ATOMIC WEAPONS ESTABLISHMENT

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Source Parameters of Explosions in Granite at the French Test Site in Algeria (UK UNCLASSIFIED)

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CONTENTS

SUMMARY

Short period and broad band seismograms recorded at Eskdalemuir (Scotland) and Yellowknife (Canada) are given for six explosions detonated in granite at the former French test site in the Hoggar Massif Southern Algeria. The broad band seismograms have been corrected for the assumed anelastic attenuation on the path from the test site to the station and should approximate to the pulse radiated from the source.

Magnitude measurements from the short period records are presented. Estimates are given of the long term level of the reduced displacement potential of the source function (ψ_∞), the rise time (τ) and duration (D) of the initial P pulse. Estimates of source size idicate that the relation between ψ_∞ and the yield (Y) is

$$\mathrm{Log}_{10}\ \psi_\infty \times \log_{10} Y + 2$$

Estimates of τ and D scale roughly as $Y^{1/3}$ in agreement with the theoretical source model predictions.

1. INTRODUCTION

To verify compliance with a Threshold Test Ban Treaty (TTBT) using seismological methods the yield of an underground nuclear explosion has to be estimated from the seismic signals generated. The normal procedure is to determine the seismic magnitude of an explosion and relate this to the yield via calibration curves for a specific test site and shot-medium. If a particular relationship established for one test site is used to monitor another, corrections may be needed to compensate for the effects of source-region bias and recording-network bias (1). At present the seismic magnitude determined from P waves recorded on short-period (SP) seismographs and long-period (LP) surface (Rayleigh) waves are used to estimate yield. To date little or no use has been made of broad-band (BB) seismograms for yield estimation. Such seismograms which cover almost the whole P-wave spectrum should provide more stable estimates of source size than SP data from SP seismograms.

It is possible that an improvement in the accuracy of yield estimation can be achieved by estimating the long term level of the reduced displacement potential ψ_∞ of the source. ψ_∞ is estimated from BB P-wave recordings and Lyman et al (2) demonstrate a strong correlation between ψ_∞ and yield for nuclear explosions detonated in saturated porous material such as tuff at the Nevada Test Site (NTS) . However very little data are available on ψ_∞ measurements from explosions in low porosity rock such as granite and in this report six explosions in granite at the Hoggar Massif in southern Algeria and recorded at seismometer array stations at

Eskdalemuir (EKA), Scotland and Yellowknife (YKA), (Canada) are analysed to provide such data.

Additional information concerning the source function can be extracted from BB recordings. Here the scaling laws for explosions in granite as a function of source size are determined from the rise time (τ) and duration (D) of the P pulse. Simple theory predicts that the rise time of the source function is proportional to $Y^{1/3}$ where Y is the yield of the explosion but as is shown by Stewart (3) this appears not to be true for all explosions. The coupling of the explosion to the surrounding rock may be a factor in determining how the source scales with yield. It may be possible to identify the medium in which a series of explosions occurred by investigating the source rise-time as a function of explosion size. A problem in estimating the yield of an explosion is that assumptions have to be made about the type of rock in which the explosion took place. If however it is shown that, for example, rise-time as a function of ψ^{∞} is dependant on the type of rock it would clearly be a useful method to indicate which calibration curve should be used to estimate the yield and this might lead to a significant reduction in the uncertainty in yield estimates by seismological methods and hence improve the techniques for monitoring a TTBT.

Furthermore, estimates of ψ_{∞}, rise-time and pulse duration for explosions in different media may prove of value in redefining the explosive source model and could lead to an improvement in source identification which is the key to the verification of compliance with any proposed treaty to limit nuclear testing.

In this report the SP seismograms from the explosions are converted to BB seismograms which are then corrected for the effect of anelastic attenuation over the transmission path between the source and the receiver. To do this it is necessary to estimate t*, the ratio of the travel time in seconds to the average quality factor (Q) over the transmission path. This final stage of processing produces a seismogram which approximates to the P-wave pulse radiated downwards from the source and it is this seismogram which is used to estimate ψ_{∞}, τ and D of the source function.

The epicentral details of the six explosions analysed are given in table 1 and are taken from the complete listing of underground explosions in the Hoggar Massif published by Duclaux and Michaud (4). The purpose of this report is to make available in a convenient form the SP and BB seismograms, P wave magnitudes and estimates of ψ_{∞}, τ and D from the six explosions.

2. PROCESSING METHODS

The original P wave recordings of the explosions were made on analogue magnetic tape at the EKA and YKA array stations. Full details of these arrays including the location of the seismometers, recording system and instrument response are given by Mowat and Burch (5). The original recordings were transcribed, at a later date, onto an analogue library tape. The transcribed recordings were digitised at 20 samples per second to produce a digitised waveform which is readily converted to a BB recording. It is possible that the transcription of the original analogue recordings onto an analogue library tape introduced additional system noise into the recordings but this does not cause any significant problems in the subsequent processing and analysis techniques used in the preparation of data for this report.

To produce the SP seismograms given in figure 1 the output of the individual elements of the array are time shifted to correct for the differences in the arrival time of the signals at each seismometer and summed to produce an "array-summed" P-wave recording. Before estimates of ψ_∞, D and τ are made the array-summed recordings are converted to equivalent BB recordings following the procedure described in (2).

The BB seismograms are derived by passing the SP recordings through a filter with a response, as a function of frequency (ω) of $|a_2(\omega)|a_1(\omega)$ where $a_1(\omega)$ and $a_2(\omega)$ are the instrument responses of the SP and BB instruments respectively. The BB response used here is one that is flat to displacement in the frequency range 0.05 to 10 Hz. However even with such a flat response over a wide frequency range distortion of the recorded pulse due to the phase shift of the BB instrument can occur. Stewart and Douglas (6) have demonstrated that by using $|a_2(\omega)|$, that is, removing the phase shift due to the recording system, P-wave pulses are obtained with less distortion than observed on conventional BB recordings. The seismograms produced in this way are called phaseless BB seismograms (PBB).

