EVENT SCREENING PROCEDURES AT THE PIDC

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ABSTRACT

Event screening is defined as the process of filtering out events that are considered to be consistent with natural or non-nuclear man-made phenomena, leaving a pool of ambiguous events that may require further examination. An experts working group representing many States Parties has been established to recommend appropriate screening guidelines for use at the International Data Centre (IDC). Event screens, which have been constructed from the key global discriminants: location, depth and Ms:mb, are capable of screening approximately 70% of the events in the REB. It is expected that there will be significant progressive enhancements to the screening procedures over time as the International Monitoring System (IMS) expands and becomes calibrated, and as additional discriminants are evaluated and included into the screening system. Other discriminants suggested for use in event screening (in Annex 2 to the Protocol of the CTBT) have been investigated. Preliminary results of their application and effectiveness are reported.

To assist in this work, the nuclear explosion database at the prototype IDC (pIDC) is being extended, with new seismic waveform data and the addition of phase arrival time information and event characterization measurements. In the future this dataset, including measurements, will be available through the World Wide Web.

Key Words: Event Screening, Discrimination, Groundtruth

OBJECTIVE

In Annex 2 to the protocol of the Comprehensive Nuclear-Test Ban Treaty (CTBT), a set of discriminants have been suggested for use in event screening. Our first goal is to investigate the capability of these discriminants in a global monitoring system and to develop event screening guidelines that can be implemented into the IDC processing system. Our second objective is to augment the nuclear explosion database at the pIDC with new seismic waveform data, the addition of phase arrival time information and event characterization measurements. The extended database will assist in the development of event screening procedures and be a useful data source for those working in the field of seismic event discrimination.

RESEARCH ACCOMPLISHED

Research has been undertaken in three areas. The principal focus has been on further developing and obtaining agreement on event screening criteria to be tested and implemented into Release 3 of the IDC software. Further, a preliminary assessment of screening with other discriminants has been performed and a summary is given of the groundtruth data that has been collected and processed. Each area of research is described below.

1. Event Screening

An experts working group representing many States Parties has been established to recommend appropriate event screening guidelines for use at the IDC. At the second Event Screening Workshop in Vienna, June 1998, the working group agreed upon a set of provisional event screening criteria to be tested and implemented into Release 2 of the IDC software. The initial screening criteria which consisted of both Ms:mb and depth, was approved by Working Group B, and was installed at the IDC during June 1999. Since that meeting, work has progressed with a third meeting held in May 1999 to build upon the existing criteria and procedures. A summary of the currently recommended event screening criteria and event scoring procedures to be tested at the pIDC for the Release 3 version of the event-screening system (installation date: mid 2000), is provided below. The recommendations are conservative in their approach and are thought to be robust in their application. It is expected that there will be significant progressive enhancements to the screening procedures over time as calibration information is added to the applications software, as more experience is gained in the operation of the IMS, as additional stations are added to the IMS, and as additional event characterization parameters are evaluated and included in the screening system.

1.1 Provisional Event Screening Criteria

To date, the event screening criteria are a combination of the discriminants: Ms:mb, depth and joint seismic-hydroacoustic locations. The recommended screening criteria for each discriminant is detailed below.

1.1.1 Ms:mb

Ms:mb has proved to be the most robust teleseismic discriminant for shallow seismic events and is based on the well-documented observation that nuclear explosions generate less surface wave energy than equivalently sized earthquakes. Taking into account differences in NEIC and pIDC magnitude estimates, Murphy (1997) showed from his analysis of 96 underground nuclear explosions and a set of earthquakes in the REB during the period 1996-1998 (see figure 1), that the discriminant line 1.25mb – Ms = 2.20 separates the earthquake and nuclear explosions populations well. It should be noted that this line is set at a level so as to ensure that no nuclear explosions would fall on the upper side of the line and be screened out.

