June 1978

Lawrence Livermore National Laboratory, Special Projects Division, 'Proliferation Group Quarterly Report, January – March 1978'

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Summary:

This issue includes an extract from a recent study on Pakistan and two highly technical articles relating to on-going research to identify the signatures of high explosives used for the implosion method of nuclear detonation. It also includes a report that utilized open literature and classified intelligence, including two satellite photographs, the purpose of the article is to illuminate how the South African Government intended to use the site, down to the depth and thickness of the bore holes.

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PROLIFERATION GROUP QUARTERLY REPORT

JANUARY-MARCH 1978

Department of Energy Declassification Review	
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PROLIFERATION GROUP
QUARTERLY REPORT
January-March 1978

Compiled and Edited by

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General Editor

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June 1978

PREFACE

This is one of a series of regular quarterly reports that provides substantive discussion of activities of the Proliferation Group, LLL Special Projects Division. This work uses the capabilities of the Special Projects Division, and of LLL generally, in a broad range of country studies and technical projects relevant to the problem of nuclear proliferation. This program, which supports DOE and the intelligence community, has been in existence since late 1974.

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PROLIFERATION GROUP QUARTERLY REPORT
January-March 1978

INTRODUCTION AND SUMMARY

This report describes work done by the Proliferation Group, LLL Special Projects Division, for the period 1 January to 31 March 1978. We present an extract from a Special study done on the nuclear program of Pakistan, an article on the geology and history of the Kalahari drill site in South Africa, and two articles from our ongoing high explosives program. Most of the work was supported by the Office of International Security Affairs of the Department of Energy, but support for the high explosives work was also received from the Office of Research and Development of the Central Intelligence Agency.

The material we present on the Pakistani nuclear program was taken from our report "An Evaluation of Pakistan's Capability to Acquire Fissile Material for a Nuclear Explosive," which was published separately during February. That work was in response to a request from the Department of State for an analysis of possible sources of fissile material for a Pakistani weapons program. The use of spent fuel from the KANUPP power reactor and the possible construction of a production reactor were considered as primary plutonium sources, and the question of fuel reprocessing was addressed from two points of view: the indigenous construction of a scaled-up version of the PINSTECH hot laboratory and the completion by Pakistan of the French reprocessing plant in the event that the French government decides to cancel the agreement to supply that plant. The study showed that the data available at that time did not permit a very detailed analysis. The conclusion was reached, however, that the Pakistanis could succeed at some of these ventures, given appropriate national prior-

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ities. Some suggestions were given for intelligence collection relevant to these questions.

The study of the geology and drilling history of the Kalahari drill site attempts to bring out finer detail than has previously been made available on this subject. Open and classified literature and overhead photography were examined, and the results provide some additional insights into possible intended uses of the site. Some comments are provided on hole depths, and corresponding capabilities with respect to nuclear test yields were calculated. Geologic data based on nearby boreholes have allowed us to draw stratigraphic cross sections that indicate a 60- to 85-m-thick sand layer overlying a granitelike rock layer. These data are consistent with the 75-m thickness estimated from hole casing and from analysis of other drilling apparatus. After the casing of the hole to 75 m there was further drilling into the hard rock, and estimates of the extent of this additional drilling are made based on the usage of bit cutters known from collateral data and on estimates of the number of days spent in drilling. The result based on number of bit cutters used, 94 to 152 m, is considered most reliable. This gives a total hole depth between 169 and 227 m.

The high explosives work that is described here is a part of an ongoing program directed toward identifying signatures of nuclear-explosives-related HE testing. [redacted] DOE b(1) Other aspects of the HE program have been described in several previous quarterly reports.

The article on energy partitioning in HE detonations deals with a question that is fundamental to an understanding of observables such as total light output, fireball growth, streamer

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phenomenology, and so on. The reported results are based on theoretical calculations using LLL weapon-design codes. At late times it is clear that most of the available energy from an event has been transferred to heating and to movement of surrounding air. Roughly 10% of the energy has gone into dispersal of pit material, and about 10% remains as internal energy of the HE products.

The final article describes and extensive series of tests fired to determine the utility of seismology for measuring HE yields. We have argued that, whereas seismic signals will not identify an implosion test per se, the ability to measure HE yield, even fairly crudely, could be very important in foreign test-site monitoring. An indication that large charges (50 kg or greater) are being fired, together with other indicators (site configuration, etc.), might identify nuclear-related testing. We fired 46 special shots over a several-week period. The explosives were, for the most part, simple configurations of bulk HE, and seismic measurements were made using a net of broadband velocity meters. We examined the following questions:

- Does the seismic-signal amplitude depend on height of burst? Series of 23-kg and 45-kg charges were fired at heights from zero to 2.1 m above the ground; no burst-height dependence was noted.
- Would seismic coupling depend on device configuration (i.e., hemisphere pointing downward vs hemisphere pointing sideways)? Tests simulating extreme cases showed at most a small perturbation on signal amplitudes.
- What is the yield scaling relationship for near-surface bursts of HE in the yield range relevant to nuclear HE work? A series of explosive masses ranging from 11 to 234 kg was fired with fixed firing geometry, and a simple scaling relationship was obtained.

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- How important is local geology? Shots were fired at different locations, and several seismic stations were used. It is clear that travel-path variations will frustrate attempts at <u>absolute</u> yield measurements by seismic means. A strong acoustically coupled signal that arrives after the direct seismic (earth-coupled) signal may hold more promise for absolute calibration.

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PAKISTAN COUNTRY STUDY

In response to a request by the U.S. Department of State, we undertook an analysis of Pakistan's capability to acquire fissile material for a nuclear explosive. Our report on the study, titled "An Evaluation of Pakistan's Capability to Acquire Fissile Material for a Nuclear Explosive," was published as TCS-326/009/78 and was distributed by DOE/OISA. We outline the report here, including its executive summary and a list of questions pertinent to future collecting on the subject.

As Pakistan's possible sources for fissile material, three scenarios were considered: the use of a production reactor, stealing fuel rods already in the cooling ponds of the Karachi Nuclear Power Plant (KANUPP) power reactor, and running unsafeguarded fuel elements through KANUPP. The success of any of these scenarios for the acquisition of weapons-usable material requires that Pakistan have facilities for reprocessing. For this, two alternatives were considered. First, we assessed Pakistan's ability to construct a scaled-up version of the Pakistan Institute of Science and Technology (PINSTECH) hot laboratory. A second evaluation centered on the possibility that Pakistan may try to complete the French-designed Kundian Nuclear Center (KNC) reprocessing plant in the event that the French Government decides to cancel or alter its agreement to supply that plant.

To limit the scope of this study, the Department of State suggested that the following general assumptions be made:

- Pakistan is attempting to acquire fissile material sufficient for one to three devices (from 10-35 kg of plutonium).
- The effort will be given priority, and financial resources will be redirected from other projects if necessary.

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- The constraints of health and safety standards will not apply.

It should be noted that this study was meant to address the issue of Pakistan's technical capabilities; no effort was made to analyze or evaluate the political and economic ramifications that might affect Pakistan's decision to follow one or another of the scenarios. It was our opinion when this study was undertaken that no very definite conclusions were likely. As we implied in one of our earlier reports on Pakistan's nuclear program, the Pakistanis have only a marginal capability to succeed at any complex, large-scale technical enterprise. They clearly have many of the required skills, but success in acquiring fissile material for a nuclear explosive device depends on factors other than pure scientific expertise; Pakistan must also possess management skills, ample capital, industrial capacity, and a host of lesser supporting capabilities. This study shows that the data available at this time do not permit a very detailed analysis. The conclusion is reached, however, that the Pakistanis could succeed at some of the ventures outlined above, given appropriate national priorities. Whereas this study does not present definitive conclusions, hopefully it will serve at least to clarify some of the relevant questions. The more important questions raised by this study are listed below.

Executive Summary

This study addressed the questions of whether Pakistan can acquire and chemically separate fissile material for one to three nuclear explosives. Unfortunately, lack of information has precluded our giving definitive answers. Rather, we have culled as much relevant data as possible and have drawn very general conclusions:

- Pakistan would be unlikely to build a production reactor due to the cost, time, and requirements of pursuing what would be, for Pakistan, a new line of technology.
- Stolen KANUPP fuel elements could be reprocessed at the cost of breaking safeguards and endangering future technology transfers.
- Repercussions of reprocessing KANUPP fuel could be avoided by running unsafeguarded fuel through the reactor and later extracting the plutonium under the guise of "peaceful nuclear purposes."
- Using KANUPP as a "production reactor" would necessitate having both unsafeguarded uranium and access to fuel fabrication facilities. [redacted]

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To give more definitive answers to the questions posed about Pakistan's capabilities, more detailed information must be provided. Below are some questions that arose in the course of this study; they may be helpful in formulating priorities for future collection.

Suggestions for Future Reporting

A number of questions need to be answered before a more definitive evaluation of Pakistan's capabilities can be made. We give here a set of collection suggestions, some of which we consider to have very high priority in the context of the present study. Much of this material could be collected by US Government personnel from open sources within Pakistan.

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GEOLOGY AND HISTORY OF THE KALAHARI DRILL SITE

Introduction

This article attempts to bring out finer analytic detail from open and classified literature and imagery of the drill-site portion of the Kalahari Probable Nuclear Test Site than has been previously available.

Detailed knowledge of the subsurface stratigraphy is vital in any functional scenario that one may be considering for the Kalahari site. Likewise, a detailed day-by-day observation of changes and procedures at the drill site, the one location we have the best history on, might give a few extra clues as to the purpose of the Kalahari site. Applying the geology of the site to what we see and know of the drill site, a minimum-maximum depth for the drilled hole has been estimated and corresponding capabilities in nuclear test yields calculated.

Geology of the Kalahari Site

Stratigraphy

Previous geologic descriptions[1,2] of the Kalahari Site were generalized ones coming from available regional open-literature geologic descriptions. P. J. Smit's description of the Karoo system[3] gives detailed stratigraphic information of nearby wells (Niete Min, 7.3 km N10°W from the drill site--Figs. 1 and 2--and Hop Hop, 13.3 km N25°W from the drill site) as well as the stratigraphy of more distant boreholes; this information allows us to determine regional trends in the direction of the drill site. From the extrapolated cross sections (Fig. 3) we can determine that the Karoo system (the primary sedimentary bedrock underlying much of the Kalahari region, has probably pinched out (i.e., is

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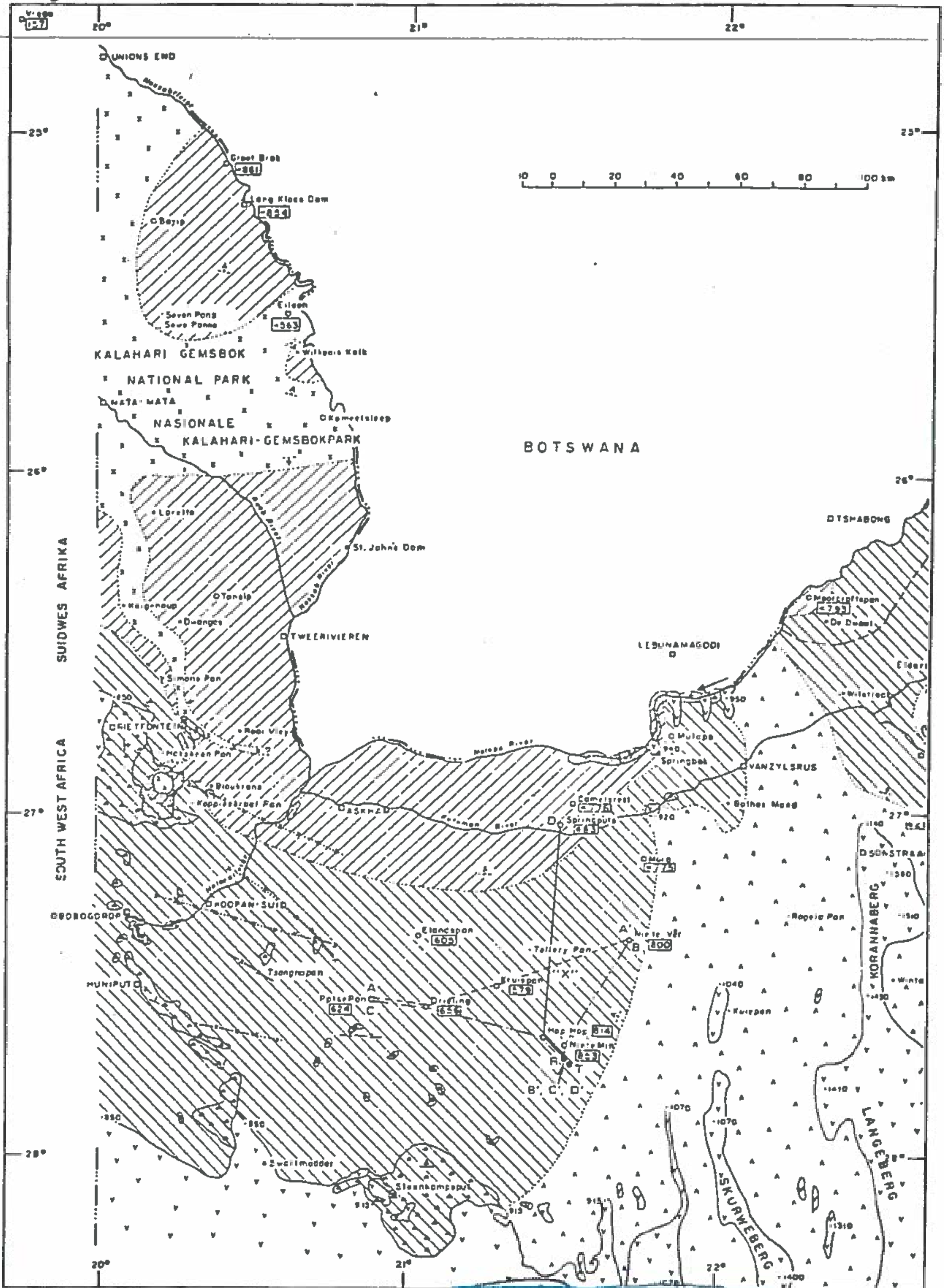

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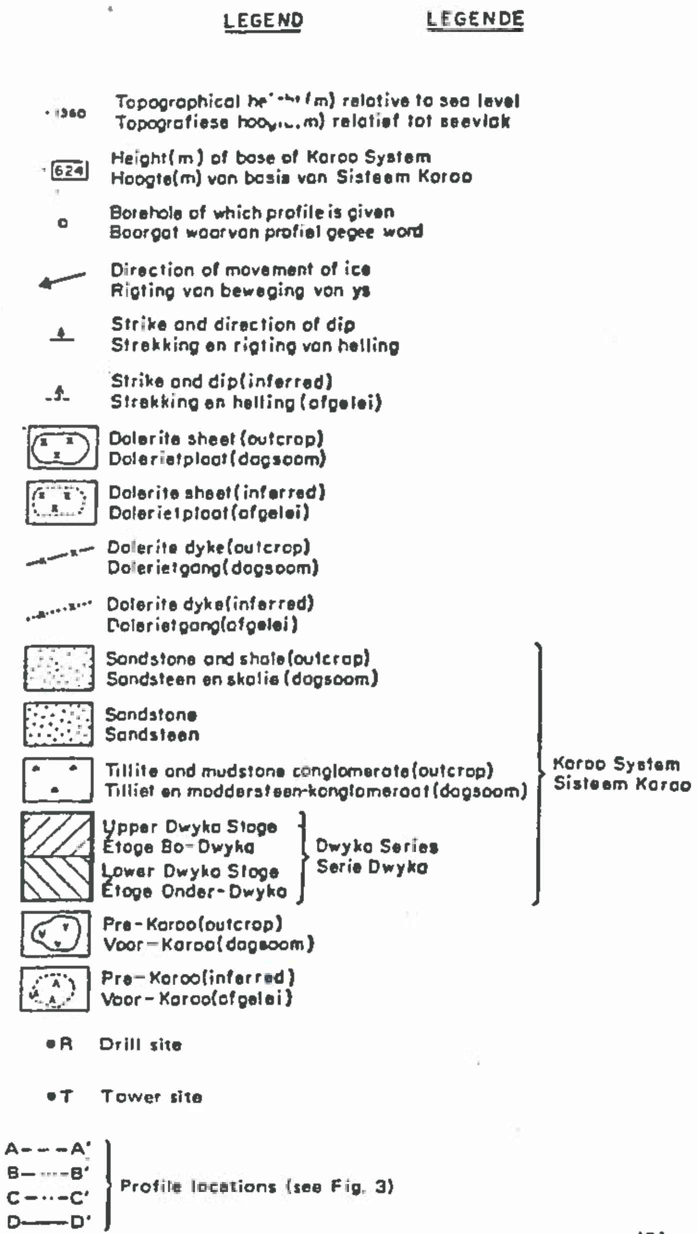

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Figure 1. Distribution of the Karoo system in the Kalahari, Cape Province.

