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SAND--88-3327

DE89 010520

SAND88-3327
Unlimited Release
Printed January 1989

Statistical Analysis of Yield Calibration Curves at NTS

by

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Abstract

Data from the Sandia Seismic Net is used to analyze the precision of yield calibration curves from the point of view of a Threshold Test Ban Treaty. These curves are determined using the same methodology that is applied in our present techniques at NTS. Initially, no constraints are placed on the data set in order simulate the lack of knowledge of a foreign test site. Restrictions are then placed on events with respect to the water table, areal extent and yield range with improvements in the standard deviation in almost all cases. For NTS, the results indicate that large events (> 80 kt) can be measured reasonably well (RMS deviation 1.21) with no additional restriction on the data set. As the yields are lowered, the precision gets progressively worse with the depth of burial moving above the water table. At this point, reduction of the areal extent becomes more important. The one sigma level of events with yield < 20 kt is 1.66 for NTS. Smaller areas (70 km^2) are better (1.40), but still high.

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Introduction

One of the major concerns of a Threshold Test Ban Treaty (TTBT) for the USA is the verification that the yield limit is not exceeded. Presently there are two primary methods expounded for use in the monitoring of nuclear tests to insure the compliance of a treaty limit. One is hydrodynamic yield estimation and the other is teleseismic analysis. Each of these methods has their advantages and disadvantages. Teleseismic monitoring has been applied to US and Soviet tests for several decades so the method has a considerable track record.

Although hydrodynamic yield analysis is a relatively recent development when compared to seismic methods, it appears to estimate yield of individual US events better than seismic techniques without requiring extensive calibration. However, the technique requires accurate placement of the cable very close to the explosion, well within the strong shock (hydrodynamic) interval. To avoid an erroneous yield estimate, the location of a device must be known. Also, its yield estimates appear to be less reliable at low yields. In any case, the hydrodynamic method is very intrusive. On the other hand, teleseismic monitoring is almost completely avoids a foreign host's involvement. Stations can be situated on friendlier soil in a much a more controlled environment. However, now there are other limitations such as signal to noise considerations and seismic site calibrations at both source and receiver.

Neither of these methods are completely satisfactory at low yields (≈ 10 kt). However, a regional net could augment the monitoring in a significant manner. First, although initial calibration is necessary, regional seismic methods are not as intrusive as the hydrodynamic method. Second, a regional net can still record signals with yields substantially less than what has been applied in either hydrodynamic or seismic techniques. Sandia National Laboratories has been monitoring seismic activity at NTS and estimating yields using a regional net for over 25 years. During this period, error in the estimates provided by Sandia have been quite low (one sigma of about 1.16)[1]. This low sigma level is due directly to the large number of events in your data base. This allows us to divide the test site into several geophysically distinct regions and determine a calibration curve for each of these regions. As more data became available, we began to apply a master event technique. That is; our data base is large enough to allow us in most cases to further sub-divide the tests and directly compare similar events that are within 1 km of each other with about the same yield and depth of burial. This detail will probably not be available at a foreign test site and it will be necessary to define a geophysically distinct region much more crudely. The 1.16 value should be looked upon as a lower bound for our seismic estimating capabilities.

So the question arises, how well can yield be estimated from a regional net if less than ideal conditions exist? In an earlier paper[2], I examined the sigma level as a function of the number of calibration events in a very ill-defined source region (all of NTS). A small set of sources (21) was used in this analysis to accommodate the use of strain data obtained from a laser strain seismometer that Sandia was operating between 1975-77. A greater sample size was simulated by a permutation technique. The analysis of the seismic net produced 1 sigma levels initially in the range of 1.7 and decreased asymptotically to 1.3 as more events were added to a calibration set. Unfortunately, there was a sparse population of events in the lower yields.

In this report I look at how well yield can be estimated in various regions of NTS with different environments (above or below water table) and for selected yield ranges. Unlike the previous study, the source population is greatly increased to include most events in the period between 1969-86. I will determine how well each station measures yield and how well the net estimates yield under the constraints of assuming NTS as one geophysically distinct region. The analyses will also be done on a selected subset of areas to see what improvement can be made. This study confronts the problem of precision, not accuracy, i.e. The consistency of the analysis is studied, not the absolute calibration.

