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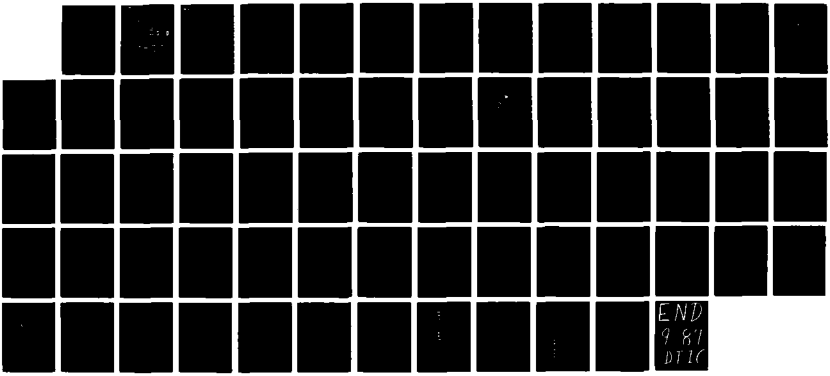
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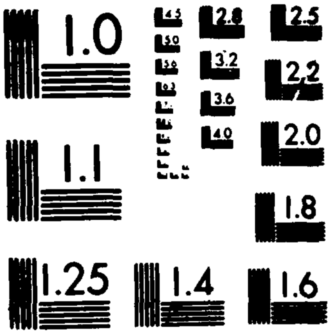

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AN ANALYSIS OF THE EFFECTS OF TECTONIC RELEASE ON SHORT-PERIOD P WAVES OBSERVED FROM SHAGAN RIVER EXPLOSIONS

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FINAL REPORT

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16. Abstract (Limit: 200 words)

Large samples of teleseismic P wave amplitude and waveform data recorded from Shagan River underground explosions have been collected and systematically analyzed in an attempt to identify any effects which may correlate with the amount of tectonic release accompanying these explosions. ~~The~~ results of these analyses indicate that these teleseismic P wave data do not provide any unambiguous evidence of effects of tectonic release in the short-period range of interest in m_b determination. However, the results of a preliminary theoretical analysis indicate that such negative evidence is not definitive in that there are plausible models of tectonic release for which no detectable variations in the observed teleseismic P waveforms are theoretically expected to result from the superposition of these two sources. At the same time, such models of tectonic release predict significant positive bias in the network-averaged m_b values for explosions accompanied by the mode of tectonic release traditionally associated with the Shagan River test site. Thus, the currently available data do not exclude the possibility that tectonic release may be introducing a positive bias of as much as several tenths of a magnitude unit into the network-averaged m_b values computed for some Shagan River explosions.

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EXECUTIVE SUMMARY

This report summarizes the results of an investigation into the possible effects of tectonic release on the m_b values determined for underground explosions conducted at the Russian nuclear test site near Semipalatinsk. The primary objectives of this study have been to collect and systematically analyze large samples of short-period, teleseismic P wave data recorded from explosions at this test site in an attempt to identify any effects which may correlate with tectonic release and to evaluate the results of these empirical studies by using a simple theoretical model to simulate the range of potential effects of tectonic release on short-period explosion P waves.

The teleseismic P wave data base which has been assembled for the purposes of this project is described in Section II where the associated source and station parameters required for the investigation are documented and described in detail. This data base is composed primarily of digital, short-period P wave data recorded at 11 selected stations of the Global Digital Seismic Network (GDSN) from 25 representative Shagan River explosions. The results of a variety of careful statistical analyses of these data are then described and it is concluded that these data, by themselves, do not provide any convincing evidence of effects of tectonic release on m_b. More specifically, it is demonstrated that the observed waveforms and amplitudes show no evidence of significant changes which can be correlated with the level of tectonic release inferred from the corresponding long-period surface wave data.

The significance of the empirical results of Section II are evaluated theoretically in Section III where a simple, analytical model of tectonic release is used to simulate the expected effects on short-period P wave amplitudes for a mode of tectonic release equivalent to the 45 degree thrust mechanism which has traditionally been associated with explosions at the Shagan River test site. In particular, it is demonstrated that the teleseismic P waveforms predicted for this assumed mode of tectonic release are essentially identical to those predicted for the explosion alone and, consequently, that no detectable variations in the

observed waveforms are theoretically expected to result from the superposition of these two sources. Furthermore, the simulation model is used to illustrate the fact that the azimuthal variation in teleseismic P wave amplitude associated with this tectonic release model are too small to be detected experimentally, even for explosions accompanied by large tectonic release components. At the same time, however, this tectonic release model is shown to predict a positive bias in the network-averaged m_b values for some Shagan River explosions which could potentially be as large as 0.3 units and still be unaccompanied by detectable changes in the observed short-period, teleseismic P waves. It is concluded that the available data cannot be used to exclude the possibility that the tectonic release accompanying Shagan River explosions may be significantly inflating the computed network-averaged m_b values in some cases.

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I. INTRODUCTION

In 1974, the U.S. and U.S.S.R. signed a Threshold Test Ban Treaty (TTBT) which prohibits the testing of underground nuclear explosions with yields greater than 150 kilotons. Upon ratification, the treaty calls for the bilateral exchange of certain geologic and geophysical data, as well as the yields of two calibration events, in each so-called "geophysically distinct" testing area, in order to facilitate verification of treaty compliance. Although not defined explicitly in the TTBT protocol, the term "geophysically distinct" is intended to denote an area within which the geophysical parameters controlling the magnitude-yield relationship are uniform; that is, an area within which a single yield-scaling relation holds for all explosions. However, a problem arises in that for areas such as the principal U.S.S.R. underground nuclear testing area near Semipalatinsk, it is not obvious how such geophysically distinct areas can be recognized using information known to us at the present time. For this reason, over the past several years we have been conducting a series of research investigations directed toward assessing the feasibility of using teleseismic P wave data recorded from explosions to identify geophysically distinct testing areas within the Shagan River region of the Semipalatinsk test site.

In a previous study, Dermengian et al. (1985) demonstrated that there are some pronounced variations of m_b residuals as a function of explosion location within the Shagan River test site and concluded that these variations must be primarily related to lateral variations in the subsurface geologic structure beneath the test site. Thus, the results of that preliminary study indicated that the teleseismic data may indeed be useful for identifying geophysically distinct testing areas within the Shagan River test site. In the present study, we have extended this previous investigation to include an analysis of possible effects of tectonic release on the m_b values. It has long been recognized that many underground explosions are accompanied by the release of stored tectonic strain energy and that, in some cases, this tectonic release can significantly affect the observed seismic signals, particularly the long-period surface waves (Toksoz and Kehrer, 1972; Rygg, 1979; North and Fitch, 1982; Sykes and Cifuentes, 1984; Given and Mellman, 1986). This is illustrated in Figure 1 where a suite of long-period Rayleigh waves recorded at SRO station KAAO, Kabul, Afghanistan from Shagan River explosions associated with different levels of tectonic release are displayed for purposes of comparison. In this figure, the tectonic classifications A, B and C refer to those originally proposed by North and Fitch (1981) in which type A denotes a low tectonic release event in which the polarities of all the observed Rayleigh waves are coincident with those expected from an explosion alone, type B denotes an intermediate tectonic release event in which the polarities of some of the Rayleigh waves are reversed and type C denotes a strong tectonic release event in which the Rayleigh wave phases are reversed in all azimuths. Note from Figure 1 that the waveforms from the two C events have been inverted prior to plotting and yet appear identical to the A-type waveforms, confirming Rayleigh wave phase reversals in these two cases. Such evidence of phase reversals in all azimuths indicates that the mode of tectonic release at Shagan River is predominantly of the thrust type, at least for the C-type events, and this fact has important implications with respect to the expected tectonic effects on m_b. Thus, Figure 2 shows the predicted teleseismic short-period P and long-period Rayleigh wave radiation patterns corresponding to the commonly assumed mode of tectonic release at Shagan, which is equivalent to thrust motion on a fault dipping at 45°. It can be seen from this figure that the long-period Rayleigh waves predicted for this mode of tectonic release are everywhere out of phase with the explosion Rayleigh wave (as indicated by the shaded area) and show strong azimuthal dependence. On the other hand, the predicted short-period P waves corresponding to this mode of tectonic release are everywhere in phase with the explosion P waves and show only a modest azimuthal dependence. It follows that in this case any effects of tectonic release on the short-period P waves can be expected to lead to a network-averaged m_b value with a positive bias.

It is also evident from Figure 2 that for this assumed mode of tectonic release, observed seismic amplitudes from explosions of the

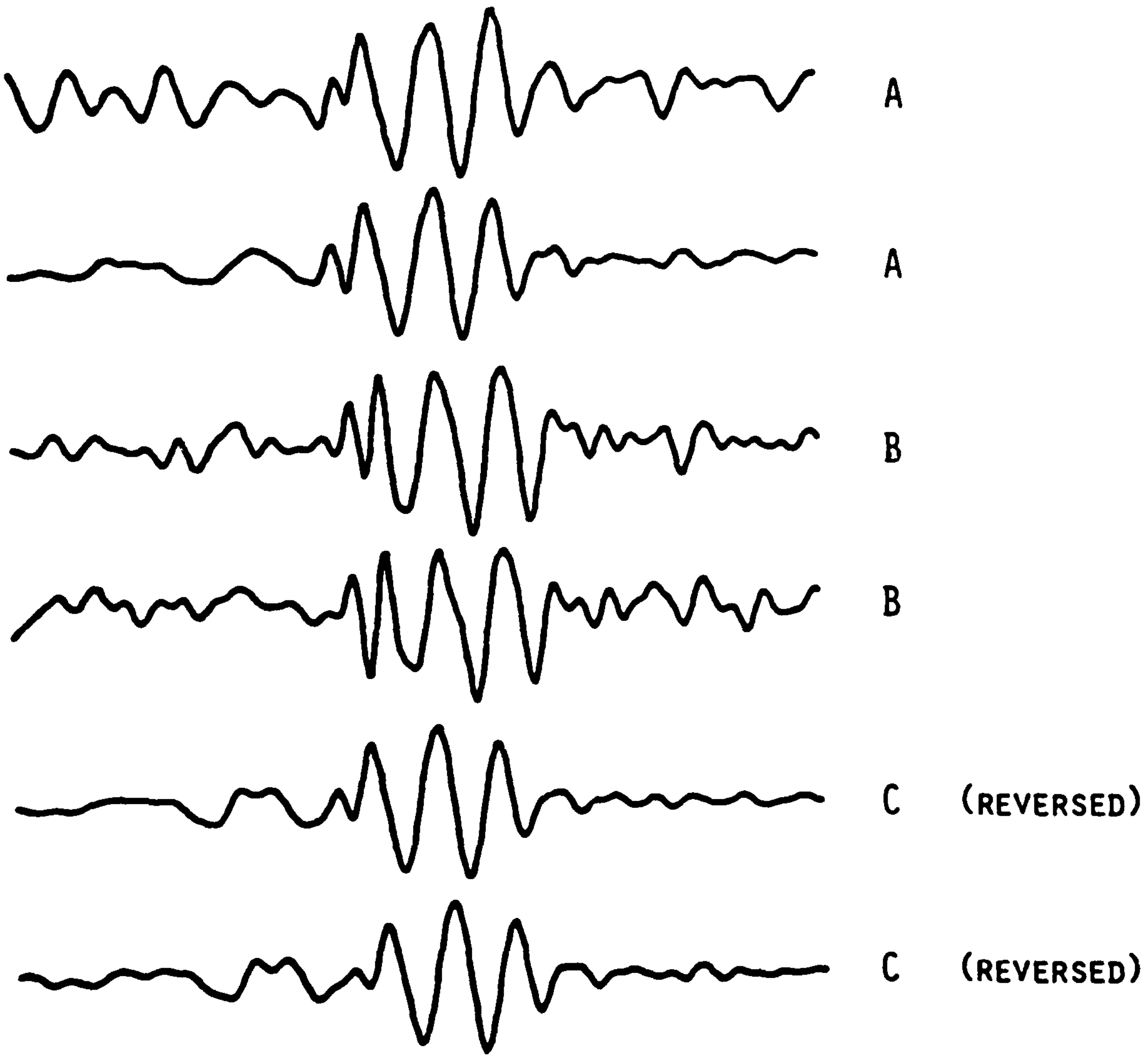
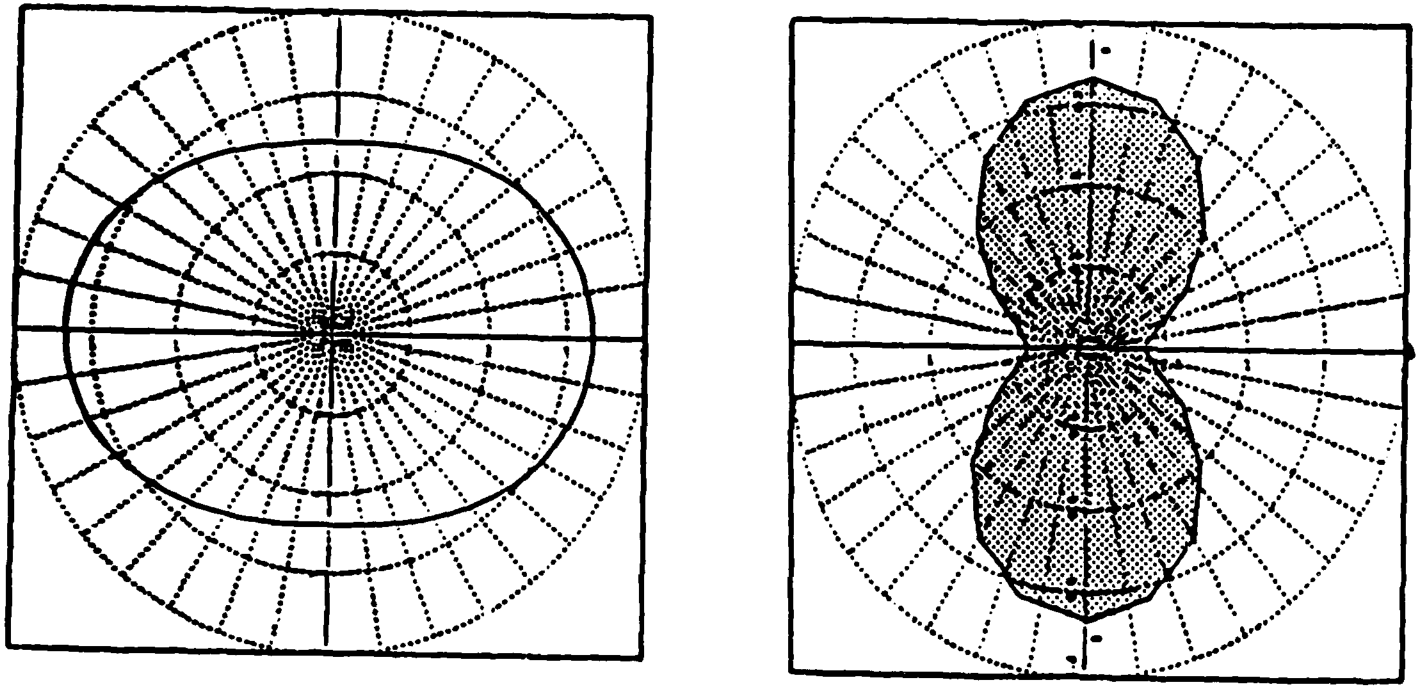


Figure 1. Comparison of long-period Rayleigh waveforms observed at SRO station KAAO from Shagan River explosions accompanied by different levels (i.e., A,B,C) of tectonic release.



P WAVE (Δ = 40°)

RAYLEIGH WAVE (T = 20 SECONDS)

Figure 2. Theoretical radiation patterns for body and surface waves for tectonic release in a uniform prestress field equivalent to 45° thrust faulting. Shaded areas indicate polarity opposite to the explosion. Body waves are calculated at 1 Hz and have a 28° takeoff angle. Surface wave amplitudes are computed at 20 second period (Stevens, 1982).

same yield are predicted to vary as the tectonic contribution to the signals increase in a manner which depends on the station azimuth and, in fact, such amplitude variations have been well documented (e.g., North and Fitch, 1981). For example, Figure 3 shows the observed KAAO Rayleigh waveforms from Figure 1, replotted at a fixed absolute amplitude scale after having been normalized to the same network-averaged m_b value. Note the dramatic variation in amplitude, with the waveforms from the B-type events representing nearly complete cancellation of the explosion component by the tectonic release component at this azimuth. In contrast to this, the corresponding normalized short-period P waveforms displayed on the right hand side of Figure 3 show no significant variations in amplitude level or waveform which appear to correlate with the level of tectonic release. This latter observation has often been used to argue that the tectonic effects on the short-period P waves are negligible or, at least, much less pronounced than those associated with the corresponding long-period surface waves. However, Murphy and Archambeau (1986) have demonstrated that this argument is not conclusive in that there are certain modes of tectonic release which can have a significant effect on the network-averaged m_b value without producing any easily observable perturbations in the short-period P waveforms. Thus, the objective of the present investigation has been to carefully assess whether the tectonic release accompanying explosions at the Shagan River test site is having a detectable effect on the observed short-period P waves and the corresponding m_b values derived from them.

