

Crustal investigations from explosion data along Kaveli-Udipi section of Peninsular India

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(Received 9 August 1982)

सार — 1972-75 के दौरान भारत और रूस की सहयोगी परियोजना के अन्तर्गत कवेली-उदीपी क्षेत्र में किए गए गहन भूकंपनीय परिज्ञापन से संग्रहीत विस्फोटन आंकड़ों का विश्लेषण करके उनका निर्वचन किया गया है। P_g, P^*, P_n प्रावस्थाओं का वेग क्रमशः 5.97 ± 0.00 , 6.81 ± 0.04 और 8.18 ± 0.15 कि० मी०/से० और S_g, S^*, S_n के लिए 3.60 ± 0.00 , 4.01 ± 0.02 , 4.75 ± 0.03 कि० मी०/से० ज्ञात हुआ है। इस क्षेत्र के लिए उसके आवर्तन अध्ययनों से एक द्विस्तरीय भूपर्पटी निदर्श का निर्वचन किया गया है। ग्रेनाइट की परत की औसत मोटाई 22.4 कि० मी० तथा बेसाल्टिक परत की औसत मोटाई 16.2 कि० मी० रखने से मोहो की गहराई 38.6 कि० मी० प्राप्त हुई। परावर्तन अध्ययनों से प्राप्त परिणाम उपरोक्त परिणामों की काफी हद तक पुष्टि करते हैं। इस प्रच्छेदिका के लिए तीन फील्ड ऋतुओं के क्रमानुगत तीन प्रखंडों के लिए चार्ज की मात्रा तथा अभिकेन्द्रीय दूरी में परिवर्तन के सदर्थ में P प्रावस्था के आयाम में परिवर्तन के परस्पर संबंध को ज्ञात किया गया है।

ABSTRACT. Explosion data collected during 1972-75 from the deep seismic sounding (DSS) field experiments carried along the Kaveli-Udipi profile under the Indo-Soviet collaboration project has been analysed and interpreted. The velocity of the phases P_g, P^*, P_n have been found to be 5.97 ± 0.00 , 6.81 ± 0.04 and 8.18 ± 0.15 km/sec and for S_g, S^*, S_n to be 3.60 ± 0.00 , 4.01 ± 0.02 , 4.75 ± 0.03 km/sec respectively. A two layered crustal model has been interpreted from the refraction studies for the region. The average thickness of the granitic layer has been found to be 22.4 km and that of basaltic layer to be 16.2 km giving 38.6 km as the depth of Moho. The results obtained from reflection studies broadly confirm the above results. Relationship of the variation of P phase amplitude with charge size and epicentral distance has been derived for three sectors corresponding to the three field seasons along the profile.

1. Introduction

Exactness of source parameters makes controlled explosions superior to earthquake for studies of crustal structure. The use of controlled explosions for studying the crustal structure of Peninsular India was first started under the Indo-Soviet deep seismic sounding (DSS) project in 1972. From the Indian side, National Geophysical Research Institute (NGRI), Hyderabad was the principal coordinator for the project and India Meteorological Department (IMD) also participated in this project. The DSS profile chosen was from Kaveli in Andhra Pradesh to Udipi in Karnataka in the Peninsular India. The profile was covered in three field seasons, each of about 4 months duration. Five mobile seismological observatories were established by India Meteorological Department during each field season along/near the profile for recording the seismic waves generated by explosions of different charges from a number of short points along the profile (Fig. 1). The quantity of charge varied from 50 to 1000 kg.

The objectives of the participation by India Meteorological Department are somewhat different from those of NGRI. The technique employed by NGRI gives

detailed crustal structure, the layer thickness including the surficial layer and the wave velocities. The range of parameters and finer details so obtained cannot be easily adopted as a working model for determining epicentral parameters of seismic events occurring in the region. I.M.D's method is a direct approach to obtain the average crustal model by calibrating the region with the help of explosions detonated for the deep seismic sounding project. An additional advantage of the participation by India Meteorological Department was that the S -wave velocities could also be obtained from the explosion records providing additional information about geophysical properties of the crustal rocks. It also enables us to utilize the S phase observations for the epicentral determination of seismic events. The velocity models obtained from the individual field seasons are shown in Fig. 1. However, in the individual field seasons the quantity of data available was small except for the direct phases. Therefore, an average profile structure using the data from all the three field seasons has been attempted.

