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Surface-wave generation by underground nuclear explosions releasing tectonic strain

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ABSTRACT

Seismic surface-wave generation by underground nuclear explosions releasing tectonic strain is studied through a series of synthetic radiation-pattern calculations based on the earthquake-trigger model. From amplitude and phase radiation patterns for 20-s Rayleigh waves, inferences are made about effects on surface-wave magnitude, M_s, and waveform character. The focus of this study is a comparison between two mechanisms of tectonic strain release: strike-slip motion on vertical faults and thrust motion on 45° dipping faults. The results of our calculations show that Rayleigh-wave amplitudes of the dip-slip model at F values between 0.75 and 1.5 are significantly lower than amplitudes of the strike-slip model or of the explosion source alone . This effect translates into M_s values about 0.5 units lower than M_s of the explosion alone. Waveform polarity reversals occur in two of four azimuthal quadrants for the strike-slip model and in all azimuths of the dip-slip-thrust model for F values above about 3. A cursory examination of waveforms from presumed explosions in eastern Kazakhstan suggests that releases of tectonic strain are accompanying the detonation of many of these explosions. Qualitatively, the observations seem to favor the dip-slip-thrust model, which, in the case of a few explosions, must have F values above 3.

INTRODUCTION

The subject of this paper is the release of tectonic strain by underground nuclear explosions and the effects of this release on the generation of long-period seismic waves, especially surface waves. The study of these effects is important because one discriminant between explosions and earthquakes, the M_s-m_b discriminant, is based on the amplitude of long-period surface waves, measured by surface-wave magnitude, M_s, relative to the amplitude of short-period body waves, measured by body-wave magnitude, m_b. Furthermore, the yield of a nuclear explosion is proportional to the seismic moment, which is a source parameter determined from the long-period amplitude of seismic waves.

The effects on surface-wave radiation of tectonic strain release by nuclear explosions have been studied by numerous investigat)rs (Brune and Pomeroy, 1963; Aki, 1964; Aki an l Tsai, 1972; and Toksoz and Kehrer, 1972, to na ne a few). The results of these studies have supported a model of tectonic strain release by the mechanism of "earthquake triggering." According to this model, the nuclear explosion triggers an earthquake on a fault in the vicinity of ground zero at or soon after detonation time. (The transit time of the shock wave from the explosion to the fault is usually ignored in studies of seismic waves with periods longer than 10 seconds.) Since the earthquake releases strain energy in the form of seismic waves, the total seismic-wave field is a superposition of radiation from the explosion and the earthquake. Hence, this model involves a compound- or multiple-event source description.

Toksoz and Kehrer (1972) interpreted Rayleigh waves from explosions at the Nevada Test Site (NTS) and other test sites using this model, with the constraint that tectonic strain release occur as vertical, strike-slip faulting. This simplification reduces the number of parameters in the model to essentially two: a quantity F, which is a measure of the amount of tectonic strain release relative to explosion strain release, and θ, the azimuth of fault strike. F is related to the seismic moments of the explosion, M_x, and of the earthquake, M_Q, as follows (Muller, 1973):

$$F = \frac{\alpha^2}{2\beta^2} \frac{M_Q}{M_x} ,$$

where α and β are p- and s-wave velocities in the source region, respectively. Table 1, taken from Toksoz and Kehrer (1972), is a compilation of F values and fault strikes obtained from their analysis of observed long-period Rayleigh-wave amplitudes. Toksoz and Kehrer drew two conclusions: (1) tectonic-strain energy released as surface waves is usually less than the surface-wave energy from the explosion alone and (2) tectonic strain release does not have a significant effect on the M_s-m_b discriminant.

For explosions releasing relatively large amounts of tectonic strain, such as Piledriver and Hardhat (see Table 1), the amplitude and phase radiation patterns of Rayleigh waves are expected to be significantly altered from the isotropic patterns of the explosion alone. Consider, for example, the Rayleigh-wave initial phase pattern, which is directly related to the sense of motion at the source.

TABLE 1. Tectonic strain release characteristics of underground nuclear explosions—after Toksoz and Kehrer (1972).

Event	Date	Region	Medium	F value	Fault azimuth	Energy ratio E_{tect}/E_{exp}
Pile Driver	6/2/66	Yucca Flat	Granite	3.20	340°	13.65
Hardhat	2/15/62	Yucca Flat (north end)	Granite	3.00	330°	12.00
Shoal	10/26/63	Fallon, Nevada	Granite	0.90	346°	1.05
Greeley	12/20/66	Pahute Mesa	Zeolite tuff	1.60	355°	3.41
Benham	12/19/68	Pahute Mesa	Zeolite tuff	0.85	345°	0.96
Chartreuse	5/6/66	Pahute Mesa	Rhyolite	0.90	353°	1.05
Duryea	4/14/66	Pahute Mesa	Rhyolite	0.75	355°	0.75
Half Beak	6/30/66	Pahute Mesa	Rhyolite	0.67	345°	0.60
Boxcar	4/26/68	Pahute Mesa	Rhyolite	0.59	346°	0.46
Corduroy	12/3/65	Yucca Flat	Quartzite	0.72	347°	0.69
Rulison	9/10/69	Grand Valley, CO	Ss. and shale	0.60	335°	0.48
Faultless	1/19/68	Central Nevada	Sat. tuff	0.50	344°	0.33
Cup	3/26/65	Yucca Flat	Tuff	0.55	200°	0.40
Bilby	9/13/63	Yucca Flat	Tuff	0.47	340°	0.29
Tan	6/3/66	Yucca Flat	Tuff	0.39	347°	0.20
Bronze	7/23/65	Yucca Flat	Tuff	0.33	185°	0.15
Buff	12/16/65	Yucca Flat	Tuff	0.31	208°	0.13
Haymaker	6/27/62	Yucca Flat	Alluvium	0.33	340°	0.14
Sedan	7/6/62	Yucca Flat	Alluvium	0	–	0
Salmon	10/22/64	Hattiesburg, MS	Salt	0	–	0
Gnome	12/10/61	Carlsbad, NM	Salt	0	–	0
Milrow	10/2/69	Amchitka	Andesite	0.60	–	0.48
Cannikin	11/6/71	Amchitka	Andesite	0.60	60°	0.48
U.S.S.R.	10/27/66	Novaya Zemlya	–	0.90	5°	1.05
U.S.S.R.	10/21/67	Novaya Zemlya	–	0.71	43°	0.67
U.S.S.R.	2/26/67	East Kazakh	–	0.85	6°	0.96
U.S.S.R.	3/20/67	East Kazakh	–	0.81	155°	0.87
U.S.S.R.	2/13/66	East Kazakh	–	0.67	101°	0.60

For earthquakes, this motion can be outward in some azimuths and inward in others, but it is always outward for explosions. Theoretically, a triggered earthquake, if large enough, could reverse the polarity of the explosion-generated Rayleigh wave on azimuths along which the earthquake motion on the fault is inward. This, in fact, was observed for Piledriver at several stations northeast of NTS by comparing the waveforms of this explosion with a reference explosion which did not release much tectonic strain. These observations are in agreement with the model of strain release adopted by Toksoz and Kehrer.

