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Use of Kazakh nuclear explosions for testing dilatancy diffusion model of earthquake prediction

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ABSTRACT. *P* wave travel time anomalies from Kazakh explosions during the years 1965-1972 were studied with reference to Jeffreys Bullen (1952) and Herrin Travel time tables (1968) and discussed using *F* ratio test at seven stations in Himachal Pradesh. For these events, the temporal and spatial variations of travel time residuals were examined from the point of view of long term changes in velocity known to precede earthquakes and local geology.

The results show preference for Herrin Travel time tables at these epicentral distances from Kazakh explosions. *F* ratio test indicated that variation between sample means of different stations in the network showed more variation than can be attributed to the sampling error. Although the spatial variation of mean residuals (1965-1972) could generally be explained on the basis of the local geology, the temporal variations of such residuals from Kazakh explosions offer limited application in the testing of dilatancy model of earthquake prediction.

1. Introduction

P wave arrivals from nuclear explosions are quite sharp owing to relatively strong high frequency content. They are, therefore, extensively used for estimation of station corrections, detection of low velocity layers and examination of the nature of plate boundaries. The data in the form of time averaged residuals are useful for mapping the pronounced spatial changes in crustal velocity and/or thickness in a region. Long term changes in residuals or velocities may be related to the occurrence of large future earthquakes on the basis of dilatancy diffusion model of earthquakes. The frequency distributions of *P*-wave residuals are also needed for assigning appropriate weights while computing the epicentral parameters and thereby increasing the accuracy of the locations of earthquakes and nuclear explosions in the regions.

Robinson and Iyer (1976) used eight large Novaya Zemlya explosions and found that the average residuals variations at individual stations could be attributed to complex crustal geology and changes in crustal thickness. Utsu (1973) examined data from Nevada nuclear explosions as recorded at several stations in Japan but because of large scatter in residuals, no positive relationship to earthquake ocurrence could be seen. Kind (1972) using Nevada explosions reported a correlation between P_n residuals and local geology besides effect of changes in crustal thickness in San Andreas seismic network.

During the years 1965-1972, seven seismological observatories were established in a phased manner in Himachal Pradesh for studying seismicity related to the Pong and Pandoh dams. In the epicentral distance of 17° to 18°, large number of Kazakh nuclear explosions provided ample data to study the temporal and spatial distributions of mean residuals at the closely spaced seismic network. The object of this paper is to examine these aspects after discussing the suitability of Jeffreys Bullen (1952) and Herrin Travel Time Tables (1968) for this path.

2. Data and analysis

Although precise epicentral coordinates of the Kazakh underground nuclear explosions are not known, they are considerably more accurate than for earthquakes for travel time studies since the constraints of focal depth determinations are eliminated in the case of nuclear explosions. While locating earthquakes as source events, greater scatter is caused by inhomogeneity in velocity or structure along different wave paths and thus utility of nuclear explosions for such studies as undertaken in this paper is significant since the wave path followed from source to receiver is almost identical for Kazakh explosions.

The network of seismic stations used in the study is shown in Fig. 1. All these observatories use Hagiwara electromagnetic seismographs where the recording is done on 35 mm film. After magnification on the film reader, these records give a time

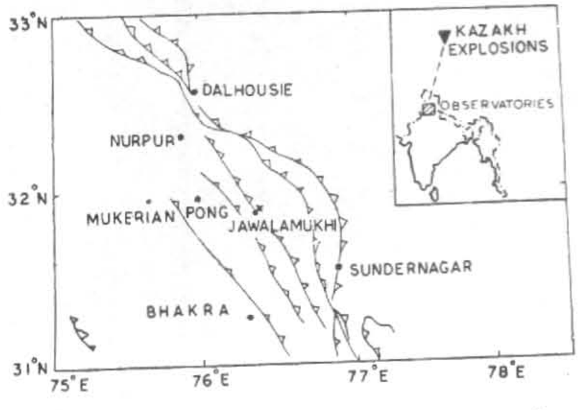

Fig. 1. Location indicator of seismological stations. Thrust faults are shown by slant teeth. Cross indicates earthquake of 5 November 1968 close to Jawalamukhi. Inset shows the orientation of Kazakh explosions with respect to the observatories.