This report consists of four sections including these introductory remarks. In Section II a large sample of short-period P wave amplitude and waveform data recorded from Shagan River explosions representing a wide range of tectonic release are correlated with the corresponding long-period tectonic release classifications and examined for evidence of tectonic release effects at short periods. Simple theoretical models of tectonic release are described in Section III where they are used to theoretically simulate the waveform and amplitude effects on the short-period explosion P waves which would be predicted for the preferred mode of tectonic release at the Shagan River test site. These

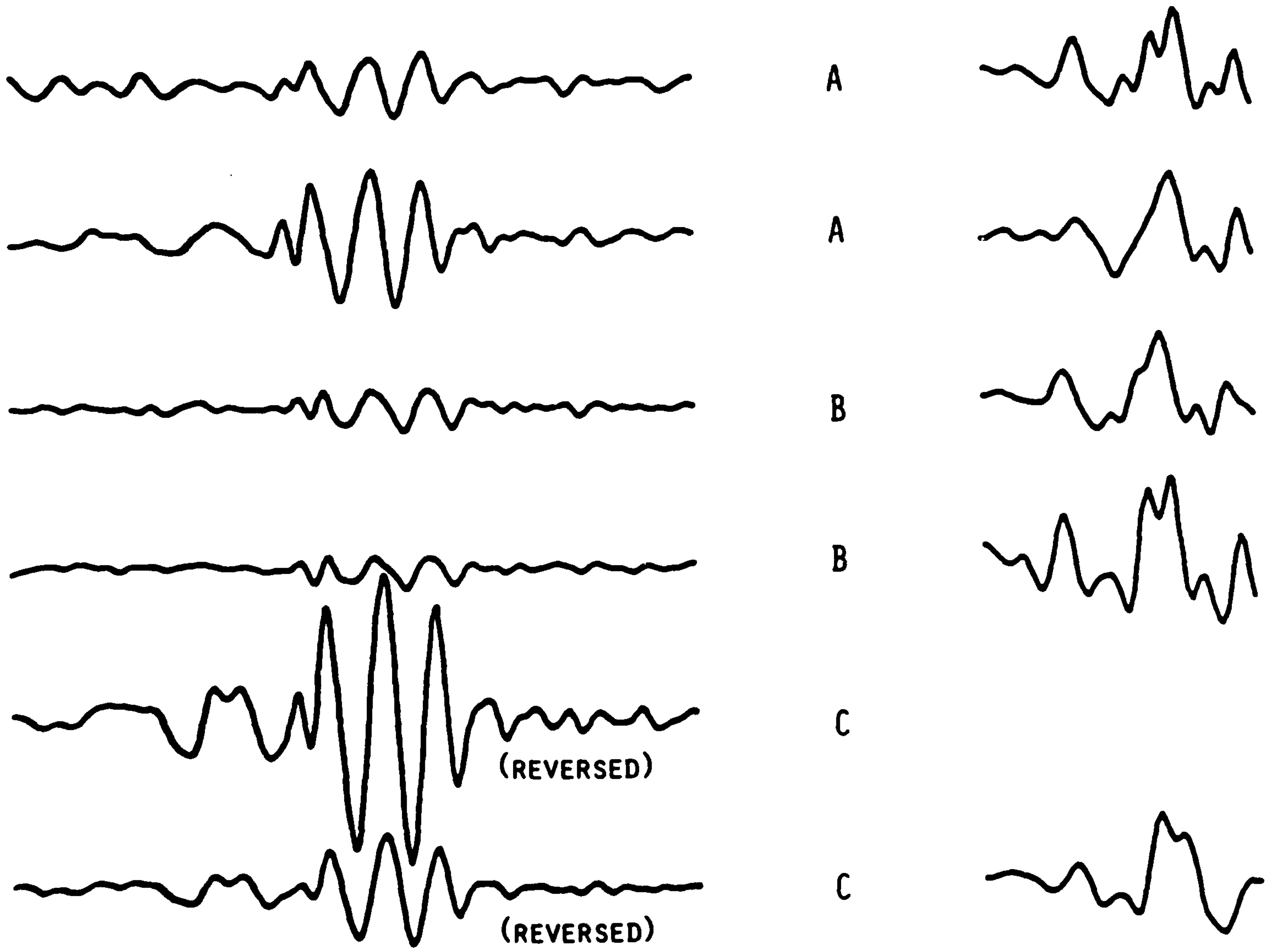


Figure 3. Comparison of long-period Rayleigh (left) and short-period P (right) waveforms observed at SRO station KAAO from Shagan River explosions accompanied by different levels (i.e., A,B,C) of tectonic release. All waveforms have been normalized to the same network-averaged m_b value and plotted at a fixed absolute amplitude scale.

predictions are then used to evaluate the results of the analyses of the observed data described in Section II. This is followed in Section IV by a summary and a listing of preliminary conclusions concerning the effects of tectonic release on the short-period P waves observed from underground explosions at the Shagan River test site.

II. DATA ANALYSIS

Large samples of short-period P wave amplitude and waveform data recorded from Shagan River explosions representing a wide apparent range of tectonic release have been compiled for the purposes of this investigation. These data have been selected on the basis of availability of both digital waveform data and tectonic release classification for the selected explosions. The tectonic release classifications of Shagan River explosions used throughout this report are those recently published by Given and Mellman (1986) based on their moment tensor inversion analyses of long-period surface wave data recorded from these explosions. In their analysis, they assumed that the mode of tectonic release for all explosions at Shagan River is equivalent to thrust motion on a plane dipping at 45 degrees and then determined the orientation (i.e., strike) and relative strength of the tectonic component on an event-by-event basis. As is customary in such studies, they quantified the relative strength of the tectonic release through the parameter F, which is defined as the ratio of the moment of the equivalent point double couple tectonic release to the moment of the explosion. Most of the analyses to be described in the following discussion are not sensitive to the details of this source model, but assume only that the effects of tectonic release increase as the inferred F value increases.

The source parameters for the 25 selected Shagan River explosions are listed in Table 1, together with the F values and apparent strikes of the associated tectonic release inferred by Given and Mellman (1986). The epicenter locations and origin times in this table are those reported by Marshall _et_ _al_. (1984), who used a Joint Epicenter Determination (JED) method to accurately locate these events relative to the known location of the Shagan River cratering explosion of January 15, 1965. The associated m_b values are from the recent report by Dermengian _et_ _al_. (1985) and are based on a least squares statistical analysis of a large sample of ISC single station m_b data reported for these explosions.

The JED locations of the 25 explosions listed in Table 1 are displayed as a function of position within the Shagan River test site in

Table 1

Source Parameters For Selected Shagan River Explosions

Event #	Date	Origin Time	Lat.(N)	Long.(E)	F	Strike	m_b
1	08-29-78	02:37:06.2	50.00	78.98	.67	320	5.94
2	09-15-78	02:36:57.7	49.92	78.88	.29	327	5.99
3	11-04-78	05:05:57.3	50.03	78.94	.61	324	5.57
4	11-29-78	04:33:02.5	49.95	78.80	.33	333	5.99
5	06-23-79	02:56:57.5	49.90	78.85	.37	320	6.18
6	07-07-79	03:46:57.3	50.03	78.99	1.49	321	5.82
7	08-04-79	03:56:57.1	49.89	78.90	.33	321	6.16
8	08-18-79	02:51:57.1	49.94	78.94	.84	318	6.19
9	10-28-79	03:16:56.9	49.97	79.00	.37	339	5.97
10	12-02-79	04:36:57.4	49.89	78.80	.15	327	6.00
11	12-23-79	04:56:57.4	49.92	78.75	.29	322	6.16
12	06-12-80	03:26:57.6	49.98	79.00	.37	329	5.53
13	06-29-80	02:32:57.7	49.94	78.81	.33	345	5.70
14	09-14-80	02:42:39.1	49.92	78.80	.64	320	6.22
15	10-12-80	03:34:14.1	49.96	79.03	.29	333	5.87
16	12-14-80	03:47:06.4	49.90	78.94	.44	307	5.97
17	12-27-80	04:09:08.1	50.06	78.98	1.62	322	5.87
18	03-29-81	04:03:50.0	50.01	78.98	.61	332	5.57
19	04-22-81	01:17:11.3	49.88	78.81	.26	328	5.92
20	09-13-81	02:17:18.2	49.91	78.91	.35	316	6.09
21	10-18-81	03:57:02.6	49.92	78.86	.30	331	6.03
22	11-29-81	03:35:08.6	49.89	78.86	.24	333	5.61
23	12-27-81	03:43:14.1	49.92	78.79	.32	336	6.28
24	04-25-82	03:23:05.4	49.90	78.91	.33	334	6.11
25	12-05-82	03:37:12.5	49.92	78.81	.33	328	6.18

Origin times and locations are from Marshall, Bache and Lilwall (1984).
F values and strikes are from Given and Mellman (1986).
m_b values are from Dermengian, Murphy and Barker (1985).

Figure 4 where it can be seen that they are fairly broadly distributed across the testing area. The F values assigned to these events by Given and Mellman (1986) are listed in parenthesis next to each event location and it can be seen that although the highest F values have generally been assigned to events in the northeast portion of the test site, there is also a substantial range in the amount of tectonic release assigned to events in the central and southwestern portions of the test site. Thus, the selected sample of explosions appears to provide representative distributions with respect to both source location and tectonic release classification. We will now proceed with an analysis of the teleseismic short-period P wave data recorded from these explosions in an attempt to identify any effects which may be correlated with the degree of tectonic release.

First, considering variations in the recorded P waveforms, the analysis has focused on GDSN (Global Digital Seismic Network) data recorded from these explosions because these data are in digital form and thus can be easily filtered and replotted at a constant scale to facilitate detailed interevent comparisons. A subset of eleven of these stations which recorded data from a representative number of the Shagan River explosions listed in Table 1 has been selected for analysis and these are listed in Table 2 together with their locations and approximate distances and azimuths to the Shagan River test area. The coverage provided by these stations is illustrated more clearly in Figure 5 where the map locations of the stations are shown on an azimuthally equidistant projection centered on the Shagan River area. It can be seen from this map that, with the possible exception of the northeast quadrant, the azimuthal distribution of the selected GDSN stations about the Shagan River test area appears to be quite satisfactory.

Now if tectonic release is having a significant effect on the teleseismic short-period P waves observed from Shagan River explosions, then it might be expected that the recorded waveforms would show evidence of complexity which increases with increasing levels of tectonic release. Thus, for example, Wallace et al. (1983, 1985) claim to have observed such complexity in the long-period P waves observed from some NTS

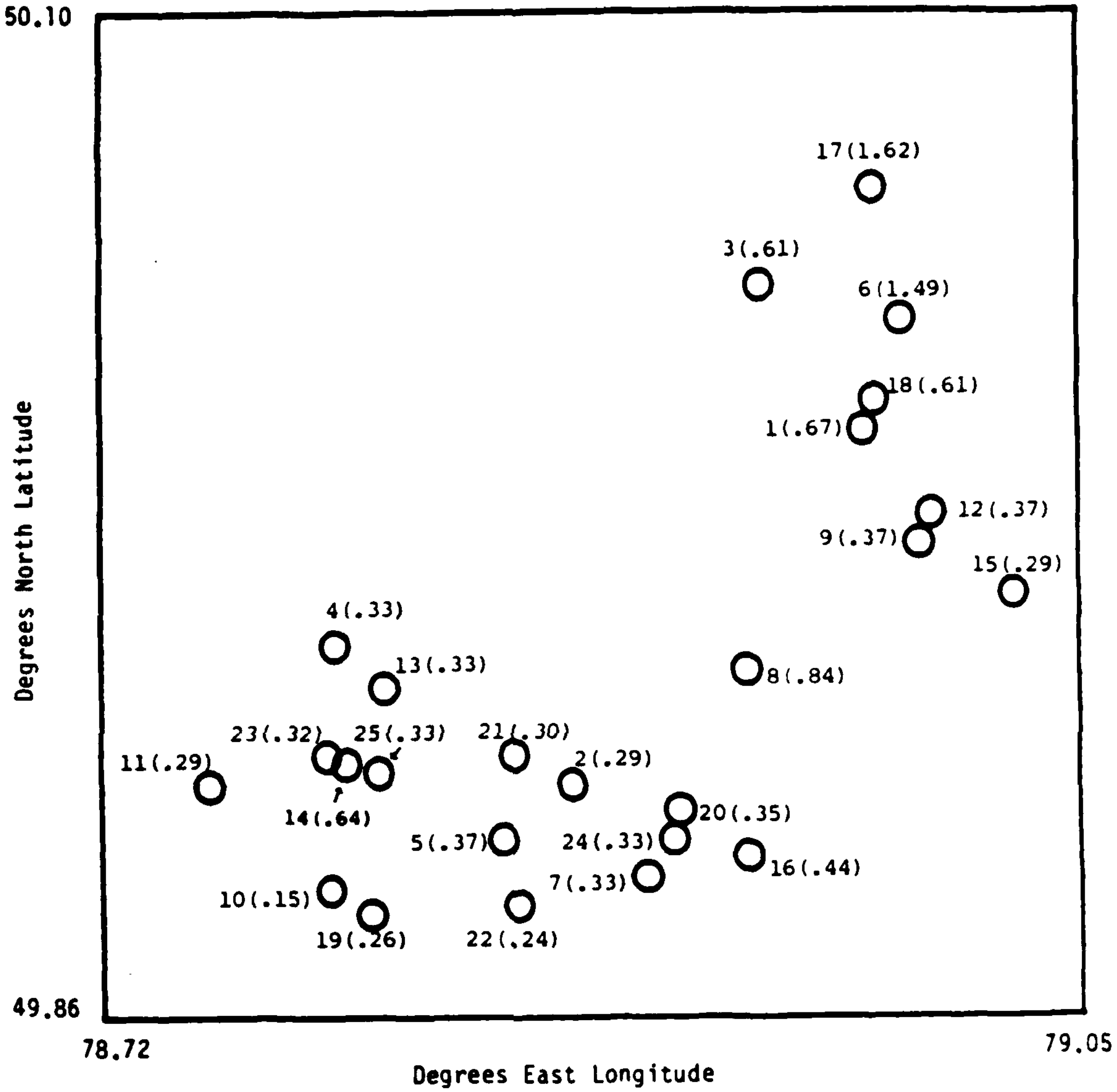


Figure 4. JED locations for the Shagan River explosions of Table 1. Values in parentheses denote tectonic release F factors assigned to these explosions by Given and Mellman (1986).

Table 2

Locations of GDSN Stations Selected For Analysis

Name	Location	Lat.(°)	Long.(°)	Distance(°)	Azimuth(°)
ANMO	Albuquerque, New Mexico	34.9N	106.5W	95.4	4.4
ANTO	Ankara, Turkey	39.9N	32.8E	33.7	270.7
BCAO	Bangui, Central African Republic	4.4N	18.6E	67.9	249.3
CHTO	Chiengmai, Thailand	18.8N	99.0E	34.9	145.4
CTAO	Charters Towers, Australia	20.1S	146.2E	91.5	119.8
GRFO	Grafenberg, Germany	49.7N	11.2E	42.3	296.8
KAAO	Kabul, Afghanistan	34.5N	69.0E	17.0	208.9
KONO	Kongsberg, Norway	59.6N	9.6E	39.4	311.5
MAJO	Matsushiro, Japan	36.5N	138.2E	44.1	84.2
NWAO	Narrogin, Australia	32.9S	117.2E	89.2	148.5
SHIO	Shillong, India	25.6N	91.9E	26.3	152.7

Distance and azimuth are from Shagan River area (49.9N,78.9E).

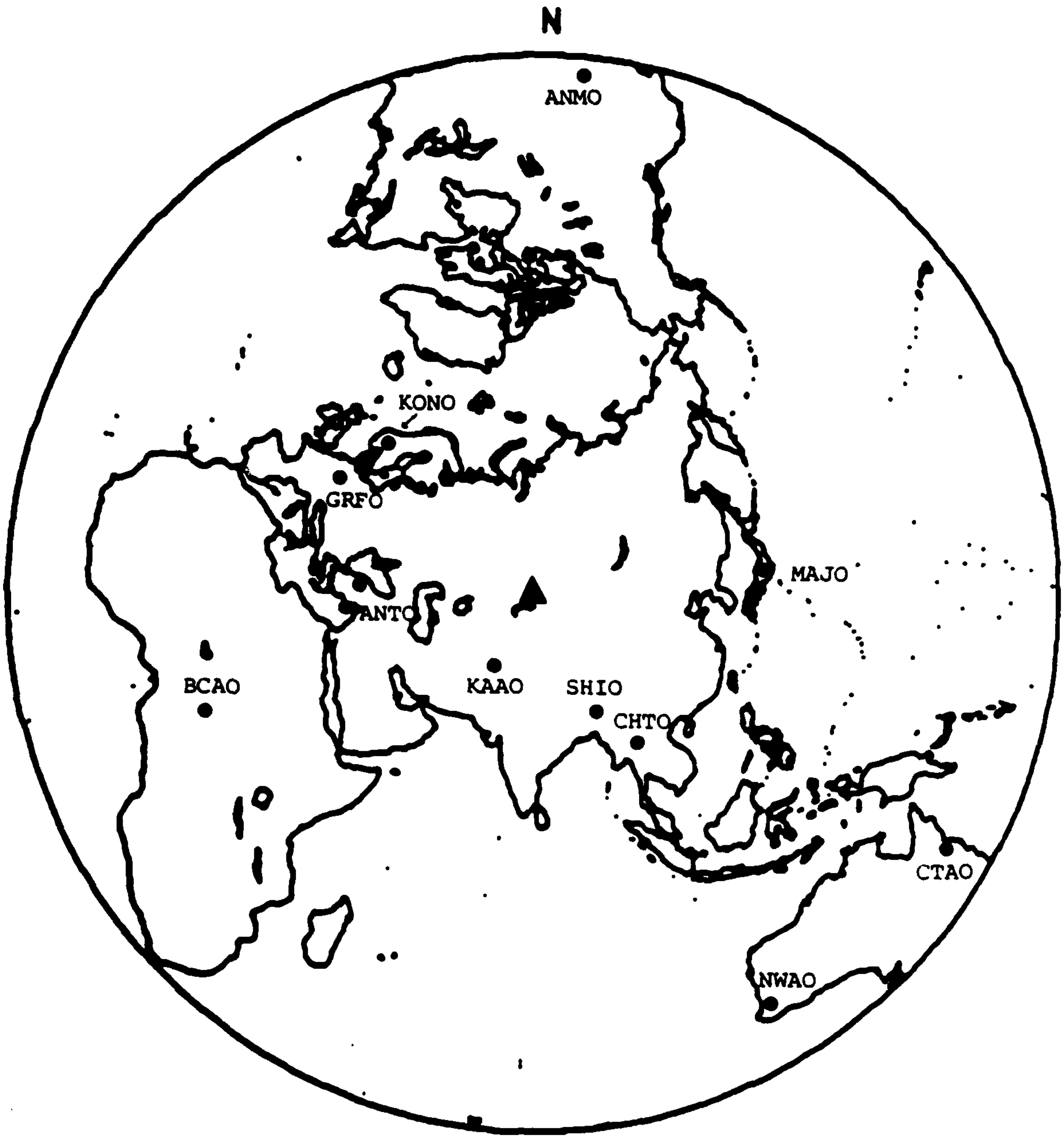


Figure 5. Map locations of selected GDSN seismic stations.

explosions and have attributed it to the effects of interference between the P and pP waves from the explosion and the sP phase from the tectonic release. Observations of increased complexity later in the explosion P waveforms have also been reported (e.g., Douglas, 1984), although this type of evidence is probably more appropriately attributed to aftershock activity. With respect to explosions at Shagan River, it has already been noted that the mode of tectonic release is generally thought to be equivalent to predominantly thrust motion on a plane dipping at about 45 degrees. It follows from Figure 2 that given an estimate of the strike, the relative effects of the tectonic release corresponding to this mechanism can be estimated at the various GDSN stations. This is illustrated more specifically in Figure 6 which shows the locations of the selected GDSN stations relative to the P wave radiation pattern predicted at a representative teleseismic distance of 40 degrees for a 45 degree thrust fault striking at an azimuth of 325 degrees (Given and Mellman, 1986). It can be seen from this figure that tectonic effects are expected to be more pronounced in the P waves observed at stations CHTO and SHIO, for example, then in the P waves observed at stations such as ANTO or BCAO, although for this assumed mode of tectonic release the predicted variation in the P wave amplitude is only about 40 percent. The waveforms observed at these four stations from selected Shagan River explosions are displayed in Figures 7 and 8 where they have been arranged in order of increasing amount of tectonic release (i.e., F) as inferred from the long-period surface waves by Given and Mellman (1986). It can be seen that although there are some minor trace-to-trace variations in these waveforms, there is no evidence of any correlation between waveform and F factor at these four stations. The waveforms recorded at the other seven selected GDSN stations are reproduced in Appendix A where it can be seen that similar comments apply regarding the overall lack of correlation between waveform complexity and event F value. In fact, the only station which shows any evidence of systematic waveform variation with F is KONO (cf. Figure A-2), and even this variation appears to relate more closely with event location than degree of tectonic release. This fact is illustrated graphically in Figure 9 which shows these same KONO