Data

The data used in the study were obtained from recordings of the Sandia Seismic Net (SSN). The net consists of five stations reasonably distributed outside the test site (figure 1). The ranges vary between 110 km to 400 km depending on the event location. Presently, each of the stations has a three-component wide band seismometer and four of the sites (Darwin, Leeds, Nelson and Tonopah) have a two-component short period Benioff seismometers. These instruments are aligned vertically and radially with respect to NTS. The three-component system has an addition tangential channel. This system is described in greater detail elsewhere[1].

Although Sandia National Laboratories has been monitoring nuclear tests at NTS since 1960, only events in the years from 1969-1986 are used in this study. There are several reasons for this slight restriction. First, the net has changed and several of the early stations are no longer in use. The present configuration has been in existence since 1964. Second, the wave amplitudes from 1969 to the present are available in ascii format and relatively easy to convert to a readable file by a Fortran program. Data prior to 1969 would need to be copied from microfiche and since there are a sufficient number of events in the years after 1968, the data base was restricted to the years 1969-86.

In this study, most multiple and all tunnel events are not considered. The phases chosen for the analysis are the first motion amplitude (Va) recorded on vertical short period Benioff seismometer and the next vertical peak to peak amplitude (Vb). These amplitudes are related to the yield by an empirical calibration curve of the form:

$$\text{Log } Y = a + b \text{ Log } A \quad (1)$$

where Y is the yield, A is the wave amplitude corrected for range (r^{-2}) and a and b are constants determined by a least square analysis. A calibration curve for each phase type and each station must be determined. The standard deviation for the yield is found by regression analysis of equation (1) and taking the inverse log with respect to 10 of the RMS deviation obtained in the analysis.

The wide band instruments are not used in the analysis because we have changed seismometers recently (1983). The Benioff instruments are the original short period equipment in the net. Rather than apply instrument corrections so that comparisons of our previous wide band seismometers to the present system can be made, only the short period data is considered.

Analysis

The data set contains 253 events after eliminating unwanted events for various reasons (tunnel events, double events, etc.). The analysis consists of several different studies in which constraints are placed on the events. The constraints are designed to determine how well (RMS deviation) yield can be measured under possible conditions imposed by a Threshold Test Ban Treaty. Initially I will assume no constraints and treat the entire NTS as one geophysically distinct area. This will be followed by looking at two subsets of the data, those events above the water table and those below the water table.

The above studies are worst cases because of the large variations in geology over the test site. If the geology of the source region could be restricted, presumably the variations due to geophysical anomalies in the source region could be greatly reduced. The next study simulates this by putting constraints on the event locations and thus considers smaller geophysically distinct areas. The only areas I consider are 2, 3, 7, 19 and 20 (figure 2). Each of these sets have 55, 70, 41, 22 and 26 events respectively in them. The other areas have fewer events and it would be difficult to draw any conclusions from the statistics.

One more additional class of analyses is done. This study divides the data set several different yield bands. The idea behind these constraints is to simulate verification at different possible yield limits. The bands considered are 80 - 250 kt, 10 - 50 kt and .5 - 20 kt. These restrictions allow us to determine our capabilities of verifying not only the 150 kt treaty, but also possible lower limits. The results of course only pertain to our test site but should give general guide lines at lower limits.

The RMS deviations used in the analyses are calculated with respect to the calibration curves represented by equation (1). Since there are two amplitudes per station and four stations (Darwin, Leeds, Nelson, and Tonopah), there are eight calibration equations to determine. There is also a second standard deviation. The first deviation is associated a particular station-amplitude pair. The second deviation is related to a net average. That is, the yield results for a particular event are averaged over the net (each station) and the total standard deviation is recalculated from the average net yield. The individual station amplitudes can reflect tectonic strain release. By averaging over the net, this bias should decrease. In all cases, those events whose yield was a factor of 4 greater or less than that predicted by the calibration curves were not used in determining the standard deviation.