2. Geological setting of the region and seismic history

Peninsular India represents a stable block of the earth's crust which had remained unaffected by the

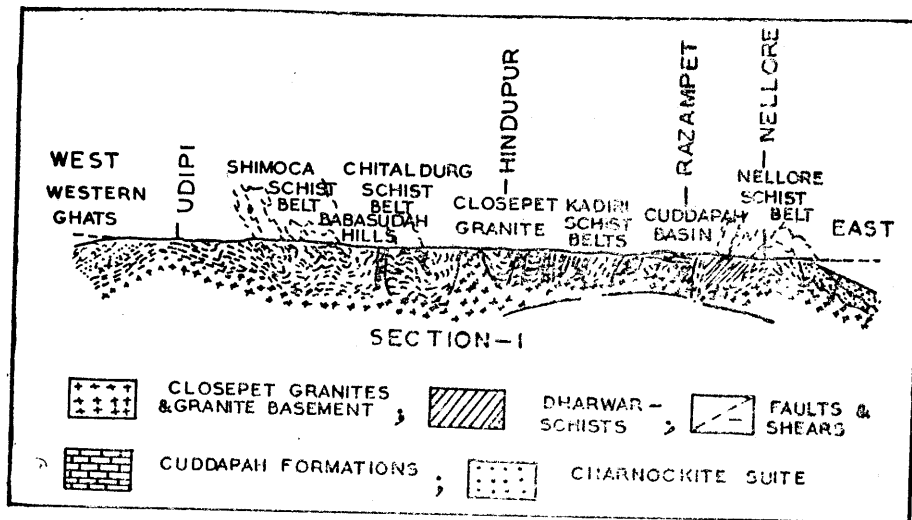


Fig. 1. Geological cross-section across Precambrian shield of south India

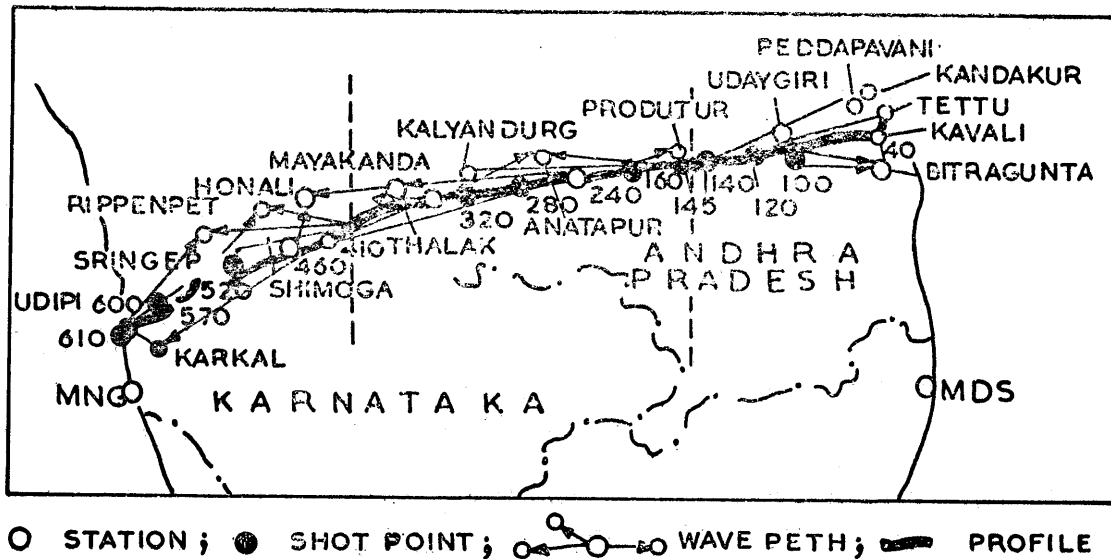


Fig. 2. Location of observatories and shot points along the profile

mountain building activity since the close of Pre-Cambrian era. Its study is of paramount importance to understand the evolution of the earth's continental crust. The region under investigation has been subdivided into two prominent lithotectonic provinces, namely, Cuddapah and Dharwar (Fig. 2).