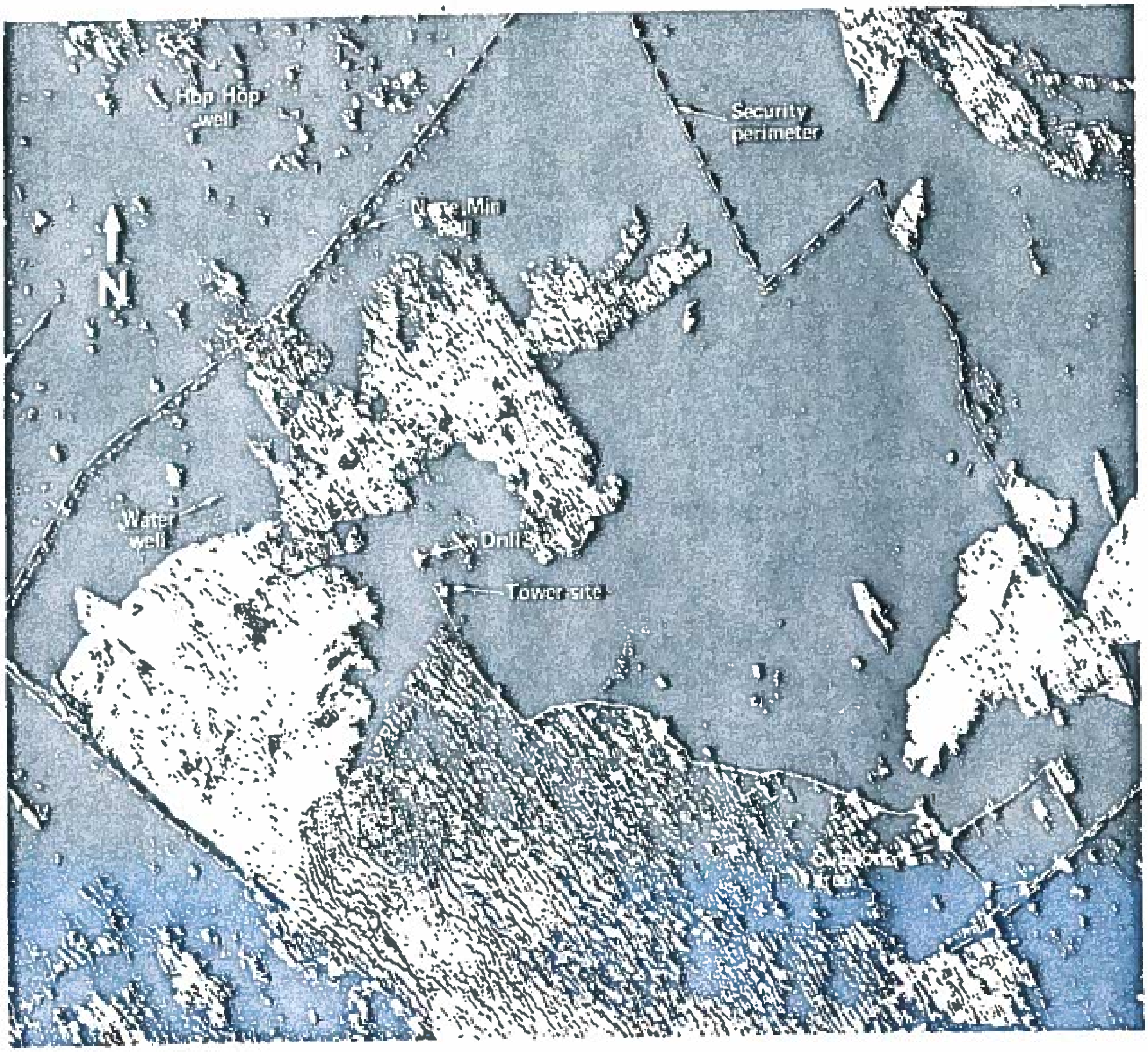

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Figure 2. The Kalahari Site, showing nearby wells.

nonexistent) at the tower and drill sites. The rock type immediately underlying the Kalahari sand in Smit's report is designated by a symbol normally denoting granite on South African geologic maps. We therefore assume it is granite or a similar hard, granitelike rock below the thick surface sands. This information substantiates the need for hardrock cutters for drill bits, as indicated in collateral reports.

Figure 3, four stratigraphic cross sections produced from data from boreholes shown on Fig. 1, show regional trends as follows:

1. The portion of the Kalahari we are interested in lies on the eastern slope of a troughlike depression of sedimentary facies, which deepens to the northwest from the Kalahari site and thins to the west and south of the site. The Karoo sediments thin drastically to the east, apparently pinching out just a few kilometres north and west of the drill site (Fig. 3). The Karoo beds, the aquifer system of the region, pinch out between the Niete Min well, which is located within the security perimeter of the Kalahari site and the drill site. This is corroborated on KH imagery by the fact that the nearest water well to the tower and drill sites is 4.5 km north-northwest of the drill site, probably at a point where the Karoo system beds are still present. Water was piped from this well to the artifact water reservoir near the tower site and to the reserve water reservoir at the drill site (Fig. 2).

2. The Kalahari beds comprising aeolian (windblown) sands thicken from west to east (Fig. 3, cross sections A-A' and D-D') but appear rather uniform in thickness from north to south (cross section B-B') through the drill site. At the drill site, the sand thickness appears to be from 60 m (Fig. 3, cross section C-C') to 85 m (cross section B-B'). From the casing seen at the drill site and subsequently installed in the hole and from analysis of the observed drill pipe and drilling-assembly string seen

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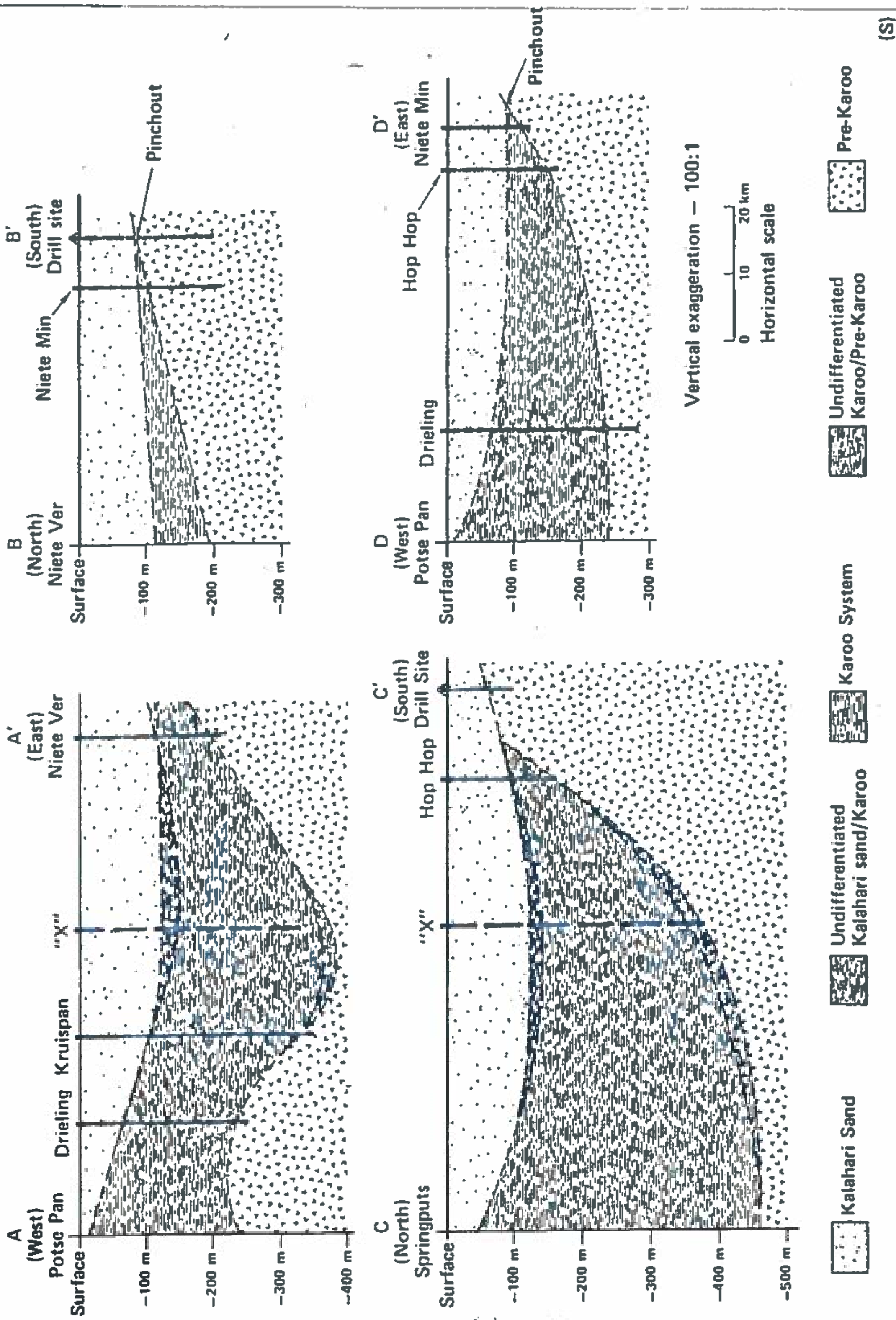

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Figure 3. Generalized stratigraphic cross sections A-A'--D-D'.

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by the rig, the depth to the base of the sand at the drill site is 75 m, well within the range indicated by the cross sections. Variations in sand thickness can be accounted for by the uneven uncomformable contact of the granitelike rock and the sands and by elevational variations in the surface sand dunes.

3. The hard granitelike rock approaches the surface to the east and south of the drill site, apparently lying directly below the Kalahari sand at the drill site. No sediments other than the Kalahari sand and the Karoo are present in this portion of the desert. It may be noted that, according to our profiles, the dashed line approximating the easternmost limit of the lower Dwyka stage of the Karoo system on Fig. 1 falls more than 10 km east of where our analysis indicates it should be.

The Fig. 3 profiles are generalized and do not show the surface topography. From profiles we have constructed but do not show here we can outline the regional trends of the surface as follows:

- From east to west the regional surface elevation rises about 8.5 m/km, rising from 865 m at Potsepan to 995 m at Niete Ver.
- From north to south the regional surface elevation remains fairly uniform, with only local variations.

Figure 4 shows what we believe is the most likely geology at the drill site.

Seismicity of the Kalahari Site

From seismicity maps of South Africa[4] (Fig. 5), the Kalahari site can be seen to be in an aseismic area, where the nearest earthquake between 1950 and 1975 was 90 km to the east. The site is several hundred kilometres away from any earthquake epicenters having a body wave magnitude (M_b) of 4.0 or more for the same time period. Therefore, any seismic signal emanating from the

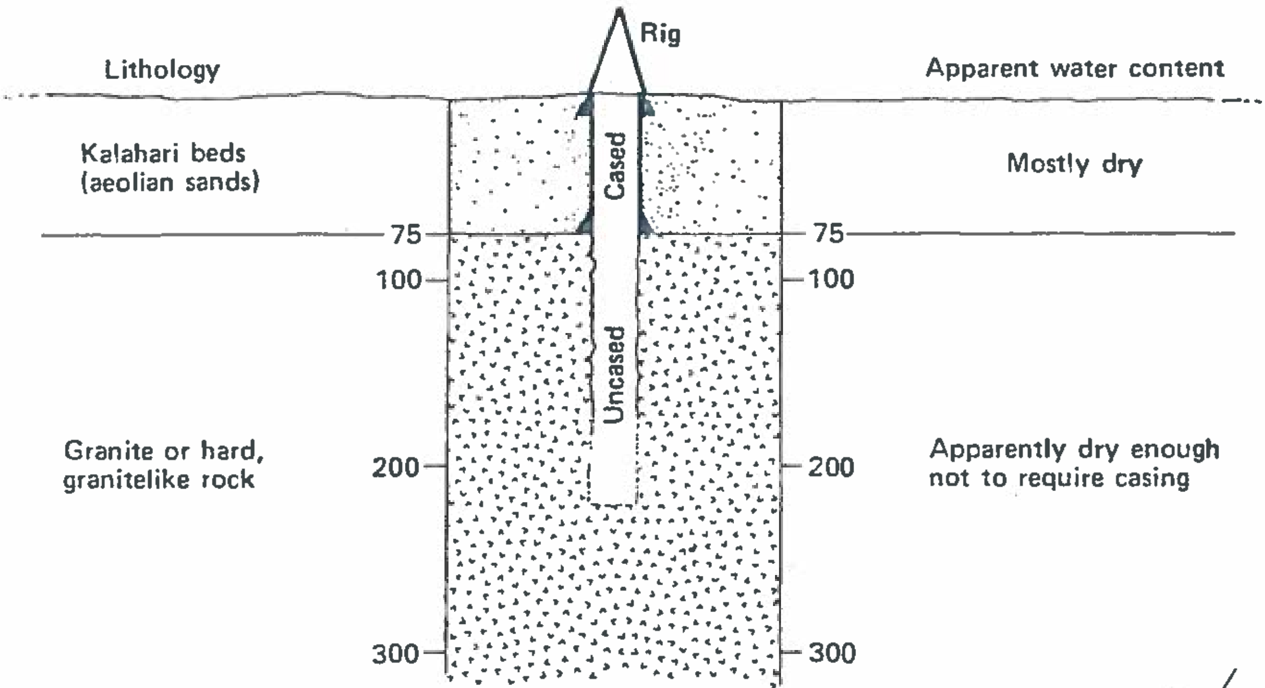

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Figure 4. Stratigraphic cross section at the drill site.

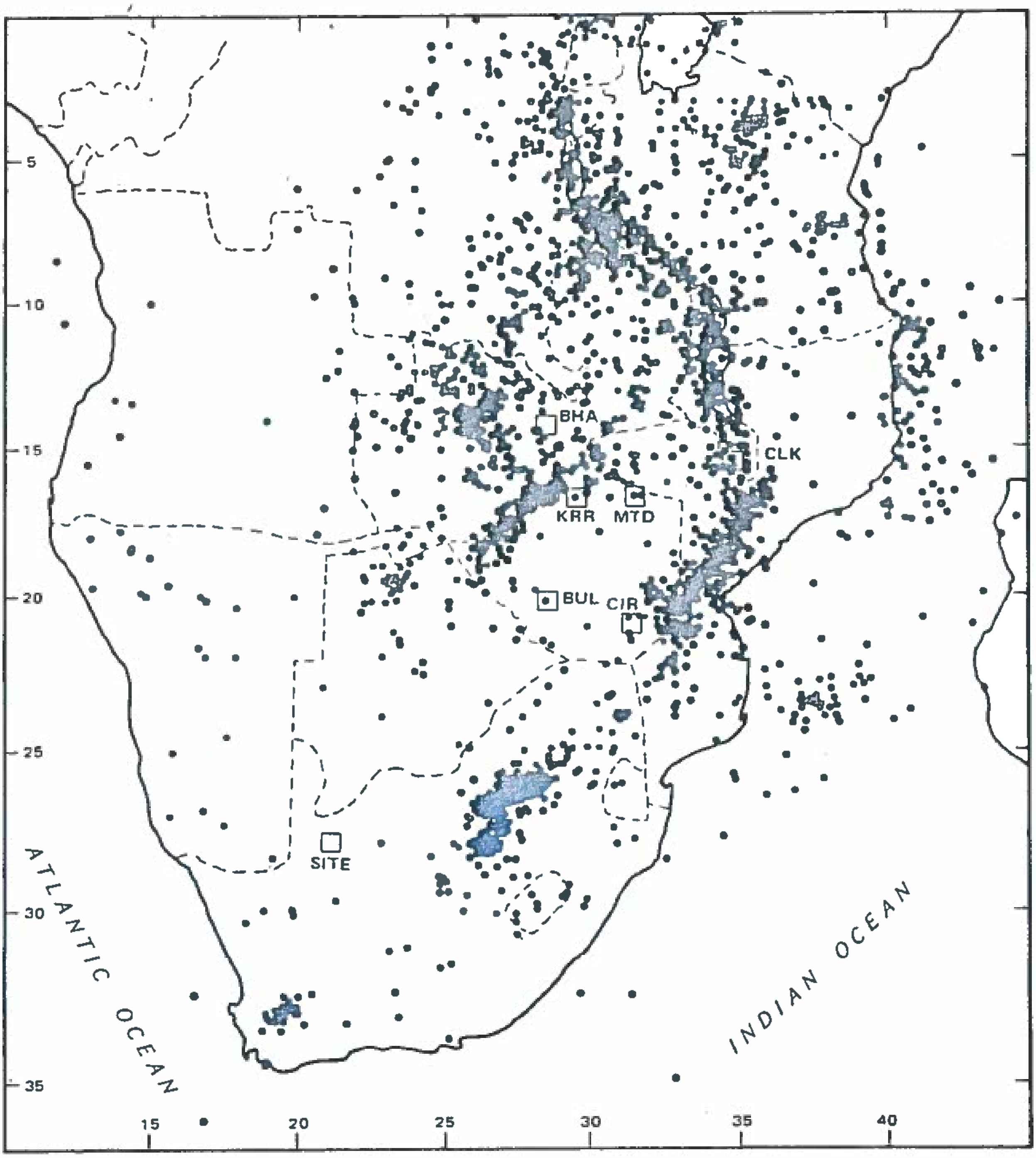

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Figure 5. The seismicity map of Africa for the period January 1950-May 1975. Seismograph stations used by the Rhodesian Meteorological Services are shown.

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general location of the Kalahari site should be looked at as a probable explosion.

Ground Water

From the procedures used in the drilling and casing operations there is no evidence of any saturated rock being encountered. Though we are reasonably sure the surface sands are dry,[1] the water content of the hard, granitelike rock is not clear. Because of the apparent lack of casing used in the hard, granitelike rock portion of the drill hole (see Drilling Rates and Procedures) it is unlikely that any saturated rock was encountered. If this rock were truly competent granite with few fractures, one normally would not expect to encounter the water table within it.

Chronology of Activities at the Drill Site, July-December 1977

Site Layout

The drill site when first imaged on 4 July 1977 comprised the following:

a. A Wirth (German-manufacture) trailer-mounted A-frame drill rig, either L-10 or L-15,[5] having a height of 19.7 m and a nearby support shed.

b. A drilling-fluid supply system comprising four pits (numbers referenced in Fig. 6):

No. 1. Mud pit into which the shale shaker discharges.