Results

NTS is a region located 75 miles NW of Las Vegas, Nevada. The particular regions of interest (shown in figure 2) include Pahute Mesa and Yucca Flats and is about 50 km square with a total areal extent of about 2500 km^2. The geology varies from an alluvial plain in Yucca Flats to competent rock in Pahute Mesa. In spite of the vast geological variation, initially the test site is treated as one homogeneous region. Figures (3) is a representative plot of a calibration curve for the Va amplitude at Darwin using the entire data set. Most of the calibration curves are similar to this curve, some with higher RMS deviations and others with lower deviations.

Figure (4) is a plot that compares how well the net determines the yield. The ordinate is the official lab yield as determined by a multitude of techniques (rad-chem, etc.). The abscissa is the yield estimated by the calibration curves and averaged over the net. The straight line is the ideal curve; official yield = calculated yield. A complete summary of RMS values for station amplitude pairs and the net average is given in Table I.

The RMS deviation averaged over the net is 1.55. The deviations for the calibration curves for the individual stations vary from a low of 1.52 at Darwin to a high of 1.95 at Tonopah. This precision under the stated conditions is clearly inferior to the historical estimate (1.16).

Before we completely eliminate the idea of NTS as a sufficiently small area to estimate yield, let us see if the water table has any effect on the analysis. Let the data set be divided into two parts; those events above the water table and those below the water table. Tables II and III give the RMS deviations under these conditions. The RMS deviation increases to 1.60 for those events above the water table and decreases to 1.46 if the events are below the water table. These are only slight incremental change when compared to the 1.16 value. The direction of the changes however are of some significance. The increase for those events above the water table should be expected for several reasons. First the coupling in "dry" porous rock is more variable than in a wet saturated medium. More energy must be expended in crushing the rock and closing voids than in a saturated medium. Also lower yields are buried at relatively shallow depths and tend to be above the water table. This adds more variability because of a reduced signal to noise ratio.

The next constraint imposed on the data set limits the areal extent of the events. In Tables I-III, RMS deviations are given for areas 2, 3, 7, 19 and 20 (figure 2). All of these regions reduce the areal extent from 2500 km^2 to about 60-70 km^2. In all cases, the localized RMS deviations for the net average are reduced when compared to the NTS results. The RMS deviations for the individual station-area pairs is a mixed result. The vast majority of cases have RMS deviations less than the NTS results. However the variation in these deviations is widely scattered from 1.17 for area 7 at Darwin to 1.72 for area 3 again at Darwin. The average net deviations for the areas are much lower than this and vary from a low of 1.26 for area 7 to 1.46 for area 3. A large part of this decrease in the seismic net deviations is probably due to the averaging out the strain release. That is, if the strain release is due to a strike slip source, this component tends to cancel out when averaged over the net.

The large scatter in yield estimates for area 3 as compared to areas 7 and 20 could be attributed to the water table. Area 3 has few events below the water table while area 20 has almost none above the water table. Area 7 has a 27/14 split of the population below/above the water table. Although this might be a good explanation for the scatter in area 3, it does not explain why area 19 has such a large scatter since almost all its events are below the water table. The above discussion also illustrates that the division of events with respect to the water table is not completely independent of the water table criterion. However, this areal constraint of the events to a much narrower range causes a dramatic lowering of the deviations when compared to the 1.55 value for all NTS.

The last constraint restricts the events to particular yield bands. Again, the data set are not completely independent of the previous restrictions. For instance, the population is restricted to only high yield events, then the data is weighted heavily in areas 19 and 20. Similarly, area 3 contains only low yield events. Also, the water table bias still exists. With this in mind, consider the yield interval 80-250 kt. Table IV is an abbreviated version of Table I without the individual stations but with the number of events used in the statistical analysis. In this energy range, the net average RMS deviations are phenomenally good. The 1 sigma for NTS is 1.21 with a total of 66 events in the data set. Out of the 66 events, only one is above the water table. The individual areas all have 1 sigmas less than 1.20. Area 3 is not represented in the table due to the lack of events in the yield interval.

Table V exhibits the RMS deviations for events restricted to the 10-50 kt range. These deviations are lower than the unrestricted case of Table I, but are higher than the 80-250 kt interval. The individual areas are still at reasonably small sigma levels with area 7 again exhibiting the lowest value. The net average deviation for NTS is 1.38 and the population now has a greater number of events above the water table (72). Note that areas 19 and 20 are no longer represented while area 3 has 32 events in the data set. With the lower yields, the depth of burial of the events migrate toward the surface above the water table.