It is pointed out in (2) that the widening of the passband amplifies the seismic and system noise and to remove this noise high-pass (0.1 Hz) and low-pass (4.5 Hz) filters are used. To suppress noise at frequencies close to the predominant signal frequency a Wiener filter designed on the noise preceding the signal is employed (7).

To correct for the effects of attenuation the BB seismograms are passed through a filter with a response $\{b(\omega)\}^{-1}$, where $b(\omega)$ is the response as a function of frequency of an attenuation operator. The attenuation operator used is that of Carpenter (8) in which the amplitude response $|b(\omega)|$ is defined as $\exp(-\omega t^*/2)$ and the phase spectrum is specified using the theory of Futterman (9). The value to be assigned to t^* (the ratio of the travel time to the average specific quality factor, Q) depends on the amount of attenuation expected over a particular path. The attenuation beneath the Hoggar Massif is believed to be similar to that beneath the NTS (1) for which Lyman et al (2) use $t^* - 0.35$ s, so that value is used here. The final BB seismograms, corrected for attenuation, are given in figure 2.

3. SOURCE PARAMETERS

The source function of an explosion can be defined by the reduced displacement potential ψ (t). For t greater than a second or two, ψ (t) rapidly approaches ψ_∞ which is usually assumed to be directly proportional to yield. An estimate of ψ_∞ in cubic metres is made from the BB seismograms corrected for anelastic attenuation by measuring the area under the P pulse and correcting for the effects of geometric spreading by multiplying by $\{2G(\Delta)\}^{-1}$ where $G(\Delta)$ is the geometric spreading term given in (10).

There are two major difficulties which could arise in estimating ψ_∞ in this way: firstly the reflection at the free surface above the shot point (pP) may interfere with the direct P so that the complete pulse is not observed; and secondly, the presence of low frequency noise may introduce errors into the estimates. It is possible that there are errors from both sources in the data presented here since the SNR of the original SP recordings is not large for the low yield explosions. Such explosions tend to be conducted at a shallow depth which means the pP-P may be short.

To complete the study of source parameters, estimates were made of the rise time and duration of the P-pulse. Here I use the rise-time τ (s) as defined in (11) which is obtained by dividing the maximum gradient of the leading edge by the peak pulse amplitude and should be an estimate of the rise time of the radiated P pulse. The pulse duration, D (s), is taken as the time between the beginning of the P-pulse to the time when the pulse returns to the same level as at the onset. Estimates of ψ^{∞} should not be affected by attenuation over the transmission path (12). The effect of correcting for attenuation using t* is to enhance the pulse relative to the noise which makes the measurement of ψ_∞ easier. The effect of attenuation on the pulse is to spread the pulse and increase its duration and the likelihood of contamination with noise. Estimates of ψ and τ and D are affected by the choice of t*. However the way in which ψ or D scales with source size should be less affected than the absolute values. The slope, or variation of ψ and D with source size is important because these should be inversely proportional to the corner frequency of the source which is itself a function of source size.

4. SEISMOGRAMS

The P-wave seismograms from EKA are more complex than those at YKA possibly due to the effects of the transmission path: the rays to EKA propagate totally within the upper mantle whereas rays to YKA propagate mainly in the more homogeneous lower mantle. The seismograms are fairly consistent from shot to shot at each station; the variations are presumably due to differences in the depth of emplacement.

The locations of the explosions relative to the topography are given in figure 3 (13). It would appear that although there are large variations in the topography between firing sites the seismograms of all the explosions are quite similar suggesting that the P wavelengths recorded at large distances are not sensitive to variations in the topography of the free surface above or near the shot point.

The large negative pulse seen in the seismograms in figure 2 could be interpreted as the free surface reflection pP but it arrives too late given the high speed of sound waves in granite ($\tau > 5$ km s^{-1}) and the apparent over-burden thickness. The presence of a large negative, late arrival is also observed in teleseismic recordings of the NTS explosion PILEDRIVER which was fired in granite (14).

From the appearance of the seismograms in figure 2 it is assumed that the second (negative) pulse arrives too late to interfere with the initial (positive) pulse and that the estimates of ψ_∞ and duration are made on the full width of the direct P pulse.

It is interesting to note that in figure 1 the ratio of the maximum peak-to-peak amplitude in the P wave relative to the amplitude of the first motion varies with magnitude. In the YKA seismograms the second positive oscillation in the signal increases in amplitude relative to the first motion as the magnitude decreases, whereas at EKA the opposite effect is seen in that the second positive oscillation decreases in relative amplitude with decreasing magnitude. At EKA the ratio of maximum amplitude to first motion is a factor of two greater for SAPHIR compared to TOURMALINE whereas at YKA the ratio for TOURMALINE is a factor of 2 greater than SAPHIR. The peak-to-peak amplitude is used to determine magnitude and it is possible that given amplitudes from stations well distributed in azimuth about the epicentre the effect of this variation is averaged out. If by chance the stations used to determine m_b all exhibited the characteristics of YKA then the slope of a magnitude-yield curve would be reduced whereas if the stations used behave like EKA the slope would be increased. This illustrates the caution that needs to be exercised in determining m_b: yield relationships for a particular test-site and network of stations. This particular problem does not arise if ψ_∞ is used to estimate the yield of the source and is an important piece of evidence to indicate that ψ_∞ may be a better estimater of source size than the conventional SP magnitude.