The Cuddapah basin is a unique sedimentary basin of upper Pre-Cambrian stratified rocks. It is crescent shaped which has been described as a remarkable tectonic and orogenic belt. The Purana basin of the Cuddapah and Kurnool sediments rests with a pronounced un-conformity on the older crystalline rocks of Andhra Pradesh. The floor of the basin gradually subsided with the pace of sedimentation. According to Narayanswami (1966) the Cuddapah province is

an arcuate north plunging low amplitude asymmetrical synclinorium having a gently dipping, little disturbed western limit and intensely overfolded and over thrust eastern limits. The structure is complicated by a major domal upward across the middle of the basin marked by monoclinial flexures or doubly plunging fold in the un-conformably overlying Kurnool rocks and by many culminations and depressions in the northeastern part (Valdiya 1973). Many prominent thrusts and strike faults are evident within the basin. Associated with the strike faults and thrusts, are several NNW-SSE to NW-SE trending faults.

The Dharwar province is a sharply outlined north-east plunging synclinorium of schistose rocks running in the NNW-SSE direction amidst the vast expanse of

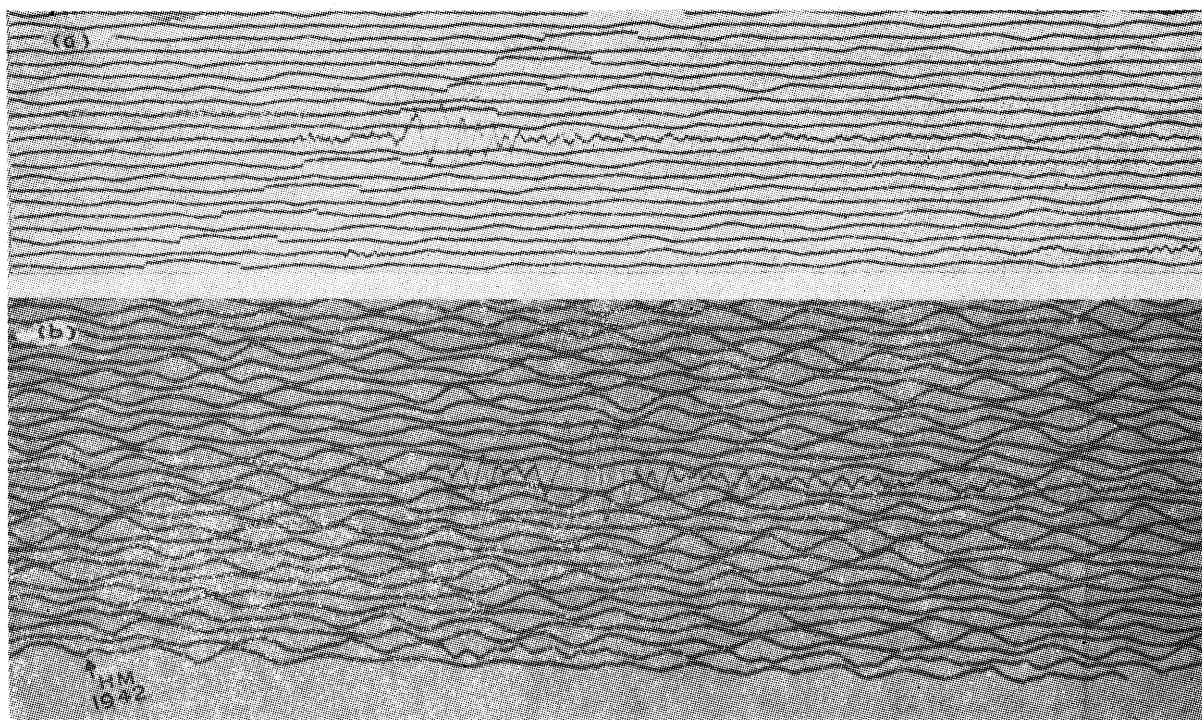


Fig. 3. Some typical shots recorded by seismographs

the Peninsular gneisses. The constituent rocks essentially comprise metamorphosed eugeosynclinal flysch sediments. The Dharwar province has been moulded in its present shape by two phases of orogenic movements. The earlier movement resulted in the formation of north plunging isoclines that trend NNW-SSE to N-S. There are many NW-SE, WNW-ESE and ENE-WSW striking faults and shear zones in the Dharwar province. The transcontinental deep fault towards south cuts across the Mysore plateau. The other two faults are more or less parallel to this major fault and have similar trends.

