The seismic *Lg* waves and their propagation along the granitic layer of the crust of Indian Sub-Continent

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ABSTRACT. Guided or channel waves of the *Lg* type were observed in Colaba seismograms due to an earthquake and its aftershock originating in Nepal. Similar observations are also available from another earthquake having its origin in Assam-Bhutan border. No such waves were, however, recorded by similar seismographs at Shillong and Madras. They are also absent in the records of Quetta (Pakistan) seismographs having different characteristics. *Lg* waves are also absent in the records of the shocks originating in the zones to the north of the Himalayas. The geological significance of the existence and non-existence of *Lg* waves in earthquake records is discussed. Similarity between ordinary microseisms of 4 to 10 seconds periods is also considered and an explanation has also been suggested why microseisms could propagate through the ocean bottom while the *Lg* waves are completely deleted during its passage through the oceanic path. The well defined *Lg* and *Rg* phase in records of the Assam-Bhutan border shock probably goes to show the importance of the focus in the granitic layer for the generation of this type of guided waves.

1. Introduction

Channel or guided waves were long known for the effective propagation of sound in the sea. This was due to the existence of low velocity layer at a certain depth known as 'SOFAR' channel. Submarine earthquakes are able to send longitudinal waves through this channel, the land path to a seismic station being travelled as ordinary body waves. Such waves called *T* phases were recorded at several observatories. The existence of the low velocity layer at sea could also be investigated by direct methods. It is not, however, possible to have any direct method of investigation on the existence of any such low velocity layer in the crust or in the mantle. Accordingly the geophysicists were in search of channel or guided waves. The first discovery of such waves was made by Press and Ewing (1952) for the north American continent, and these waves called *Lg* have been found on other continents and studied by many investigators [Lehmann 1952, 1957, Bath 1954, Gutenberg 1955, Oliver *et al.* 1955, Press *et al.* 1956, Press 1956, Oliver and Ewing 1957, 1958 a, Utsu 1958 a, 1958b]. According to Press and Ewing (1952) *Lg* phase is a short period (1 to 6 secs) large amplitude arrival in which the motion is predominantly transverse but accompanied by appreciable vertical components. The phase occurs only when the earthquake epicentre and the seismograph station are so situated as to make the path entirely continental. As little as 2° intervening ocean is sufficient to eliminate the phase entirely. Accordingly *Lg* waves could be used as a tool for the investigation whether the structure of a region is continental or oceanic.

The amplitude of *Lg* phase is very large compared to the amplitude of the body waves which precede *Lg* phase. The very sharp beginning is a good criterion to recognise them on the seismograms. The velocity of the *Lg* is about 3·5 km/sec which is essentially the velocity of shear waves in the upper part of the continental crust. Although the exact mechanism of the propagation is not understood, it is, however, certain that a very efficient wave guide is necessary for its propagation. On account of velocity gradient in the crust, there will be tendency in the short period *Lg* waves to concentrate in the zone of lowest velocity, *i.e.*, in the uppermost granitic layer. Oliver and Ewing (1958 a) have, however, pointed

TABLE 1

Station	Compt.	Seismometer period T_o (sec)	Galvanometer period T_g (sec)	Synchronous magnification
Shillong	E	6·7	6·7	4100
Madras	E	6·1	7·1	5000
Colaba (Bombay)	E	7·4	7·4	5000

out that it is possible to explain *Lg* as the result of normal mode propagation within a crust in which velocity increases in some manner with depth and there is no need to postulate a low velocity layer to explain these phases. They have further pointed out that the beginning of the *Lg* phase is associated with the group velocity maximum of the M_2 or second Love mode and that only by coincidence this is near the shear velocity in the upper crust. It is now well established that the *Lg* phase constitutes short period spectrum of the normal mode surface wave propagation. The shorter wave-lengths associated with the higher modes have generally higher resolution and it is quite likely that these higher mode short period waves will prove to be a very valuable guide in the fine structure study of the crust when combined with the fundamental modes of surface wave propagation, which has been extensively used in the study of crustal structure.