The seismograms given in figures 1 and 2 illustrate the variation in SNR which is typical for recordings of explosions between a few kilotons and a hundred kilotons. Some of the high frequency noise clearly seen before the onset of the signal is due to system noise introduced in the transcription of the original analogue recordings onto a library tape. However the presence of this high frequency noise has little effect on the measurement of ψ^∞ ; it may increase the difficulty of estimating precisely where the pulse starts which would affect the estimation of τ and D.

5. RESULTS

The measurements made on the SP and BB seismograms are summarised in table 2. The array magnitudes are determined from the SP seismograms using the Gutenberg and Richter (15) method in which the magnitude m_b is defined as

$$m_b = \log_{10} A/T + B(\Delta)$$

where A is the maximum amplitude in nanometres and within the first few cycles T is the period in seconds of the cycle from which A is measured and $B(\Delta)$ is a distance normalising term. Observations from two stations are too few to give a reliable estimate of the world average value of m_b so for completeness a least squares estimate has been determined from a global network of stations for each explosion.

Little data are available to establish a relationship between the magnitude and yield for explosions in granite. However a relationship between m_b and Y for explosions in "hard-rock" has been published (1) in which the magnitude m_b (or m_2 as defined in (1) is related in the following way:

$$m_b = 0.77 \log_{10} Y + 4.08$$

This relationship is used to estimate the yield of the explosions in the Hoggar Massif; the results are given in table 3. It can be seen that for the two explosions for which the yield has been published the estimated and published yields are in reasonable agreement. The magnitude of each explosion is plotted in figure 4 as a function of the mean ψ_∞ estimate: there is clearly a strong correlation between them which supports the conclusion of (2) that ψ_∞ is a reliable indicator of source size.

The precision of the measurements of τ and D are dependent on the SNR. Of the two stations used in this study the SNR is better at YKA than at EKA (see figure 2) and whereas τ and D are given in table 2 for both stations only the results obtained from YKA data in which the scatter is low are plotted (figures 6 and 7). A line with a slope of $^1/_3$ is drawn on the diagrams to illustrate that both τ and D appear to scale in accordance with that predicted from theoretical source models. A $Y^{1/3}$ dependence is also observed by Lyman et al (2) for explosions in saturated porous rocks at the Nevada Test Site but differs from the results of Stewart (3) who finds that for explosions at the Soviet test site at Shagan River the scaling is proportional to $Y^{1/10}$ or less.

6. CONCLUSIONS

Teleseismic SP recordings made at two seismological array stations (EKA and YKA) from six underground explosions in granite at the French test site in the Hoggar Massif (Algeria) have been processed to provide BB recordings. The main conclusions are:

(a) Estimates of ψ_∞ correlate with m_b indicating that ψ_∞ may be used as a measure of source size.

(b) The relation between ψ_∞ and Y for explosions in granite is approximately:

$$\mathrm{Log}_{10}\, \psi_\infty \simeq \log_{10} Y(\mathrm{kton}) + 2$$

(c) Estimates of τ and D measured at YKA appear to scale roughly as $Y^{1/3}$ for explosions in granite. This is in accord with theoretical explosion-source models.

Finally, if the yields of all the Hoggar Massif explosions are ever published it will be possible to establish a more reliable relation between ψ_∞ and yield for explosions in granite than is possible at present. The yield estimates determined from the magnitude are used here to give an idea of what the relation might be.

7. ACKNOWLEDGEMENTS

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TABLE 1
List of Explosions

Date	Origin Time	Name	Latitude	Longitude	Yield	Medium	Stations Available
18 Mar 63	10 02 00.351	EMERAUDE	24.041°N	5.052°E	<20 kton	Granite	EKA YKA
20 Oct 63	13 00 00.011	RUBIS	24.035° N	5.039°E	52 kton[1]	Granite	EKA YKA
14 Feb 64	11 00 00.347	OPALE	24.053°N	5.052°E	<20 kton	Granite	- YKA
27 Feb 65	11 30 00.039	SAPHIR	24.059°N	5.031E	117 ± 12[2]	Granite	EKA YKA
1 Dec 65	10 30 00.088	TOURMALINE	24.044° N	5.047°E	<20 kton	Granite	EKA YKA
16 Feb 66	11 00 00.035	GRENAT	24.044°N	5.041°E	<20 kton	Granite	EKA YKA

(1) Reference 16

(2) Reference 17

TABLE 2
Summary of Results

Name	Array Magnitude m_b		Rise Time (s)		Duration (s)		$\mathrm{Log}_{10}\psi_\infty$		Mean Values ± SD from Array Data		World -wide Aver- age
	EKA	YKA	EKA	YKA	EKA	YKA	EKA	YKA	$\mathrm{LOG}_{10}\Psi_\infty$	m_b	m_b
EMERAUDE	5.35	5.32	0.11	0.21	0.45	0.52	3.08	3.11	3.10 ± 0.02	5.34 ± 0.02	4.86
RUBIS	5.63	5.65	0.20	0.21	0.60	0.65	3.76	3.64	3.70 ± 0.08	5.64 ± 0.01	5.49
OPALE	4.51	4.78	-	0.10	-	0.41	-	2.55	2.55	4.65 ± 0.19	4.52
SAPHIR	5.63	5.77	0.26	0.28	0.81	0.82	3.85	4.10	3.98 ± 0.18	5.70 ± 0.10	5.70
TOURMALINE	5.24	4.89	0.13	0.24	0.51	0.56	2.80	3.08	2.94 ± 0.20	5.07 ± 0.25	4.86
GRENAT	5.15	4.87	(0.27)	0.18	0.82	0.50	3.35	3.04	3.20 ± 0.22	5.01 ± 0.20	4.94

TABLE 3
Yield Estimates of Explosions in Granite at the Hoggar Massif

Name	m_b	Yield, kton
EMERAUDE	4.86	10
RUBIS	5.49	68
OPALE	4.52	3.7
SAPHIR	5.70	127
TOURMALINE	4.86	10
GRENAT	4.94	13

