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SAUDI ARABIAN MISSION

PROJECT REPORT 259

SEISMIC REFRACTION PROFILE, KINGDOM OF SAUDI ARABIA

FIELD OPERATIONS, INSTRUMENTATION, AND INITIAL RESULTS

by

H. Richard Blank, John H. Healy, John Roller, Ralph Lamson, Fred Fisher, Robert McClearn, and Steve Allen

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SEISMIC REFRACTION PROFILE, KINGDOM OF SAUDI ARABIA: FIELD OPERATIONS, INSTRUMENTATION, AND INITIAL RESULTS

by

H. Richard Blank, John H. Healy[1], John Roller[1], Ralph Lamson[1], Fred Fisher[1], Robert McClearn[1], and Steve Allen[2]

ABSTRACT

In February 1978 a seismic deep-refraction profile was recorded by the USGS along a 1000-km line across the Arabian Shield in western Saudi Arabia. The line begins in Paleozoic and Mesozoic cover rocks near Riyadh on the Arabian Platform, leads southwesterly across three major Precambrian tectonic provinces, traverses Cenozoic rocks of the coastal plain near Jizan (Tihamat Asir), and terminates at the outer edge of the Farasan Bank in the southern Red Sea. More than 500 surveyed recording sites were occupied, including 19 in the Farasan Islands. Six shot points were used--five on land, with charges placed mostly below water table in drill holes, and one at sea, with charges placed on the sea floor and fired from a ship. The total charge consumed was slightly in excess of 61 metric tons in 21 discrete firings.

Seismic energy was recorded by means of a set of 100 newly developed portable seismic stations. Each station consists of a standard 2-Hz vertical geophone coupled to a self-contained analog recording instrument equipped with a magnetic-tape cassette. The stations were deployed in groups of 20 by five observer teams, each generally consisting of two scientist-technicians and a surveyor-guide. On the day prior to deployment, the instruments were calibrated and programmed for automatic operation by means of a specially designed device called a hand-held tester. At each of ten pre-selected recording time windows on a designated firing day, the instruments were programmed to turn on, stabilize, record internal calibration signals, record the seismic signals at three levels of amplification, and then deactivate. After the final window in the firing sequence, all instruments were retrieved and their data tapes removed for processing.

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A specially designed, field tape - dubbing system was utilized at shot point camps to organize and edit data recorded on the cassette tapes. The main functions of this system are to concatenate all data from each shot on any given day onto a single shot tape, and to provide hard copy for monitoring recorder performance so that any problems can be corrected prior to the next deployment.

Composite digital record sections were produced from the dubbed tapes for each shot point by a portable processing and plotting system. The heart of this system is a DEC PDP 11VO3 computer, which controls a cassette playback unit identical to those used in the recorders and dubbers, a set of discriminators, a time-code translator, a digitizer, and a digital plotter. The system was used to maintain various informational data sets and to produce tabulations and listings of various sorts during the field operations, in addition to its main task of producing digital record sections.

Two master clocks, both set to time signals broadcast by the British Broadcasting Corporation, provided absolute time for the recording operations. One was located on the ship and the other was stationed at a base camp on the mainland. The land-based master clock was used to set three additional master clocks located at the other active shot points a few days in advance of each firing, and these clocks were then used to set the internal clocks in the portable seismic stations via the hand-held tester. A master clock signal was also linked to the firing system at each shot point for determination of the absolute shot instant.

It is possible to construct a generalized crustal model from examination of the six shot point composite record sections obtained in the field. Such a model rests upon a number of simplifying assumptions and will almost certainly be modified at a later stage of interpretation. The main assumptions are that the crust consists of two homogeneous isotropic layers having no velocity inversion, that the Mohorovicic discontinuity is sharp, and that effects of surface inhomogeneities and elevation changes can be ignored. The main characteristics of the tentative model are the following:

(1) The thickness of the upper crustal layer northeast of Shot Point 5, that is, beneath the shield and platform on the line of traverse, is quite consistent and averages about 23 km. The total crustal thickness as computed ranges from 35 to 45 km and averages 40 km.

(2) A dramatic change in the crust occurs in the vicinity of Shot Point 5, that is, near the western margin of exposed shield. Southwest from here the upper crustal layer thins to approximately 9 km and the total thickness is about 15 km. This result confirms the interpretation of a transition from continental to oceanic crustal type near the inland edge of the Tihamat Asir.

INTRODUCTION

During January and February of 1978 the U.S. Geological Survey (USGS) recorded a seismic deep-refraction profile across western Saudi Arabia, in accordance with the objectives of Program 6.9 of the Directorate General of Mineral Resources (DGMR) Sectoral Plan, Second Five-Year Development Plan, and under the terms of the Fourth Extension of a Work Agreement between the USGS and the Ministry of Petroleum and Mineral Resources.

Initial plans and preparation for this large undertaking were documented by a report by Lamson and Blank (1978). The present report repeats much of the earlier documents but gives a more thorough description of the instruments used and presents initial results of the field operations. The significance of composite analog record sections in their current unrefined state is discussed briefly.

The concept of a seismic investigation of the crust beneath the Arabian Precambrian Shield was first formulated by the USGS/DGMR geophysics group more than three years ago. The refraction profile extends for about 1000 km across the eastern and southern parts of the shield, more or less normal to first-order structural boundaries (fig. 1). From Paleozoic cover rocks west of Riyadh, it traverses the Al Amar fault zone, the Shammar, Najd, and Hijaz-Asir tectonic provinces of Greenwood and others (in press), the exposed western margin of the continental plate at the foot of the Asir escarpments, and almost all of the Red Sea shelf from coastal plain to axial trough, on the west side of the Farasan Bank in the southern Red Sea. The project was designed to probe the crust beneath this region and to provide information on thickness, structure, and bulk composition of crustal layers to depths of the order of the Mohorovicic discontinuity (50 km or more).

Much of the shield area traversed is covered by modern geological maps at a scale of 1:100,000, and the entire region has been mapped at 1:500,000 scale. Aeromagnetic and gravity maps of the region are also available. In

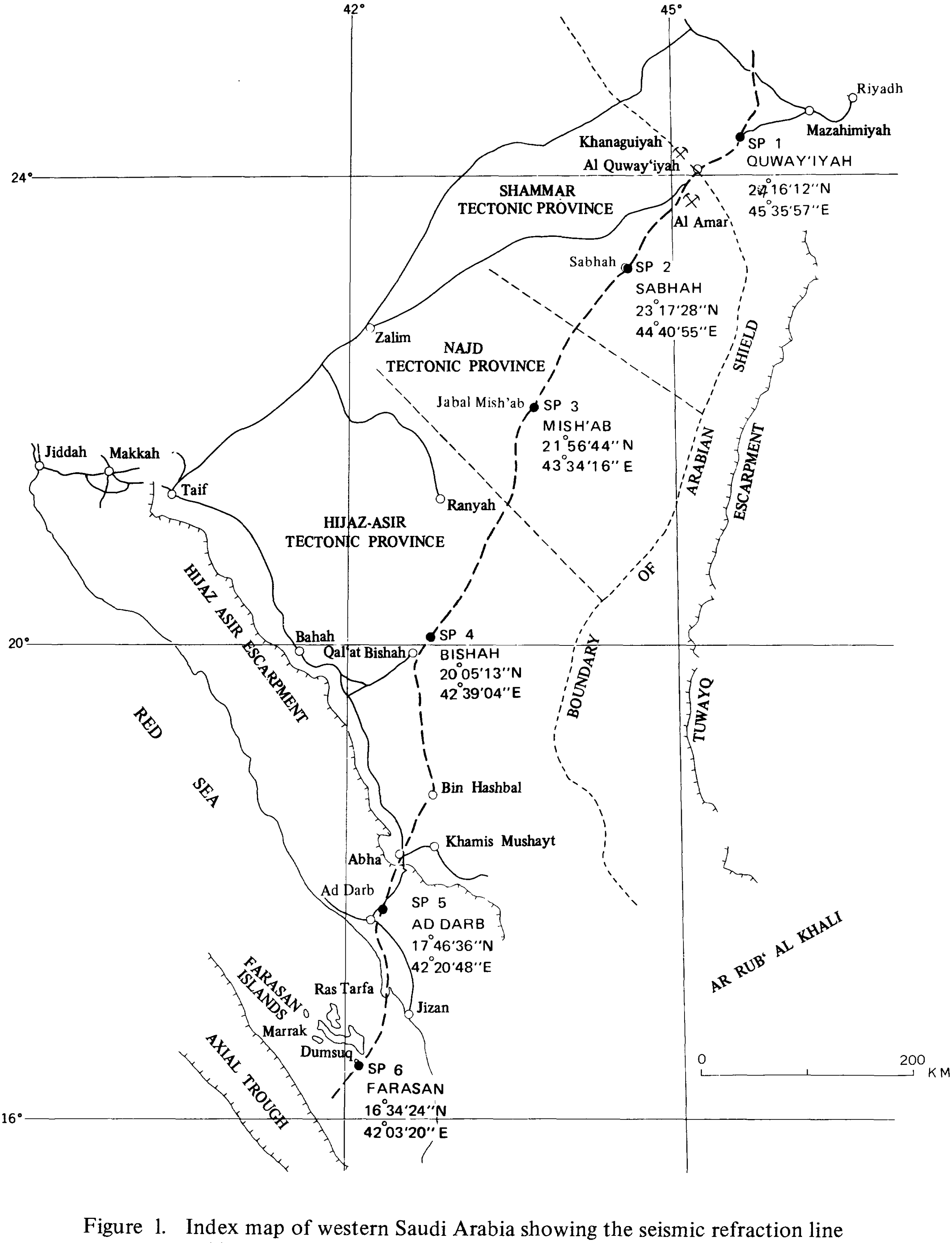


Figure 1. Index map of western Saudi Arabia showing the seismic refraction line (dashed) and shot points (SP). Paved access roads shown by solid lines.

conjunction with these data, the seismic model aims to shed new light on such fundamental questions as the late Proterozoic cratonization and tectonic evolution of the Arabian Shield, the origin and significance of tectonic, magmatic, and metallogenic provinces of the shield, and the nature of a continental plate margin in an active spreading zone. It is hoped that the data will make a substantial contribution to an understanding of the geological framework of western Saudi Arabia.

The refraction project was carried out by a team of specialists from the USGS Office of Earthquake Research and Crustal Studies, Menlo Park, California, under the direction of J.H. Healy of Menlo Park, and with the assistance of the USGS Mission professional staff and support personnel. Administrative responsibility rested with the USGS Mission. These groups also provided technical advice and logistical support for two closely related projects that were conducted by the Geophysics Section of DGMR.

A new, highly advanced system of portable field instruments developed over the past several years by the USGS for seismic crustal investigations was used on the Saudi Arabian profile. One hundred cassette-tape recording units, each equipped with internal crystal clock and programmable automatic switching device, were deployed successively in each of five 200-km recording spreads.

A field tape-playback and plotting center was moved along the profile to provide quick-response data reduction to monitor the quality of the data. Five drill-hole shot points were on land, and a sixth shot point was at the southwest end of the profile in the Red Sea, where explosives were set on the bottom and fired from a ship. Heat flow measurements were made in the drill holes immediately prior to loading explosives. Synchronously with recording of the profile, seismicity and shot arrivals were recorded at five Geotech Portacorder (portable recorder) stations on the Red Sea coastal plain (Tihamat Asir). The heat flow and Tihamat Asir projects are under the direction of the Geophysics Section of DGMR.

THE PROFILE

The seismic refraction profile was laid out so as to cross the principal tectonic boundaries of the Arabian Shield as nearly as possible at right angles within the constraints of the existing road system. Fortunately, a combination of road and track exists that is almost ideally suited to this requirement. The seismic profile begins about 100 km west-northwest of Riyadh and 35-40 km north of the Jiddah-Riyadh highway, and proceeds along a track that intersects the Zalim-Mazahimiyah highway between Mazahimiyah and Al Quway'iyah, at the first shot point. From there it follows pavement to Al Quway'iyah and thence a system of tracks southward to Bishah, Khamis Mushayt, and Abha. The western of two roads leading south from Bin Hashbal is followed to the Abha/Khamis Mushayt paved highway, which it joins near Abha. In a few places the route is deeply rutted or very sandy, particularly where it traverses dune fields south of the Jiddah-Riyadh highway and in the Wadi Bishah distributaries east of Ranyah. The line passes directly through several villages (Al Quway'iyah, Sabhah, Bin Hashbal) but by-passes the larger communities (Bishah, Khamis Mushayt, Abha). Elevation along the line gradually increases from a minimum of just over 600 m in the northeast to a maximum of nearly 2300 m near the edge of the Hijaz-Asir escarpment.