No. 2. Small possible mud mixing pit.

No. 3. Settling pit containing a baffle. No connecting line to the rig is visible.

No. 4. Reserve water supply pit connected by line to Pit No. 3.

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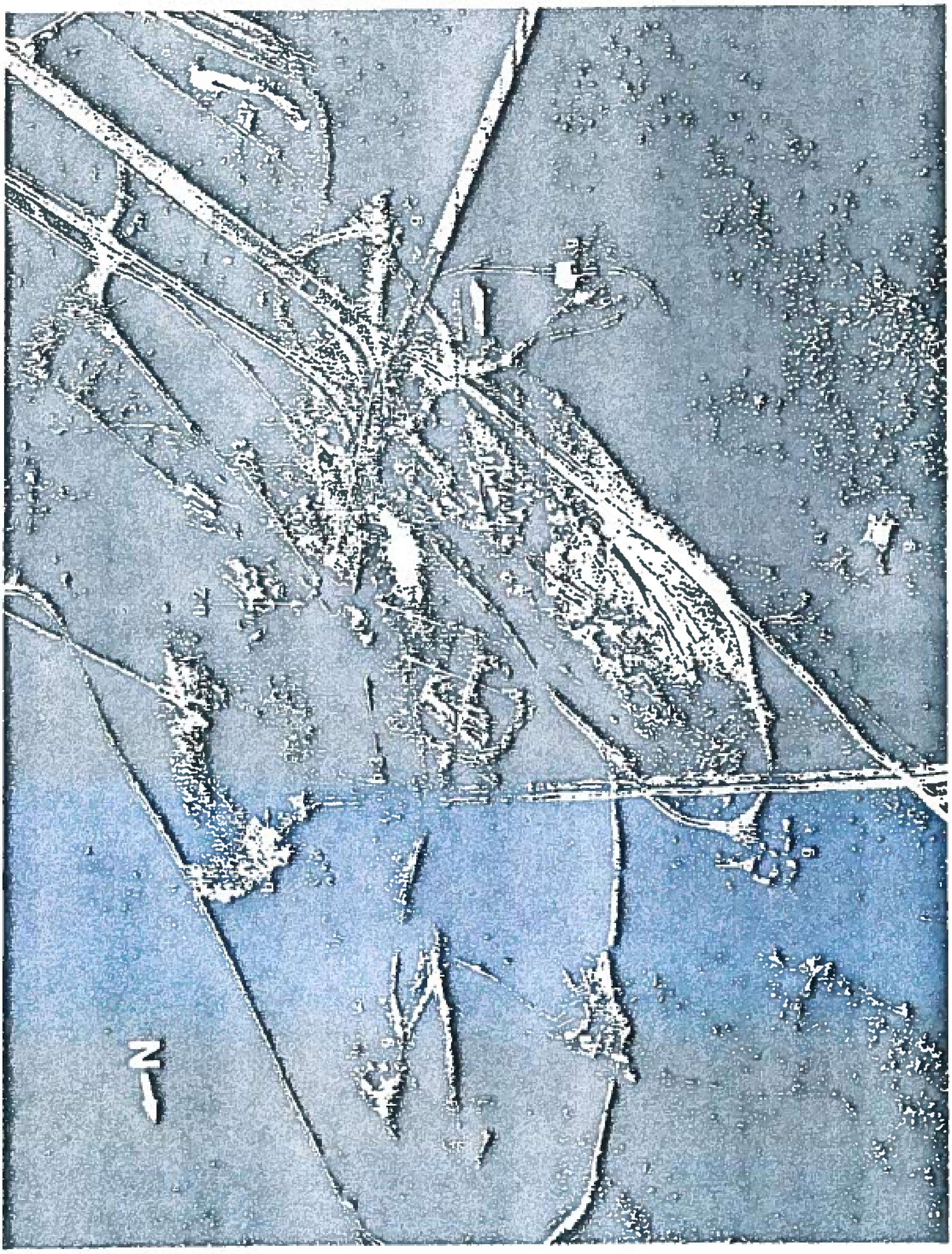

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Figure 6. The drill site, 12 Aug. 1977.

c. A probable shale shaker to receive the drilling mud on its return to the surface and to screen out coarser cuttings.

d. Two turbine generators with four fuel storage tanks.

e. An open drilling-equipment yard.

f. A metal gable-roofed shed, possibly for equipment storage.

g. Six locations of concrete pads, most of which have small sheds, both open and closed. Their exact purpose is unidentified, but they apparently support the drilling operation because they were removed after drilling stopped.

h. An open-canopied structure that apparently has camouflage-type garnishment on top. The garnishment and/or the materials underneath frequently change in outline. This may be simply a location for open storage of "Jerry" gas cans or an attempt to camouflage such things as drill pipe that could be counted to determine the hole depth. If it is for drill-pipe concealment, the pipe would have to come in short sections. It seems unlikely that drill pipe would have been stored here due to the difficulty in handling and moving it even in short sections.

i. Miscellaneous support trailers and tents.

Drilling Method

The Kalahari drilling operation appears to utilize direct circulation (i.e., downward flow of drilling fluid through the drill pipe and upward in the annulus around the drill pipe (Fig. 7). The fluid or "mud" is discharged at the surface over a probable shale shaker into a series of three earthen "mud" or settling pits. The drilling technique observed is less sophisti-

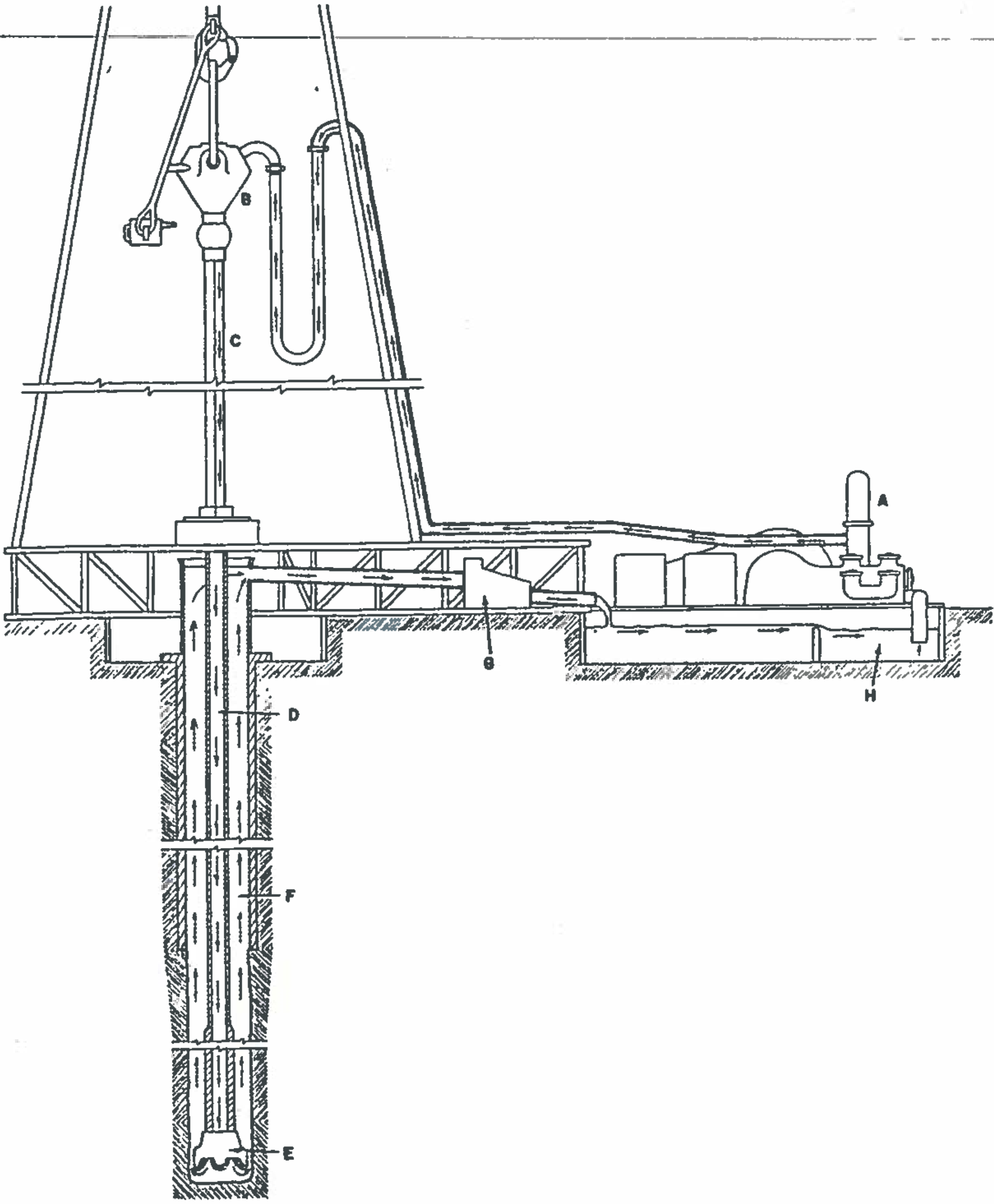

Figure 7. Circulation method believed to have been used at the Kalahari drill site. Arrows show path of drilling fluid: from slush pumps (A) to swivel (B) down through kelly (C) through the drill pipe (D) to bit (E). Fluid washes cuttings from hole bottom, carrying them to surface through annulus (F), through shale shaker (G), to mud pit No. 1 (H), on to pit No. 3 (not shown), from which entire cycle begins again.

cated than those currently in use at NTS, where concentric dual drill strings are presently used with fluid circulation down the inner string and air-assisted circulation return up the annulus between the inner and outer drill strings.

Reconstructed History of the Drill Site

Figure 8 is a chronology of activities at the drill site from 4 July, when it was first seen, through 26 December, when the rig had been removed and other equipment was being removed. Our reconstructed history shows the various activities we believe to have taken place at the drill site during that period. The gaps between activities, notably between completion of drilling a 48- or 52-in.* hole and the beginning of 1-m-diam casing installation and between the 1-m casing installation and the resumption of drilling, suggest that there was no high priority in completion of this hole. The crews could even have been given time off between the casing operation and resumption of drilling.

Drilling Rates and Procedures

An estimate of drilling rates must take into consideration the working depth, hole size, and lithology. Typical large-diameter hole drilling operations are done in stages:

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*Normal dimensions such as hole bit sizes that are standard throughout the world are given in inches; all other dimensions are given in SI units. Hole sizes have been estimated based on what would be required to accommodate the mensurated 1-m-diam casing.

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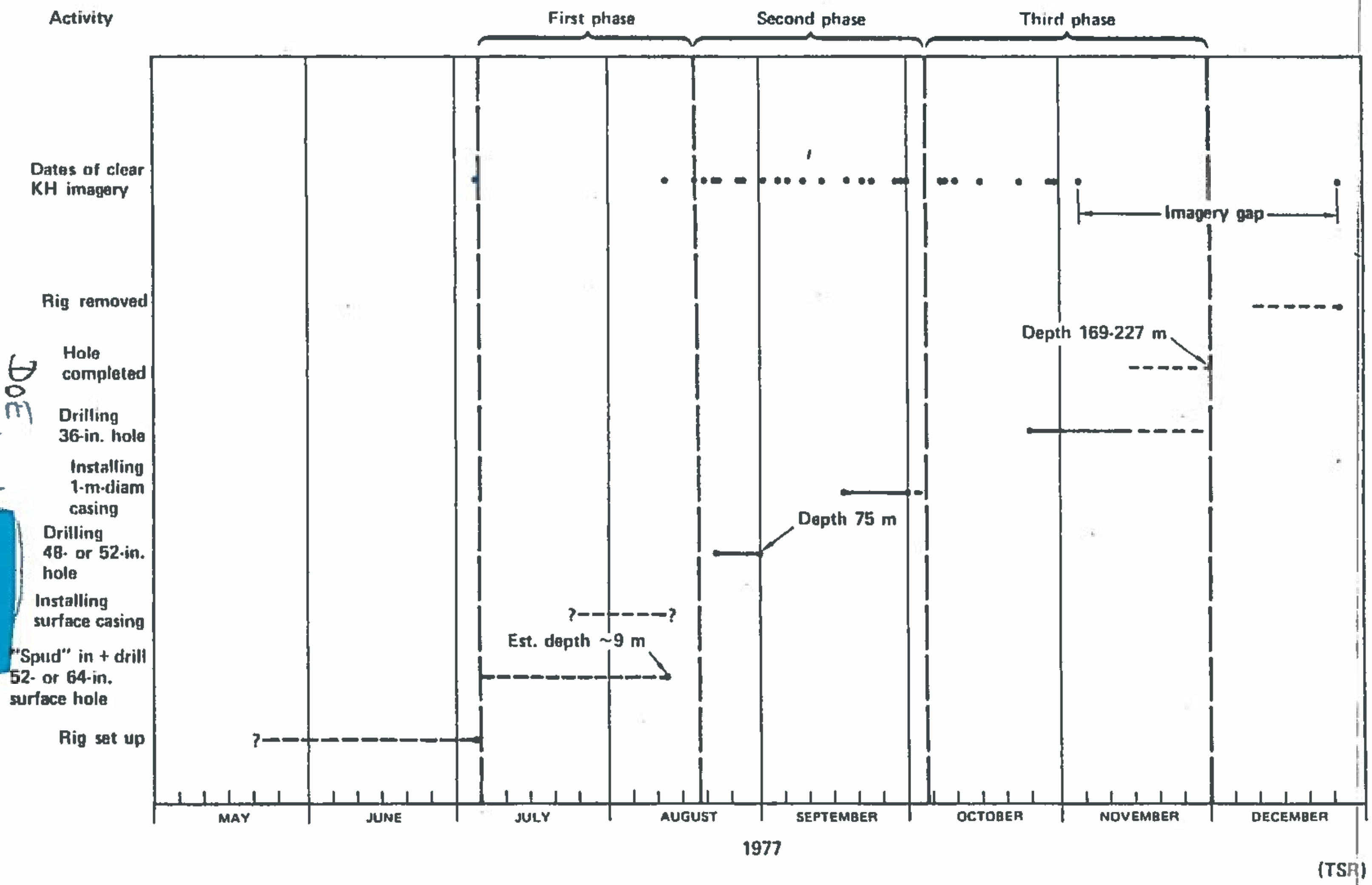

Figure 8. Reconstructed history of the drill site.

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1. The rig "spuds" in, drilling a large-diameter hole to a shallow depth. This hole is normally cased with surface casing, and the annulus between the hole and casing is usually cemented. This procedure minimizes the hazard of having the hole wash out or slough out from the weight of the drill rig.
2. Cleanout of the hole and continued drilling with a smaller-diameter bit to fit inside the casing, in this case to the bottom of the Kalahari sand, and installation of 1-m-diam casing.
3. Hole cleanout into the hard, granitelike rock below the sand to a desired depth. Casing of an estimated 26-in. diameter could have been installed, particularly if the granite were saturated and a dry hole were desired. (Few nuclear devices are tolerant of submergence under any significant head of fluid, whether it be water or mud. Because of lack of imagery during this critical third phase of drilling, we cannot determine if the hole was pumped down or dewatered.) We believe that casing is unlikely due to lack of evidence of casing being delivered to the site. For the first or second emplacement of a nuclear device, the constraints of a hole diameter smaller than 26 in. seem excessive.

The drilling rates and procedures in the Kalahari sand and the hard, granitelike rock will be discussed separately.

Sand Drilling Rate and Procedures - A hole 52-in. or more in diameter (probably 64 in.) was started and drilled to a depth of about 9 m sometime between 4 July and 12 August 1977. Surface or conductor casing was probably installed. Based on the drilling rate seen later in the site history, we estimate this early drilling time was about 2 days, using 4-5 m/day as an average penetration rate.

The evidence for this first phase consists of mudpit No. 1 having been cleaned out at least once by 12 August 1977. On 4 July 1977 the pit was clean in outline, apparently unused, and certainly never cleaned out. No surface casing was visible on 4 July or 12 August imagery. (A 5-m-long cylinder large enough to be surface casing appeared in the storage yard at the drill site between 18 and 21 September 1977.)

The second phase of drilling, drilling to the bottom of the sand and possibly about a metre into the hard, granitelike rock, took place from about 22 August through 1 September 1977. (The new drilling assembly--consisting of several pieces of 9-5/8- or 13-3/8-in. drill pipe, drill collars, weights, and bit--was present on the ground on 20 August but gone on 22 August.) The hole was deepened to 75 m during this time. Because the hole was smaller in diameter (estimated to be 52 or 48 in.*), a drilling rate of about 5.5 to 6 m/day was achieved during this 11- to 12-day period. In sand this rate still is not good, and the slow rate suggests crew inexperience. The hole was apparently fairly stable because the installation of casing did not begin until about 17 September 1977. This time gap between completing the 48- or 52-in. hole and when the installation of casing was started is most unusual. Casing installation is normally started as soon as possible to minimize the danger of the hole caving in. Even holes in more competent rock tend to slough or deteriorate with time. Thirty sections of casing totaling 75 m in length were installed between 14-17 September and 1 October. Figure 9 shows the apparent rate of installation, with annotations speculating on what happened during casing installation.

No evidence of cementing the casing was ever seen, although cementing could have been carried out during a one-week gap in imagery (30 September-7 October 1977). An explanation for this

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*48 in. if surface casing of 52 in. diam were used.

