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The seismic channel P waves πg or $\bar{P}$ and their propagation along the crust of the Indian sub-continent

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ABSTRACT. In a previous communication (Saha 1961) the author has studied the seismic *Lg* waves and their propagation along the granitic layer of the crust of the Indian sub-continent. In his search for the counterpart in longitudinal P waves, the author has been successful in observing very clear recording of the $\bar{P}$ or πg phase in the records of the Chatra, Agra and Quetta (Pakistan) seismological observatories from earthquakes originating in the boundary fault zones of the Himalayas. The presence or absence of the phase in the records of the other observatories in relation to the structure of the crust is discussed. Although for the propagation of the wave, the *Lg* waveguide consisting of the free surface and the bottom of the granitic layer is suggested but the amplitudes of the πg or $\bar{P}$ wave are small as compared to the amplitudes of the *Lg* waves. The cause of the weakness of the phase is also discussed.

1. Introduction

Since the discovery of *Lg* waves in the North American continent by Press and Ewing in 1952, the seismologists were in search for the counterpart in the longitudinal P wave. Bath (1954) and Gutenberg (1955) made attempts to identify the phase on seismograms. Although there were some indications of the phase on seismograms these authors concluded that it was either very small or absent. This was probably due to the restricted conditions under which the phase is recorded. The phase was, however, identified later by Press and Gutenberg (1956) on examination of seismograms from North American stations for the Kern County earthquake of 1952. The characteristics of the phase πg or $\bar{P}$ in relation to *Lg* were interpreted by the authors in terms of propagation in a crustal channel bounded on the top by the earth's surface.

Recently Shurbet (1960) observed $\bar{P}$ or πg phases recorded at Lubbock, Texas and Lawrence, Kansas. He attributed the phase to propagation of longitudinal waves in the near surface waveguide which has been hypothesized to explain the propagation of the *Lg* phase. Herrin and Richmond (1960) tested for several crustal models on the hypothesis that *Lg* is propagated within a crustal waveguide formed by the free boundary and rapid increase in velocity with depth below. Herrin (1961) has very recently corrected for several errors and has shown that only sedimentary basin model would allow propagation of $\bar{P}$ waves within the *Lg* waveguide.

2. Scope of observations

The channel S wave which constitutes the *Lg* phase on seismograms was studied by the author (1961) in respect of a few earthquakes of Indian origin. Like *Lg* waves the observations of πg or $\bar{P}$ phases are limited to purely continental paths and they are also likely to be deleted completely during its passage across young mountain chains like the Himalayas. Accordingly, the author had to search for the phase from records of earthquakes originating in zones to the south of the Himalayas. Gutenberg (1951) has suggested that the *Pg* phase in the seismograms of the near earthquake

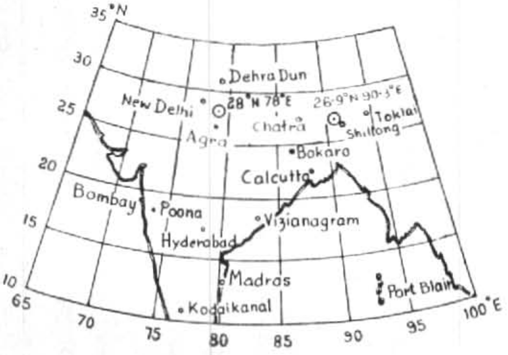

Fig. 1

shock at distances less than 8° corresponds to πg phase at intermediate distances. The examination of the phase in respect of earthquakes at intermediate distances from the records of the stations to the south of the Gangetic alluvial trough was not fruitful. Inspite of the fact that the number of records at intermediate distances from stations to the north of the above trough are very few, it has been possible to detect the phases on a few records from stations with thick crustal sections which form the subject of the present study.

Press and Gutenberg (1956) have expressed some doubt as to the distance where πg begins and P group ends. Although the present observation of the πg phase is limited to short distances on account of the limitations of observations already mentioned, the clarity of the phase recorded leaves little doubt as to the correct identification of the phase. In the case of the Agra seismogram, the reported πg phase was tabulated in the station bulletin as 'i' in the absence of any nomenclature of the phase in the travel time tables of Jeffreys and Bullen (1948). In the case of the Chatra seismograms the reported πg phase was tabulated as a P phase from an after-shock from the same origin. But this is not justified because according to above authors, the possibility that these observations result from an after-shock is excluded by apparent velocity of the waves. In the case of the Quetta record in respect of Assam Bhutan border shock, the distance is about 2250 km.

