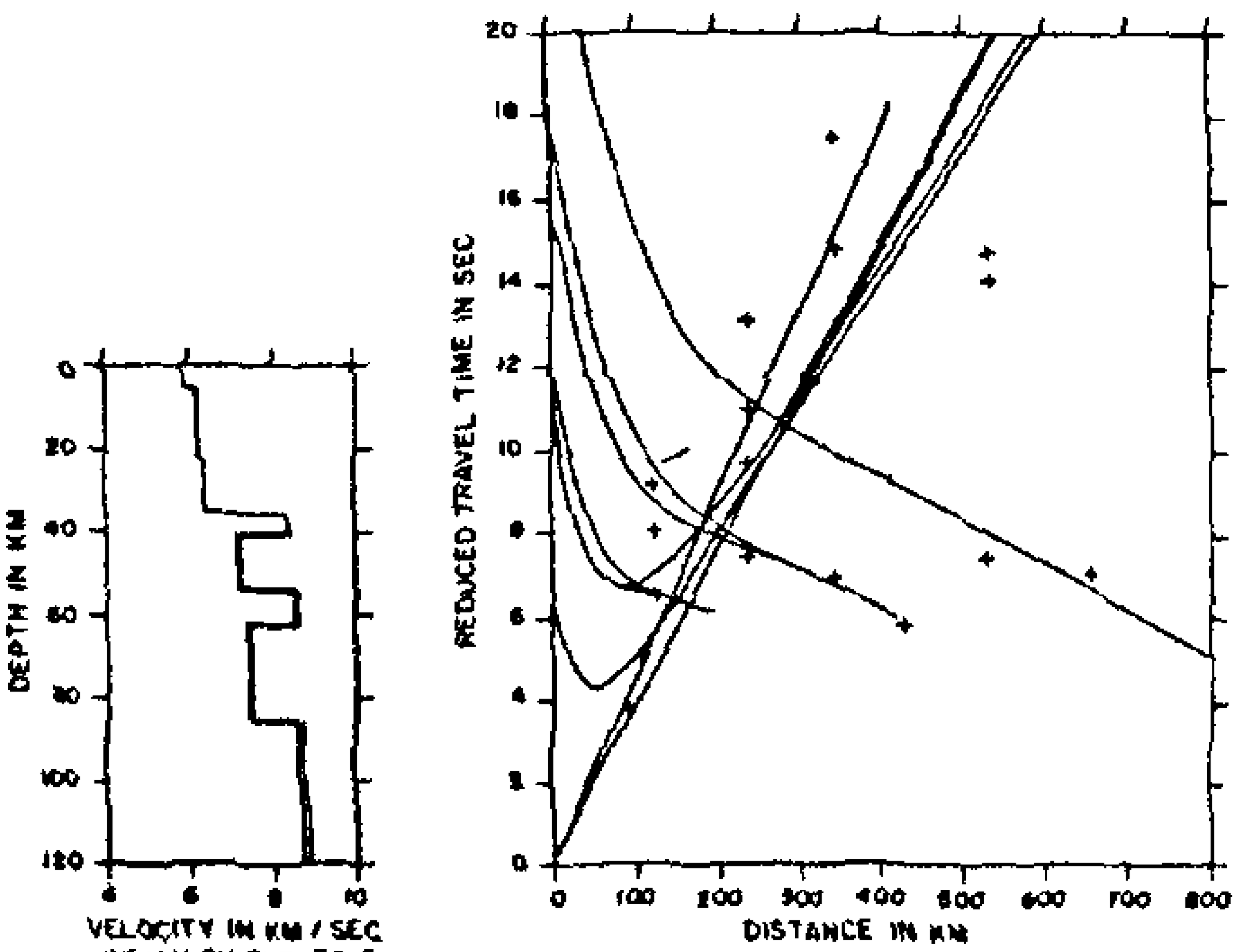

FIGURE 7(b) P wave travel time observations, plotted with reduction velocity 8.0 km/s, from a shallow earthquake on the west coast, recorded by stations towards the eastern direction. The travel time curves, giving satisfactory fit to the observations, computed by using the inferred velocity-depth function, are also shown. Note the presence of alternating LVL in the subcrustal lithosphere in this region. (Reproduced from ref. 43).

tion experiments on a few selected transects in the Indian region for studying the fine structure of the subcrustal lithosphere.