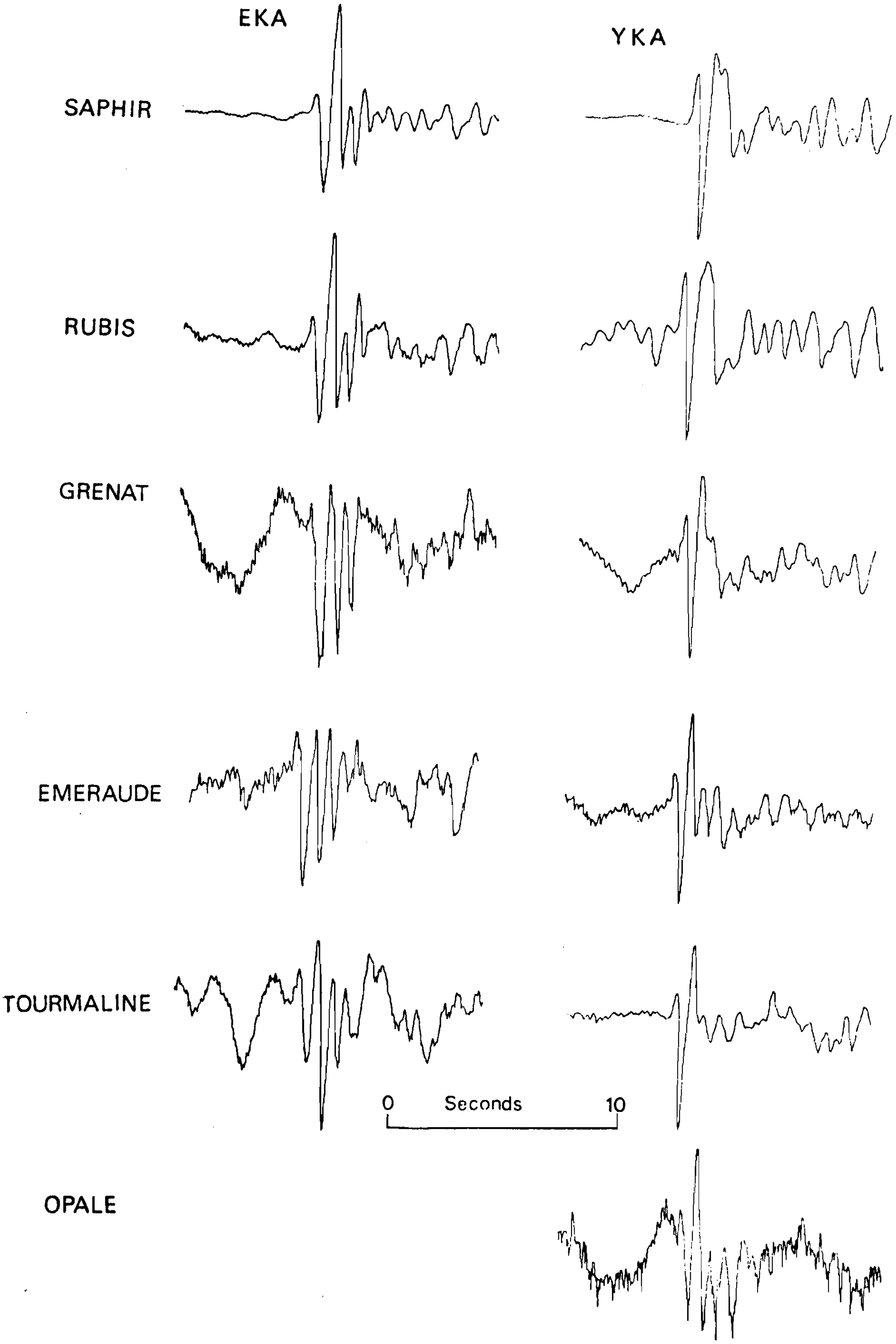

FIGURE 1: SHORT PERIOD P-WAVE ARRAY RECORDINGS OF EXPLOSIONS IN GRANITE AT HOGGAR, ALGERIA.