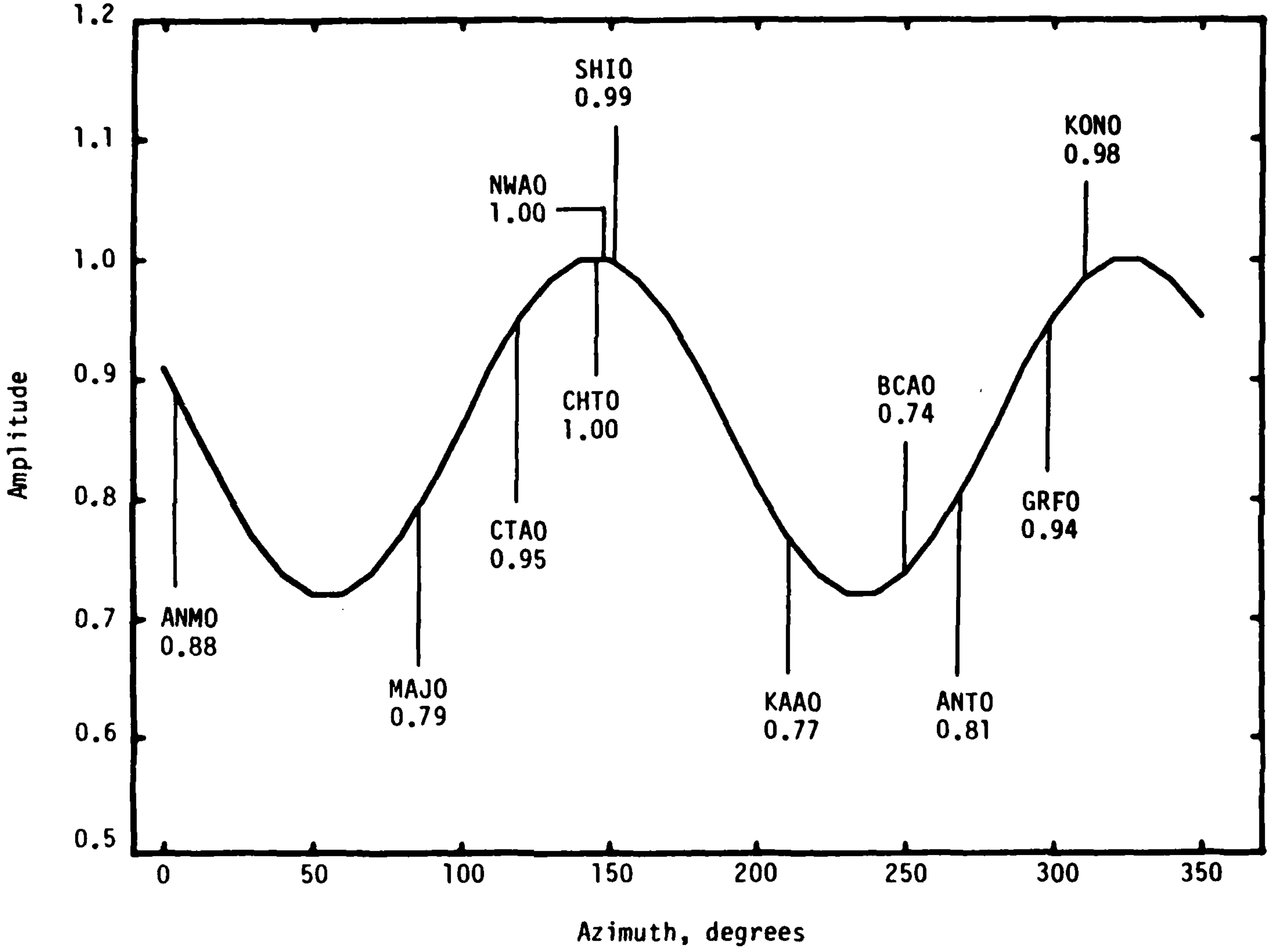


Figure 6. Locations of selected GDSN stations with respect to the teleseismic P wave radiation pattern corresponding to a model of the tectonic release accompanying Shagan River explosions.

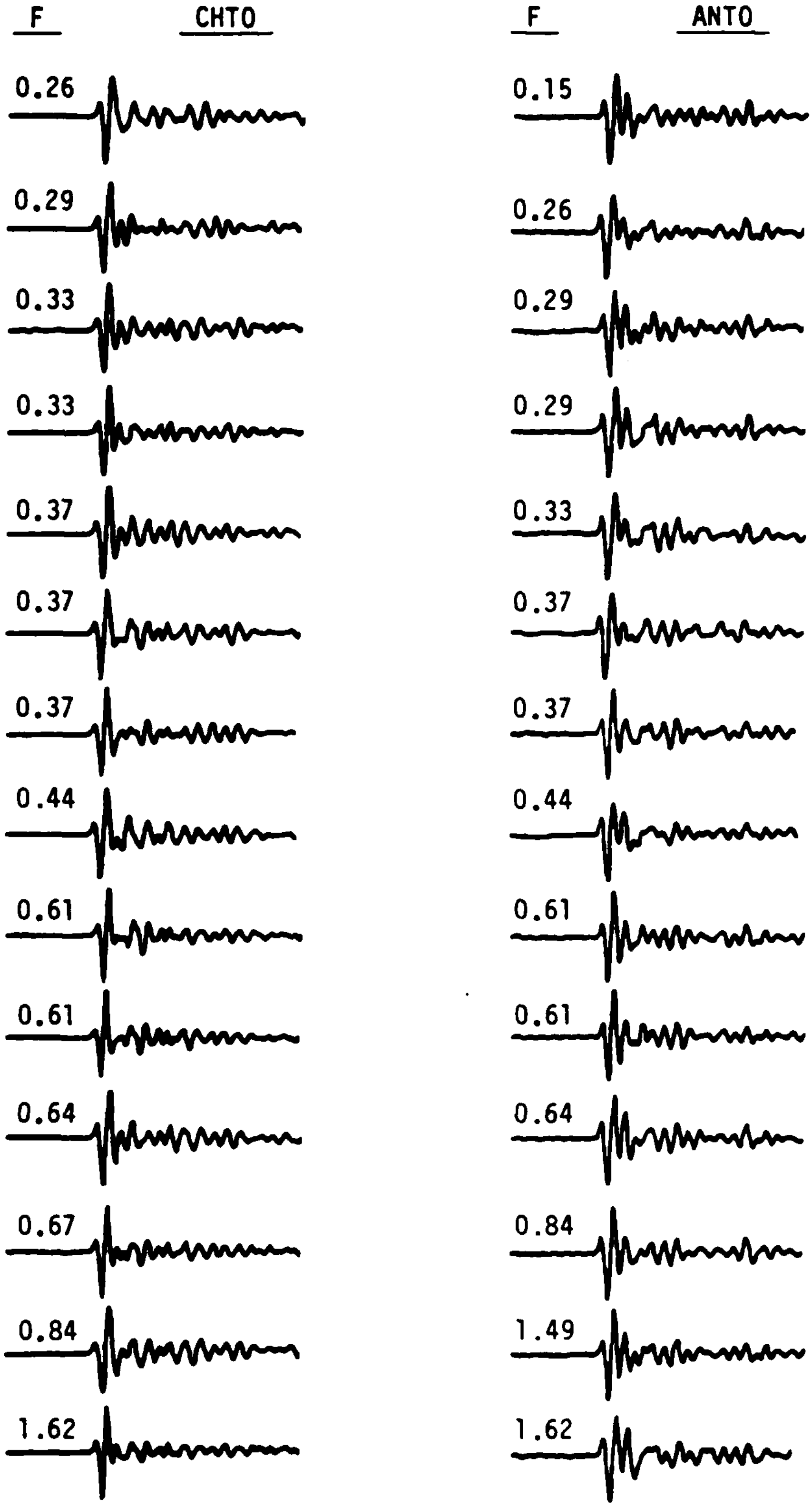


Figure 7. Teleseismic short-period P waveforms recorded at GDSN stations CHTO (left) and ANTO (right) from Shagan River explosions representing various levels of tectonic release, F.

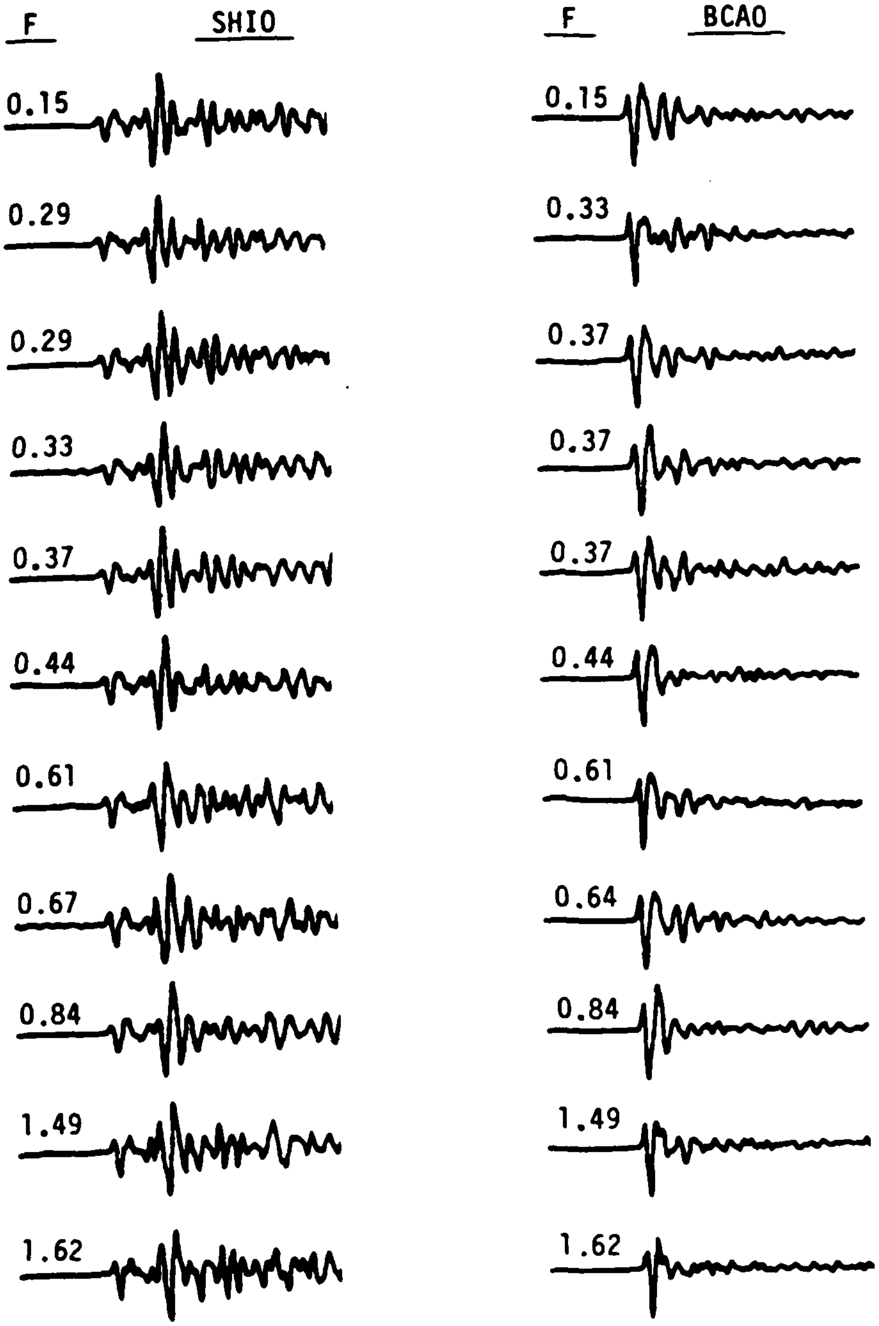


Figure 8. Teleseismic short-period P waveforms recorded at GDSN stations SHIO (left) and BCAO (right) from Shagan River explosions representing various levels of tectonic release, F.

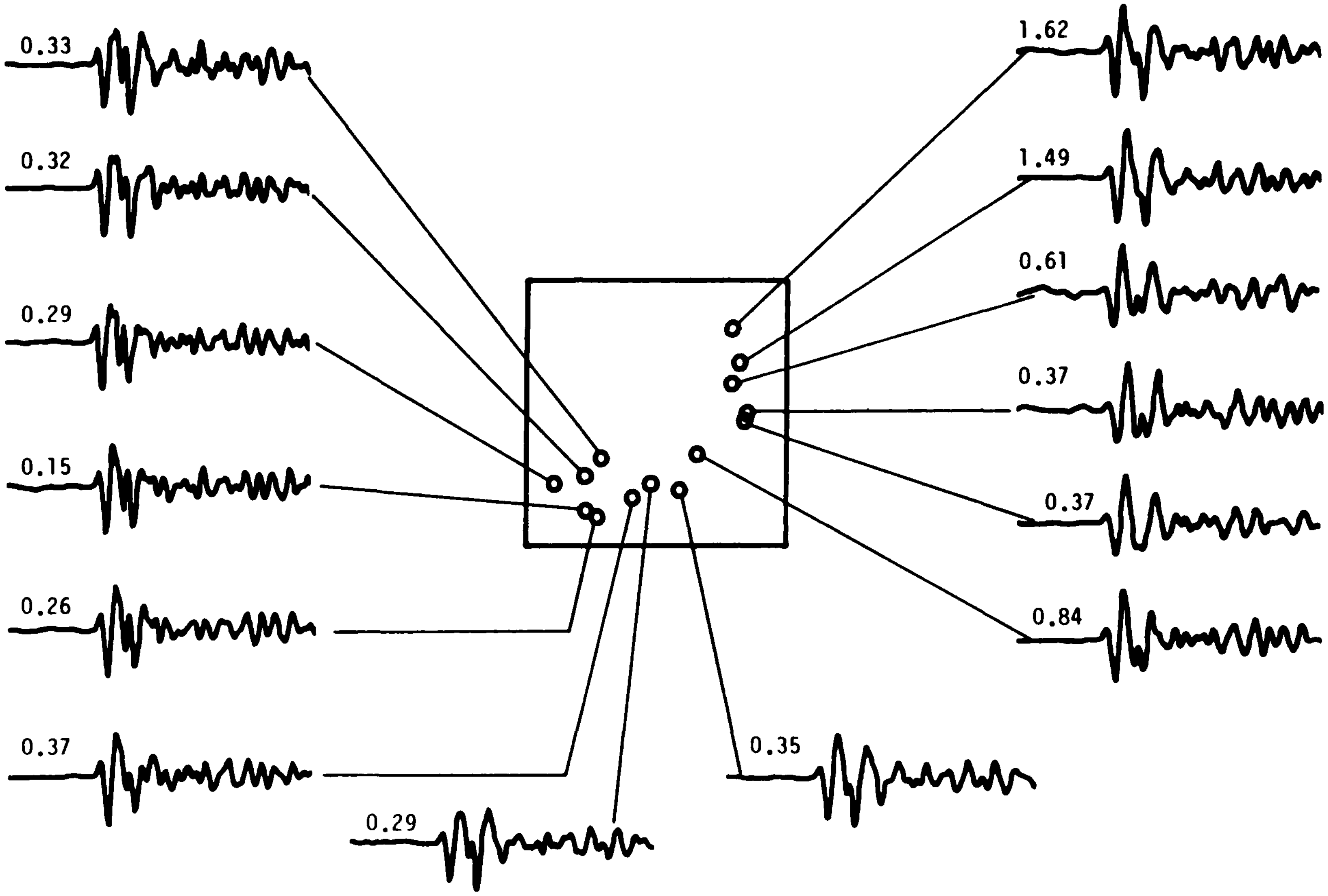


Figure 9. Map showing station KONO waveforms versus event location within the Shagan River test area.

waveforms displayed as a function of event location on the test site. It can be seen here that the waveforms recorded from explosions in the southwestern portion of the test site have a characteristic appearance at station KONO which is quite different from that seen for events located in the northeast portion of the test site. However, within each geographical subgroup, the KONO waveforms appear to be remarkably similar, independent of event F value. In this regard, it is quite surprising how similar the waveforms are at some stations (e.g., CHTO, Figure 7) in view of the variations in explosion size, source depth and location. In any case, there is no evidence that tectonic release is having a significant effect on the waveforms of the teleseismic, short-period P waves recorded at these GDSN stations from Shagan River explosions.

With regard to amplitude effects, it follows from Figure 6 that the variation in P wave amplitude associated with tectonic release is expected to be more rapid at some stations that at others, depending on the location of the station with respect to the tectonic P wave radiation pattern. As a result, if the single station m_b residuals computed with respect to the large network average m_b value are plotted as a function of F on a station-by-station basis, any tectonic effects should manifest themselves in the form of trends which correlate with azimuth. Therefore, the maximum amplitudes of the initial P waves recorded at the selected GDSN stations from the Shagan River explosions of Table 1 have been measured and used to compute single station m_b residuals, r_i, according to the definition

$$r_i = \bar{m}_b - \log A_i \tag{1}$$

where $\bar{m}_b$ denotes the large network average m_b value and A_i is the maximum peak-to-peak amplitude in the first few cycles of the observed short-period P wave. The computed m_b residuals for the various GDSN stations are plotted as a function of event F value in Figures 10-12. Since previous investigations have already revealed some important correlations between station m_b residuals and event location at Shagan River (e.g., Marshall et al., 1984; Dermengian et al., 1985), different symbols have

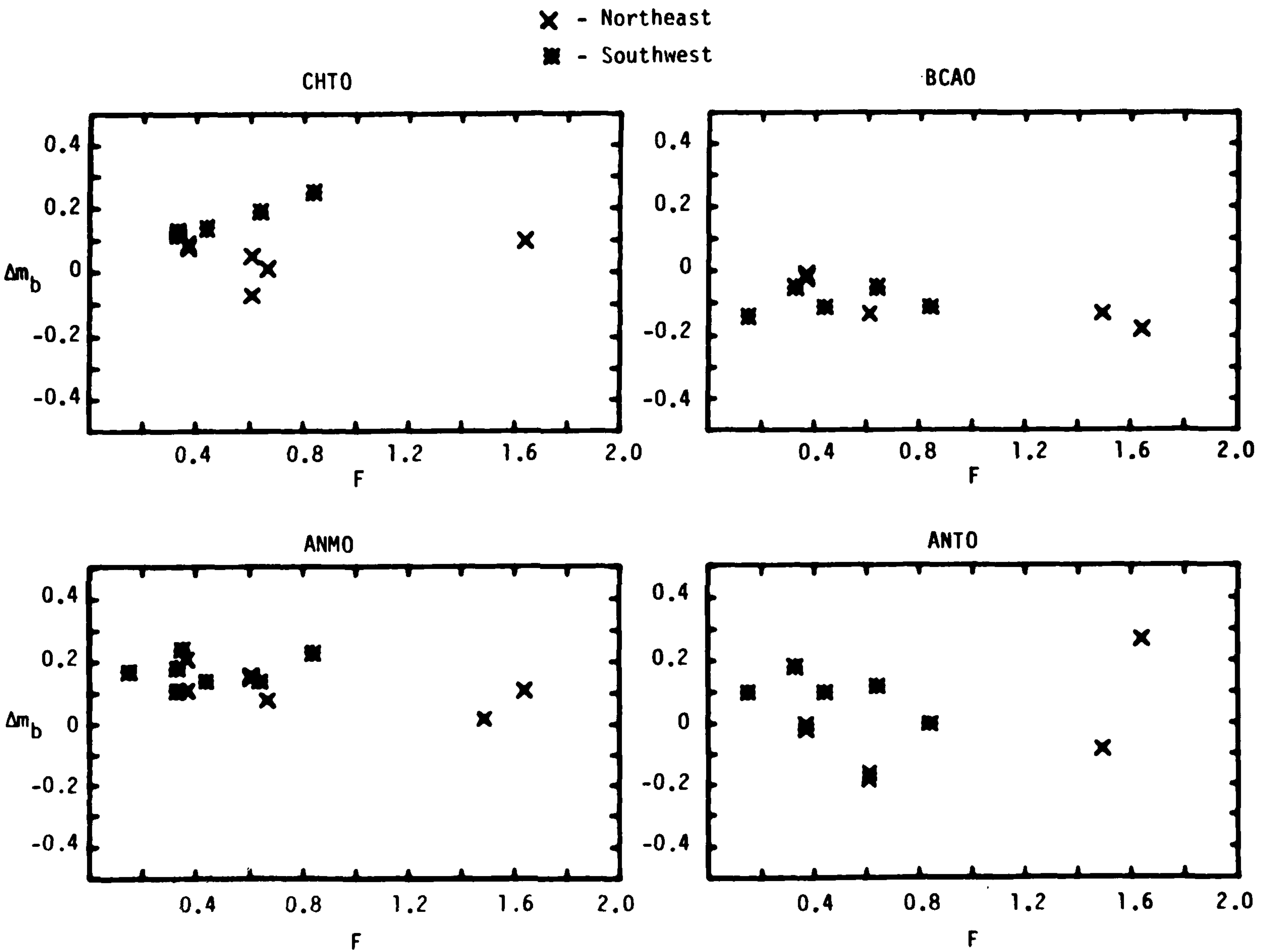


Figure 10. Single station m_b residuals as a function of tectonic release F factors for selected Shagan River explosions; stations CHTO, BCAO, ANMO and ANTO.

