THE NIGERIAN SEISMOGRAPH NETWORK
A REPORT SUBMITTED TO
THE GEOLOGICAL SURVEY OF NIGERIA

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Executive Summary

This report deals with a review of the Nigerian Seismograph Network carried out by staff members of the Geological Survey of Canada and by Mr. Clement Ugwuja of the Geological Survey of Nigeria during his visit to Ottawa. The report assesses the current status and includes concrete proposals regarding the future direction and development of the network.

Seismograph stations in Nigeria should be relocated away from cities and sources of interfering noise. The increase in gain will result in improved coverage for the country, a decrease in operating costs and a decreased magnitude threshold for recording seismicity. The ground sensors for the seismographs should be replaced with larger seismometers designed to have direct calibration. The result will be increased confidence in and greater ease in the interpretation of the recorded data. The accuracy of the timing for the seismographs must be addressed. The solution to this problem is not clear at this time. Further investigation should provide the direction needed. The improvements to timing will enhance the quality of the network data and allow accurate epicenter location. The seismographs should be backed up with standby power to continue recording in the event of power failures, so common after an earthquake.

It is highly recommended that the network convert to a personal computer based operation. This enhancement to network operations will permit the use of internationally recognized methodology for epicenter locations while satisfying the interface requirements necessary for the proposed digital seismographs.

A magnitude determination method, based on the Canadian experience, has been chosen for application to the Nigerian landmass.

The recommendations included in this report do have costs involved. A significant level of effort will be required to adopt the measures outlined and the capital cost will be in the order of $Cdn 40,000. The return on this investment should provide the Geological Survey of Nigeria with a high–quality network with reduced operating costs and manpower requirements. The product of the network should not only serve domestic goals well but will also be attractive to the international scientific community, bringing staff into closer contact with their global colleagues.

The span of subject material that Mr. Ugwuja reviewed during his visit is indeed impressive. He delved into the many areas of seismology observatory practice, of seismic data interpretation and analysis and of seismic research with enthusiasm and a profound curiosity. Mr. Ugwuja should prove to be a very valuable asset to the Nigerian Seismograph Network and to the decision making process on the network's behalf. It has been a pleasure to have had him visit us.

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A. Introduction

Following some recent widely felt earthquakes, the Geological Survey of Nigeria (GSN) has recently installed a six station seismograph network to monitor seismicity within the country and the immediate offshore area. Since the seismological expertise within the GSN has naturally been focused upon the hydrocarbon exploration aspects of the subject, Mr. Clement Ugwuja, Assistant Chief Geophysicist of the GSN, visited the Geological Survey of Canada (GSC) during the last three months of 1990 in order to gain additional practical experience in earthquake studies. The GSC has operated a seismograph network for over 30 years and developed proven techniques for the collection and analysis of seismic data. In addition to taking the standard GSC seismograph station operator's course, Mr. Ugwuja has discussed virtually all aspects of modern earthquake seismology with our staff. He has proved to be a willing and diligent student and we are certain that he is now much better equipped to operate a high-quality national network for Nigeria.

Through discussions with Mr. Ugwuja, GSC staff became quite familiar with the siting and operating conditions in Nigeria, and, through manuals, with the equipment currently in place. This document contains recommendations for the improvement of the network as well as information that will be helpful in its operation. These recommendations are neither difficult nor costly to implement and should considerably increase the quantity, quality and accuracy of the information provided by the Nigerian network. The report is divided into two main sections dealing with siting and instrumentation and with data analysis and supplemented by technical details provided in seven appendices.

B. Network Plan

B.1. Seismograph siting

Experience gained in Canada has shown that the siting of seismographs is critical to their performance. The geology of Nigeria is similar enough to that of Canada to surmise that considerations used in siting in Canada would likely be equally applicable to Nigeria. General information on seismograph siting was discussed at length and the summary description is included as Appendix 1.

The current sites installed by the Geological Survey of Nigeria are situated at Survey offices at Ibadan, Ilorin, Kaduna, Makurdi and Yola; a sixth seismograph is installed at Calabar. The recent seismicity is reported to be in the vicinity (to the south) of Ibadan; an event was widely felt in Ibadan, Abeokut and Ijebu–Ode on 28 July, 1984, and another was felt in Ibadan on 28 June, 1990. Smaller events have been reported felt locally near Lohafia on 12 July, 1961 (not felt in Ikot–Ekpene, Uyo or Calabar), near Dambarta (not felt in Kano) and near Durum (not felt in Bauchi). The current distribution of these units would yield good coverage to most regions of the country if the seismographs were sited in quiet enough locations to have all six units trigger on seismic events. The units, however, are currently operating at a gain level of 64dB which is not sufficiently sensitive enough to trigger on most small to medium seismic events. The network will only trigger on very large seismic events. To further complicate matters, the seismographs are currently sited on soil or overburden; it will not be possible to detect, analyse and locate a smaller seismic event at all and the analysis of large seismic events will be severely limited by the corrupted data that will be recorded.

The seismographs should all be relocated in accordance, as much as possible, with the criteria outlined in Appendix 1. Ibadan could be moved northwest to the vicinity of Wasinmi and Elewa. Ilorin could be moved southeast to the vicinity of Awtun, Ado–Ekiti or Ikare, but certainly not Akure. Calabar could be moved due north or northeast past Ikom. Makurdi could be moved southeast to the vicinity of Ghoko and Yandev or, more preferably, north–northwest to the vicinity of Laminga. Kaduna could be moved northwest to the vicinity of B. Gwari or, more preferably, further out towards Bawa and Bageda. Yola could be moved west–southwest to the vicinity of Jalingo or, more preferably, north to the vicinity of Biu or Shaffa. These suggestions are shown in Figure 1.

These relocations should provide enhanced azimuthal coverage for the zones of recent felt seismicity south of Ibadan. There will be an arc of stations, much like a central spine, running north–northwest to south–southeast and there will be a single station towards the eastern border with the Cameroon and the volcanically active area there. The areas reporting seismicity in the north will be contained in a well distributed triangle of stations. This redistribution should allow recording of seismicity with a magnitude threshold of 3.5 if the stations are operating at the maximum gain setting of 84 dB. These settings are similar to lower gain seismographs installed at noisier locations on the Canadian Shield. The northeast and northwest extremes of the country will not be that well served as the minimum distance to three stations will increase from a maximum of about 500 kilometres to a maximum of 750 to 850 kilometres. These limitations are difficult to overcome with a network of six stations.

Benefits of relocation are not limited to increased probability of recording seismicity. The

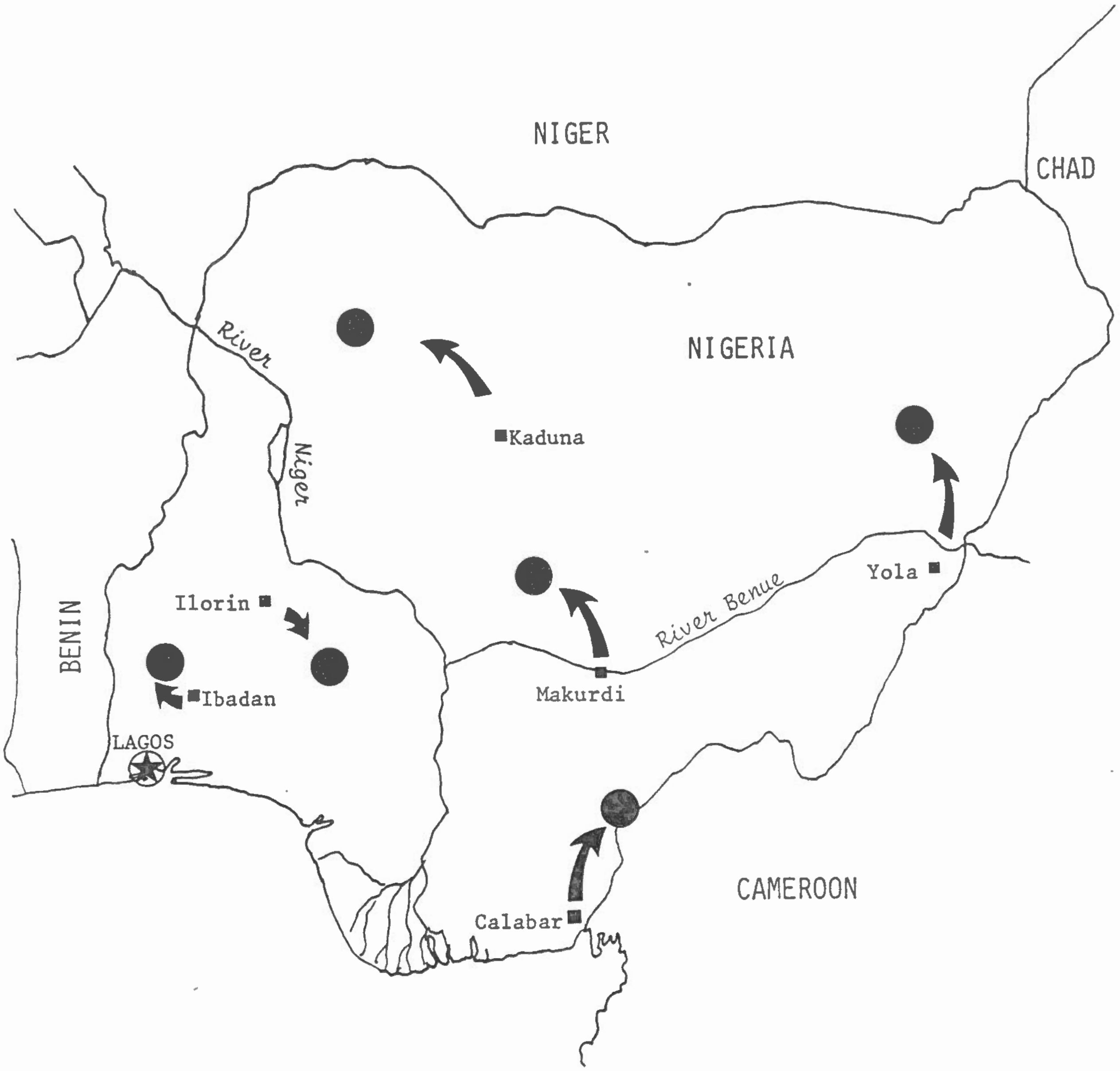


Figure 1: Relocation configuration for the Nigerian Seismograph Network.