The Western Ghats form a well marked feature along the western coast. The northern part is composed of Deccan traps while the southern part consists of archaic gneisses, schists and charnokites. The average elevation of these is between 1000 and 1300 metres.

As already mentioned, the area is by and large stable and has not been affected by major seismic activity except along and near the Western Ghats. To the east over the plateau, however, minor and swarm type seismic activity has been noticed occasionally.

3. Observational network and collection of data

As mentioned earlier, five temporary observatories were set up during each field season along the profile. In all the observatories, sensitive IMD electromagnetic seismographs coupled with high speed (1 cm/sec) photographic recording were installed. All the observatories were provided with either crystal clocks or precision chronometers. For achieving better synchronization of the clocks, arrangements for automatic radio time signal impingment on the records were made

at every full hour GMT. The onset of each phase was recorded to an accuracy of 0.05 sec.

A total of 26 shot points were operated during the three field seasons. The depth of the shot points varied from 10 to 21 metres and the quantity of explosive used varied from 25 kg to 1000 kg. Analysis of the recorded events indicated the presence of direct crustal phases P_g & S_g . Fig. 3 shows as the first arrivals on a number of records. The refracted phases P^* , S^* , P_n and S_n were also recorded. In addition, other phases were also noticed on a number of records. The arrival times of these phases indicated that these could be reflected phases from the discontinuities below. The most prominent on all the records was a group of dispersed waves of the nature of surface waves.

4. Crustal studies

4.1. Refractions data

The travel time analysis of the phases P_g , P^* , P_n , S_g , S^* and S_n was carried out and the transit times were plotted against the epicentral distance (Distance between the shot point and the recording station). The points were fitted to straight lines using the method of least squares. Assuming a two layered model, with horizontal layers of isotropic rock media without velocity inversions, the velocities and the crustal structure from the refraction data have been worked out using the technique of delay times which is based on the relation :

$$T = \Delta V^{-1} + T_{SH} + T_{REC} \quad (1)$$

where, Δ = the distance between shot point and the recording station,

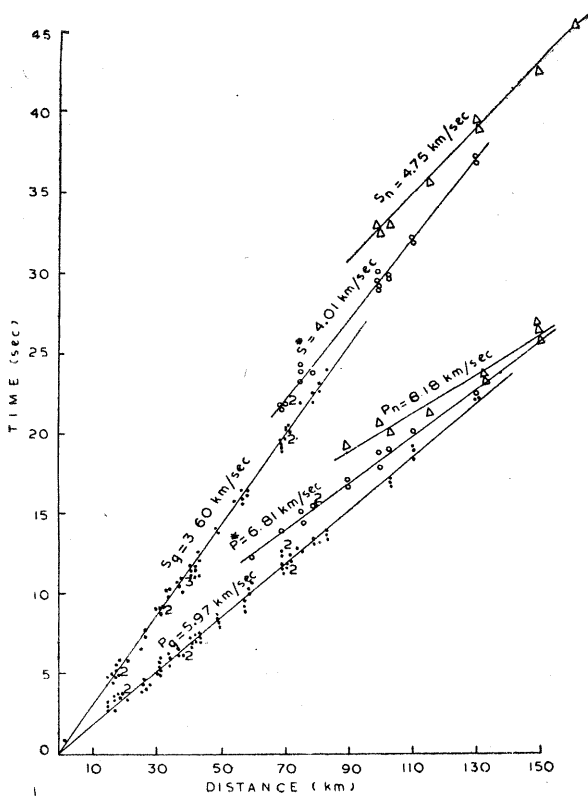


Fig. 4. Time-distance curves for direct and refracted waves using combined data of all the three field seasons

V = Refractor velocity, T_{SH} = Delay time at the shot point,

T_{REC} = Delay time at the recording point.