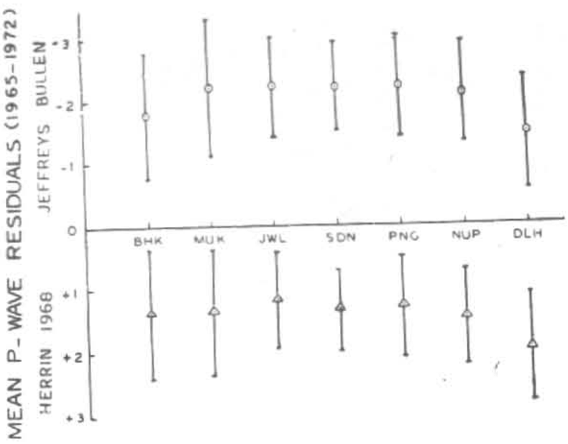

Fig. 2. Mean *P*-wave anomalies (1965-1972) with respect to Jeffreys Bullen and Herrin Tables. Bars denote the standard deviations.

spread of 160 mm/minute and enable us to read the times accurate to 0.1 second. The equipment has, however, one limitation, namely the recording is interrupted during power failure as no provision even has been made to supply the power to light source though crystal clocks and recorders continue to operate through a AC/DC switching relay. In addition, changing the film at about 04-05 GMT has coincided with the explosion records on some occasions. A close scrutiny of data has shown that in general, Kazakh explosions of magnitude greater than 5.4 were nicely recorded at Nurpur, Pong, Jawalamukhi, Dalhousie and Sundernagar where peak magnification was around 1,00,000. In case of Bhakra and Mukerian observatories, however, the explosions were generally recorded for magnitudes around 6 since the peak magnification was about 5000 at these observatories. The present study includes all the Kazakh explosions during the years 1965-1972.

The epicentral distances from the observatories were computed through IBM 360/44 using well known relationship :

$$\cos \Delta = 1 - \tfrac{1}{2} \left[(a-A)^2 + (b-B)^2 + (c-C)^2 \right] \quad (1)$$

where a, b and c and A, B and C have their usual meanings for explosions and epicentres respectively.

P-wave residuals at the observatories were computed with reference to the Jeffreys-Bullen tables (1952) as well as Herrin tables (1968). *P*-wave residuals of more than 4 sec have been neglected for computation of mean values as they may possibly be attributed to errors of observations. All Herrin residuals were positive. Jeffreys Bullen table gave negative residuals at these epicentral distances but in one or two cases positive residuals were also obtained which were ignored in computing mean residuals as they may also be attributed to the errors of observations. Annual mean residuals, were computed if three observations for explosions were available in a particular year. Hence even though a few observations were available from 1965, data was not sufficient to work out annual mean residual. The results are shown in Fig. 2 for Jeffreys Bullen and Herrin tables.

Height corrections were applied for Dalhousie observations, taking 0.1 sec for each kilometre of height. Since the exact depth of Kazakh explosions was not known, no correction due to this effect could be applied.

3. Results and discussion

The histograms of *P*-wave anomalies with respect to Jeffreys Bullen tables at Dalhousie, Nurpur, Mukerian, Pong, Jawalamukhi, Sundernagar and Bhakra are shown in Fig. 3, while mean *P*-wave residuals from Kazakh explosions using Herrin as well as Jeffreys Bullen tables for the years 1965-1972 are shown in Fig. 2. It may be seen that except for Dalhousie, mean *P* residuals are smaller at all the stations with respect to Herrin tables than Jeffreys Bullen table. Standard deviations for the stations using Jeffreys Bullen tables are given in Table 1. It shows that largest values are found at Mukerian or Bhakra and least values at Sundernagar. This may be due to the presence of alluvium and sedimentary rocks at Mukerian and Bhakra respectively, which rarely give impulsive *P* wave recordings.