From Jiddah to Shot Point 1, surface access was via Mazahimiyah and entirely on paved road; to Shot Point 2, access was via Shot Point 1 and half this distance was on pavement; to Shot Points 3 and 4, access was by paved road to Ranyah and thence on sandy track; and Abha and points on the Tihamat Asir were reached via the paved road through Taif and Bahah. Shot Point 4 can also be reached by pavement from the escarpment road.

From Abha an arterial road descends sharply in a series of switchbacks down the face of the escarpment. The first 40 km of this road were still under construction when the seismic line was recorded. The line takes a more direct route down the crest of a ridge system, requiring deployment of the recording instruments by helicopter. Pavement resumes near Shot Point 5 and continues to Ad Darb and Jizan; however, the refraction line leaves the highway near Shot Point 5 and passes through sandy terrain on unimproved tracks to Ras Tarfa. This segment and the Farasan segment of the line also required helicopter deployment. The southwest end is Marrak, a coral island at the outer edge of the Farasan bank about 90 km west of Jizan.

SURVEYING

After an initial aerial reconnaissance in January, 1977, during which Shot Points 1-4 were selected (Shot Point 5 was established in May), surveying was commenced to establish absolute coordinates for each shot point and every recorder site. This task was begun in February 1977 by D.J. Faulkender and F.J. Fuller of the USGS Mission, and except for a few stations, was completed by the end of the year. The surveying was accomplished with a Wild T-2 theodolite and a microwave distance-measuring instrument, Electrotape Model DM20 (Cubic Corporation). Wherever feasible, the line was tied to control points of the Kingdom Geodetic Net. The nominal spacing of recorder stations was 2 km, but departures from this optimum spacing were often necessary.

A combination of radial line and transit traverse survey methods was used, depending on the local situation. The radial line method is applicable where interstation visibility exists between each recording site of a sequence of sites and an established station having geodetic coordinates. In this case two complete sets of measurements are made to obtain horizontal and vertical angles, and the distance between the established station and each recording site is obtained by microwave measurement. In the transit traverse method, one established station having geodetic coordinates must be visible from at least one recording site of a sequence of sites having interstation visibility. Schematic diagrams illustrating both methods are given in figures 2 and 3.

Coordinates of each shot point are given in figure 1 (Shot Point 6 on the first day of firing was located about 30 km northwest of the position shown). The number of recorder stations on either side of the shot point in each 100-station spread is indicated on figure 4. This illustration also serves as an index for 1:100,000-scale photomosaics, which were used for station plots. A complete list of station coordinates, elevations, and interstation distances is on file at the USGS Mission and was entered in the field data processing computer memory.

Recording stations were marked either by rock cairns piled up to 1 m high or by outcrops. Each site was painted in red or orange and numbered. The numbering system is not strictly sequential along the profile, owing to the segmental and bidirectional surveying process.

SHOT POINTS

The criteria considered for selection of the land shot points were:

(1) Location at roughly 200-km intervals.

(2) Geologic environment favorable for efficient energy transfer to the surrounding medium, i.e., for maximum wave energy propagation per unit weight of explosive. Shallow water table was essential.

(3) Accessibility for heavy drilling equipment.

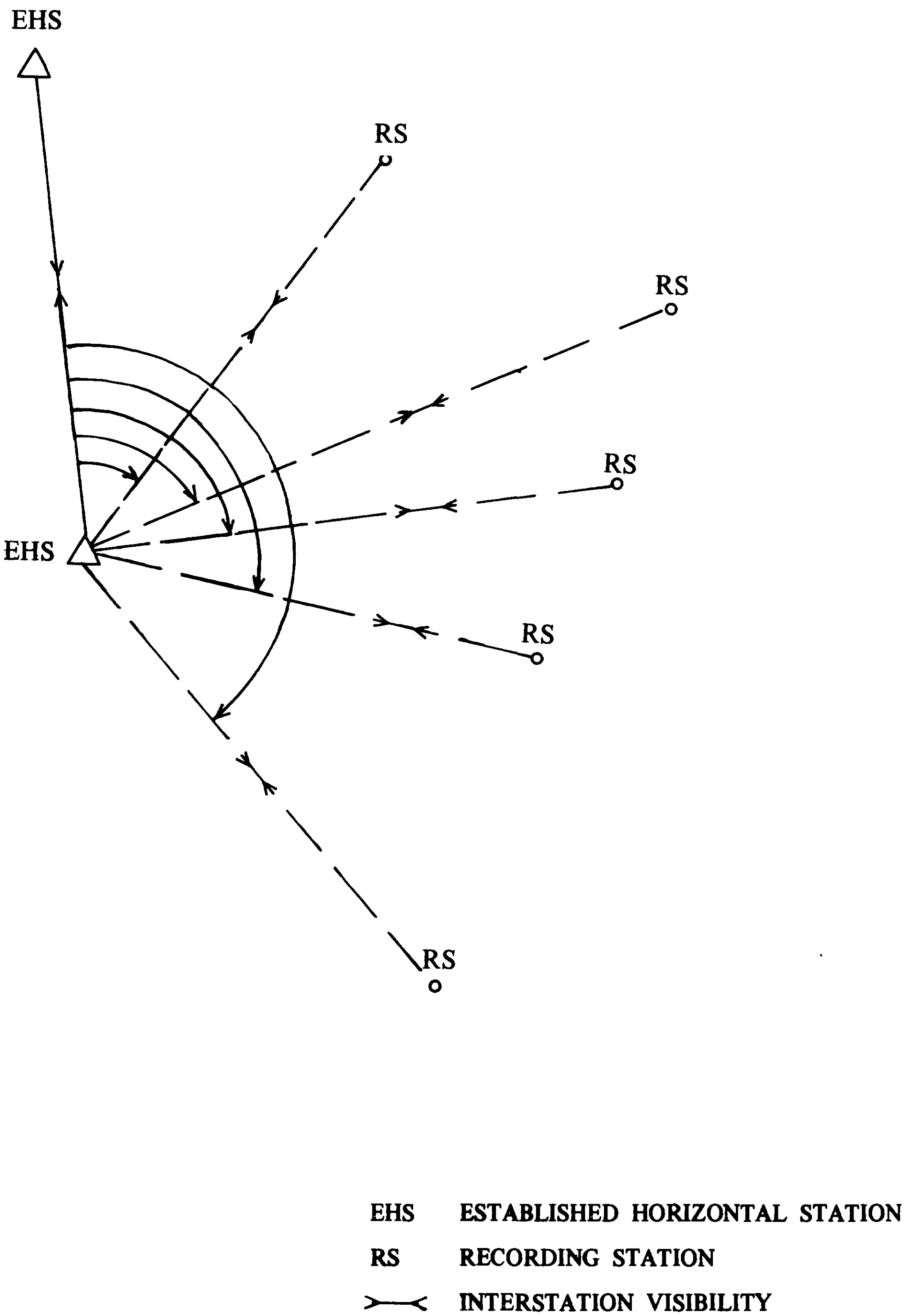


Figure 2. Schematic of radial line surveying method.

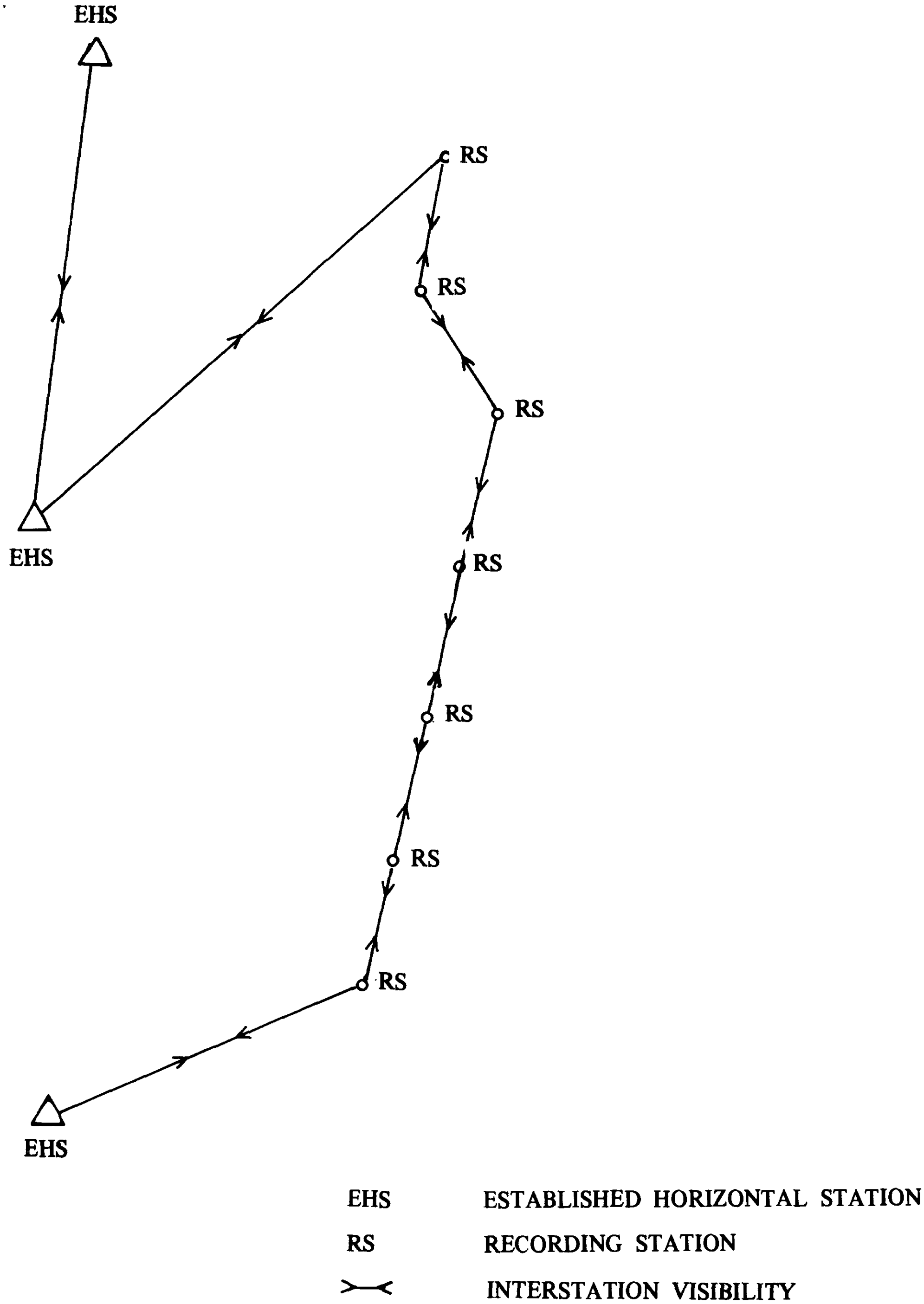


Figure 3. Schematic of transit traverse surveying method.