Polarity reversals of Rayleigh waves have been reported recently by Rygg (1979) for several nuclear explosions at the Soviet test site in eastern Kazakhstan. Rygg's observations were limited to two stations, Kongsberg, Norway, and Chiang Mai, Thailand, which are on azimuths northwest and southeast of the test site, about 180° apart. Observations of surface waves from Kazakh explosions at Seismic Research Observatory (SRO) stations in Europe and southern Asia have revealed that both the Rayleigh-wave amplitude and phase radiation patterns are quite different from the isotropic patterns for an explosion alone. Examples of polarity reversals for several eastern Kazakhstan explosions are given in Fig. 1. This figure shows that all of the waveforms observed by the SRO station at Meshed,

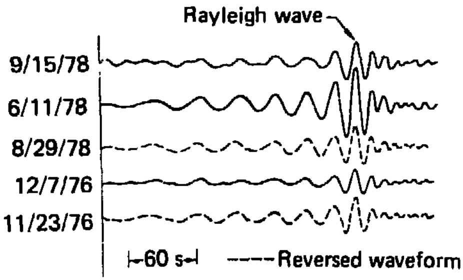

FIG. 1. Long-period Rayleigh waves observed at Meshed, Iran for events in eastern Kazakhstan. Meshed is 2200 km from the test site and at an azimuth of 233° east of north.

Iran, are similar once the reversed waveforms are inverted and time-aligned with the normal explosion waveforms. Polarity reversals are observed at all stations for a few events, such as the event on 11/23/76 shown in Fig. 1 and an event on 7/7/79. The waveforms for the 7/7/79 event, observed at eight different stations, are plotted in Fig. 2 along with waveforms observed for a reference event. This figure illustrates the substantial change with azimuth in the relative amplitudes of these events, as well as the phase reversals.

This cursory look at the waveform observations of eastern Kazakh explosions suggests a

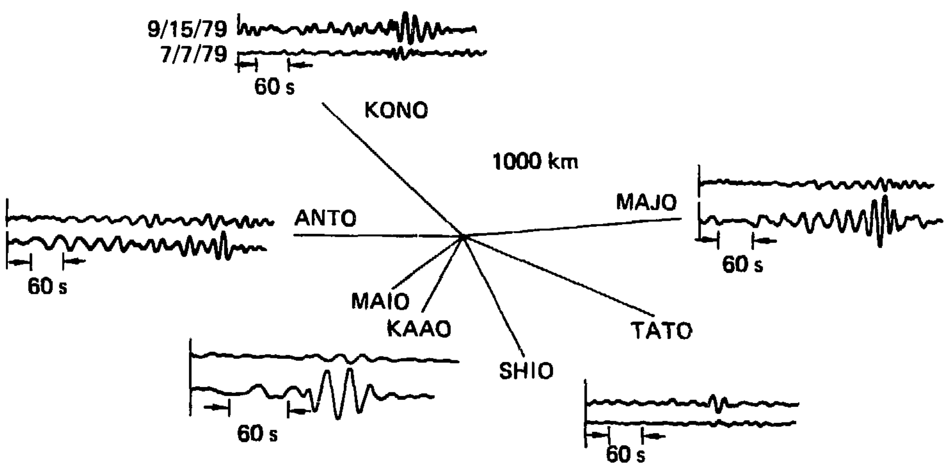

FIG. 2. Comparison of Rayleigh waves at SRO stations around Asia for two events in eastern Kazakhstan.

complicated source. If these explosions are releasing tectonic strain, the model of strain release by strike-faulting cannot explain the ubiquitous phase-reversal observations for some events. This will be shown later in this study. A priori, there are no physical reasons why underground explosions should release tectonic strain by strike-slip faulting. In fact, field data indicate that faults in the vicinity of ground zero experience greater vertical than horizontal displacement during an explosion (McKeown and Dickey, 1969).

In this paper, the problem of tectonic strain release by nuclear explosions is studied theoretically, in a series of Rayleigh-wave radiation-pattern calculations. On the basis of these calculations, inferences are made about the effects of tectonic strain release on surface-wave magnitude, M_s, and about waveform character. Detailed results are presented for calculations using two specific models of strain release: strike-slip faulting on a vertical fault, and thrust faulting on a 45° dipping fault. The following section briefly describes the parameters and assumptions that are used in calculating the radiation patterns.

PARAMETERS FOR THE EARTHQUAKE-TRIGGER MODEL

As mentioned above, the earthquake-trigger model of tectonic strain release involves a multiple source, the explosion and the triggered earthquake. The problem of synthesizing radiation patterns for a multiple source may be tackled by first calculating the radiation patterns of each source separately, using appropriate source descriptions, and then obtaining the desired pattern by simple, linear superposition (summing amplitude and phase in the complex plane) of these patterns.

Rayleigh-wave excitation by explosion sources in a realistic layered-earth model is calculated following the method of Tsai and Aki (1971). The source of an explosion may be described as a "center of dilatation" which is represented by three equal, mutually perpendicular dipole body forces. For the long periods, the time dependence of the body forces is usually assumed to be a step function. The amplitude of the step function is proportional to the seismic moment of the nuclear explosion.

Rayleigh-wave excitation by earthquakes in a realistic earth model is calculated following the method of Tsai and Aki (1970). The earthquake source is represented as a slip dislocation on a planar fault. For point sources this source is elastodynamically equivalent to two equal force couples acting at right angles to each other, resulting in no net angular moment. As in the case of explosions, the time dependence of the body forces is usually assumed to be a step function for long-period studies, and the amplitude of the step function is proportional to the seismic moment.

The remaining parameters in the earthquake-trigger model are the following: the location, depth, and fault-plane mechanism (orientation of double-couple forces) of the earthquake, the time separation between explosion and earthquake, and the size of the earthquake relative to the size of the explosion. The last parameter is the F value defined above, which is a free parameter in this study. The time separation is assumed to be zero, and the location and depth of the earthquake are assumed to be coincident with those of the explosion. Arbitrarily, the Gutenberg continental earth model (Tsai and Aki, 1970) is used as the medium for the calculation of excitation. Since this is a parameter study to compare source excitation, the choice of earth model is not critical.

