P-wave velocities in the upper mantle of the Indian sub-continent from Russian Nuclear Explosions and inferred upper mantle structure

G. S. VARMA

Central Seismological Observatory, Shillong

(*Received 29 July 1969*)

ABSTRACT. The arrival times of the *P*-phases from 28 nuclear detonations conducted by Russia in the eastern Kazakhstan have been determined by the Indian seismograph stations. These arrival times have been plotted against the distance from various Indian seismograph stations; the distance ranges from $\triangle=16°$ to 40°. The travel times of *P*-waves indicate abrupt velocity changes arround $\triangle=18°$ and $\triangle=24°$. The *P*-wave velocity in the top of mantle comes out to be 8·16 km/sec, the sharp discontinuities are seen at $\triangle=18°$ and 24° at a depth of 350 and 650 km respectively below the crust. The velocities below these three discontinuities have been found to be as 9·33 and 11·24 km/sec respectively.

The T-JB residuals *versus* $\triangle$ have been plotted. Travel times of seismic waves have been compared with the travel times tables of JB. The velocities of various depths have been compared with those obtained by others. The densities at various discontinuities have also been determined with the knowledge of *P*-wave velocities using Birch's formula.

1. Introduction

In the studies of the low velocity channel travel times are customarily plotted against the apparent distances—the distance as measured on the surface of the earth from the epicentre to the recording station. This method of plotting is only acceptable, however, if all the events are of nearly the same focal depth. In the present study the author has selected nuclear explosions conducted in the south of Kazakhstan region of S.S.R. which is very near from Indian seismograph stations as shown in Fig. 1. The determination of velocity from nuclear explosions has 3 main advantages—(1) The coordinates of the epicentre is predetermined, (2) The time of occurrence of the explosion is accurately known; and (3) The depth of the focus is known.

In determining the velocity from natural earthquakes the accuracy of these above three factors is not high. Many such upper ground as well as under-ground explosions were conducted by Russia either in the Kazakhstan region or in Novaya Zemliya region. The later is much distant from Indian stations and will not yield any result about the upper mantle velocities. Thus the former was considered to be a suitable site for the present study. In his paper on the Montana earthquake of 1925, Byerly (1926) pointed out that a study of a single event would perhaps reveal more of the earth's interior than a statistical study of many events because of smoothing over of small anomalies with consequent overlooking of details which may have significance. Thus a single source has been selected for the present study.

The evidence that regional differences in the travel time exists raises difficulties with regard to the choice of standard travel times. This has been recognised by Jeffreys (1966) who remarked 'I have several times sought for differences of the travel times of *P* according to azimuth, but have never found anything significant'.

2. Collection of data and processing

For the study of the velocities in the upper mantle 28 nuclear explosions were selected from the period 1964 to 1969. The magnitude varies from 5·0 to 6·3. High magnitude explosions were especially used in this study so as to be recorded by the maximum Indian seismograph stations. The epicentres and the origin time were taken either from the *International Seismological Summaries* or from U.S.C.G.S. These explosions were recorded by many Indian seismograph stations and their initial *P*-times were noted from the monthly *Seismological Bulletin* of India Meteorological Department. The distance of the station from the place of explosion was determined by the direction cosine method knowing the coordinates of both the epicentre as well as the recording station. In case of any discrepancy the available original record of the station was checked. Various points were plotted on a graph with the distance as X-axis and the time taken by the wave from the focus to the recording station as Y-axis. After plotting all the points in the graph (Fig. 2) one can easily see that all these points can be represented satisfactorily into 3 straight line-segments representing 3 velocity discontinuities. For drawing the straight lines representing the velocities the method of least squares was used.

3. Travel times and velocities

The travel times of a wave can be represented as $T = \triangle V + I$ where I is the intercept it makes on the Y-axis which is also called the delay time, the wave takes starting from the focus; V is the apparent velocity. Thus in Fig. 2, the travel times of the three straight lines can be represented by the following equations—

$$T = \frac{\triangle}{8.22} + 8.5 \tag{1}$$

where $\triangle$ lies between 16° and 18°

$$T = \frac{\triangle}{9.95} + 51.0 \tag{2}$$

where $\triangle$ lies between 18° and 24°

$$T = \frac{\triangle}{12.62} + 107.0 \tag{3}$$

where $\triangle$ lies between 24° and 40°

The travel times of the P-wave was determined from different values of $\triangle$.

From the apparent velocities the true velocities were derived using the relationship $V_h = V\,[1-(h/R)]$ where V_h is the true velocity of the wave at a depth h from the surface of the earth, and R is the mean radius of the earth. The true velocities come out to be 8·16, 9·33 and 11·24 km/sec respectively corresponding to the apparent velocities 8·22, 9·95 and 12·62 km/sec respectively. For calculating true velocities the crust is assumed to be uniform and thickness 45 km.