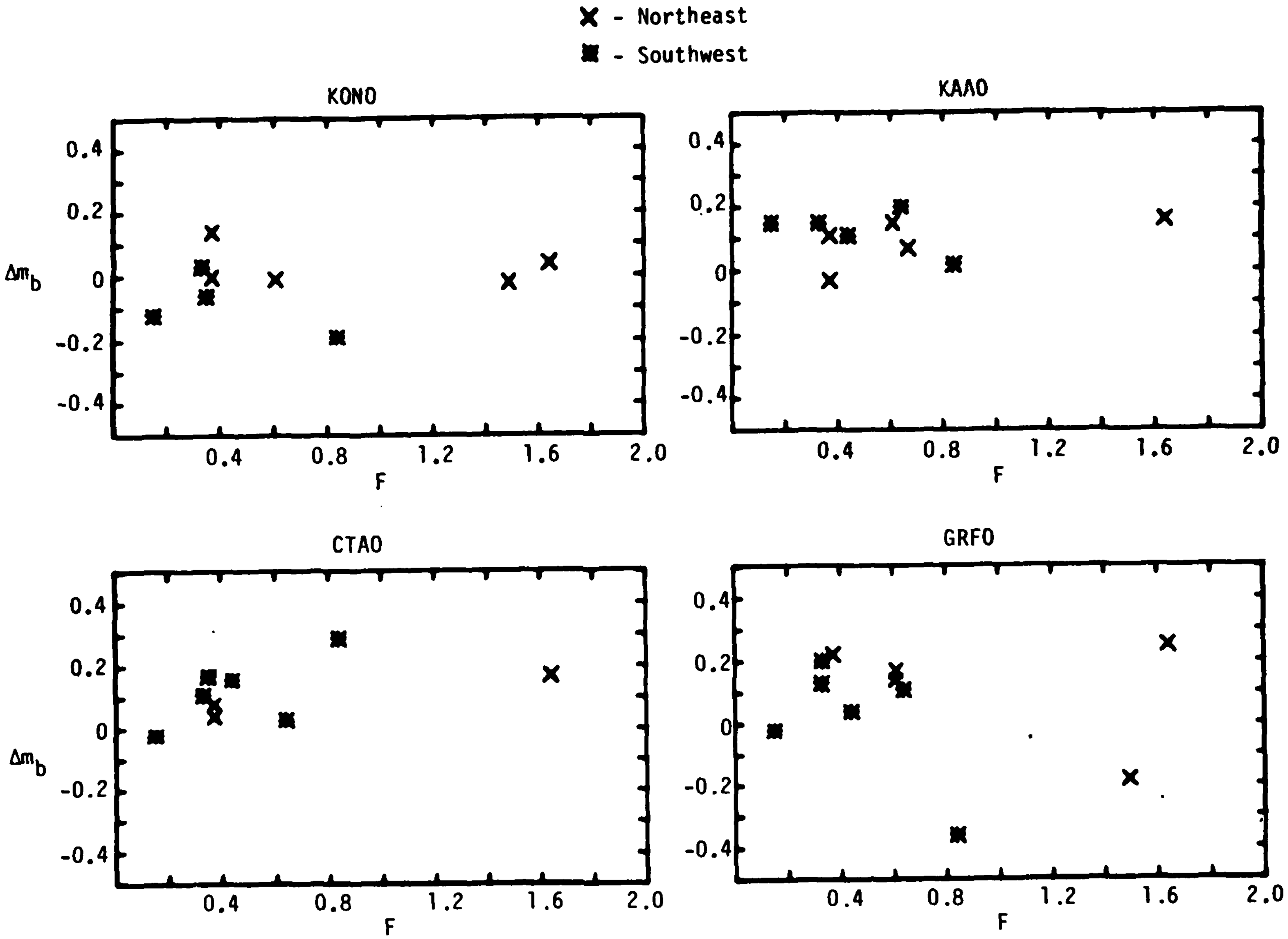


Figure 11. Single station m_b residuals as a function of tectonic release F factors for selected Shagan River explosions; stations KONO, KAAO, CTAO and GRFO.

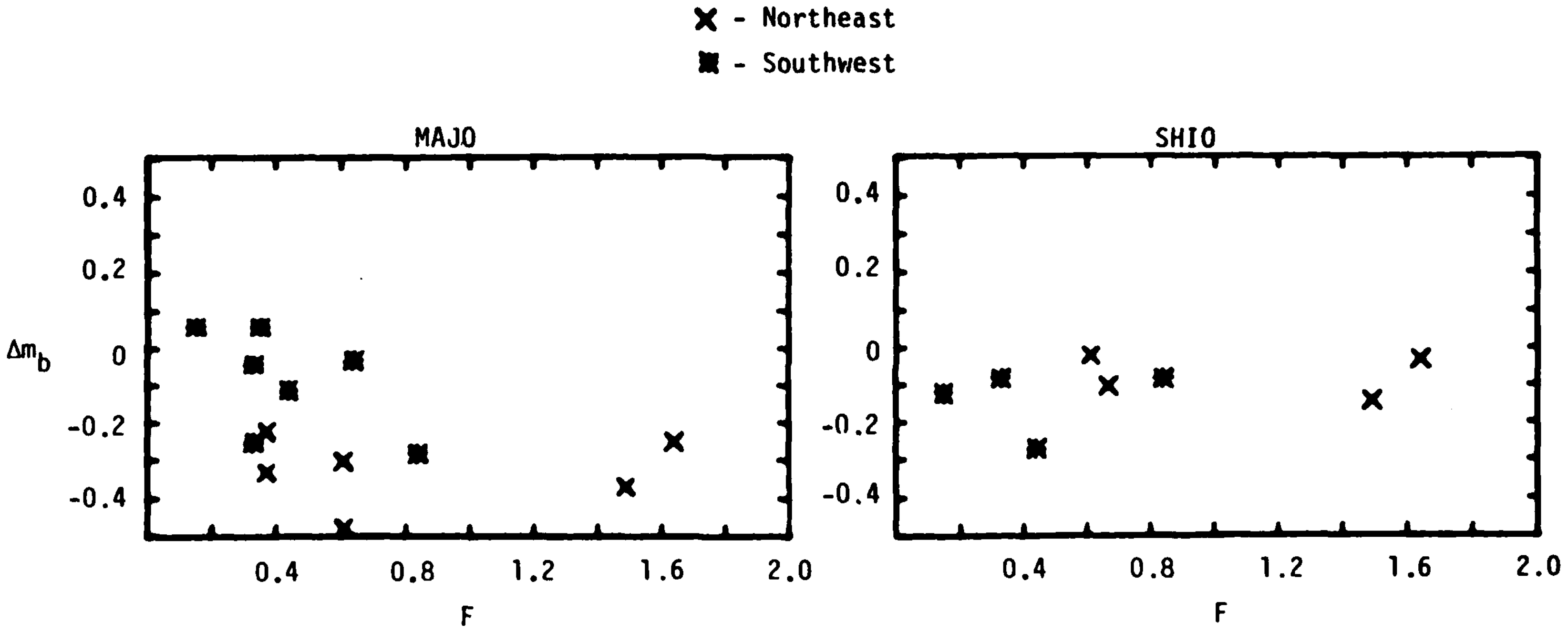


Figure 12. Single station m_b residuals as a function of tectonic release F factors for selected Shagan River explosions; stations MAJO and SHIO.

been used on these figures to denote events in the northeast (X) and southwest (⊠) portions of the test site. It can be seen from these figures that although hints of trends with F can be detected at some stations (e.g., the southwest events at CHTO, Figure 10), the scatter in these m_b residual data is generally too great to permit any definitive conclusions. However, it is perhaps significant that no trends with F are evident for those stations at which the residual data appear to be most consistent (i.e., BCAO, ANMO, KAAO, SHIO).

An alternate way of looking for any subtle effects that tectonic release may be having on the short-period P wave radiation pattern from Shagan River explosions is to compare the single station m_b residuals between pairs of stations at different azimuths. That is, if pairs of stations on opposite ends of the radiation pattern can be identified, then any tectonic effects on the amplitudes would be amplified by computing the interstation residual differences, thereby improving the probability of detecting any significant trends with F. With reference once again to Figure 6, it can be seen that the GDSN stations CHTO and KONO are located near a maximum of the P wave radiation pattern predicted for the Shagan River tectonic release model equivalent to thrust motion on a plane dipping at 45 degrees and striking at an azimuth of 325 degrees, while stations ANTO, BCAO, MAJO and KAAO are located near a predicted minimum. Therefore, interstation m_b residual differences have been computed between these latter four stations and stations CHTO and KONO. The results obtained using each of these reference stations are plotted as a function of F in Figures 13 (CHTO) and 14 (KONO) respectively. It can be seen from these figures that, as with the single station residual data shown previously in Figures 10-12, the scatter in the data at any given F value makes it difficult to draw any definitive conclusions. Once again, however, in those cases in which the variability is relatively small (e.g., BCAO-KONO and KAAO-KONO in Figure 14), no significant trends with F can be detected.

Thus, it can be concluded that the single station m_b residual data for Shagan River explosions show significant variability associated with non-tectonic effects which makes it difficult to isolate any

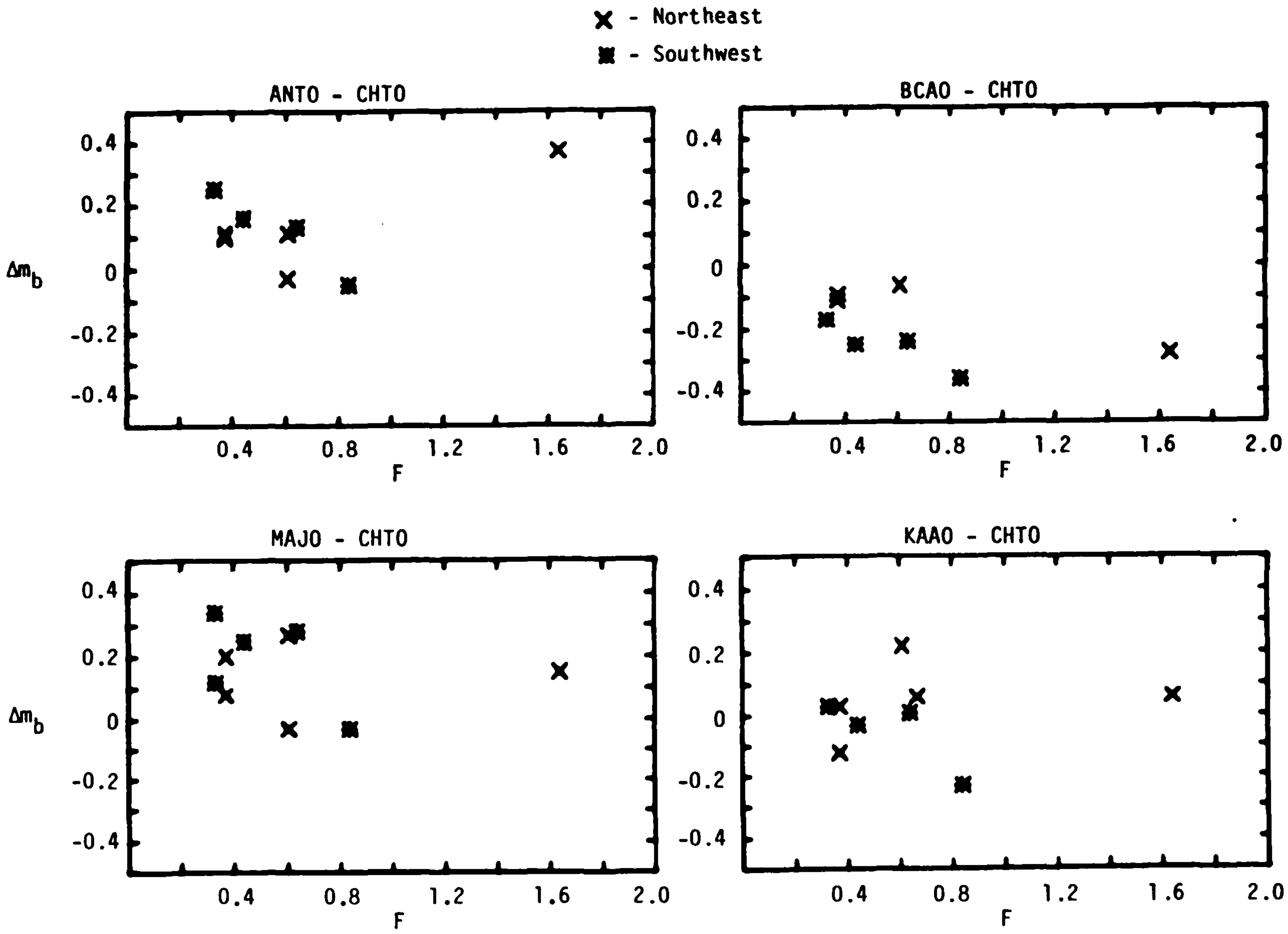


Figure 13. Differences of single station m_b residuals with respect to reference station CHTO as a function of tectonic release F factors for selected Shagan River explosions.

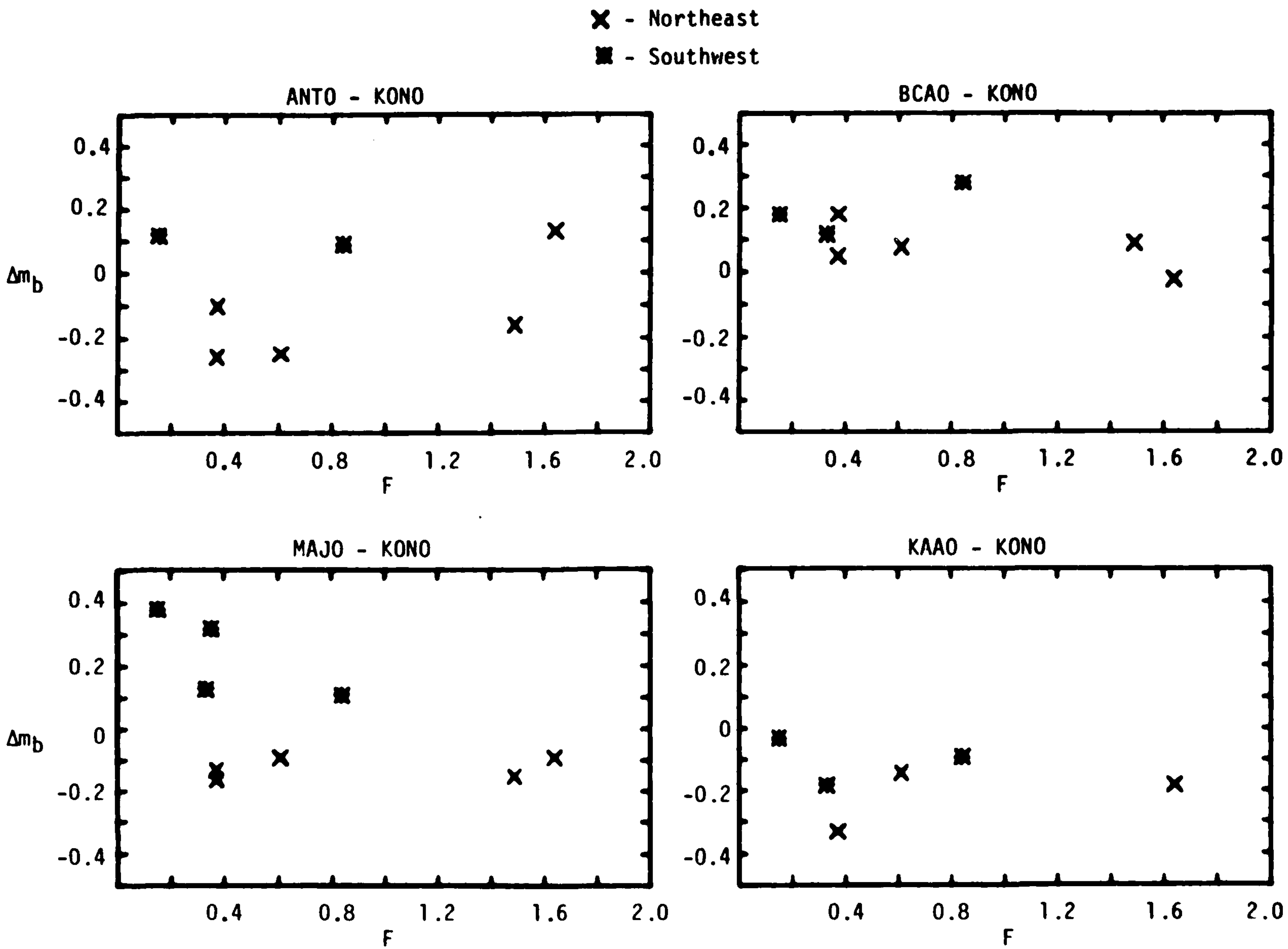


Figure 14. Differences of single station m_b residuals with respect to reference station KONO as a function of tectonic release F factors for selected Shagan River explosions.

tectonic effects on the short-period P wave radiation pattern. This finding is not surprising in view of the fact that Dermengian et al. (1985) have recently demonstrated that there are some pronounced correlations between m_b residual patterns and explosion location within the Shagan River test site which appear to be related to lateral variations in the subsurface geologic structure beneath the test site. In an attempt to minimize such non-tectonic effects, we have utilized the extensive ISC data base described by Dermengian et al. (1985) to test for effects of tectonic release using groups of nearby events representing a range of inferred tectonic release (i.e., F). In this analysis, inter-event correlate analysis has been used to determine whether the single station m_b residual patterns are correlated with the level of tectonic release inferred from long-period surface wave analyses. Thus, for a pair of events i and j with N recording stations common to both, the correlation between the event m_b residuals is defined as

$$r_{ij} = \frac{\text{sum } xy}{\sqrt{\text{sum } xx \cdot \text{sum } yy}} \qquad (2)$$

where

$$\text{sum } xy = \sum_{k=1}^{N} (x_k - \bar{x})(y_k - \bar{y})$$

$$\text{sum } xx = \sum_{k=1}^{N} (x_k - \bar{x})^2$$

$$\text{sum } yy = \sum_{k=1}^{N} (y_k - \bar{y})^2 \qquad (3)$$

$$\bar{x} = \frac{1}{N} \sum_{k=1}^{N} x_k$$

$$\bar{y} = \frac{1}{N} \sum_{k=1}^{1} y_k$$

x_k = the station-corrected m_b residual for event i at station k

y_k = the station-corrected m_b residual for event j at station k

Thus, if the tectonic release is having a significant effect on the P wave radiation pattern, then it would be expected that the interevent correlations computed between nearby events with comparable F values would be consistently higher than the interevent correlations computed between nearby events with different F values. In order to test this hypothesis, two clusters of eight events located in the northeast and southwest portions of the Shagan River test site were selected for analysis. The map locations of these two clusters are shown in Figure 15 where the event numbers and F values from Table 1 are indicated for reference purposes. It can be seen that the F factors assigned to the eight northeastern events range from 0.29 (event #15) to 1.62 (event #17) while the corresponding range for the eight southwestern events is between 0.15 (event #10) and 0.64 (event #14). The interevent correlation coefficients computed using an average of 30 common stations per event pair are displayed in Figures 16-19. In these figures the interevent correlation between each of the eight events and the other seven events in the cluster are displayed for purposes of comparison. Figures 16 and 17 show the results for the selected southwestern cluster of events. It can be seen that the interevent correlation coefficients characteristic of this cluster are generally quite low, typically on the order of ± 0.2. Moreover, there does not appear to be any evidence that the correlation coefficients are higher between events with similar F values. Thus, the interevent correlations computed with respect to event #14 (Figure 16), which has been assigned the highest F value (0.64) in this cluster, are quite similar to those computed with respect to some of the other reference events.