As a result, the following Ms:mb provisional screening criteria was adopted in Release 2. It was recommended that an event be screened out if.

$$1.25\overline{m}_b - \overline{M}_s + 2\sigma_M < 2.20$$

Where

$$\sigma_M^2 = 1.25^2 \frac{\sigma_b^2}{N_b} + \frac{\sigma_s^2}{N_s}$$

$\overline{m}_b$ *and* $\overline{M}_s$ are the network averaged estimates of mb and Ms from N_b and N_s stations respectively, and σ_b and σ_s are the standard deviations of the single-station mb and Ms measurements, respectively. Determination of uncertainties for Ms and mb estimates is still under development. At present, conservative values of $\sigma_b = \sigma_s =$ 0.3 are used. It was recommended that the Ms:mb screening criterion be applied to all events in the Reviewed Event Bulletin (REB) for which mb >= 3.5 and which have a Ms value. This criterion, including the two-sigma term, is equivalent to requiring that the 97.5% one-sided confidence interval for 1.25mb-Ms is entirely less than 2.20.

Recently, Murphy (1999) has derived preliminary mb station corrections for the IMS network of 89 seismic stations that are currently operational. The corrections lead to an average reduction of more than 40 percent in the variance and an average increase of nearly 0.2 magnitude units in the network-averaged mb values. Murphy indicated that the Ms:mb screening threshold would need to be refined (from 2.20 to 2.45), if these preliminary mb station corrections are used.

These results have stimulated a debate regarding the best way of estimating unbiased station corrections, given that: (1) the IMS network is evolving; (2) mb estimates depend on which, if any, auxiliary stations are used; and (3) the method of estimating mb may need improvements. For Release 3, it was recommended that potential biases in the preliminary mb station corrections be investigated and that the Ms:mb screening criterion be refined appropriately, pending resolution of this issue and results of further testing.

1.1.2 Depth

Events that are confidently deeper than a depth threshold for which it is feasible with existing technology to test an underground nuclear explosion, are very likely to be of natural seismic origin. A provisional screening criterion based on the depth confidence interval, is being tested at the pIDC to screen out such events.

The recommended depth screening criterion to be tested in the Release 3 software is as follows. Let $\hat{D}$ be the hypocentre depth estimate and s_{zz} be the variance of the depth estimate that are reported in the REB. It was recommended that an event be screened out if:

where

$$\hat{D} - 2\sigma_D > 10km$$

The value of k depends on whether depth phase criteria are met:

$$2\sigma_D = 2\sqrt{s_{zz}} + k,$$

k = 0km if number of depth phases >= 3 and ΔT(pP-P) >= 1.5 sec for stations between 25 & 100º
k = 20km otherwise

It was recommended that the depth screening criteria be applied to all events in the REB with mb >= 3.5 and for which depth estimates were not constrained by an analyst. This criterion, including the two-sigma term, is equivalent to requiring that the 97.5% one-sided confidence interval is entirely deeper than 10km.

Comparisons of REB depth estimates with those of the PDE and local bulletins has shown that REB depth estimates exhibit significant regional biases and that the depth uncertainties do not adequately reflect all of the model and random errors. As an interim approach, a constant term k has been introduced to account for errors not adequately represented by s_{zz}. It has been shown by Jepsen and Fisk (1999) that the value of k=40km in Release 2 could be reduced to 20km and would still provide the appropriate coverage at the specified level of confidence.

1.1.3 Joint Seismic-Hydroacoustic Location Event Screening

Hydroacoustic data is sometimes required to assist in screening out events whose epicentres are on the water.

Oceanic seismic events which are confidently located, in water depths for which it is infeasible to install and test explosions in sub-oceanic material and with no associated hydroacoustic bubble pulse or high frequency energy (e.g., above 32 Hz), are very likely to be natural phenomena.

-- The following screening criteria were recommended for testing. The screening criteria would only be applied to events detected and located by seismic data and for which:
  - The minimum water depth (*min_water_depth*) within the 90% location error is ellipse at least 500 meters, based on the two-minute bathymetry grid, in the latitude range of ±72 degrees (the latitude range over which the Smith and Sandwell (1997) grid is valid); and
  - The entire 90% location error ellipse does not overlap or contain any onshore portions of an appropriate high-resolution coastline grid.

-- Such events <u>without</u> a detected hydroacoustic signal are to be screened out if:
  - The entire 90% location error ellipse has a clear path to at least one IMS hydrophone, based on signal blockage grids currently used at the prototype IDC; and
  - Hydrophone(s) without predicted signal blockage are operating properly at the predicted detection time interval; and
  - The noise level in the 32-64 Hz band during the predicted arrival time interval is less than three standard deviations above the long-term average noise level for the hydrophone.

