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SHORT NOTES

EPICENTRAL CONFIDENCE REGIONS OF NUCLEAR TEST EVENTS AT TELESEISMIC DISTANCES

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The accurate location of seismic events is a basic discriminant for underground nuclear test monitoring (Bolt, 1976; Dahlman and Israelson, 1977; Blandford, 1982). Of particular interest are determining epicentral confidence regions and providing constraints on estimated focal depths. In this study, only routine teleseismic *P* travel-time data are used, as provided by worldwide stations reporting to the International Seismological Centre (ISC). This lessens the need to model the effects of crustal and shallow-mantle velocity variations, as is necessary with seismographic networks operating at regional distances (Blandford, 1981; Evernden *et al.*, 1986).

A method for source location in a tectonically regionalized earth (Tralli and Johnson, 1986b) is calibrated for events in the Nevada Test Site (NTS) in the south-central Basin and Range province. The locations are demonstrated in the context of epicentral confidence regions. The site calibration, in the form of a travel-time bias estimation, incorporates the effects of the crustal and shallow-mantle velocity structure, and is determined as a function of slowness. The principle is somewhat similar to the "master" event location scheme (Evernden, 1969; Blandford, 1977; Douglas, 1981).

Disclosed or accurately known locations are needed in order to estimate a travel-time bias. Calibration for sites outside the United States is more difficult since knowledge of the locations of a handful of events, as for example the "1004" experiment in Eastern Kazakh (Nordyke, 1975; Gubarev, 1976, 1978; Rodean, 1979; North and Fitch, unpublished data, 1980), is required. In view of this limitation, the calibration determined for NTS is used for Eastern Kazakh, both sites being in active continental regions. A similar method of travel-time bias estimation for seismogenic zones can also be undertaken if the earthquake locations are constrained by local seismographic networks.

Given the interest in developing discriminants that can be used to monitor small explosions from outside the country conducting the testing, the study has been restricted to teleseismic *P*-wave data only. This is a realistic situation for Eastern Kazakh, where travel-time data are unavailable within a range of about 15° (Rodean, 1979; North and Fitch, unpublished data, 1980). The problem of focal depth estimation cannot be approached using such data. In principle, *pP-P* and *sP-P* times could be used to constrain focal depths, but the differences are small and difficult to analyze for shallow sources (Douglas, 1981). It is assumed that the location discriminant considered here would be used to supplement other discrimination criteria such as $m_b : M_S$ magnitude ratios, first motions, and spectral methods. An on-site approach, as discussed by Evernden *et al.* (1986), may allow an even more complete set of criteria to be applied. Nevertheless, it should be pointed out that accurate location remains one of the more robust discriminants as the size of the explosion decreases and is a necessary ingredient in many other discrimination criteria.

Data Reduction

P-wave travel-time data in the epicentral distance range 15° to 95° were obtained from the *Bulletin of the ISC* for the period March 1978 through October 1981 for nuclear test events in NTS (36.6° to 37.4°N and 115.9° to 116.6°W) and events in the eastern portion of the Eastern Kazakh Nuclear Testing Ground (NTG) (49.3° to 50.3°N and 77.8° to 79.3°E) in the Soviet Union. A listing of the disclosed hypocentral parameters of NTS events is provided by Howard and Richardson (1984).

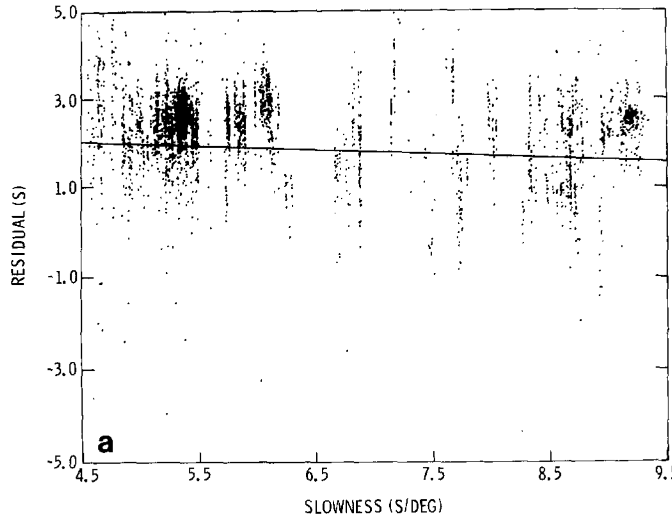
The method of estimating the P travel times is based on the tectonically regionalized tau functions and slowness-dependent source and receiver corrections obtained by Tralli and Johnson (1986a, b), and is not reviewed here. The hypocenter parameter estimation code is a standard nonlinear least-squares algorithm which follows the general approach of Levenberg (1944) and Marquardt (1963) as cited by Brown and Dennis (1972).