The reduced travel times ($T = \triangle$/velocity) have been plotted against $\triangle$ to show clearly the cross over points from one straight line segment to another. In all the above three cases the intercept and the epicentral distance at which the cross over takes place is shown in Figs. 3 to 5 justifying the velocity discontinuity there.

4. Density determination

It is a very complicated phenomenon to relate the density to elastic velocities without any assumption. The relationship derived from the equation of state necessarily involved assumptions of solidity and homogeneity, which cannot be reasonably justified. A relationship has been given by

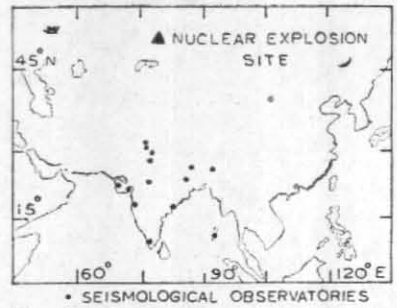

Fig. 1. Map showing locations of Indian seismological observatories and nuclear explosion site

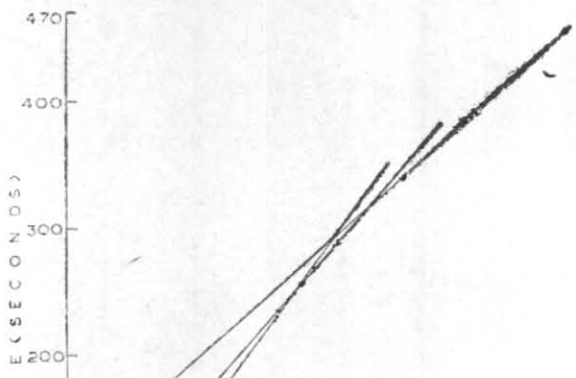

Fig. 2. P-wave travel time curves for Indian sub-continent determined from Russian nuclear explosions.

Fig. 3. Reduced travel time curves showing epicentral cross regions

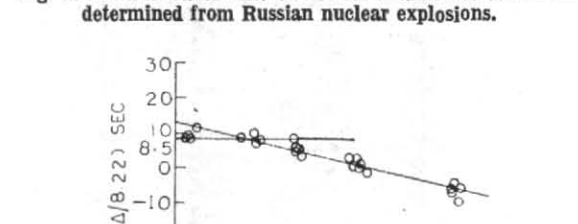

Fig. 4. Reduced travel time curves showing epicentral cross over regions for adjacent straight lines segments

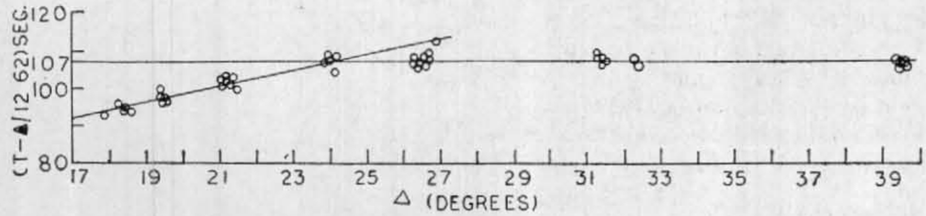

Fig. 5. Reduced travel time curves showing epicentral cross over regions

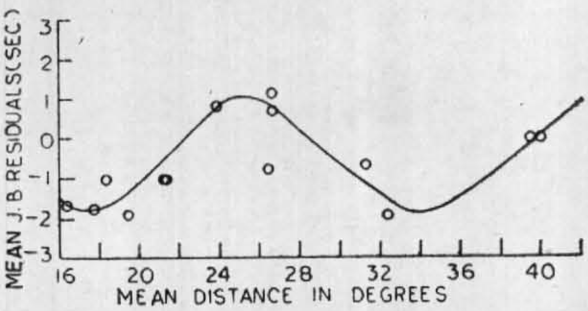

Fig. 6. Mean differences from JB. times *versus* △ at Indian station from Russian nucelar explosions

Birch (1964) which is independent of assumptions of constant phase but not constant mean atomic weight. He found two empirical relationship relating to ρ_h and V_h based on laboratory observations and depending upon the actual density at the top of the mantle. These are

$$\rho_h = 0 \cdot 768 + 0 \cdot 328\ V_h \quad (4)$$

and also $$\rho_h = 0 \cdot 252 + 0.3788\ V_h \quad (5)$$

From the relationship (4) the densities of the mantle corresponding to the velocity anamolies come out to be 3·45, 3·83 and 4·45 gm/cc respectively (*see* Table 2).

5. Evidence from residuals

T-JB residuals are found mostly negative (Table 1). A negative residual corresponds to an early-arrival of the wave. T-JB residuals are generally found negative in Asia or in shield areas. Large negative residuals are found where deep focus earthquakes originate. A positive residual corresponds to the late arrival of the wave such as continental areas which have been uplifted. Mild oceanic regions have small positive residuals.