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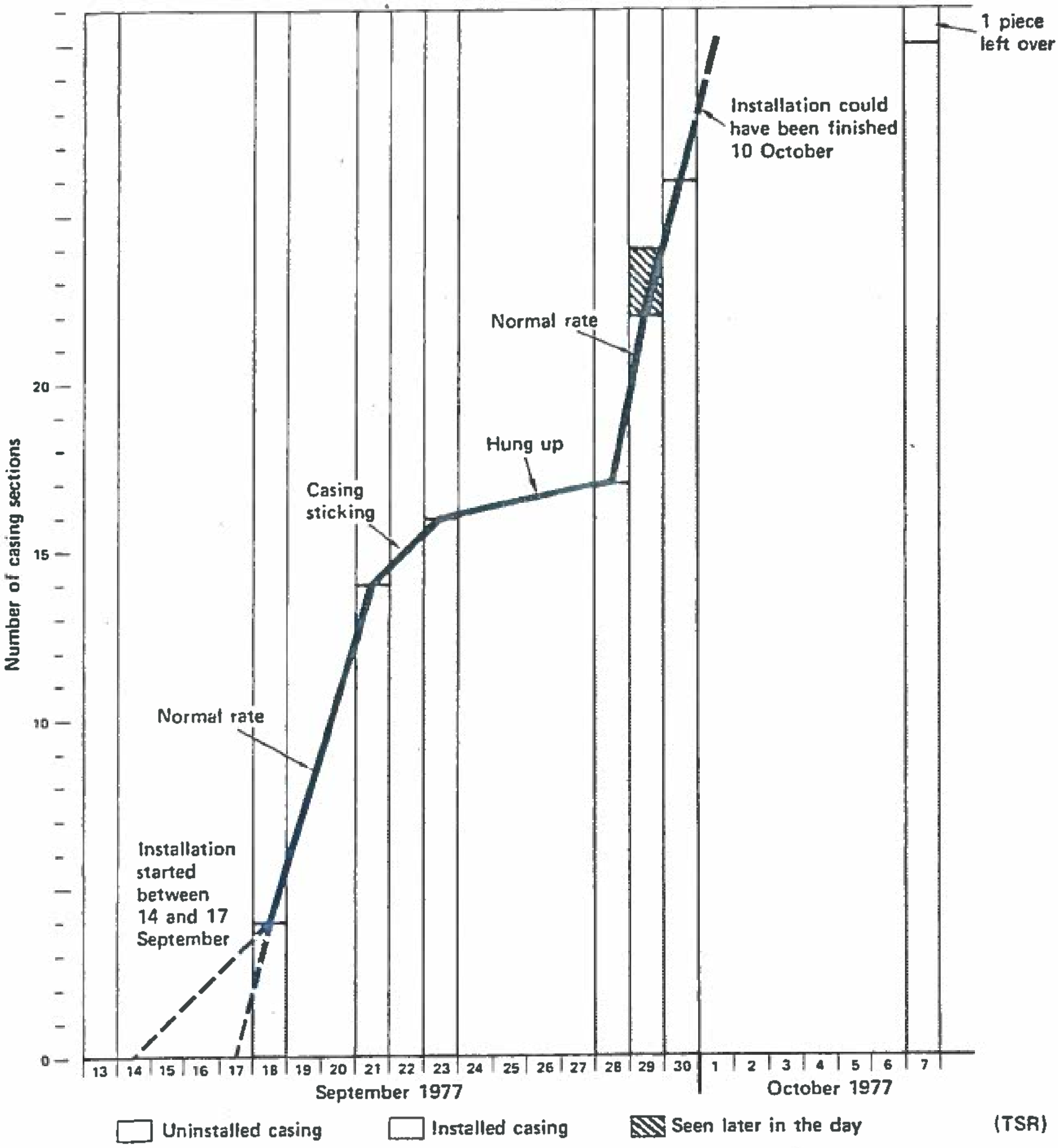

Figure 9. History of drill site casing installation.

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might be, that the casing was run open-ended (at the bottom) a metre or so into the hard granitelike rock and "tacked" by pouring in cement, completely filling the bottom of the hole for a few metres. Then the remainder of the hole outside the casing was either filled with sand or gravel or left open. The cement inside the hole was drilled out when drilling started again.

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[redacted] This method of cementing also reduces costs.

For this "tacking" cementing technique to be used, the load capacity of the rig must be enough to suspend 75 m of 1-m-diam casing weighing about 29 000 kg (32 tons). This load is far short of the hook capacity of 90 000 kg (100 tons) for the small L-10 rig.[6]

Further corroborating the open-end tacked-casing premise is the apparent difficulty or delay in installing the 1-m casing to the bottom of the drilled hole. If the casing had been "floated" in, the bottom of the casing would have been closed with a hemispherical head, allowing additional fluid to have been pumped into the casing to give it added weight and facilitate getting it past any tight spot to the bottom.

Hard-Rock Drilling Rates and Procedures - The third phase of drilling to a planned depth in the hard, granitelike rock began about 25 October 1977 and was completed by 1 December 1977. The Keyhole imagery for this time period is unfortunately scarce (*there was no imagery between 5 November and 1 December*), and therefore we do not know with any accuracy the number of days used for drilling.

We can calculate the hole depth two ways: from the usage of the bit cutters known from collateral data[5] and from the number of days drilling was in progress.

It is known that six sets of bit cutters were ordered and delivered. One set was returned unused.[5] Therefore it is likely that somewhat more than four but no more than five sets of cutters were used to drill in the hard granitelike rock. At the rate of 22.9 to 30.5 m/set (minimum and maximum cutting capability per set in hard rock)[5] the depth drilled in the hard, granite-like rock ranges between 94 and 152 m. Total hole depth would range between 169 and 227 m.

As stated above, the number of days spent drilling in the third phase of drilling is not known. We estimate it to range between 20 days to a definite maximum of 35 days. Given the daily minimum and maximum capabilities of the cutters in hard rock (3.85 to 7.7 m),[5] if the rig were operational 70% of the time* the estimated depth in the granitelike rock ranges from 77 to 270 m. Total hole depth would range from 190 to 345 m.

Additional imagery during the 5 November 1977 through 26 December 1977 period might have allowed us to determine:

1. Whether casing or a liner was installed in the hard rock.
2. The amount of drill pipe and a more accurate calculation of hole depth.
3. Whether or not the hole was dewatered. If a hole is not to be used shortly, it will "keep" better with fluid in it.
4. Whether anything was put in the hole before it was covered.
5. Whether the hole was stemmed or not.
6. The number of days of drilling.

---

*The amount of actual time the drill bit was on bottom in a drilling mode was probably considerably less. At the Nevada Test Site drill bits are working on bottom about 35-45% of the time.

Best Estimate of Total Hole Depth

We believe the minimum-maximum depth of hole estimates based on cutters alone is better than the estimates calculated from the number of days drilling due to the large range in the number of days. The best overall estimate of the depth in the hard, granitelike rock is 94 to 152 m, and the best total-hole-depth estimate is 169 to 227 m. Based on a drilling rate in granite of between 3.85 and 5.0 m/day (we do not believe a faster drilling rate was achieved since the average daily rate in the sand was only 5.5-6 m) the time spent drilling in granite was 19 to 39 days. Drilling should have been completed by the end of the first week in December. The cancellation of the order for additional cutters on 1 December 1977 indicates that drilling was completed on or about that date.

Nuclear Yields Possible at the Drill Site

Given a depth range of 169 to 227 m, what nuclear yields might one expect if the drill hole were to be used for a nuclear test? [redacted]

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Table 1. [redacted]

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ENERGY PARTITION IN HE DETONATIONS

The energy from an HE detonation divides itself among the following:

- Internal and kinetic energy of any associated metal parts.
- Internal and kinetic energy of the detonation products.
- Internal and kinetic energy of the surrounding air.

For a typical 90-kg (200-lb) detonation the partitioning process is complete after 100 μs. By this time the radius of the detonation products is only three or four times the original radius of the HE.

We have done calculations on four spherical implosion test devices that we fired last summer. The four devices, which were described in detail in our July-September 1977 Quarterly Report, were:

- K2: [redacted]
- K3:
- K4:
- K5:

We have calculated and plotted in Fig. 10 the kinetic energy per unit volume of the pit material for the K2 and K3 tests. The time of this calculation is 75 μs after detonation; by this time the pit has undergone compression and has started to expand. In Fig. 10 (and Figs. 11-13 as well), though we give the energy at 75 μs after detonation, for clarity of presentation we describe the location of the pit material in terms of its position at zero time. A similar plot for the K4 and K5 tests is shown in Fig. 11. Note that kinetic energy is proportional to the square of the velocity. At the time of these calculations (75 μs) all pit material is moving outward.

[redacted]

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Figure 10. Kinetic energy per unit volume of pit material for devices K2 and K3 calculated for 75 μs after detonation, plotted as a function of the zero-time position of the pit material.

[redacted]

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Figure 11. Kinetic energy per unit volume of pit material for devices K4 and K5, calculated for 75 μs after detonation, plotted as a function of the zero-time position of the pit material.

Plotted in Fig. 12 is the internal energy per unit volume of the pit material for the K2 and K3 tests. By the time of these calculations, the pit material has attained its ballistic conditions. [redacted] Plotted in Fig. 13 is the internal energy per unit volume of the pit material for the K4 and K5 tests. [redacted]

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We now address transfer of energy into the pit material as a function of time. [redacted]

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Figure 12. Internal energy per unit volume of pit material for devices K2 and K3, calculated for 75 μs after detonation, plotted as a function of the zero-time position of the pit material.

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Figure 13. Internal energy per unit volume of pit material for devices K4 and K5, calculated for 75 μs after detonation, plotted as a function of the zero-time position of the pit material.

[redacted]

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Figure 14. Fraction of energy in the pit material as a function of time.

Therefore, the calculations of the energy transfer into the air were made for an implosion device with no pit material. We think it entirely proper to simply subtract the energy carried away by the pit from the total energy of the HE before the transfer to air begins.

In Fig. 15 we show as a function of time the total partition of energy of an HE detonation. The calculation was made specifically on the K5 test; however, this will serve as a close approximation for all the events that we have considered.

At late times it is clear that most of the energy has been transferred to heating and movement of the surrounding air. Roughly 10% of the total energy has gone into the pit material and about 10% remains as internal energy of the HE products. This latter component is the source of energy output in the optical spectrum. Note that most of the energy that is imparted at early times into motion of the HE products has been transferred to the air. It is this transfer that defines fireball size; the maximum occurs when hot HE products have expanded into pressure equilibrium with the surrounding air. It is important to emphasize that in these calculations we have not considered "afterburn" phenomena, in which the turbulent mixing of air with unburned HE products can contribute considerable additional late-time energy. This phenomenon is difficult to calculate, varies with different HE compositions, and presently frustrates attempts at rigorous calculation of fireball-growth dynamics.

[redacted]

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Figure 15. Total partition of energy as a function of time for event K5. This result will closely approximate the situation on the other events we have examined.

EVALUATION OF HE CHARGE SIZES FROM SEISMIC AMPLITUDES

Introduction

We have discussed in an earlier report[8] the possibility that an HE-yield identification algorithm could be established based on seismic data. [redacted] We noted that follow-on experiments were planned. DOE b(1)

In this article we describe those experiments and present the first portion of our analyses of the experimental results. The work we will describe involved 46 special HE detonations directed specifically toward the seismology question. They were, for the most part, firings of simple configurations of bulk HE. The seismic measurements were made by seismologists associated with the LLL Earth Sciences Division. The present analysis should be viewed as very preliminary, and more detailed analyses will be contained in the final report to be written by our seismology team. The present report is based on only the vertical components of the direct P-wave signal. A stronger signal, arriving at acoustic-signal transit times, is not discussed at all here; it is being examined by the seismologists and may in fact hold more promise than the other signal components as a means of arriving at an absolute calibration for an amplitude-vs-yield relationship.

We first present site details covering the locations of the various firings and the positions of the seismometers. Following that we discuss the specific types of experiments made and analyses to date considering:

- Height-of-burst dependence. How does the seismic amplitude vary with the height of burst? We cover the full range of heights expected in nuclear hydrodynamics testing.
- Geometric perturbation effects. How do seismic amplitudes vary with different device types and different device orientations? We consider some extreme examples.
- Yield dependence. How does the seismic amplitude vary with the explosive yield of a shot? We cover the full range of explosive yields expected in nuclear hydrodynamics testing. In this preliminary article we deal only with the question of relative rather than absolute yields.
- High-explosive-type dependence. How does the seismic amplitude vary with different HE compositions? We cover more than the full range of types of HE expected in nuclear hydrodynamic tests.
- Shot-site variation effects. How do seismic amplitudes vary for different shot sites?

Site Details

All the HE firings were at LLL's Site 300 HE test area (Fig. 16). Most of the firings were on a level area near Bldg. 802. The area was covered with about 150 to 300 mm of pea gravel for the firings, and this was smoothed after each firing. To evaluate local variations with geology, one set of shots was fired in a cross-shaped distribution with about 75-m arms centered on the normal firing point. One shot was fired at each of Bldgs. 801, 804, 845, and 851 to evaluate the effects of major changes of location.

For most of the shots three-component broadband Geo-Tech seismometers that measured ground velocity, with useful frequency

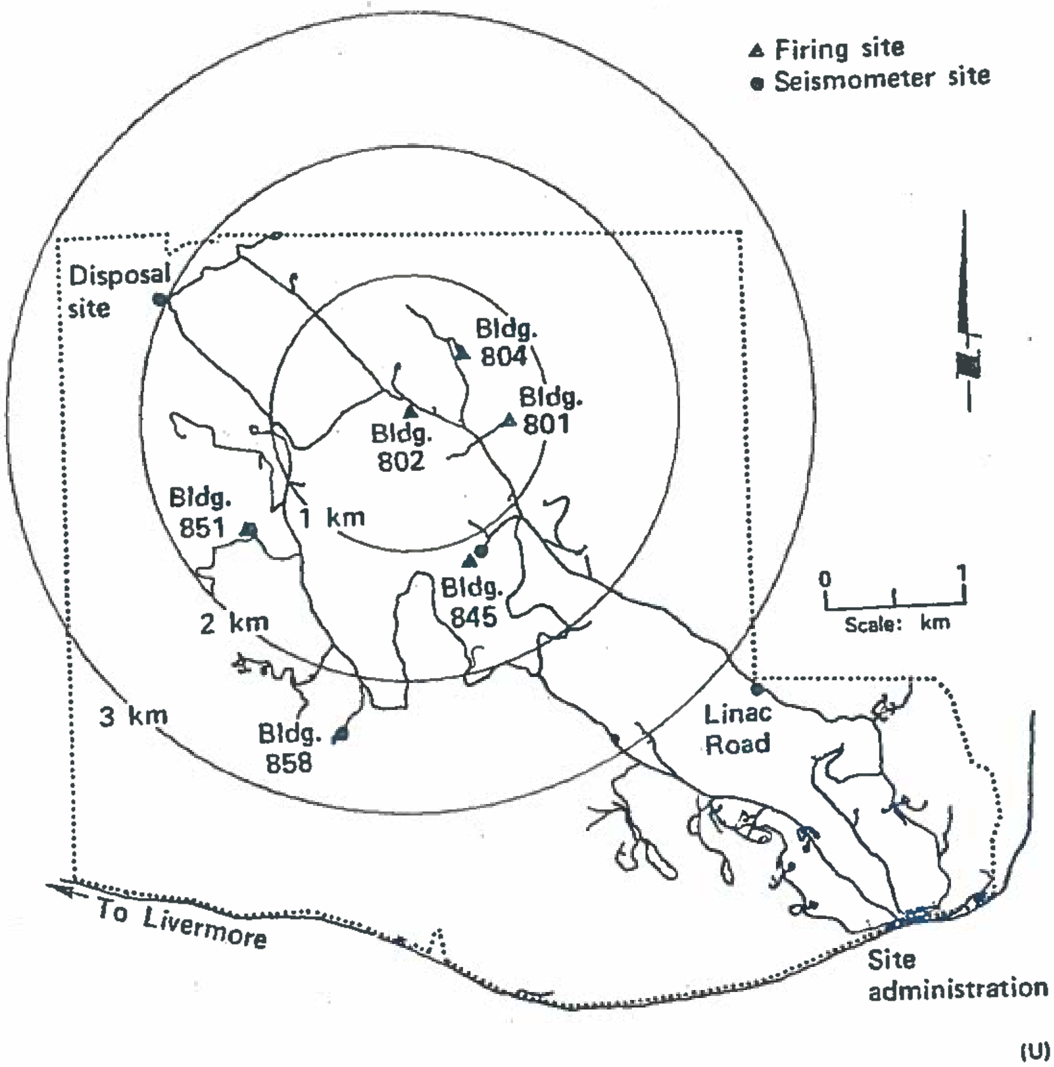

Figure 16. Seismometer emplacements at LLL's Site 300 HE test area.

response from esentially 1/6 to 60 Hz, were emplaced at Bldg. 845, Bldg. 858, and a Linac Road site as noted on Fig. 17. After the main shot series was completed the seismometer at Bldg. 858 was transferred to the position noted on Fig. 17 as the disposal site. This simulated field emplacement at an "uncalibrated site."

We show in Fig. 17 the position of a "long-range" seismic station fielded on several of the firings. The seismometer was a Hall Sears 10 (1 Hz) that measured vertical velocity only.