It may now be worthwhile to examine whether the differences among station means can be attributed to chance. Since the sample data satisfies the assumptions that the samples are based on independent observations, we can analyse the results using well known theory of analysis of variance. A simple model by assuming only two sources of variation, namely, explosions and stations is given by (Cooper 1969) :

$$x_{ij} = A + E_j + Z_{ij}$$

TABLE 1

Mean P wave residuals (1965-1972)

Station	Location Lat. (°N)	Long. (°E)	Geology	Jeffreys Bullen (sec)	σ (J.B.)	Number of observation
Nurpur (NUP)	32 18	75 52	Sandstones	—2·10	±0·84	25
Pong (PNG)	31 55	75 55	Sandstones, Claystones	—2·21	±0·82	31
Jawalamukhi (JWL)	31 52	76 20	Sandstones	—2·23	±0·84	29
Sundernagar* (SDN)	31 33	76 54	Sandstones Shales	— 2·21	±0·73	20
Mukerian (MUK)	31 57	75 37	Alluvium	—2·21	±1·16	10
Bhakra (BHK)	31 25	76 25	Sedimentary rocks	—1·72	±1·02	18
Dalhousie (DLS)	32 50	75 58	Glacial gravel, granite	—1·48	±0·89	31

TABLE 2

F ratio test

	Sum of squares	Degrees of freedom	Estimate of variance	F ratio
Between stations	236·23	6	39·37	33·08
Within stations	217·93	183	1·19	

where A is a general level common to all observations, x_{ij} is the observation of i the explosion at the j the station, E_j is fixed or constant departure from A due to the jth station and common to all member of the jth station. Z_{ij} is a random error having a normal distribution with zero mean and variance σ (σ is often called the residual variance). The null hypothesis that the population means are equal is equivalent to the hypothesis that the E's are all zero and hence the population means are all equal to A. The presence of non-zero E's may be tested by using F ratio test. The results are generally expressed in the form of an analysis of variance table for quick computations as given in Appendix (Cooper 1969). Somewhat similar method of analysis was used by Freedman (1966) while discussing the variability of P_n residual from explosions (c.f. Table 4). However, lack of observations and higher standard deviations do not allow us to examine more complicated analysis of variance models involving the interaction terms between explosions and stations as done by Freedman (1966).

The results obtained with the above method are given in Table 2. F ratio has been found as 33.08 which has been evaluated with 6 and 183 degrees of freedom. It is seen from the tables of statistics that F ratio of 2.90 is needed for significance at the 1 per cent level which is considerably less than 33.08 given in Table 2. The implication according to hypothesis is that the sample means show more variation than can be attributed to sampling error. It may thus be worthwhile to examine the differences in the station means with reference to the local geology.

4. P wave residuals and geological setting

Mean P wave residuals (1965-1972) with respect to Jeffreys Bullen tables at Jawalamukhi, Nurpur, Pong, Sundernagar and Mukerian are of the same order. Except Mukerian, all the other stations are located on sandstones of middle Miocene age and belong to lower/middle Siwalik formations (Krishnaswamy *et al.* 1964). At Sundernagar, conglomerates and shales belonging to the Siwalik system are also present while at Pong, clay shales/