Slowness and azimuthal biases were determined empirically from the apparent functional form of the travel-time residuals for hypocentral parameters fixed at the disclosed values of NTS events using both Pahute Mesa and Yucca Flat data. A slowness-dependent travel-time baseline correction of $-2.43 + 0.092p$ (sec), where p is the horizontal slowness, is obtained from these residuals and is used for relocation of both NTS and NTG events. In addition, an azimuthal correction of the form $-0.52 \cos \phi - 0.29 \sin \phi$ (sec) is obtained, where ϕ is the receiver-to-source azimuth, measured east of north. This azimuthal correction is applied only to the NTS data. The residuals in slowness and azimuth are shown, respectively, in Figure 1, a and b. The differences in the distribution of data between slowness and azimuth, particularly the more uniform sampling in slowness, are discussed further by Tralli and Johnson (1986a).

Although the above corrections are used in this study, travel-time biases were also determined separately from 1677 Pahute Mesa residuals and 1504 Yucca Flat residuals. This yielded combined slowness and azimuthal corrections of the form $-2.58 + 0.110p - 0.58 \cos \phi - 0.38 \sin \phi$ (sec) and $-2.30 + 0.076p - 0.46 \cos \phi - 0.18 \sin \phi$ (sec), respectively. The azimuthal terms suggest slow directions at about 33° and 21° azimuth. This does not agree with the more detailed studies of Spence (1974) and Taylor (1983). However, a mean global baseline bias is still present in the correction terms (see Tralli and Johnson, 1986b), and only a comparison of bias estimates using travel-time residuals from other source regions would help isolate regional variations.

Epicentral Confidence Regions

Epicentral confidence ellipses are obtained from the sums of the weighted station residuals, or estimates of the sample variances, and the covariance matrices of the epicentral parameters. The station weights are determined using Jeffreys' (1961) method of uniform reduction, where the residuals are assumed to be random variables which follow a quasi-Gaussian distribution. No *a priori* knowledge of the station data is invoked, and only first arrivals as given by the ISC are used. Stations yielding residuals greater than about 4 sec are essentially weighted null. Focal depth is not a free parameter in the locations, as all focal depths are fixed at the surface. However, the disclosed burial depths and elevations of NTS events were used for the site calibration. For epicenter determination, the geographical orientation and ratio of the axes of the ellipse are then related only to the distribution of stations