The travel times of direct and refracted waves have been computed and the results were found as follows (Fig. 4) :

$$T_{Pg} = (0.07 \pm 0.00) + (0.16764 \pm 0.00014)\Delta \quad (2)$$

$$T_{P^*} = (3.61 \pm 0.12) + (0.14689 \pm 0.00087)\Delta \quad (3)$$

$$T_{Pn} = (7.77 \pm 0.96) + (0.12227 \pm 0.00257)\Delta \quad (4)$$

$$T_{Sg} = (0.16 \pm 0.09) + (0.27763 \pm 0.00026)\Delta \quad (5)$$

$$T_{S^*} = (4.38 \pm 0.44) + (0.24946 \pm 0.00112)\Delta \quad (6)$$

$$T_{Sn} = (11.59 \pm 0.59) + (0.21045 \pm 0.00170)\Delta \quad (7)$$

Thus knowing the delay times and velocity distribution in each layer the thickness of the crustal layers were worked out from P -wave data as well as from S -wave data using the well known relations as follows :

$$t^* = 2 H_g \frac{\sqrt{V_b^2 - V_g^2}}{V_b \cdot V_g} \quad (8)$$

$$t_n = 2 H_b \frac{\sqrt{V_m^2 - V_b^2}}{V_m \cdot V_b} + 2 H_g \frac{\sqrt{V_m^2 - V_g^2}}{V_m \cdot V_g} \quad (9)$$

where,

t^* = Intercept time of S^* (P^*)

t_n = Intercept time of S_n (P_n)

H_g = Thickness of the granitic layer

H_b = Thickness of the basaltic layer

V_b = Velocity of S^* (P^*)

V_m = Velocity of S_n (P_n)

The results obtained are given in Table 1. It may be noticed from Table 1 that there is some variation in the thickness of granitic and basaltic layers determined from P and S wave velocities. This is attributed to the errors in reading the onset times of S -phase which have been read from vertical component seismographs. A comparison of the results of the present study with the other works done in the region (given in Table 2) suggests fairly good agreement. Results of the individual field seasons are also given in Table 3 and Figs. 5 (a, b, c) for the sake of comparison.

4.2. Reflection data

In recent years secondary phases regarded as reflections from horizons deep within the crust have been used to determine the crustal velocity structure. Stewart (1968) showed that the analytical method ($T^2 - \Delta^2$) is simpler to use for determining the average velocity structure from reflected phases even in case of crustal models characterised by continuous velocity depth function and that it gives reasonable results. In the present study, the same method has been used for this determination of crustal structure from the reflected phases. While interpreting the data, two distinct secondary phases were observed on the seismograms.

A plot of T^2 versus Δ^2 (Fig. 6) showed that the points fall on straight lines. The linear character of this plot supports their interpretation as reflected phases. The travel times of the phases reflected from 'Conrad' and 'Moho' boundaries have, therefore, been determined as follows ;

$$T_{1P}^2 = (46.12 \pm 0.84) + (0.02682 \pm 0.00017)\Delta^2 \quad (10)$$

$$T_{2P}^2 = (155.55 \pm 1.40) + (0.02330 \pm 0.00033)\Delta^2 \quad (11)$$

The total thickness of the crust from reflection study comes out to be 40.8 km with 20.7 km granite and 20.1 km basalt. The average P -wave velocity in the granite and in the crust as whole are found to be 6.10 and 6.55 km/sec respectively (Table 1). Considering the various approximations involved in this method, the results are fairly good in agreement with those obtained from refraction data.