number of false recordings due to noise should be reduced thereby saving on the cost of the paper. It should not be necessary to visit the stations as often. Canadian stations are run with a small caretaker contract where local university or technical staff maintain the seismograph and telephone in any readings from recorded events; the original seismogram of the event is mailed in. A variation of this scheme for Nigeria might include a tour of the seismic network after there is a felt report of an earthquake; this would allow for *in–situ* verification of the seismograph and its operating parameters before any detailed interpretation is done on the records. Improved siting should also allow the seismographs to record more distant seismicity which would be of value to neighbouring nations and to the international community at large.

The possible future addition of two digital seismographs will affect the above siting plan quite dramatically. Digital seismographs have a much higher dynamic range and, like the current analogue seismographs, run in trigger mode. The difference is that the digital units do not have the massive recording reserve that the current units do (these analogue units have a 100 metre roll of paper, enough for one earthquake a day for a year!). The requirements for siting these units will be even more stringent. They will require the quietest of sites in order that false triggers do not fill up the recorders' memory with noise and prevent the recording of a true seismic event. They will need to be sited where telephone service exists in order to have a telecommunications link directly to the seismograph; data will have to be unloaded routinely to make sure that each unit's memory is always available for the next earthquake. Failing this, the units will have to be close enough to a GSN office that someone can visit them often. A computer will have to be purchased to interface with the seismographs; this will be discussed later in this document. The positive aspects of these units includes the prospect that, if properly sited, these two units should reduce the magnitude threshold for the whole country.

Siting suggestions for these two units would be to place them at the relocated Calabar and Kaduna locations freeing up two units to be newly sited. One location would be the northern border area just west of Gumsi on Jurassic granite. The Kaduna and Makurdi relocations could be moved westward (to Mahuta and Paiko) and another new station could be installed in the vicinity of Ningi or Foggo. Site testing will indicate which locations are the best for the digital seismographs; a preliminary suggestion would be Mahuta and Ikom as they are not too close to one another and are approximately centered for any seismicity in the country. These suggestions are shown in Figure 2.

B.2. Seismograph instrumentation

General information on seismograph instrumentation was discussed at length and the summary description is included as Appendix 3.

The present instrumentation used is the Takamisawa Cybernetics seismograph, STR–100.

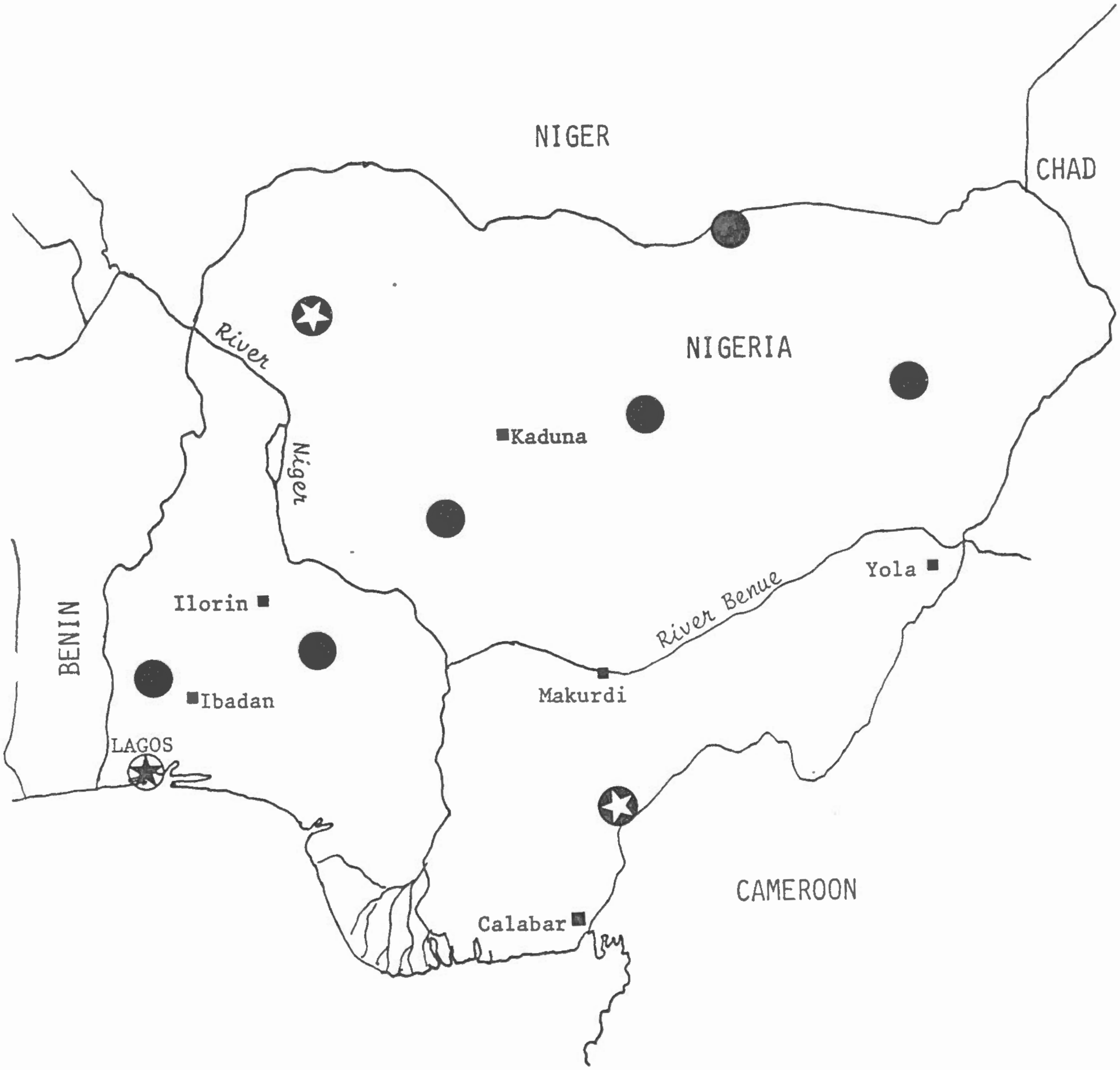


Figure 2: Relocation configuration for the Nigerian Seismograph Network, as enhanced with the addition of two digital seismographs.

There are some limitations to these units as they are currently deployed. The recommended improvements in siting will allow the gain to be raised ten–fold over the current operating level of 64 dB, thus lowering the threshold of detection by one full magnitude unit. The maximum gain of 84 dB is still fairly low and may need to be addressed. Increased sensitivity could be realised by changing the ground sensor. The seismometer in use is the Mark Products L–22 geophone. This unit has a 2 Hz natural frequency and limits the seismograph's response from 0.3 seconds out towards longer period. The physical parameters of these units are more loosely controlled than for observatory grade seismometers; the generator constant is only accurate within ± 10%, as is the natural frequency. There is no calibration coil fitted and this makes direct overall response determination impossible. The replacement of these L–22 units with the more robust L–4C (1 Hz geophone) would improve overall sensitivity and gain and is discussed in Appendix 3.

The amplifier and the internal clock in these seismographs appear to be well thought out judging from the technical specifications provided; these should require no major adjustments.

The most difficult instrumental question to be resolved is that of providing true time to the seismograph to keep the internal clock within 0.05". Appendix 3 deals with some of the possibilities. The salient point is that true time is a necessary function to be able to locate earthquakes accurately; this is also an expensive venture. If a major retrofit is required then the equipment purchased should be of a type that will be useful for any type of seismograph; the GPS system appears to have the edge both in terms of price and long–term continuity. The most optimistic scenario is that a true time source will be generally available in the country (television signals) and that an inexpensive decoder can provide true time to the seismograph's clock correction circuitry. The possibility of such an enhancement will only be known after careful study of the technical manual for the STR–100. We would be willing to provide advice on this when the manual and information on time signals are made available to us.

Improving the timing will not only provide the required accuracy for earthquake location analysis in Nigeria but will also impart higher quality to the phase readings. This will render Nigerian network data attractive for inclusion in international seismic reporting programs.