2. Scope of observations

In Indian observatories, the observations of *Lg* waves were very much limited on account of the instrumental difficulties because most of the observatories in India are equipped with either long period or short period instruments like the Milne-Shaw ($T_o=12^s$) and Wood Anderson Seismographs having a natural period near about one second. At relatively short distances, the various waves guided by the lithosphere channel can rarely be studied in great detail on records of the short period instruments as a consequence of their large amplitudes and of other phases with short periods which are superimposed. On the other hand, long period instruments emphasize the long period surface waves arriving at about the same time. Consequently *Lg* waves are clearest when recorded on medium period instruments where frequently they are riding on the top of the longer waves. Fortunately, however, the medium period instruments of the type Sprengnether Microseismographs were installed at Madras, Colaba (Bombay) and Shillong as a programme for the study of the storm microseism.

The constants of the instrument are given in Table 1.

Fig. 1 shows the distribution of the earthquake epicentres to the north of the country from which we may expect earthquake shocks having purely continental path, because as small as 2° oceanic path is sufficient to delete the *Lg* waves from the records. Accordingly the writer was searching for the *Lg* phase in seismograms of the moderately great earthquakes originating in China or U.S.S.R. But he was completely disappointed to find that none of the records show the existence of this type of guided waves of *Lg* or *Rg* type and he was led to the conclusion that the elevated land mass of Tibet and the young mountain chains like the Himalayas probably forms a great barrier to the transmission and propagation of the *Lg* and *Rg* type of waves. These observations are in complete accord with the observations of Gutenberg (1955 a) and Bath (1954). According to them *Lg* and *Rg* waves are weakened or even disappear in crossing recent mountain chains where probably the channels are too much distorted to permit transmission of guided waves. In California they seem to be more weakened in crossing transverse ranges and Sierra Nevada than along paths between Mexico and Southern California. Accordingly he had to take recourse to the records of the earthquake shocks originating only in zones situated to the south of the Himalayas. The author could not, however, observe *Lg* and *Rg* phases on the records of the Central Seismological Observatory at Shillong

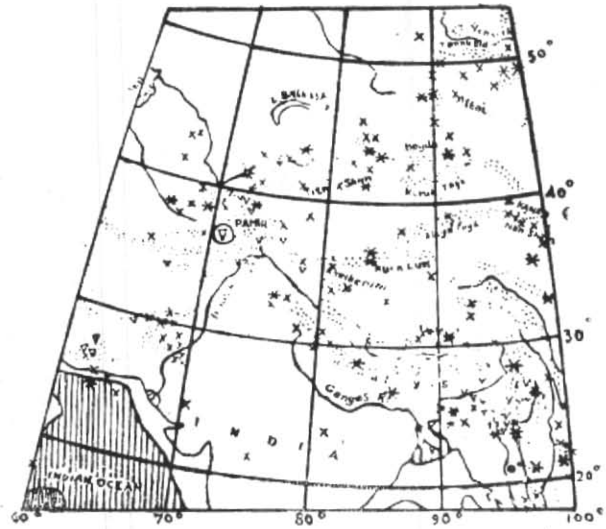

Fig. 1

but was successful in finding *Lg* type of waves in the records of the Colaba micro-seismograms in respect of an earthquake shock and its aftershock which originated in Nepal and also from a shock originating in Assam-Bhutan border. It is, however, important to observe that in Madras seismographs *Lg* waves are not so well developed while in the Shillong and Quetta records they are completely absent. It may be worthwhile to mention here that the instruments at Colaba are located in an underground room on a solid rocky foundation of Deccan trap.

3. Purpose of the study

The intention of the present report is not to add a few observations on the so-called channel waves of the *Lg* and *Rg* type because much study has been made in other countries giving the characteristics of *Lg* and *Rg* waves. The detailed studies like the motion of the particle and the direction of approach of the waves are not possible from the records of the single component instruments available for the study. The main purpose of the report is to show that the *Lg* phase was well developed at some stations while at other stations they were either ill developed or not developed at all, although the paths of seismic waves from the epicentre to the recording stations can be regarded to be continental in the ordinary sense of the storm. This observation of relative amplitudes of *Lg* waves may provide information on crustal discontinuities or variations. The epicentral distance from Colaba (Bombay) is about 12°·7 as compared to 16° from Madras, 10°·3 from Shillong and 12°·3 from Quetta and the instruments are more or less equally sensitive except for Quetta. No effect other than the strong attenuation at the roots of the hilly tracts seems capable of explaining these observations.