5. P -phase amplitude variations with charge and distance

Amplitude of a wave depends upon local geological conditions and varies from rock to rock under similar conditions. It also enables us to identify low velo-

TABLE 1

Results from refraction and reflection studies

Rock layer	Velocity (km/sec)				Thickness (km)			
	Refraction		Reflection		Refraction		Reflection	
	P-wave	S-wave	P-wave	S-wave	P-wave	S-wave	P-wave	S-wave
Granite	5.97	3.60	6.10	—	22.4	18.0	20.7	—
Basalt	6.81	4.01	—	—	16.2	19.0	20.1	—
Crust as whole	—	—	6.55	—	—	—	—	—
Upper mantle	8.18	4.75	—	—	—	—	—	—
Depth of Moho	—	—	—	—	38.6	37.0	40.8	—

TABLE 2

Comparison of crustal thickness determined by various workers in Indian Peninsula using P-waves

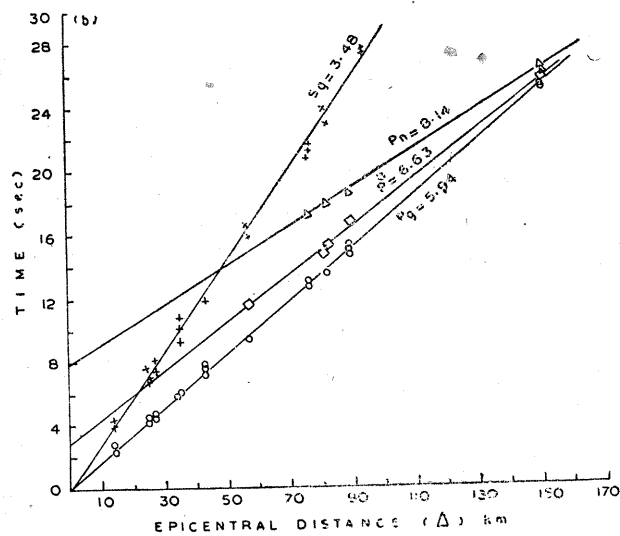
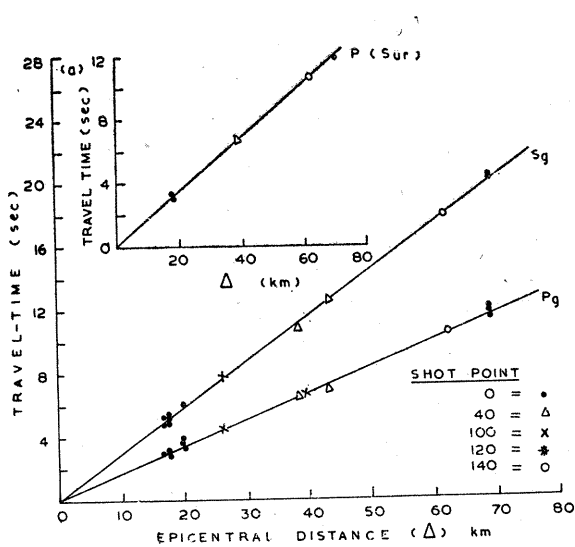
Authors	Region studied	Crustal thickness (km)		
		Granic layer	Basaltic layer	Depth of Moho
Present authors	Kaveli to Udipi	22.4	16.2	38.6
Arora (1971)	Gauribidanur	15.8	18.9	34.7
Dube, Bhayana and Chaudhury (1973)	Koyna region	20.1	18.7	38.8
Srivastava, Verma and Verma (1982)	Indore-Khandwa	18.0	19.9	37.7
Srivastava, Verma, Verma and Chaudhury (1982)	Koyna region	17.5	18.8	36.3
Srivastava, Verma and Verma (1982)	Peninsular India	21.6	16.7	38.3
Tandon and Chaudhury (1968)	Koyna region	22.5	18.5	41.0

TABLE 3

Wave velocities and crustal thickness of individual field seasons

Year	Profile	Velocities (km/sec)						Crustal thickness (km)		
		P_g	P^*	P_n	S_g	S^*	S_n	Granic	Basaltic	Total
1972-73	Cuddapah	6.08	6.52*	—	3.48	—	—	16.2*	—	—
1973-74	Dharwar	5.94	6.63	8.14	3.48	—	—	20.0	19.0	39.0
1974-75	Western Ghat	5.89	6.83	8.20	3.53	4.08	4.75	22.2	15.7	37.9