The final interval is 0-20 kt. Table VI shows the RMS deviation and number of events within each area. In general, these deviations are comparable to the unrestricted case (Table I) with the NTS analysis being substantially higher (1.66). Almost all the events are above the water table (5 of 117 are below). The area 7 RMS deviation (1.23) continue to be small compared to the other areas.

Summarizing the tables presented above, a number of conclusions can be drawn. First, localizing the events into data sets restricted to small areas reduces the sigma level significantly when it is compared to the other analyses. Second, analyses of events below the water table produces some improvement. The greatest reduction occurs if the data set is constrained to yield bands > 80 kt. As the yield interval is reduced, the RMS deviation gets progressively worse. At yields < 20 kt, the RMS deviation is larger than the unconstrained case. For the high yields, the improvement seems to be independent of regionalization. Since depths of burial are scaled, the constrains are not completely independent of one another.

Conclusions

Yields of nuclear tests are estimated from signals emanating from NTS and measured by the regional Sandia Seismic Net. The data was analyzed from the point of view that the net is a monitoring instrument for a limited test ban treaty. To do this, a number of constraints were imposed. In the most general case, the entire test site was assumed to be a geophysically distinct region. Calibration curves were determined for the individual stations along with their standard deviations. These deviations varied substantially over the stations and were quite large (1.6-2.1). Averaging over stations and eliminating outliers greater than or less than a factor of 4 reduces the sigmas to 1.55. These results are improved further if the data set is restricted to events below the water table (1.43). Additional improvements are found if NTS is subdivided into smaller areas. Area 7 has the a standard deviation of 1.2, which is considerably lower than all the other areas. However further studies need to be made on what role structure, coupling and stress release play in regional signals.

References

[1]L.F. Brady and H. D. Garbin, "The Sandia National Labs off-site Seismic Net," Conference on DOE Ground Motion and Seismic Programs On, Around, and Beyond the NTS, Albuquerque, NM, November 4-5, 1981 (Albuquerque, NM: Sandia National Laboratories) 1981.

[2]H. D. Garbin."Dependence of Fractional Standard Deviation of Seismic Yield on Number of Calibration Events,"SAND82-2193 (Albuquerque, NM:Sandia National Laboratories) 1983.