Height of Burst Dependence

If the seismic signal is strongly affected by height-of-burst variations typical of those expected in hydrotesting, seismic evaluation of Nth country HE testing would have little or no practical value. Plausibility arguments, as follows, suggested that height-of-burst effects would be minimal. Over a reasonable range of height values, from detonation on the pad to detonation 2 m above the pad, half the explosive energy will be directed downward with negligible attenuation expected. The region of seismic coupling will have a characteristic dimension about equal to the wavelength of interest λ, where λ is greater than c/ν, c being the velocity of sound in air and ν being a frequency characteristic of the seismometers. Details of the coupling mechanism need not be known precisely; the real velocity to use in our estimate cannot be less than c, so we obtain an estimated lower bound on λ. For $\nu = 10$ Hz, $\lambda \approx 35$ m. The solid angle subtended at the shot point by the intersection of the ground plane and a sphere of radius r centered at a height H above the ground is $2\pi(1 - H/r)$. We have $r = \lambda \approx 35$ m and $H \approx 2$ m, so the bracketed term is no smaller than about 0.95. Thus, in the worst-case situation (H = 2 m) we expect that about 94% of the energy that can be coupled to the ground will be coupled to the ground. We

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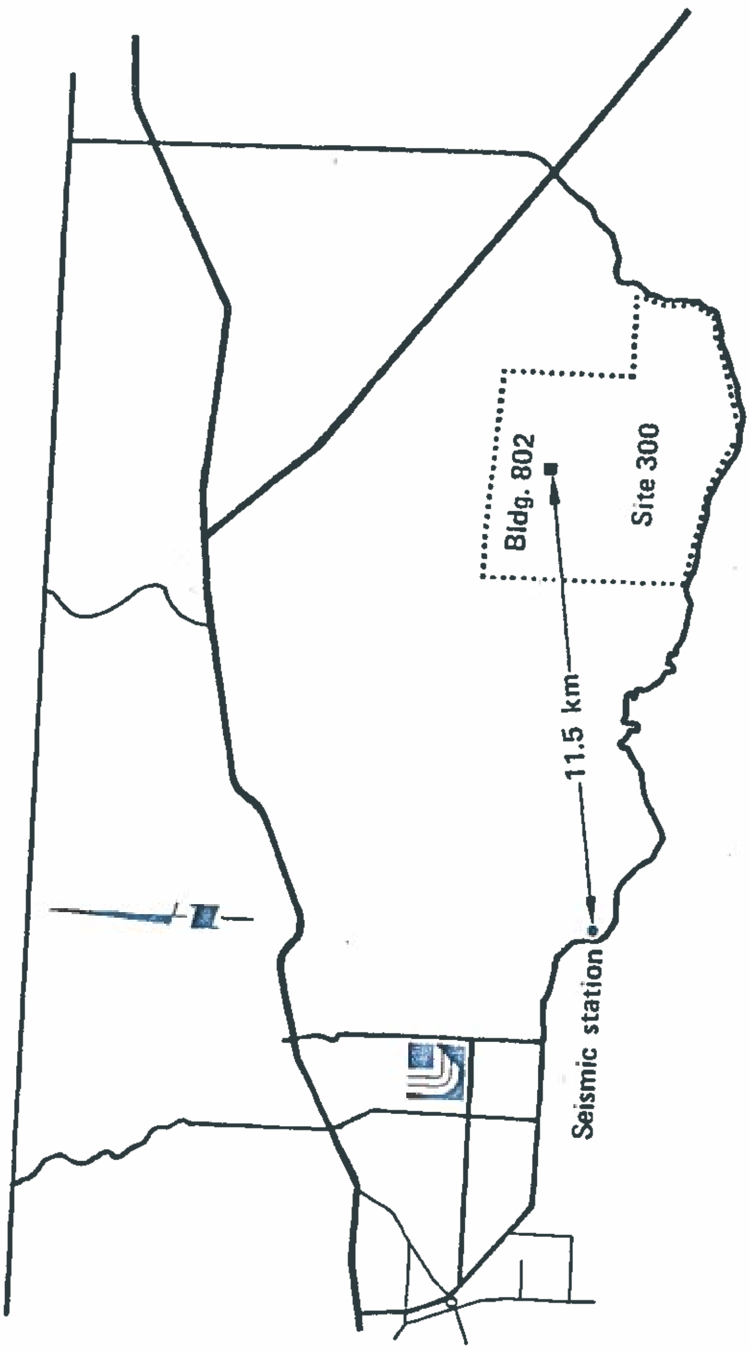

Figure 17. Position of the "long range" seismic station. The logo shows the location of the Lawrence Livermore Laboratory main facility. (U)

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thus expected, on this basis, that the seismic signal should be only weakly dependent on height of burst.

Several firings were devoted to experimental verification of our conclusion. A series of 23-kg (50-lb) charges of the explosive C-4 was fired at heights from 0 to 2 m above ground, and a similar series was run using 45-kg (100-lb) charges of LX-04-1. Table 2 lists the 23-kg series along with relevant firing details. Note that the temporal order of the shots was randomized to eliminate possible systematic-error effects. The seismometers were emplaced at Bldg. 845, Bldg. 858, and the Linac Road sites for these shots. The data were stored on magnetic tape for subsequent playback and analysis. We show amplitude results in Figs. 18-20. In these (and subsequent) figures the A-amplitude is the amplitude of the zero-to-peak initial vertical velocity (P-wave) and the B-amplitude is the peak-to-trough amplitude.

Consider, for example, the A-amplitude data portion of Fig. 18. We have plotted the values of the vertical velocity amplitudes recorded at the Bldg. 845 seismic station vs the base heights of the corresponding 23-kg (50-lb) Comp. C-4 HE charges. That there is no trend with HE base height value is obvious. The mean amplitude of the seven experiments was 49.6 units (the units are arbitrary--actually seismometer output in millivolts), with a standard deviation of 8.5 units. The two horizontal lines bracketing most of the data depict the ±1 standard deviation limits. The same type of information is shown for the B-amplitude data.

Figures 19 and 20 present the same type of data and analyses for the stations at Bldg. 848 and Linac Road, respectively. None of the results in any instance suggests that height of burst influences the seismic signal.

Pertinent details for the 45-kg KSA series are listed in Table 3. The A- and B-amplitudes obtained at the vertical motion

[text continues on page 51]

Table 2. Firing details of the 23-kg (50-lb) charges detonated in the evaluation of possible height-of-burst effects on seismic signals.

Shot designation and location[a]	HE	HOB,[b] m	Local date and approx. detonation time	Detonation time (GMT)
KSO-A 802FP	23 kg (50 lb) Comp. C-4	0.3	1/30/78 3:28 p.m.	30:3438:10.014
KSO-B 802FP	23 kg (50 lb) Comp. C-4	0.3	1/30/78 4:00 p.m.	31:0000:9.972
KSC-1 802FP	23 kg (50 lb) Comp. C-4	0	1/31/78 3:03 p.m.	31:2303:10.000
KSC-2 802FP	23 kg (50 lb) Comp. C-4	0.6	1/31/78 3:38 p.m.	31:2338:10.083
KSC-3 802FP	23 kg (50 lb) Comp. C-4	0.9	1/31/78 1:48 p.m.	31:2148:9.973
KSC-4 802FP	23 kg (50 lb) Comp. C-4	1.5	1/31/78 11:49 a.m.	31:1949:10.006
KSC-5 802FP	23 kg (50 lb) Comp. C-4	2.1	1/31/78 2:28 p.m.	31:2228:10.001

[a] We designate the leveled, grounded firing pad near Bldg. 802, where most of the shots were fired, as 802FP.

[b] HOB is the height of burst measured from the firing-pad surface to the base of the HE. Typically the center of gravity of the HE was 100 to 150 mm higher than the base.

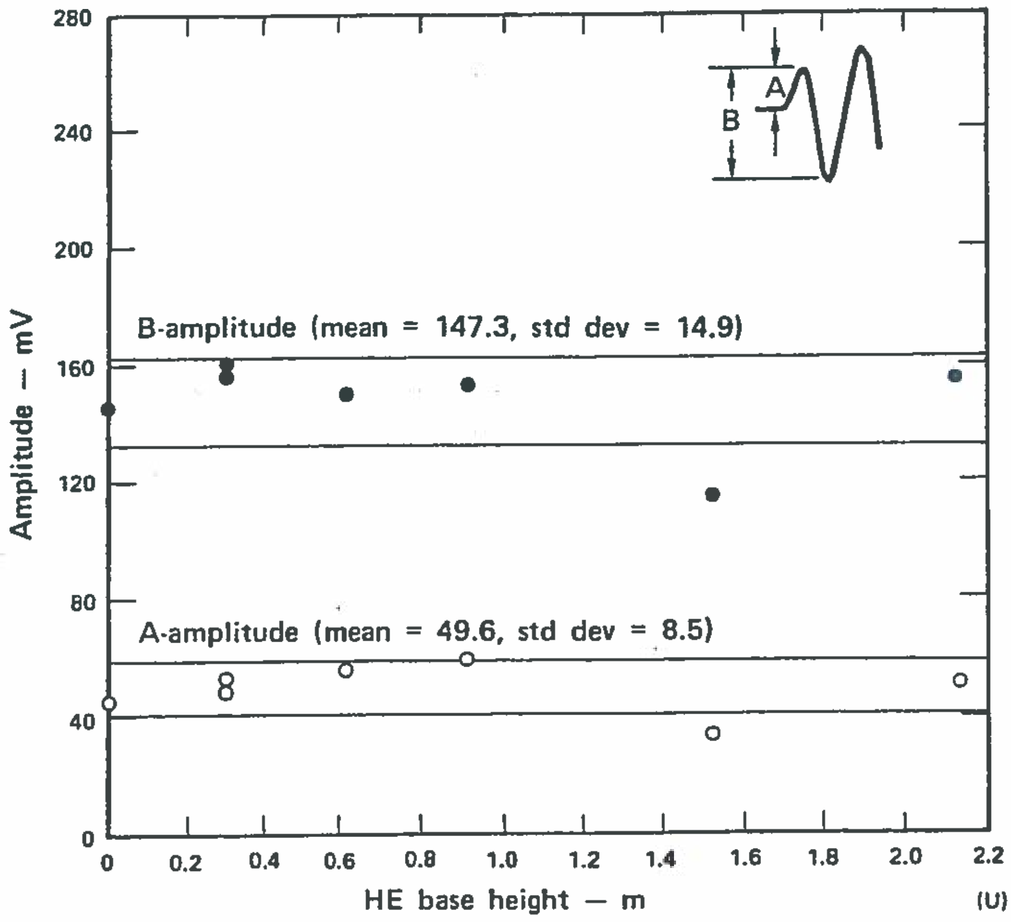

Figure 18. Amplitudes of the P-wave vertical velocity signals (see inset) recorded at the Bldg. 845 seismic station vs the base heights of the 23-kg Comp. C-4 charges detonated in the KS0 and KSC series of experiments. The horizontal lines are at ±1 std dev from the mean amplitude.

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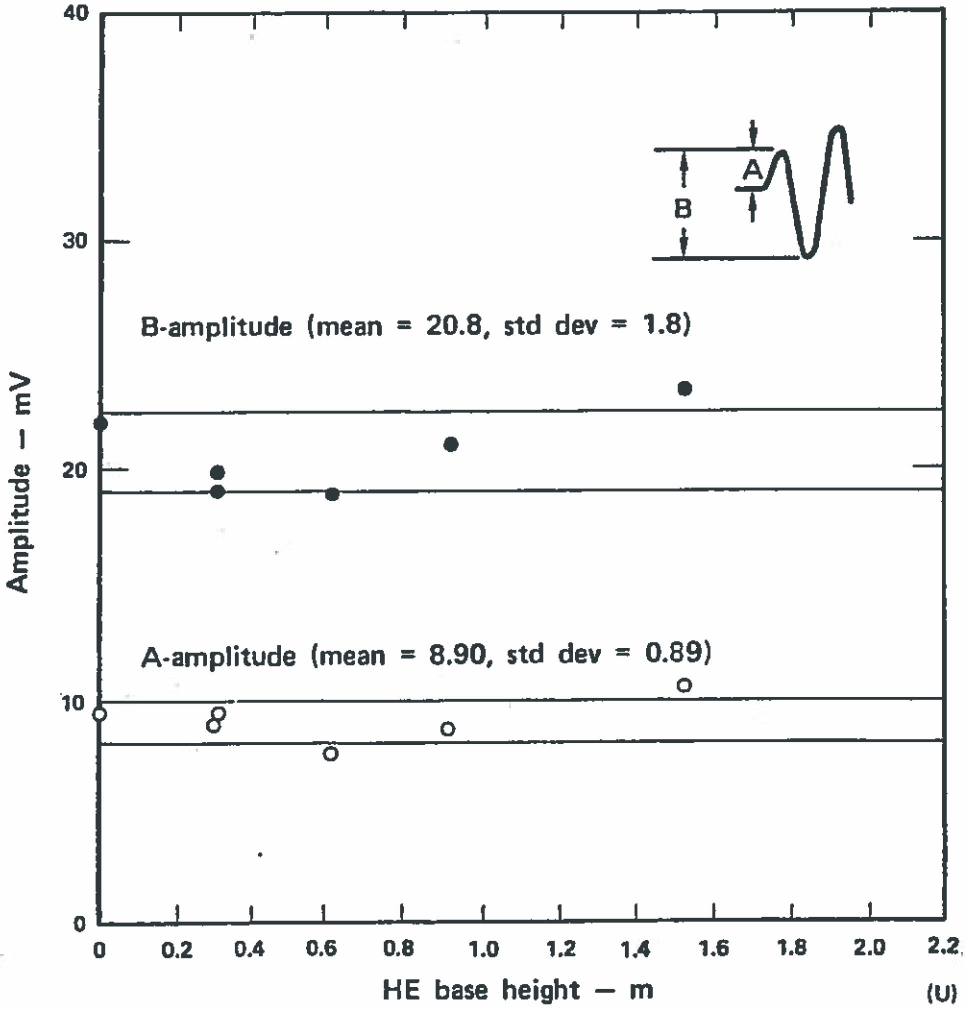

Figure 19. Amplitudes of the P-wave vertical velocity signals (see inset) recorded at the Bldg. 858 seismic station vs the base heights of the 23-kg Comp. C-4 charges detonated in the KS0 and KSC series of experiments. The horizontal lines are at ±1 std dev from the mean amplitude.

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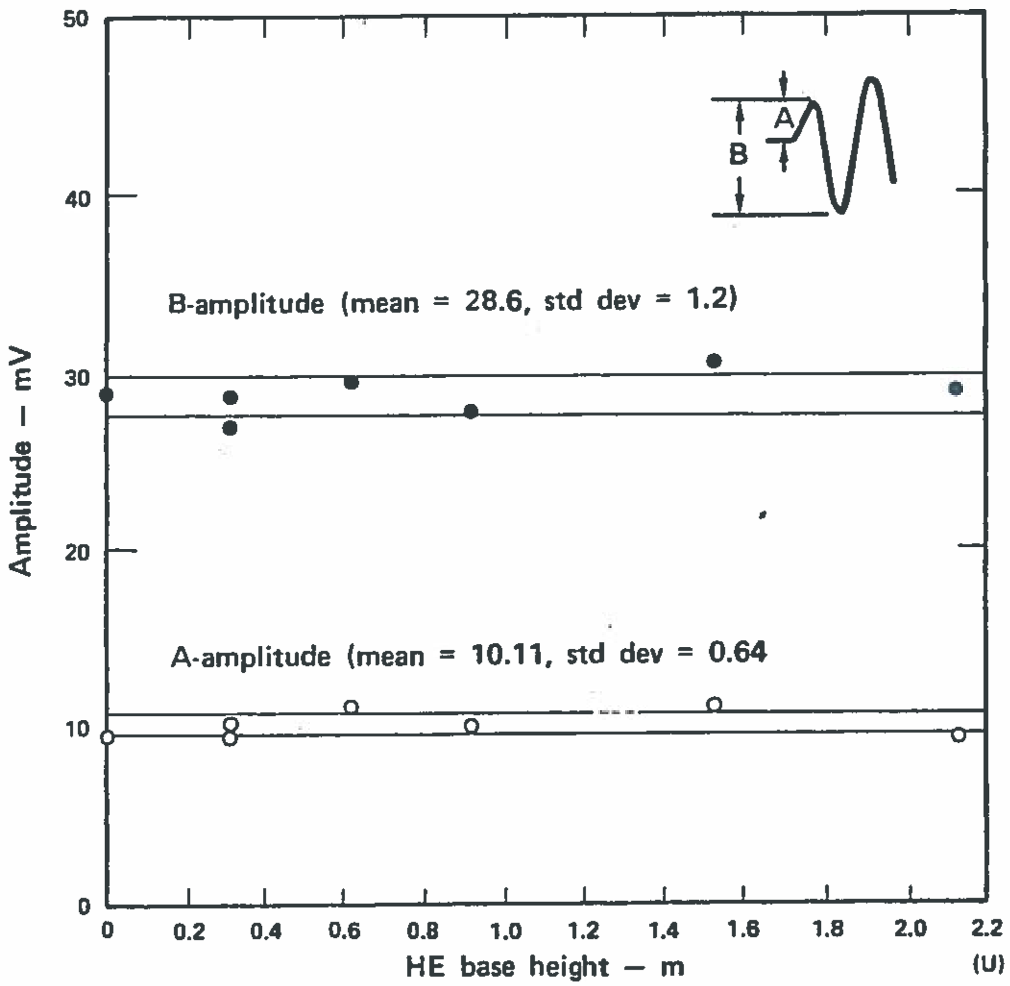

Figure 20. Amplitudes of the P-wave vertical velocity signals (see inset) recorded at the Linac Road seismic station vs the base heights of the 23-kg Comp. C-4 charges detonated in the KSO and KSC series of experiments. The horizontal lines are at ±1 std dev from the mean amplitude.

seismometers at Bldg. 845, Bldg. 858, and the Linac Road stations are shown in Figs. 21, 22, and 23, respectively. These data again support the conclusion that there is no correlation between height of burst and seismic signal amplitude.