The fault-plane mechanism considered in this study is either vertical strike-slip or dip-slip thrust faulting. The angles used are:

Strike slip

Slip = 0°
Dip = 90°
Fault strike = 0°

Dip-slip thrust

Slip = 90°
Dip = 45°
Fault strike = 0°

where the slip angle is measured on the fault plane counterclockwise from the strike direction, the dip angle is measured from the horizontal, and the strike angle is measured clockwise from north.

Before describing the results of the multiple-source calculations, it is beneficial to examine the radiation patterns of each source separately. The radiation patterns for the strike-slip, dip-slip, and explosion sources, each having a seismic moment of 1×10^{25} dyn-cm, are shown in Figures 3a and 3b for

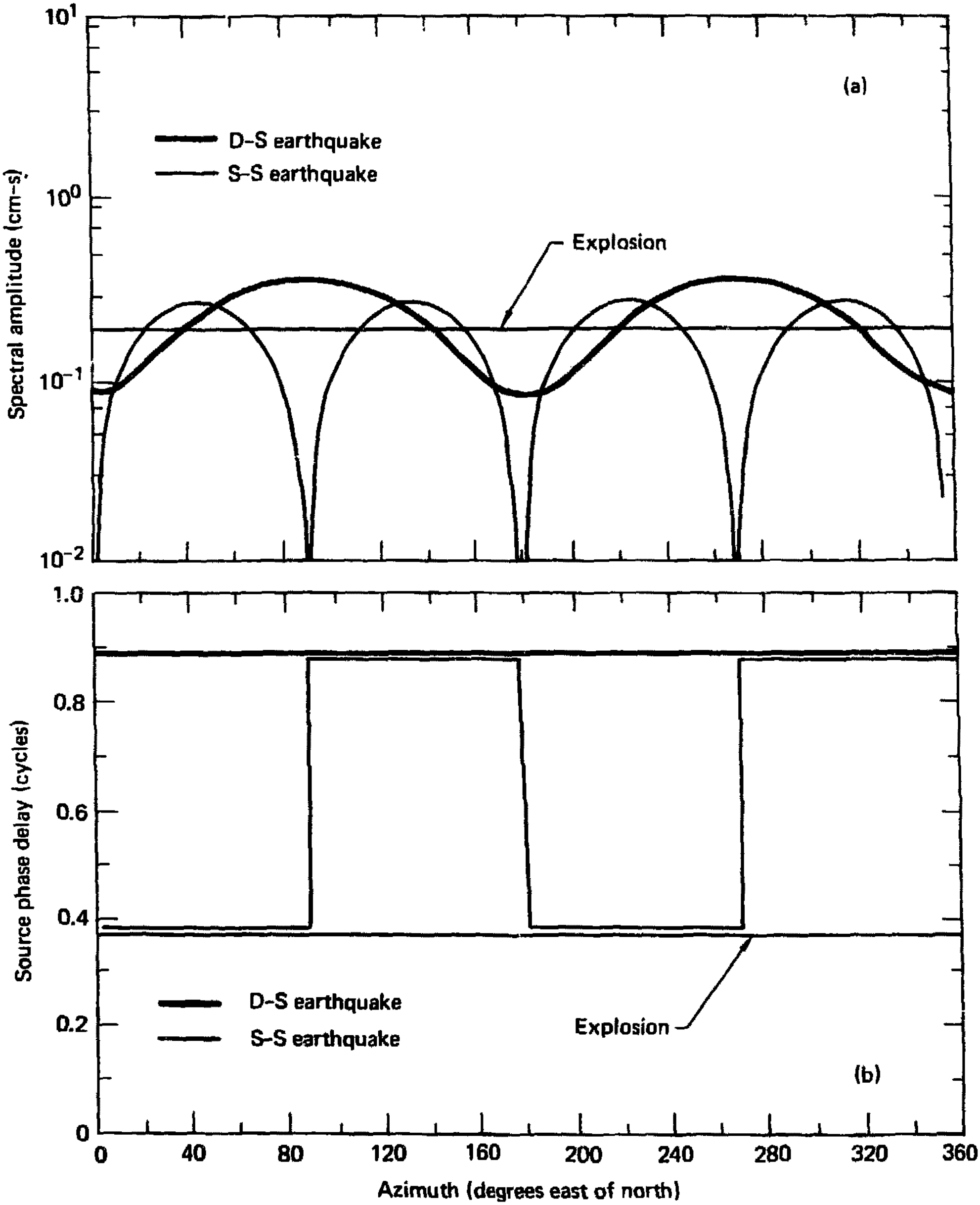

FIG. 3. Radiation patterns of 20-s-period Rayleigh waves for three types of sources: an explosion, a dip-slip (D-S) earthquake, and a strike-slip (S-S) earthquake: (a) amplitude patterns, (b) phase patterns.

Rayleigh waves of 20-s period. Notice the four-lobe, two-lobe, and circular amplitude patterns for the strike-slip, dip-slip thrust, and explosion sources, respectively. The dip-slip thrust and explosion sources have radiation patterns in which the source phase takes on constant values of $7\pi/4$ and $3\pi/4$, respectively, while the strike-slip source has a phase pattern that varies by 1/2 cycle (π) from lobe to lobe. For all three sources, the source phase takes on one of two possible values: $3\pi/4$ or $7\pi/4$ radians, which are different by π, a polarity reversal.

SYNTHETIC RADIATION PATTERNS

The Rayleigh-wave radiation patterns for the earthquake-trigger model are shown in Figs. 4 through 7, with F values increasing from 0.75 in Fig. 4 to 6 in Fig. 7. The change in character of the patterns with increasing earthquake content is apparent. The absolute amplitudes were computed using a seismic moment of the explosion of 1×10^{25} dyn-cm—corresponding to a body-wave magnitude of about 6.6 based on data summarized in Aki et al. (1974). The radiation patterns were calculated for sources buried 1 km deep in the Gutenberg earth model. This depth determines the α and β used to relate the F values to the moments. Hence, an F value of 0.75 implies a moment ratio of 0.50, i.e., an explosion moment twice that of the earthquake.

As the figures show, there are significant differences between the amplitude patterns of the multiple-source model and the isotropic pattern of the explosion alone. Interestingly, the shape of radiation patterns, whether two-lobe or four-lobe, does not seem to depend on the mechanism of the triggered earthquake as much as it does on the F value. However, above an F value of 3, the amplitude patterns appear to be dominated by the earthquake component, as comparisons among Figs. 3 through 7 show.

The phase radiation patterns are unaffected by the earthquake component for F values below about 1.0. For F values above 1.0, it is apparent that polarity reversals occur first in the azimuths where the amplitude pattern of the triggered earthquake has lobes (see Fig. 3). The strike-slip case has two quadrants with the same phase as the explosion; reversals do not occur in these quadrants. Therefore, at most 50% of the azimuths can be affected by polarity reversals for earthquakes triggered on strike-slip faults. On the other hand, the dip-slip thrust earthquake gives reversals in all azimuths at F values above about 3, as Fig. 8 shows. Figure 8 also shows that there is a fairly narrow range of F ($1.0 < F \gtrsim 3.0$) which gives a mixture of explosion and earthquake polarities.