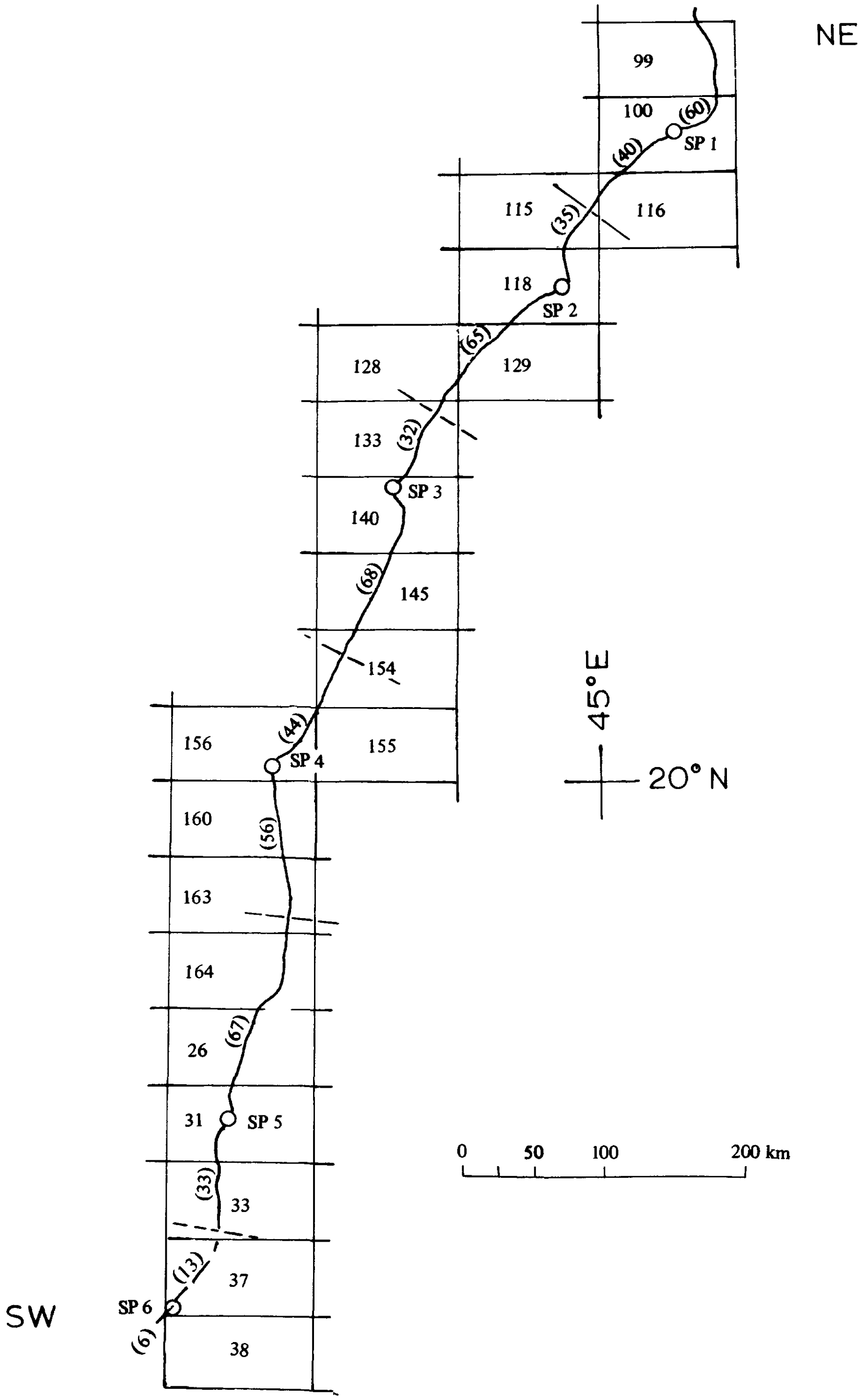


Figure 4. Seismic refraction line and index of 1:100,000 scale photomosaic maps showing recorder spreads. Number of surveyed recorder sites between shot points and end of spreads are indicated in parentheses.

(4) Relative isolation from human habitation or other cultural features and livestock.

That the tentative choices met the geologic criterion was subsequently confirmed by a program of test drilling.

Shot Point 1 is situated in a low valley in outcrops of the Permian or Triassic Sudeir shale formation, 43 km northeast of Al Quway'iyah and the eastern boundary of the Precambrian shield. The site is 50-60 km east of the Khanaguiyah sulfide prospect, where exploratory drilling was in progress at the time of field operations, and 83 km west-southwest of Mazahimiyah on the Jiddah-Riyadh highway.

Shot Point 2 is in andesite terrane of the Halaban group 5 km northeast of the village of Sabhah and about 66 km southwest of the Al Amar mine.

Shot Point 3 is 1 km northeast of Jabal Mish'ab, 183 km southwest of Sabhah, and 223 km northeast of the town of Qal'at Bishah. It is also situated in Halaban andesite.

Shot Point 4 is located in Halaban outcrops about 15 km northeast of Qal'at Bishah and 220 km north of Khamis Mushayt.

Shot Point 5 is 11 km northeast of Ad Darb, in deeply weathered calcareous quartz-sericite-chlorite schist of the Abla formation. It lies some 52 km southwest of Abha and about 25 km inland, near the inner edge of the Tihamat Asir.

An oceanographic research vessel, R/V *Comandante Giobbe* of Italian registry, was engaged on a contract basis for execution of the sea shots (fig. 5). The ship carried a JMR-1 satellite receiver for precise coordinate determination.

DRILLING

Shot hole drilling was carried out by the Arabian Drilling Company (ADC), under the direction of USGS representative J.C. Roller. Additional holes were drilled in Shot Points 1 and 2 by a crew of the Bureau de Recherches Géologique et Minières (BRGM) using ADC equipment during the shooting program.

Drilling by ADC using a Gardner 1500 rig commenced in February 1977 with a series of test holes at the first four tentatively selected shot points. Both rotary tri-cone bits and down-hole hammers were employed, the former only in soft shale or highly weathered material.

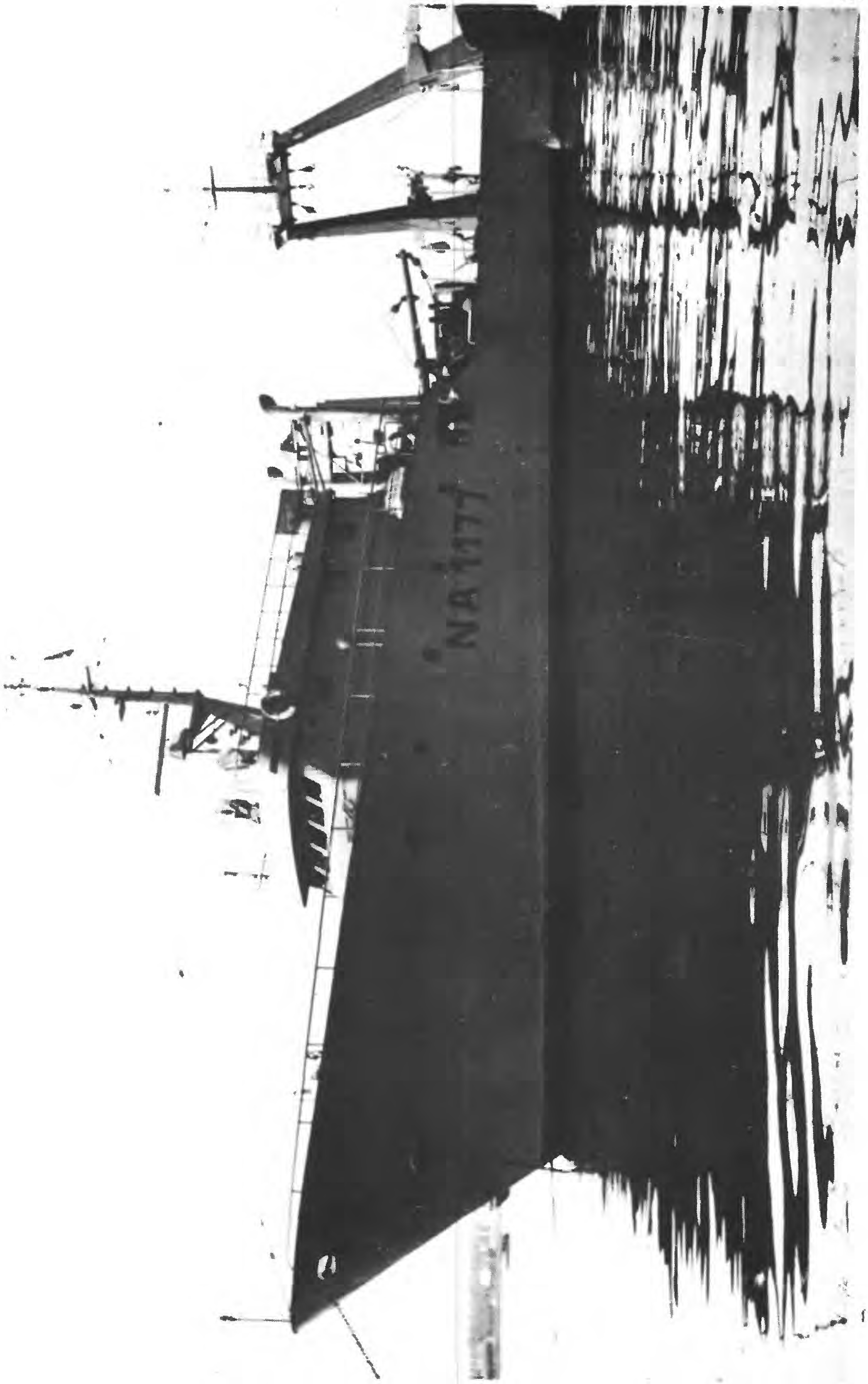


Figure 5. *Comandante Giobbe.*

One or two 5 inch- to 7 inch-diameter holes were drilled to a depth of 60 m at each site. The results helped to establish rock type, depth of water table, and time schedules for pattern drilling (see table 1).

All test holes descended below the water table. Rock cuttings from Shot Point 1 indicate strata of shale with thin interbeds of sandstone. The water table was intersected 13 m beneath the ground surface, and drilling continued through 47 m of saturated shale. Experience has shown that water-saturated shale is an optimum medium for transferring explosive energy into seismic waves. The hole was completed in one day.

Rock cuttings from Shot Point 2 have an aphanitic texture and are presumably andesite of the Halaban group. The weathered zone is approximately 6 m thick and below this depth the drilling rate decreased from 6 to 3 m/hr. The water table was intersected at 36 m, and 24 m of saturated rock were penetrated. The hole was completed in 2 days.

The weathered zone of Shot Point 3 is 6 m thick. Rock cuttings from this site are andesite to a depth of 60 m. The water table was intersected at 27 m, and 33 m of saturated rock were penetrated. The hole was completed in 2 days at an average drilling rate of 4 m/h.

The weathered zone of Shot Point 4 is 18 m thick. Rock cuttings below 18 m are thought to be slaty schist containing zones of amphibolite. The water table was intersected at 18 m, and 42 m of saturated rock were penetrated. The hole was completed in 2 days at an average drilling rate of 3 m/h.

Because of the time and expense required to move heavy equipment down the escarpment, no test drilling was done at Shot Point 5.

The test drilling program was terminated in early March 1977 and was immediately followed by a program of pattern drilling, which was completed by mid-summer. The upper few meters of each hole were cased with steel pipe and the hole capped for protection.

Before the refraction program began the ADC drill rig returned to the shot points to clean out the drill holes.

EXPLOSIVES AND FIRING

All explosives required for the seismic refraction profile were provided by the Saudi Chemical Company (Limited) (SCC), a domestically controlled affiliate of NitroNobel of Sweden. Purchase and use of the required quantity were authorized by the Saudi Arabian Ministry of the Interior.

Table 1.--*Test drilling results*
[No test drilling was done at Shot Point 5.
Holes are in schistose metasedimentary(?)
rocks of the Ablah group]

Shot Point	Hole diameter (cm)	Depth (m)	Formation and rock type	Depth to water table (m)	Method of drilling	Drilling rate
1	17.78	0-6 0-60	Sand Shale and sandstone stringers Sudeir shale	13	3-cone rock bit	10 m/hr
2	17.78	0-6 6-60	Weathered zone Halaban andesite	36	down-hole hammer	3 m/hr
3	17.78	0-10 10-60	Clay, greenish-red, grey Halaban andesite	27	down-hole hammer	4 m/hr
4	13.97	0-3 3-18 18-28 26-60	Sand and clay Clay-lime-stone-gravel Gravel-ande-site Halaban andesite	18	down-hole hammer	3 m/hr

Specific permits for release of explosives from SCC's stores in Riyadh (for Shot Points 1 and 2) and Jiddah (for Shot Points 3-6), and for trans-shipment to shot points, including to the *Comandante Giobbe* in the port of Jizan, were issued by the Director of Police for the Kingdom of Saudi Arabia.

Trucks to transport the explosives and accessories, field storage containers, and field storage areas, as well as the shot points themselves, were inspected by a technical committee appointed by Kingdom authorities. Approved trucks and storage containers were procured by SCC under a contractual agreement with the USGS. SCC also furnished licensed blasting engineers to supervise shot hole loading and firing.

The types of gelatin explosives employed at the shot points were Hercules Gelatin Extra and Nobel Dynamex B for the land shots, and Hercules Vibro-Gel for the shots at sea. All three products have 75-80 percent absolute strength (a measure of pure nitroglycerine equivalence), a detonation velocity of 6000-7000 m/sec (the velocity with which the explosion travels away from the point of detonation), and a specific gravity of 1.4-1.5. However, Vibro-Gel is superior for sea shots because of packaging and greater resistance to deterioration in an aqueous environment. It can be fired at depths up to 200 m. Gelatin Extra or Dynamex B can be loaded in drill holes but may undergo a significant decrease in reliability if holes are loaded more than a few days in advance of firing, particularly if groundwater movement is appreciable (nitroglycerin is dissolved and extracted). Technical specifications for explosives and blasting accessories--caps, boosters, and primacord--are given in table 2.