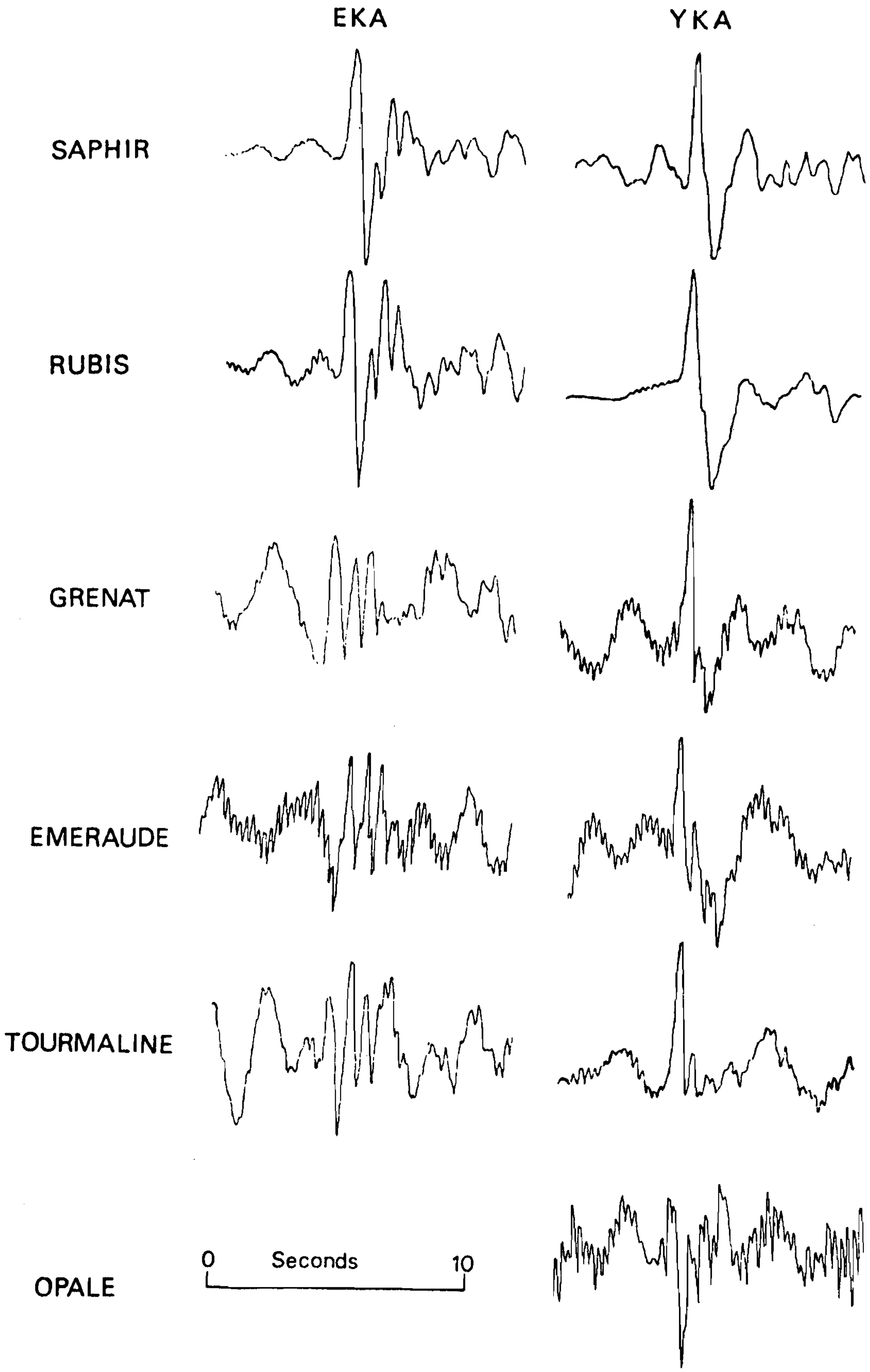

FIGURE 2: DECONVOLVED PHASELESS BROAD BAND P-WAVE SEISMOGRAMS OF EXPLOSIONS IN GRANITE AT HOGGAR MASSIF.