3. Purpose of the study

It has not been possible to study the phase in great detail on account of the limitations of the waveguide for the propagations of the longitudinal channel waves along the crust. The purpose of the present report is to point out the characteristics of the phase from the records of earthquakes at intermediate distances and thereby to indicate some characteristics of the local structure of the crust. The present writer on his study on Lg waves has concluded that the Lg waves guide is very efficient along certain paths while they are quickly attenuated while traversing across hilly ranges. It will be, however, noticed that the limitations of the waveguide propagation are very much more in the case of the πg or $\bar{P}$ wave as compared to the waveguide propagation of the Lg wave. The conditions at the source should also be considered. Bath (1954) has actually tabulated the various reasons when no Lg has been recorded and has pointed out that the focal depth greater than normal is one of the reasons. The above limitations will also apply for the source so far it relates to channel P waves πg or $\bar{P}$. This is in perfect accord with the observations of Shurbet that the average depth of focus is somewhat less than 33 km. Herrin (1961) has shown that Lg waves can propagate in five crustal model considered by him but it is only sedimentary basin model that would allow propagation of channel P waves within the Lg waveguide. A strong recording of the πg or $\bar{P}$ phase would indicate that the path between the epicentre and the recording station is of the sedimentary basin type which assumes 5 km of shale and limestone increasing rapidly in velocity with depth above granite layer.

4. Discussion

Fig. 1 gives the location of epicentres and observing stations. It is seen that the great circle paths of the waves in most of the observing stations are continental. But the phase is not recorded in all the observing stations at intermediate distances. It is generally observed that the phase is not well recorded at stations to the south of the Gangetic alluvial trough. But it is recorded under favourable conditions by some stations in northern India and Pakistan due to earthquakes in the Himalayan Boundary fault region. The Delhi earthquake of 27 August 1960 gave a clear recording of the phase at Chatra (Nepal) and Quetta (Pakistan) seismological observatories and the records of the shock are reproduced in Figs. 2 and 4. The phase under discussion is shown as πg. The Assam-Bhutan Border shock of 29 July 1960 gave rise to a πg phase in the Agra and Quetta records which are reproduced in Figs. 3 and 5.

The fact that the phase is recorded at Agra and Chatra and Quetta, the sub-Himalayan stations, but they are not recorded at stations to the south of the Gangetic alluvial trough goes to suggest the peculiarity of structure of the crust of the intervening path. On certain occasions when the shock originates at a depth much below the crustal boundary, it is quite natural that the phase might not be recorded at any station. In the case of underground nuclear explosions and out to a distance of 1700 km Romney (1959) noted the arrival of a phase with a velocity of 6 km/sec (which he called $\bar{P}$ phase) which is probably the equivalent of πg or $\bar{P}$ phase due to natural earthquakes. It appears quite probable that a comparatively shallow explosion near the axis of the waveguide would put more energy into the channel as compared to a source at appreciable depth below the axis of the guide for an efficient propagation of the phase. The fact that a very clear πg phase was recorded at Chatra and Quetta due to recent Delhi earthquake of 27 August 1960 goes to suggest a shallow focus for the earthquake. This is in complete accord with the conclusions of the author on his study on the depth of focus of the Delhi earthquake (Saha 1962) from the consideration of the relative amplitudes of the *Lg* waves observed in the records of different seismological observatories.

Press and Gutenberg (1956) have offered an explanation for the small amplitudes of the phase. This is due to greater leakage of the πg phase on account of conversion to waves of SV type on reflection at the earth's surface. The observations of the author as well as the observations by the previous workers go to suggest that the phase is propagated in regions of the continent where thick sections of low velocity sediments exist. This observation of the author is in complete accord with the conclusions of Oldham (1917) from geological considerations. According to him the maximum thickness of the Gangetic alluvium 15,000 to 20,000 ft deep is located near the main bounding fault on the north, the thickness gradually decreasing in the southerly direction. The above estimate of Oldham as to the thickness of the sedimentary deposition of 15,000 ft appears to be correct from the consideration of the sedimentary basin model considered by Herrin and Richmond (1960). The sedimentary rocks of Quetta region are generally more than 7 km thick. This is why the phase is not recorded at stations to the south where the thickness of the low velocity sedimentary layer above granitic layer is small as compared to the wave-length. This explains the absence of the phase in the records of seismological observatories at Madras, Colaba (Bombay) and Poona located to the south of the Gangetic alluvial trough on account of earthquake shocks originating in the boundary fault zones of the Himalayas. The sources of earthquake of sufficient magnitude to excite these phases are very rare from the country to the south of the above trough. The seismograms of the Kutch earthquake of 21 July 1956 (Epc. 23°.6 N and 70°E) obtained at Bokaro ($\triangle$ = 1580 km) and Dehra Dun ($\triangle$ = 1070 km) observatories were examined but no strong recording of the phase could be observed.