*Data scanty



Figs. 5(a & b). Time-distance curves for individual field seasons

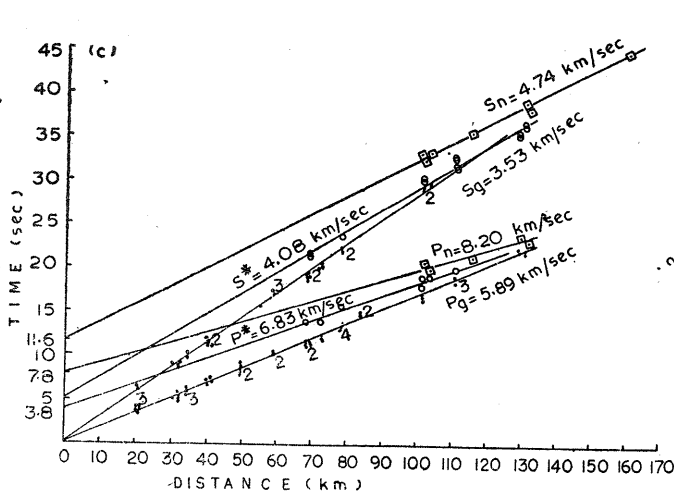


Fig. 5 (c). Time-distance curves for individual field seasons

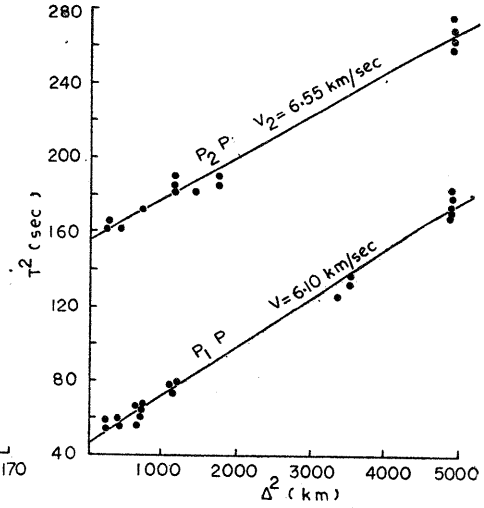
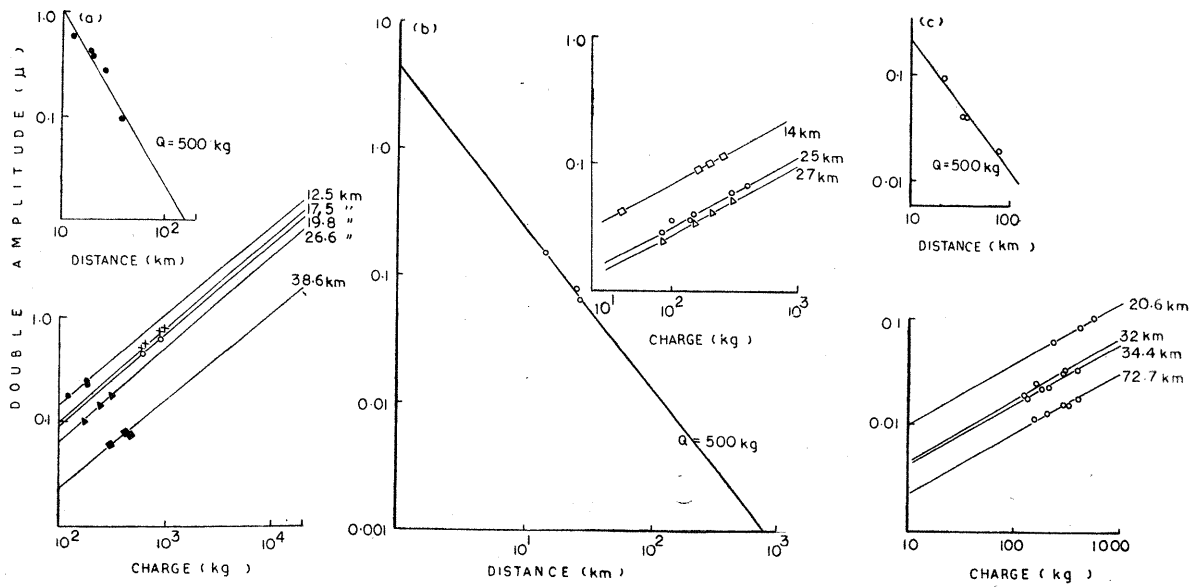