Table 3. Firing details of the 45-kg (100-lb) charges detonated in the evaluation of possible height-of-burst effects on seismic signals.

Shot designation and location[a]	HE and C-4 equivalent	HOB,[b] m	Local date and approx. detonation time	Detonation time (GMT)
KSA-1 802FP	45 kg (100 lb) LX-04-1 (42 kg/93 lb C-4)	0	2/2/78 10:34 a.m.	33:1833:59.983
KSA-2 802FP	45 kg (100 lb) LX-04-1 (42 kg/93 lb C-4)	0.6	2/2/78 11:08 a.m.	33:1908:00.082
KSA-3 802 FP	45 kg (100 lb) LX-04-1 (42 kg/93 lb C-4)	0.9	2/2/78 9:58 a.m.	33:1757:59.09
KSA-4 802FP	45 kg (100 lb) LX-04-1 (42 kg/83 lb C-4)	1.5	2/2/78 11:40 a.m.	33:1939:59.953
KSA-5 802FP	45 kg (100 lb) LX-04-1 (42 kg/93 lb C-4)	2.1	1/31/78 10:45 a.m.	31:1844:09.938

[a] We designate the leveled, graded firing pad near Bldg. 802, where most of the shots were fired, as 802FP.

[b] HOB is the height of burst from the pad surface to the base of the HE.

In Figs. 24 and 25 we show the firing geometries of the two extremes of the KSA series. For KSA-1 the charge was placed directly (except for a thin layer of padding) on the firing pad. At the other extreme, for KSA-5 the charge was supported by a 2.1-m-high firing table. The HE charges, however, were identical. The firing geometries of the KSC series were the same as for the KSA series.

Note that four shots from the KSD series are included in Figs. 21-23. The KSD series will be discussed in more detail in

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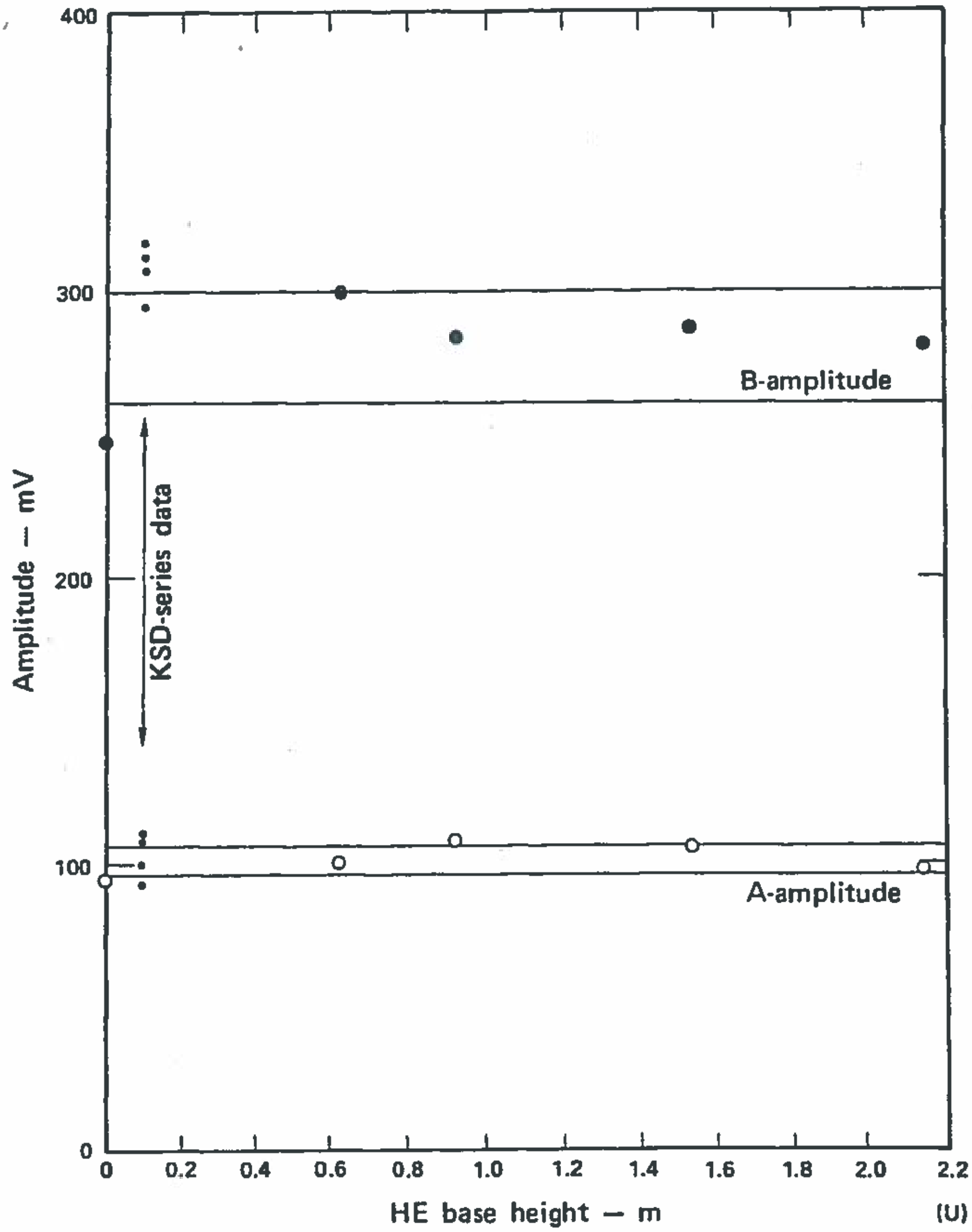

Figure 21. Amplitudes of the P-wave zero-peak (A-amplitude) and peak-to-trough (B-amplitude) vertical velocity signals recorded at the Bldg. 845 seismic station vs the base heights of the 45-kg LX-04-1 charges detonated in the KSA series of experiments. The results of four KSD series shots are included for convenience in visual comparison. As discussed in the text, we would expect these values to fall about 8% higher than the KSA-series values. The ±1-std-dev lines shown refer only to the KSA-series data.

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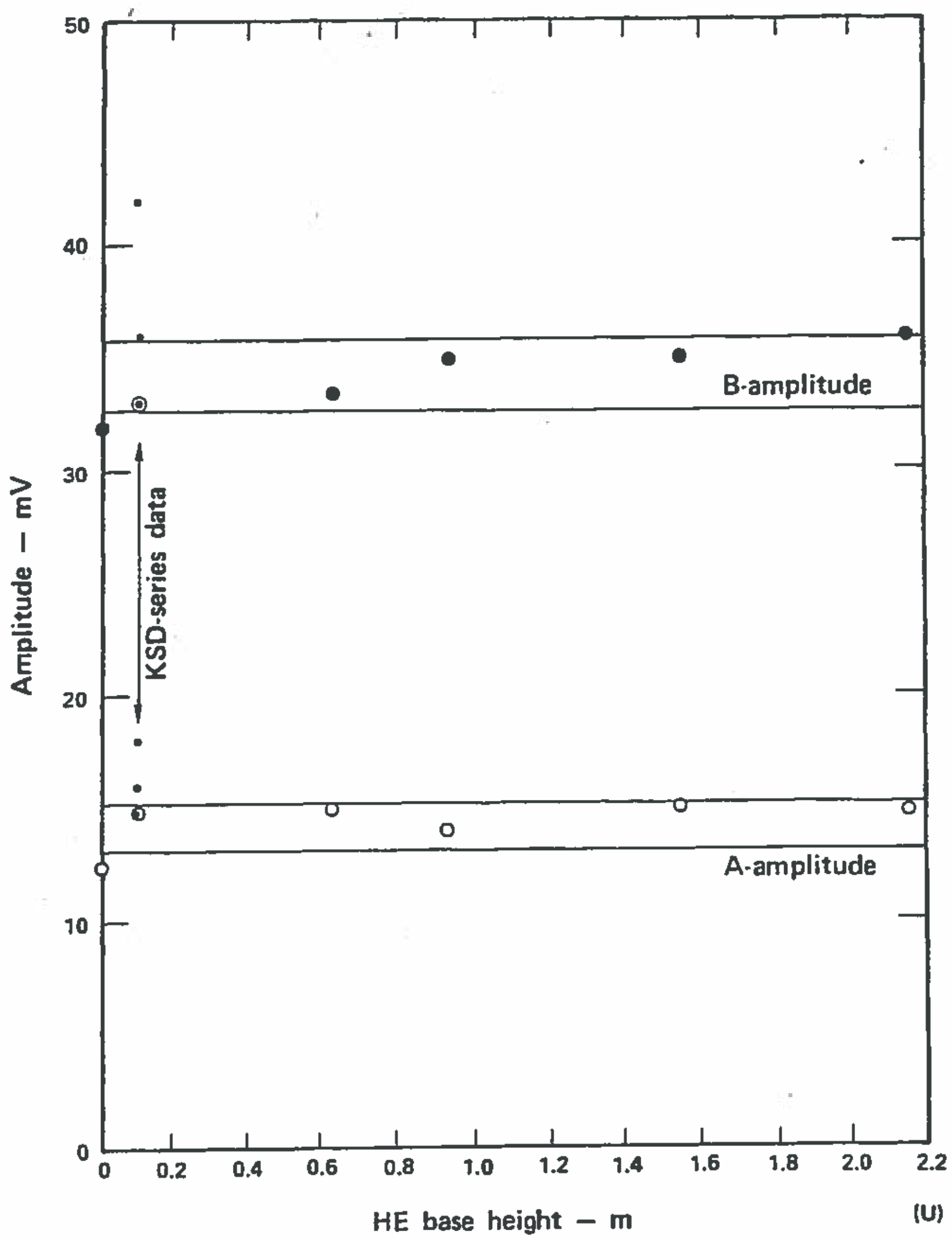

Figure 22. Amplitudes of the P-wave zero-peak (A-amplitude) and peak-to-trough (B-amplitude) vertical velocity signals recorded at the Bldg. 858 seismic station vs the base heights of the 45-kg LX-04-1 charges detonated in the KSA series of experiments. The results of three KSD series shots are included for convenience in visual comparison. As discussed in the text, we would expect these values to fall about 8% higher than the KSA-series values. The ±1-std-dev lines shown refer only to the KSA-series data.

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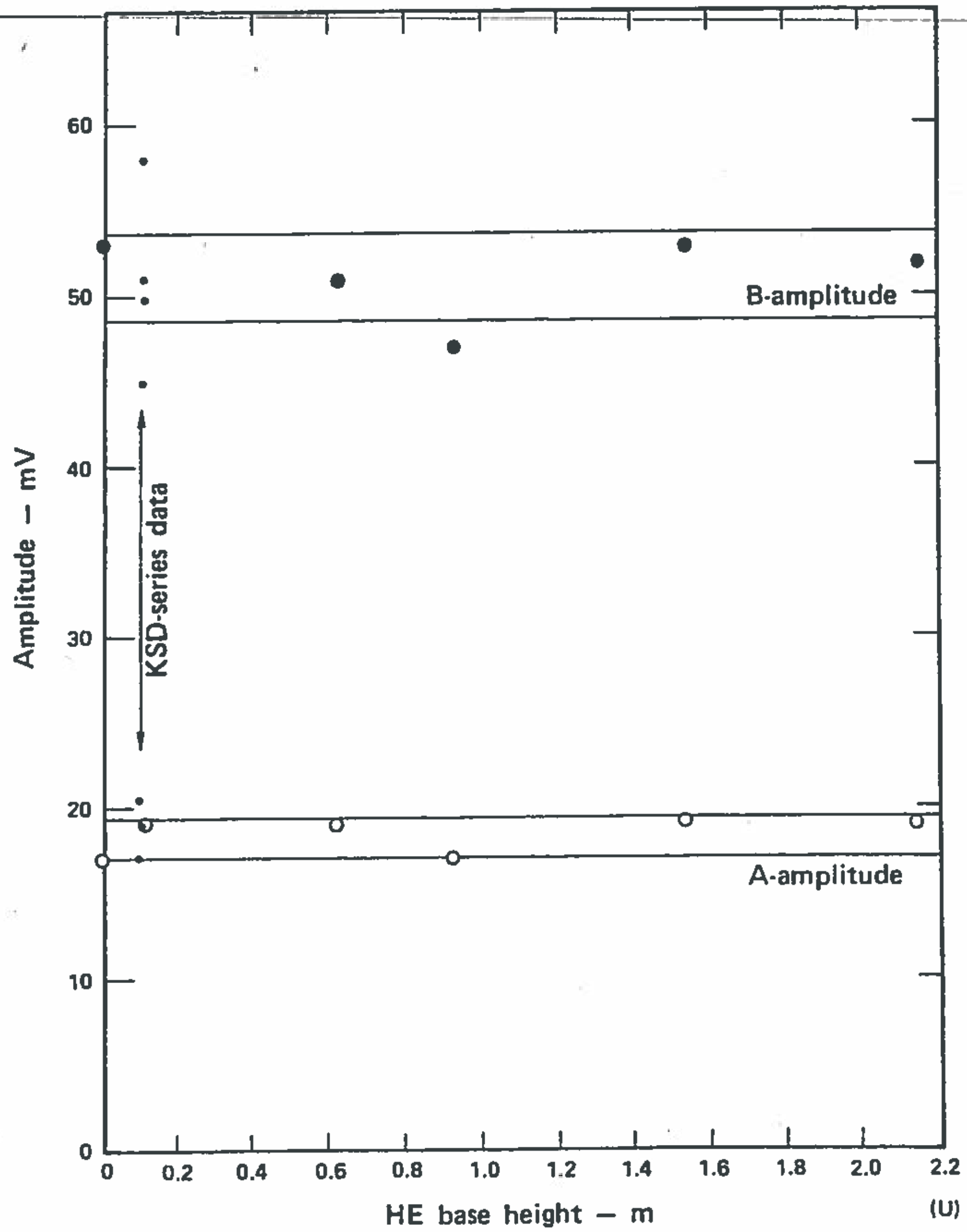

Figure 23. Amplitudes of the P-wave zero-peak (A-amplitude) and peak-to-trough (B-amplitude) vertical velocity signals recorded at Linac Road seismic station vs the base heights of the 45-kg LX-04-1 charges detonated in the KSA series of experiments. The results of four KSD series shots are included for convenience in visual comparison. As discussed in the text, we would expect these values to fall about 8% higher than the KSA-series values. The ±1-std-dev lines shown refer only to the KSA-series data.

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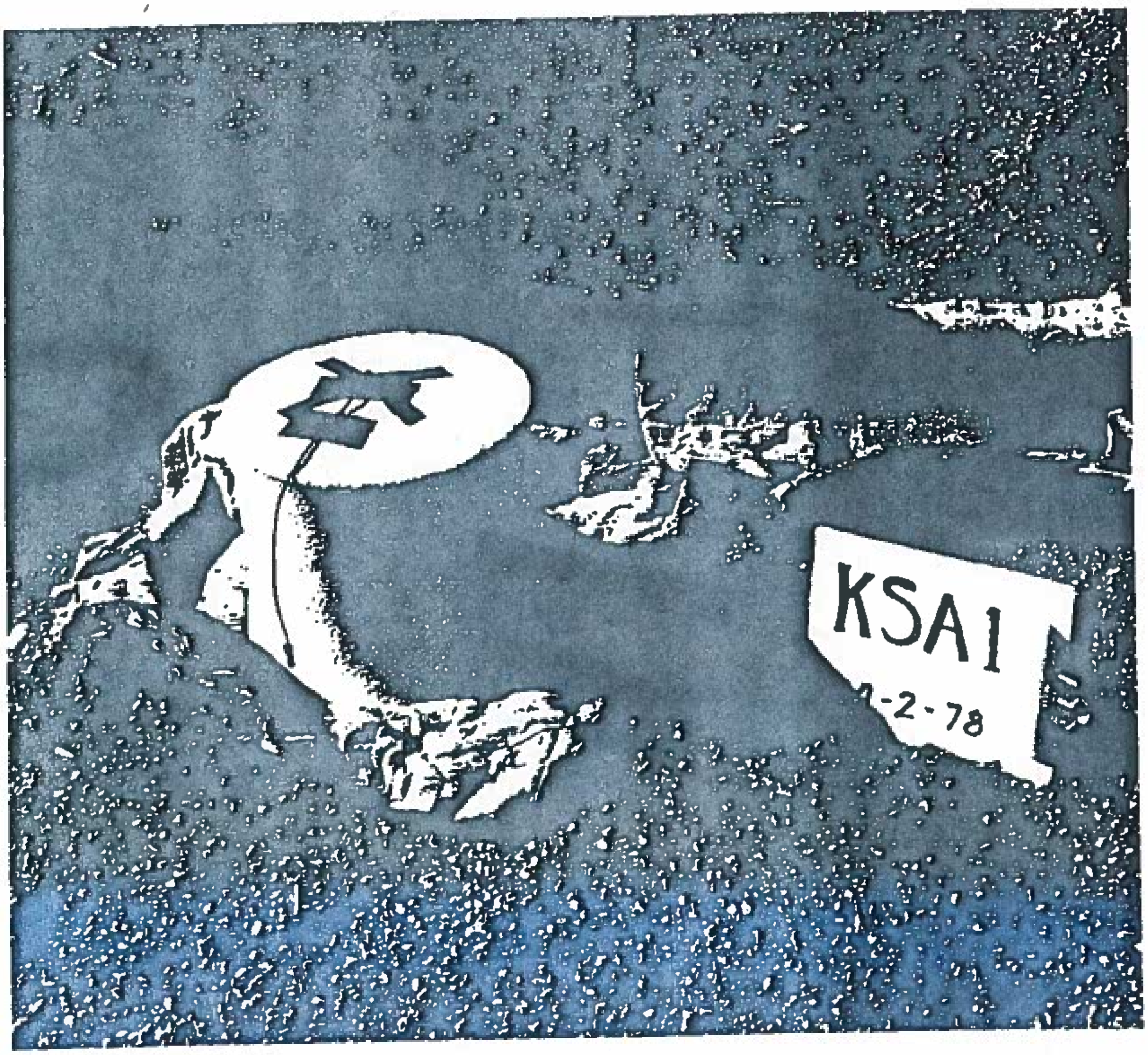

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Figure 24. One of the simplest shots to field, KSA-1, was the firing of 45 kg of LX-04-1 high explosive directly on the gravel firing pad. Note the detonation taped to top of HE charge.