B.3. Seismograph response

The analysis of seismic waveforms collected from earthquakes yields, amongst other things, the event's magnitude. The classical method is based on a knowledge of the true ground motion at the recording station. The calibration of the seismograph provides the relationship between the observed (i.e. recorded) waveform and the causative true ground motion. It is imperative that the response of the seismographs used in a network be very well known. The polarity of the recorded signal must also be well documented. The direction of the first motion is often used in a p–nodal plot to derive source parameters of the earthquake. Individual station calibrations are the surest way to fully determine these characteristics. A brief outline on station calibration methodology is included as Appendix 4.

The current seismographs in use employ the L–22 seismometer which is not fitted with a calibration coil. The implication thus is that all response curves for the network will be theoretical and unproven. These curves can nonetheless be very useful if carefully prepared. The instrument manufacturer has provided some details of the seismograph's response and a theoretical calibration curve has been derived (see Appendix 4); it was used in the production of magnitude estimate tables (included in Appendix 7). The use of L–4 seismometers would not only boost the overall gain of the seismographs but would also permit direct calibration. The effects of this upgrade are also shown in the theoretical calibration curve.

C. Network Data Processing

C.1. Seismogram reading and interpretation

The Canadian Seismograph Network developed as a manned network of independent stations reporting their seismic phase readings to the central office daily. Seismogram reading and interpretation were done on site and verified at the central office after the records were mailed in on a weekly basis. Station operators soon became proficient at the analysis and corrections and review decreased. Staff at these sites rotated on an annual basis and it became necessary to develop a training course and to write an operator's manual. The course was developed and refined by Mr. R. J. Halliday, Manager of the network, and he and Mr. Ugwuja discussed this course at length. A short synopsis is included as Appendix 5.

C.2. Earthquake epicenter location

The initial interpretation of network seismograms can yield the approximate epicenter location using seismic wave travel time charts for that geological regime. The procedure is limited by the accuracy and applicability of those travel time charts. Most epicenter locations are now calculated on a computer using wave velocities and a crustal model to characterize the area of study. Time of arrival readings for the observed phases are used for a least–squares fitting algorithm to give the best hypocenter and the epicenter location; an analysis of the residuals left after calculation gives an indication of the quality of the solution determined. The Geological Survey of Canada has developed an earthquake location program that is routinely used to produce the catalogues of seismicity in the country.

The International Association of Seismology and Physics of the Earth's Interior (IASPEI) has established a PC (Personal Computer) Working Group to promote the sharing of software for use in seismology. An IASPEI Software Library is being developed and is being published in collaboration with the Seismological Society of America. Volume 1 of this series is entitled "Toolbox For Seismic Data Acquisition, Processing, and Analysis" and contains the well respected computer program HYPO71. The following quote from the manual describes the program.

'For the past 18 years, HYPO71 (Lee and Lahr, 1972; 1975) has been one of the popular computer programs for locating local earthquakes. It was written in Fortran IV language and has been successfully executed under a large number of computers. It is a "stable" program in that no major changes have been made since its original release in 1971, except a minor revision in 1973.'

The software is well documented and tested and is recommended for use by the Geological Survey of Nigeria. The results obtained from this package will be consistent with many users throughout the world. Mr. Ugwuja used this package extensively during his visit and compared the results obtained with it with the results produced by the GSC's location program; the differences were minimal when exactly the same data set was used as input. The input of HYPO71 allows for the definition of the crustal model to be used, the appropriate wave velocities and the location of Nigerian stations as they are or however they may be relocated. The output of HYPO71 includes an analysis of the input data and quality factors for the hypocenter determinated. The software package is also extremely useful for organizing and archiving seismic data into a database.

The move to a computer based operation is highly recommended. More and more analysis tools will become available with time. The analogue seismograph is rapidly giving way to the more advanced and capable digital seismograph. Computers are essential for this mode of operation. The recommended type of computer to acquire is described in Appendix 6.

C.3. Earthquake magnitude determination

The size of an earthquake is usually given in terms of its magnitude, frequently referred to as the "Richter" magnitude after the originator of the magnitude concept. Unfortunately, as described in Appendix 7, there are many different formulae used to calculate magnitude from the amplitude or duration of particular seismic phases in given distance ranges. Formulae designed for use at short (up to 2000 km) distances include factors correcting for distance and these generally vary with the structure of the regional crust and upper mantle.

Given the nature of the instrumentation, magnitudes based on maximum amplitude, rather than signal duration, would be most suitable for the Nigerian network. Since the geological structure of Nigeria is quite similar to that of eastern Canada, it seems appropriate to use a magnitude scale based on the amplitude of the L_g phase which will, as in Canada, be the largest phase recorded at distances greater than about 50 km. The formula employed for magnitude in Canada has been only slightly adapted from one originally proposed by Nuttli in 1973 and now widely used throughout eastern North America. It is a suitable formula for use in Nigeria until local experience leads to a more appropriate one, and is of the form

$$m_{\mathrm{N}} = -0.10 + 1.66 log_{10}(d) + log(A/T)$$

where m_{N} is the (Nuttli) magnitude, A the maximum (zero-peak) ground displacement amplitude in micrometers, T the corresponding dominant period in seconds, and d the distance in km.

The amplitude A must be measured from the recorded trace and corrected for the magnification at the period T. Appendix 7 includes tables for use in calculating ground displacement divided by period (A/T) from the records produced by the STR–100 seismograph operating at a gain of 84 dB (Table 7.1) and in computing magnitudes from these values of (A/T) (Table 7.2). It may not always be possible to determine the period T, particularly for smaller closer events, and in such cases the trace amplitude can be used directly (Table 7.3) in the calculation of magnitude, as long as it is appreciated that the results are correct only if the (unknown) period T is less than the natural period of the seismometer (for the L–22, 0.5 seconds) and greater than 0.05". This last condition is almost certain to be satisfied for all events of magnitude less than 3.5.

Wherever possible, the magnitude reported should be an average of that given by several stations. Magnitude should not be calculated from records made at distances of less than 50 km (S-P less than 7 seconds) and should be given simply as magnitude to the media and to non-seismologists, without any mention of the exact method used, as this invariably leads to confusion.

D. Conclusions and Recommendations

This report deals with a review of the Nigerian Seismograph Network carried out by staff members of the Geological Survey of Canada and by Mr. Clement Ugwuja of the Geological Survey of Nigeria during his visit to Ottawa. Mr. Ugwuja was here for a period of ten weeks and involved himself in almost every aspect of the study of earthquake seismology practiced by the GSC. Practical discussions and informal workshops formed the backbone of this review process and both parties gained a tremendous insight of the operations of each other's network.

The report assesses the current status and includes concrete proposals regarding the future direction and development of the network. A summary of these recommendations follows.

- Seismograph stations in Nigeria should be relocated away from cities and sources of interfering noise. The increase in gain will result in improved coverage for the country, a decrease in operating costs and a decreased magnitude threshold for recording seismicity. This first recommendation is the least costly from the point of view of capital expenditures but represents a very real and sizeable task. We have only included a cost of $Cdn 2,000 for the construction of vaults. These improvements are prerequisites for the following recommendations.

- The ground sensors for the seismographs should be replaced with larger seismometers designed to have direct calibration. The result will be increased confidence in and greater ease in the interpretation of the recorded data. This recommendation should only be carried out if high–quality sites can be established. The associated cost is $Cdn 8,500.

- The accuracy of the timing for the seismographs must be addressed. The solution to this problem is not clear at this time. Further investigation should provide the direction needed. The improvements to timing will enhance the quality of the network data and allow accurate epicenter location. The most promising of the universally available time sources is the Global Positioning System (GPS) proposal with a cost of $Cdn 15,000 and this cost was included in the overall amount. These time pieces will be useful for any future seismograph acquisitions.

- The seismographs should be backed up with standby power to continue recording in the event of power failures, so common after an earthquake. The cost for this feature is $Cdn 6,000. Although this is a fairly large expenditure, the return of capturing aftershock activity during a power failure can easily justify the cost. These recordings are crucial to the analysis of an earthquake.

- It is highly recommended that the network convert to a personal computer based operation. This enhancement to network operations will permit the use of internationally recognized methodology for epicenter locations while satisfying the interface requirements necessary for the proposed digital seismographs. The cost is $Cdn 6,500. Once installed, the computer will very quickly become one of the most versatile and heavily used tools of the network.

- A magnitude determination method, based on the Canadian experience, has been chosen for application to the Nigerian landmass.

The recommendations included in this report do have costs involved. A significant level of effort will be required to adopt the measures outlined and the capital cost will be in the order of $Cdn 40,000. The return on this investment should provide the Geological Survey of Nigeria with a high–quality network with reduced operating costs and manpower requirements. The product of the network should not only serve domestic goals well but will also be attractive to the international scientific community, bringing staff into closer contact with their global colleagues.

The span of subject material that Mr. Ugwuja reviewed during his visit is indeed impressive. He delved into the many areas of seismology observatory practice, of seismic data interpretation and analysis, and of seismic research, with enthusiasm and a profound curiosity. Mr. Ugwuja should prove to be a very valuable asset to the Nigerian Seismograph Network and to the decision making process on the network's behalf. It has been a pleasure to have had him visit us.

E. Acknowledgements

The authors would like to thank the many staff members who participated in this very fruitful endeavour. We would especially like to acknowledge the tremendous contribution of Mr. R. J. Halliday, Manager of the Canadian Seismograph Network. His enthusiasm and broad corporate knowledge of seismic networks was an invaluable asset to this review.