The seismographic records of the shock which originated in Nepal on 5 March 1960 are reproduded in Figs. 2-4 and 7. The epicentre of the shock as given by U.S.C.G.S. was Lat. 29°N and Long. 81°E. The origin time of the shock was $H=11^h\ 25^m\ 00^s$ GMT. The shock was followed by an after-shock (Figs. 5 and 6) from the same origin on the same day and its origin time as given by U.S.C.G.S. was $H=23^h\ 50^m\ 38^s$.

The lower undulations are due to the earthquake having epicentre near 1° N and 129°E. The arrow mark indicates the tip of the maximum trace amplitude. The Madras

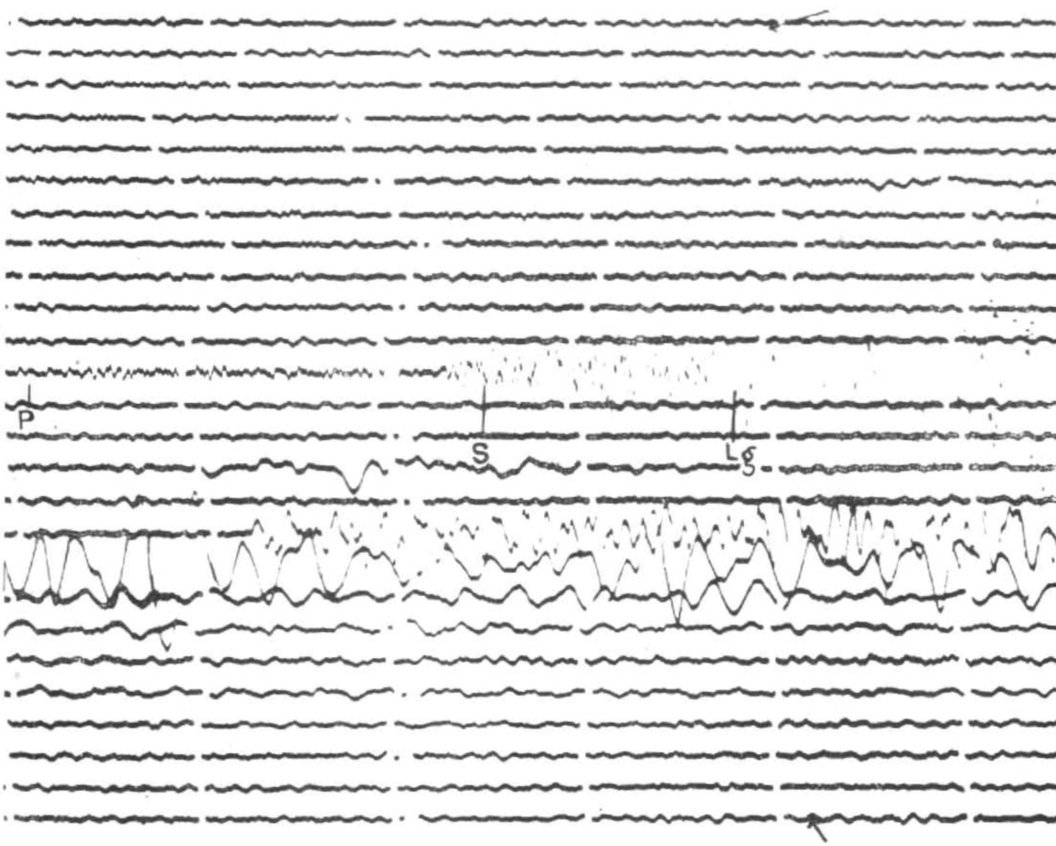

Fig. 2. The records of Colaba Electromagnetic Seismograph of the Nepal shock of 5 March 1960
($\triangle = 1410$ km)