The effect of tectonic strain release on surface-wave magnitude can be estimated from the amplitude radiation patterns in Figs. 4 through 7. Toksoz and Kehrer computed a ΔM_s, which they called "maximum increase in magnitude due to tectonic component," as follows:

$$\Delta M_s = \frac{1}{1.6} \log \left(\frac{E_{exp} + E_{tect}}{E_{exp}} \right) ,$$

where E_{exp} and E_{tect} are the elastic wave energy of surface waves from the explosion and from the earthquake, respectively. This formula ignores the behavior of the surface-wave source phase since it assumes that the total energy of the multiple source is the sum of the energies from the individual sources. A better approach is to estimate ΔM_s from the difference in average log amplitude levels,

$$\Delta M_s = < \log A > - \log A_x ,$$

where $\log A_x$ is the log amplitude level of the explosion alone and $<\log A>$ is the log amplitude of the explosion with tectonic release averaged over azimuth. Figure 9 shows the results of calculating ΔM_s values using this equation for explosions releasing tectonic strain at selected F values.

According to Fig. 9, explosions triggering strike-slip faulting above F values of 1 have higher M_s values than if there were no tectonic release. The calculations show that the M_s differences increase as the relative size of the strike-slip event increases. On the other hand, explosions triggering thrust earthquakes have lower M_s values by up to about a half unit for relatively small releases of tectonic strain ($F \gtrsim 0.75$). At F values near 3.0 the release of tectonic strain by dip-slip faulting has negligible effects on M_s, and larger relative releases of tectonic strain result in increased M_s values.

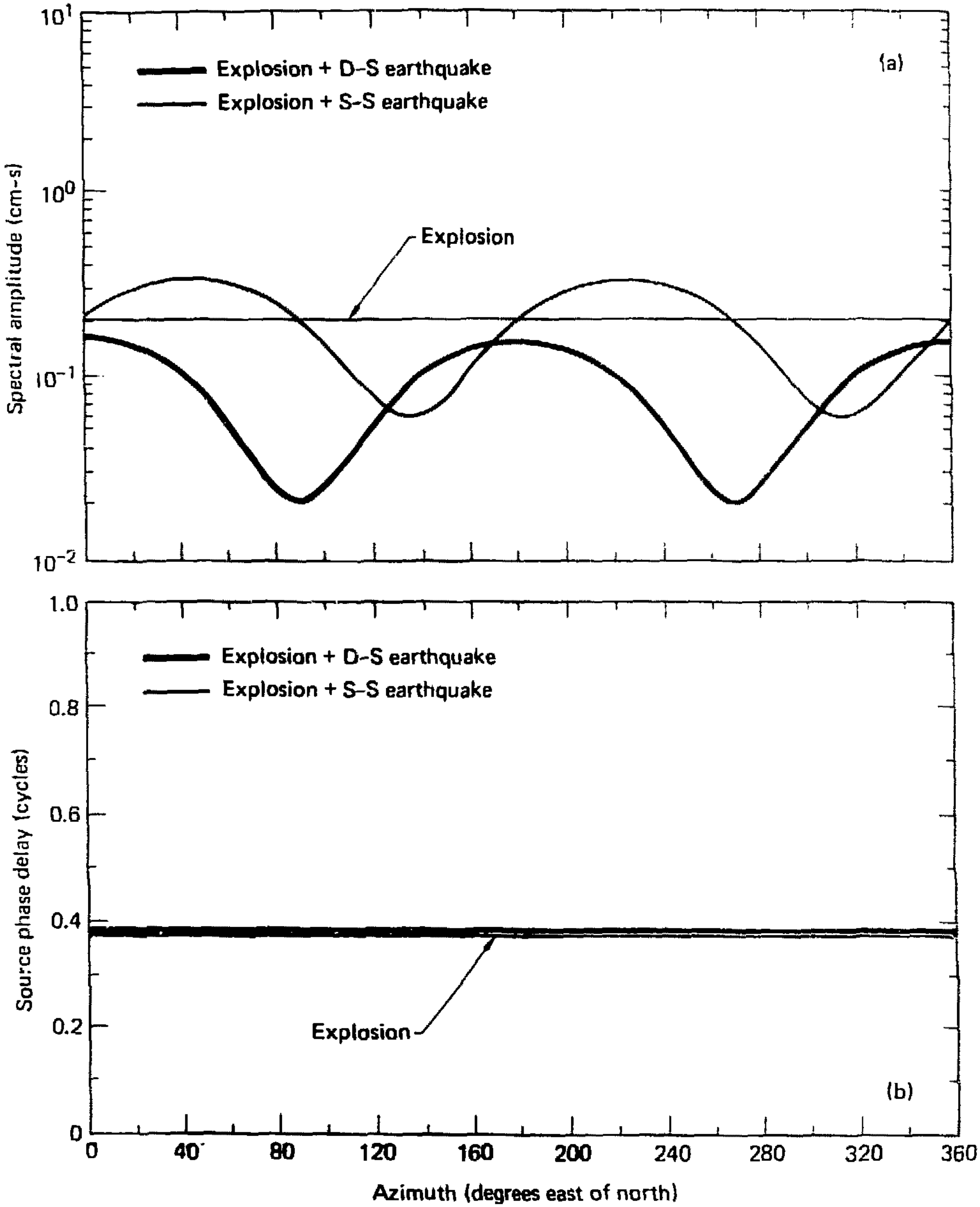

FIG. 4. Radiation patterns of 20-s-period Rayleigh waves for multiple sources with F = 0.75: (a) amplitude patterns, (b) phase patterns. Isotropic patterns of the explosion source are shown for reference.