As the source in this study is taken as a single source the mean residuals from all these stations have been plotted against the mean distance and a smooth curve is drawn (Fig. 6) giving a minimum at 18° and maxima at about 25° indicating the change in the residuals due to the change in velocity which is due to the change of the crustile structure in that region. If at a given place residuals differ much it points to a structural anomaly, relative to the J-B model within the mantle.

6. Comparison with other authors' data

P-wave velocity determination reveals two first order discontinuities at the depth of about 350 and 650 km below the crust. Hales *et al.* (1968) while studying *P*-wave of North American stations from 20° to 96° found only one discontinuity in the travel time curve at 24° and no other major discontinuity was observed by them.

Jeffreys (1962 b) found the upper mantle velocity for the Central Asia as 8·146 km/sec. Carder *et al.* (1966) found, for the nuclear explosions, that in North America the cross over occurs at 18·5° to 19·0° and at 23·5° and the corresponding velocity to the depth of 650 km was 11·2 km/sec. Niazi and Anderson (1965) found two velocity discontinuities at depths of about 320 and 640 km corresponding to the epicentral distances 17° and 24° respectively for Western North America. Jeffreys (1963) found a discontinuity at 18·6° while determining the travel time from Pacific explosions. In Japan Nishimura *et al.* (1958) found two discontinuities for *S*-wave near 18° and 24°.

7. Conclusion

In summary, the travel times of the *P*-wave has been investigated and the following may be concluded about the crustal structure in the upper mantle to the Indian sub-continent.

TABLE 1

Seismograph station	Mean △ (Deg.)	Mean T—JB Residuals
Warsak dam	16·43	—1·7
Jawalamukhi	17·88	—1·7
Bhakra	18·41	—1·0
Dehra Dun	19·47	—1·9
New Delhi	21·09	—1·0
Quetta	21·33	—1·0
Chatra	24·01	+0·8
Shillong	26·45	—0·8
Bokaro	26·59	+0·7
Sehore	26·65	+1·1
Poona	31·38	—0·7
Visakhapatnam	32·31	—2·0
Kodaikanal	39·53	—0·1
Port Blair	39·92	—0·1

TABLE 2

The upper mantle structure of the Indian sub-continent from the *P*-waves

Depth (below the crust) (km)	Apparent velocity (km/sec)	True velocity (km/sec)	Density (gm/cc)
0	8·22	8·16	3·45
350	9·95	9·33	3·83
650	12·62	11·24	4·45

(1) The velocity is constant at 8·16 km/sec beneath the crust to about 350 km having a density 3·45 gm/cc.

(2) Beyond 18° the first arrivals fit a slope of 9·95 km/sec on travel time plot and infer a speed of 9·33 km/sec within layer at a depth of about 350 to 650 km with density 3·83 gm/cc.

(3) The third branch of travel time curve intersect the second leg near 24° and corresponds to a velcoity of 11·24 km/sec beneath a depth of 650 km. The density at this depth has been determined as 4·45 gm/cc.

(4) Near 24° the velocity attains a value of 11·24 km/sec which is maintained throughout upto 40° and no other discontinuity has been observed beyond it as determined by other workers.

(5) The upper mantle velocity of 8·16 km/sec as determined by the present author is fairly in good agreement with that determined by Jeffreys (1962 b) for Central Asia. He found it 8·146 km/sec. The small negative T-JB residuals is a further proof that the velocity in this region of the mantle is slightly higher than that determined by Jeffreys. The travel times proposed for Indian sub-continent also do not show much deviation from that of Jeffreys.

It is, therefore, quite clear from the present study that in this sub-continent the upper mantle has two major discontinuities at depths of 350 and 650 km below the crust having the *P*-wave velocities 9·33 and 11·24 km/sec respectively, the velocity at the top of mantle has been determined as 8·16 km/sec.

REFERENCES

Birch, F.	1964	*J. geophys. Res.*, **69**, pp. 4377-4388
Byerly, P.	1926	*Bull. seismol. Soc. Amer.*, **16**, pp. 209-265.
Carder, D. S., Gordon, D. W. and Jordan, J. N.	1966	*Ibid.*, **56**, pp. 815-840.
Hales, A. L., Clearly, J. R. and Roberts, J. L.	1968	*Ibid.*, **58**, pp. 1975-1989
Jeffreys, Harold	1962(a)	*The Earth*, Cambridge. Univ. Press, pp. 61-64.
	1962(b)	*Geophys. J. R.A.S.*, **6**, pp. 493-508.
	1963	*Ibid.*, **7**, pp. 212-219.
	1966	*Ibid*, **11**, pp, 5-12.
Kaila, K. L., Reddy, P. R. and Narain, Hari	1968	*Bull. seismol. Sec. Amer.*, **58**, pp. 1879-1897.
Niazi, M. and Anderson, D. L.	1965	*J. geophys., Res.*, **70**, pp. 4633-4640.
Nishimura, E., Kisthimoto, Y. and Kamitsuki	1958	*Tellus*, **10**, p. 137.