Appendix 1. **Seismograph Siting**

Seismographs have a fixed dynamic range and the recording range chosen will be controlled by the background noise, or microseism, level present at that site. A seismic signal has to be larger than this noise level to be recognized if recording is done on a continuous basis and the seismic signal has to be significantly larger than the noise to start a seismograph that is running in a non–continuous, or trigger, mode. Widely distributed large scale microseismic noise is naturally induced by wave action on oceanic shelves and on large lakes and by wind action on large topographical features. Wind induced noise will also be prevalent on a more local scale as the energy is coupled into the ground by the topography of the local terrain, by trees and by any nearby structures.

To further complicate the background noise there are man–made sources of ground vibration in the frequency range of the seismograph. The more notorious of these are hydro–electric projects, mines, industrial complexes and railways. Cities and towns also contribute a tremendous amount of noise simply resulting from human activity and from the infrastructure that they require. General guidelines suggest that quiet locations be sought at distances of 30–50 kilometres from dams, mines and large cities, 20–30 kilometres from large industrial complexes, 10-15 kilometres from railways and 2–3 kilometres from main highways. It is not always possible to find ideally perfect sites. The requirements for electricity, telephone service, ease of access and qualified station personnel often limit the availability of potential seismograph site locations. When faced with such constraints the goal becomes one of finding the best site that the region has to offer. Comparisons of potential sites within a region where a seismograph is to be installed can be made more relevant by first collecting some samples of the noise levels at the quietest location that the region has to offer. Such samples are best collected in rural areas of low population where the guidelines given above are most likely to be satisfied. One can now compare the results of a siting survey against this low noise model and choose the most appropriate location amongst those tested.

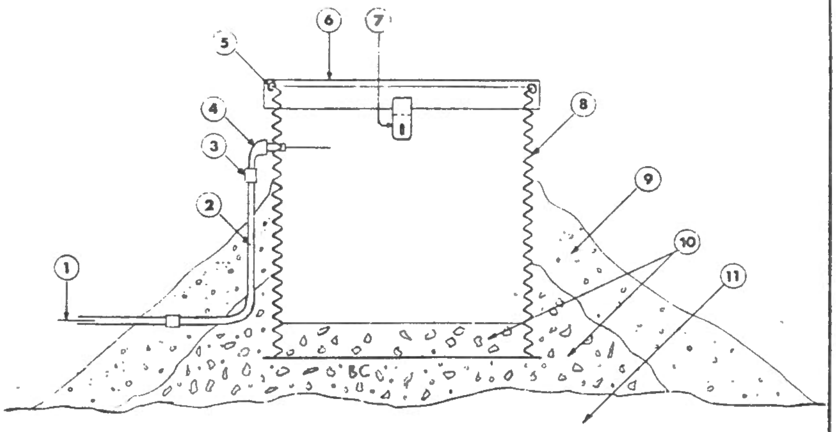
The siting and installation of the seismic sensor is critical and will govern the quality of seismic data collected by the seismograph. Without a doubt, the single most important characteristic of a seismic vault is that it be firmly and cleanly founded to a large bedrock formation, preferably Precambrian basement. This type of formation is very efficient at conducting seismic signals, without altering their frequency content. Such formations overlain by thick, undisturbed sedimentary beds have also proved very useful. The quality of a site is very quickly degraded by the presence of soil or overburden. Soil or overburden founded sites are notoriously noisy. The soft layer oscillates much more to the sources of noise and causes the trigger threshold of the seismograph to be set unnecessarily high; seismic signals have to be much larger to be recorded at such sites and these signals are contaminated by the elevated noise. A thin layer (in the ranges of metres of depth) can amplify the seismic signal so dramatically that magnitude determinations and energy attenuation relationships cannot be calculated. Deeper soil layers (tens to hundreds of metres) will, in addition, dramatically alter the frequency content of the seismic signal. The background noise of a seismic station is not only composed of the afore–mentioned sources but also of the noise sources in the immediate vicinity of the sensor's containment structure and within this seismic vault itself. The vault should be made of very rigid material (poured concrete, corrugated steel pipe, etc) that will not vibrate and should not contain any wood or other soft material. The contact with the rock must be clean and sure. The vault should be protected against wind noise by landscaping the immediate vicinity of the vault with overburden (1–2 metres around the vault). The vault should not be adjacent (i.e. less than 500 metres) to structures that will induce wind generated energy into the rock (i.e. building, tower, large fence, stand of trees, etc.) nor should it be close (i.e. less than 500 metres) to local sources of mechanical vibration (i.e. house, driveway, etc). A drawing of a typical seismic vault used for a single short–period vertical seismometer is included as Appendix 2.

Appendix 2. **Seismic Vault Specification**

DATE	SYM	REVISION RECORD	AUTH	DR	CK

Installation Notes

1.) Clear the overburden from the bedrock.
2.) Make a concrete pad on the bedrock and set the vault on the pad with the concrete still wet. Run concrete up the sides of the vault at least 15 cm.
3.) Assemble items 2, 3 & 4 as shown; ensure that the bend of the conduit is in the concrete.
4.) Pour 8 cm of slightly thinned concrete inside the vault and trowel to produce a smooth finished surface.
5.) Fish two runs of seismic cable through the conduit; leave at least 2 metres spare cable at each end.
6.) Either bury or cover the conduit run, as much as possible.
7.) Pile sand or crushed rock over the concrete pad and up the sides of the 't to within 15 cm of the top.



ITEM	DESCRIPTION	QTY
1	CABLE 22 AWG 2PR + SHIELDS · 8723 BELDEN	A.R.
2	CONDUIT ½" MIN.	A.R.
3	CONDUIT COUPLER	A.R.
4	STREET ELBOW 1"	1
5	GASKET ½" I.D. GARDEN HOSE	10'
6	VAULT COVER	1
7	LOCKING FACILITY	2
8	VAULT (CULVERT)	1
9	SAND OR CRUSHED STONE	A.R.
10	CONCRETE 8-90LB BAGS or MIX	A.R.
11	BEDROCK	

TOLERANCES (EXCEPT AS NOTED)
DECIMAL ±
SCALE
DRAWN BY B [illegible]
APPROVED BY
FRACTIONAL ±
TITLE SEISMIC VAULT INSTALLATION
ANGULAR ±
DATE JULY 26/73
DRAWING NUMBER SM-595B

Appendix 3. Seismograph Instrumentation

Seismograph instrumentation is in state of rapid transition. Very large scale integrated circuitry and the low power requirements of these devices have led to tremendous advances in both personal computers and in the adaption of microprocessors into individual instruments, such as the seismograph.

The elements of a seismograph include the seismometer, a ground sensor that is typically a velocity transducer with a natural period in the order of 1 second, an amplification stage, where the seismic signal is boosted and the bandpass is shaped, a clock to keep track of time, a time signal receiver used to rate and correct the seismograph's clock, typically a radio receiver or a specialized receiver to accept satellite or terrestrial broadcasts of time and position, a recording medium to record the seismic signal either continuously or in short sections and in analogue or digital form and, finally, a power supply to run the whole system. A short discussion of each follows.

i.) Seismometer

The most commonly used ground sensor is the short–period vertical seismometer. These devices have a wide range of suspended inertial mass, typically of the order of 500 grams for smaller microseismic study units to 5 kilograms for the observatory grade units. The natural period of the suspension is often fixed at one second or 0.5 seconds, although observatory grade units have adjustable natural periods. The choice of natural period controls the response at longer periods. A natural period of one second opens up the bandpass for recording L_g phases but also enhances the recording of one second microseism caused by wave action and wind induced noise on large lakes and oceanic shelves. A natural period of 0.5 seconds (2 Hz) favours the recording of shorter period body waves but does limit the overall recording of the seismic wavetrain.

Seismometers have a fixed generator constant, typically expressed in units of electrical output per unit of input ground velocity. The most common form of expression is volts/metre–sec^{-1} or , alternatively, volt–sec/metre. A form of expressing the generator constant that is unique to Japan is the unit the "Kine"; a Kine is equivalent to 1 volt/centimetre–sec^{-1}. The only way to increase the output of the seismometer is to replace it; a more effective and less expensive way to compensate for a lower output seismometer is to increase the amplifier gain for the seismic signal. Many seismometers also have a calibration (or force) coil; the specification for this coil is expressed typically in units of force output per unit current input. The most common form of expression is Newtons per Ampere. Such coils permit the direct calibration of a seismograph from end to end; that is, from the seismometer right through to the recorded data. These coils also allow a pulse to be put on the seismogram as an occasional check on the proper functioning of the seismograph.

The current sensor used with the STR–100 seismograph is the Mark Products L–22 short period vertical geophone with a natural period of 0.5"; the typical inertial mass is 72.8 grams. This transducer has quite a low generator constant and, thus, limits the overall gain at which the seismograph can operate.