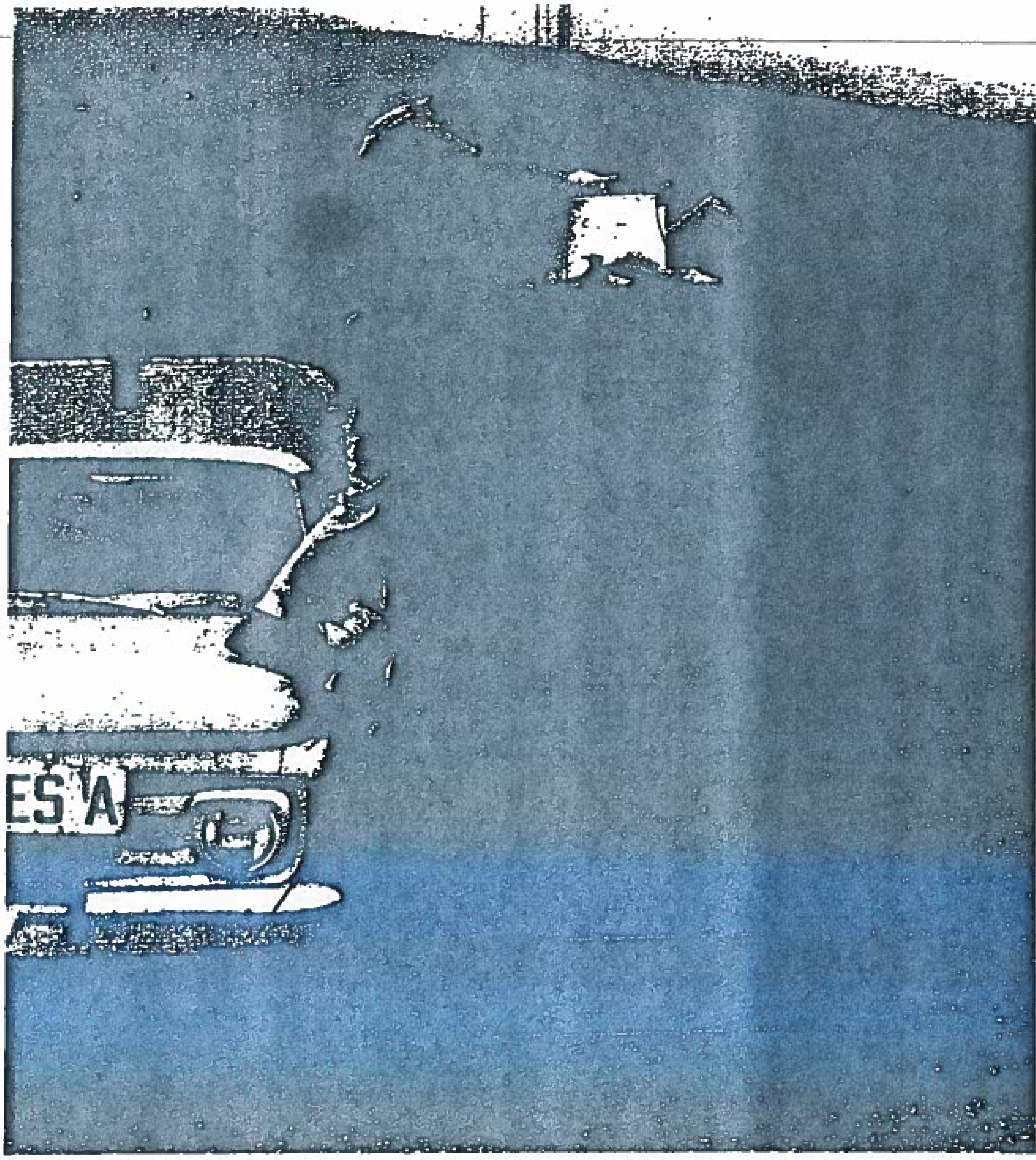

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Figure 25. At the other extreme from KSA-1 shown in Fig. 24, the KSA-5 charge of 45 kg of LX-04-1 was detonated atop a crude, but very sturdy, wooden table 2.1 m high.

the next section; here we note that they were 45-kg charges of C-4 rather than LX-04-1 and that their energy (heat of detonation) was about 8% greater than that of the KSA-series shots. Thus we would expect signals to be about 8% larger than the KSA signals. There is apparent agreement with these expectations.

Summarizing to this point, we have shown that there is no correlation between height of burst and seismic signal amplitude over the complete range of heights of burst that can reasonably be expected in a nuclear-weapons-related hydrodynamics test program.

Geometric Perturbation Effects

The KSD series of shots was designed to estimate the size of the perturbations likely to result from the differing firing geometries expected in nuclear-weapon hydrodynamics testing. For example, there could be a test involving half a device so that internal motion during the implosion phase could be studied. Conservation of momentum and energy indicate that most of the blast energy in such a device would be directed outward from the open face. [redacted] DOE b(3)

For KSD-2 the HE was in an open steel frame that supported such a slab of iron <u>over</u> the HE, and so it simulated a device fired with the open face downward. For KSD-3 the slab was to the side of the HE, simulating a device with the open face to the side. For KSD-4 no slab was involved. The same type and weight HE charge was used in each of the four firings. This information and other pertinent firing details are summarized in Table 4.

Table 4. Firing details of the 45-kg (100-lb) charges detonated in the evaluation of possible seismic signal variations resulting from variations in the geometrical configurations of the firings.

Shot designation and location[a]	HE	Steel slab position	Local date and approx. detonation time	Detonation time (GMT)
KSD-1 802FP	45 kg (100 lb) Comp. C-4	Beneath the HE	2/2/78 2:08 p.m.	33:2208:00.030
KSD-2 802FP	45 kg (100 lb) Comp. C-4	Over the HE	2/2/78 3:03 p.m.	33:2303:00.002
KSD-3 802FP	45 kg (100 lb) Comp. C-4	Beside the HE	2/3/78 10:58 a.m.	34:1857:59.931
KSD-4 802FP	45 kg (100 lb) Comp. C-4	None used	2/3/78 11:47 a.m.	34:1947:00.011

[a]We designate the leveled, graded firing pad near Bldg. 802, here most of the shots were fired, as 802FP.

In Fig. 26 we show a photograph of the setup for event KSD-2. The steel slab is resting at a slight angle from the horizontal on the steel frame housing the HE charge. The angle was deliberate--we wanted to be reasonably sure which way the slab would go when the charge was detonated. On detonation the slab was thrown nearly vertically upward, landing about 60 m away, forming an impact crater comparable in size to the one directly made by the explosion. It is interesting that this impact does not seem to have been picked up by the seismometers. This would seem to indicate that energy expended in crater formation is not a major contributor to the overall energy coupling that creates the seismic signature from an HE airburst. A calculation of the energy required for crater excavation is, in fact, consistent with this observation.

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Figure 26. Firing arrangement for KSD-2. Inside the steel framework is 45 kg of Comp. C-46 in two boxes). The 600-mm-square, 100-mm-thick steel slab was hurled nearly vertically upward. The slight angle at which it was mounted caused the slab to land 60 m away in a safe direction.

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From conservation of energy and momentum considerations we would expect shot KSD-2 with the steel plate over the HE to impact the ground with the greatest energy. This seems to have happened, for the KSD-2 amplitude is larger at each station than that of any of the other three shots in the series. It is the uppermost point in each of the KSD-series results plotted in Figs. 21-23. The ratio of the KSD-2 amplitude to the mean amplitude of the other three shots of the KSD series averaged 1.14 for the six sets (3 seismometers x 2 types of amplitudes) with a standard deviation of 0.07. If this difference is real, the geometrical effect approximating the worst-case situation is thus about 15%. Statistically, the signals and amplitudes from KSD-1, -3, and -4, and perhaps even KSD-2, were the same.

In any event, we may conclude that differing geometrical configurations in nuclear weapons hydrodynamics HE testing produce only small variations in the seismic signals--probably less than about 15%.

Relationship Between HE Yield and Seismic Signal Amplitude

In this section we address the question: To what extent can we estimate the relative size of an HE charge from the amplitude of the seismic signal produced by its detonation? The KSG series of tests involved the firing of a range of HE masses, with height of burst and other parameters fixed. [redacted] The actual weight of the charges, their equivalent weights in Comp. C-4 high explosive, and other firing details are listed in Table 5. The total weight of the charges required was 705 kg (1555 lb), and to expedite the program and to economize we obtained scrap HE from DOE's Pantex plant. For our analyses we converted from actual weight to equivalent weight of Comp. C-4 on the basis of experimental heats of detonation. Each of the shots was fired directly on the firing pad. The actual firing points may have varied by as much as 6 m from one another. The KSA and KSD series of shots discussed earlier indicated this much variation in position should not perturb results. Indeed, if it did, there would be no practical point in continuing the experimental program. The seismometers were emplaced in the same positions they occupied for all the firings discussed so far.

Table 5. Firing details of the HE charges detonated in the evaluation of the relationship between yield and seismic signal amplitude.

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In Figs. 27-31 we have plotted P-wave A- and B-amplitudes vs the C-4 equivalent weights of the charges. We consider the results from Bldg. 845 last because we found it necessary to reduce the gain of that seismometer part way through the series when it became obvious that the larger shots would overload the instrument. The complications of this gain change will be discussed later in this section.

The A-amplitude calibration points for the vertical-motion seismometer at Bldg. 858 are shown in Fig. 27. The point for the 98-kg (215-lb) charge is missing; by accident it was not recorded. The data points suggest fitting a straight line on a full logarithmic plot. In other words, we seek a best fit to the equation

$$\text{amplitude} = a\ (\text{equivalent weight})^{b},$$

where a and b are constants selected to give the best fit in the least-squares sense.[9] Performing this operation, we obtain the regression line

$$\text{A-amplitude} = 4.92\ \text{wt}^{0.816},\quad (\text{wt in lb})$$

with coefficient of determination $r^2 = 0.952$. Since

$$0 < r^2 = \frac{\text{explained variation}}{\text{total variation}} < 1,$$

the value of r^2 we have obtained indicates a very good fit indeed, as we see in Fig. 27. The least-squares fit or regression line is plotted in the figure.

[text continues on page 68]

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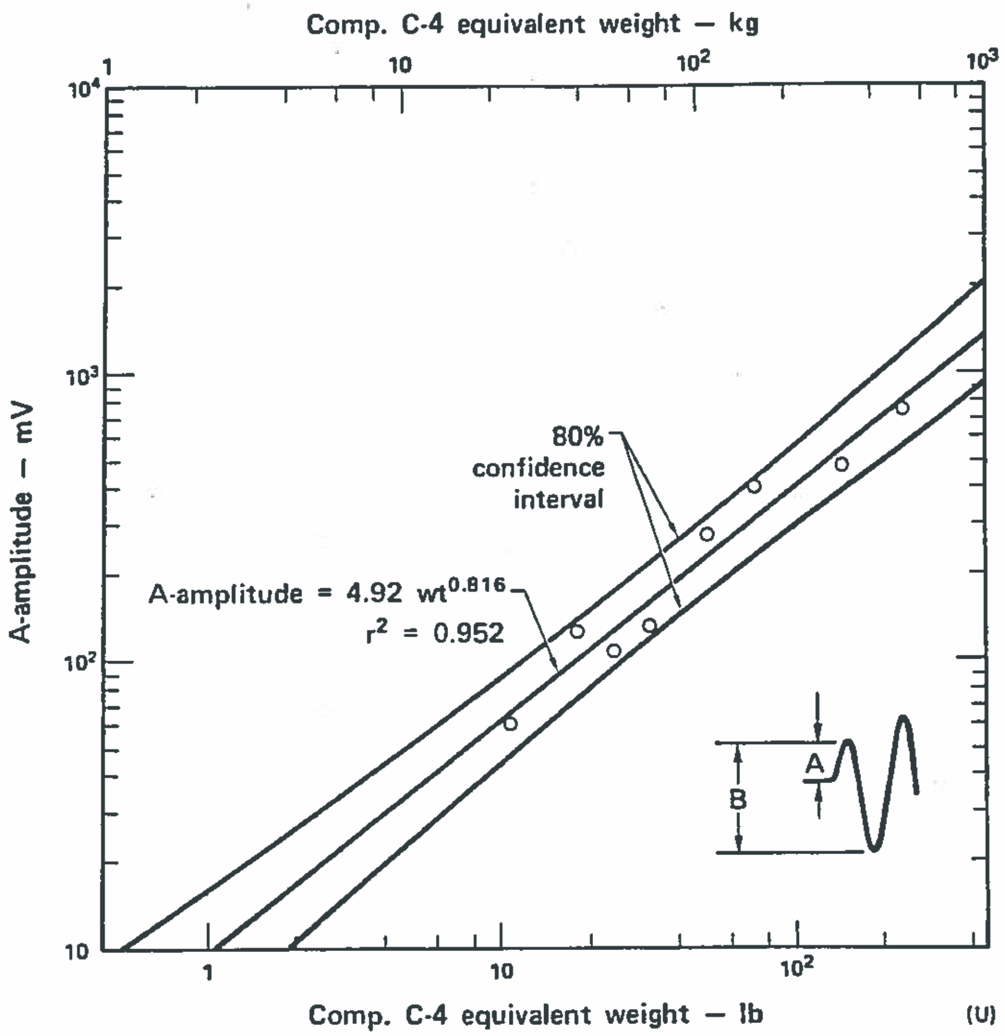

Figure 27. Least-squares fit to the A-amplitude data points obtained at the Bldg. 858 station. The 80% confidence interval on the predicted A-amplitude is also shown.

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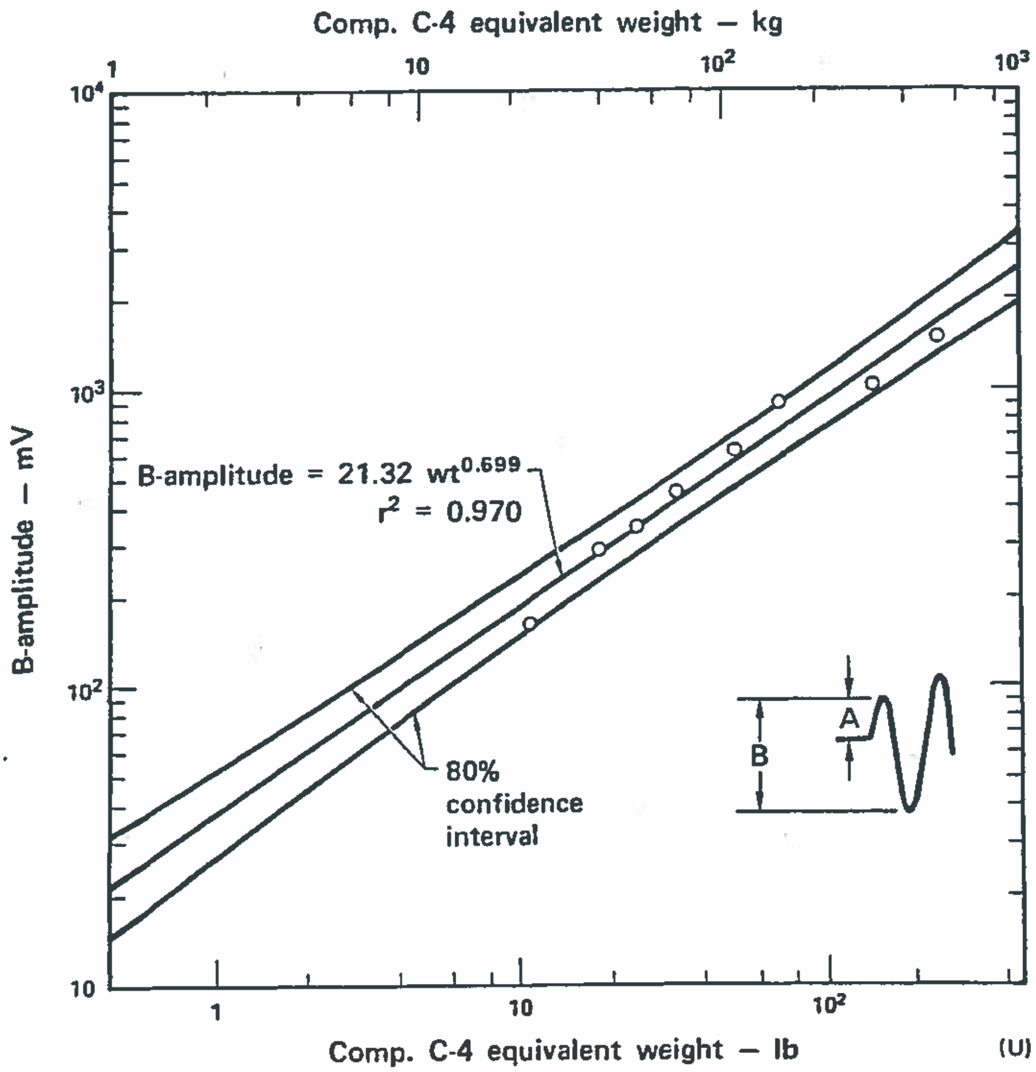

Figure 28. Least-squares fit to the B-amplitude data points obtained at the Bldg. 858 station. The 80% confidence interval on the predicted B-amplitude is also shown.