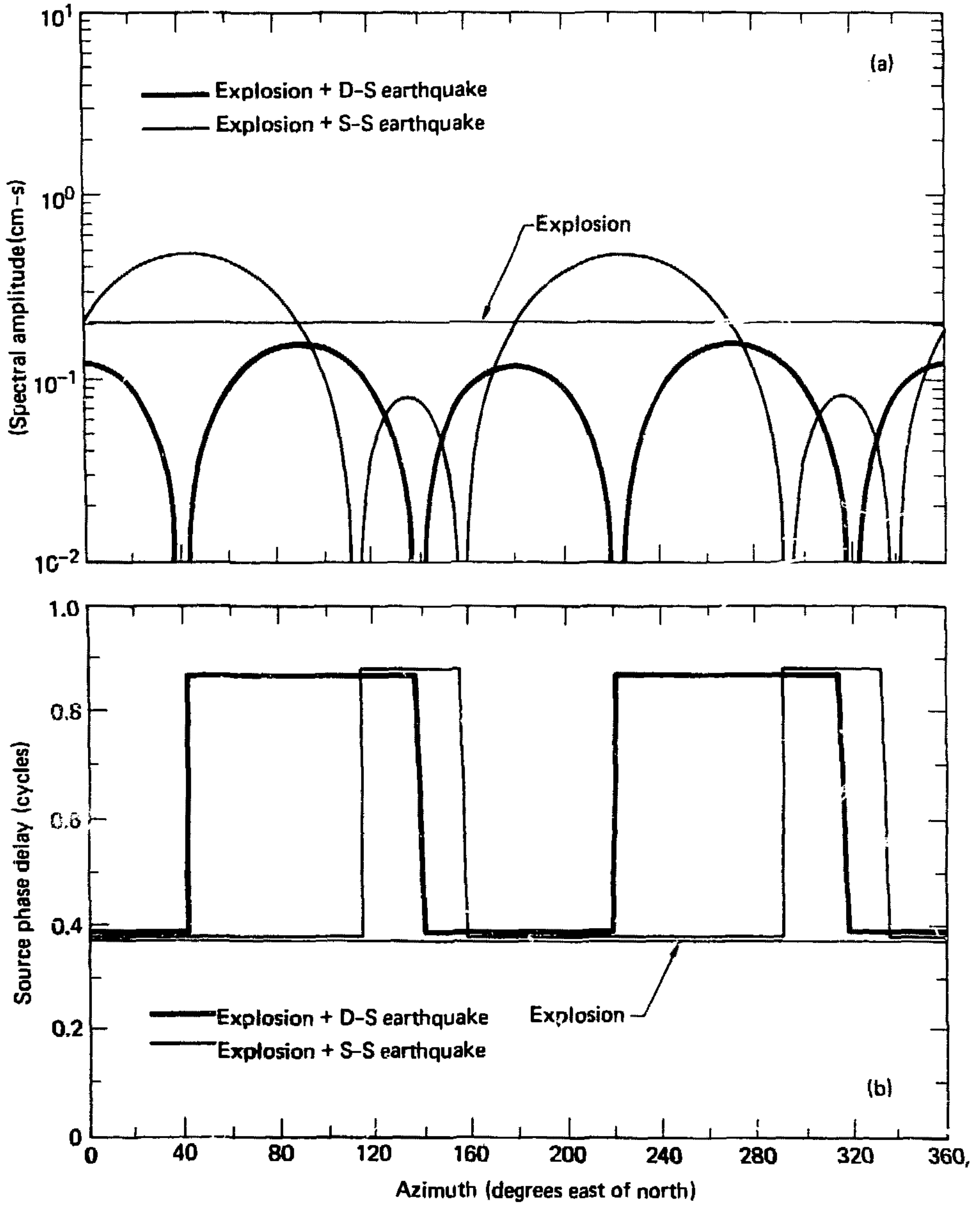

FIG. 5. Radiation patterns of 20-s-period Rayleigh waves for multiple sources with F = 1.5: (a) amplitude patterns, (b) phase patterns. Isotropic patterns of the explosion source are shown for reference.

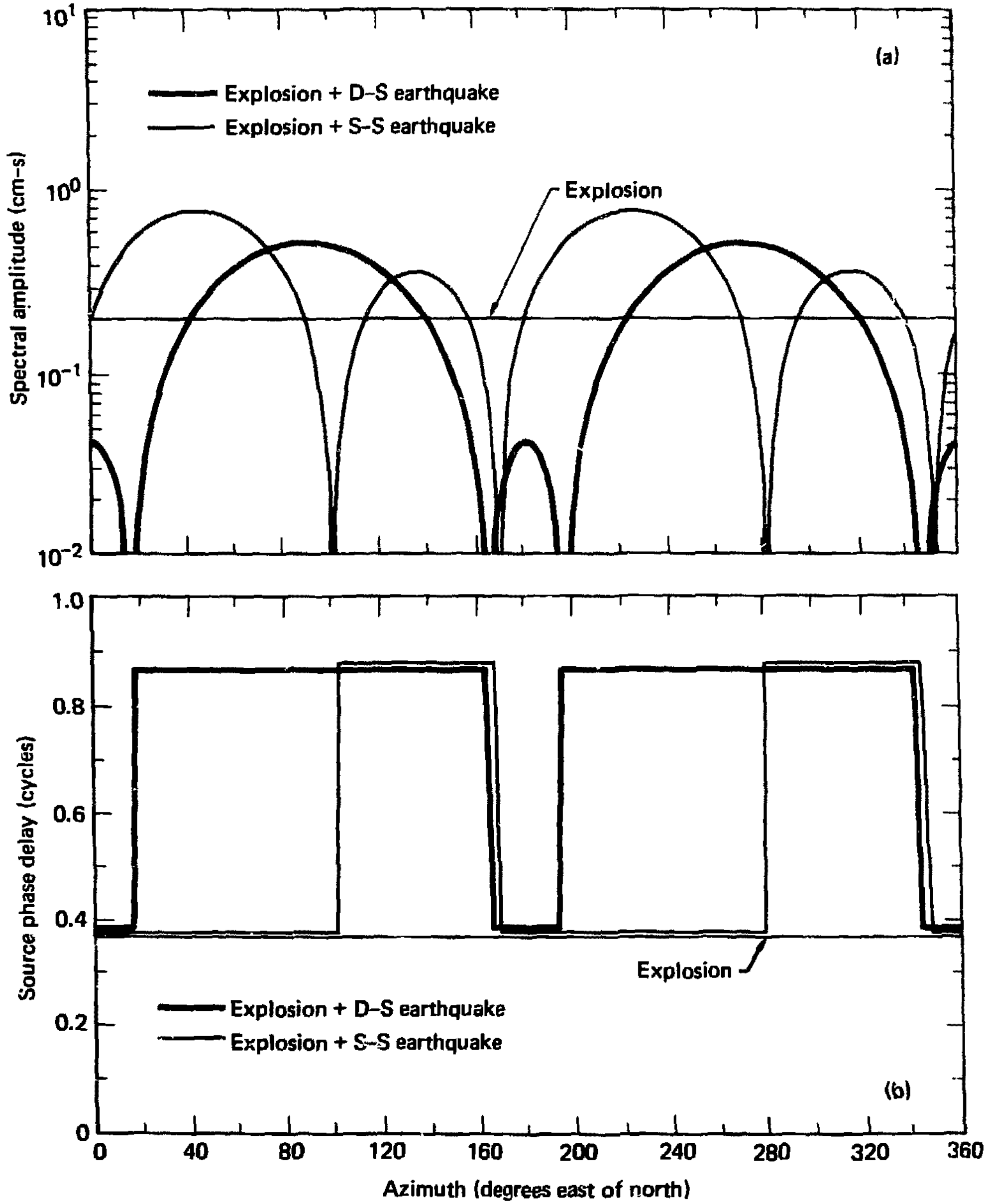

FIG. 6. Radiation patterns of 20-s-period Rayleigh waves for multiple sources with F = 3.0: (a) amplitude patterns, (b) phase patterns. Isotropic patterns of the explosion source are shown for reference.