Similar comments apply to the results of the analysis of the northeastern cluster of events which are displayed in Figures 18 and 19. In this case, the interevent correlation coefficients are somewhat

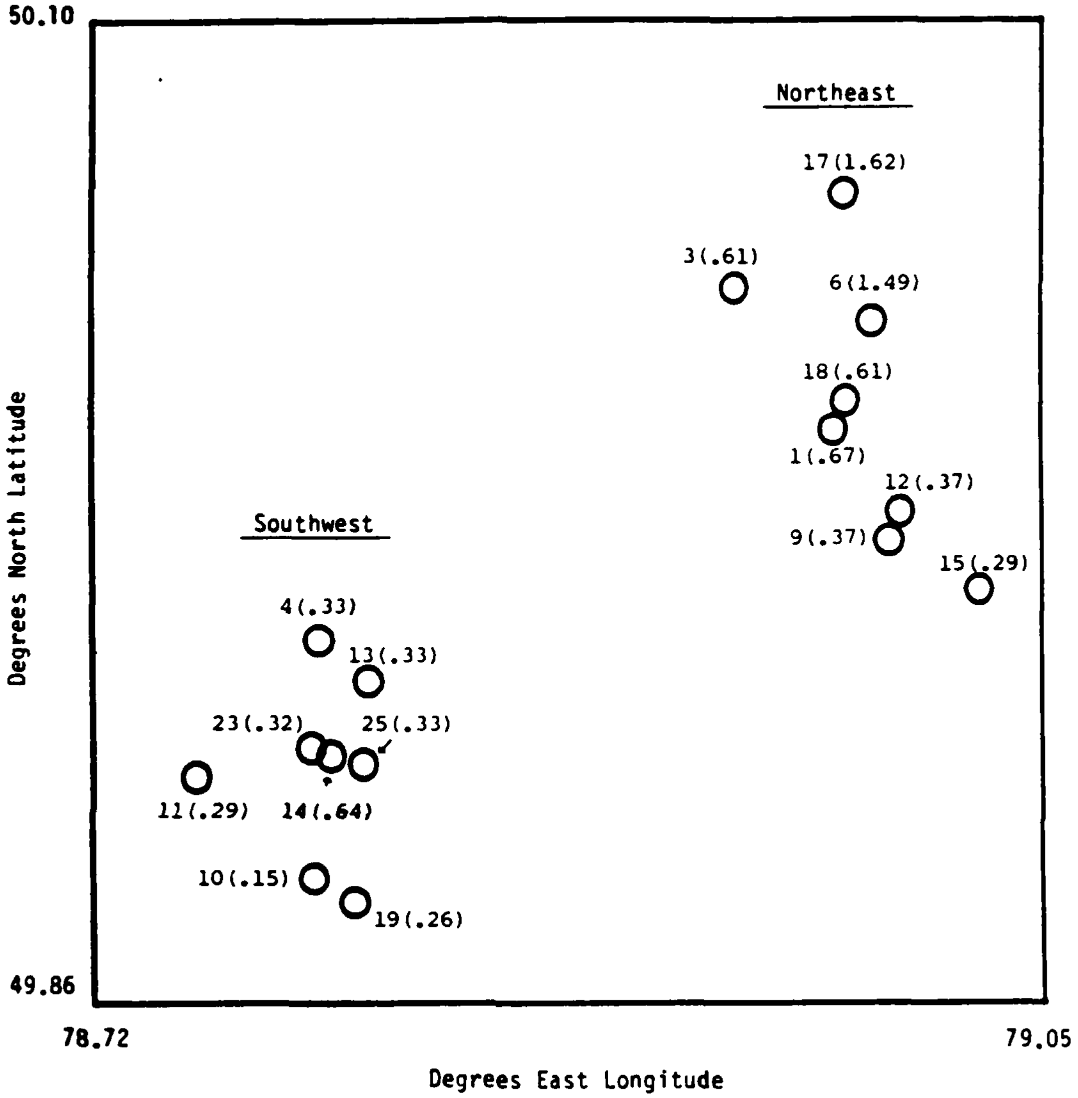


Figure 15. Map locations of northeast and southwest Shagan River explosions used in the interevent correlation analyses.

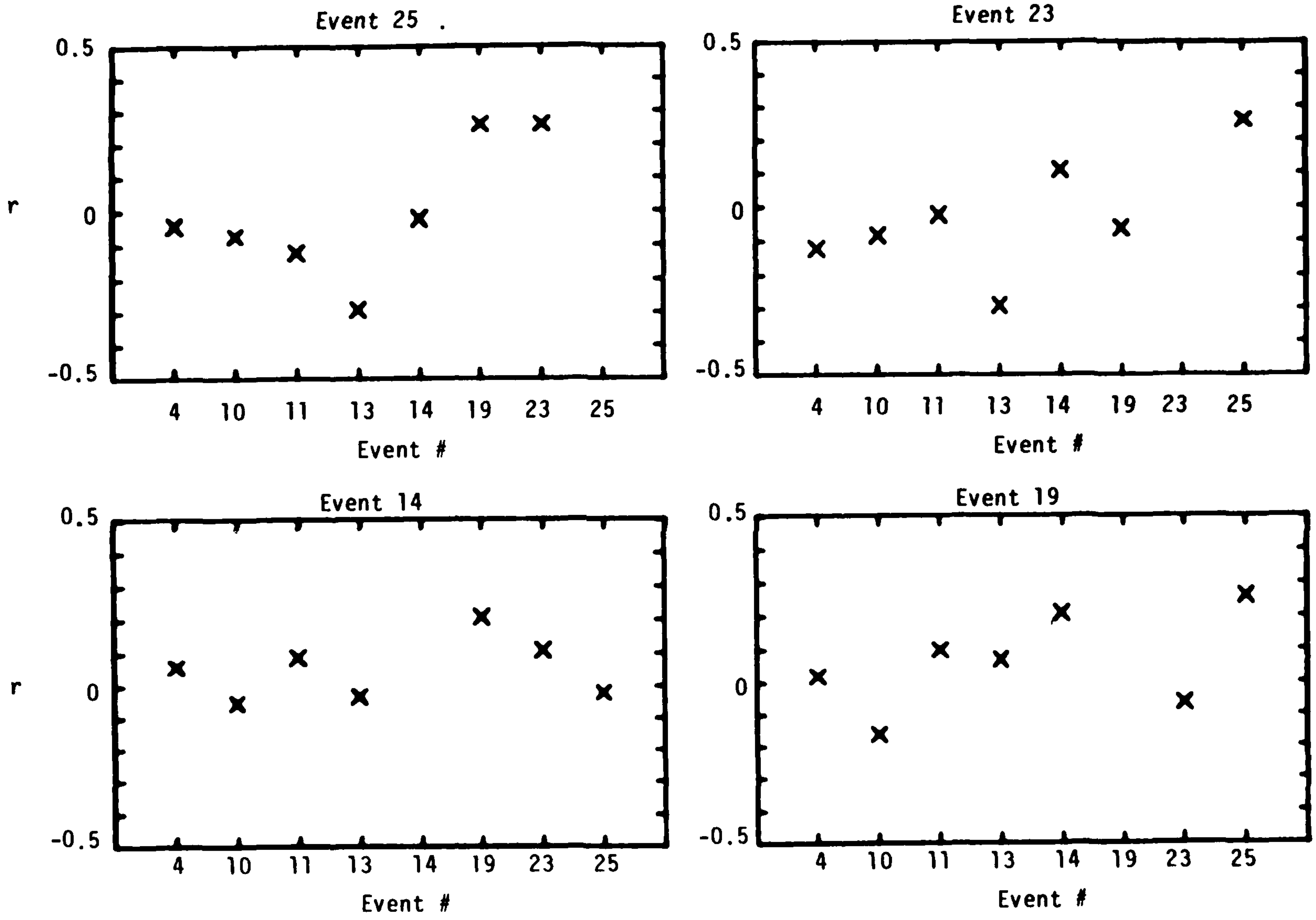


Figure 16. Interevent correlations between events 25, 23, 14, 19 and other nearby southwest Shagan River explosions.

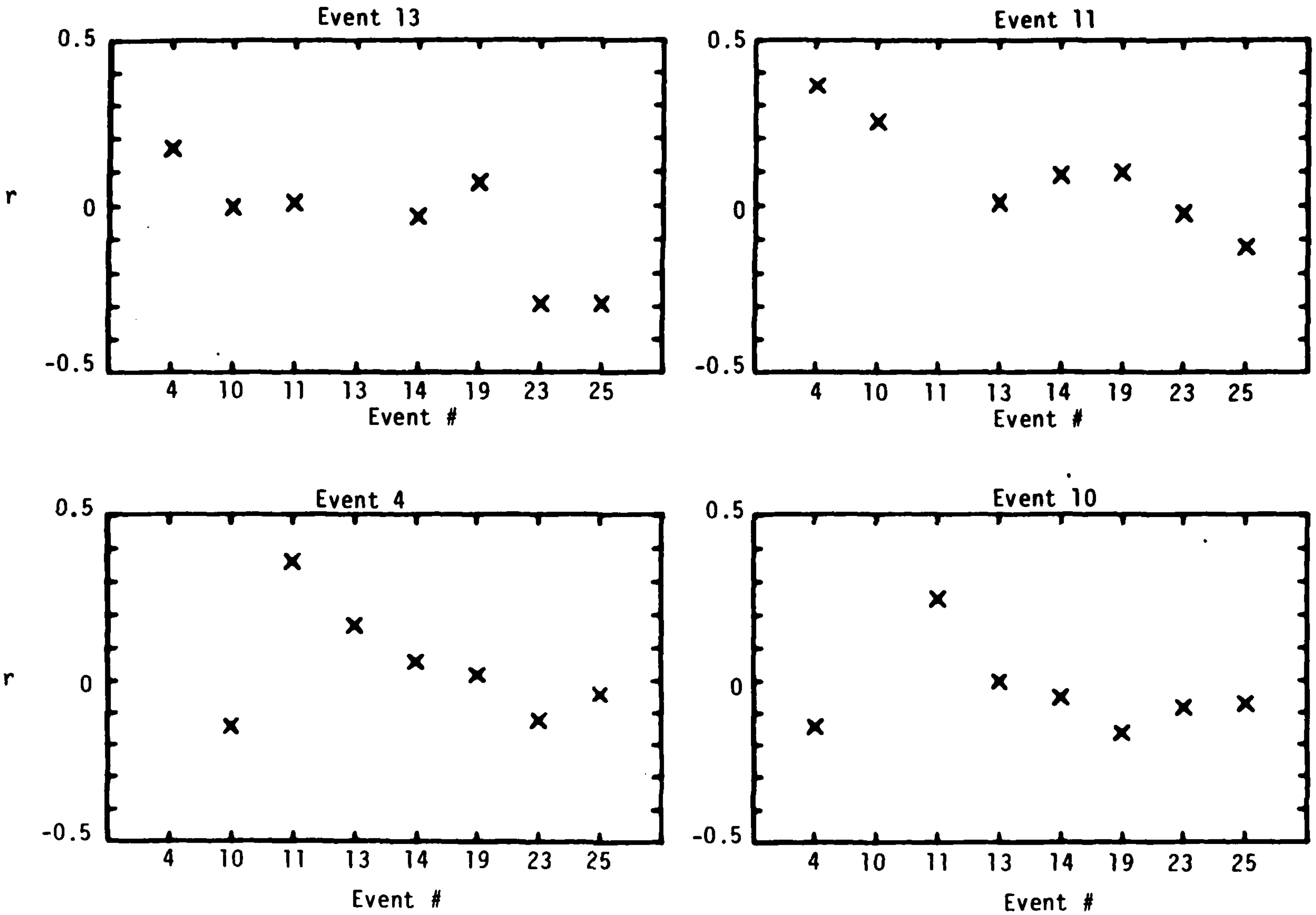


Figure 17. Interevent correlations between events 13, 11, 4, 10 and other nearby southwest Shagan River explosions.

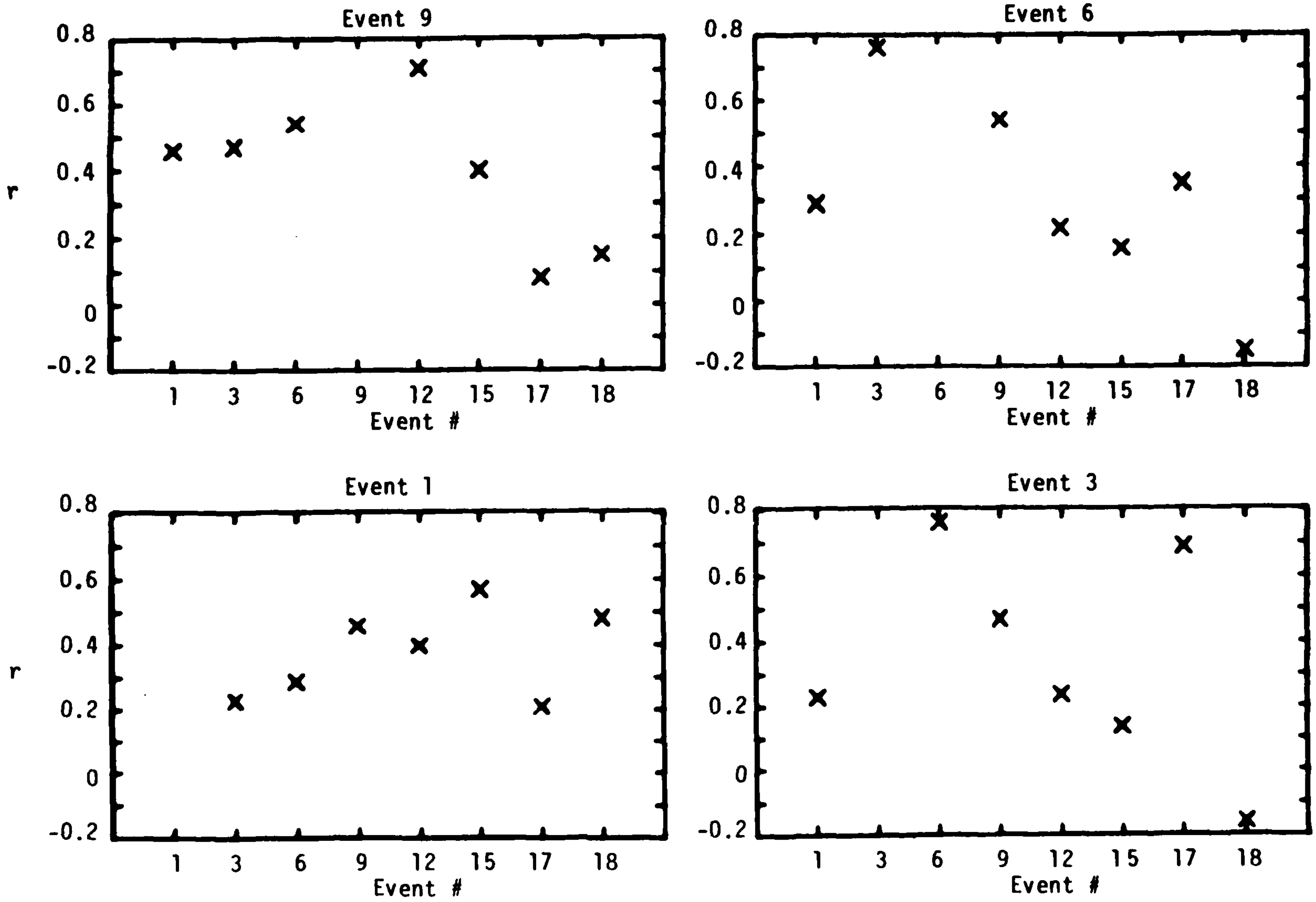


Figure 18. Interevent correlations between events 9, 6, 1, 3 and other nearby northeast Shagan River explosions.

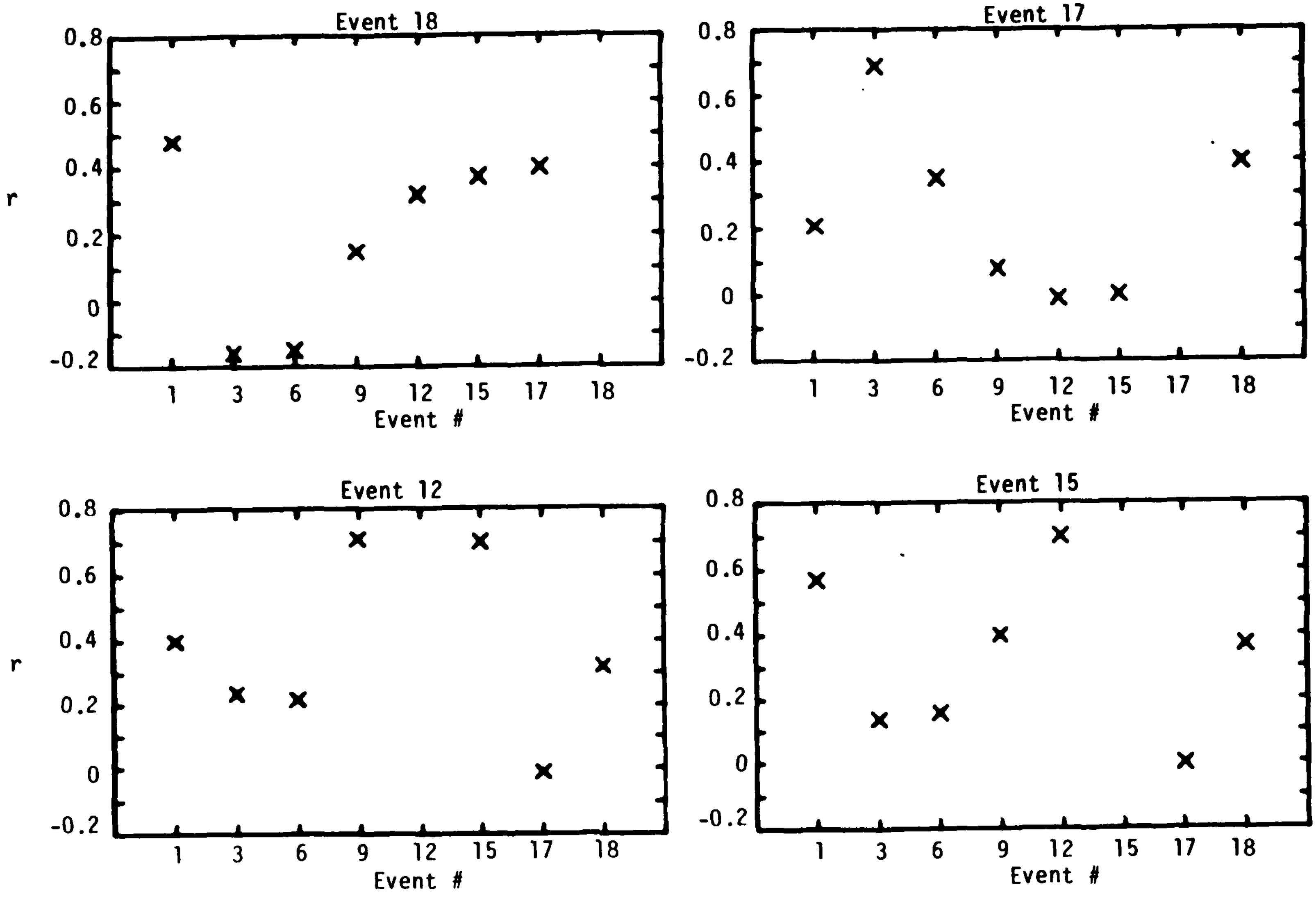


Figure 19. Interevent correlations between events 18, 17, 12, 15 and other nearby northeast Shagan River explosions.

higher, but again there is no indication that there is any systematic dependence on event F values. Thus, for example, the highest interevent correlation is observed between events #3 and #6 which have been assigned very different F values (i.e., 0.61 versus 1.49) and is significantly higher than that between events #1 and #18 which have been assigned essentially identical F values (i.e., 0.67 versus 0.61). Thus, these data also provide no conclusive evidence that tectonic release is affecting the short-period, teleseismic P wave radiation patterns observed from Shagan River explosions.