Fig. 6. Velocities of the waves reflected from 'Conrad' and 'Moho' boundaries



Figs. 7 (a-c). Dependence of amplitude of phase on charge size and distance, for all the three field seasons as Kavali

city layers in a region. In the present work the dependence of amplitude on the charge size and distance has been studied for the P_g phase which has been observed in most of the cases as the first arrival phase. The double amplitude in mm of the first arrival was measured and then converted into microns by using the response curve of the system. It is related with the charge as follows :

$$\log A = \log K + n \log Q \quad (12)$$

where K and n are constants.

Another relation between amplitude and distance at an arbitrary charge of 500 kg was also obtained. Combining these, the amplitude-distance-charge relations have been worked out for all the three field seasons separately (Figs. 7a, b & c)

$$A = 0.49 Q^{0.87} \Delta^{-1.86} \quad \text{Kaveli to Proddatur} \quad (13)$$

$$A = 0.31 Q^{0.63} \Delta^{-1.26} \quad \text{Proddatur to Maya Konda} \quad (14)$$

$$A = 0.48 Q^{0.53} \Delta^{-1.20} \quad \text{Maya Konda to Udipi} \quad (15)$$

As expected, these results show that the P -wave amplitude increases with the charge and decreases with the distance. It may be noticed that the attenuation of P -wave amplitudes is relatively more in Cuddapah basin as compared to Western Ghats.

6. Discussion

It may be seen from the Tables 1 to 3 that the wave velocities and the crustal structure agree with the results of other workers. Balkrishna *et al.* (1967) in a regional magnetic and gravity survey of Cuddapah basin estimated a crustal thickness varying from 34 to 38 km becoming higher towards Western Ghats.

The deep seismic sounding studies along the same profile (Kaila *et al.* 1979) showed that the velocity in granites and granitic gneisses range between 5.8 & 6.1 km/sec, whereas in Cuddapah sediments and the Dharwar schists the velocities range between 5.5 & 5.8 km/sec. Srivastava *et al.* (1982) have found the crustal thickness as 36.3 km in Koyna region with a thinner granitic layer as compared to the Kaveli-Udipi profile. Kaila *et al.* (1979) also reported from DSS studies that the velocity of P -wave in basement rock varies from 5.9 to 6.2 km/sec in Koyna region of the Peninsula and the total crustal thickness varies from 36 km to 40 km. Our results broadly agree with their findings.

Over the Scandinavian shield, Wahlstrom (1975) has reported slightly lower values of velocities in the Moho with the total crustal thickness as 36.7 km. Using under water explosions called 'Blue Road experiment' they could identify two branches of S_g , i.e., S_{g1} and S_{g2} . In addition R_g , the granitic wave of Rayleigh wave type was observed for small distances with its velocity as 2.81 ± 0.02 km/sec. Pentila (1974) presented a summary of crustal data from many explosions and earthquakes in Fennoscandia and found a granitic layer of 20 km and a basaltic layer of 17 km as an average for the Baltic shield.

The P -wave amplitude variation with distance has shown that there is relatively larger attenuation of seismic wave energy in Cuddapah basin as compared to the neighbouring region including Western Ghats.

7. Conclusions

The following important conclusions have been drawn from the explosion experiments along Kaveli-Udipi section of the Peninsular India:

(1) The crust consists of two layers with total thickness of 38 km as revealed by direct and refracted waves. The velocities of the phases computed come out to be $P_g = 5.97 \pm 0.00$, $P^* = 6.81 \pm 0.04$ and $P_n = 8.18 \pm 0.15$ km/sec. The corresponding S -wave velocities are found to be 3.60 ± 0.00 , 4.01 ± 0.02 and 4.75 ± 0.03 km/sec.

(2) The total thickness of the crust as obtained by reflection study comes to 41 km with an average velocity of 6.55 km/sec in the crust.

(3) The relationship between the amplitudes of the first P -wave onset with the charge and the distance shows relatively larger attenuation in Cuddapah basin as compared to Western Ghats.

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