-- Such events <u>with</u> associated hydroacoustic signals are to be screened out if:
  - There are no *significant* cepstral peaks in any of the associated signals from IMS hydrophones (indicating the absence of a bubble pulse); and
  - The total energy in the 32-64 Hz band (TE7) is less than 20 dB above the long-term average noise level in the same band (AN7) at each IMS hydrophone with an associated signal and with a Nyquist frequency greater than 64 Hz (i.e., TE7–AN7 < 20 dB for all single hydrophones with an associated hydroacoustic signal); and
  - The pre-signal noise level in the 32-64 Hz band is not greater than three standard deviations above the long-term average noise level for the associated IMS hydrophone.

1.2 Event Scoring

It was recommended that individual scores be computed for each event to numerically indicate the degree to which that event does, or does not, meet the depth, Ms:mb, and joint seismic-hydroacoustic location event-screening criteria. The following individual scores were recommended for testing:

$SCORE_{Depth}$ $= (\hat{D} - 10.0 \text{ km})/2\sigma_D - 1.0$; if the depth estimate is unconstrained

$= -999.0$; if the depth is constrained to the surface

$SCORE_{Ms:mb}$ $= [2.20 - (1.25\overline{m}_b - \overline{M}_s)]/2\sigma_M - 1.0$

$= -999.0$; if an Ms measurement was not computed

$SCORE_{Hydro}$ $= +1.0 - (\text{TE7} - \text{AN7})/20.0$ dB; if TE7 is above the detection threshold

$= +1.0$; if the *min_water_depth* > 500 m, there is no predicted signal blockage, and TE7 is below the detection threshold

$= -999.0$; if the *min_water_depth* <= 500 m or there is predicted hydroacoustic signal blockage

It was recommended that an event be screened out if $SCORE_{Depth}$ or $SCORE_{Ms:mb}$ or $SCORE_{Hydro}$ is greater than zero, unless there are conflicting Ms:mb and hydroacoustic screening results. Note that the explicit expression for $SCORE_{Ms:mb}$ may be modified, as appropriate, depending on the resolution of issues regarding mb station corrections and the results of further testing.

Table 1 summarizes the recommended event-screening categories and the corresponding criteria to be tested. Each event in the REB will be assigned to one of the five screening categories in Table 1. Only events in the "Screened Out" category are to be screened out.

Table 1. Summary of recommended standard event-screening categories and criteria.

Screening Category	Screening Criteria
Not Considered	mb < 3.5
Insufficient Data	$SCORE_{Depth}$ = -999.0 and $SCORE_{Ms:mb}$ = -999.0 and $SCORE_{Hydro}$ = -999.0
Not Screened Out	$SCORE_{Depth}$ <=0.0 and $SCORE_{Ms:mb}$ <=0.0 and $SCORE_{Hydro}$ <=0.0, and at least one score is greater than –999.0
Conflicting Evidence	($SCORE_{Ms:mb}$ > 0.0 and –999.0 < $SCORE_{Hydro}$ <=0.0) or (-999.0 < $SCORE_{Ms:mb}$ <=0.0 and $SCORE_{Hydro}$ > 0.0)
Screened Out	$SCORE_{Depth}$ > 0.0 or $SCORE_{Ms:mb}$ > 0.0 or $SCORE_{Hydro}$ > 0.0, unless there are conflicting Ms:mb and hydroacoustic scores

1.3 Results

Application of Release 2 Ms:mb and depth event screening criteria on all REB events during 1998 was performed. It was found that a total of 46% of events of mb >= 3.5 were screened out. Figure 2 shows the breakdown of screening by category versus the magnitude of the event. It is evident that the Ms:mb and depth screening criteria complement each other very well, as a majority of the screened events are individually screened by either depth or Ms:mb. The physical basis for this is that Ms:mb is generally applicable to shallow events, whereas the depth criterion is intended to screen out deep earthquakes where Ms:mb is ineffective. Ms:mb provides the main contribution to the screening of events above mb 4.5, and in combination with depth, almost manages complete screening of earthquakes of mb 5.0 and above. It is expected that as the IMS system evolves, the screening capability based on the global discriminants alone will be able to meet the coupled 1KT explosion target (around mb 4.2). About 45% of the events not screened (30% of the total) are confidently located offshore. It is expected that future testing will demonstrate that most of these events will be screened out by the joint seismic-hydroacoustic location screening criteria. This would take the total number of screened events up towards the 70% mark.