In summary, empirical investigations of short-period, teleseismic P wave data recorded from Shagan River explosions have not revealed any convincing evidence of tectonic release effects on m_b. These investigations have encompassed detailed comparisons of P waveforms recorded at selected GDSN stations as well as careful statistical analyses of large samples of short-period P wave amplitude data. It now remains to evaluate the significance of these observations in terms of an appropriate theoretical model, and that evaluation constitutes the subject to be discussed in the following section.

III. A PRELIMINARY THEORETICAL ANALYSIS OF THE EFFECTS OF TECTONIC RELEASE ON TELESEISMIC EXPLOSION P WAVES

Although the variety of careful empirical analyses described in the preceding section failed to turn up any unambiguous evidence of tectonic release effects on the short-period, teleseismic P waves observed from Shagan River explosions, this evidence is not sufficient to rule out the possibility that tectonic release may nevertheless be introducing systematic bias into the network-averaged m_b values assigned to these explosions. That is, as was noted in the introduction, it has already been demonstrated theoretically that there are modes of tectonic release which can significantly affect the amplitudes of the observed teleseismic P waves without producing any easily observable perturbations in the short-period P waveforms (e.g., Murphy and Archambeau, 1986). Therefore, it is appropriate to consider the types of effects which could theoretically be expected to be associated with the mode of tectonic release generally attributed to explosions at the Shagan River test site and to re-evaluate the observational results of Section II in terms of these theoretical predictions.

Despite the fact that the precise mechanism of the tectonic release accompanying underground explosions is still the subject of some controversy (e.g., Massé, 1981), it has generally been assumed for purposes of long-period analysis that the tectonic contribution can be modeled as a point double couple, co-located with the explosion source and sharing the same step function time dependence (e.g., Given and Mellman, 1986). The extension of this simple model into the short-period regime is subject to a variety of uncertainties. However, for the purposes of the present analysis, we will proceed with the simplest model and assume that the source of the short-period tectonic radiation is effectively coincident in space and time with that of the explosion. This assumption is consistent with the Archambeau model of tectonic release in which the relaxation of the tectonic prestress field around the explosion-induced fracture zone surrounding the detonation point is the source of the tectonic radiation (Archambeau, 1972; Stevens, 1980). Alternate models which predict significant time delays between the explosion and tectonic short-period P waves, while perhaps appropriate in some cases, would appear to be inconsistent with the results of the Shagan River waveform comparisons described previously in Section II.

Following Stevens and Day (1985), the teleseismic P wave displacement spectrum associated with an underground explosion can be expressed in the form

$$U_x(\omega) = \frac{M_x(\omega)}{4\pi(\rho\rho_x\ \alpha\alpha_x^5)^{\frac{1}{2}}\ S(\Delta)} \tag{4}$$

where $M_x(\omega)$ is the P wave source spectrum, $S(\Delta)$ is the geometrical spreading factor, α_x, ρ_x are the P wave velocity and density of the source medium and α, ρ are the P wave velocity and density of the medium at the observation point. Similarly, the teleseismic P wave displacement spectrum due to a point double couple tectonic release can be written in the form

$$U_q(\omega) = \frac{M_q(\omega)\ R(\theta,\phi)}{4\pi(\rho\rho_q\ \alpha\alpha_q^5)^{\frac{1}{2}}\ S(\Delta)} \tag{5}$$

where $R(\theta,\phi)$ is the P wave radiation pattern given by

$$\begin{aligned} R(\theta,\phi) = \cos\lambda & \left[\sin\delta\ \sin^2\theta\ \sin 2\phi\ - \cos\delta\ \sin 2\theta\ \cos\phi\right] \\ & + \sin\lambda\left[\sin 2\delta\ \cos^2\theta\ - \sin 2\delta\ \sin^2\theta\ \sin^2\phi\ + \cos 2\delta\ \sin 2\theta\ \sin\phi\right] \end{aligned} \tag{6}$$

where δ and λ are the dip and rake associated with the double couple orientation, θ is the takeoff angle of the ray at the source and ϕ is the station azimuth measured clockwise from the strike direction. Now, if as is generally assumed, the mode of tectonic release accompanying explosions at the Shagan River test site is equivalent to thrust motion on a plane dipping at 45°, then $\delta = 45°$ and $\lambda = 90°$ and (6) reduces to

$$R(\theta,\phi) = \cos^2\theta - \sin^2\theta \sin^2\phi \tag{7}$$

It follows that the teleseismic P wave displacement spectrum due to the superposition of an explosion and a coincident tectonic release can be written as

$$U(\omega) = \frac{1}{4\pi(\rho\rho_s \alpha\alpha_s^5)^{\frac{1}{2}} S(\Delta)} \left[M_x(\omega) + M_q(\omega) (\cos^2\theta - \sin^2\theta \sin^2\phi) \right] \tag{8}$$

where subscript s denotes the source medium common to both sources.

This model can be used to theoretically simulate the expected effects of tectonic release on the explosion short-period teleseismic P waveforms and amplitudes. First, with respect to the waveforms, Figure 20 shows a comparison of synthetic P waves corresponding to an explosion and associated tectonic release, as well as the results of superposing these two waveforms with different relative amplitudes. In this case the simulation has been carried out for a recording through a standard WWSSN short-period instrument at an epicentral distance of about 4000 km. The explosion source function corresponds to the Mueller/Murphy (1971) approximation for a 100 kt detonation at a depth of 1 km in granite, while the tectonic source function is that predicted by the Archambeau model for the case in which the prestress orientation is equivalent to thrust motion on a fault dipping at 45°. It can be seen that the synthetic P waveforms corresponding to these two sources are essentially identical. As a result, the superposition of the two leads to a waveform which is indistinguishable from the explosion waveform, even for cases in which the amplitude of the tectonic release P wave is taken to be larger than that of the explosion P wave. Moreover, although the results in Figure 20 are for one particular azimuth (i.e., $\phi = 0$), they are in fact generally applicable in that the teleseismic P waveform predicted for this assumed mode of tectonic release is nearly independent of azimuth. This fact is illustrated in Figure 21 where the tectonic P

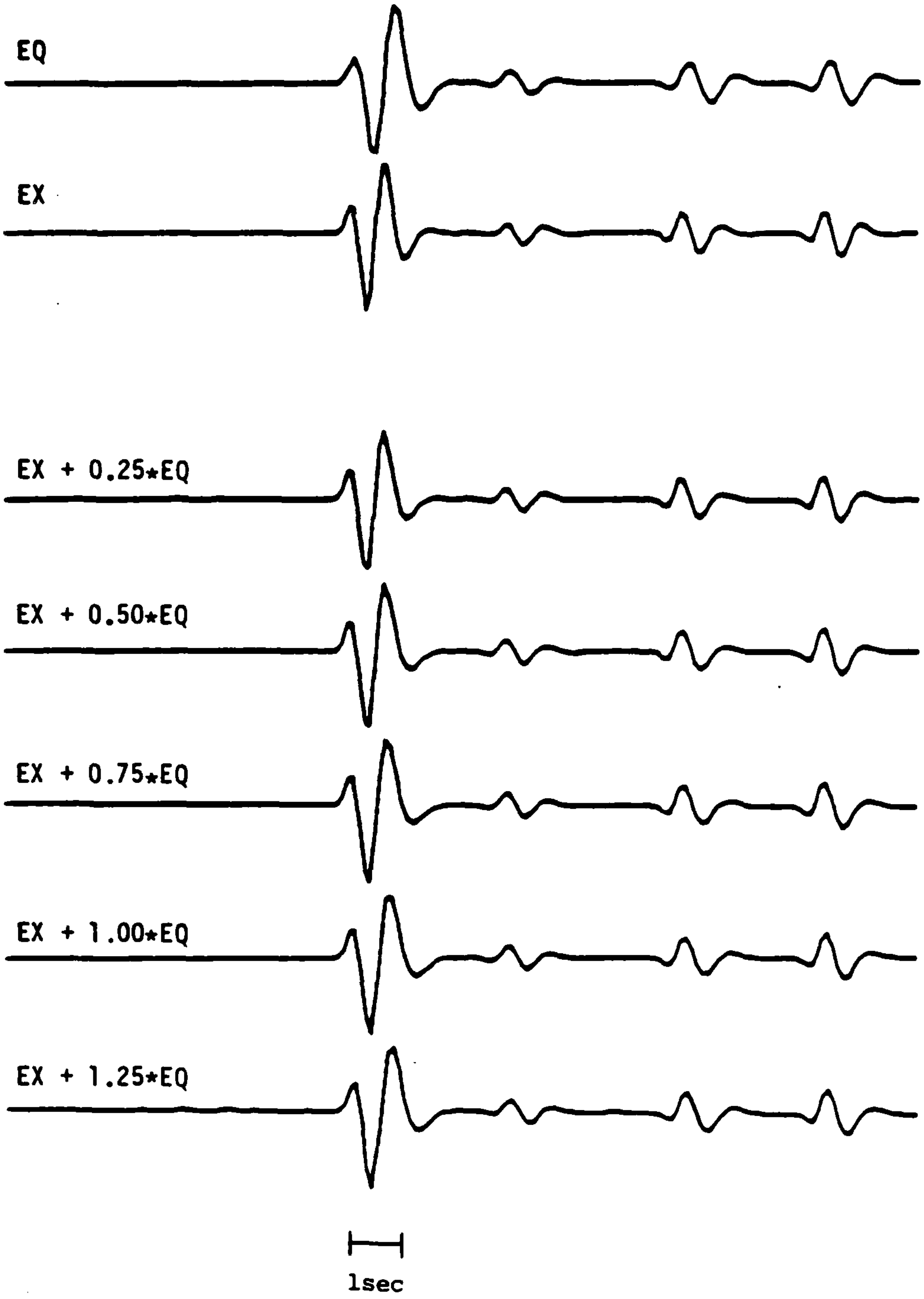


Figure 20. Comparison of synthetic teleseismic P waves corresponding to an explosion (EX), an associated tectonic release (EQ) and the results of superposing the two waveforms with different relative amplitudes.

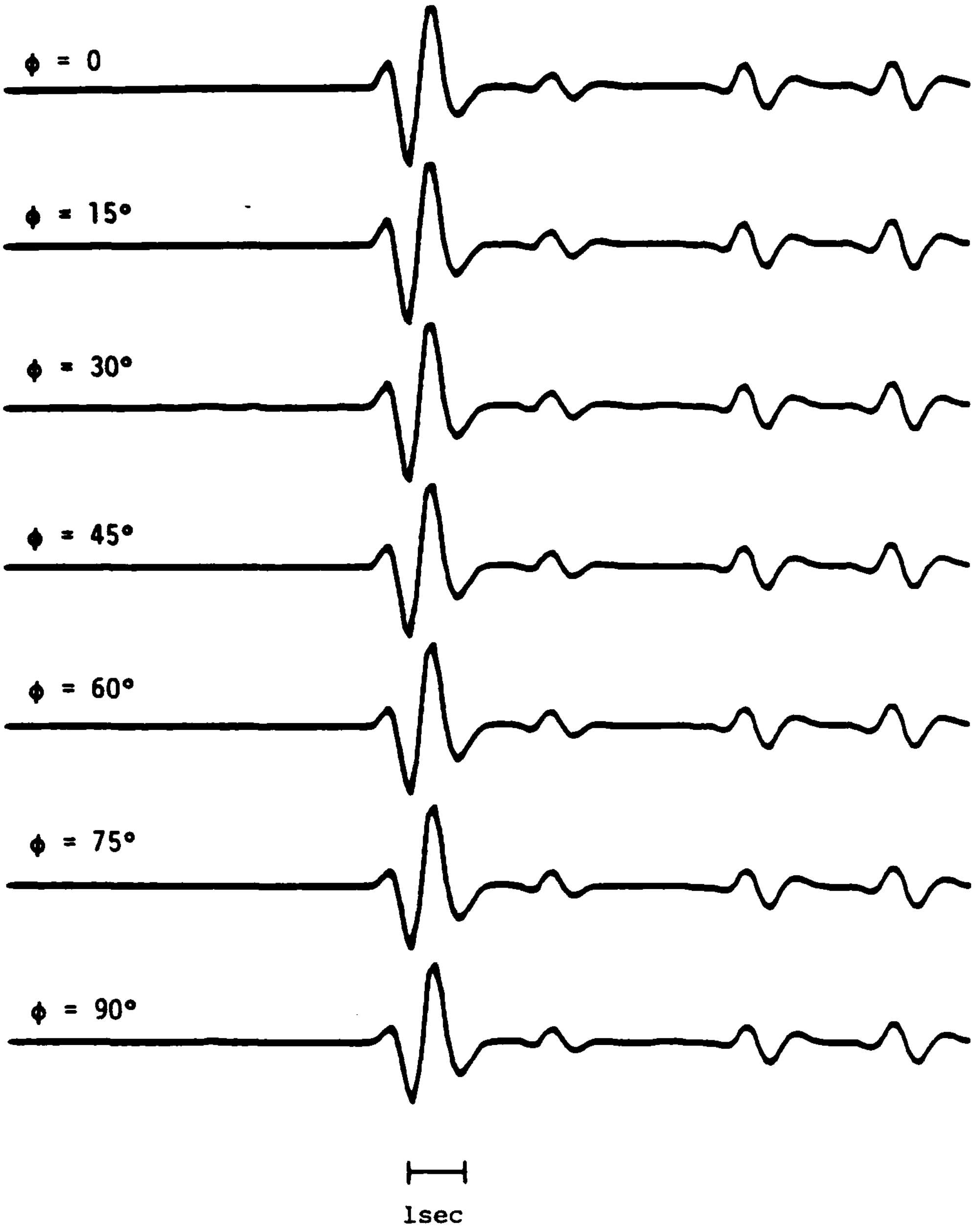


Figure 21. Azimuthal dependence of synthetic teleseismic P waves corresponding to a mode of tectonic release equivalent to thrust faulting on a plane dipping at 45 degrees.

waveforms are displayed as a function of azimuth between 0 and 90 degrees for the same source and epicentral distance employed in Figure 20. It follows that such a model of tectonic release is consistent with the observed P wave data from Shagan River explosions described in Section II in that it predicts no detectable effects on the teleseismic P waveforms.

The corresponding effects on the P wave amplitudes can be estimated by applying some additional approximations in equation (8). Thus, factoring out the explosion source function, $M_x(\omega)$, (8) can be rewritten in the form

$$U(\omega) = \frac{M_x(\omega)}{4\pi(\rho\rho_s \, \alpha\alpha_s^5)^{1/2} \, S(\Delta)} \left[1 + \frac{M_q(\omega)}{M_x(\omega)} \left(\cos^2\theta - \sin^2\theta \, \sin^2\phi\right) \right] \tag{9}$$

Now if it is further assumed that $M_q(\omega)$ and $M_x(\omega)$ have the same frequency dependence, it follows that

$$\frac{M_q(\omega)}{M_x(\omega)} \approx \frac{M_q(o)}{M_x(o)} = F \tag{10}$$

where F is simply the ratio of the tectonic to the explosion moment traditionally used in surface wave analyses to quantify the relative strength of the tectonic release at long periods (e.g., Given and Mellman, 1986). This extension of the long-period description of tectonic release to short-periods is highly uncertain, but it should provide upper bound estimates of the effects of tectonic release on m_b in that Stevens and Day (1985) have shown that, for a given moment, $M_x(1\text{Hz}) > M_q(1\text{Hz})$ for explosions with yields in the 100 kt range due to overshoot in the explosion seismic source function. In any case, it follows from equations (9) and (10) that for a teleseismic takeoff angle of $\theta = 30°$, the effect of tectonic release on m_b is given approximately by the expression

$$\Delta m_b \approx \log \left[1 + F \, (0.75 - 0.25 \sin^2\phi) \right] \tag{11}$$

Note that for the assumed thrust mechanism Δm_b is always greater than zero, which indicates that this mode of tectonic release would be expected to lead to estimates of network-averaged explosion m_b values which are biased high.