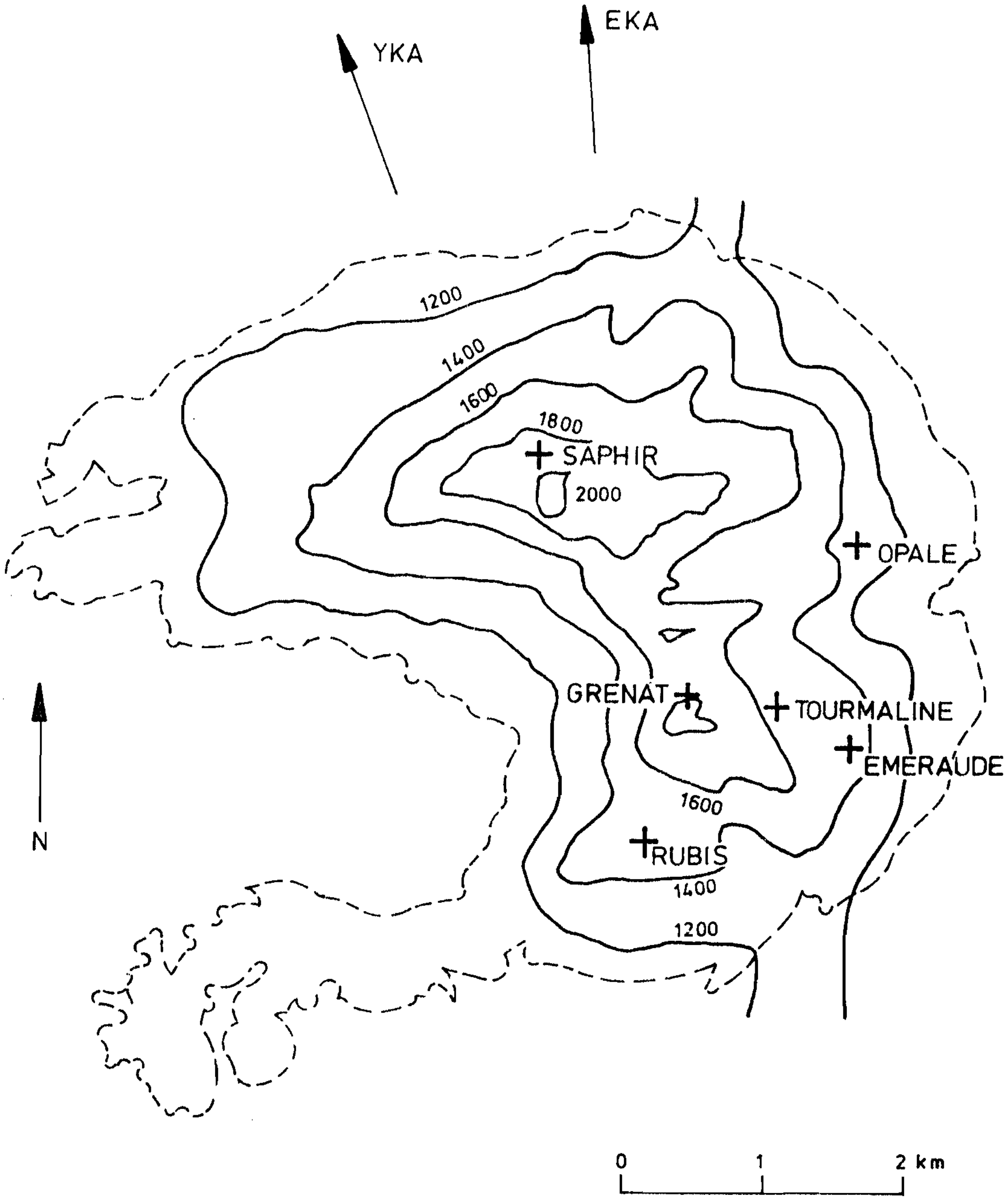

FIGURE 3. CONTOUR MAP OF HAGGAR, ALGERIA (FAURE 1972) AND LOCATIONS OF THE EXPLOSIONS (DUCLAUX AND MICHAUD 1970). CONTOURS ARE AT 100 m INTERVALS AND THE LIMIT OF THE GRANITE OUTCROP IS SHOWN WITH A DASHED LINE. THE AZIMUTHS TO EKA AND YKA ARE SHOWN WITH ARROWS