2.0 Other discriminants for event screening

There are numerous other discriminants listed in the treaty to be tested for use in event screening. Algorithms for most of them have been written and implemented into the pIDC system (see Jepsen and Spiliopoulos, 1997). In this section a preliminary assessment of the global discriminants: teleseismic complexity, first motion and third moment of frequency are discussed. These discriminants have been in existence for decades but are currently not in favor for screening events worldwide. Issues that will be addressed are: will they help with the screening of natural phenomena and non-nuclear man made events? Do they complement the present screening criteria? How much do they add? Should future work of these discriminants be prioritized?

2.1 Teleseismic complexity

The measure of complexity follows the energy ratio technique of Douglas (1980). In this method the coherent beam of the P signal is filtered in the band 0.8 to 2.0Hz, squared and smoothed with an exponential window. Complexity is then computed as:

$$\text{Complexity} = \frac{S(5\text{-}35\text{sec} - N)}{S(0\text{-}5\text{sec} - N)}$$

except in following two cases:
If S(0-5) – N < 0, complexity = -1
If S(5-35) – N <= 0, complexity = 0

Complexity fell out of favor when complex signals from underground nuclear explosions were observed. Modeling by Bowers (1996) however, has suggested that a network averaged measure of complexity may prove to be viable. The basis for this is that simple sources, such as nuclear explosions, should be observed as simple recordings at many points on the earth and a network averaged value will make use of this. One useful network averaged measure is taking the average of the five lowest complexity measurements of the event. Figure 3 shows the network averages of a set of nuclear explosions from 7 test sites and all REB events during 1998 with at least five complexity measurements with SNR >=4. As expected, the nuclear explosions are in general less

complex than the shallow earthquakes. As a first step, an average network complexity of 1 could be used as the screening criterion and any event with a larger value would be screened out. Such a value ensures that no nuclear explosion would be screened out. Deep earthquakes are generally less complex and will not be screened out using this complexity screen. This is of no concern as the process only intends on screening out events that are more complex than the most complex nuclear explosion, and there are other discriminants such as depth that will help with screening these events. Of the 17299 events in the REB, the network averaged complexity could only be calculated for 1984 events, of which 1200 (60%) would be screened out with this criteria. However in conjunction with Ms:mb and depth, only an additional 180 events (1% of the total) would be screened out by complexity alone. It is expected that as the regional variability of complexity is investigated, and as other methods of calculating complexity are considered, complexity will provide a greater contribution to event screening.

2.2 First Motion

First motion is traditionally difficult to measure and is normally only possible with recordings from large events or events within a close regional network. This imposes a severe constraint on its use for event screening and so it is not expected to add any extra capability to the present screening criteria. The first motion algorithm implemented at the pIDC searches for the first maxima or minima after the onset and then assigns the appropriate direction. However, when this was implemented into the pIDC system it was found that many of the first motions were incorrect, indicating that this measurement is difficult to automate reliably. Analysis of the three nuclear explosions on the Indian sub-continent in 1998 showed that the analysts were incorrectly picking the onsets from many recordings, and hence the first motion were inaccurate. In addition, disagreement was found when Australian NDC analyst picks were compared with automatically calculated pIDC first motions for events recorded at ASAR, WRA and STKA during the first 3 months of 1999. It is of concern that the first motion onsets differ remarkably (see figure 4). Many of the events are emergent, so in these cases a first motion estimate is meaningless. Of the remaining events at least one-third of the impulsive recordings were in disagreement. Using a SNR criterion to resolve this problem is currently not a solution because there is a vast overlap between the SNR ranges of those events that the analysts agreed or disagreed with. As a result, first motion, in the way it is currently implemented, can not be used for event screening.

2.3 Third Moment of Frequency

The TMF measure follows that of Weichart (1971) and is calculated as

$$TMF = \left(\int_{0.5}^{5.0} f^3 sig(f)\,df \Big/ \int_{0.5}^{5.0} sig(f)\,df \right)^{1/3}$$

where the signal has been corrected for noise. This measure gives more weight to high frequencies, so events with a greater proportion of high frequency energy will have higher TMF values.