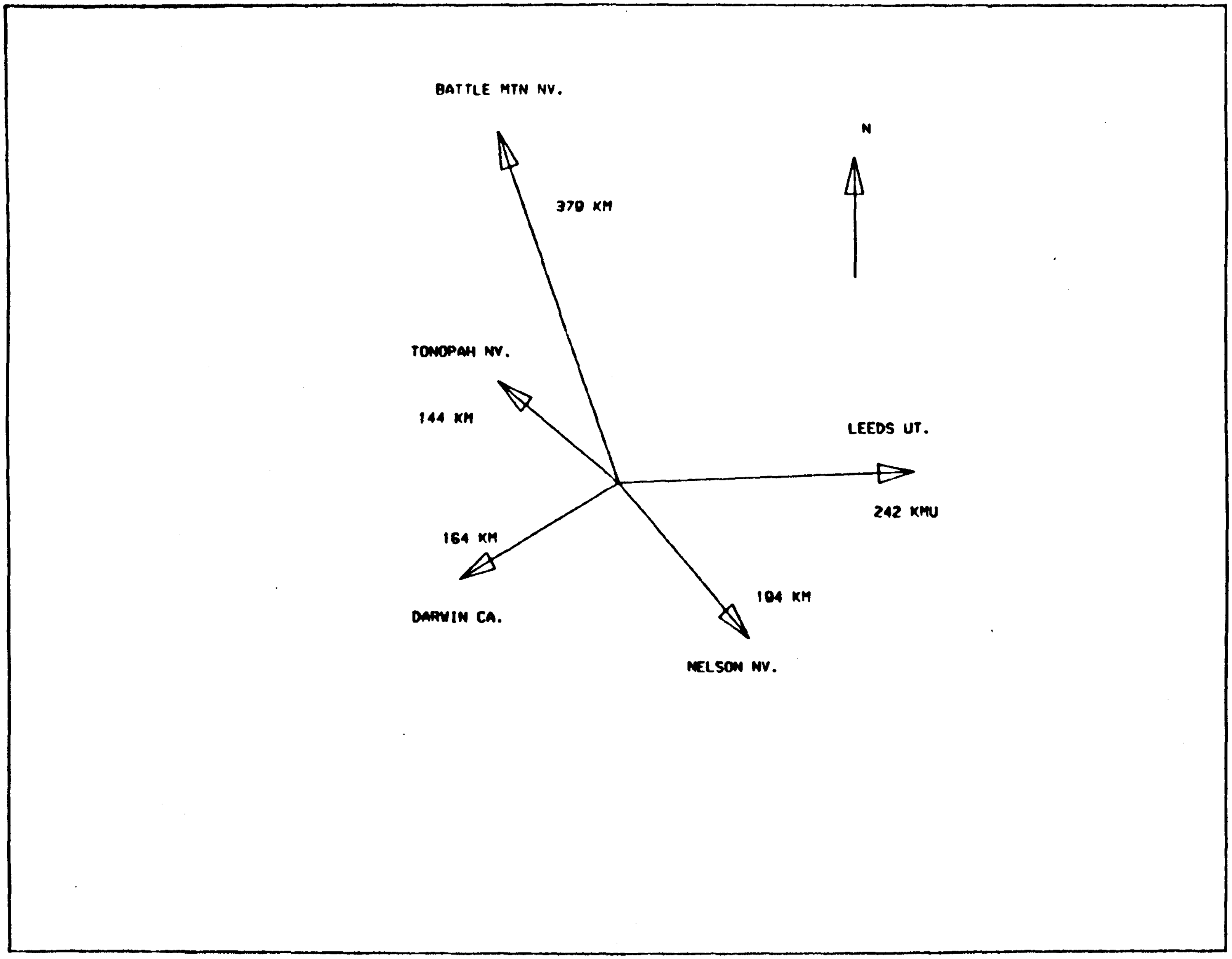

Figure 1. SSN Seismometer Stations Relative to NTS Reference
Lat. 36° 08′, Long. 116° 06′