An alternative choice for the seismometer is the L–4 , from the same manufacturer. The natural period is 1 second, which would extend the bandpass significantly, and is well controlled (±0.5Hz). The output is almost five times as great giving an increased gain of almost 15 dB. The inertial mass is 1000 grams. Most importantly, this seismometer is equipped with a calibration coil which allows for direct seismograph response determination. Some modifications would be necessary to the way the seismometer is connected to the seismograph but these should be fairly minor in nature. The current cost of these units is $Cdn 1,420. The effect of this change is shown on the response curve included in Appendix 4.

ii.) Amplifier

The seismic signal generated by the seismometer is sent, via cable, to the amplifier for boosting the signal and shaping the bandpass for eventual recording. Amplifiers typically have many settings for the overall gain and a fixed gain for each of these settings. Gains are often separated by 6 dB (that is equivalent to a factor of two) and the seismographs are typically operated at the maximum gain that the local microseism will allow. Some amplifiers allow the setting of bandpass filters while others have fixed values built in to the electronics. Typical bandpass settings see the high–cut or low–pass filter set in the vicinity of 0.1 seconds (10 Hz) and the low–cut or high–pass filter set in the vicinity of 1 to two seconds. The bandpass is also shaped by the seismometer which is equivalent to a second–order high–pass filter set at the natural frequency of the sensor.

The current sites have the gain of the system set to 64 dB. This is an extremely low gain setting for recording regional seismicity (100–1500 kilometres). The maximum gain of 84 dB should be used at all seismograph sites. It would be preferable to have even higher gain however this would not be possible without either the addition of an external amplifier to boost the seismic signal , a new transducer with a much higher generator constant or a modification to the existing amplifier to have more signal gain while using the same seismometer. This increased sensitivity can, of course, only be realised if the sites are improved.

iii.) Clock

The accurate location of an earthquake hypocenter is derived from a knowledge of the speed of wave propagation for seismic energy. The distribution of the arrival times of different phases of the wavetrain enable the seismologist to calculate the location of the source.

These calculations are only as accurate as the time base that all the seismographs use. In order to fully utilize the information available from each site the seismograph must have its own clock; all seismographs in the network must use a common time scale. Furthermore all clocks must be kept accurate to better than the readability of the output; that is to say, if one can read the time on the seismogram to 0.1" then the clock must be accurate to at least 0.05". Clocks are therefore rated and adjusted sufficiently often to keep their accuracy within tolerance. A short history of the clock performance will soon reveal the clock's drift rate away from true time and will indicate how often the clock must be checked.

The specification for the drift rate of the clocks in the STR–100 seismographs is better than 0.05" between successive ratings of the clock; the automatic rating of the clock, when the seismograph is installed in Japan and can receive the Japanese time broadcast, occurs every six hours.

iv.) True time broadcast receiver

Seismographs have some form of true time broadcast receiver either built into them or else they have a connection point whereby true time can be imprinted on the output and used to rate and adjust the internal clock. The seismographs currently in use have the capability of adjusting their internal time automatically four times a day. When used in Japan, these seismographs can tune in the Japanese National Time Service (radio station NHK1) and automatically correct the clock, keeping the clock's accuracy within 0.05" of true time. We know of no similar broadcast service in Nigeria that would broadcast true time with a 440 Hz and an 880 Hz audio signal and using a carrier frequency between 540 and 1605 kHz. What can be done, however, is to determine what time service is available to the proposed locations and produce a 440 Hz audio feed locally from that time source. This can be used to replace the function of the receiver and can still take advantage of the automatic clock correction feature built into these units. This procedure will require minor modifications to the circuitry, but this is unavoidable as the time base for these seismographs was dependant upon their being deployed in Japan.

There are currently many true time broadcasts that are distributed on a global scale. The U.S. has time available from the GOES satellites; receivers are available from Kinemetric's and are quite expensive at US$8,000 and the signal may end at Ghana or Togo. There are many true time broadcasts by radio, but these tend to be in the 2.5 to 20 MegaHz range and could not be received by your seismograph. Navigation systems have true time embedded in their signals and receivers can be purchased to decode this time source; these are again available from Kinemetric's and others at an approximate cost of $3,000. True time is available from the Global Positioning System (GPS) satellites but the current receivers are US$5,000 (although a newer version should be available in 1992 for approximately US$2,000).

The current hope is that the Nigerian television network may have true time embedded in its broadcasts and that a small receiver could be used to create the required time code. The possibility of such enhancements will only be known after careful study of the technical manual for the STR–100. At present, the time is set manually at each seismograph site and the variability in time is very large. Accurate locations of earthquakes will not be possible using this scheme.

v.) Recording method

There are two methods of recording the seismic signal produced; analogue and digital. Recording may be done continuously, typically used for analogue recording systems, or may be done in selected segments where the ground motion "triggers" the seismograph and starts the recording process. Triggered systems may record in analogue or digital format.

Continuous systems have the advantage of recording all of the data in a time period; there is no risk of losing any possible event. Their limitation lies in the fact that, in order to reduce the bulk of the recording medium, the data must be recorded in a compact form. This usually means reduced overall dynamic range and, often, limited recording speed and thus limited discrimination of the period of the seismic waves.

Triggered systems must rely on the performance of the trigger algorithm used to initiate recording; the more dependable the algorithm the higher the capture rate. The advantage is that the signal can be displayed with an enlarged time scale making the determination of the period of the seismic waves more accurate and much easier. The same limitations to the dynamic range apply for triggered analogue systems (such as the STR–100) as for the continuous recording analogue seismographs. Digital systems are only limited by the dynamic range of the components and these are usually quite high (100 dB or more). Digital systems have the additional requirement of having to use either a custom electronics module (less desirable) or a personal computer (more desirable and versatile) to interface with the seismograph and to retrieve the recorded data.

vi.) Power supply

A power supply is necessary to feed all of the components of the seismograph. It is normal practice to ensure the continuity of power to the instrument during a power failure by using an uninterruptible power supply (UPS); batteries keep the seismograph going during these occurrences. There are often large power outages after an earthquake of some size (M5) and it is during this time, shortly after the main shock, that it is imperative to keep seismographs in full operation in order to record any aftershocks. Aftershock activity will continue in the weeks to months after the main shock and this too is a crucial recording period.

The STR–100 appears to be very well designed with respect to power consumption; the units use only 30 watts in standby mode and only 70 watts in recording mode. It is highly recommended that the seismographs be backed up by UPS's; the approximate cost is $Cdn 1,000 each.

Appendix 4. Seismograph Calibration

The analysis and interpretation of seismic waves that are recorded on seismographs is based on a thorough understanding of the effects the recording instrument has on the incident seismic signal. The captured data must be resolved to original ground motion to calculate the earthquake's magnitude. The easiest tool used to present these effects is the calibration, or response, curve where the sensitivity of the seismograph is graphed in units of output recorded per unit input ground motion. Seismographs may be defined as a set of individual filters that cascade together to form an overall bandpass filter. Only waves of a certain frequency band will be favorably recorded while other frequencies will be attenuated.

The calibration of a seismograph defines the response of the instrument as a function of frequency, or as is more commonly used in seismology, period. The entire seismograph can be calibrated at once if a known simulated ground motion, for a given range of periods, is used as input to the seismometer; the instrument's output is recorded in exactly the same fashion as earthquake data would be. This type of calibration is end–to–end and is complete. This method requires that the seismometer is fitted with a calibration, or force, coil to excite the seismometer into steady–state harmonic motion at a fixed period.

The response of the seismograph is determined at periods that go from one end of the bandpass to the other. A signal generator is used to produce sine waves at the desired period and with known output to simulate a fixed angular ground velocity. The starting point for the method is the equation

$$F = ma$$

where F = force in Newtons, m = inertial mass of the seismometer in kilograms and a = angular acceleration in metres–sec^{-2}. As the seismometer is a velocity transducer, substitute angular velocity for acceleration where

$$v = \frac{aT}{2\pi}$$

The motor constant, μ, of a calibration coil is expressed in units of force per unit current input; typically Newtons/Ampere is used. We now have

$$\frac{2\pi mv}{T} = \mu A$$

Substituting $\frac{E}{R}$ for A, where E = voltage and R = resistance in ohms, and rearranging gives

$$R = \frac{\mu E T}{2\pi m v}$$

We now have an equation defining the total circuit resistance, R in ohms, that the signal generator should see as a function of sine wave period, T in seconds. Convenient numbers to use for the other parameters are $E = 10$ volts peak–to–peak for the signal generator output level and $v = 10x10^{-6}$ metres–sec^{-1} for the simulated ground velocity. The motor constant, μ in Newtons/Ampere, and the inertial mass, m in kilograms, are provided by the manufacturer of the seismometer. Note that the total circuit resistance, R, includes the resistance of the calibration coil and the wires connecting it to the seismograph and includes the output resistance of the signal generator, typically 50 Ω. One has now only to inject the sine waves at the appropriate periods, measure the sensitivity of the seismograph as the output/input and plot these values as a function of period. Note that the output of an analogue seismograph is typically a trace displacement measured in metres while the input is a simulated ground velocity measured in metres–sec^{-1}; sensitivity is thus expressed as seconds.

The calibration of seismographs that are not equipped with calibration coils is much more difficult and is beyond the scope of this short summary note. The procedure requires extensive laboratory equipment and well controlled experimental conditions.

Theoretical response curves may be generated from the manufacturer's specifications. This method assumes that the manufacturer correctly identifies the components used and that the documentation provided has no errors in it. This method also does not allow for any variations due to unforseen problems or human error in the construction, configuration or installation of the seismograph. Such a theoretical response curve for the STR–100 is included in this report. It must be very clearly understood that this is an unproven response curve and has no certainty of being accurate.