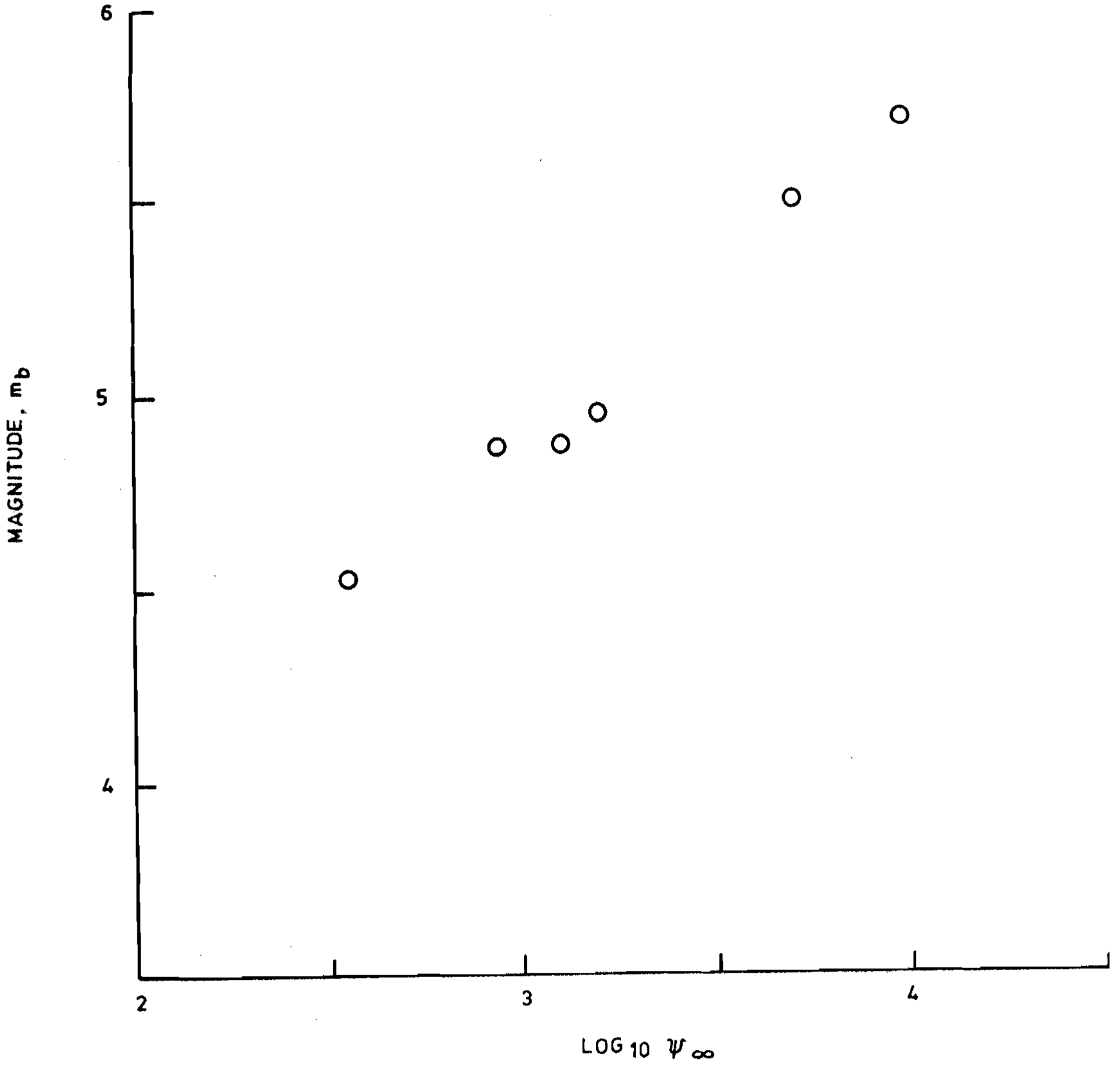

FIGURE 4. GLOBAL ESTIMATES OF m_b AS A FUNCTION OF $LOG_{10}\psi_\infty$

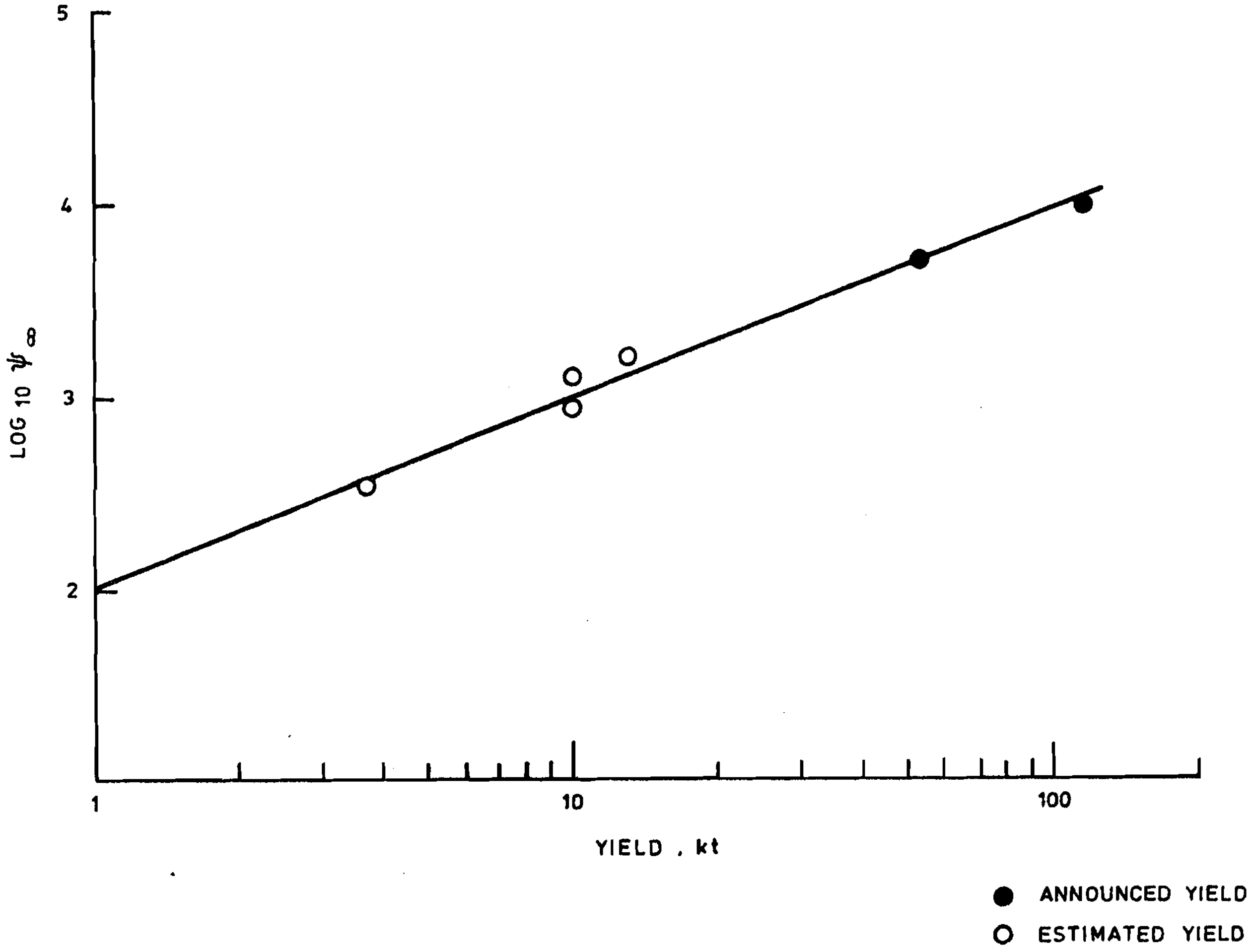

FIGURE 5. RELATIONSHIP BETWEEN YIELD (kton) AND ψ ∞ FOR EXPLOSIONS IN GRANITE AT THE HAGGAR TEST SITE