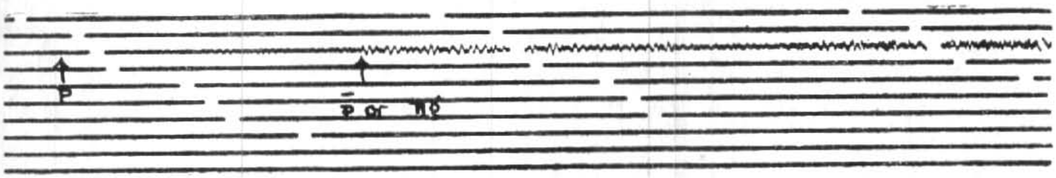

Fig. 2

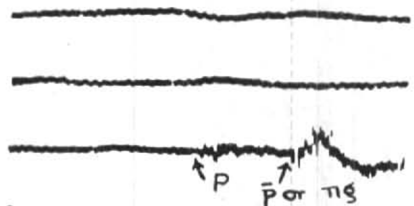

Fig. 3

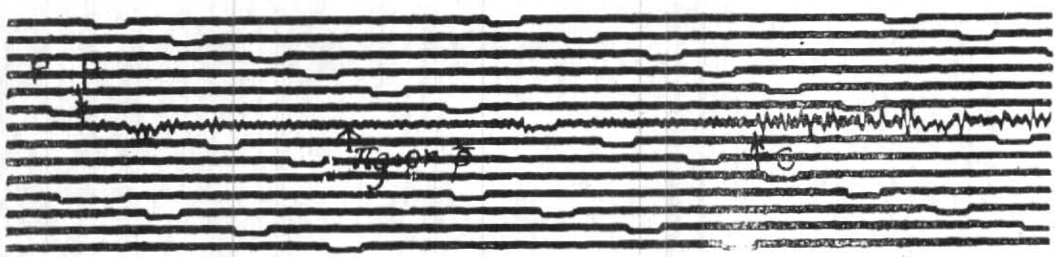

Fig. 4

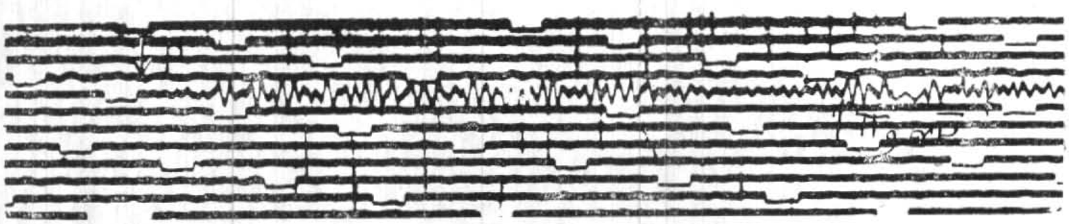

Fig. 5

Fig. 2. Section of Chatra Wood Anderson (N-S) of 27 August 1960 (T_0 = 1·0 sec), Damping nearly critical; time scale 60 mm/min ($\triangle$ = 1000 km)

Fig. 3. Section of Agra Columbia Long Period (E-W) of 29 July 1960 (T_0 = 15 sec), Damping both Galvanometer and Seismometer critical; paper speed 15 mm/min ($\triangle$ = 1180 km)

Fig. 4. Section of Quetta Sprengnether Vertical of 27 August 1960 ($T_g = T_0 = 1 \cdot 8$ sec), Damping critical; time scale 60 mm/min ($\triangle$ = 980 km)

Fig. 5. Section of Quetta Sprengnether (N-S) of 29 July 1960 ($T_g = T_0 = 1 \cdot 9$ sec), Damping critical; paper speed 60 mm/min ($\triangle$ = 2250 km)

