550.34: 550.346(547.1)

A surface reflected phase from Koyna aftershocks

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ABSTRACT. It is suggested that the second signal in the *P*-phase of the aftershocks from Koyna recorded at Gauribidanur ($\triangle=5\cdot1°$) is surface reflected signal. The focal depths of twentytwo aftershocks were determined using the observed lags between the two signals and the known values of a_n and a_g for the crust near Gauribidanur. It is found that the depth of these events varies from 4 to 14 km.

1. Introduction

The major earthquake which occurred at Koyna (75°·75 E, 17°·40N) on 10 December 1967 was followed by a number of aftershocks which were recorded at various seismic observatories (Tandon and Chaudhury 1968), Ambraseys and Sarma (1968). In several aftershocks observed at Gauribidanur (GBA 77°·40E, 13°·61N) seismic array one finds a signal which follows the first arrival after a lag of a few seconds. One sees this features in every record where the noise background is low and the coda of the first arrival decrease sufficiently in amplitude. In Figs. 1, 2 and 4 are shown typical seismograms of Koyna aftershocks recorded at some of the pits of Gauribidanur array. One sees in these records that the first signal is followed by another after a lag of 2·5 to 3·5 sec. The exact amount of the lag cannot be determined in the records of Figs. 1 and 2 as the onset of the second signal is not quite clear, but it can be determined accurately in the records of Fig. 4, which was taken at Gauribidanur on 30 December 1967 at 12:44: 59·2. This event is of low intensity (magnitude approximately 4·7) and the noise background was also low that day. The onsets of the first and second signal are clearly seen on the records at some of the pits along the Blue and Red arms of the GBA array. As shown in Fig 4 the phase of the first motion of the first arriving signal at B_1, B_3,, R_4 and R_6 is definitely opposite to that of the first motion of the second signal which arrives at all these pits after a lag of 3·3 sec. In the pit R_1 also the situation is very much like that obtaining at B_1, B_3, R_4 and R_6 though amplitude in the first motion of the second signal is not as large as it is in the other records at B_1, B_3, R_4 and R_6.

2. Surface reflected signal

To interpret physically the second signal in the *P*-phase, we to have consider the following six possibilities of its (the second signal's) origin : (*a*) multiple shocks, (*b*) signal generated noise, (*c*) critical refraction at different layers, (*d*) refraction at a lower level followed by reflections at free surface and at an intermediate layer, (*e*) surface reflection followed by refraction, and (*f*) *SP*-phase due to *S*-wave incident at the Moho discontinuity at the critical angle giving rise to the refracted *P*-wave which travels parallel to the Moho with the *P*-wave speed of the medium below the Moho.

In the case of alternative (*a*), the lag between the two signals for each events in the *P*-phase will be equal to that in the *S*-phase, and will be the same in the seismograms recorded at each sensor of the array. In the case of alternative (*b*) the apparent speed of the second signal will be different from that of the first (Key 1967). In the case of alternative (*c*) also, the apparent speeds of the two signals will be different. In the case of alternative (*d*), the apparent speeds of the two signals will be equal and the lag between the two signals will, irrespective of focal depth, be the *same for all events*. In the case of alternative (*e*) the apparent speeds of the two signals will be equeal in the *P*-phase, and will also be equal in the *S*-phase, but the lag between the two signals in the *S*-phase will be larger than that in the *P*-phase. It is possible to have at the free surface a reflected *P*-wave due to an incident *S*-wave giving rise to *sP*-phase. One can show that the travel time of *sP*-phase is longer than that of *pP*-phase. Therefore, the phase which arrives first after reflection at the free surface is the *pP*-phase but not the *sP*-phase. In the case of alternative (*f*), the *SP*-phase can arrive earlier than the *pP*-phase provided the focus is close enough to the Moho discontinuity. Since the aftershock sequence from Koyna is coming from