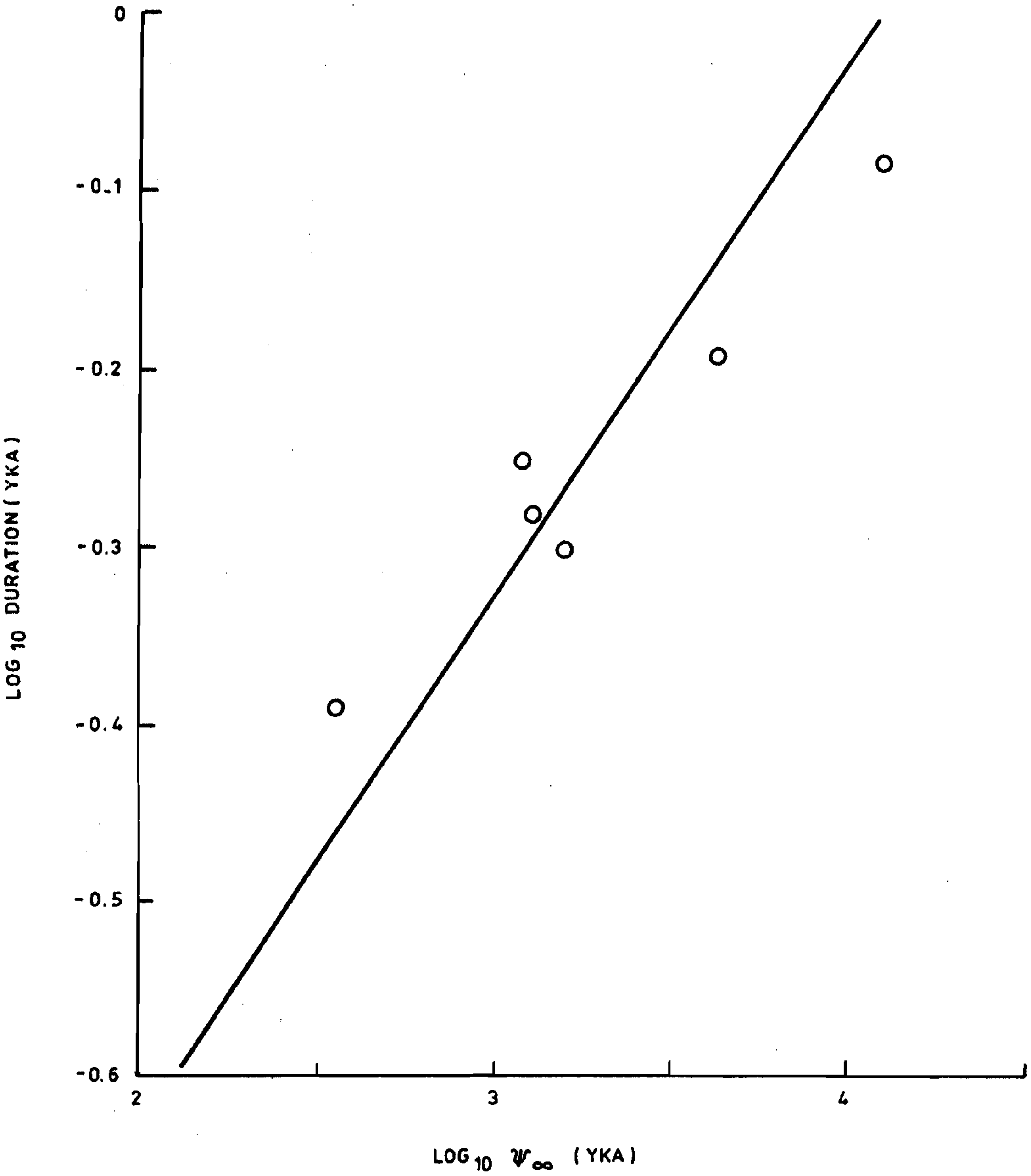

FIGURE 6: DURATION AS A FUNCTION OF ψ_∞ MEASURED FROM YKA SEISMOGRAMS.

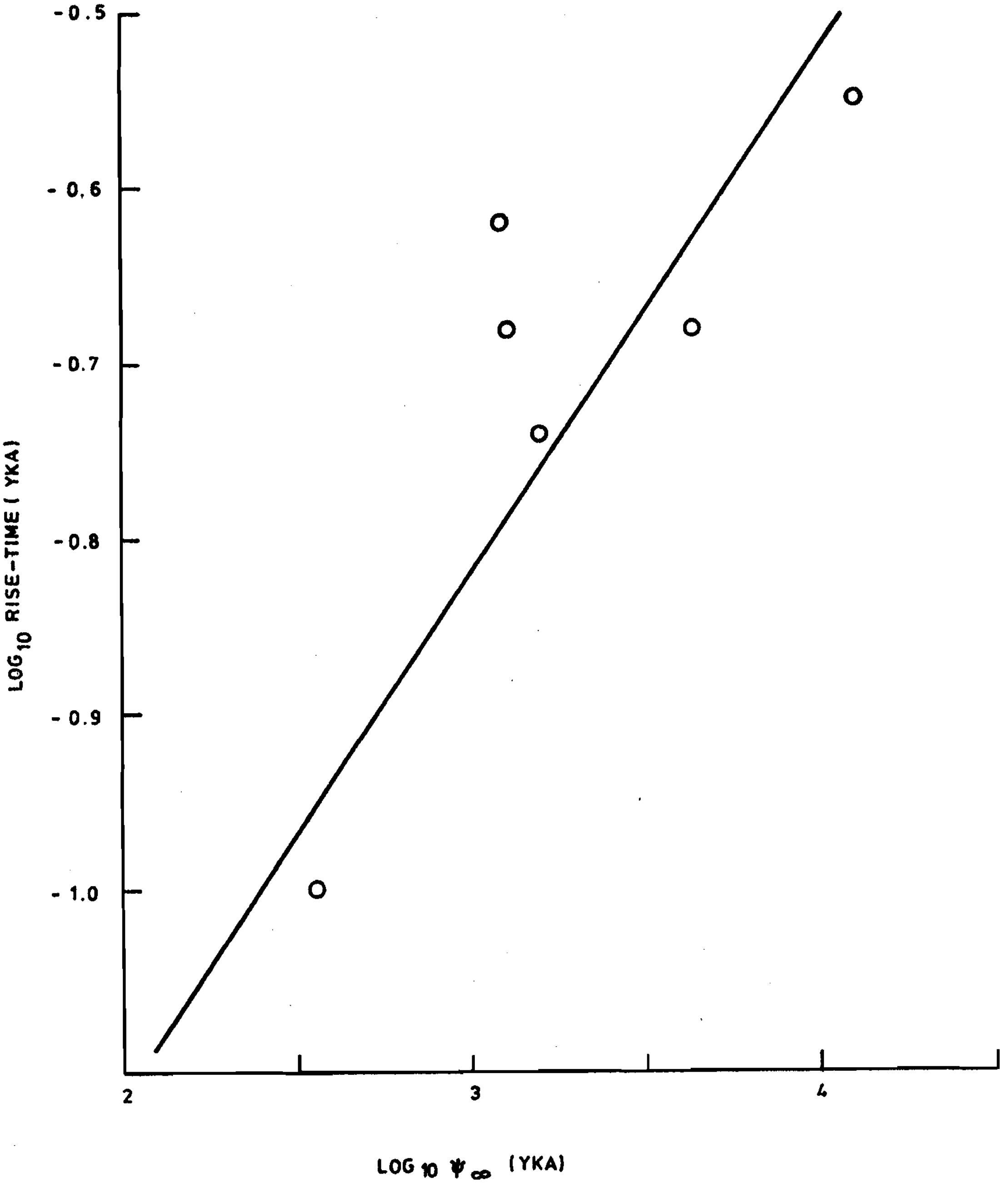

FIGURE 7: RISE-TIME AS A FUNCTION OF ψ_{∞} MEASURED FROM YKA SEISMOGRAMS.

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