CONCLUSIONS AND OUTLOOK

Significant results are obtained concerning the velocity structure of the upper mantle from a variety of analyses of body wave travel time observations in India. However, in order to resolve the fine structural details particularly of the nature of high velocity gradient (transition) zones and/or first-order discontinuities with sharp velocity contrasts in the lower lithosphere and the underlying mantle, there is an urgent need to model both travel times and amplitudes of later arriving branches, out to at least 25° distance. Travel times and waveform modeling of seismic record sections, obtainable from earthquakes and/or powerful explosions recorded on selected transects covered by nearly linear arrays of portable digital recording instruments should provide viable models of the structure of the lower lithosphere and the subjacent mantle in India. Specially designed explosion seismic experiments would be necessary for studying the anisotropic structure of the continental crust and the subcrustal lithosphere in order to substantiate the preliminary results already obtained in the Indian shield. DSS experiments along a large number of profiles in India provided deep structural models of the continental crust in various regions, the results of which are discussed in detail in a separate article in this volume. Seismic tomographic experiments, recently initiated by inversion of teleseismic travel time residuals, provided new images of 3-D velocity structure of the upper mantle in the south Indian shield.

REFERENCES

1. Bullen, K. E., *Geophys. J. R. Astron. Soc.*, 1961, **4**, 93.
2. Dowling, J. and Nuttli, O., *Bull. Seismol. Soc. Am.*, 1964, **54**, 1981.
3. Kaila, K. L. and Narain, H., *Geophysics*, 1970, **35**, 613.
4. Kaila, K. L., Reddy, P. R. and Narain, H., *Bull. Seismol. Soc. Am.*, 1968, **58**, 1879.
5. Kaila, K. L., Reddy, P. R. and Narain, H., *Bull. Natl. Geophys. Res. Inst.*, 1968, **6**, 167.
6. Jeffreys, H. and Bullen, K. E., *Seismological Tables*, British Assn. London, 1940.
7. Kaila, K. L., Reddy, P. R. and Narain, H., in *Second Symposium on Upper Mantle Project*, Abstracts Volume, 1970.
8. Kaila, K. L., Krishna, V. G. and Rao, G. S. P., in *Regional Assembly*, IASPEI, Abstracts volume, 1984, S7/1, 172.
9. Kaila, K. L., *Bull. Seismol. Soc. Am.*, 1970, **60**, 447.
10. Kaila, K. L. and Sarkar, D., *Bull. Seismol. Soc. Am.*, 1975, **65**, 915.
11. Ram, A. and Mereu, R. F., *Geophys. J. R. Astron. Soc.*, 1975, **42**, 653.
12. Ram, A. and Mereu, R. F., *Geophys. J. R. Astron. Soc.*, 1977, **49**, 87.
13. Jeffreys, H., *Mon. Not. R. Astr. Soc. Geophys. Suppl.*, 1939, **4**, 498.
14. Herrin, E., *Bull. Seismol. Soc. Am.*, 1968, **58**, 1193.
15. Ram, A., in Regional Assembly, *IASPEI*, Abstracts volume, 1984, S10/3, 255.
16. Wiechert, E., *Nachr. Ges. d. Wiss. Gottingen, Math. Phys. Kl.*, 1907, 415.