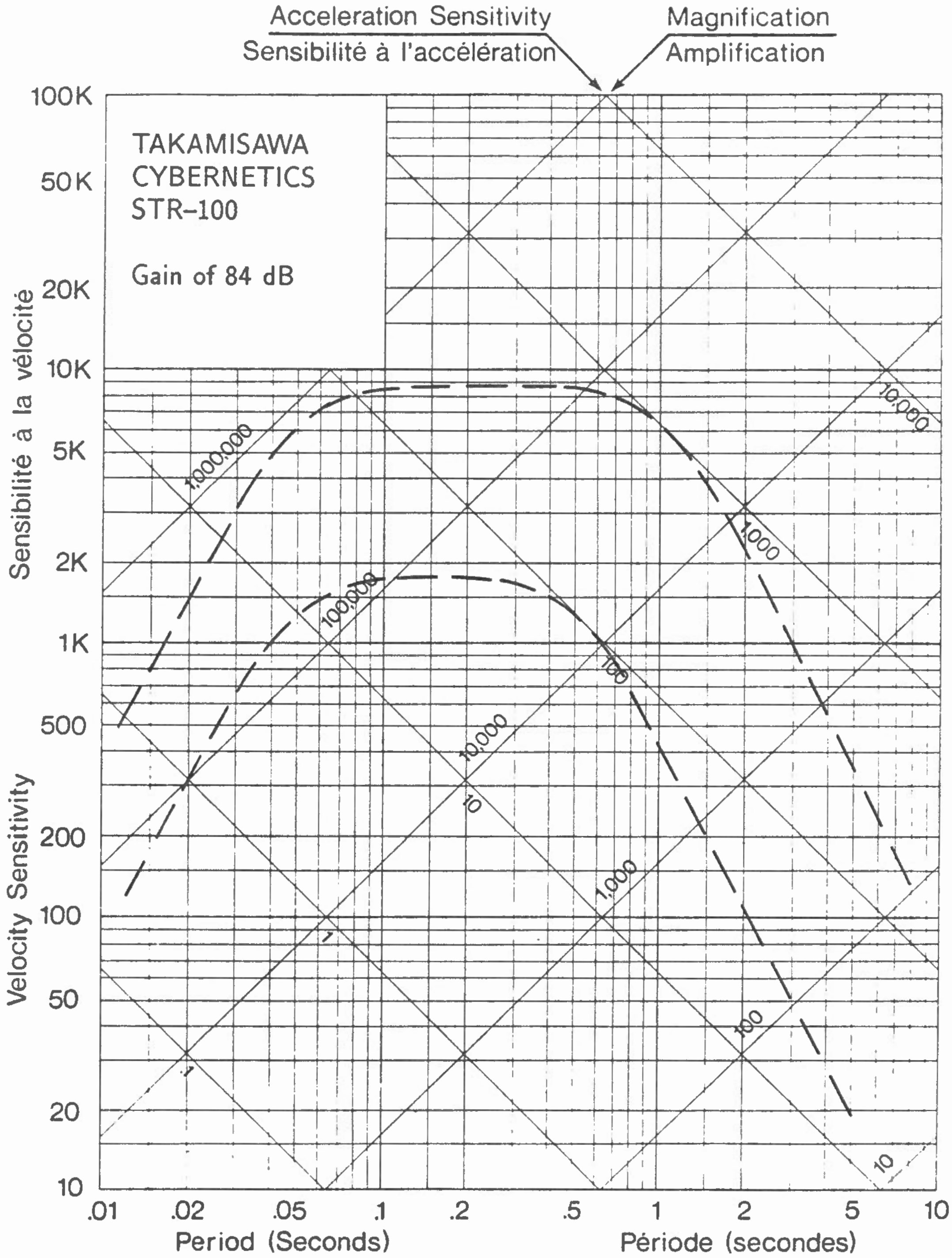


Figure 4.1: Theoretical response curve for the STR-100. The lower curve is for an L-22 seismometer and the upper curve is for an L-4 seismometer.

Appendix 5. Standard Station Operator's Course; Synopsis

The standard station operator's course was designed to familiarize technical staff with the operation of a six–component seismic station and in the reading and interpretation of the seismographs produced. A manual has been written summarizing the course curriculum. The topics include:

- terminology used in seismology;
- the earth and seismic waves;
- appearance of most seismic waves as recorded by short–period and long–period seismographs;
- interpretation of signals on seismograms, including:
  - *i.)* microseism;
  - *ii.)* man–made noise;
  - *iii.)* local earthquakes; and,
  - *iv.)* teleseisms;
- timing, including the rating and calibration of seismograph clocks with radio time signals and the calculation of time corrections;
- measurements of p–waves, their period and amplitude and the calculation of m_b magnitudes for teleseisms;
- use of travel time charts for seismic phases;
- use of seismograph calibration curves;
- study of local earthquakes using single–component short–period vertical seismograms, including:
  - *i.)* establishing/determining hypocentral distance using P and S wave differences;
  - *ii.)* locating approximate epicenters by describing arc distances from 3 or more seismic stations; and,
  - *iii.)* calculating m_L from each station;
- supervision of station operation, including:
  - *i.)* standardized annotation and presentation of records;
  - *ii.)* quality control of seismograms;
  - *iii.)* organizing the collection of seismograms;
  - *iv.)* station supply; and,
  - *v.)* station operator's course presentation either at headquarters or *in–situ*.

Appendix 6. Seismic Analysis Computer Specification

The IASPEI software library defines a minimum specification for the hardware requirement for the hypocenter location program HYPO71PC. Other chapters in the first two volumes of this software suggest hardware requirements as appropriate for those tasks. The rapid advances in computer hardware and software must also be considered in the specification of a computer purchase. More and more software tools are using graphical interfaces to make these products more "user friendly". The following specification culls together the most pertinent of these recommendations.

- Microprocessor: 386 type with a minimum speed of 20-MHz
- Coprocessor: 387 type math coprocessor rated at the same speed as the microprocessor
- System memory: 640KBytes; must support the Lotus/Intel/Microsoft Expanded Memory Specification (LIM/EMS) Standard Version 4.0 or higher; it is preferable and advantageous to have at least 3MB of expanded memory installed at purchase time
- Disk drives: a fixed disk drive of 100MB and a floppy disk drive of 1.44MB ($3\frac{1}{2}$"; high density)
- Monitor: standard VGA colour monitor of 640 x 480 resolution
- Expansion slots: three 8-/16-bit full-sized and one 32-bit full-sized
- Standard interfaces: pointing device (mouse);
  parallel printer; and,
  asynchronous (serial) communications;
  all mounted on the system board.
- Printer: industry standard type laser printer with 300 dpi resolution and a 4 page/minute feed–through; to have HPLaserjetII and Epson emulation capabilities
- Mouse: 100% Microsoft compatible mouse
- Software: operating system; DOS 3.31 or 4.01 or higher
  IASPEI Toolbox for Seismic Data Acquisition, Processing and Analysis; available from the Seismological Society of America, 210 Plaza Professional Building, El Cerrito, CA 94530, USA (Phone: 415–525–5474)
  Norton Editor
  XTREE Professional disk management system
- Cost: the approximate cost is $Cdn 6,500
- Configuration: the GSC would be willing to help with this in any manner possible

Appendix 7. Earthquake Magnitude Determination

Few subjects in seismology have caused as much confusion as earthquake magnitude. The original simple concept introduced by Richter for application to records made by a particular type of seismograph in California has had to be extensively modified for use in other parts of the world, in different distance ranges, and for different phases. The characteristics of these various factors vary sufficiently that, despite the best efforts at consistency, the various magnitudes that can be calculated for a given event do not necessarily agree to better than about half a magnitude unit. The magnitude formulae in common use today may be divided into those used at teleseismic (greater than 2000 km) and those employed at the shorter regional and local distances.

Teleseismic Magnitudes

Two formulae are in common use and routinely employed by the two agencies (US Geological Survey and the International Seismological Centre) that compute locations and magnitudes for worldwide events. The most used is the m_b, or body-wave magnitude, scale, calculated from the maximum amplitude A and period T of the first six seconds of the P wave, recorded on a short-period vertical instrument. The observed values of period T lie in the range 0.2-2.0 seconds. The value of $log(A/T)$ is corrected for both distance and source depth, using tabulated correction factors, to provide the individual (station) m_b value. All values of station m_b are then averaged to provide the event m_b.

For larger events, the long period Rayleigh waves that are generated are large enough to be seen above the noise level on long-period vertical seismographs, and the M_S, or surface wave magnitude, scale is based upon their maximum amplitudes. $Log(A/T)$, where T must lie in the range 18-22 seconds, is computed and M_S calculated using a correction factor which depends on distance only. As for m_b, a number of individual station values are averaged to produce the event M_S.

Because they sample either the deep interior of the earth (m_b) or the entire crust and uppermost mantle (M_S), the waves involved in these magnitudes are not greatly affected by regional variations in structure, which are largely constrained to the crust. Consequently the average magnitude is quite well determined and individual measurements rarely differ from it by more than 0.3 magnitude units. These two magnitudes are now widely accepted as the best measure of earthquake size for events large enough to be recorded at distances greater than 2000 km. This, however, restricts their use to events of magnitude larger than about 4 - 4.5 on the m_b scale.