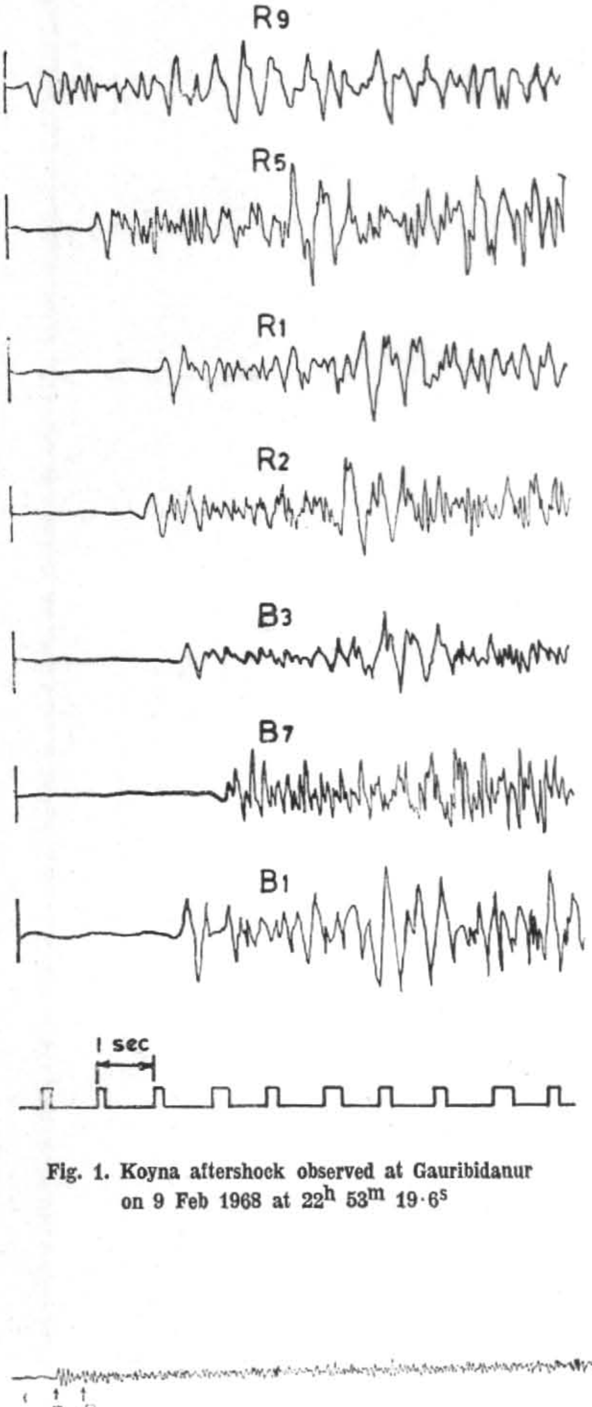

Fig. 1. Koyna aftershock observed at Gauribidanur on 9 Feb 1968 at 22^h 53^m $19{\cdot}6^s$