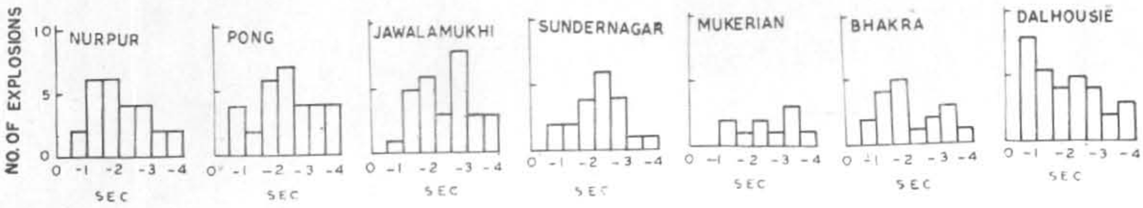

Fig. 3. Histograms of *P* wave residuals at seven Himachal Pradesh stations

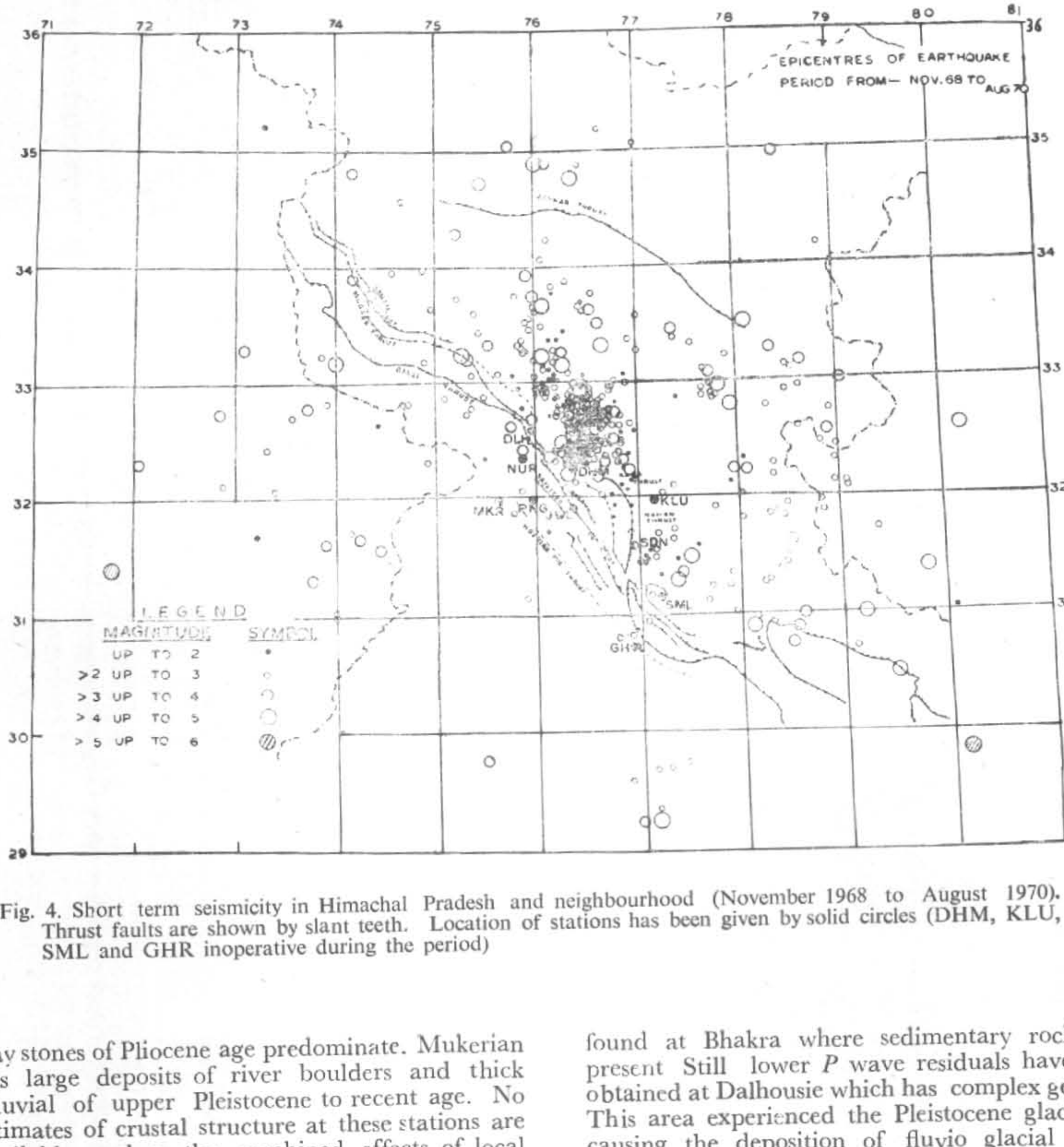

Fig. 4. Short term seismicity in Himachal Pradesh and neighbourhood (November 1968 to August 1970). Thrust faults are shown by slant teeth. Location of stations has been given by solid circles (DHM, KLU, SML and GHR inoperative during the period)

clay stones of Pliocene age predominate. Mukerian has large deposits of river boulders and thick alluvial of upper Pleistocene to recent age. No estimates of crustal structure at these stations are available and so the combined effects of local geology at Jawalamukhi, Nurpur, Pong and Sundernagar *vis-a-vis* crustal thickness at these stations cannot be examined. This is also the reason why minor differences in local geology could not be revealed.