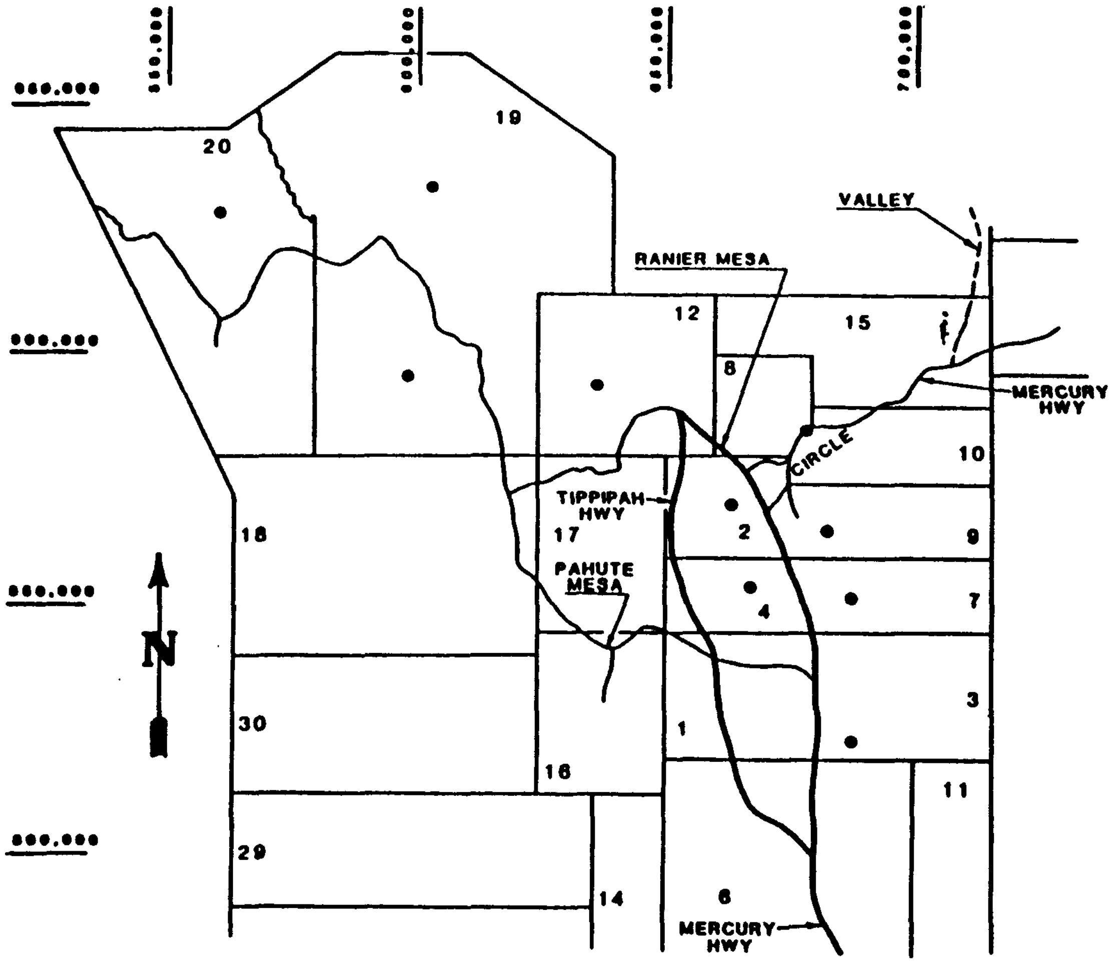

Figure 2. Map of NTS Areas

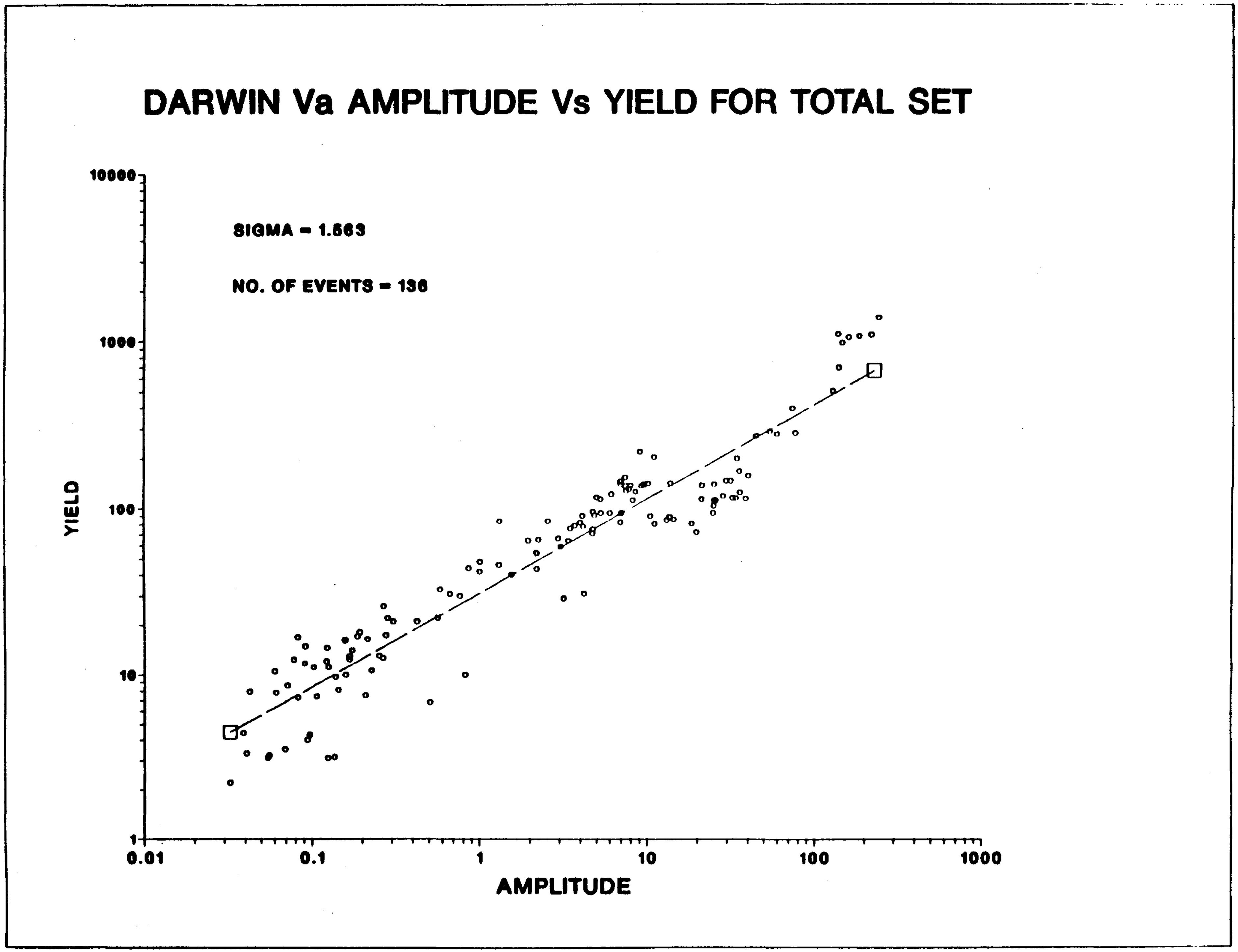
DARWIN Va AMPLITUDE Vs YIELD FOR TOTAL SET
SIGMA = 1.563
NO. OF EVENTS = 136
YIELD
AMPLITUDE
10000
1000
100
10
1
0.01
0.1
1
10
100
1000