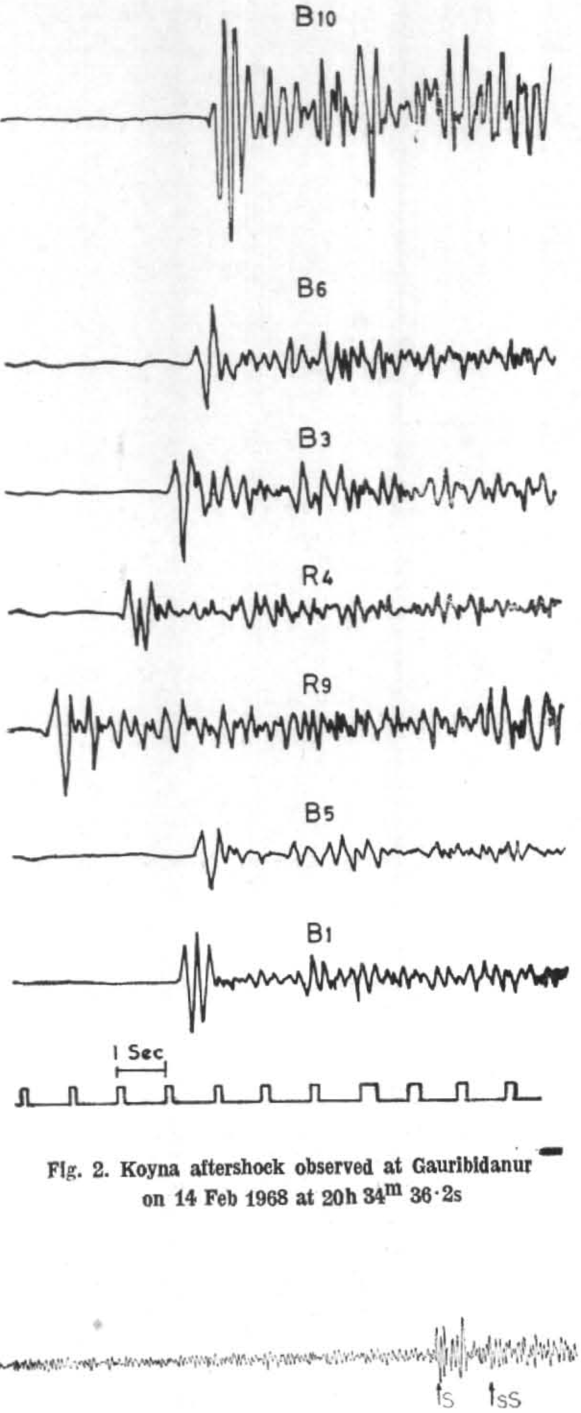

Fig. 2. Koyna aftershock observed at Gauribidanur on 14 Feb 1968 at 20h 34^m 36·2s

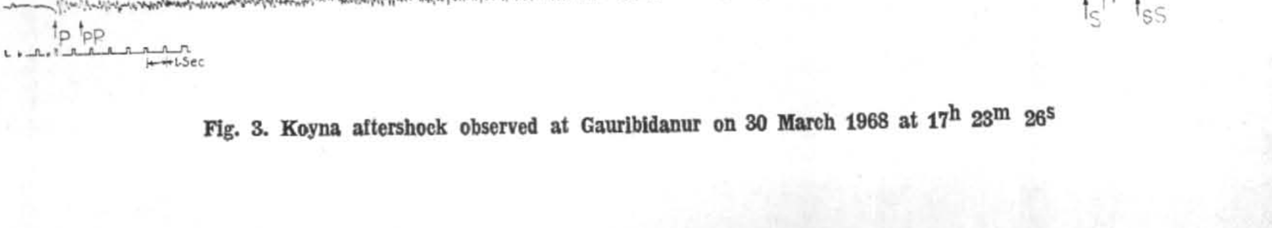

Fig. 3. Koyna aftershock observed at Gauribidanur on 30 March 1968 at 17^h 23^m 26^s

TABLE 1

22 Koyna aftershocks observed at Gauribidanur (GBA) seismic array station showing a surface reflected pulse

Date	Onset time at GBA	Average lag between 1st and 2nd signal in *P*-phase (sec.)	No of sensor which the 1st and 2nd *P*-signals observed unambiguously	Calculated depth, *h* (km)
11 Dec 67	11 : 20 : 50·2	1·0±0·2	3	4·0
,,	14 : 01 : 20·0	1·7±0·2	7	6·8
,,	17 : 31 : 00·0	1·8±0·2	4	7·2
,,	19 : 16 : 53·6	2·0±0·2	6	8·0
,,	20 : 36 : 28·3	2·3±0·2	6	9·2
12 Dec 67	14 : 58 : 12·0	2·3±0·2	3	9·2
,,	20 : 17 : 40·0	3·3±0·2	3	13·2
14 Dec 67	15 : 07 : 38·6	2·5±0·2	7	10·0
30 Dec 67	12 : 44 : 59·2	3·3±0·2	5	13·2
4 Jan 68*	07 : 25 : 15·7	2·3±0·2	3	9·2
27 Jan 68	16 : 53 : 24·9	1·5±0·2	5	6·0
27 Jan 68	23 : 45 : 05	2·7±0·2	3	10·8
8 Feb 68*	19 : 38 : 54·2	1·5±0·2	6	6·0
11 Feb 68	07 : 48 : 40	1·6±0·2	4	6·4
14 Feb 68	20 : 34 : 26·2	2·5±0·2	6	10·0
20 Feb 68	17 : 50 : 24·4	2·5±0·2	4	10·0
28 Mar 68	09 : 59 : 25·5	3·5±0·2	5	14·0
30 Mar 68*	17 : 23 : 26·9	1·5±0·2	4	6·0
1 May 68	07 : 47 : 34·8	1·0±0·2	6	4·0
2 Sep 68*	02 : 56 : 43·6	2·0±0·3	4	8·0
5 Dec 68	22 : 53 : 45·3	2·2±0·2	5	8·8
22 Dec 68	22 : 18 : 27·0	3·0±0·4	5	12·0