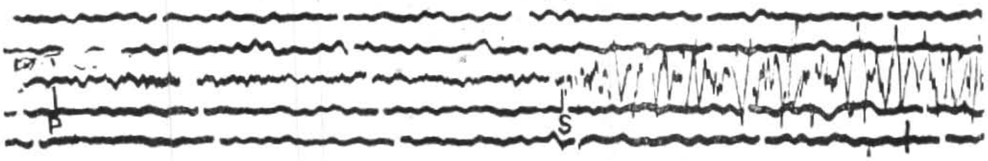

Fig. 3

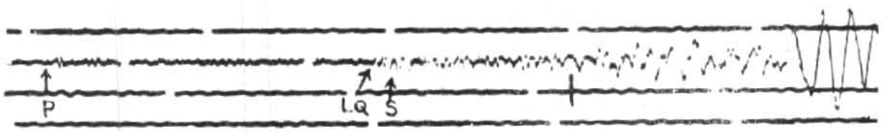

Fig. 4

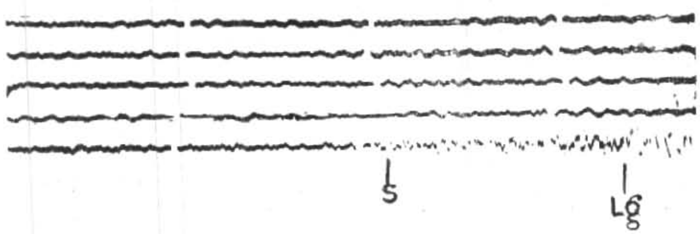

Fig. 5

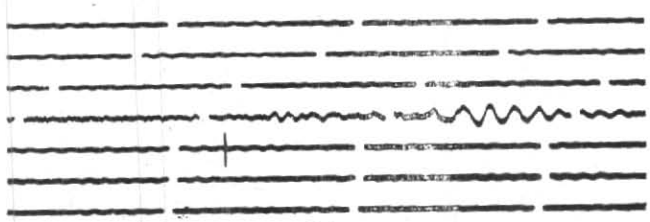

Fig. 6

Fig. 7

Figs. 3 and 4. Electromagnetic Seismograms of the shock of 5 march 1960 at Madras ($\triangle$ =780 km) and Shillong ($\triangle$ =1140 km) respectively

Figs. 5 and 6. Electromagnetic Seismograms of the after shock of Colaba and Shillong respectively from the same origin

Fig. 7. Quetta record of the Electromagnetic Seismograph T_0 =T_g =16·2 sec Magnification 15200 ($\triangle$ =1380 km)

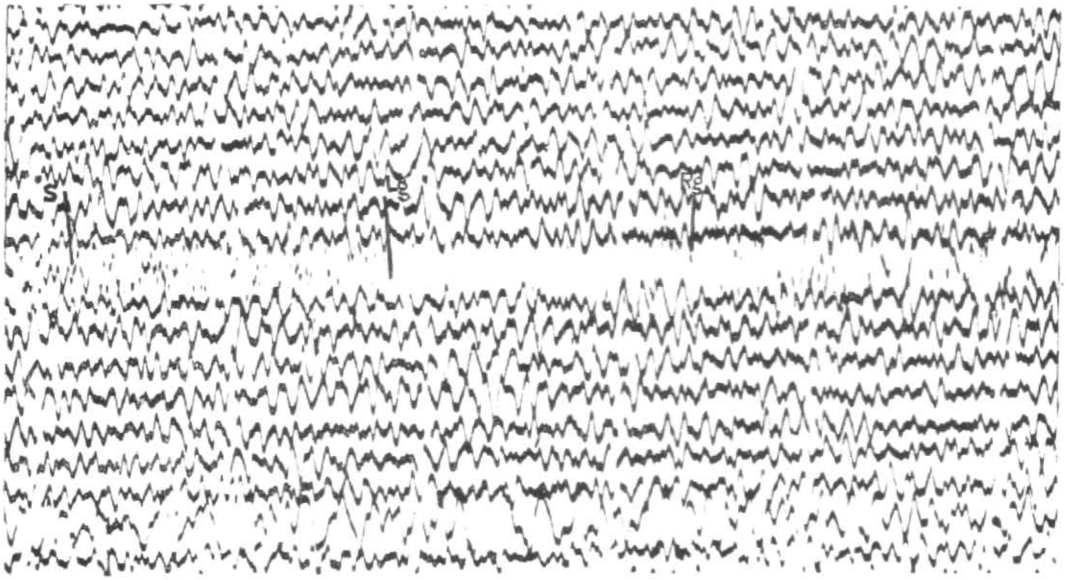

Fig. 8. Record of Colaba Electromagnetic Seismograph of 29 July 1960 ($\triangle$ =1990 km)

Fig 9. Location of the epicentre, observing stations and paths of the seismic waves

seismogram of the aftershock was lost on account of some defect in the recording mechanism.