Figure 3.

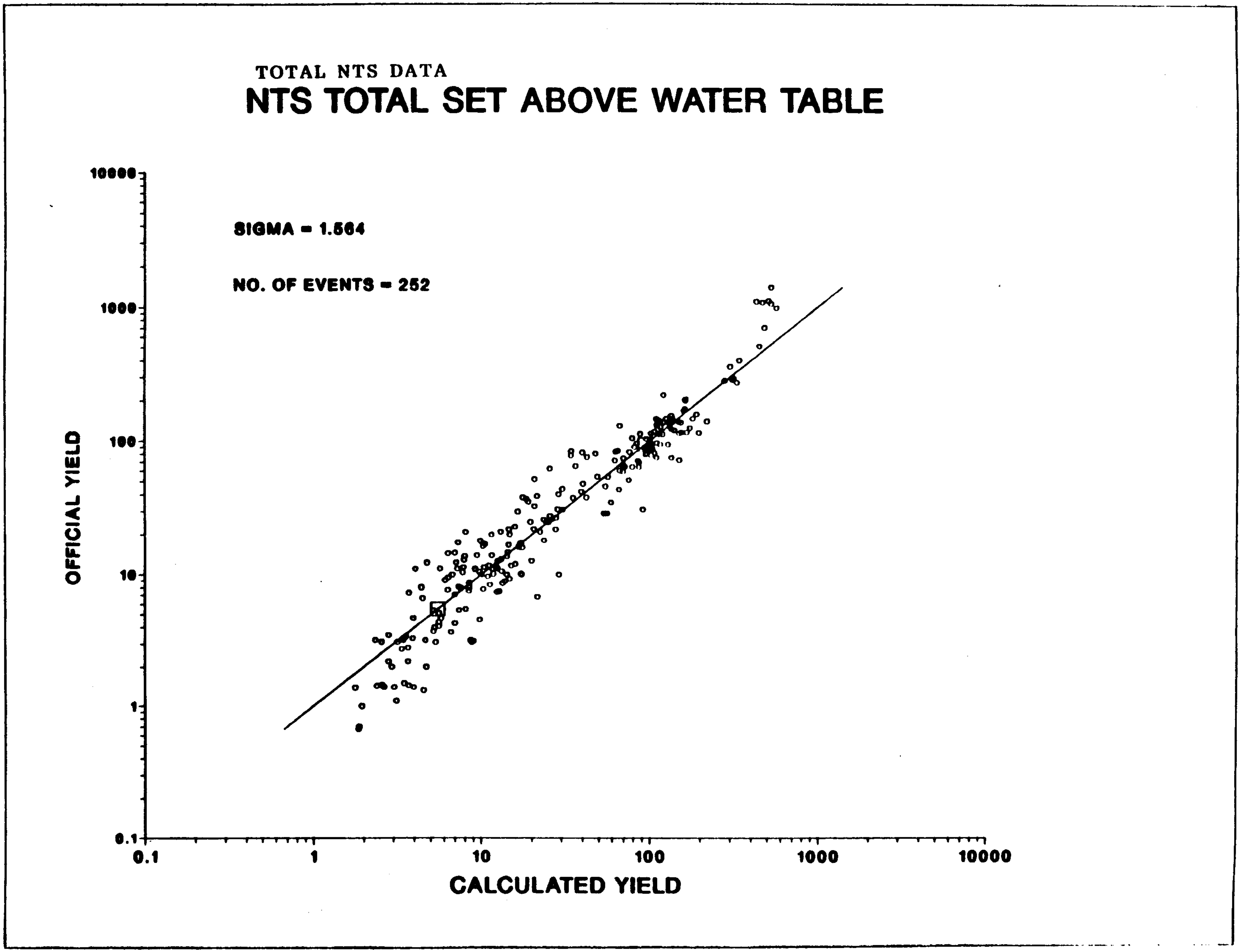
TOTAL NTS DATA
NTS TOTAL SET ABOVE WATER TABLE
SIGMA = 1.564
NO. OF EVENTS = 252
OFFICIAL YIELD
CALCULATED YIELD
0.1
1
10
100
1000
10000