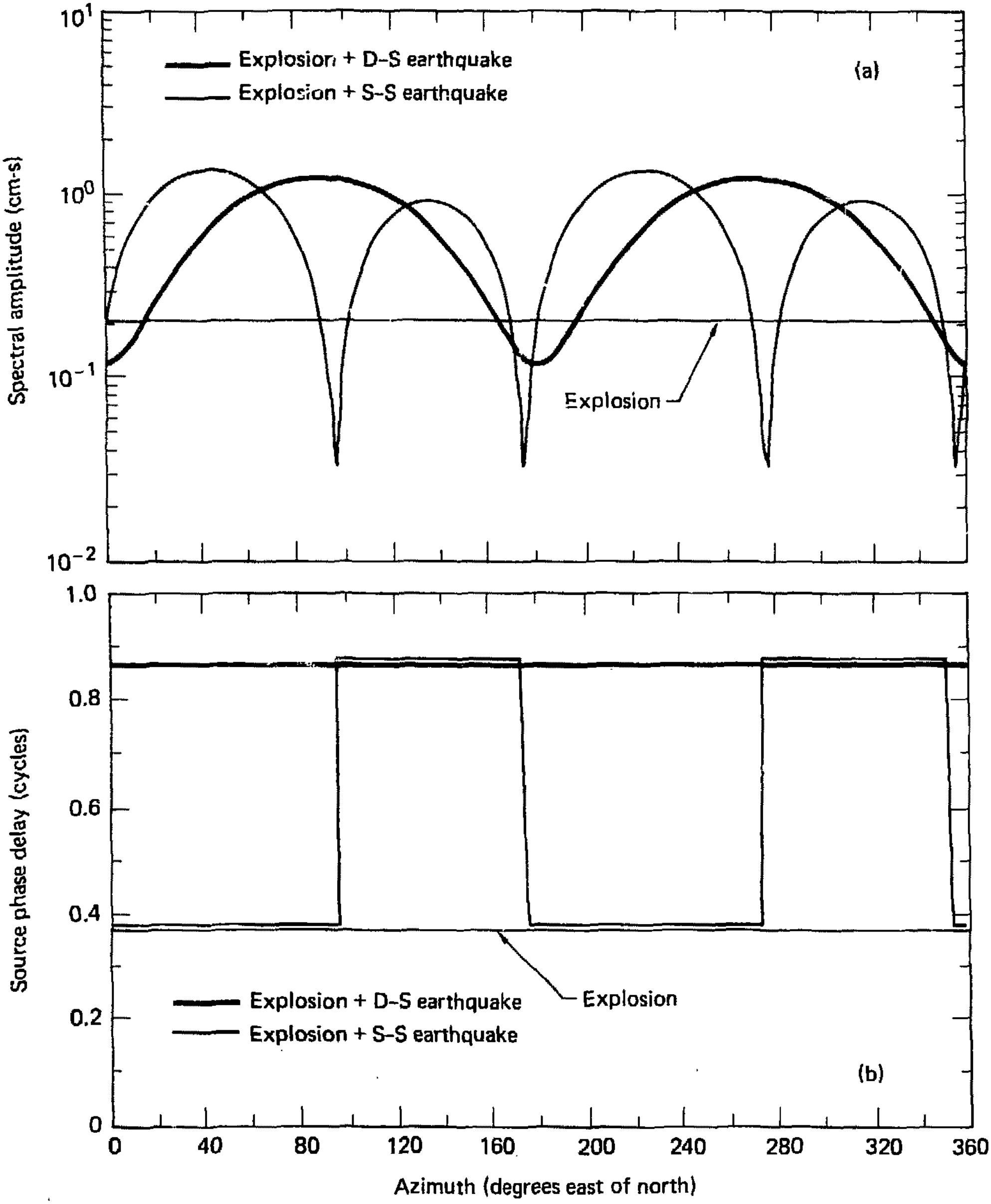

FIG. 7. Radiation patterns of 20-s-period Rayleigh waves for multiple sources with F = 6.0: (a) amplitude patterns, (b) phase patterns. Isotropic patterns of the explosion source are shown for reference.

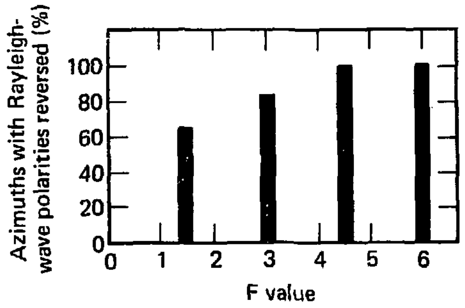

FIG. 8. The azimuthal extent of Rayleigh-wave polarity reversals as a function of F value for the dip-slip thrust model.

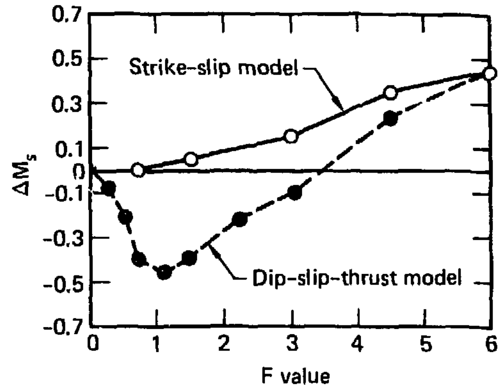

FIG. 9. Change in average surface-wave magnitude as a function of F value for the strike-skip and dip-slip-thrust models of tectonic strain release.

DISCUSSION

It is important to note that the results in Fig. 9 represent an expected change in M_s only if the station coverage sampled the source radiation pattern thoroughly . In practice M_s determinations may be based on an amplitude reading from a single station, or at best from a network of stations with nonuniform sampling in azimuth around the source. Therefore, these calculations have limited applicability to predicting the ΔM_s values actually observed, as experience with NTS shots has shown. Toksoz and Kehrer concluded that the tectonic strain released on strike-slip faults by NTS shots has little effect on M_s values because most measured F values are less than one (see Table 1) and because the azimuthal sampling by seismic stations in North America is biased toward azimuths that would have low amplitudes on the radiation pattern. For example, the M_s measured for Piledriver is not unusually large for its m_b. In fact, this event falls in the explosion population on an M_s-m_b plot even though the earthquake-trigger model predicts a ΔM_s of nearly 0.2 unit.