*This event shows a phase which can be identified as *sS* and which comes, after the *S*-phase, with a lag consistent with the alternative (*e*) mentioned in the text.

a region which experienced earth tremors after Koyna reservoir was impounded (Guha *et al.* 1968), it is reasonable to expect that the foci of the tremors and the aftershocks were shallow. Accordingly, we estimate the depth of the aftershocks assuming the second signal is *pP*-phase but not *SP*-phase. The calculated depth (4 to 14 km *see* Table 1) of the aftershocks show that the focus is nearer to the free surface than to the Moho whose depth is estimated to be 35 km by Arora (1969).

An examination of the twentytwo seismograms of the events listed in Table 1 revealed the following features :

(1) For every event, the lag between the two signals in *P*-phase is the same within experimental errors, at all pits of the seismic array, showing that the apparent speeds of these signals are the same. These lags are listed in column 3 of Table 1.

(2) There is no marked difference in the frequency of these two signals in the *P*-phase.

(3) In seismograms of only four events, it had been possible to observe the existence of a second signal in *S*-phase which can be identified as the one likely to be a surface reflected phase. Though the exact onset cannot be estimated, it is found that the lag between the two signals in the *S*-phase is larger than that between the two signals in *P*-phase as indicated in Fig. 3. In the rest of the seismograms, the *S*-phase is either not available in the records, or it is so complicated that it is impossible to identify the two signals. (For those events for which the *S*-phase record is not available in 8 channel output, the epicentres were determined with the aid of the helicorder records).

(4) There is one event not listed in Table 1 which presumably is a double shock. The initial