Due to the small source dimension of a nuclear explosion compared to an equivalently sized earthquake, it would be expected that nuclear explosions would have higher frequency content than earthquakes, and so have higher TMF values. A comparison of TMF values of earthquakes in the REB and nuclear explosions (figure 5), shows no separation between the two source types and implies that no global screening criterion can be developed. These observations can be largely explained by the fact that attenuation of seismic energy differs dramatically in different regions of the world. A preliminary analysis of Lop Nor explosions on a station by station basis shows some separation, indicating that TMF could be used as an event screening tool for some source-receiver paths. However, since the TMF measure requires that the signal is significantly greater than the noise in the frequency band of interest, and can only be calculated for large events, it is certain that it will not contribute greatly to screening out additional events.

2.4 Regional Discriminants

Regional phase amplitudes have been studied extensively. Recently, Fisk (1999) has drawn upon many of these studies to devise a preliminary, systematic, global approach using P/S amplitude ratios for screening regional events. Baumgardt (1988), Hedlin et al. (1998) and Sereno & Wahl (1993) have found spectral techniques to be effective in discriminating ripple fired events from other source types. It has been demonstrated that the most successful applications of these techniques occur in areas of low attenuation and with recordings of events out to

10 degrees. Regional equivalents of mb:Ms, such as SPLP energy ratio (Woods and Helmberger, 1997), Ml:Mo and mb:Mo (Patton and Walter, 1993; Woods et al. 1993) have been successfully used to discriminate small regional events in the western US. Application of these discriminants has been limited to specific regional areas, and much work needs to be performed on a global basis before they can be successfully imported into some systematic screening mechanism. We are currently in the data gathering phase, collecting groundtruth data and making routine measurements. It is envisaged that a detailed event screening analysis using each discriminant will be made in the future.

2.5 Prioritization

The prioritization of future work on discriminants that are not currently part of the existing screening criteria was discussed at the 3rd Event Screening Workshop. Prioritization was based on the degree to which the discriminant could contribute to event screening, taking into account current progress and perceived limitations. It was recommended that investigations in terms of event screening should continue with regional phase amplitudes, spectral methods, regional Ms:mb measures and teleseismic complexity. It was agreed that further development of first motion and third moment of frequency should not be pursued in the near future.

3.0 Groundtruth

A Ground Truth data set consisting of seismic waveform data, phase arrival times, event characterization measurements and other associated source information from seismic events with known source type is under construction. This data set is and will be used to develop the event screening methodologies to be employed at the CTBT IDC.

The starting point for this data set was the Nuclear Explosion Database developed at the Center for Monitoring Research (CMR) (Yang et al, 1999). This database consists primarily of a table of origin data for 2041 distinct nuclear explosions. Waveform data for at least 742 of these events is also available. The data set was incomplete for our purposes in that phase arrival time information was not always available with the seismic waveform data, instrument calibration information was required and extensive quality control of the waveform data needed to be undertaken. Consequently only the waveform data from the CMR dataset was used.

The data from the CMR database has been augmented with seismic waveform and ancillary data from a number of other sources. These include:

- The Balapan data set assembled by Jack Murphy, which consists of data from explosions at the former Balapan Test Site.
- Data from the chemical calibration explosions detonated at the Semipalatinsk Test Site in 1997 and 1998.
- Data from IRIS of seismic recordings of nuclear explosions that are not contained in the CMR waveform data set.

Data has been obtained from as many seismic stations as possible and has not been limited to those stations that comprise the International Seismic Monitoring (IMS) network. This has been done in order to sample as many paths as possible for the purpose of possibly investigating the transportability of discriminants. In addition to the CMR and Balapan datasets, some 4000 extra waveform segments have been collected. Also 2600 arrivals have been analyzed and their associated waveforms have been checked for quality control. Figure 6 shows the locations of explosions (nuclear and chemical) from which data is available.