Compared to the above stations, which have more or less similar residuals, lower values are found at Bhakra where sedimentary rocks are present Still lower *P* wave residuals have been obtained at Dalhousie which has complex geology. This area experienced the Pleistocene glaciation, causing the deposition of fluvio glacial gravel and erratic blocks of granite. The volcanic suite of rocks that intervenes between the pre-tertiaries and the tertiaries belong to carboniferrous age (Krishanaswamy *et al.* 1964).

It may thus be inferred that spatial variation of mean *P* wave residuals could generally be attributed to local geology. However, finer variations in

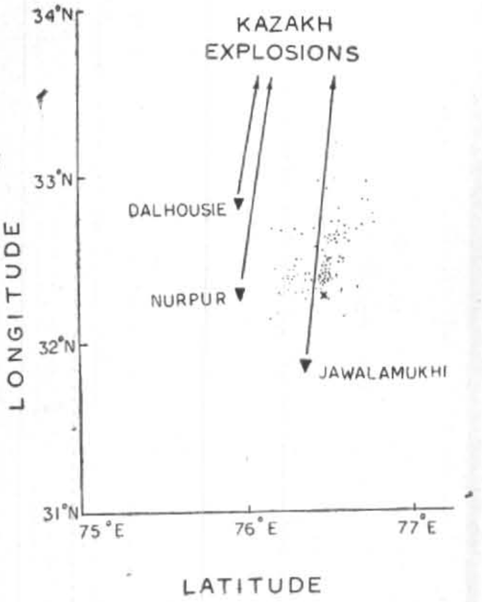

Fig. 5(a). Foreshocks and aftershocks of 5 November 1968 earthquake.

[Cross denotes the location of main shock. Error in epicentre (ISC) is indicated by circle. Long arrows show the orientation of Kazakh explosions with reference to the earthquake and stations]

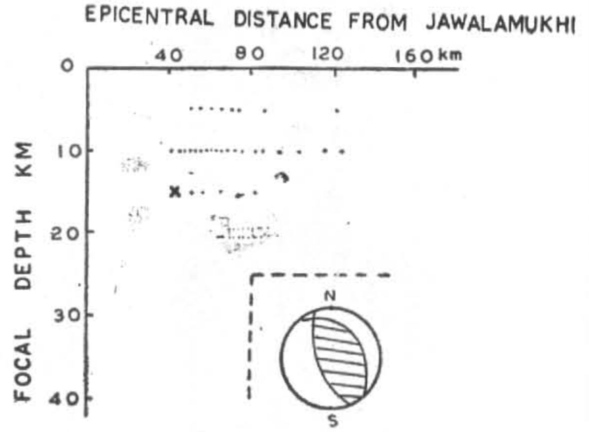

Fig. 5(b). Cross-section (focal depth *versus* epicentral distance from Jawalamukhi) along aa.

[Main shock is indicated by a cross. Inset shows the focal mechanism of main earthquake. Compressions are indicated by hatched lines surrounded by two nodal planes. Dilatations by blank outside the two planes. N indicates true north]

the mean P wave anomalies remained unexplained due to large standard deviations and lack of information about the crustal structure below these stations.

5. Temporal variation of P-wave residuals

Recent studies have shown that changes in seismic wave velocities can be monitored by studying the travel time anomalies of P-waves which occur in association with the dilatancy phenomenon (Wyss and Holcomb 1973, Sutton 1974). Nur *et al.* (1970) have shown that thrust faults are capable of large dilatancy. Geologically, several thrust faults called Panjal, Jawalamukhi and Satlita thrusts are present in Himachal Pradesh. Focal mechanism studies of earthquakes in the region (Chaudhury *et al.* 1974) have also shown that the nature of faulting in Himachal Pradesh is of thrust type and therefore, precursory changes of seismic wave velocities should be expected in the region. The region is seismically active where Kangra earthquake of 1905 occurred, killing more than 20,000 people. Fig. 4 shows short term seismicity (1968-1970) in Himachal Pradesh detected by our seismic network.