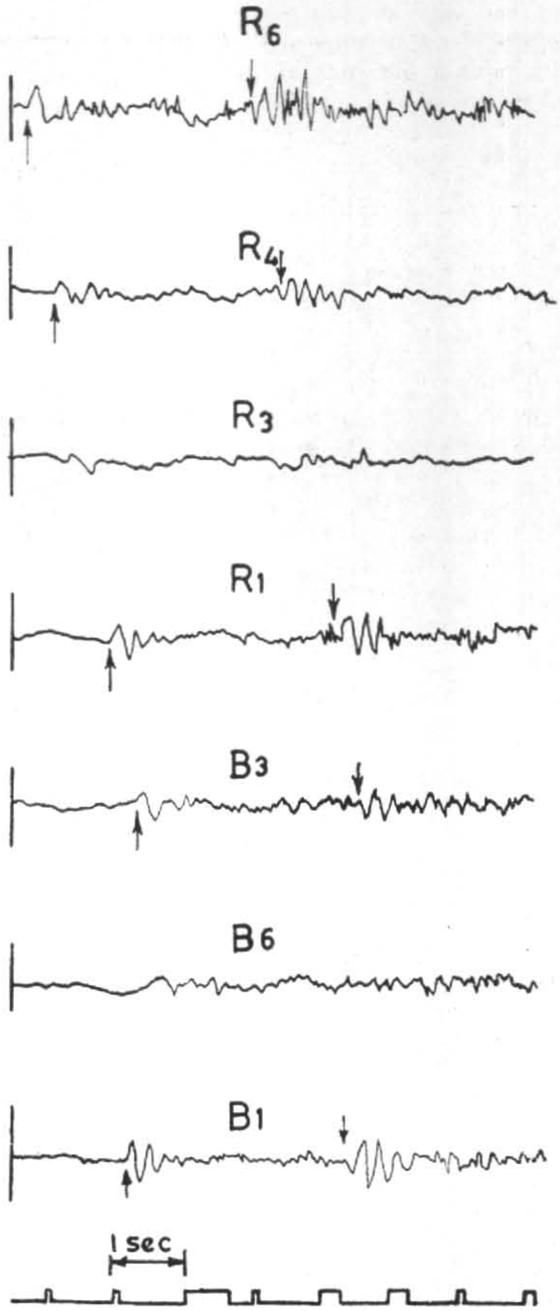

Fig. 4. Koyna aftershock observed at Gauribidanur on 30 Nov 1967 at 12h 44m 59.2s

part of the seismogram of this event, which was recorded on 25 January 1968 is reproduced in Fig. 5. We see in this figure that the frequency in the first cycle is nearly half of the frequency in the subsequent record. We see also in this record a 'third' singal which can be identified as a surface reflected pulse.

(5) The spectral analysis of the two signals in the seismogram at B_1 for the event on 30 November 1967 which showed a reversal of phase, is done and the results are shown in Fig. 6 in which the two signals give a peak at the same frequency of 4 cps.

On the basis of the above observations, we can conclude that the two signals in the *P*-phase have the same apparent velocity and that they have a frequency which is more or less equal. Since some of records show also a second *S*-signal which favour the alternative (*e*), and since at least one record shows a reversal of the phase, it is inferred that the events listed in Table 1 indicate the presence of a surface reflected phase, and the lag is due to the extra-path which this signal travelled from the source to seismic sensor.

If the above interpretation is accepted, we can estimate the depth of the source of the events listed in Table 1 on the following lines. Let α_g be the speed of the *P*-wave in the layer where the seismic disturbance originates, and let α_n be the speed of the *P*-wave in layer where the critically refracted wave travels. For the events from Koyna region, the first arrival at Gauribidanur ($\triangle$=5·1°) is the *Pn*-phase, which is the wave that has travelled below and parallel to the Moho discontinuity. If h is the focal depth, and if we assume that the Moho is parallel to the free surface, the difference in the travel time, δt, of the first arrival and the surface reflected signal is given by

$$\delta t = \frac{2h\,(\alpha_n^2 - \alpha_g^2)^{\frac{1}{2}}}{\alpha_n\,\alpha_g}$$

For the Koyna region, the values of $\alpha_n = 8 \cdot 0$ km/sec and $\alpha_g = 5 \cdot 7$ km/sec are representative (Arora 1969; Tandon and Chaudhury 1968). These values are used in conjunction with the observed values of δt to calculate h and the results are listed in the column 5 of Table 1. The relative error in the estimate of h is essentially the same as that of the estimate of δt, which is not more than 10 per cent in most of the cases. The depth of the events listed in Table 1 vary from 4 to 14 km, and nearly half of these twentytwo events have a depth varying from 8 to 11 km. It is interesting to note that the focal depth increases from 4 to 13 km for successive events listed in that table.

The depth of the main shock had been determined as 29 km by USCGS (Dutta 1969), 15 km by Thirlaway (private communication), 12·1 km by Guha *et al.* (1968) and 8 km by Tandon and Chaudhury (1968). The estimates by Guha *et al.* and Tandon and Chaudhury are based on observations of seismograms at stations within 130 km distance from the source while the estimate of Thirlaway was based on an examination of teleseismic record.