The shot holes were drilled approximately 8 months before the shooting took place. The number, size, and depth of the holes at each shot point were calculated on the assumption that the explosives would be a slurry type (DuPont Flogel, Hercules Tovex, or equivalent), which completely fills the drill hole. Unfortunately, this type of explosive proved not to be available in Saudi Arabia and as a result several new holes had to be drilled and previously fired holes had to be cleaned and reused. The BRGM graciously supplied a drill a second time, to recover holes at Shot Points 1 and 2, and ADC moved their drill to Shot Point 4 to provide the necessary holes in which to load the final charges.

Because the explosives provided were not familiar to the USGS or even to the SCC explosives engineers, several of the shots were not loaded to the desired amount at the start of the project. After some experimentation, however, loading proceeded in a routine and orderly manner.

Table 2.--*Technical specifications of explosives and accessories*

Hercules Gelatin Extra and Nobel Dynamex-B (for land shots)

- 75 percent absolute strength
- 3-packed 3 inch x 24 inch (65 x 400 mm) cartridges, at 1.3 kg each
- Cartridges are plastic bags (Dynamex-B) or paper (Gelatin Extra)
- Detonating velocity 23,000 ft/sec
- Specific gravity 1.4

Hercules Vibro-Gel (sea shot)

- 80 percent absolute strength
- 3-packed 3 inch x 24 inch cartridges (hard plastic tubes)
- 6-8 1/3 pound 3-pack tubes are packed in 50-pound (net) paper boxes
- Detonating velocity 19,700 ft/sec
- Specific gravity 1.5

Primacord

- High velocity, cap-sensitive explosive cord
- Detonating velocity 23,000 ft/sec

Blasting caps (detonators)

- Resistance 3.9 ohms
- Firing current 3.5 amps
- Up to 2 ms delay

Titan-500 Boosters

- High velocity, non-nitroglycerin, cap-sensitive explosive
- 2 1/4 inch diameter x 4 1/2 inch height, each
- 1-pound, 60 per case

Obtaining, loading, and detonating explosives in Saudi Arabia presented the USGS with requirements not normally encountered in the U.S. Permission to obtain and detonate explosives is very carefully controlled by the Internal Security Office in Saudi Arabia. All explosives from the time they are purchased from the licensed distributor (SCC) until they are actually detonated are carefully counted and signed for by the user (USGS), the licensed blasting engineer (SCC), and a representative of the Internal Security Office of the Kingdom.

The procedure for shooting is outlined in the following steps.

(1) Explosives were delivered to the field storage containers by approved trucks under police guard. The amount and type of explosive were carefully checked and signed for. The field storage containers were double-locked; one key was held by the police and the other key by the licensed blasting engineer.

(2) The desired amount of explosives, exclusive of blasting caps, was removed from the magazine and taken to the drill holes. The amount and type was counted by both the USGS representative and the police.

(3) The drill holes were then charged and any excess explosives, usually primacord, were returned to the storage container and signed back in.

(4) Police guards were stationed at the blast site and remained until the explosives were detonated.

(5) A few hours (usually 2) before the blast, the police and USGS representative removed the necessary blasting caps from a separate storage container.

(6) The charge was armed with blasting caps (detonators) by the licensed blasting engineer.

(7) After testing the firing circuit, the blasting engineer connected the firing line to the special USGS blaster.

(8) The blasting site was then carefully checked by the police to make sure it was safe to fire the charge.

(9) The charge was automatically detonated, at a preselected time, by the special blasting circuit and accurately timed on a paper record to the nearest millisecond.

(10) The site was then checked by the police and the USGS representative to determine if all charges did indeed explode and the area was safe to leave.

(11) Any surface disturbance potentially dangerous to people or livestock was restored to a safe condition before the area was finally evacuated.

SEISMIC RECORDING SYSTEM

Introduction

The study of the fine structure of the earth's crust and mantle with seismic methods has been limited in the past by the high cost of these experiments, both in money and in the number of man-hours required to do the work. The cost of the experiments arises from constraints imposed by the available instrumentation, of which there have been basically two types: truck-mounted multichannel instruments, with from six to 50 geophones connected to a truck-mounted recording system by cable, and single point recorders that recorded the data from one position. The multichannel systems work well where it is desirable to record many data points along a short segment of profile, but for long profiles that have larger distances between recording positions, the task of laying out and picking up long lengths of cable imposes severe practical limitations, particularly in rough terrain where road access is limited. Single point recorders avoid the problems associated with long cables but place severe limitations on the number of data points that can be observed at any one time. Most instruments required an operator for each recording position, and large-scale seismic experiments required 50 to 100 operators.

The cost of an experiment is dominated by the amount of explosive required to produce seismic signals of adequate amplitude. The amount of explosive needed at a given distance range is proportional to the number of data points desired divided by the number of available recorders.

It is obviously desirable to have a large number of single point recorders that do not require an operator for each station. Such a system allows flexibility in the design of an experiment and maximizes the use of each explosive source. Advances of electronics in recent years have reduced the cost, size, weight, and power consumption of seismic systems and made it possible to build highly automated single point recorders at a reasonable cost. A number of groups have experimented with such a recorder but to our knowledge this project is the first full scale test of this new type of instrument.

One other cost item that is important in seismic experiments is the cost of retrieving the recorded data and preparing the data for interpretation. The system used in this project has a field data processing center designed specifically for this instrument system, to minimize the time and effort required to prepare the data for interpretation.

Seismic recording system

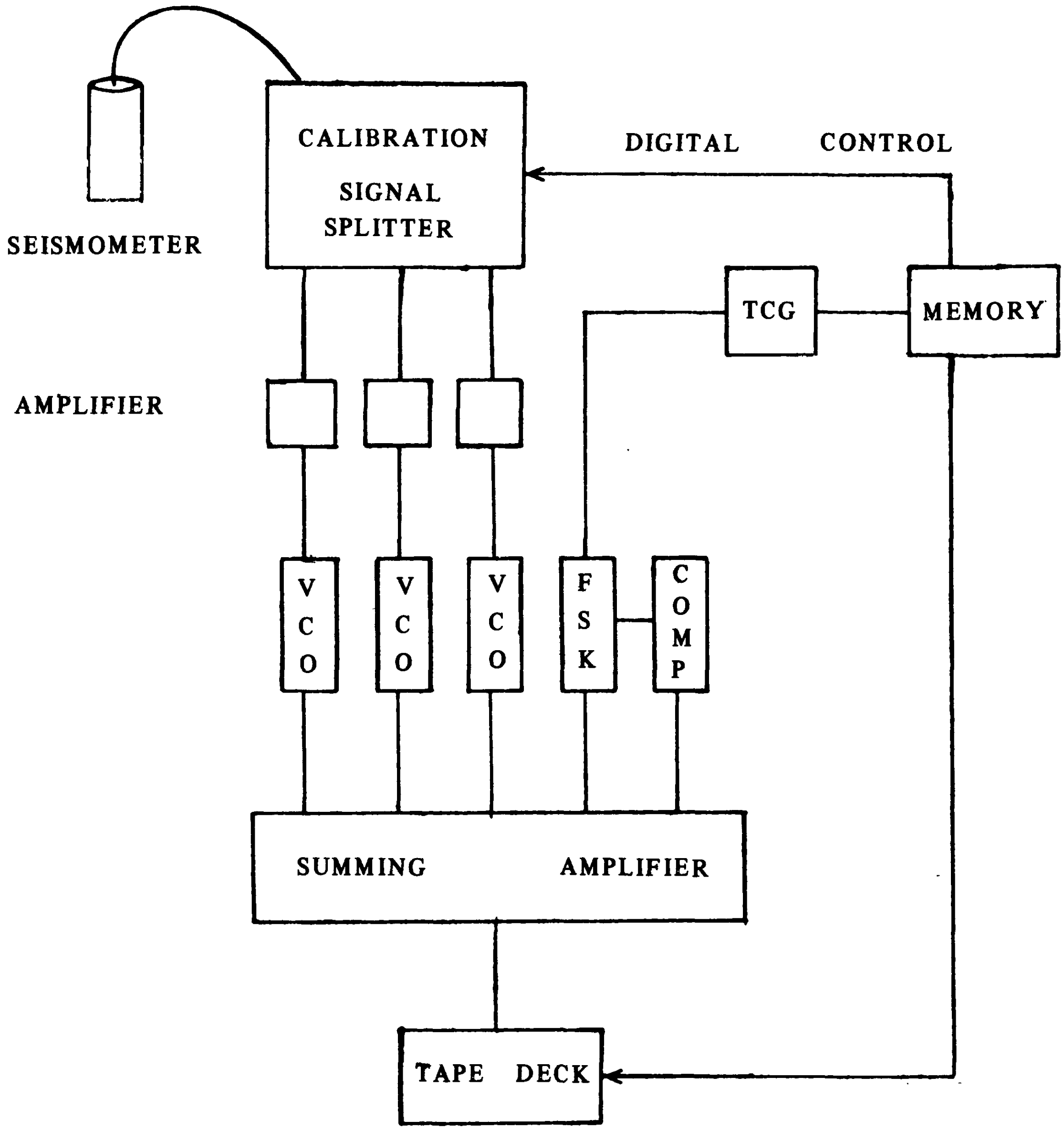
The seismic recording system used in the Saudi Arabian profile is an analog instrument with calibration, seismic, and timing data stored on cassette tape. The instrument typically was calibrated, programmed, and then deployed the day prior to shooting. At each of the preselected recording windows, the instrument would stabilize, internally calibrate, and then record the shot energy.

Internally the instruments function in the following way (see figure 6). The USGS time code generator contains a memory board that provides the digital control in the instrument. During the ten minutes prior to the expected shot-energy arrival, the instrument warms up and stabilizes, and then records a calibration train, which includes a seismometer pulse, amplifier step, and 1, 10, 100, and 1000 mv, 10 Hz sine wave calibration signals. This calibration train is followed by a recording window where the shot energy is sensed, amplified, and recorded. The output of the seismometer is split without attenuation, and amplified at selected gains by three independent amplifiers, which allow the instrument to record a larger dynamic range. The output of these amplifiers is then frequency-modulated as is the serial IRIG E time code pulse train. These four signals are then summed with a subtractive compensation reference signal prior to being recorded. This sequence is then repeated for each of the following programmed 'turn on' times.

After each shooting sequence, the instruments are retrieved, the clock drift checked, and the data tape removed.

The Hand-Held Tester

The Hand-Held Tester (HHT) is the interface unit between the field technician and the portable seismic station (fig. 7). Environmental protection is required for the portable seismic station and makes such a unit necessary. The HHT is highly portable and capable of being used both at the deployment site of the seismic stations and for maintenance in the field camp. It allows access to all critical functions necessary for efficient operation of the portable seismic station as



COMP = COMPENSATION
FSK = FREQUENCY SHIFT KEYING
TCG = TIME CODE GENERATOR
VCO = VOLTAGE-CONTROLLED OSCILLATOR

Figure 6. Schematic of recording units.