The effect of the low velocity sediments is to reduce the angles of incidence at the free surface which results in the increased amplitudes for the reflected longitudinal component as compared to the amplitudes of the reflected SV component. Shurbet (1960) observed that earthquake 12 was located beyond the continental margin and yet the phase $\bar{P}$ was recorded at Lubbock. The granitic layer under the sea near the continental margin has more or less the shape of a wedge, the narrower end pointing towards the ocean. During the passage of *Lg* or πg waves through the crust under the continent towards the narrow wedge of the crust under the sea, the angle of incidence gradually decreases and this helps the escape of much of the energy into the bottom resulting in the quick attenuation of the waves in the lithosphere channel. In the case of the passage of the guided waves from the narrow wedge of the granitic layer under the sea towards the continent the angle of incidence, instead of decreasing gradually increases as they proceed towards the continent with thick granitic section and this results in the minimum escape of energy into the bottom. The above explanation is very similar to the explanation suggested by Ewing, Jardetzky and Press (1957). According to them disturbances from the atmosphere or from the ocean entering the granitic layer in transition zone will find that the sloping boundary constitutes a Lummer-Gehreke plate strongly favouring propagation toward the continent rather than toward the ocean. The strong attenuation of *Lg* or πg waves during its passage across the young mountain chains could be explained if we assume that the thickness of the granitic layer is more under the mountain bottom as compared to the same under the continental platforms on either side. The above will constitute a double wedge strongly attenuating the waves during its passage. The assumption is supported by observation that the thickness of the crust under mountain chain is more as compared to the thickness of the crust under the continental platforms. The greater thickness of the crust under the mountain chain is mainly a result of greater thickness of the upper most granitic layer.

Shurbet (1960) attributes the propagation of the $\bar{P}$ phase with thick crustal section and explains the absence of the phase due to interruption of waveguide on account of the decrease in the depth of the M discontinuity. The presence of the phase at intermediate distances in the records of the northern Indian stations and its absence at southern Indian stations could be similarly explained if we assume that there is a significant decrease in the depth of the M discontinuity under the hidden range of Burrard extending northwest and southeast of Jabalpur from Karachi to Orissa as inferred from the measurements of the gravity and deflections of the plumb line. But Herrin has, however, pointed out that even with a thick sediment section *Lg* waveguide need extend only 12 to 15 km below the surface and would not be affected by the presence of the M discontinuity. This anomaly could be explained if only the upper crust, *i.e.*, the granite layer is involved in the propagation and if the relief of the intermediate layer sink to form the roots and rise to form antiroots like the M discontinuity. This is the type of the structure of the crust in some parts of the earth. In northern Pamirs both discontinuity sinks to form the roots while in western Turkmenia both rise to form antiroots. Gutenberg (1943) has also concluded that this root is mainly a result of a greater thickness of the upper most (granitic) layer. The velocity, of about 5·7 km/sec for the πg phase observed corresponds to the speed of the longitudinal waves in the upper part of the crust. It is, therefore, quite likely that the waveguide consisting of the free-surface and the bottom of the granitic layer is involved in the propagation. This mechanism of propagation is further supported by the observation of the author on the existence of the P^*

phase with velocity of propagation of 6·6 km/sec, at intermediate distances. The velocity and other criteria suggest that probably entire crust is involved in transmitting the phase P^* at intermediate distances.

5. Conclusions

1. The $\bar{P}$ or πg phase could propagate in a granitic crust overlain by thick sections of low velocity sediments. No such sedimentary low velocity surface layer is required for the propagation of the Lg waves.

2. The phase is recorded strongly at stations with thick crustal section which generally indicate thick sections of granite suitable for waveguide transmission of the phase. The absence of the granitic layer under the ocean and thin sections of granitic layer under platform regions may act as a barrier to the propagation of the phase. Both Lg and πg phase are not transmitted through the crust under the ocean bottom where the granitic layer is absent. The presence of the Lg phase at Colaba and Poona records and the absence of the $\bar{P}$ or πg phase on these records may be due to transformation of $\bar{P}$ or πg phase into Lg at the margin of the sedimentary basin as suggested by Herrin.

3. The observations of the seismic waves Lg or πg combined with the gravity and refractions measurement may be used for the study of the fine structure of the earth's crust.

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