Local and Regional Magnitudes

The original local magnitude M_L devised by Richter was intended only for use in California with seismograms recorded on the Wood-Anderson seismograph. It has been extended to other parts of the world and to different instrumentation, but this requires a lengthy study, using many events, to establish the exact formula and distance correction factors that are appropriate for the region in which it is to be applied.

Magnitude scales based upon the duration of the entire signal, or coda, have been developed, mostly for use at close distances (typically 200 km or less). These are known as coda magnitude (m_c) or duration magnitude (M_d) and, like the regional M_L scale, the determination of the formula to be employed is a lengthy process. A particular drawback of these types of magnitude is that the measurable duration of the signal can be affected by many factors such as the background noise level, variations in the detector shut-off level for automatically triggered systems, the station operator on duty, and so on.

In shield areas or areas where sedimentary cover over the precambrian basement is not too thick and reasonably well layered, the largest phase observed at distances greater than about 50 km is the L_g phase which results from multiple bounces of S within the crust and travels at a relatively constant velocity of between 3.5 and 3.7 km/s. Magnitude scales based upon the maximum amplitude of L_g are in regular use in stable continental regions of North America and elsewhere in the world. Most of these are of the form derived by Nuttli in 1973 for use in the central US. Nuttli proposed two formulae, one for use at distances of 50-400 km and the other for distances greater than 400km. He derived his formulae from seismograms recorded on narrow-band (centered at 1 sec period) instruments and it was found that use with wider-band instruments, such as those installed in eastern Canada (and Nigeria) caused the formula proposed for shorter distances to exaggerate magnitude due to the division of A by T, where T was often considerably less than 1 second. In eastern Canada it was found that using Nuttli's formula for distances greater than 400 km at all distances (greater than 50km) gave more consistent results over the entire range of distances. This formula is

$$m_N = -0.10 + 1.66 log_{10}(d) + log(A/T)$$

where m_N is the (Nuttli) magnitude, A the maximum (zero-peak) ground displacement amplitude in micrometers, T the corresponding dominant period in seconds, and d the distance in km. This formula is considered to be appropriate for use in Nigeria.

Just as the effect of the instrumentation in use in eastern Canada had to be considered in the application of the m_N formula, the effect of the seismograph systems installed in Nigeria (L–22 seismometers recorded on the STR–100 seismograph recorder) must be evaluated. Seismograms recorded on the eastern Canada network (1 Hz seismometers) were converted to appear as they would recorded on an L–22 (2 Hz) seismometer and the change in amplitude A and period T, and (A/T) determined. For three events with magnitudes varying from 4.1 to 6.0 it was found that (A/T) on the L–22 systems was slightly larger, by amounts ranging from an average equivalent 0.08 magnitude units for the smallest event to 0.20

for the largest. This is what would be expected given that the period at the maximum amplitude would be shorter on the seismograms recorded by the L–22. For events smaller than magnitude 4, which have more high frequency content, the seismograms recorded by the L–22 system would be almost identical with those given by longer-period (e.g. 1 Hz) seismometers.

The amplitude A must be obtained from the recorded trace amplitude recorded on the STR–100 paper records, corrected for the magnification at the period T. While it is always preferable to calculate the individual magnitudes directly, the following tables may be used to determine ground displacement divided by period (A/T) from the records (Table 7.1) produced by the STR–100 seismograph operated at the 84 dB gain setting, and to determine magnitudes from these values of (A/T) (Table 7.2). These tables will also be useful in checking individual calculations for large errors.

It may not always be possible to determine the period T, particularly for smaller closer events, and in such cases the trace amplitude can be used directly (Table 7.3) in the calculation of magnitude, as long as it is appreciated that the results are correct only if the (unknown) period T is less than the natural period of the seismometer (for the L–22, 0.5 seconds) and greater than 0.05". This last condition is almost certain to be satisfied for all events of magnitude less than 3.5.

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.5	0.027	0.026	0.025	0.022	0.019	0.015	0.012	0.010	0.008	0.006
1.0	0.053	0.052	0.050	0.045	0.038	0.030	0.024	0.019	0.016	0.013
2.0	0.106	0.105	0.100	0.089	0.075	0.059	0.048	0.038	0.032	0.025
3.0	0.159	0.157	0.150	0.134	0.113	0.089	0.072	0.057	0.048	0.038
4.0	0.212	0.210	0.199	0.178	0.151	0.119	0.095	0.076	0.064	0.051
5.0	0.265	0.262	0.249	0.223	0.188	0.148	0.119	0.095	0.080	0.064
6.0	0.318	0.315	0.299	0.267	0.226	0.178	0.143	0.115	0.095	0.076
7.0	0.371	0.367	0.349	0.312	0.264	0.208	0.167	0.134	0.111	0.089
8.0	0.424	0.420	0.399	0.356	0.301	0.238	0.191	0.153	0.127	0.102
9.0	0.477	0.472	0.449	0.401	0.339	0.267	0.215	0.172	0.143	0.115
10.0	0.530	0.525	0.498	0.445	0.376	0.297	0.239	0.191	0.159	0.127
11.0	0.583	0.577	0.548	0.490	0.414	0.327	0.262	0.210	0.175	0.140
12.0	0.636	0.630	0.598	0.534	0.452	0.356	0.286	0.229	0.191	0.153
13.0	0.689	0.682	0.648	0.579	0.489	0.386	0.310	0.248	0.207	0.165
14.0	0.742	0.735	0.698	0.624	0.527	0.416	0.334	0.267	0.223	0.178
15.0	0.795	0.787	0.748	0.668	0.565	0.445	0.358	0.286	0.239	0.191
16.0	0.848	0.840	0.798	0.713	0.602	0.475	0.382	0.305	0.255	0.204
17.0	0.901	0.892	0.847	0.757	0.640	0.505	0.406	0.325	0.270	0.216
18.0	0.954	0.945	0.897	0.802	0.678	0.534	0.430	0.344	0.286	0.229
19.0	1.007	0.997	0.947	0.846	0.715	0.564	0.453	0.363	0.302	0.242
20.0	1.061	1.050	0.997	0.891	0.753	0.594	0.477	0.382	0.318	0.255
21.0	1.114	1.102	1.047	0.935	0.791	0.624	0.501	0.401	0.334	0.267
22.0	1.167	1.155	1.097	0.980	0.828	0.653	0.525	0.420	0.350	0.280
23.0	1.220	1.207	1.146	1.024	0.866	0.683	0.549	0.439	0.366	0.293
24.0	1.273	1.260	1.196	1.069	0.904	0.713	0.573	0.458	0.382	0.305
25.0	1.326	1.312	1.246	1.114	0.941	0.742	0.597	0.477	0.398	0.318
26.0	1.379	1.365	1.296	1.158	0.979	0.772	0.620	0.496	0.414	0.331
27.0	1.432	1.417	1.346	1.203	1.016	0.802	0.644	0.515	0.430	0.344
28.0	1.485	1.470	1.396	1.247	1.054	0.831	0.668	0.534	0.445	0.356
29.0	1.538	1.522	1.445	1.292	1.092	0.861	0.692	0.554	0.461	0.369
30.0	1.591	1.575	1.495	1.336	1.129	0.891	0.716	0.573	0.477	0.382

Table 7.1: (A/T) in microns/sec as a function of period T. Periods (top row) are in seconds. Trace amplitudes (leftmost column) are *peak–to–peak* in millimetres at 84 dB setting of the STR–100. The table provides *peak–to–peak* (A/T) in microns/sec for any given combination of period and trace amplitude. If the gain is at a setting of less than 84 dB, the values given by the table are to be multiplied by two for each gain reduction of 6 dB (e.g. at 78 dB multiply (A/T) by 2; at 66 dB multiply by 8; etc.).