The seismographic records of the shock which originated in Assam-Bhutan border on 29 July 1960 are reproduced in Fig. 8. The epicentre of the shock as given by U.S. C.G.S. was Lat. 26°·9 N and Long. 90°·3 E (India). The origin time of the shock was $H=10^h\ 42^m 44\cdot 6^s$, focal depth h=11 km (about). The magnitude of the shock determined at Shillong is about 6½ in the Richter-Gutenberg Scale. The shock was well recorded at different observatories and the shock was also felt at Shillong and other places near the epicentre.

The Shillong record of the above shock has not been produced as it is difficult to recognise *Lg* waves in the records of the near shocks. The distance of the epicentre from Shillong is 210 km only. The Quetta record of the above shock has not been obtained. The Madras record of the Assam-Bhutan border does not show any development of the *Lg* waves possibly on account of its oceanic path under the Bay of Bengal.

It is noticed from the above records that *Lg* phase was very well defined in the Colaba records while at Madras, if developed at all, is very poorly so. At Shillong and Quetta they are not developed at all. It is to be observed, however, that the *Rg* phase which on most occasion is a counter part of the *Lg* phase does not appear to be prominent on the record of the Nepal shock but the *Rg* phase appears to be quite prominent in the record of the Assam-Bhutan border shock.

Lg and *Rg* phases have been marked in the Colaba records and the region of the record where *Lg* phase should appear has been indicated by a small dark line in the other records.

The reported velocity of the *Lg* was found to vary in the different regions of the continents and the mean velocity is near about 3·5 km/sec. The mean velocity figure as obtained from the Colaba records comes out to be 3·49 km/sec. This observed value of the *Lg* waves probably goes to show that the velocity of shear waves in Indian region is not very much different from the velocity of shear waves in north American continent. It may be mentioned here that *Lg* phase was not, however, observed in the long period Milne-Shaw records of the Colaba Observatory.

4. Discussion and conclusion

Fig. 9 gives the location of the epicentre, observing stations and the paths of the seismic waves.

It is seen that the paths of waves in all the recording stations are practically continental except for Madras where a small portion of the path passes near the coast for the Nepal shock and a portion of the path is over Bay of Bengal in the second shock. It has been pointed out by most of the workers on the *Lg* phase that the most distinctive characteristic of *Lg* waves is that their propagations are limited to the continental paths only. The observations, however, also show that the high lands of big mountains form a barrier to the paths of the *Lg* waves. Otherwise there is no reason why moderately large earthquakes originating in China and U.S.S.R. and other countries to the north of the Himalayas could not give rise to *Lg* waves in the seismograms of the Indian Observatories. The reason why the *Lg* waves were not recorded in the Shillong and Quetta seismograms is probably the existence of high lands and mountain chains on the path between the earthquake epicentre and Shillong and Quetta. It may be mentioned here that no pronounced *Lg* waves have been observed in Colaba records from earthquakes originating in northeast India. It is, however, very difficult to explain the non-existence or the poor development of *Lg* waves on the Madras seismograms of the Nepal shock although there is a little bit of intervening sea path. But this portion of the sea path must have continental structure on account of the shallow nature of the sea very near the coast. The only explanation that can be offered is that the crustal structure between the epicentre and the Madras station is not the same as in the case of the path between the epicentre and Colaba, as Oliver and Ewing (1958b) have shown that near surface sedimentary layer greatly influences the propagation of short period surface waves. Similar to the propagation of microseisms probably the roots of the cross mountain ranges act as a barrier for the propagation of *Lg* waves from the epicentre to Madras station. The absence or ill development of *Lg* or *Rg* type of waves in the Madras record of the Assam-Bhutan border shock may be due to an oceanic structure or a structure intermediate between continental and oceanic. The other alternative explanation may be in the earthquake mechanism so far it relates to the mechanism of generation of *Lg* type of waves in natural earthquakes. No such mechanism has yet been suggested in the case of the *Lg* waves although unsymmetrical radiation pattern on surface waves showing a very strong dependence on the azimuth of the station was observed by Gutenberg (1955 b) on his study in the earthquakes in Kern County, 1952. His observations show that the azimuth in which the largest surface waves were recorded agrees with the strike of the fault. A qualitative explanation on the above observations of unsymmetrical radiation has been offered by Benioff (1955). The author is not aware of any such explanation in the case of *Lg* waves. Bath (1958) has, however, pointed out that quite different channel waves can be recorded from different earthquakes even if the paths are nearly the same.