The m_b bias as a function of F predicted by equation (11) is plotted versus azimuth in Figure 22. It can be seen that while this model does predict some azimuthal variation in the single station m_b values, the predominant effect is a potentially large positive bias in the network-averaged m_b value. For example, for an F value of 1.3 this model predicts a bias of more than 0.25 units in the network-averaged m_b value. However, the accompanying predicted azimuthal variations in the single station m_b values are so small that they would be extremely difficult to detect in the observed data. This fact is illustrated in Figure 23 which shows the predicted single station m_b residuals, with respect to the predicted network-averaged m_b value, plotted as a function of F for stations at azimuths of 0 and 90 degrees, where the maximum effects are expected for the assumed mode of tectonic release. It can be seen that even for F factors as large as 2, the absolute value of the predicted m_b residuals are less than 0.05 units. Thus, once again, this model is consistent with the teleseismic P wave amplitude data described in Section II in that it predicts no detectable azimuthal variations in the P wave amplitudes. Of course, Figures 22 and 23 are derived from equation (11) which describes effects of tectonic release on the direct P waves alone and does not account for the effects of the surface reflected phases pP and sP. It is not yet clear to what extent such depth phases contribute to the teleseismic P waves for shallow explosions accompanied by nonlinear surface interactions such as spall. However, if anything, the radiation pattern predicted by including the classical elastic pP and sP phases results in an even less pronounced azimuthal variation in the single station m_b values for this mode of tectonic release. This fact is illustrated in Figure 24 where the azimuthal variation of the single station m_b values predicted with and without depth phases are compared for an assumed source depth of 1 km. The effects of the pP and sP phases on the predicted tectonic P wave amplitudes are

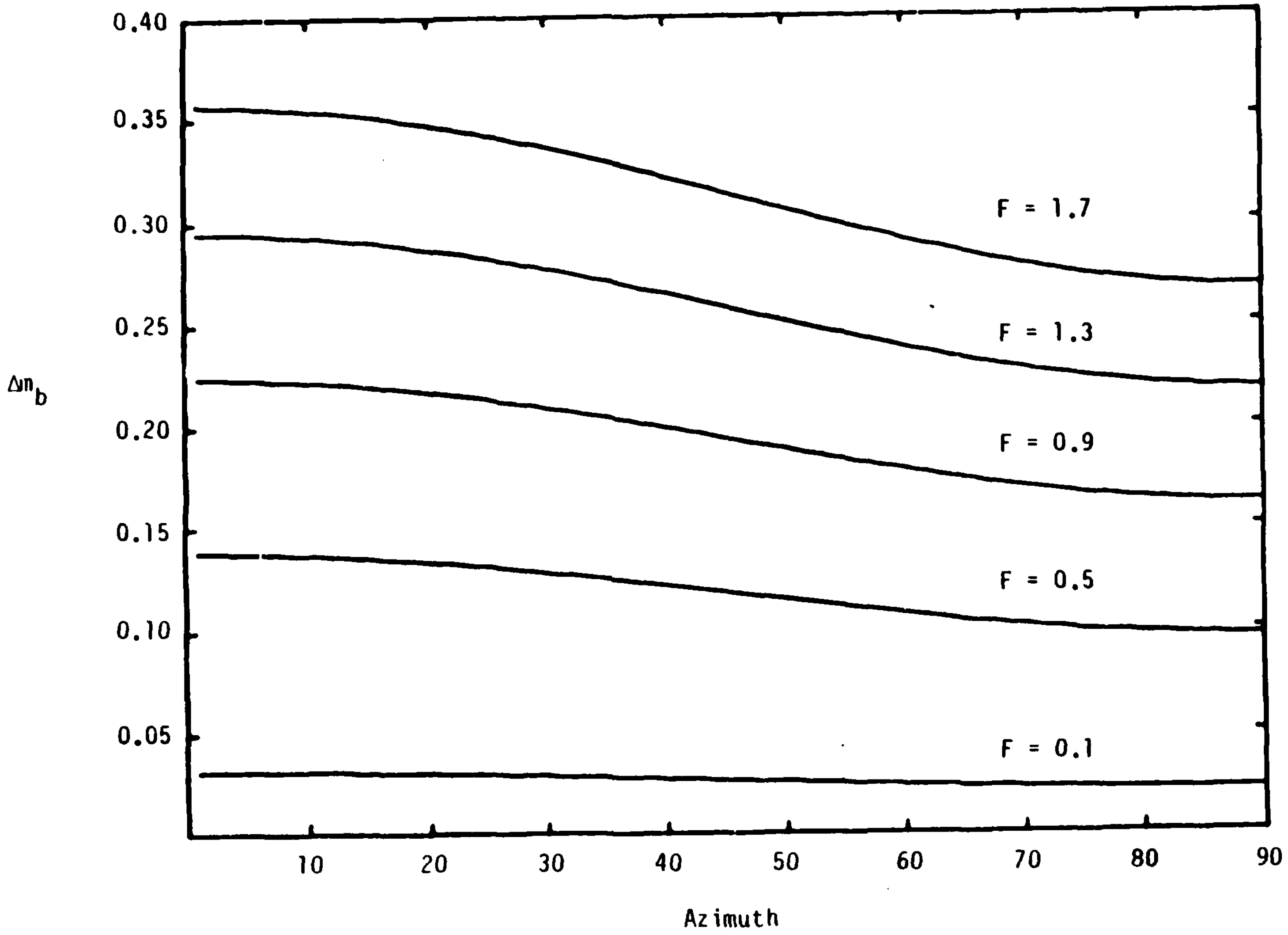


Figure 22. Predicted bias in single station explosion m_b values as a function of station azimuth due to tectonic release effects corresponding to different F values.

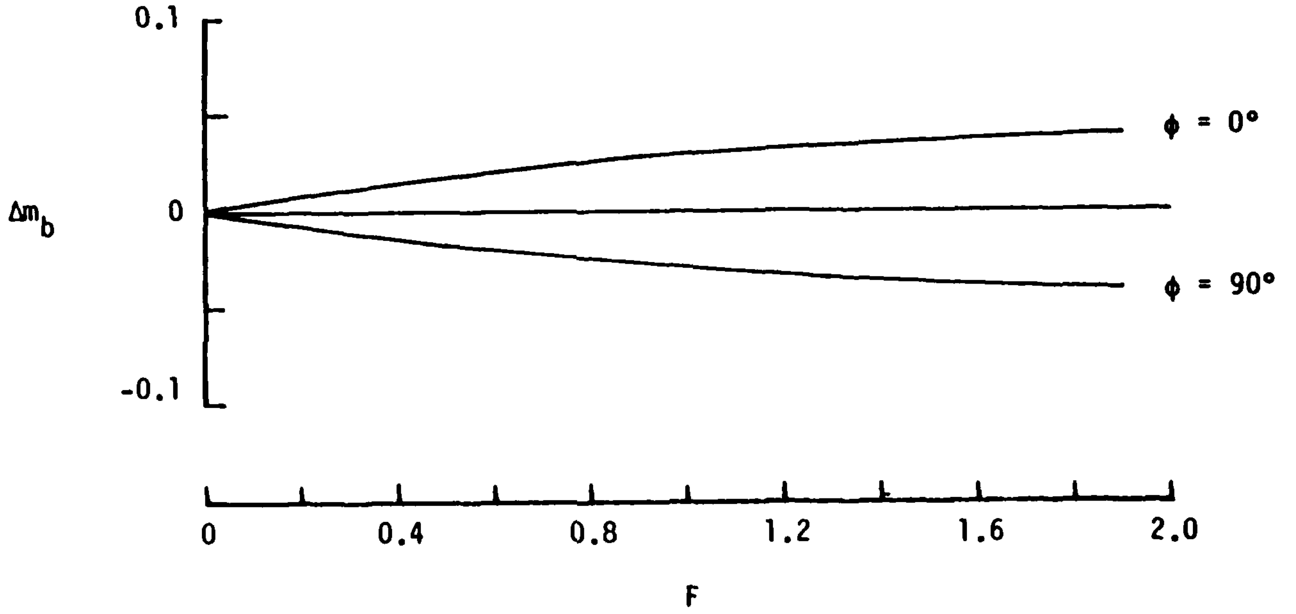


Figure 23. Predicted variation of single station explosion m_b residuals as a function of the tectonic release parameter F for stations at azimuths of 0 and 90 degrees.

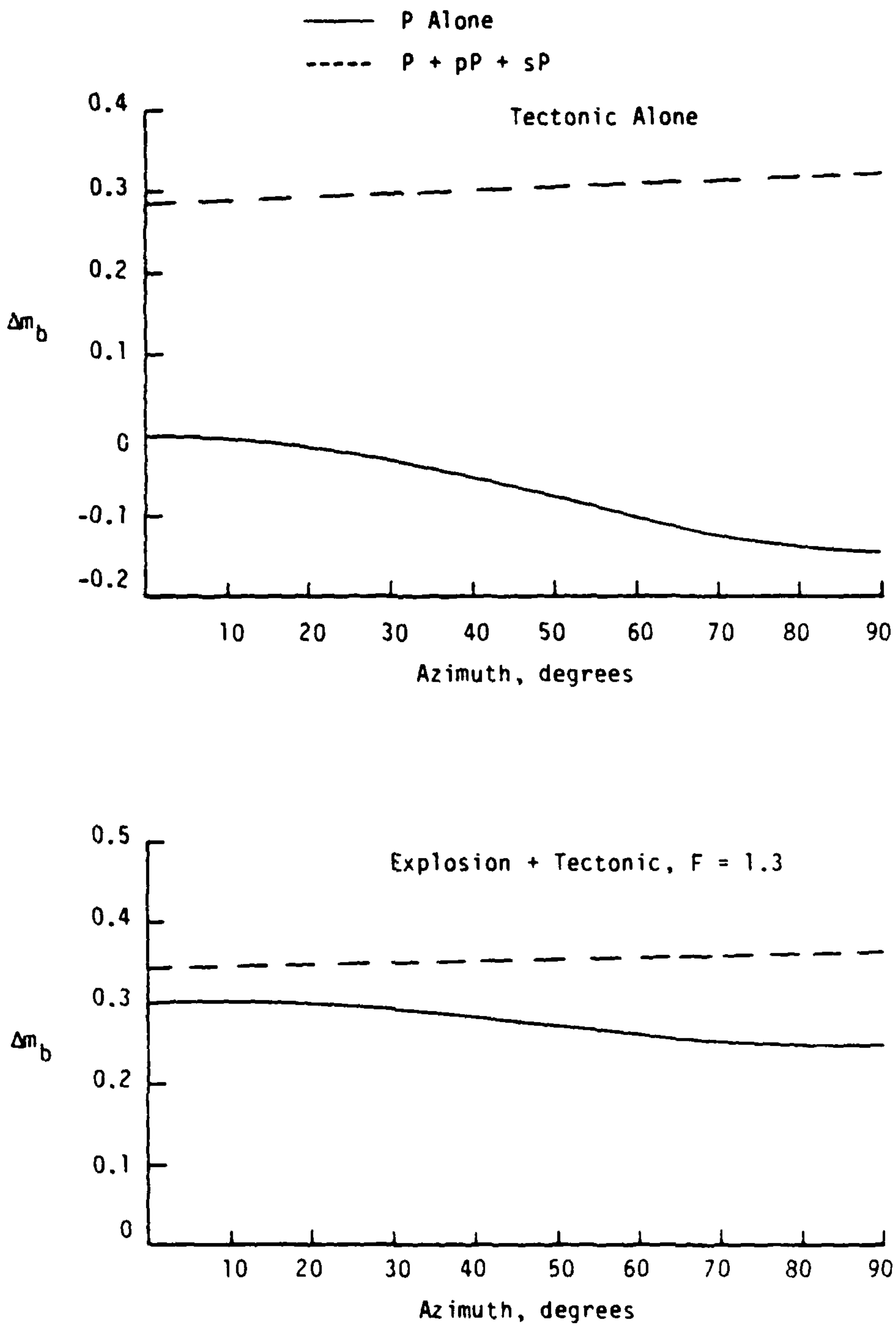


Figure 24. Comparison of predicted effects of source depth phases (pP and sP) on the teleseismic P waves corresponding to tectonic release alone (top) and to the superposition of explosion and tectonic release waveforms consistent with an F value of 1.3 (bottom).

illustrated at the top of Figure 24 where it can be seen that the inclusion of these depth phases results in a radiation pattern which is even more nearly independent of azimuth than that predicted for the P wave alone. As for the corresponding shallow explosion, the principal predicted effect of the depth phases is to increase the m_b values by about 0.3 units (i.e., to essentially double the P wave amplitude). The radiation patterns and m_b bias predicted for the superposition of explosion and tectonic release with and without depth phases are compared at the bottom of Figure 24 for the case F = 1.3. Again, it can be seen that the inclusion of depth phases results in an even smaller azimuthal dependence in the predicted single station m_b values and, at the same time, increases the estimated bias in the network-averaged m_b value by a small amount. This latter effect is due to the influence of the sP phase which has no counterpart in the explosion waveform. In any case, neither model predicts an azimuthal variation in the single station m_b values which is large enough to be detectable in the measured data.

It follows from the above analysis that tectonic release at Shagan River may be producing a significant positive bias in some explosion m_b values which is unaccompanied by any detectable change in the observed short-period teleseismic P waves. The predicted magnitude of this effect at a fixed yield is displayed as a function of F in Figure 25 where it can be seen that the predicted bias is greater than 0.1 units m_b even for events with F factors as low as 0.4 and exceeds 0.3 units m_b for events with F factors greater than about 1.5. These predicted effects are large and would presumably be detectable if the observed Shagan River m_b values could be normalized to a common yield. Now while the yields of these explosions are not currently known, Given and Mellman (1986) have recently published a list of isotropic (i.e., explosion) moment estimates (M_I) for a number of Shagan River explosions which they have estimated through moment tensor analyses of the long-period surface wave data recorded from these events. Now, making the usual assumptions that M_I is directly proportional to yield and that the slope of the magnitude-yield curve is about 0.9 (Given and Mellman, 1986), it follows that the quantity $0.9 \log M_I - m_b$ as a function of F should be directly comparable to

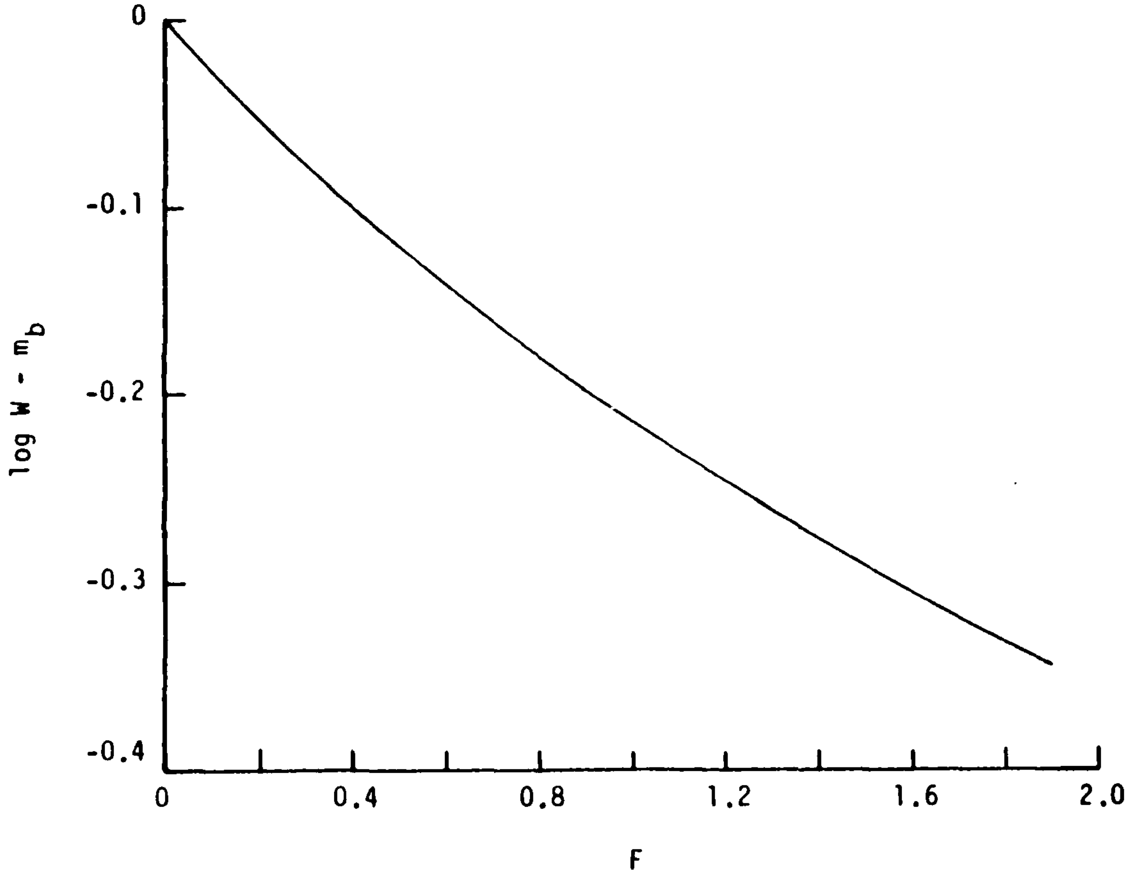


Figure 25. Predicted bias in explosion network-averaged m_b values due to tectonic release effects corresponding to different F values.

the predicted bias dependence on F shown in Figure 25. Such a comparison is shown in Figure 26 where the observed values were computed using the M_I and m_b values for the Shagan River explosions listed in Given and Mellman (1986). It can be seen that there may be some hint of a trend in these data which parallels the F dependence predicted by the simple tectonic model. However, the large scatter at fixed F values makes it impossible to draw any definitive conclusions. This scatter has been noted before and may reflect variations in the mode of tectonic release accompanying different Shagan River explosions. About all that can be said at the present time is that these data do not exclude the possibility that the tectonic release accompanying Shagan River explosions may be introducing a significant positive bias into the network-averaged m_b values computed for some explosions. Additional independent data will be required to finally resolve this issue. In the meantime, the effects predicted by the simple model described in this section should provide conservative, upper bound estimates of the influence of tectonic release on Shagan River explosion m_b values.

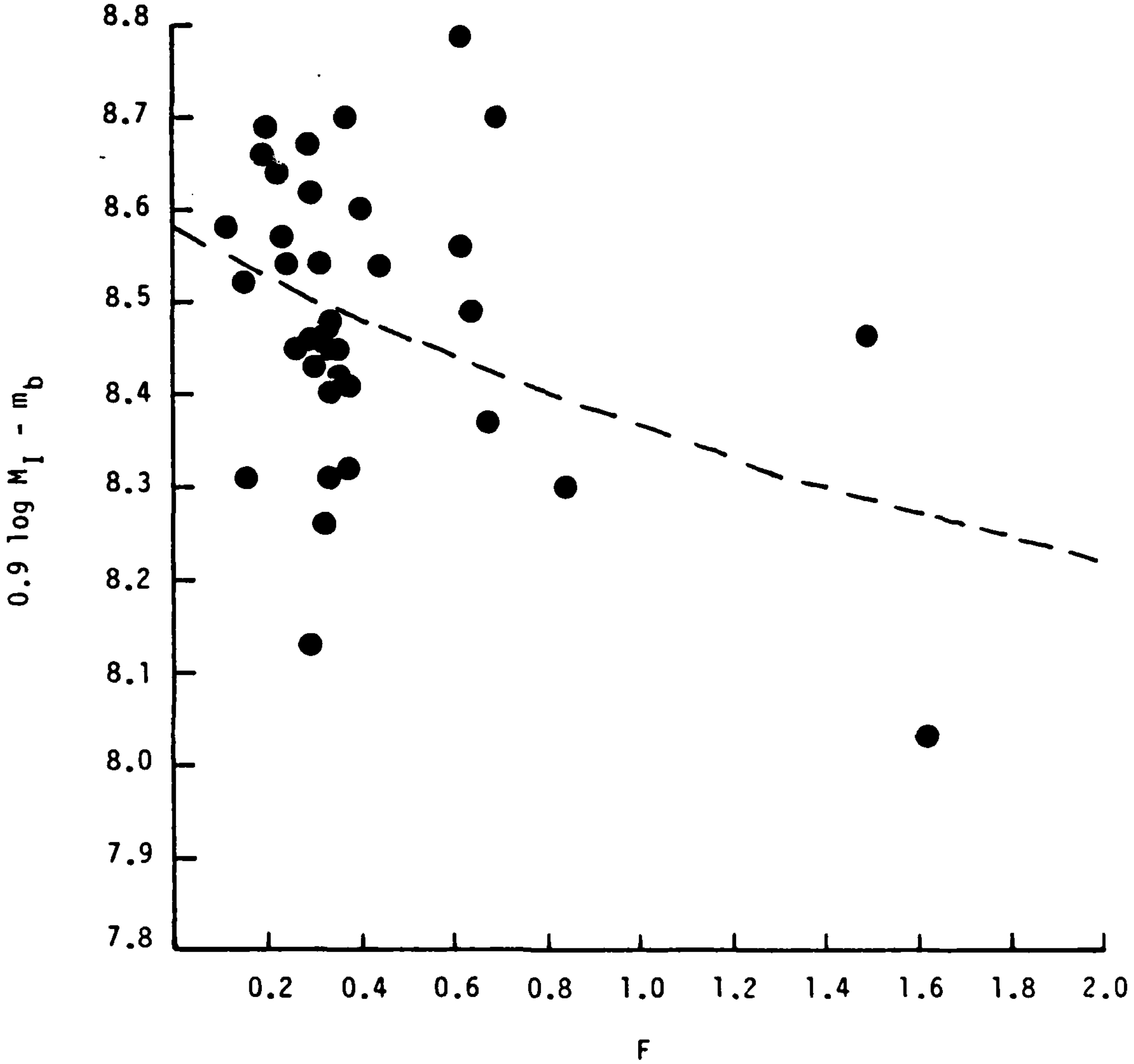


Figure 26. Comparison of observed variations in log M_I - m_b as a function of F for selected Shagan River explosions (Given and Mellman, 1986) with the variations predicted due to tectonic release effects on m_b (dashed line).