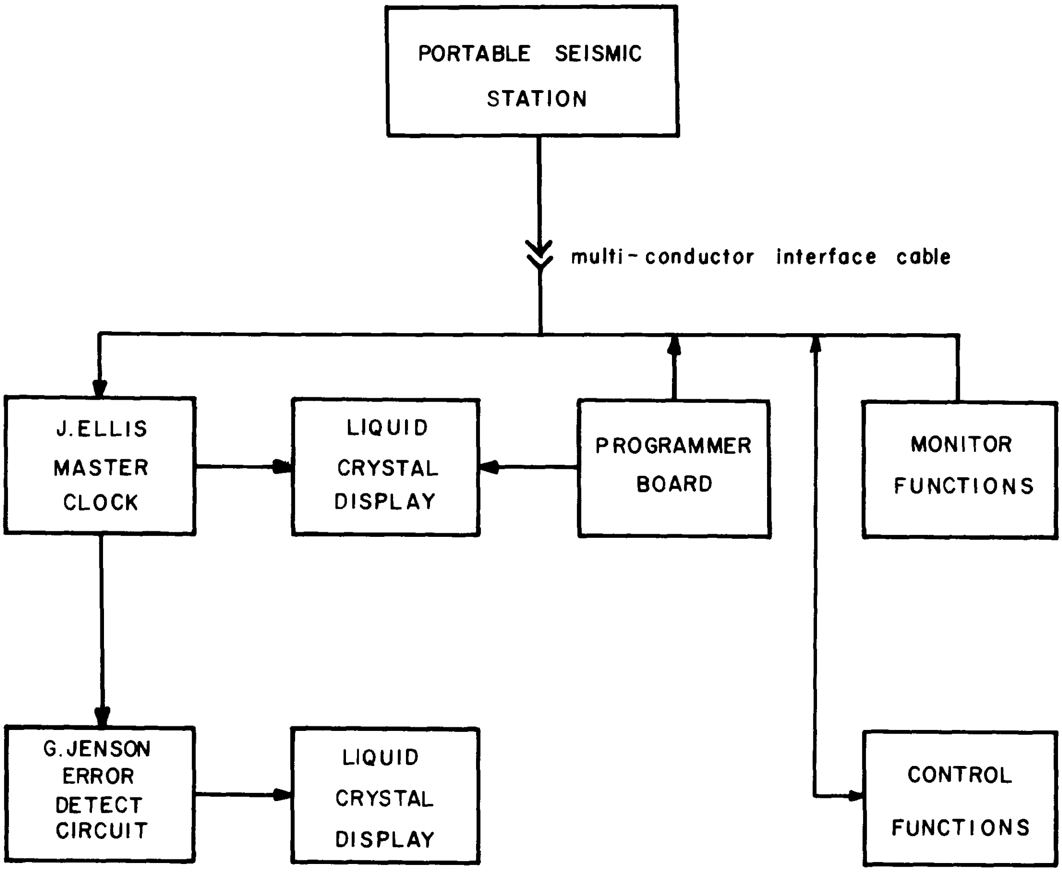


Figure 7. Hand-held tester.

a data collection system. The primary functions of the HHT include switching controls, timing, monitoring, and programming.

The timing functions are provided by a J. Ellis chronometer with essentially no modifications. Control of the HHT master clock is provided on the front panel of the HHT and controls are identical in function to those on the portable seismic station chronometer.

Electrical interface between the HHT and the portable seismic station is through a multi-conductor cable link. Along with other functions, this link allows for a timing reference signal to be generated by the E.G. Jensen Error Detect circuit and is displayed, along with the master clock time, on the front panel of the HHT. This error is correctable by use of switches on the HHT to control the portable seismic station chronometer remotely.

Switching functions are provided on the HHT face plate to control operation of the primary functions in the portable seismic station. These include the afore-mentioned time correction controls, VCO and tape recorder power controls, and monitoring of tape handling functions.

Monitor functions are provided through the multi-connector link, which allows access to portable seismic station signals without opening the seismic instrument case.

Programming functions are available in the HHT for setting recorder start and stop times, and for allowing the instrument to be left unattended for periods up to 10 days with 10 variable length recording periods, which are limited by the record time available on the cassette tape.

Tape dubbing system

The tape dubbing system was developed in order to reorganize and edit data recorded on the seismic data recorders. Such a procedure is necessary in order to save time in processing data into the computer/digitizer system. It also allows immediate playback of the data tapes for evaluating the operating condition of the data recorder.

The original data tapes contain records of several shots from a single recorder. In order to process data rapidly, however, it is desirable to have them organized in such a way that all the records of a given shot from the various recorders are together, and therefore this dubbing system was designed. Figure 8 is a block diagram of the system. Four recorders are connected to one TEAC playback machine. By turning on the appropriate recorder

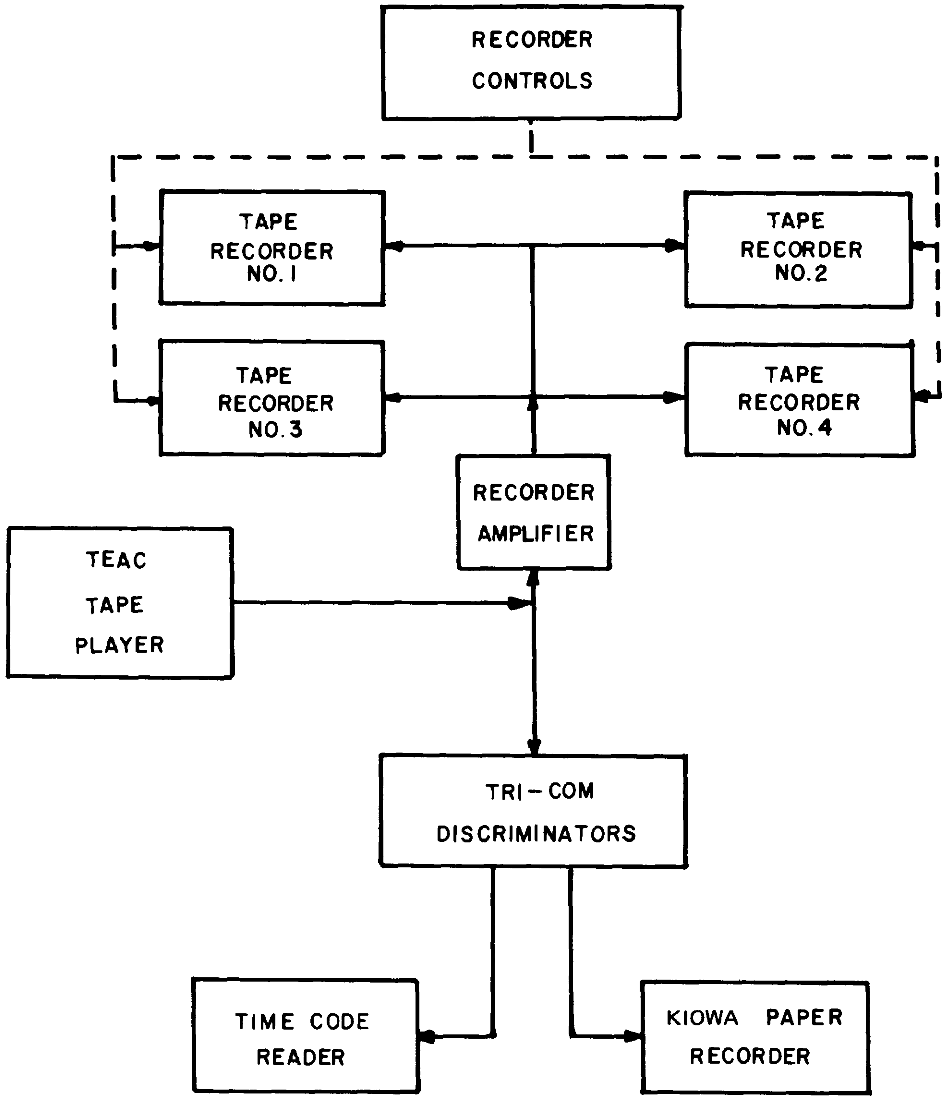


Figure 8. Tape dubbing system.

at the proper time while the playback unit is playing one of the original data tapes, data on that segment of the tape are transferred to the dubbed tape.

The recorders are controlled by two sets of four switches. The first set are toggle switches labeled one through four and are switched to either "MANUAL" or "AUTO". The second set are pushbutton switches labeled "STOP", "PLAY", "FAST FORWARD", and "FAST REVERSE". The numbers of the toggle switches correspond to each of the four recorders. When a given recorder's toggle switch is in "MANUAL", the corresponding recorder is controlled by the four pushbuttons. When it is in "AUTO" the recorder cannot be controlled by the pushbuttons. The recorders can be controlled individually or in any combination.

The playback unit is also connected to a bank of TRICOM discriminators, which, in turn, is connected to a KIOWA photosensitive paper recorder. This arrangement allows the data to be viewed while dubbing. The discriminators are also connected to a time code reader. This device reads the IRIG-E code on the tape allowing the operator to determine what part of the record is being played back and on what unit the record was made. For design ease, the reader displays a time that is 6 seconds behind the time actually on the tape. The reader requires about 10-20 seconds from the time it begins receiving time code until it displays the proper time.

The operating procedure is as follows: One new tape is placed into a dubbing recorder for each segment of data to be dubbed. Then the starting and ending times for each segment must be determined. The toggle switch for the recorder of the first segment is switched to "MANUAL" while all others are in "AUTO". The first data tape is then played in the playback unit. When the time code reader indicates the first starting time, the "PLAY" pushbutton is pushed and the first recorder will begin dubbing. When the reader indicates the ending time, the "STOP" button is depressed, which action stops the dubbing.

Next, the first toggle switch is returned to "AUTO" and the second is placed in "MANUAL". Then the second segment is dubbed in the same manner as the first, and so on. After all the segments have been dubbed, the next data tape is played starting with the first toggle switch in "MANUAL" again. The first segment of the second data tape is then dubbed. In this way, the same segment from all the data tapes is transferred to one dubbed tape; i.e., all the records from Shot 1 are on one dubbed tape, all those from Shot 2 on another dubbed tape, and so forth.

A hard-copy record can be made anytime during the playback process by starting the KIOWA recorder. The reel counter on the TEAC playback unit can be used in conjunction with the fast-forward mode to shorten the gaps between the segments to be dubbed. With the counter zeroed at the beginning of the tape, the count is simply noted for the start and stop times for each segment on the first tape. Then these counts are used for advancing from the end of one segment to the beginning of the next. In this way, the amount of time required to dub the tape can be kept to a minimum.

Processing and plotting system

Among the final products of a seismic refraction survey are digital plots of seismograms called record sections. Customarily, digitization and plotting of data by computer are done in the office. This approach frequently results in problems and delays due to misunderstandings of data content, unclear field notes, incorrect instrument settings, and problems with computer system hardware and software such as revisions in the computer operating system that require rewriting of processing programs. Consequently, production of record sections can often take months after receipt of the field data.

For this project a small field-deployable computer system has been developed so that the computer can be brought to the data rather than the reverse. Experience in the field with this system showed that record sections containing approximately 75 seismograms could be produced within 36 hours of a shot.

The main objectives in developing a field-deployable computer system were to provide quick turnaround for record sections, thereby avoiding some of the problems inherent in post-experiment processing, and to provide the field team with feedback on instrument and recorder performance. The guiding principles included the following:

- the system should be small enough and rugged enough to be easily transported to the field

- the system should be simple and convenient to use so that one or two people could be responsible for all computer operations, including set-up

- the system should be functionally equivalent to a larger office-based seismic processing system

- the computer itself should be able to function as a general purpose computer when not used in its dedicated digitizing and plotting mode

-- the operating software supplied for the computer system by the manufacturer should be sufficiently advanced and encompassing to minimize the effort required to create and maintain application programs and to provide for easy data-file management

-- operation of the system software should be simple enough that users versed in processing of seismic data can be easily trained to run the programs.

A sequence of processing steps is required in order to plot a record section. A tape cassette containing dubbed seismic records is mounted onto a cassette playback unit so that the tape can be wound to a particular record to be digitized and the analog data signal can be read. Because the instrument output signal is recorded in an FM format with nine channels frequency-multiplexed, it is necessary to run the cassette signal through a set of discriminators to extract the voltage output of the desired channel. The nine channels for the recorders as set up for this experiment consisted of three data channels corresponding to three different attenuation settings in the geophone amplifier, three unused data channels, an IRIG-E time code channel, a compensation frequency channel, and one additional unused channel. The time code output from the discriminators is fed into a time code translator so that the timing information on the tape can be used to position the tape to the data section to be digitized. After the tape has been wound to the appropriate point, a section of a desired channel is digitized and the resulting samples stored on some computer storage medium such as disk. Finally, the digitized samples are sent to a digital plotter to be plotted as a seismic trace in a record section. This sequence is controlled by interaction between an operator and the computer.

The appropriate components and interconnections required to perform this processing sequence appear in the block diagram of figure 9.