	50	75	100	125	150	200	250	300	350	400	500	600	800	1000
0.001	-0.6	-0.3	-0.1	0.1	0.2	0.4	0.6	0.7	0.8	0.9	1.1	1.2	1.4	1.6
0.002	-0.3	0.0	0.2	0.4	0.5	0.7	0.9	1.0	1.1	1.2	1.4	1.5	1.7	1.9
0.003	-0.1	0.2	0.4	0.6	0.7	0.9	1.1	1.2	1.3	1.4	1.6	1.7	1.9	2.1
0.004	0.0	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.4	1.5	1.7	1.8	2.0	2.2
0.005	0.1	0.4	0.6	0.8	0.9	1.1	1.3	1.4	1.5	1.6	1.8	1.9	2.1	2.3
0.006	0.2	0.5	0.7	0.9	1.0	1.2	1.4	1.5	1.6	1.7	1.9	2.0	2.2	2.4
0.007	0.3	0.6	0.8	0.9	1.1	1.3	1.4	1.6	1.7	1.8	1.9	2.1	2.3	2.4
0.008	0.3	0.6	0.8	1.0	1.1	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.3	2.5
0.009	0.4	0.7	0.9	1.0	1.2	1.4	1.5	1.7	1.8	1.9	2.0	2.2	2.4	2.5
0.010	0.4	0.7	0.9	1.1	1.2	1.4	1.6	1.7	1.8	1.9	2.1	2.2	2.4	2.6
0.020	0.7	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.1	2.2	2.4	2.5	2.7	2.9
0.030	0.9	1.2	1.4	1.6	1.7	1.9	2.1	2.2	2.3	2.4	2.6	2.7	2.9	3.1
0.040	1.0	1.3	1.5	1.7	1.8	2.0	2.2	2.3	2.4	2.5	2.7	2.8	3.0	3.2
0.050	1.1	1.4	1.6	1.8	1.9	2.1	2.3	2.4	2.5	2.6	2.8	2.9	3.1	3.3
0.060	1.2	1.5	1.7	1.9	2.0	2.2	2.4	2.5	2.6	2.7	2.9	3.0	3.2	3.4
0.070	1.3	1.6	1.8	1.9	2.1	2.3	2.4	2.6	2.7	2.8	2.9	3.1	3.3	3.4
0.080	1.3	1.6	1.8	2.0	2.1	2.3	2.5	2.6	2.7	2.8	3.0	3.1	3.3	3.5
0.090	1.4	1.7	1.9	2.0	2.2	2.4	2.5	2.7	2.8	2.9	3.0	3.2	3.4	3.5
0.100	1.4	1.7	1.9	2.1	2.2	2.4	2.6	2.7	2.8	2.9	3.1	3.2	3.4	3.6
0.200	1.7	2.0	2.2	2.4	2.5	2.7	2.9	3.0	3.1	3.2	3.4	3.5	3.7	3.9
0.300	1.9	2.2	2.4	2.6	2.7	2.9	3.1	3.2	3.3	3.4	3.6	3.7	3.9	4.1
0.400	2.0	2.3	2.5	2.7	2.8	3.0	3.2	3.3	3.4	3.5	3.7	3.8	4.0	4.2
0.500	2.1	2.4	2.6	2.8	2.9	3.1	3.3	3.4	3.5	3.6	3.8	3.9	4.1	4.3
0.600	2.2	2.5	2.7	2.9	3.0	3.2	3.4	3.5	3.6	3.7	3.9	4.0	4.2	4.4
0.700	2.3	2.6	2.8	2.9	3.1	3.3	3.4	3.6	3.7	3.8	3.9	4.1	4.3	4.4
0.800	2.3	2.6	2.8	3.0	3.1	3.3	3.5	3.6	3.7	3.8	4.0	4.1	4.3	4.5
0.900	2.4	2.7	2.9	3.0	3.2	3.4	3.5	3.7	3.8	3.9	4.0	4.2	4.4	4.5
1.000	2.4	2.7	2.9	3.1	3.2	3.4	3.6	3.7	3.8	3.9	4.1	4.2	4.4	4.6
2.000	2.7	3.0	3.2	3.4	3.5	3.7	3.9	4.0	4.1	4.2	4.4	4.5	4.7	4.9
3.000	2.9	3.2	3.4	3.6	3.7	3.9	4.1	4.2	4.3	4.4	4.6	4.7	4.9	5.1
4.000	3.0	3.3	3.5	3.7	3.8	4.0	4.2	4.3	4.4	4.5	4.7	4.8	5.0	5.2
5.000	3.1	3.4	3.6	3.8	3.9	4.1	4.3	4.4	4.5	4.6	4.8	4.9	5.1	5.3
6.000	3.2	3.5	3.7	3.9	4.0	4.2	4.4	4.5	4.6	4.7	4.9	5.0	5.2	5.4
7.000	3.3	3.6	3.8	3.9	4.1	4.3	4.4	4.6	4.7	4.8	4.9	5.1	5.3	5.4
8.000	3.3	3.6	3.8	4.0	4.1	4.3	4.5	4.6	4.7	4.8	5.0	5.1	5.3	5.5
9.000	3.4	3.7	3.9	4.0	4.2	4.4	4.5	4.7	4.8	4.9	5.0	5.2	5.4	5.5

Table 7.2: Magnitude (m_N) as a function of distance in km and (A/T) in microns/sec. Distance is on the top row in km and (A/T) values (leftmost column) are *peak–to–peak* in microns/sec (obtained from Table 7.1).

	50	75	100	125	150	200	250	300	350	400	500	600	800	1000
0.5	0.8	1.1	1.3	1.5	1.6	1.8	2.0	2.1	2.2	2.3	2.5	2.6	2.8	3.0
1.0	1.1	1.4	1.6	1.8	1.9	2.1	2.3	2.4	2.5	2.6	2.8	2.9	3.1	3.3
2.0	1.4	1.7	1.9	2.1	2.2	2.4	2.6	2.7	2.8	2.9	3.1	3.2	3.4	3.6
3.0	1.6	1.9	2.1	2.3	2.4	2.6	2.8	2.9	3.0	3.1	3.3	3.4	3.6	3.8
4.0	1.7	2.0	2.2	2.4	2.5	2.7	2.9	3.0	3.1	3.2	3.4	3.5	3.7	3.9
5.0	1.8	2.1	2.3	2.5	2.6	2.8	3.0	3.1	3.2	3.3	3.5	3.6	3.8	4.0
6.0	1.9	2.2	2.4	2.6	2.7	2.9	3.1	3.2	3.3	3.4	3.6	3.7	3.9	4.1
7.0	2.0	2.3	2.5	2.7	2.8	3.0	3.2	3.3	3.4	3.5	3.6	3.8	4.0	4.1
8.0	2.0	2.3	2.5	2.7	2.8	3.0	3.2	3.3	3.5	3.5	3.7	3.8	4.0	4.2
9.0	2.1	2.4	2.6	2.8	2.9	3.1	3.3	3.4	3.5	3.6	3.8	3.9	4.1	4.3
10.0	2.1	2.4	2.6	2.8	2.9	3.1	3.3	3.4	3.5	3.6	3.8	3.9	4.1	4.3
11.0	2.2	2.5	2.7	2.8	3.0	3.2	3.3	3.5	3.6	3.7	3.8	4.0	4.2	4.3
12.0	2.2	2.5	2.7	2.9	3.0	3.2	3.4	3.5	3.6	3.7	3.9	4.0	4.2	4.4
13.0	2.3	2.6	2.8	2.9	3.1	3.3	3.4	3.6	3.7	3.8	3.9	4.1	4.3	4.4
14.0	2.3	2.6	2.8	3.0	3.1	3.3	3.5	3.6	3.7	3.8	4.0	4.1	4.3	4.5
15.0	2.3	2.6	2.8	3.0	3.1	3.3	3.5	3.6	3.7	3.8	4.0	4.1	4.3	4.5
16.0	2.3	2.6	2.8	3.0	3.1	3.3	3.5	3.6	3.8	3.8	4.0	4.1	4.3	4.5
17.0	2.4	2.7	2.9	3.0	3.2	3.4	3.5	3.7	3.8	3.9	4.0	4.2	4.4	4.5
18.0	2.4	2.7	2.9	3.1	3.2	3.4	3.6	3.7	3.8	3.9	4.1	4.2	4.4	4.6
19.0	2.4	2.7	2.9	3.1	3.2	3.4	3.6	3.7	3.8	3.9	4.1	4.2	4.4	4.6
20.0	2.4	2.7	2.9	3.1	3.2	3.4	3.6	3.7	3.8	3.9	4.1	4.2	4.4	4.6
21.0	2.5	2.8	3.0	3.1	3.3	3.5	3.6	3.8	3.9	4.0	4.1	4.3	4.5	4.6
22.0	2.5	2.8	3.0	3.1	3.3	3.5	3.6	3.8	3.9	4.0	4.1	4.3	4.5	4.6
23.0	2.5	2.8	3.0	3.2	3.3	3.5	3.7	3.8	3.9	4.0	4.2	4.3	4.5	4.7
24.0	2.5	2.8	3.0	3.2	3.3	3.5	3.7	3.8	3.9	4.0	4.2	4.3	4.5	4.7
25.0	2.5	2.8	3.0	3.2	3.3	3.5	3.7	3.8	3.9	4.0	4.2	4.3	4.5	4.7
26.0	2.6	2.9	3.1	3.2	3.4	3.6	3.7	3.9	4.0	4.1	4.2	4.4	4.6	4.7
27.0	2.6	2.9	3.1	3.2	3.4	3.6	3.7	3.9	4.0	4.1	4.2	4.4	4.6	4.7
28.0	2.6	2.9	3.1	3.3	3.4	3.6	3.8	3.9	4.0	4.1	4.3	4.4	4.6	4.8
29.0	2.6	2.9	3.1	3.3	3.4	3.6	3.8	3.9	4.0	4.1	4.3	4.4	4.6	4.8
30.0	2.6	2.9	3.1	3.3	3.4	3.6	3.8	3.9	4.0	4.1	4.3	4.4	4.6	4.8

Table 7.3: Magnitude (m_N) as a function of distance in km and STR–100 trace amplitude in mm with a setting of 84 dB. *NOTE:* This table only applies when the dominant period is between 0.05 and 0.4 seconds — this is likely to be true only for events of magnitude less than 4. Distance is on the top row in km and trace amplitudes (leftmost column) are *peak–to–peak* in mm at 84 dB setting of the STR–100. The table provides magnitude for any given combination of distance and trace amplitude. If the gain is at a setting of less than 84 dB, the magnitudes given by the table are to be increased by 0.3 for each gain reduction of 6 dB (e.g. at 78 dB add 0.3; at 66 dB add 0.9; etc.).