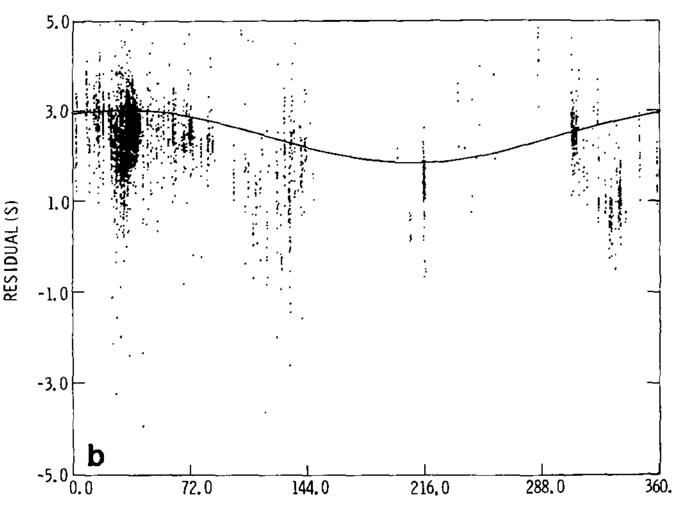


FIG. 1. (a) NTS travel-time residuals as a function of slowness p given hypocentral parameters fixed at the disclosed values. Uniform reduction is not used to weigh the residuals for bias estimation. Only ray paths with slownesses of 9.5 to 4.5 sec/deg are used in order to avoid the effects of upper mantle heterogeneity. The corresponding correction, $-2.43 + 0.092p$ (sec), is used for all events. (b) NTS residuals as a function of azimuth, yielding a travel-time correction of the form $-0.52 \cos \phi - 0.29 \sin \phi$ which is applied only to the NTS events. Azimuth (ϕ) is measured east of north.

about the epicenter. The appropriate expressions are given by Flinn (1965) for confidence ellipses linearized about the epicenter.

Briefly, the confidence ellipses are scaled by an F statistic according to the number of stations (N) and the number of hypocentral parameters estimated (K), at a chosen confidence level w. The scaling term c_K is given by

$$c_K{}^2 = KF(w;\, K,\, N - K)s^2$$

where sec^2 is the estimate of the sample variance. Sample variances for events located in this study are typically less than 0.50 sec^2 with a mean of 0.32 sec^2 for NTS events and 0.60 and 0.34 sec^2, respectively, for NTG events (Tralli and Johnson, 1986b). At NTS, the mean epicentral mislocation is 3 km. Confidence ellipses are shown in Figure 2. The F statistic used is at the 95 per cent confidence

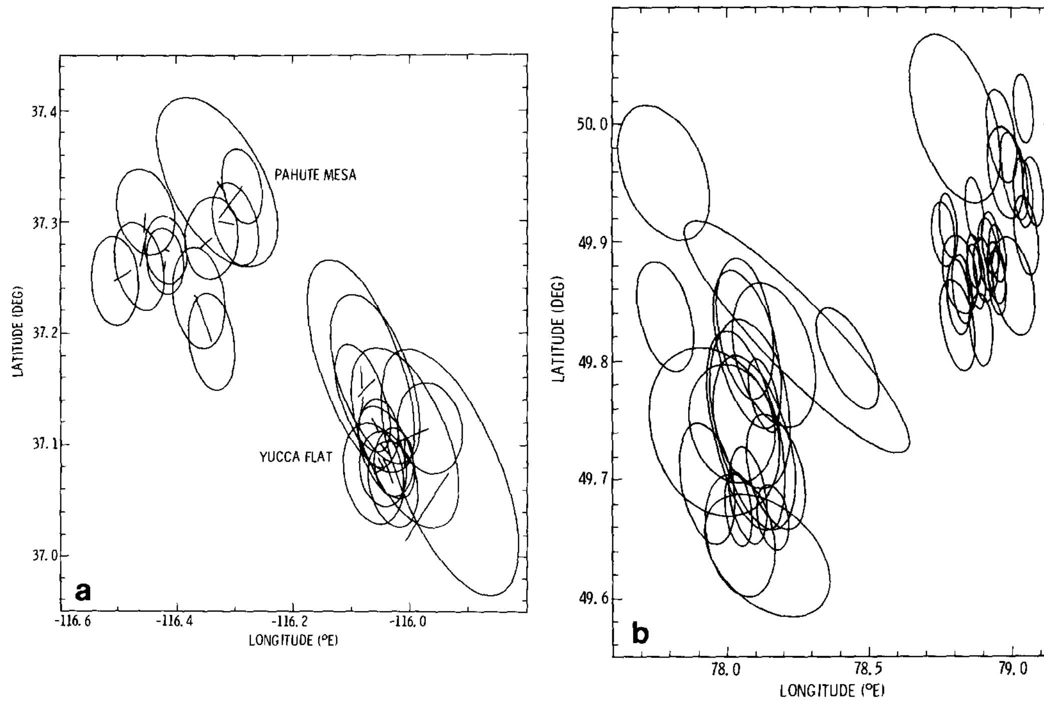


FIG. 2. (a) Ninety-five per cent confidence ellipses of NTS events. Mislocation vectors are relative to the disclosed locations. (b) Ninety-five per cent confidence ellipses of Eastern Kazakh events.

level. The linearized confidence regions in a small neighborhood about the estimated epicenter behave statistically as the exact regions, which they approach asymptotically as the number of stations becomes large (Flinn, 1965). The axes of the confidence ellipses obtained here are typically on the order of 10 km, and the approximation is valid.