Control lines and data lines are represented by interconnections between components. Double lines indicate the two-way information transfers used in a control function, and single lines represent data flow. The cassette is wound in the fast-forward mode on the playback unit to a predetermined revolution count corresponding to the record section to be digitized. The computer then shifts the cassette unit into play mode and the time code output from the discriminators is decoded in the time code translator. The decoded clock time is read by the computer to determine when to start digitizing. The digitize-start time, and in fact all control parameters, have been previously entered into the processing program through the terminal. At the proper time, the computer initiates digitization by

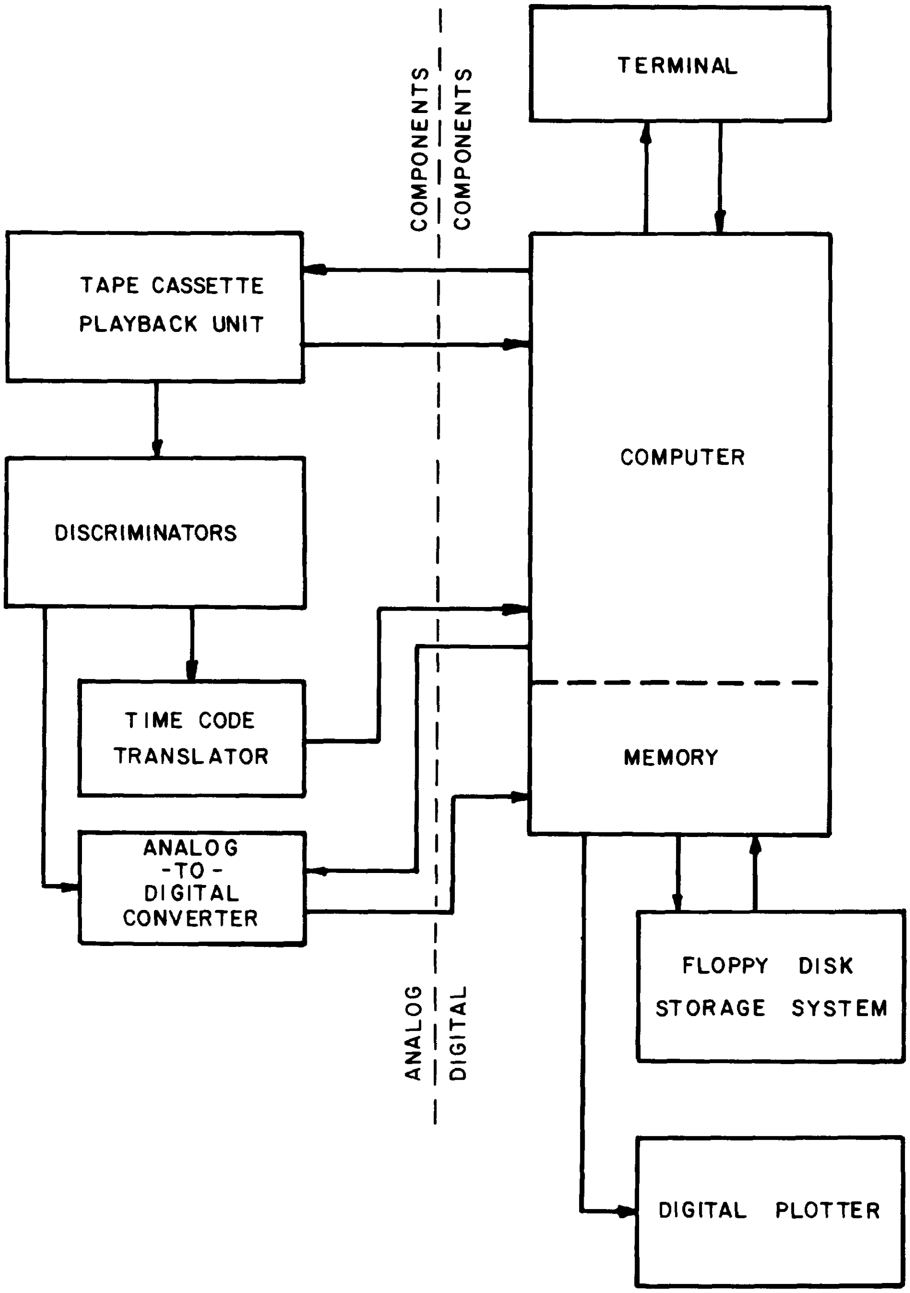


Figure 9. Schematic of seismic processing system showing control and data lines.

activating the A/D converter and causing it to digitize a fixed number of data samples at a predefined sampling rate. This data set is stored initially in the computer memory, then is transferred onto a removable floppy disk for permanent storage. Finally, upon command from the user at the terminal, the data set can be sent to the digital plotter and the seismic trace plotted as part of the record section.

The central controlling computer is a Digital Equipment Corporation LSI-11, a 16-bit word 'microcomputer' or a computer-on-a-card with 32,000 words of memory. The cassette playback unit is a Phi-Deck, identical to those used in the recorders and dubbers. The discriminators are manufactured by Tri-Com, the time code translator is a Datum Model 9200 and the A/D Convertor is a DEC ADV 11-A 12-bit successive approximation analog-to-digital convertor with built-in multiplexer accommodating 16-single-ended or eight differential-mode inputs. The digital plotting system manufactured by Houston Instruments consists of two units: a plotter controller, the PIC-SA, containing a microprocessor, and a model DP-1 digital incremental pen plotter with a 200-step/inch resolution. The plotter controller contains a read-only-memory, which controls step-by-step pen movements given the end coordinates of a vector or the code for a character. This feature simplifies the creation of plot software.

The LSI-11 is the smallest member of the well-known DEC PDP-11 family. The CPU is contained on one 22- by 25-cm printed circuit board. Together with its memory board and several interface cards the complete unit measures approximately 28 by 28 by 8 cm. All of the essential hardware architecture, i.e. the same instruction set and software features of the much larger and faster PDP-11/40 computer, are retained in the LSI-11. The LSI-11 is a general purpose computer, which can be tailored for many instrumentation, data processing, and controller applications. The LSI-11 coupled with an RXVII floppy-disk mass-storage system and any standard computer terminal forms a PDP-11VO3 development system and includes the DEC RT-11 operating system software. The RT-11 operating system includes single job and foreground/background system monitors. All the normal tools used in software development are available with the RT-11 system. These include FORTRAN, BASIC, and MACRO (assembly) language processors, system utilities such as a text editor, a linker and a program librarian, and file-management utilities such as the OEC products PIP (the Peripheral Interchange Program) used for transferring files or deleting or renaming files, FILEX used for reformatting files, and DUMP used for displaying all or selected portions of a file on a terminal.

The computer/terminal/floppy disk elements forming the core of the seismic processing system actually consist of this complete PDP-11V03 hardware/software computer system. All components except for the terminal and plotter are specially packaged in three lightweight fiberglass, rack-mount cabinets where the racks themselves are suspended from the cabinet on rubber shock mounts. Figure 10 depicts the physical layout of the components inside the fiberglass rack/cabinets. The terminal comes in an integral typewriter-plus-carrying case unit and the plotter is transported in a wooden box. In addition, an Ultra Isolation Transformer manufactured by Topaz Electronics is interfaced between the computer system and the local power source, such as a gasoline generator, as protection against voltage surges or spikes. Heavy duty cooling fans have been installed at strategic locations in the cabinet or cases to reduce the operating temperature.

The operating program for producing seismic record sections is written in FORTRAN and is called TRACES. TRACES provides all functions required to process cassettes in a series of 25 commands called macros. To process a record the user types in a sequence of these commands. Many macro commands in turn require additional input or offer selected options. These commands fall into several logical groupings. Some commands accept descriptive or control parameters relating to the shot location and time, or recorder ID and location, or record section plot specifications, or digitization rates and windows. Others control cassette tape motion. One set manages data files on the floppy diskettes. One single command will initiate plotting of an entire 120-record seismic section using data files stored on one diskette. Another grouping of commands is used for diagnostics in the event that problems develop in processing a tape. Finally, an additional sequence of commands can be used for computer system and component check-out. During normal processing, five commands are used to set up processing and three are used in a repetitive cycle for processing a batch of seismic records. Table 3 provides a tabulation of all 25 macro commands in TRACES. TRACES has been written in modular fashion so that it is very easy to add additional capability through additional commands.

Figure 11 is an example of a record section. Various arrivals of different seismic wave phases are clearly visible in the record. It requires about 1 hour to produce a 100-record section.

In addition to digitizing and plotting data using program TRACES, the computer system was put to use during the refraction survey as a utility tool for maintaining various informational data sets and producing tabulations and listings of various sorts. A Recorder Performance Summary file was

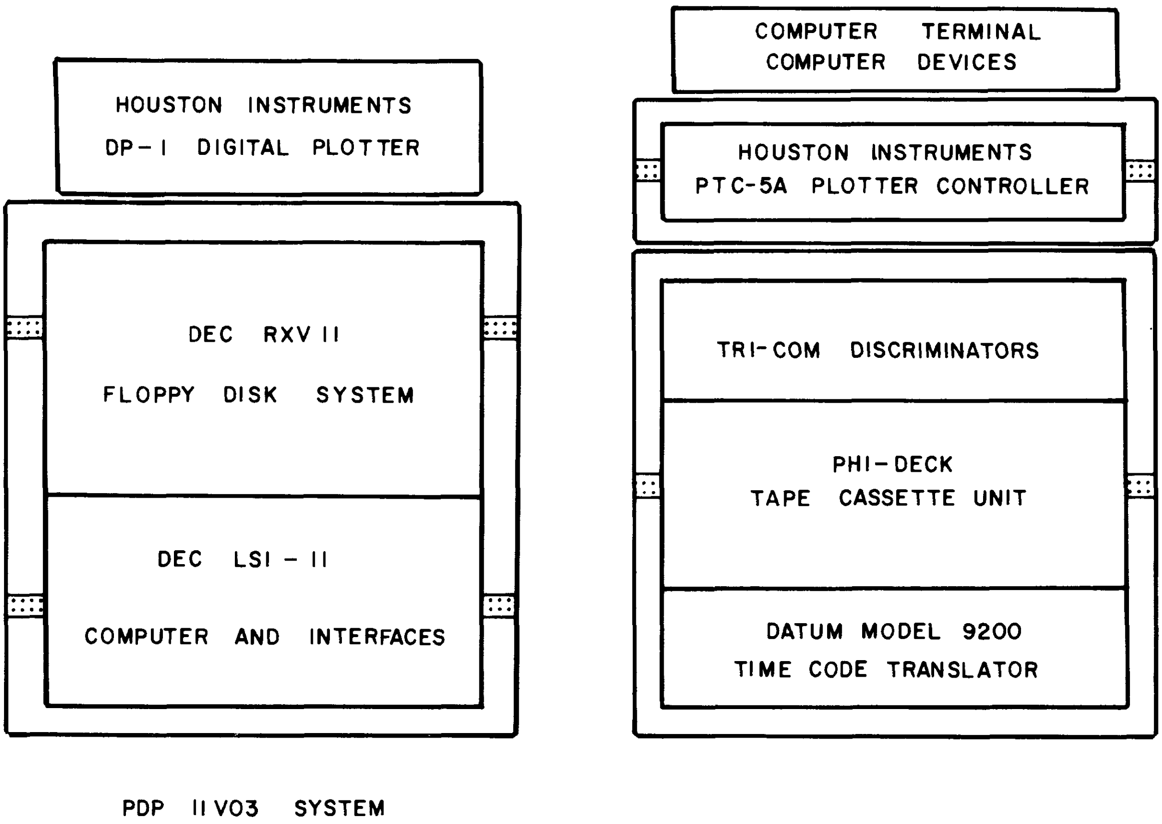


Figure 10. Components of seismic processing system.