Examination of catalogue of earthquakes in Himachal Pradesh shows that no earthquake exceeding magnitude 4.9 has occurred in the region during the year 1966 to 1970. The largest earthquake of magnitude 4.9 occurred on 5 November 1968 with its epicentre near Dharamsala where it caused minor damage and was felt at Jawalamukhi and Nurpur. The focal depth of this earthquake as reported by International Seismological Centre (ISC) was normal, that is within 33 km. Seismograms of nearby stations, namely, Jawalamukhi, Nurpur, Pong and Sundernagar showed P_g, S_g, P^*, S^*, P_n, S_n, phases very clearly and hence better estimates of focal depth were attempted. The epicentral parameters were redetermined using these data from nearly observations/stations, through a computer programme developed by Shaikh *et al.* (1977). Comparative epicentral parameters determined by I.S.C. and India Meteorological Department (IMD) are given below:—

	ISC	IMD
Epicentre	32·28°N, 76·48°E	32·26°N, 76·47°E
Origin time (GMT)	02*h* 02*m* 44·7*s*	02*h* 02*m* 46·4*s*
Depth of focus	Normal	15 km

Error in the epicentre was $\pm$ 8 km as given by I.S.C. and $\pm$5 km determined by us. The epicentral distance of this earthquake was about 42 km from Jawalamukhi (Fig. 5a). The extent of the foreshock and aftershock activity is also shown in

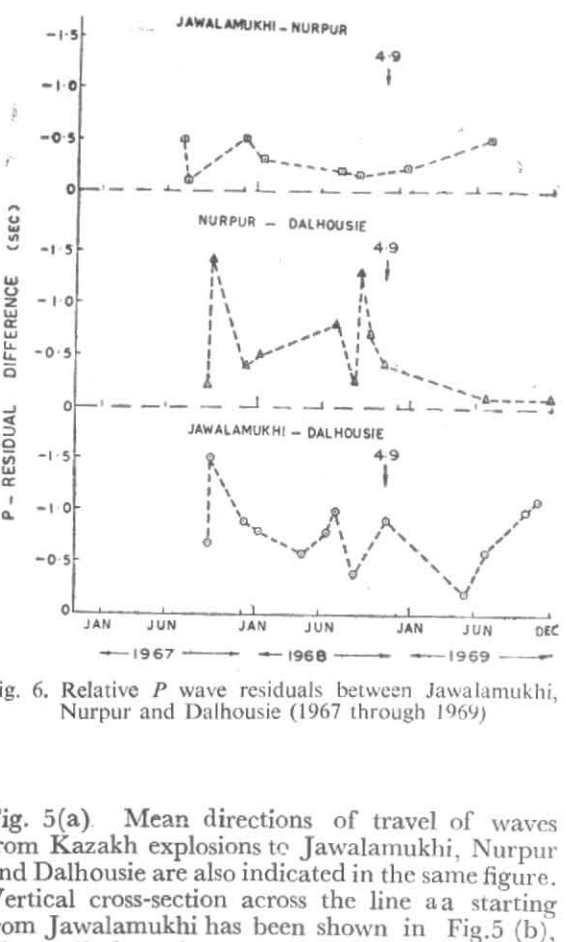

Fig. 6. Relative *P* wave residuals between Jawalamukhi, Nurpur and Dalhousie (1967 through 1969)