The observation of Rayleigh-wave polarity reversals in all azimuths for some presumed Soviet explosions may be explained by the earthquake trigger model if the earthquake mechanism is dip-slip thrust faulting. Reversals occur in practically all azimuths for the dip-slip thrust model when F values are greater than 3. The strike-slip model will reverse polarities in only two of the four azimuth quadrants. If earthquake triggering is responsible for these reversals, some Soviet explosions must be releasing large amounts of tectonic strain since F values of 3 correspond to an earthquake with twice the seismic moment of the explosion. For example, the m_b of 5.8 reported by the National Earthquake Information Service (NEIS) for the event on 7/7/79 (Fig. 2) would give a seismic moment of 4×10^{23} dyn-cm from moment-magnitude curves for explosions (Aki et al. 1974). The associated triggered earthquake would have a moment close to 1×10^{24} dyn-cm or an M_s of 5.2 and an m_b of 5.7 according to earthquake scaling models of Aki (1972). M_s-m_b plots of Eurasian earthquakes summarized in Dahlman and Israelson (1977) give an m_b of about 5.4 for an M_s of 5.2. An earthquake this large is expected to release strain on a fault between 5 and 30 km long (Chinnery, 1969). The implication is that there must be major faults in the source region would that are involved in the release of tectonic strain by the explosions in eastern Kazakhstan.

Assuming that the dip-slip model holds for other explosions at the Soviet test site in eastern Kazakhstan, it should be possible to deduce the orientation of thrust faults from the observation of polarity reversals. This is because the reversals occur first on azimuths in which the amplitude pattern of the earthquake has lobes, as was shown in the previous section. Table 2 summarizes the polarities observed for five events relative to a reference event occurring on 9/15/78. The stations listed in this table are plotted as they appear in azimuth around the source in Fig. 2. Although the observations are few, it appears that reversals occur first at stations generally south of the test site at Shillong, India, Kabul, Afghanistan, and Meshed, Iran. This implies a north-south oriented radiation pattern and consequently, an east-west-striking dip-slip thrust fault. If the event on 7/7/79, instead of the event on 9/15/78, had been selected as the reference, the interpretation would be changed to east-west-oriented radiation patterns on north-south-striking dip-slip thrust faults. The former model, which implies a north-south-oriented regional tectonic stress, is favored because it agrees well with the inferences of tectonic stress field in Central Asia drawn from earthquake fault plane solutions and mapped faults (Molnar et al., 1973; Tapponnier and Molnar, 1979).

The dip-slip thrust model, if applicable to Soviet explosions in eastern Kazakhstan, predicts a general lowering of M_s values from ideal explosion sources by as much as 0.5 of a magnitude unit, as seen in Fig. 9. There may be indication of this effect in the m_b versus M_s data of Marshall and Basham (1972) plotted in Fig. 10, which is reproduced from the paper of Marshall et al. (1979). This figure shows M_s-m_b data for Soviet explosions, most of which (70%) are located in eastern Kazakhstan, compared with data for NTS explosions. This body of data for explosions before 1970 indicates that Soviet explosions have lower M_s than explosions fired at NTS with m_b greater than 4.5. The M_s-m_b data reported by NEIS and the International

TABLE 2. Waveform polarities of Rayleigh waves from events in eastern Kazakhstan relative to a reference event on 9/15/78. (+ indicates the same polarity, – indicates reversed polarity.)

Station	8/4/79	6/23/79	11/12/78	8/29/78	7/7/79
MAJO	+	+	+		–
TATO		+		+	
SHIO	–	–	–	–	–
KAAO	+	+	+	–	–
MAIO				–	
ANTO	+	+	+		–
KONO		+	+		–

Seismological Center (ISC) for recent explosions showing polarity reversals has large scatter and is not consistent with the data set of explosions before 1970. If M_s values for NTS shots are relatively unaffected by tectonic release, as Toksoz and Kehrer claim, then the differences in the explosion populations in Fig. 10 reflect a lowering of surface-wave amplitudes from the Soviet explosions, consistent with the dip-slip model at low levels of strain release. On the other hand, an alternative explanation for the differences between NTS and eastern Kazakhstan M_s-m_b data could involve effects on body-wave amplitudes, such as the role of attenuation on p-wave amplitudes described by Marshall et al. (1979). Perhaps a combination of effects on surface and body waves is responsible for the differences in M_s-m_b trends of Soviet and NTS explosions.

Although the effect of tectonic release on body-wave amplitudes is not addressed here, there are reasons to believe that it will be considerably less than the effect on surface-waves. This is because the source spectrum for explosions is much richer in high frequencies than the source spectrum for an earthquake of comparable seismic moment is. The model of explosion-source spectrum of Aki et al. (1974), for example, shows an order-of-magnitude higher amplitude than the earthquake spectrum at 1-s period for explosions with M_s greater than 3.3. Therefore, from a source-effects point of view, yield estimates based on body-wave amplitudes (e.g., m_b) should be more reliable than estimates using surface-wave amplitudes when explosions release tectonic strain by triggering earthquakes on dip-slip faults. Unfortunately, the effects of propagation on body-wave amplitudes (Marshall et al., 1979) may detract from this source advantage.

In summary, the discussions above suggest that explosions have been releasing tectonic strain in a localized area (roughly 80 km^2) of eastern Kazakhstan over a period of 10 to 20 years. The strain release in some instances has involved earthquakes of magnitude 5.5 or more on faults 5 to 30 km long. Interestingly, this induced tectonic release occurs on the stable craton of the Russian platform that has low natural seismicity. Its "intraplate" stress regime is characterized by horizontal north-south compression, in contrast to the east-west extension active at NTS and throughout the Basin and Range province in the U.S. This contrast raises questions about the role of stress orientation and