Table 3.--*Program traces - macro commands*

Macro number	Function
1	Enter shot data
2	Initialize plotter, draw time axis, and label plot
3	Enter recorder data
4	Digitize, store, plot trace
5	Re-initialize plotter pen position
6	Set polarity flag
7	Enter digitization parameters
8	Enter plot parameters
9	Initialize Phi-Deck and rewind tape
10	Stop tape
11	Play tape
12	Fast forward tape
13	Rewind tape
14	Print tape status
15	"Monkey mode" - initiate A/D conversion from terminal
16	Relative tape motion
17	Read print time code
18	Load shot and recorder locations from diskette into memory
19	Initialize Phi-Deck but do not rewind
20	Initialize diskette
21	Open diskette file for access
22	Close diskette file
23	List contents of data diskette
24	Delete data trace from diskette
25	Automatic plot of diskette

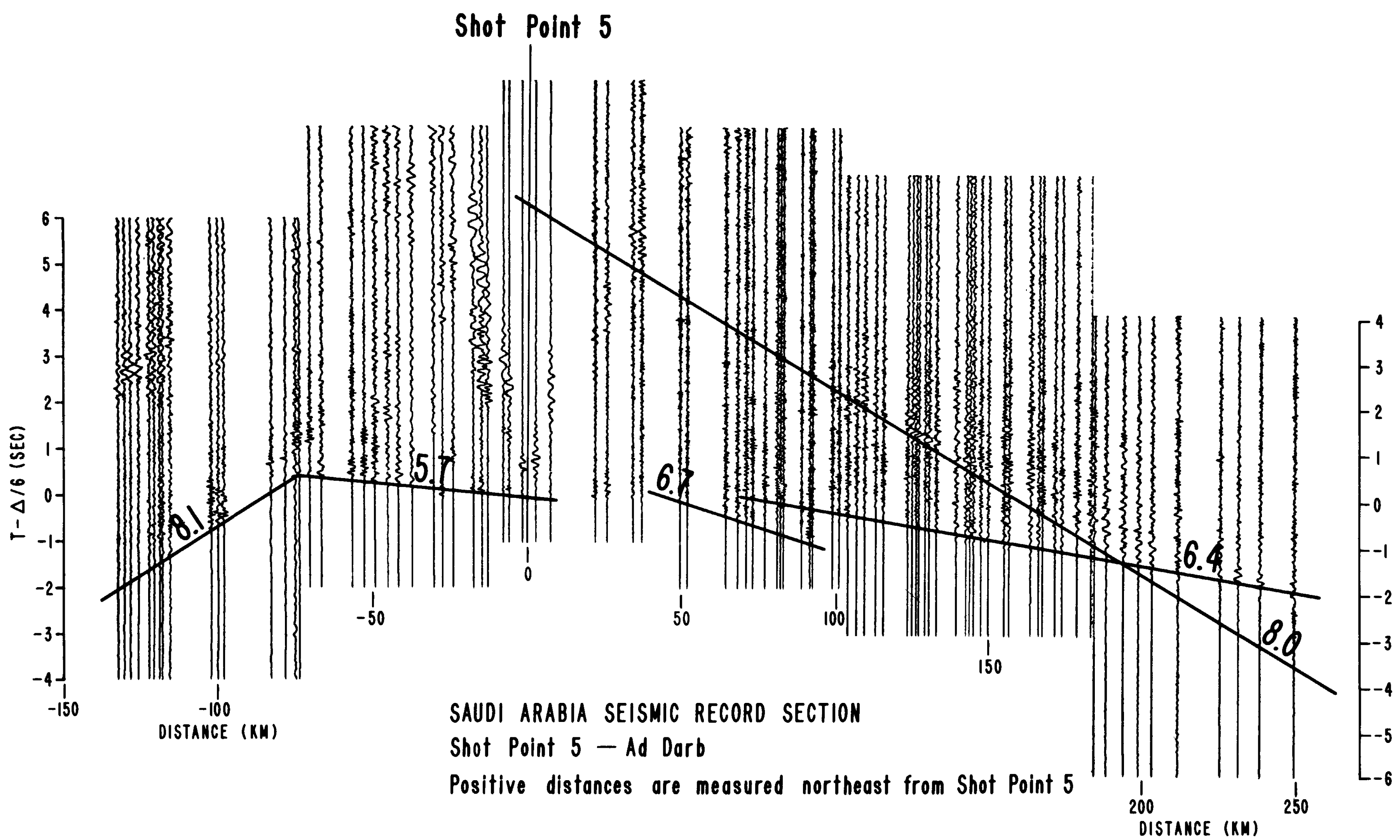


Figure 11. Sample record section from refraction survey.

instituted and updated during the course of the experiment, documenting the success or specific ills of all geophone/ recorder units. A dynamic Shot Schedule was maintained and regularly published showing scheduled and re-scheduled shot dates and supporting information. All recorder and shot locations in latitude and longitude were stored on a diskette file. Distances from shots to recorders, and expected seismic wave arrival times according to various velocity models, were computed and listed. This information was in turn used to guide parameter settings in TRACES when the time came for processing. Distances and azimuths between recorder sites were calculated and lists were distributed among observer teams as an aid in locating recorder stations. A file was set up and tabulations produced listing attenuation settings for the three recorder data channels for all shot sites and all recorder locations. Finally, a computer program was written for computing power spectra of individual seismograms. This program utilizes the standardized diskette-file-access routines developed for TRACES. These routines can be used for data-file access in future programming projects aimed at accessing and manipulating digital seismic data.

The seismic processing system can be set up in and put into operation in approximately 20 minutes. The fiberglass cabinet/cases must be positioned, the lids removed, and cables connected between components and computer. The system boxes can be easily installed in a van on a foam and plywood sandwich platform and tied down using ordinary rope or parachute cord. During the seismic refraction experiment the system was hauled approximately 1500 kilometers on highway and desert track. The only failure (apparently) resulting from transporting was a snapped rubber drive belt on a Phi-Deck cassette playback unit.

The seismic processing system was developed by Geosystems, Inc. of Palo Alto, California, USA, using components selected by the U.S. Geological Survey and according to USGS specifications.

Timing system

The master clocks used in this project contain the basic clock circuitry used in the portable seismic station (PSS) clocks with additional circuitry to provide several different functions and improved features. Like the PSS clocks, the master clocks provide an IRIG E serial time code output together with an LED display of the Julian date, hours, minutes, and seconds. Four additional features include an oven-stabilized crystal oscillator, an output pulse on a preselected minute, an internal battery charger, and a 1 MHz frequency standard output.

The oven-stabilized crystal has an aging rate of 5 parts in 10^{10}. This is two and a half orders of magnitude more stable than the crystals used in the PSS clocks. This stability allowed the construction of five identical master clocks, which needed comparisons fewer than once a week in order to maintain timing differences of less than 1 millisecond between all shot points.

The preset (START) output pulse was used to fire explosions automatically on a given minute.

The internal battery charger allowed operation of the clocks from 120 VAC, an external 25 VDC battery, or the internal 24 V 7.5 AH batteries. These internal rechargeable batteries supplied enough power to operate the clocks for 3 1/2 days, which permitted the clocks to be transported between camps and out to the actual shotpoints without loss of the time base.

The 1 MHz output was used as a standard frequency for a precision counter. The counter, in turn, was used to trim the PSS clock crystals and also to set tape deck capstan speeds.

The same methods are used to set both the master clocks and the PSS clocks. First, the main power or internal battery switch is turned on. Then, after a 1 hour warm-up period, six controls are used to set the time in the following manner:

-- Place the hold/run switch into HOLD

-- Push the RESET button

-- Turn the digit select switch to TS (to set Tens of Seconds)

-- Push the SET button once to advance the tens-of-seconds digit by 1 (push twice for 2, etc.)

-- In a similar manner, set the reset of the display digits in order from right to left (UM = Units of Minutes, UH = Units of Hours, UD = Units of Days)

-- When the present time coincides with true time, switch to RUN, then release the HOLD/RUN switch to the center position (alternately, the clock may be started by a 0 to +10 VDC level change applied to the RUN)

-- To advance or retard the clock to agree with a known standard, hold the ADV/RET switch in the correct position while holding the RATE switch in the 1 mSec/Sec or 100 mSec/Sec position for the necessary amount of time.

All timing for this project was derived from the time signals broadcast by the British Broadcasting Co. (BBC). The BBC was the source of the GMT signals: however, no correction was made for radio propagation delays. Any such delays were assumed constant over the entire length of the profile.

In practice, only two master clocks were set against the BBC standard. One clock was located on the ship (Shot Point 6), and the other started at Shot Point 1. The clock that started at Shot Point 1 was used to set the three other master clocks located at the other active shotpoints a few days before each shot series. Due to the master clock crystal stability, this transfer procedure resulted in a relative error between master clocks of less than 1 millisecond.

The BBC time standard was assumed perfectly stable and accurate. Propagation delay variations were minimized by using the same broadcast frequency each day at the same time. For the first part of the experiment, the BBC signal was received at 9 AM local time (0600 GMT) at 15.4 MHz. In order to ease recording problems on the ship, the frequency received was changed to 9.4 MHz at 6 PM local time (1500 GMT) for the second half of the experiment.

In order to determine and correct the relative timing error between the BBC and the master clocks, the following procedure was used:

(1) Set up equipment as in figure 12

(2) Tune in the correct BBC station 1 minute before desired hour

(3) Start tape recorder 45 seconds before hour. (The blaster interface contains a gated oscillator, which is used to convert the IRIG code DC level shift into a 2 KHz tone burst suitable for recording on tape. The tape recorder was used to prevent noise generated by the KIOWA strip chart recorder from interfering with the radio.)

(4) Set chart speed to 20 cm/sec and play back both timing signals

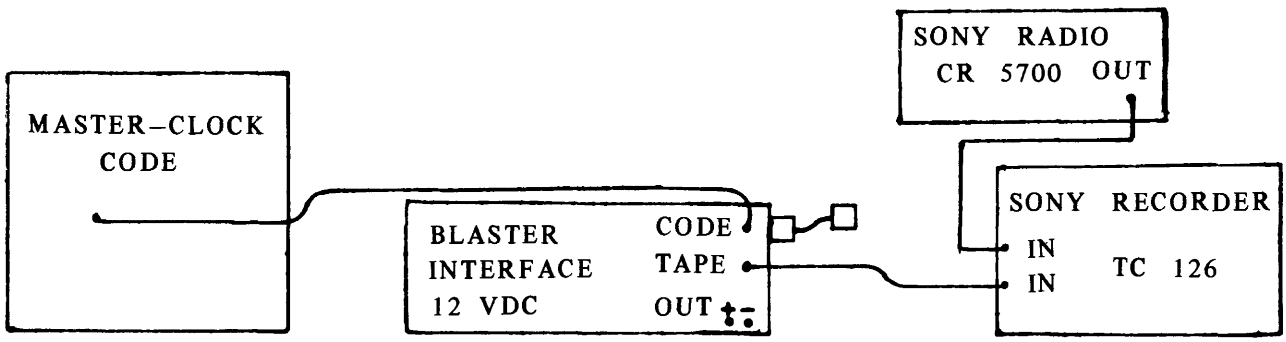
(5) Measure relative error on paper record (± 0.1 mm yields ± 0.5 mSec resolution--see sample record, fig. 13)

(6) Advance or retard master clock to eliminate error if error greater than 1 millisecond

(7) Record in master clock log book:

a. amount of error
b. date and time of correction

SCHEMATIC FOR RECORDING TIME SIGNALS



SCHEMATIC FOR PLAYBACK TIME SIGNALS

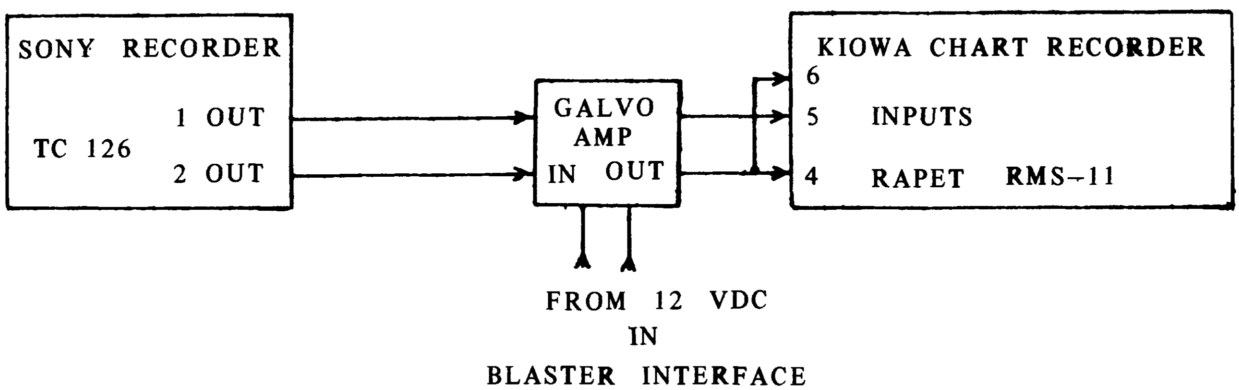


Figure 12. Equipment interconnections.

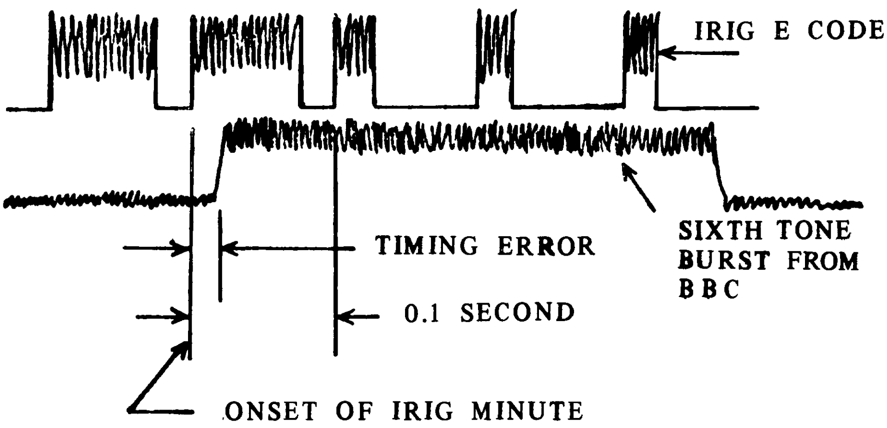


Figure 13. Sample time error measurement record.