IV. SUMMARY AND CONCLUSIONS

4.1 SUMMARY

The investigations summarized in this report have centered on an analysis of the possible effects of tectonic release on the m_b values observed from underground nuclear explosions at the Shagan River test site. Specifically, large samples of teleseismic P wave amplitude and waveform data recorded from explosions at this test site have been collected and systematically analyzed in an attempt to identify any effects which may correlate with tectonic release and the results of these empirical studies have been evaluated using a simple theoretical model to simulate the range of potential effects of tectonic release on short-period explosion P waves.

The teleseismic P wave data base which has been assembled for the purposes of this project was described in Section II where the associated source and station parameters to be used in the analysis were documented and described in detail. The primary data base is composed of digital, short-period P wave recordings of 25 representative Shagan River explosions recorded at 11 selected GDSN stations. These data were then carefully analyzed using a variety of statistical techniques in an attempt to identify any correlations with the degree of tectonic release inferred from previous analyses of the corresponding long-period surface wave data recorded from these same explosions. The results of these analyses were then used to demonstrate the fact that these teleseismic P wave data do not provide any unambiguous evidence of effects of tectonic release at the short-period range of interest in m_b determination.

The significance of the empirical results of Section II was evaluated theoretically in Section III where a simple, analytical model of tectonic release was used to simulate the expected effects on short-period P wave amplitudes for the mode of tectonic release which has been traditionally associated with explosions at the Shagan River test site. In particular, the theoretical model was used to simulate short-period P waveforms to be expected at the GDSN stations over a wide range of assumed levels of tectonic release. In addition, this model was used to simulate tectonic effects on teleseismic P wave amplitudes and plausible upper bounds were established on the possible effects on Shagan River explosion m_b values associated with the range of tectonic release inferred from the corresponding long-period surface wave data.

4.2 CONCLUSIONS

The analyses summarized above support the following principal conclusions regarding the possible effects of tectonic release on the m_b values observed from explosions at the Shagan River test site.

(1) Empirical investigations of short-period, teleseismic P wave data recorded from Shagan River explosions do not reveal any convincing evidence of effects of tectonic release on m_b. In particular, waveforms measured at selected GDSN stations from these explosions show no evidence of changes in complexity which can be correlated with the level of tectonic release inferred from the long-period surface wave data, nor do the corresponding teleseismic P wave amplitudes show any statistically significant azimuthal variations which might be correlated with a tectonic radiation pattern.

(2) Under the assumption that the source of the tectonic release accompanying Shagan River underground explosions is coincident in space and time with that of the explosion, little or no perturbation in the teleseismic, short-period P waveform is predicted theoretically for some modes of tectonic release. More specifically, predicted teleseismic P waveforms corresponding to tectonic release equivalent to the 45 degree thrust mechanism typically associated with Shagan River explosions are essentially identical to

those predicted for the explosion and, consequently no detectable variations in the observed waveforms would be theoretically expected in this case.

(3) The azimuthal variations in the single station m_b values predicted by the theoretical model for the 45 degree thrust model of tectonic release at Shagan River are too small to be detected experimentally, even for events with F factors as large as 2. However, the corresponding predicted effect on the network-averaged m_b value can still be quite large, with predicted upper bound m_b biases ranging from 0.1 units ($F \approx 0.4$) to more than 0.3 units ($F > 1.5$) depending upon the level of tectonic release.

(4) The observed variation of m_b at fixed values of the isotropic moment for explosions at Shagan River is too large to permit any definitive conclusions regarding the possible effects of tectonic release on the m_b values. However, these data do not exclude the possibility that tectonic release may be introducing a significant positive bias into the network-averaged m_b values for some of these explosions which would be unaccompanied by any detectable changes in the observed short-period P waves.

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APPENDIX A

Teleseismic Short-Period P Waveforms Recorded at Selected GDSN Stations From Shagan River Explosions Representing Various Levels of Tectonic Release, F.

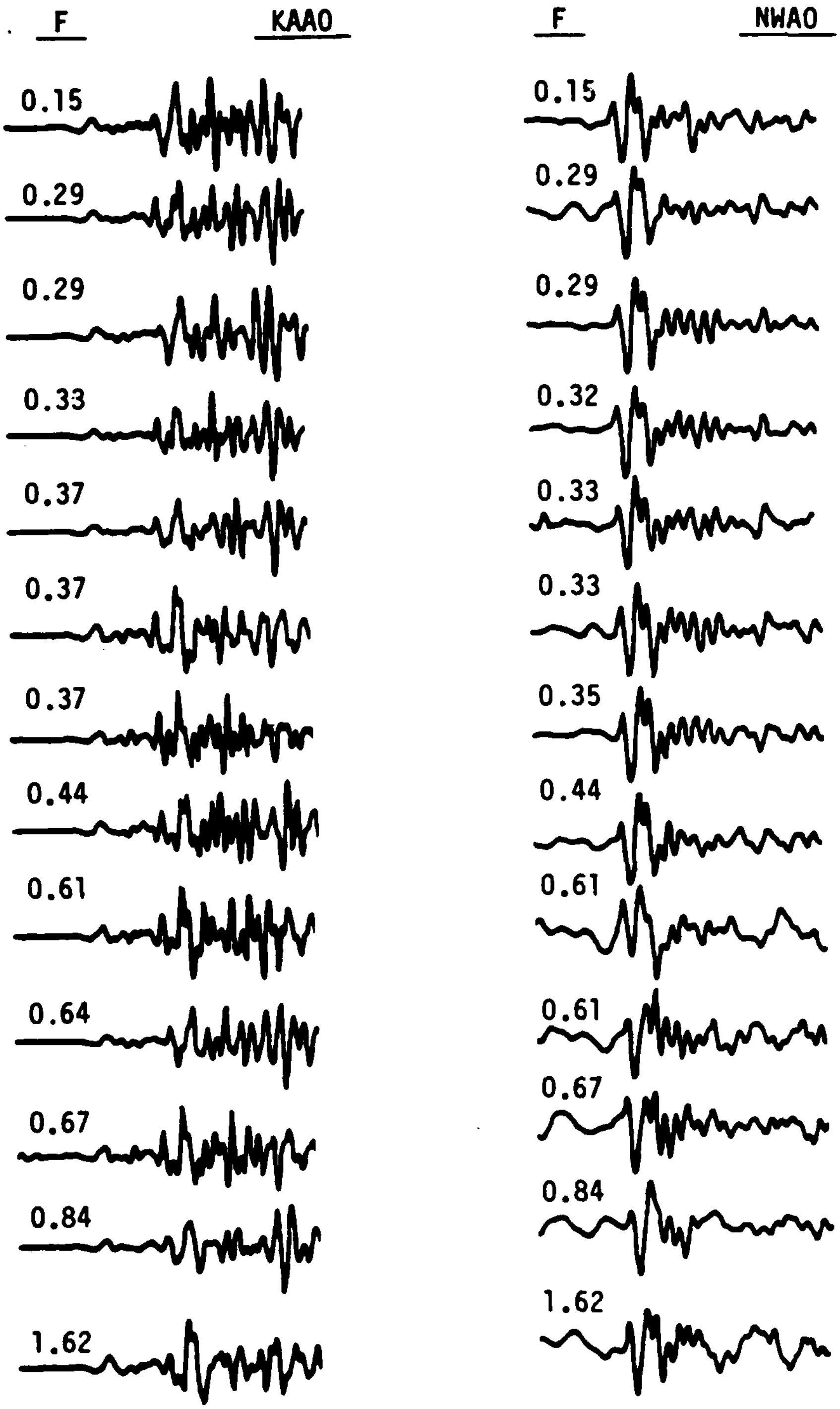

Figure A-1. Stations KAAO (left) and NWAO (right).

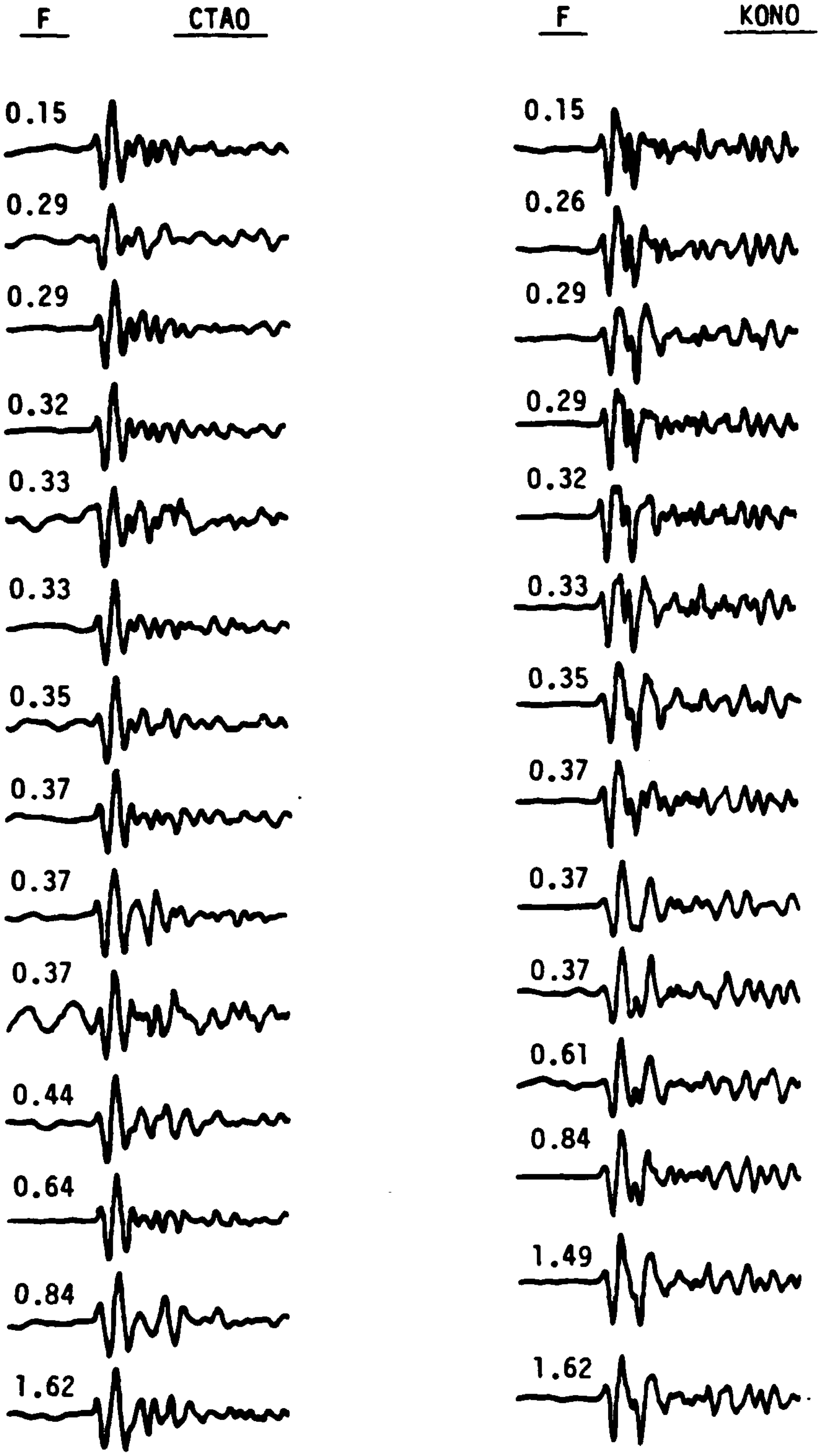

Figure A-2. Stations CTAO (left) and KONO (right).

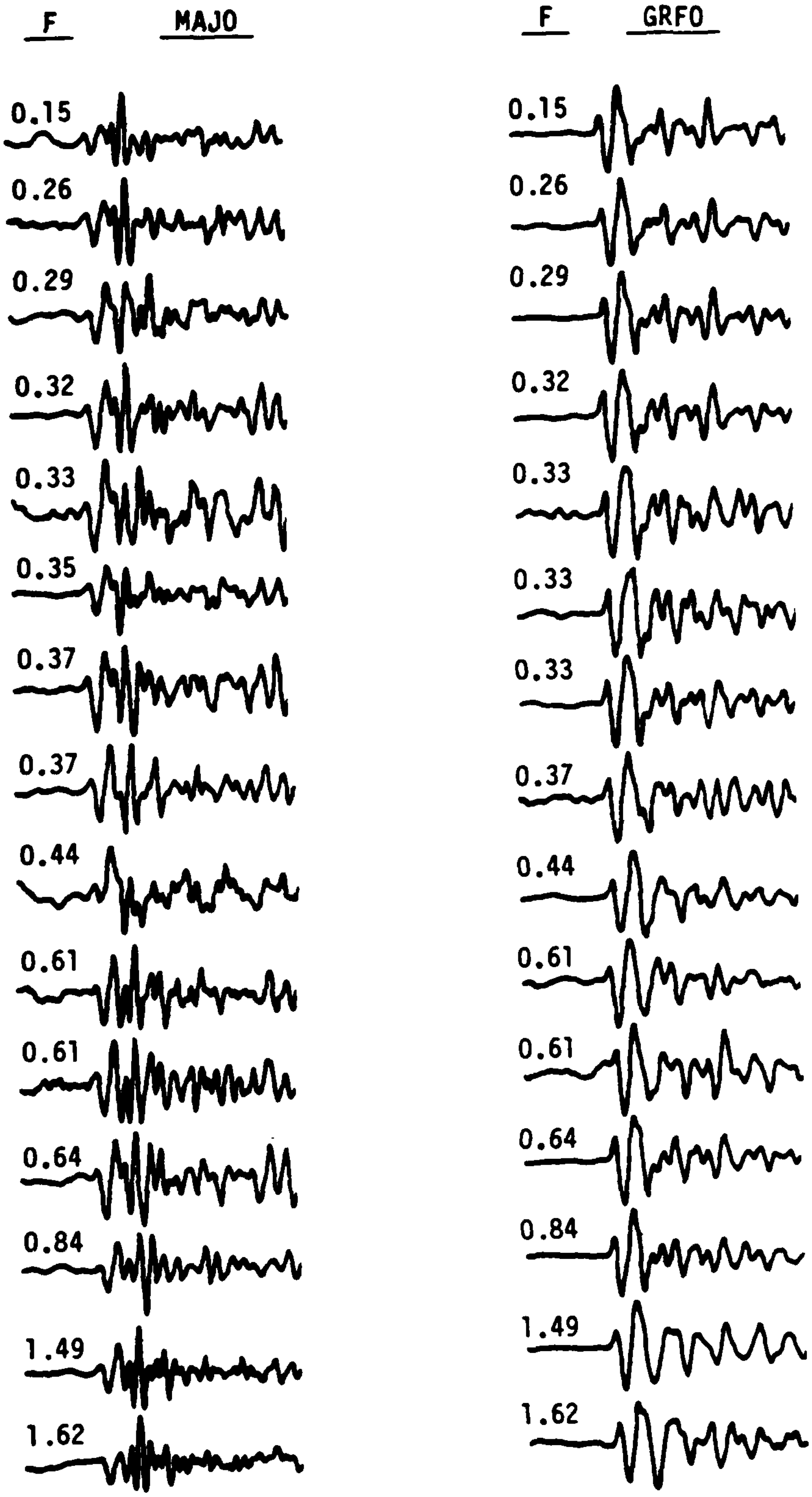

Figure A-3. Stations MAJO (left) and GRFO (right).

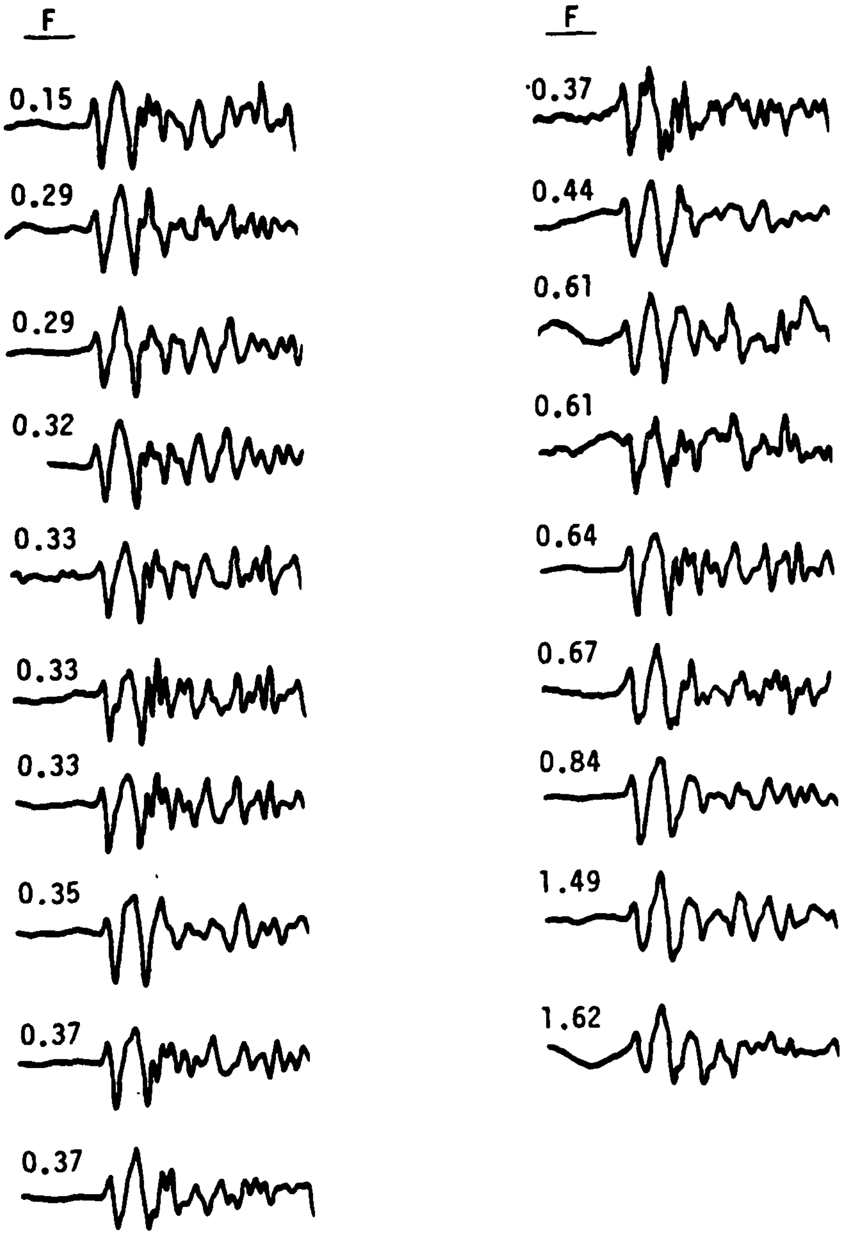

Figure A-4. Station ANMO.

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