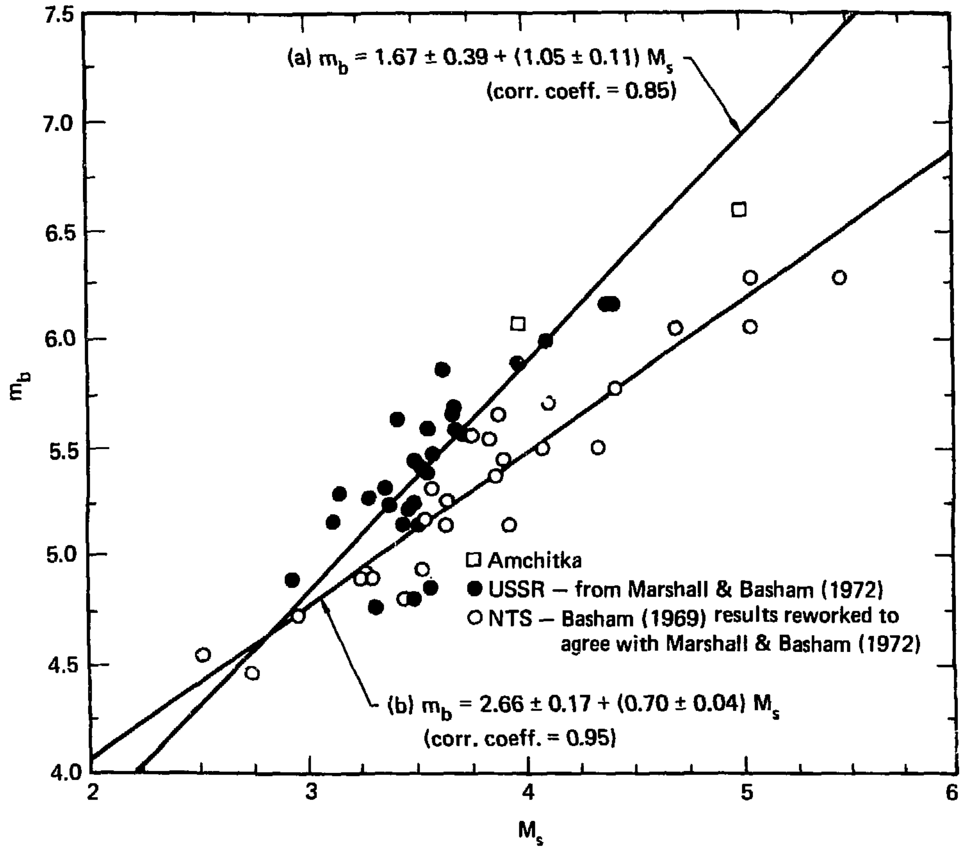

FIG. 10. Plot of body wave magnitude (m_b) versus surface wave magnitude (M_s) for nuclear explosions in North America and the U.S.S.R. Source: Marshall et al. (1979).

ambient seismic activity in determining the level of induced tectonic release by underground explosions. It is remarkable that explosions localized in space and time would repeatedly cause tectonic strain release in a setting lacking seismicity. Might the induced activity be higher in an intraplate setting because stress is efficiently transmitted through the rigid plate from the convergence boundary in southern Asia? On the other hand, the level of induced activity at NTS might be expected to be lower in light of the evidence suggesting that shear-stress transmittal from the plate boundary on the western coast of the U.S is not efficient and dies out inland in the Basin and Range province (Eaton, 1980).

It is important to keep in mind that the radiation pattern calculations are based on a source model with a number of simplifying assumptions. First, the source time function of the explosion is assumed to be a step function. Numerous studies (Werth and Herbst, 1963; Aki et al. 1974; Burdick and Helmberger; 1979, to name a few) have found evidence for some overshoot in the explosion time history. For long periods however, a step function may be a suitable representation of the explosion time function, as shown by Tsai and Aki (1971). Secondly, the triggered earthquake is assumed to be coincident in both time and space with the explosion. The study of McKeown and Dickey (1969) has shown evidence for faulting as far as 5 km from ground zero for large explosions such as Greeley with a yield of 825 KT (Springer and Kinnaman, 1971). The distance is considerably reduced for smaller shots [about 1 km for Duryea at 65 KT

(Springer and Kinnaman, 1971)], which suggests that coincidence in space may be a satisfactory assumption, considering that the wavelength of 20-s Rayleigh waves is about 70 km. Coincidence in time with the explosion can be justified from shock-wave propagation-time arguments considering the short distances between explosion and faults. However, Rygg (1979) found evidence for a 4-s delay between Rayleigh-wave waveforms generated by explosions with and without reversals. The implication is that the secondary source which caused the reversal was delayed by 4 s. This delay is extrordinarily long for a triggered event or for a spall-closure event (Springer, 1974), the explanation of polarity reversals favored by Rygg. Finally, the fault-plane mechanism of the triggered earthquake may have an oblique slip angle between strike-slip and normal, or between strike-slip and reverse faulting. The results given in this paper do not apply to oblique-slip-angle faulting; however, these results should bracket the range of effects on M_s for mechanisms with oblique slip between strike-slip and reverse faulting. The case of normal faulting has not been considered here.

CONCLUSIONS

The following conclusions may be drawn from this study:

1. It is possible for releases of tectonic strain by underground nuclear explosions to drastically alter the isotropic Rayleigh wave amplitude and phase patterns of underground nuclear explosions. Explosions with F values above 3 will have radiation patterns dominated by the earthquake contribution. This will cause reversals in the polarity of Rayleigh waves in all azimuths in the case of thrust-faulting mechanisms while strike-slip mechanisms will show reversals in two of four quadrants. Events with F values between 1 and 3 can be expected to have complicated amplitude patterns, both two-lobe and four-lobe, and phase reversals in various azimuth ranges. In general, the radiation patterns in this range are more earthquake-like than explosion-like.

2. The effects of triggered strain release on Rayleigh-wave amplitudes can translate into significant changes in average M_s from that of the pure explosion source alone. In the case of explosions triggering dip-slip thrust earthquakes, small releases of tectonic strain ($F < 1.5$) can lower the average M_s by as much as a half unit. Interestingly, this mode of strain release will aid seismic discrimination because it should give better separation from the earthquake population on M_s-m_b plots. In practice, the impact on M_s measurements depends on the azimuthal distribution of stations sampling the radiation pattern, as Toksoz and Kehrer have shown.

3. Amplitudes of observed Rayleigh waves from eastern Kazakhstan explosions show strong azimuthal dependence that must be source-related. Waveforms from certain events need to be reversed to match those from other events, indicating polarity reversals at the source. Some events show polarity reversals at all stations. These observations suggest that releases of tectonic strain may accompany the detonation of the explosions. Results based on the earthquake-trigger model show that dip-slip faulting can account for the polarity reversals seen at all stations, providing F values are above 3. On the other hand, the strike-slip model, no matter what the F value, cannot account for reversals at all stations. Assuming that the dip-slip model applies to other events releasing smaller amounts of tectonic strain, surface-wave excitation at 20-s period should be lower than if no tectonic release occurred at all. There may be support for this in the M_s-m_b data for these explosions.

This study has taken only a cursory look at the observations of seismic waves from explosions releasing tectonic strain. Concrete results on specific events await the detailed modeling of the surface-wave waveforms, not only for eastern Kazakhstan explosions but also for NTS explosions. A number of questions were raised during the course of the study that concern other problems related to tectonic strain release; for example, the effects of tectonic strain release on body-wave generation, and the repeated large releases of tectonic strain, presumably involving lengthy faults, by sources fairly localized in space and time. Better understanding of the interaction of explosions with the preexisting tectonic-stress field will come from the study of such problems.

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