Figure 4.

Sigma Levels for Stations and Phases Unrestricted Yields

Area	DVa	DVb	LVa	LVb	NVa	NVb	TVa	TVb	AVE.
Area 2	1.37	1.26	1.41	1.46	1.53	1.51	1.52	1.48	1.42
Area 3	1.72	1.69	1.56	1.46	1.52	1.48	1.6	1.59	1.47
Area 7	1.17	1.25	1.32	1.35	1.32	1.32	1.23	1.72	1.26
Area 19	1.64	1.45	1.42	1.37	1.39	1.36	1.64	1.68	1.44
Area 20	1.31	1.35	1.46	1.43	1.53	1.43	1.27	1.28	1.3
NTS	1.56	1.52	1.58	1.56	1.66	1.68	1.82	1.95	1.55

Table I

Sigma Levels for Stations and Phases Above the Water Table

Area	DVa	DVb	LVa	LVb	NVa	NVb	TVa	TVb	AVE.
Area 2	1.21	1.26	1.34	1.48	1.52	1.5	1.25	1.26	1.34
Area 3	1.42	1.45	1.53	1.46	1.48	1.47	1.51	1.46	1.4
Area 7	1.13	1.26	1.4	1.48	1.28	1.34	1.19	1.54	1.21
NTS	1.57	1.5	1.65	1.6	1.71	1.74	1.86	1.9	1.6

Table II

Sigma Levels for Stations and Phases Below the Water Table

Area	DVa	DVb	LVa	LVb	NVa	NVb	TVa	TVb	AVE.
Area 2	1.46	1.16	1.26	1.25	1.51	1.5	1.5	1.65	1.36
Area 3	1.36	1.49	1.53	1.58	1.6	1.47	1.46	1.43	1.38
Area 7	1.36	1.37	1.3	1.29	1.46	1.45	1.18	1.35	1.26
Area 19	1.64	1.45	1.42	1.38	1.39	1.36	1.64	1.67	1.44
Area 20	1.31	1.35	1.46	1.43	1.53	1.43	1.27	1.28	1.3
NTS	1.55	1.48	1.51	1.47	1.56	1.56	1.63	1.82	1.46

Table III

Sigma Levels Averaged Over the Net. Yield Restricted Between 80 - 250 kt.

Area	Sigma	Events
Area 2	1.18	13
Area 7	1.15	12
Area 19	1.15	12
Area 20	1.17	19
NTS	1.21	66

Table IV

Sigma Levels Averaged Over the Net. Yield Restricted Between 10 - 50 kt.

Area	Sigma	Events
Area 2	1.27	22
Area 3	1.24	32
Area 7	1.18	12
NTS	1.38	83

Table V

Sigma Levels Averaged Over the Net. Yield Restricted Between 0 - 20 kt.

Area	Sigma	Events
Area 2	1.39	26
Area 3	1.46	54
Area 7	1.23	9
NTS	1.66	117

Table VI

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