3. Discussion

A few comments on the variation of the depth of the aftershocks are in order. On 11 December 1967, the main shock was followed by a large number of aftershocks. It is reported that at Poona which is at a distance of 129 km from Koyna, nearly 200 aftershocks were recorded (Tandon and Chaudhury 1968) while at Gauribidanur which

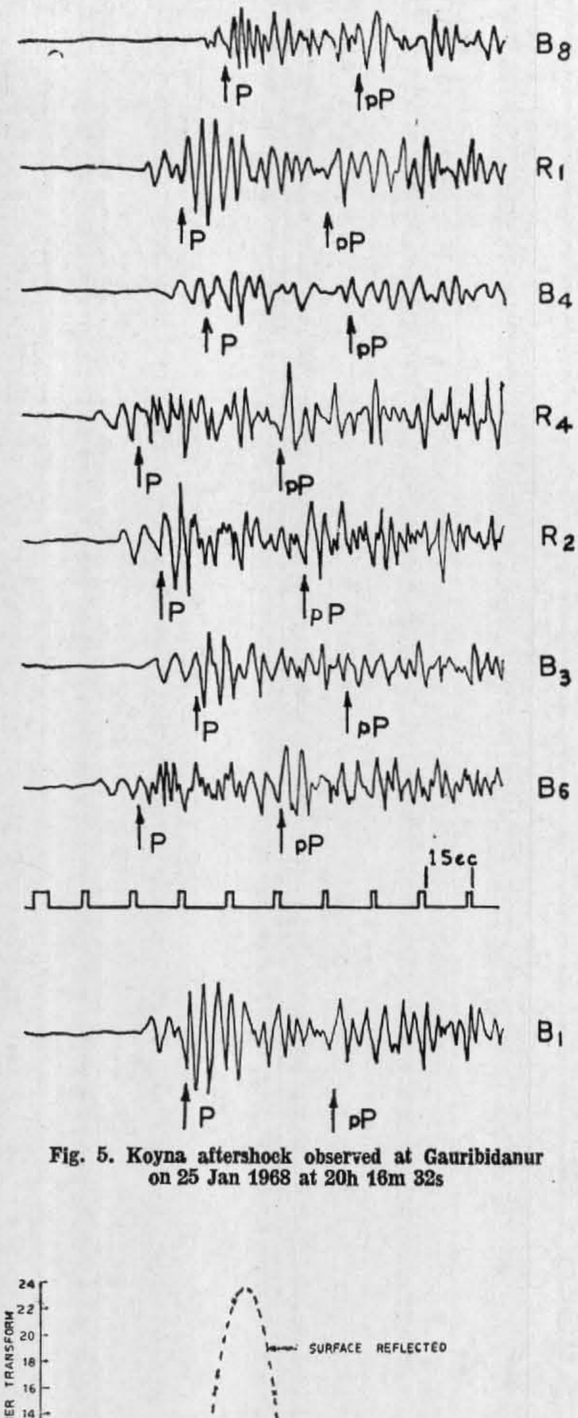

Fig. 5. Koyna aftershock observed at Gauribidanur on 25 Jan 1968 at 20h 16m 32s

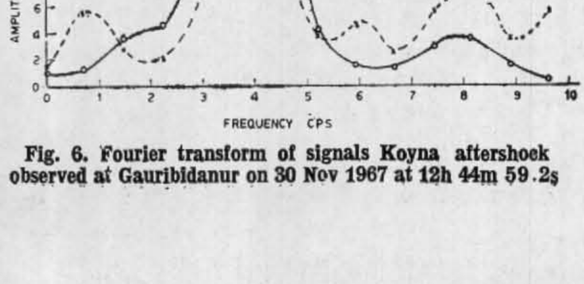

Fig. 6. Fourier transform of signals Koyna aftershock observed at Gauribidanur on 30 Nov 1967 at 12h 44m 59.2s

is at a distance of 570 km from Koyna, only 10 aftershocks were recorded. Of these ten aftershocks, only five shocks revealed a phase which can be interpreted as a surface reflected phase. It is likely that the other shocks recorded at GBA have also a second signal which is mixed up with the coda of the first signal, or the foci of these are so shallow that it is impossible to expect a surface reflected signal. However, we can conclude from Table 1 that the variation of the depth of the aftershocks on 11 December 1967 indicates that the region where the foci of these aftershocks are located spreads over a depth varying from 4 km (or less) to about 14 km, and the region where a major fraction of the foci lie is between 8 to 11 km depth. This knowledge of the focal depth of the aftershocks will be very useful for any theory which attempts to explain the seismicity of the area near Koyna and its relation to surface features like the lake, the dam and the hot springs.

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