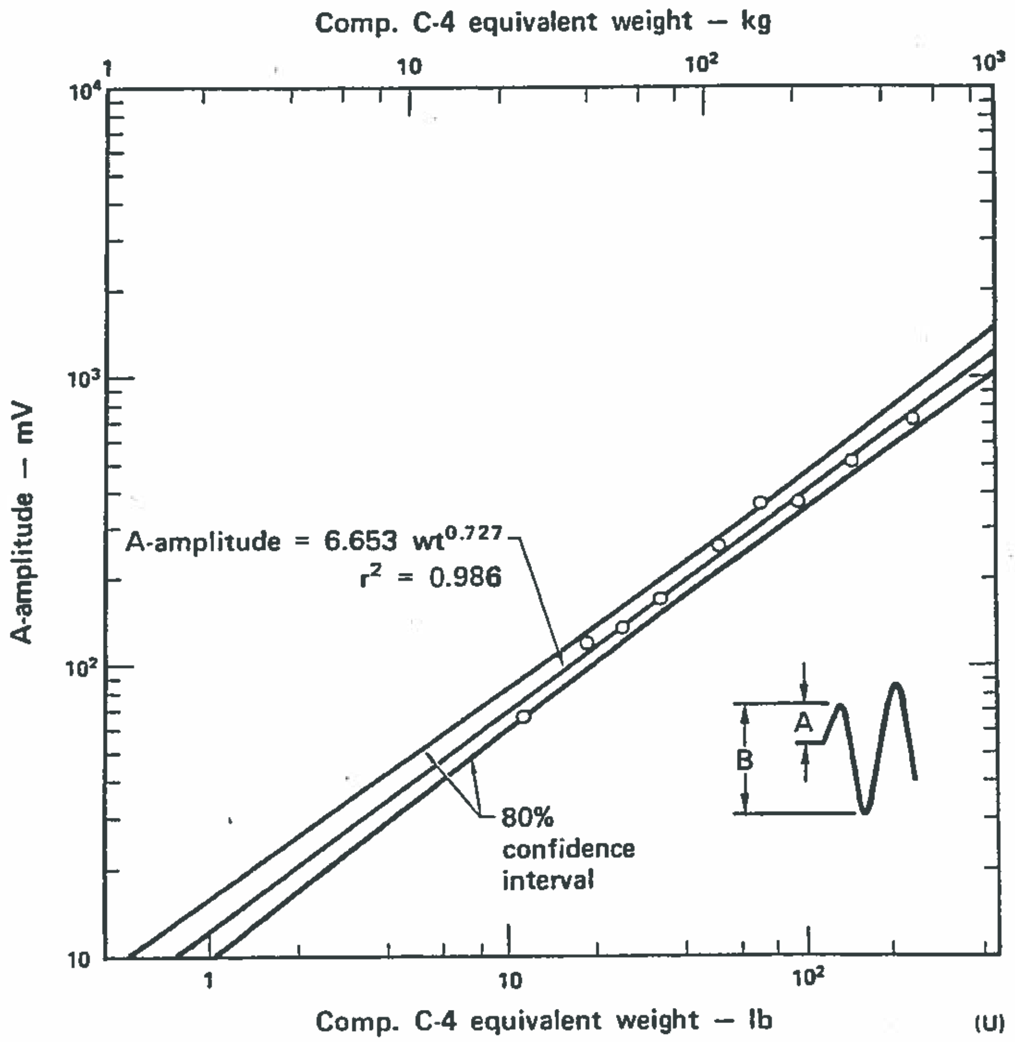

Figure 29. Least-squares fit to the A-amplitude data points obtained at the Linac Road station. The 80% confidence interval on the predicted A-amplitude is also shown.

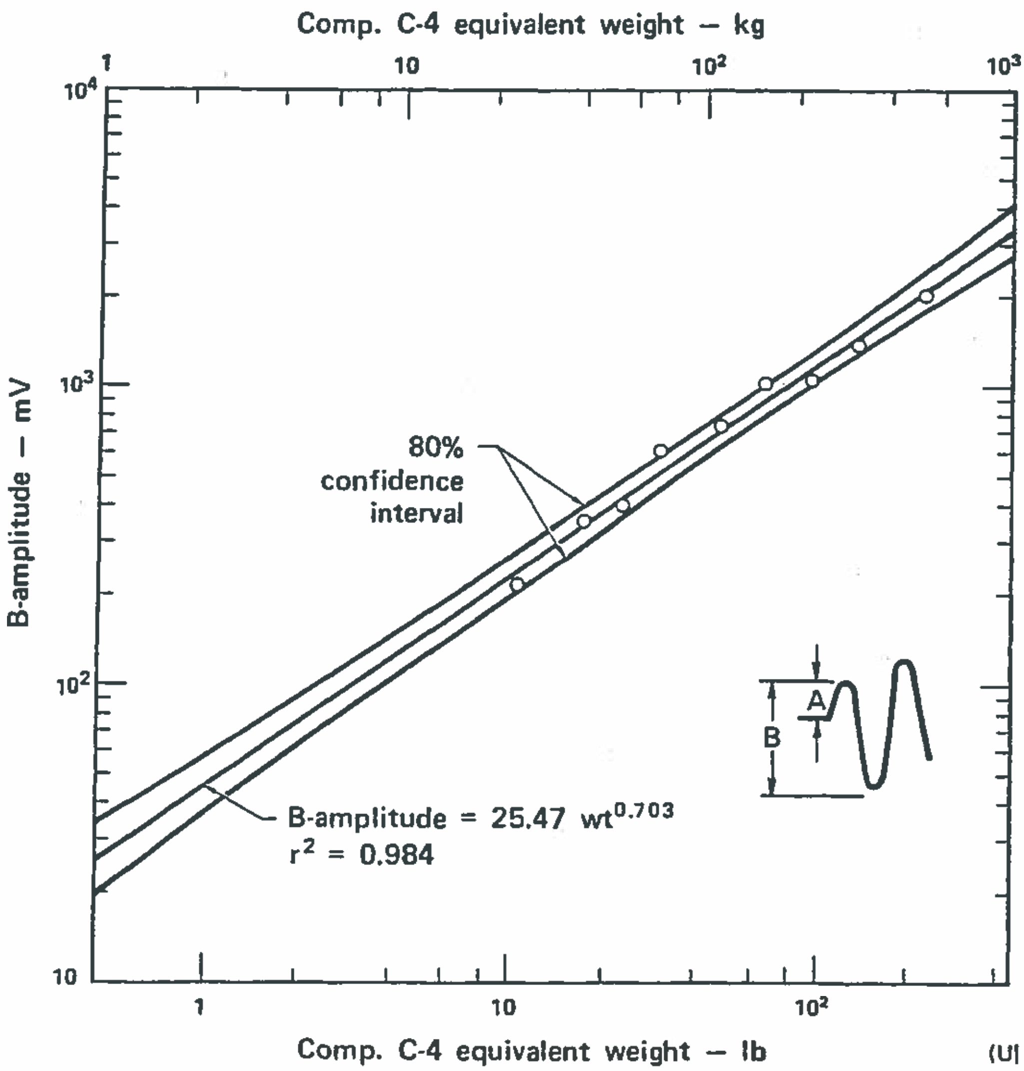

Figure 30. Least-squares fit to the B-amplitude data points obtained at the Linac Road station. The 80% confidence interval on the predicted B-amplitude is also shown.

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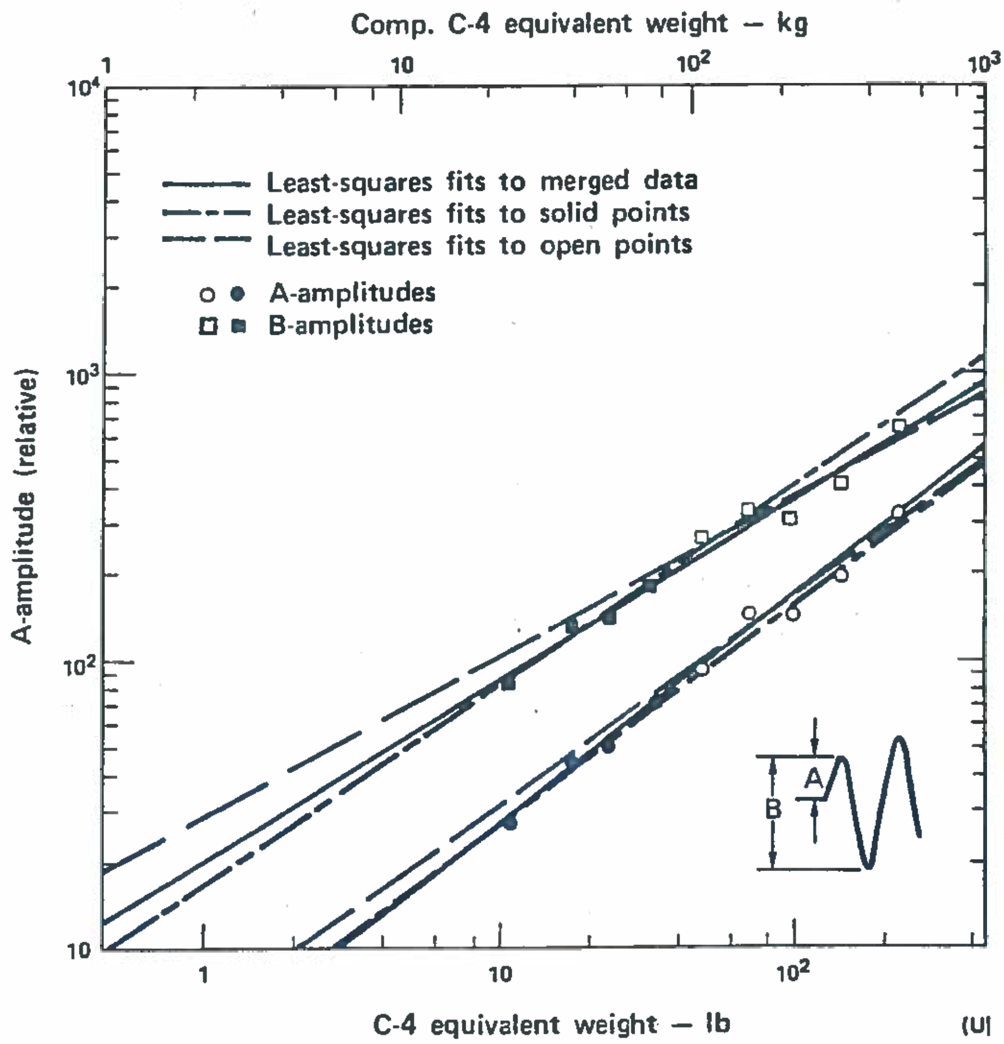

Figure 31. Least-squares fit to Bldg. 845 data. The solid points are scaled by a constant multiplier to optimize the fit with the other points (see discussion in text).

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We followed the procedures given in Gilbert[9] to obtain the limits within which the amplitude will fall, with given probability, for a given charge weight. These limits for an 80% confidence interval are also shown in Fig. 27. For example, for a 36-kg (80-lb) charge, from the figure or from the equation we see that a value of 175 mV is our best estimate for the A-amplitude. We also find we are "80% confident" that the measured amplitude will be between 128 and 240 mV.

Figure 28 is the same as Fig. 27 except that it shows the results of the analysis of the B-amplitude data obtained at the Bldg. 858 seismic station. Figures 29 and 30 show the results obtained at the Linac Road station. The Linac Road results were the best we obtained; the coefficients of determination were greater than 0.98 for both the A-type and the B-type signals. Estimates of HE weights to a factor of 1.5 appear possible at about the 95% confidence level for the Linac Road station. What we might have obtained at Bldg. 845 we can only surmise from the results shown in Fig. 31. As already pointed out, it was necessary to reduce the system gain after the smallest four shots. Unfortunately, the gain is frequency-dependent and the change in gain cannot be accounted for by simply multiplying the signals by a constant factor. For illustrative purposes only we have done this in Fig. 31 but will draw no conclusions from the merged data. The Bldg. 845 data is thus treated in further analysis as two separate sets of data for both the A- and the B-amplitudes.

The values of the exponent or slope parameter, b, in the fitted equations of the form

$$\text{amplitude} = a\ (\text{equivalent weight in lb})^{b}$$

and the corresponding standard deviations of b are collected in Table 6. The overall best estimate of b is 0.724, with standard deviation S_b of 0.018. A perusal of Table 6 suggests that dif-

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Table 6. The slope parameter from a regression analysis of least-squares fit of the KSG-series results to the equation: amplitude = $a(wt)^b$. Weighted averages are listed for the A- and B-amplitude results separately and in combination.

Seismic station and signal type	Shots included	Slope parameter (b)	Standard deviation of the slope $S_{\bar{b}}$
845 A	KSG-1 through KSG-4	0.756	0.069
845 A	KSG-5 through KSG-9	0.723	0.089
845 B	KSG-1 through KSG-4	0.689	0.084
845 B	KSG-5 through KSG-9	0.550	0.087
858 A	All KSG but KSG-7	0.816	0.075
858 B	All KSG but KSG-7	0.699	0.050
Linac Road A	All KSG series	0.763	0.034
Linac Road B	All KSG series	0.703	0.034

All results, weighted average: $\bar{b} = 0.724$, $S_{\bar{b}} = 0.018$

A-type results only, weighted average: $\bar{b}_A = 0.765$, $S_{\bar{b}_A} = 0.027$

B-type results only, weighted average: $\bar{b}_B = 0.687$, $S_{\bar{b}_B} = 0.026$

$\bar{b}_A - \bar{b}_B = 0.078$, $S_{(\bar{b}_A - \bar{b}_B)} = 0.037$

ferent values of b may be associated with the two signal types. We have included in the table estimates of $\bar{b}$ and $S_{\bar{b}}$ for each of the signal types separately and have also included estimates[10] of the difference of the slope parameters, $\bar{b}_A - \bar{b}_B$, and the standard deviation of the difference, $S(\bar{b}_A - \bar{b}_B)$:

$$\bar{b}_A - \bar{b}_B = 0.078$$

$$S(\bar{b}_A - \bar{b}_B) = 0.037.$$

It seems there has been little, if any, previous work applicable to the problem of determining HE charge size for seismic

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amplitude in the charge-size range and explosion environment of interest to the proliferation problem. There have been efforts to evaluate the size of seismic signal from underground nuclear explosions.[11-13] In this case, however, not only is the explosion environment different but the energy regime is tremendously greater. Even so, there appears to be reasonable agreement in the slope parameters obtained. Slope parameters quoted for the underground nuclear explosions range from about 0.6 to 1, with most lying between 0.7 and 0.8.

All in all, we have no direct comparisons with other work, in particular with seismic signals from chemical explosions. By inference, it appears our results are reasonable and that we might find different slope parameters for different geologic media. It should not be difficult, however, to determine empirically the appropriate slope parameter for an Nth country geology with a few experiments in an appropriately matching geology. The results of such experiments should be directly applicable to determining relative (and probably absolute) HE charge sizes in an Nth country proliferation assessment without in situ calibration.

Dependence on Type of High Explosive

Most of our experiments were made using high explosives having heats of detonation nearly equal to their heats of combustion. Thus, there was no "afterburn" in atmospheric oxygen. We tried a few charges of TNT and one charge of an aluminum-containing blasting agent. Each of these explosives has a heat of combustion appreciably larger than its heat of detonation. When analyzed, these experiments should provide information useful in determining equivalent weights of high explosive insofar as seismic signals are concerned.

Shot-Site Variation Effects

We fired several shots individually in a cross-shaped pattern centered on the Bldg. 802 firing pad to provide information on how seismic signals will vary for moderate changes of firing position. We also fixed charges at four other firing bunkers at distances from the reference pad comparable to the seismometer distances. The results have not yet been analyzed, but it appears that substantial changes in seismic signal amplitude can result from changes in local geology. One shot fired on a sandstone outcropping roughly 100 m from the main firing point gave markedly different signal amplitudes and signal shapes.

Distant Station Data

Data from the distant (11.5-km) station are not yet analyzed in detail. The P-wave signals were apparently lost in the rather considerable environmental noise, and only the acoustically coupled signal was detected.

Summary and Conclusions

In a series of experiments we have measured the vertical velocity amplitudes of seismic disturbances at distances of 1 to 3 km from HE charges in a size range covering those expected in nuclear weapons hydrodynamics testing.

We have found to date:

1. Over a reasonable range of burst heights there is no variation in seismic signal amplitude for a fixed HE mass.
2. Over a range of device geometry differences simulating those expected in nuclear weapons hydrodynamics testing, the seismic amplitude varies less than about 15%.

3. Over a range of HE charge sizes expected in nuclear weapons hydrodynamics testing, the relationship

$$\text{amplitude} = a \, (\text{equivalent charge weight})^{b}$$

holds; a is a system calibration constant and b is the slope parameter, a constant equal to about 0.72 but possibly depending on the shot/seismometer geology.

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