17. Mohorovicic, S., *Gerlands Beitr. Geophysik*, 1914, **13**, 217.
18. Gutenberg, B., *Bull. Seismol. Soc. Am.*, 1953, **43**, 223.
19. Kaila, K. L., *Bull. Seismol. Soc. Am.*, 1969, **59**, 755.
20. Kaila, K. L., Krishna, V. G. and Narain, H., *Bull. Seismol. Soc. Am.*, 1969, **59**, 1949.
21. Kaila, K. L. and Krishna V. G., *Boll. di Geofis. Teor. ed Appl.*, 1983, **XXV**, 277.
22. Kaila, K. L., Krishna, V. G. and Narain, H., *Bull. Seismol. Soc. Am.*, 1971, **61**, 1549.
23. Kaila, K. L., Krishna, V. G. and Narain, H., *Bull. Seismol. Soc. Am.*, 1974, **64**, 355.
24. Kaila, K. L. and Krishna V. G., *J. Phys. Earth, Tokyo*, 1978, **26**, 155.
25. Kaila, K. L. and Krishna, V. G., *J. Phys. Earth, Tokyo*, 1978, **26**, 139.
26. Krishna, V. G. and Kaila, K. L., *J. Phys. Earth, Tokyo*, 1984, **32**, 63
27. Krishna, V. G. and Kaila, K. L., *J. Phys. Earth, Tokyo*, 1984, **32**, 339.
28. Kaila, K. L. and Krishna, V. G., *Bull. Seismol. Soc. Am.*, 1984, **74**, 2269.
29. Kaila, K. L. and Krishna, V. G., *Tectonophysics*, 1985, **112**, 227.
30. Krishna, V. G., Kaila, K. L. and Khandekar, G., *Tectonophysics*, 1992, (in press).
31. Coudert, E. *et al.*, *J. Geophys. Res.*, 1981, **86**, 5905.
32. Krishna, V. G. and Kaila, K. L., *Tectonophysics*, 1987, **134**, 201.
33. Ringwood, A. E., *in Advances in Earth Sciences* (ed. Hurley, P. M.), MIT Press, Cambridge, Mass., 1966, p. 357.
34. Kaila, K. L. and Krishna, V. G., *Geophys. J. R. Astron. Soc.*, 1976, **46**, 185.
35. Liebermann, R. C., *Geophys. J. R. Astron. Sdc.*, 1975, **42**, 899.
36. Lees, A. C., Bukowinski, M.S.T. and Jeanloz, R., *J. Geophys. Res.*, 1983, **88**, 8145.
37. Kaila, K. L., Reddy, P. R. and Narain, H., *Bull. Seismol. Soc. Am.*, 1968, **58**, 597.
38. Reddy, P. R., Ph.D. Thesis, Andhra University, 1971.
39. Tandon, A. N. and Chowdhury, H. M., *IMD Scientific Report 59*, 1968.
40. Arora, S. K., *Bull. Seismol. Soc. Am.*, 1971, **61**, 671.
41. Kaila, K. L., *Geophys. Res. Bull.*, 1982, **20**, 309.
42. Arora, S. K., Varghese, T. G. and Krishna, C. A., *Nature*, 1970, **225**, 261.
43. Ramakrishna Rao, C. V., Ph.D. Thesis, ISM, 1989.
44. Kaila, K. L. et al., *J. Geol. Soc. India*, 1979, **20**, 307.
45. Fuchs, K., *Phys. Earth Planet. Inter.*, 1983, **31**, 93.
46. Krishna, V. G., Kaila K. L. and Reddy, P. R., in *Properties and Processes of Earth's Lower Crust* (eds. Mereu, R. F., Mueller, St. and Fountain, D. M.), 1989, AGU Geophys. Monogr. **51**, IUGG vol. **6**, 143.
47. Krishna, V. G. and Kaila, K. L., in *International Symposium on Structure and Dynamics of the Indian Lithosphere*, 1989, Abstracts volume, 108.
48. Krishna, V. G., Kaila, K. L. and Reddy, P. R., *Phys. Earth Planet. Inter.*, 1991, **67**, 288.

ACKNOWLEDGEMENTS: We are grateful to the Director, National Geophysical Research Institute, for kind permission to publish this article.