These data are currently being reviewed by a seismic analyst who is checking for quality control and also picking the arrival times of phases. After the data is reviewed, the waveform data, arrival times and calibration information are loaded into the pIDC database and event characterization measurements are made. In the future it is anticipated that this dataset will be available through the World Wide Web.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Event screening criteria recommended by the working group are based on Ms:mb, depth and joint seismic-hydroacoustic location. The criteria are believed to be conservative and robust in their application. Results of testing Release 2 criteria on REB events during 1998 showed that 46% of the earthquakes (mb >=3.5) could be screened out and it is expected that many more earthquakes will be screened (up to 70%) by the Release 3

screening criteria. Further progressive enhancements to the screening criteria will be achieved as the existing screening criteria are improved and as regional and other global discriminants are tested and implemented into the screening system. For many discriminants a single screening criterion will not be possible and it may require defining criterion based on regions or specific source-receiver paths.

A major contribution to the event screening task will be the continual testing on groundtruth data. It is therefore strongly recommended that the collection of groundtruth data should continue and be made accessible to the community.

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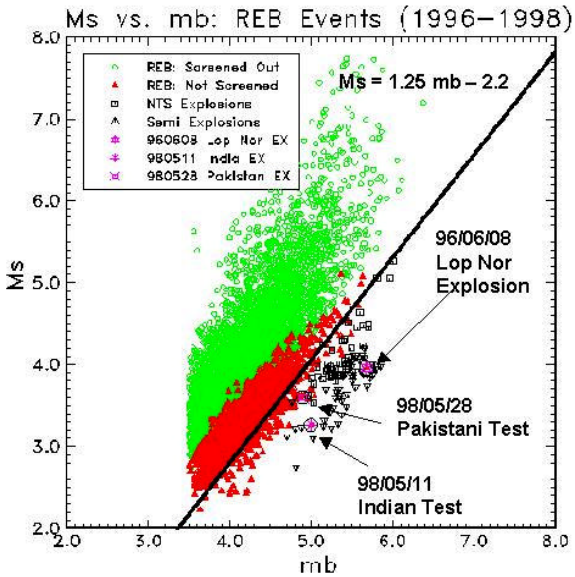

Figure 1: Ms versus mb values for 8608 REB events from 1996 to 1998 and a total of 96 underground nuclear explosions at the Nevada, Semipalatinsk, Lop Nor, Indian, and Pakistan test sites (from Fisk, 1998).

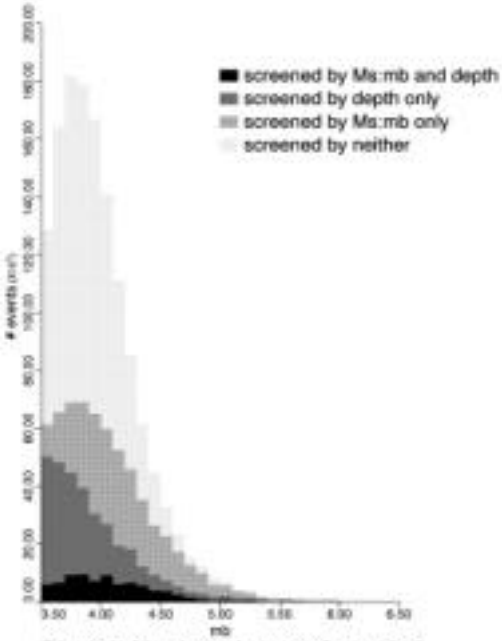

Figure2: Number of events from 1998 REBs screened by Ms:mb, depth or both versus magnitude.

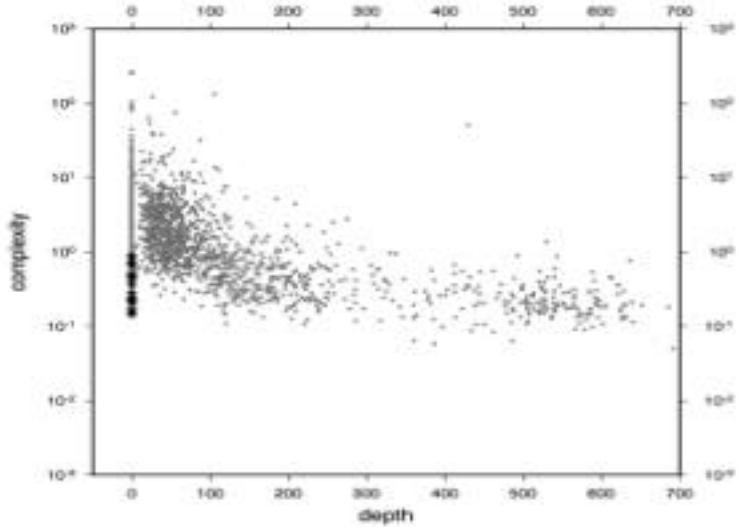

Figure 3: Network averaged complexity (of lowest 5) versus depth for 1998 REB events (grey) and nuclear explosions (black) where snr >=4.