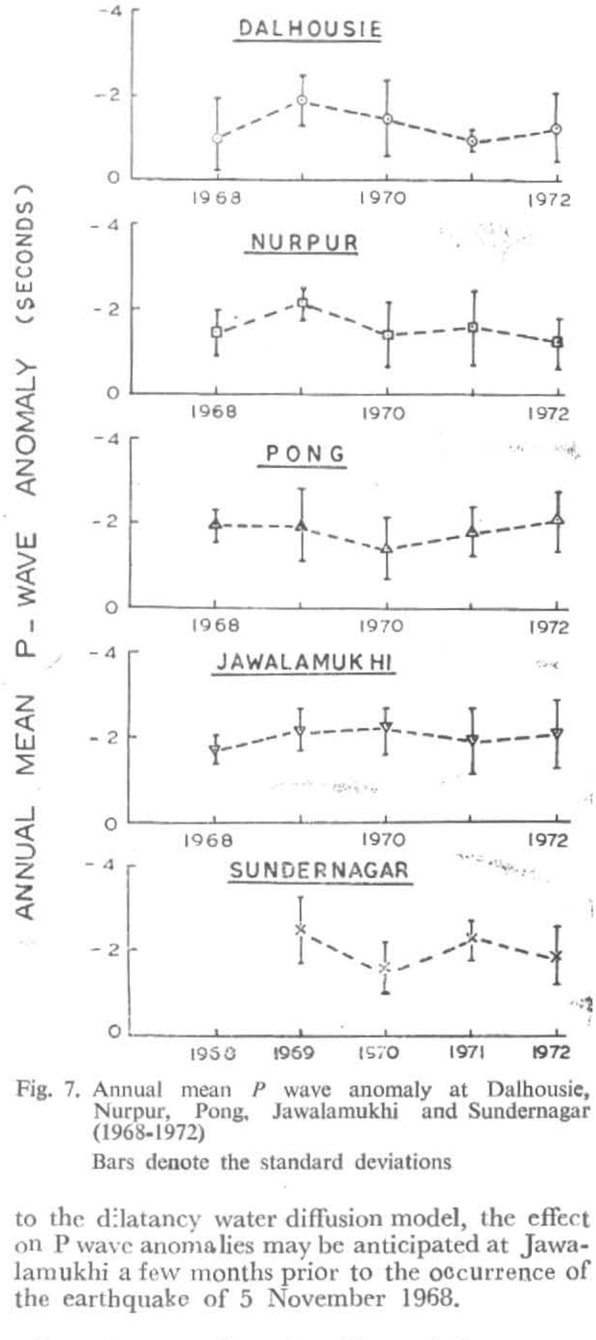

Fig. 7. Annual mean *P* wave anomaly at Dalhousie, Nurpur, Pong, Jawalamukhi and Sundernagar (1968-1972)

Bars denote the standard deviations

Fig. 5(a). Mean directions of travel of waves from Kazakh explosions to Jawalamukhi, Nurpur and Dalhousie are also indicated in the same figure. Vertical cross-section across the line aa starting from Jawalamukhi has been shown in Fig.5 (b), where all the epicentres within 8 kilometres on either side of line aa were porjected depthwise. Focal mechanism of this earthquake showing thrust faulting as reported by Chaudhury *et al.* (1974) has been given as an inset in Fig. 5 (b). Since the extent of foreshocks/aftershocks zone is generally taken to be equal to the dilatant zone, and may be seen to be fairly extensive along the direction of the travel of waves from Kazakh source, there is a reasonable chance of these waves passing through the dilatant zone before being recorded. Jawalamukhi, Dalhousie and Nurpur are located away from the dilatant zone with respect to the waves from Kazakh explosions. Thus according to the dilatancy water diffusion model, the effect on P wave anomalies may be anticipated at Jawalamukhi a few months prior to the occurrence of the earthquake of 5 November 1968.

In order to reduce the effects of the source, residuals between the stations located close to dilatant zone and that away from it were worked out. The difference of the residuals between Jawalamukhi and Nurpur are shown in Fig. 6. The relative residuals with respect to Dalhousie as well as those between Nurpur and Dalhousie are also shown in the same figure for the sake of comparison starting from 1967 through 1969. It may be noticed from the figure that scarcity of observations on many occasions does not allow firm inference to be drawn. It was noted that residual difference between two consecutive explosions in the same month (though on only very few occasions) varied by more than 0·8 sec which may be attributed to the errors of observations. Further since all three stations, namely, Nurpur and Dalhousie are located in highly seismic region (Fig. 4), second order changes in residuals in the same month may possibly be caused by small dilatant zones associated with smaller events in the vicinity. Robinson and Iyer (1976) using a denser network of stations in San Andreas region with smaller standard deviations of ± 0.2 sec have concluded, "No final statement as to the presence of anomalies precursory to several moderate magnitude earthquakes in the region could be made because of uncertainty of timing errors, noisy stations or stations too distant from earthquakes".