Discussion of Results

The mean area of the epicentral confidence regions of the 18 NTS events with greater than 100 observing stations is 48.6 ± 12.9 km^2. With less than 100 stations, the mean area is 369.4 ± 188.5 km^2, determined from nine events. Almost all mislocation vectors relative to the disclosed locations fall within the 95 per cent confidence bounds. The largest uncertainties, with areas greater than 500 km^2, correspond to events with m_b less than about 4.8 and data from about 50 stations only. Confidence ellipses are typically elongated at a NW-SE trend due to the azimuthal station distribution (Figure 1b).

For comparison with NTS, 14 Eastern Kazakh (NTG) events with 100 to 200 stations yield a mean epicentral confidence region area of 162.7 ± 103.2 km^2, and 7 events with less than 100 reporting stations yield a mean area of 208.6 ± 102.3 km^2. This corresponds to mean ellipse axes of 7 to 8 km. Twenty-four events with greater than 200 station observations yield a mean area of 29.5 ± 12.3 km^2.

As the number of measurements is increased, the location uncertainties should indeed decrease. However, an additional likely interpretation of the inverse relationship between location uncertainty and number of stations is that the number of stations reporting an event decreases as the signal-to-noise ratio decreases and that the scatter in the reported arrival times increases correspondingly. In this sense, the confidence ellipses are a measure of the magnitude of the event.

True event locations in Eastern Kazakh are not known. However, the event of 15 January 1965 (Nordyke, 1975; Gubarev, 1976, 1978), discussed as a "master" event by Rodean (1976) and North and Fitch (unpublished data, 1980), allows for some comparison of accuracy. The relocation of this event, determined from 75 stations, yielded a presumed mislocation of 7.83 km and an azimuth of 44.54° relative to the coordinates of the crater (49.917°N, 79.000°E), whereas the ISC mislocation is 5.02 km with an azimuth of 214.95°. However, the ISC lists a standard deviation of station residuals of 1.25 sec, whereas the scheme used here yields a standard deviation of 0.50 sec. The area of the 95 per cent confidence ellipse is about 108 km^2. The estimate of the origin time is now 1 sec before the hour, which would agree more with the indications of Rodean (1979) for a nuclear test event.

Adjustments in the tectonic regionalization in and about Eastern Kazakh would be appropriate. This would not affect the receiver corrections as there are no data within about 15°. However, if Eastern Kazakh were to be regionalized as stable continent for example, a systematic shift of about +0.3 sec in the source corrections would translate to an earlier shift in the origin times (e.g., Tralli and Johnson, 1986a). The epicentral coordinates are not affected.

Well-constrained locations are a useful discriminant in nuclear test monitoring programs and a necessary supplement to other discrimination criteria. Clearly, there are limitations on the resolution and level of confidence attainable imposed by the number of observing stations, the magnitude of the event, and the accuracy of the reported readings. On the other hand, the resolution is a robust measure of the source magnitude. The small uncertainties in epicenter determinations shown by confidence regions at the 95 per cent level are not unexpected after removing the observed travel-time bias, particularly at NTS. However, the level of confidence in the results when using the slowness-dependent portion of this baseline to locate events in Eastern Kazakh is encouraging.

It is worth noting the indication of Pavlis (1986) that the F statistic may not be reliable in cases where the error estimates include systematic model biases. In the results presented in this study, a systematic bias in travel times is removed by the slowness and azimuthal corrections, and uniform reduction is then applied in the location algorithm to ensure a Gaussian distribution of station residuals. The confidence ellipses obtained are therefore expected to mainly reflect data error. A measure of accuracy is then the fact that mislocation vectors at NTS for the most part remain within the 95 per cent confidence ellipse, this also suggesting the success of tectonically regionalized travel-time estimates in characterizing the effects of lateral velocity variations in the crust and mantle.

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