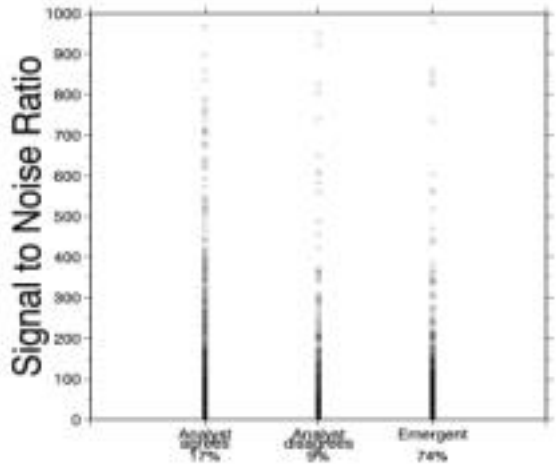

Figure 4: Comparison of analyst first motion picks with pIDC automatic first motion picks as a function of SNR.

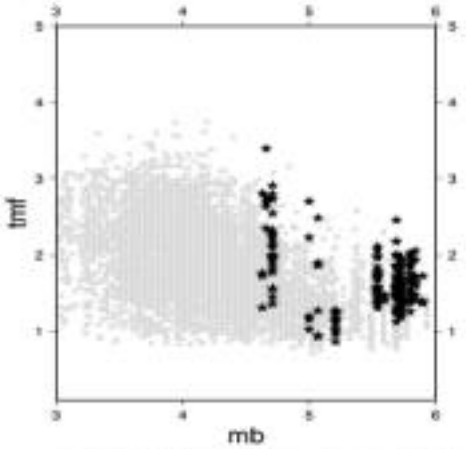

Figure 5: Third moment of frequency versus magnitude for earthquakes (grey) and nuclear explosions (black) in the REB

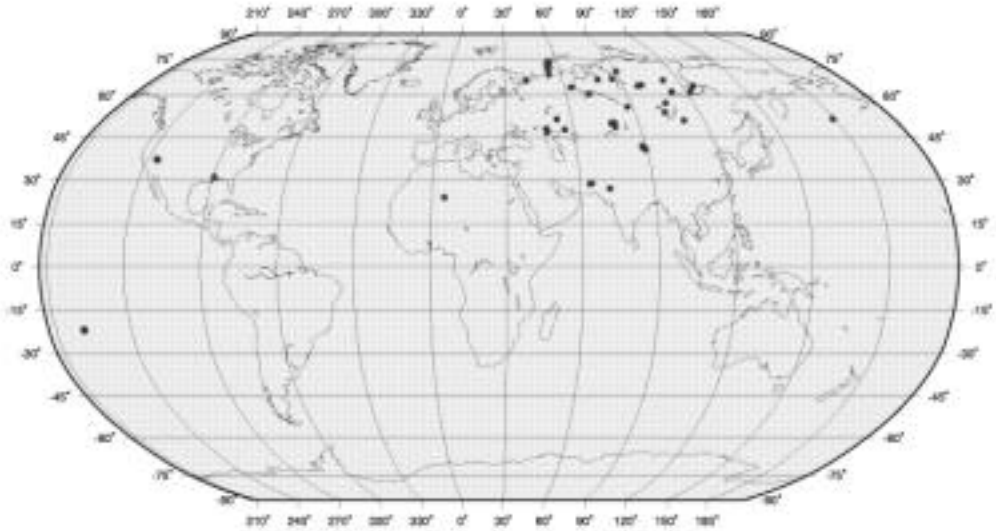

Figure 6: Location of explosions (nuclear and chemical) for which Ground Truth data is available.