Mean P wave anomalies averaged over longer periods from teleseisms have been studied by many workers in relation to moderate earthquakes (Sutton 1974, Feng *et al.* 1974). In north America and Europe, half yearly mean residuals at stations within 2° distance from the epicentres of strong earthquakes have a sudden jumps of 1.5 years before the occurrence of an earthquake (Prozorov 1977). In case of Kazakh explosions whose frequency is generally once a month, mean P wave anomalies averaged over a longer period of one or two years may be associated with moderate to large earthquakes. According to Santo (1970), the destructive earthquakes of magnitude 7.5 may occur from 1 to 3 years after the end of velocity anomaly. Fig. 7 shows the annual mean P wave anomalies with respect to Jeffreys Bullen tables at Pong, Nurpur, Dalhousie, Jawalamukhi, Sundernagar and Mukerian. As stated in the beginning, annual mean residuals were computed only if atleast three observations for explosions were available in a particular year. Thus annual means for Bhakra were not worked out. It may be noticed from the Fig. 7 that the residual change at Dalhousie is maximum between 1968 and 1969 although no damaging earthquake occurred. Beyond this period the annual change was generally 0.4 to 0.5 seconds which would correspond to 15 to 20 per cent of change in velocity for a source dimension of 20 km. Somewhat similar order of changes in residuals were observed at other stations. The observed annual changes in residuals may be attributed to the errors in the source parameters as reported by International Seismological Centre for unannounced Kazakh explosions. It is remarkable, however, to infer from Fig. 7 that if two yearly means are worked out, P wave residuals do not vary by more than ± 0.3 sec which is considerably less than the anomaly changes anticipated before great earthquakes. Thus long term changes in Kazakh residuals may be kept under surveillance for studying the dilatancy effects before great earthquakes.

6. Conclusions

The above study brings out the following results :

(1) Compared to Jeffreys Bullen travel time tables, preference is indicated for Herrin tables (1968) at Himachal Pradesh network from Kazakh explosions. F ratio test indicated that variation between sample means of different stations in the network showed more variation than can be attributed to the sampling error.

(2) The spatial variaion of mean residuals (1965-72) could generally be explained on the basis of local geology.

(3) The temporal variations of annual mean residuals from Kazakh explosions offer limited application in the testing of dilatancy model of earthquake predication in Himachal Pradesh.

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Appendix

F ratio test

Source of variations	Sum of squares	Degrees of freedom	Mean square	*F* ratio
Between stations	$S_1 = \sum_{j=1}^{k} n_j (\bar{x}_{.j} - \bar{x}_{..})^2$	$\nu_1 = K - 1$	$\frac{S_i}{\nu_1} = M_1$	$\frac{M_1}{M_2}$
Within stations (Residual variability)	$S_2 = \sum_{j=1}^{k}\sum_{i=1}^{n_j} (x_{ij} - \bar{x}_{.j})^2$	$\nu_2 = \sum_{j=1}^{k} (n_j - 1)$	$\frac{S_2}{\nu_2} = M_2$	
Total	$\sum_{j=1}^{k}\sum_{i=1}^{n_j} (x_{ij} - \bar{x}_{..})^2$	$\sum_{j=1}^{k} n_j - 1$		

K=number of stations, n_j =number of explosions at jth station. N=total number of observations.

x_j =mean of the jth station. $\bar{x}_{..}$=grand mean.

DISCUSSION

Ram Datt (BARC) : While deducing the anomalous zone using travel times or/and velocities of seismic waves the effect of the transmission path is to be considered and eliminated if the anomalous zone is interpreted to represent an earthquake zone.This is because the travel times and velocity of seismic ray is largely affected in the region where the rays bottom.

Author : In the case of Kazakh nuclear explosions, the effect of transmission path to the recording stations is almost same since they are closely located. Comparison of the anomalous changes at the station in the dilatant zone with that away from this zone enables us to differentiate the effect of changes in *P*-wave velocity.

M.L. Gogna (Kurukshetra University): I feel that Kazakh explosion should be taken as earthquakes and their parameters are needed to be recalibrated for any scientific work.

Author : The epicentral parameters for Kazakh explosions have been taken from I.S.S. If it is possible to get unpublished data from USSR or China, the study will definitely improve.