In the case of the above two earthquakes the paths of the seismic waves from the epicentres to Colaba are not very much different but the *Lg* and *Rg* phases appear to be more prominent in the records of the second earthquake. In most of the record reproduced by different authors, it is observed that the *Lg* phase begins with short period moderate amplitudes and then the amplitude increases rapidly. But it could be seen from the Colaba record of the Assam-Bhutan border shock that the *Lg* phase with large amplitude has started abruptly. It is also remarkable that the *Rg* phase also appears to be well recorded, inspite of the strong microseismic background which is apparent from the very appearance of the seismogram. Bath (1954) has pointed out that no reliable readings of *Lg* are possible when microseisms are strong because the microseisms have periods comparable with those of *Lg*. The probable explanation for the well defined *Lg* and *Rg* phases observed in the Assam-Bhutan border shock may be due to the shallow depth of focus. This is corroborated by the U.S.C.G.S. epicentre data cards according to which the depth of focus is only 11 km. The author had, however, no information on the depth of focus of the earthquake and its aftershock which originated in Nepal.

Earthquakes frequently excite *Lg* phases inspite of their depth beneath the surface. However, the relative amplitudes in the case of the Assam-Bhutan border shock are so large that a source within the granitic layer which constitutes the transmission channel is strongly suggested. Theoretical calculations will show that as the depth of the source is increased, relative excitation of the short period waves diminishes much more rapidly than that of the longer waves. Moreover, the waves in the short period range suffer great attenuation possibly by absorption and scattering. The fact that the short period *Lg* waves, which constitute the surface wave spectrum in the short period range, are strongly excited by this earthquake implies a very shallow source. It is also remarkable that *Rg* phase which is a counterpart of the *Lg* phase is absent in the record of the Nepal shock but the same is observed in the record of Assam-Bhutan border shock. Oliver and Ewing (1958a) has rightly observed that the relative excitation of the various types of surface waves may ultimately provide detailed information on conditions at the focus.

Oliver and Ewing (1957) however, in their study on higher modes of Continental Rayleigh wave have observed that the information from *Lg* waves may provide additional and unique information about fault mechanisms and depths. Further if it could be shown that shallow surface disturbances excite them effectively, then higher mode might be of effectively greater importance when the source is artificial or meteorological. Oliver and Ewing (1958a) have, however, pointed out that *Lg* may be explained as normal mode propagation in higher modes through the surface and near surface layers. Gutenberg (1955a) has pointed out that in many respects the properties of regular microseisms with periods 4 to 10 seconds show a greater similarity to those of earthquake waves guided by lithosphere channel. This similarity includes specially their velocity about 3 km/sec, their periods and barriers to their propagation in bottom of deep oceans and under young mountain chains. All recent results are in favour of the hypothesis that the microseisms are due to waves guided by lithosphere channels.

Although there are many points of similarity between the microseisms and *Lg* waves as pointed out above, still it is a fact that storm microseisms originate at sea while *Lg* waves are completely eliminated when there is as little as 2° intervening ocean. The granitic layer under the sea near the coast has more or less the shape of wedge, the narrower end protruding towards the ocean. During the passage of *Lg* waves from the granitic layer under the continent towards the narrow wedge of the granitic layer under the sea, the angle of incidence of waves gradually decreases and this helps the escape of much of the energy into the outer layers, resulting in the quick attenuation of the *Lg* waves in the lithospheres channel. In the case of the passage of microseisms from the narrow wedge of the granitic layer under the sea towards the continent, the angle of incidence of the microseismic waves, instead of decreasing, gradually increases as they proceed towards the continent and this results in the minimum escape of energy into outer layers. This is probably the reason why once microseism energy enters the continent, it can spread over great distances with very little loss. 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 crustal layer in the transition zone will find that the sloping boundary constitutes a Lummer-Gehreke plate strongly favouring propagation towards the continent rather than towards the ocean. The strong attenuation of channel waves during its passage under the mountain chains could be explained similarly if we assume that the granitic layer under mountain chains is in the form of a double wedge, the thickest portion being under the bottom of the mountain chain while the narrower end points towards the plain continent on either side. The observations on crustal structure indicate that the thickness of granitic layer under mountains is more as compared to the thickness of granite under the plain continents.

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