Shooting system

The timing and firing system automatically fires explosives on a preselected minute and also provides a paper record of the actual firing time. The system is contained in four separate units: a master clock, a blaster interface, a blaster, and a strip chart recorder. System connecting cables are stored in the lid of the master clock.

The system is powered by internal, rechargeable batteries. The clock batteries are described in the section of this report dealing with the master clocks. The only other batteries are located in the blaster interface. These 12 V 6 AH gel cells may be recharged by connecting a charger to the 12 VDC terminals on the front of the blaster interface.

The system is set up according to the diagram shown in figure 14. System tests and shot-firing steps are outlined in this figure.

FIRING SYSTEM SET-UP:

Connect CODE line from master clock to chart recorder (BNC to pins)

Connect START line from master clock to blaster interface (BNC-BNC)

Connect cap break line from master clock to chart recorder

Connect blaster interface cable from blaster (four pin end) to interface (five pin end)

Connect 12 VDC from blaster interface to chart recorder

Turn recorder off

Switch blaster to AUTOMATIC

FIRING SYSTEM TEST

Firing line must be disconnected

Connect a 10 Ohm resistor across firing line posts

Set START thumbwheel to 2 minutes beyond current minute

Hold down SAFETY INTERLOCK and crank up firing voltage to 50 volts

Turn recorder on (20 cm/sec) but do not start the recorder

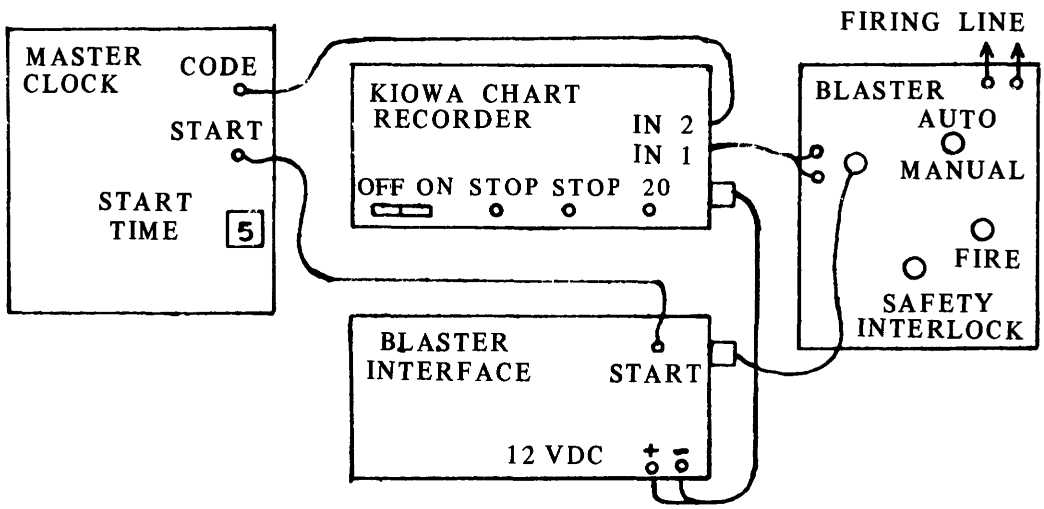


Figure 14. Shot timing and measurement system.

5 seconds before START TIME, start chart recorder

4 seconds before START TIME, pull up and hold the FIRE knob

After beep, stop recorder and develop record

FIRING SEQUENCE

Switch blaster to AUTOMATIC

Set thumbwheel on master clock for desired shot minute

1 minute before shot time, connect firing line

Crank up firing voltage (hold SAFETY INTERLOCK down until after shot)

5 seconds before shot time, start recorder

4 seconds before shot time, hold up FIRE knob

After shot, turn off recorder and develop the paper record (if shot did not fire, switch blaster to MANUAL and hold up the fire knob)

Turn clock display off

On paper record, print date, shot location and length of primacord between cap and explosives

Disconnect all cables and return them to master-clock lid

SHOT TIME DETERMINATION

The actual shot time includes delays caused by relay closure times and the finite velocity of the detonating fuse between the blasting cap and the explosives. The following steps are taken to determine the shot time (refer to fig. 14).

Locate preselected start time on paper record (IRIG code). Measure length of 0.1 sec interval (TSL)

Measure length between START time and the blasting cap break (CBL), displayed as an impulse

Cap detonation time (CT) in seconds is: CT = (0.1)(CBL)/(TSL)

Shot time is the sum of the START time, CT, and the time required for the primacord to reach the explosives. Because the primacord burns at 28 feet per millisecond:

Shot time = START time + CT + (feet of primacord) (0.001)/(28)

The data, time, charge, and depth load spread of all shots fired for the deep-refraction profile are listed in table 4.

Table 4.--*List showing the charge, time, and depth of each shot*

Shot Point	Date	Time (GMT)	Charge size in kilograms	Remarks
1	3 Feb 78	34 01:00:00.012	816	In 2-60 m holes
1	6 Feb 78	37 01:00:00.012	3410	6-60 m holes
1	9 Feb 78	40 01:00:00.012	4410	7-60 m holes
1	16 Feb 78	47 01:00:00.012	5000	6 redrill holes
2	3 Feb 78	34 01:45:00.650	1320	4-60 m holes
2	6 Feb 78	37 01:15:02.456	1364	3-60 m holes
2	9 Feb 78	40 01:45:00.876	2045	5 redrill holes
2	13 Feb 78	44 01:00:00.011	4773	5 redrill holes
3	13 Feb 78	44 01:15:00.015	1000	3-60 m holes
3	16 Feb 78	47 01:15:00.010	8545	6-60 m holes and redrills
4	13 Feb 78	44 01:30:00.015	2636	7-60 m holes
4	16 Feb 78	47 01:30:00.015	1364	3-60 m holes
4	22 Feb 78	53 04:30:00.013	5545	11 shallow pattern holes
5	20 Feb 78	51 01:00:00.013	4000	2-60 m holes
5	22 Feb 78	53 01:15:00.014	1455	5-60 m holes
6	3 Feb 78	34 01:30	1361	Sea shot 60 m
6	9 Feb 78	40 04:00:00.042	2272	Sea shot 60 m
6	16 Feb 78	47 04:00:00.057	2272	Sea shot 60 m
6	20 Feb 78	51 04:00:00.037	2272	Sea shot 60 m
6	22 Feb 78	53 05:00:00.030	2272	Sea shot 60 m

FIELD PROCEDURES

The procedures followed by members of the five two-man recording teams normally required a minimum of 2 days separation between scheduled shots. The time was generally consumed in carrying out the following activities:

(1) In the morning of the day preceding the scheduled shots, each team set the chronometer of its hand-held tester (HHT) by comparison with a master clock, then entered the specified start and stop times for recording all scheduled shots into the HHT.

(2) The HHT was then connected sequentially to each of the team's 20 recording instruments so that the chronometer could be set to within 0.1 millisecond of the time of the HHT chronometer, and the recording information programmed into the HHT was delivered to the memory of the recording instrument. The HHT was then used to query the instrument on how it was programmed, to make certain that it had accepted the instructions it had been given.

(3) The tape heads in the recording instruments were carefully cleaned and the tape cassettes were mounted in the recorders.

(4) The afternoon and evening of the day before the scheduled shots, the teams, accompanied by guides who had surveyed the locations, drove to their 20 assigned locations, where they buried each instrument's seismometer in a hole about 0.3 m deep and put the instrument box in some inconspicuous location after setting attenuation switches at levels calculated by the field manager. All of these activities took only a few minutes of time at each location. Based on the distance between the teams' assigned locations and the nearest camp, the teams then elected either to spend the night in the field or to drive back to the camp.

(5) Immediately following the shot, the teams picked up their 20 instruments after noting on their log sheets which recording instrument was installed at each location.

(6) After the teams returned to the nearest camp, the time on the chronometer at each recording instrument was compared with the time on the HHT chronometer (which was first set by comparison with a master clock) and any discrepancy in time was noted on the log sheet. The recorded tape cassettes were removed from the recording instruments and were carefully labeled and the instrument batteries were then put on charge.

(7) The tapes were dubbed by means of the tape dubbing system described above. During the dubbing process a visual record was made on photosensitive paper of the recording of at least one shot of each tape to establish that the instrument was operating properly.

(8) Any instrumental problems identified from the visual recordings were referred to the repair staff. The repair work had to be completed on the afternoon or evening of the first shot day when the shots were scheduled 2 days apart because most of the following day was dedicated to programming and deploying the instruments.

During the last 2 shooting days, when the recording instruments were deployed along the Asir escarpment and in the Farasan Islands, the field operations were carried out with helicopter support rather than with trucks. The procedures used were essentially the same as those developed for use with surface vehicles.

DISCUSSION OF DATA

The seismic refraction data recorded from the six shot points are shown as record sections in figures 16 through 21. The record sections show the first 10 seconds of data recorded at each station. Most of the record sections were made in the field during the field operation, and the remainder were made within a few days after the conclusion of the field operation. The data shown are the raw data as recorded; no attempt was made to adjust individual trace gains and no filtering was used. As a result many of the traces appear to exhibit very weak first arrivals and a few traces appear to be noisy. Before the final analysis of the data, individual traces will be timed and filtered to exhibit the optimum data such as clear first arrivals, improved secondary arrivals, and so forth. The lines shown on the record sections should be considered as guidelines only to show the approximate wave velocity of the first arrivals and in a few cases to show evidence for important secondary events. These velocities will be determined more accurately after the data have been through the final processing.

The following notation has been used in this report to identify various phases:

Pg - Direct compressional wave that travels in the upper crustal layer with a velocity near 6.0 km/sec.

P* - A refracted compressional wave traveling in the lower crustal layer with a velocity near 6.7 km/sec.

Pn - A refracted compressional wave in the upper mantle with a velocity near 8.0 km/sec.

S - Shear or Rayleigh wave in the upper crust, with a velocity near 3.5 km/sec.

Shot Point 1

Data were recorded from this shot point (fig. 16) to a distance of 80 km to the northeast and 580 km to the southwest. The data from Shot Point 1 are generally of good to excellent quality. Very clear first arrivals were recorded to a distance of 350 km, and by adjustment of the gains and the use of appropriate filters, they probably can be timed along the entire length of line recorded.

The first arrivals from Shot Point 1 can be represented approximately by two straight line segments. To the northeast the lines represent apparent velocities of 5.8 km/sec from the shot point to a distance of 40 km and 6.2 km/sec beyond 40 km. Both of these waves are probably direct waves (Pg) through the upper crustal rocks, and the change in apparent velocity is probably a change in dip of the upper sedimentary rocks.

To the southwest, the first arrivals exhibit an apparent velocity of 6.2 km/sec from the shot point to a distance of 180 km. The apparent Pg velocities of 5.8 to the northeast and 6.2 to the southwest undoubtedly reflect the dip to the northeast of about 1° or 2° in the sedimentary layer that can be seen on the surface.

Beyond 180 km to the southwest, the first arrivals show an apparent velocity of 8.2 km/sec. This phase represents a refracted wave in the upper mantle rocks (Pn).

One fairly good secondary phase P* showing a velocity of approximately 6.7 km/sec has been marked and possibly represents a refracted wave in the lower crust.

The data from Shot Point 1 appear to suggest a two-layer crust with velocities of 6.0 and 6.7 km/sec, underlain by the mantle with a velocity near 8.0 km/sec.

Shot Point 2

Although the data recorded from Shot Point 2 are weaker than those recorded from Shot Point 1, they are of sufficient quality to be usable in delineating the crustal structures.

As with the data from Shot Point 1, the first arrivals from Shot Point 2 can be represented by two straight line segments.

First arrivals to the northeast from the shot point are of fair quality to a distance of 125 km and represent a direct wave in the upper crust (Pg) traveling at an apparent velocity of 6.2 km/sec.

Although no velocity can be assigned to Pn, there is an indication of early arrivals near 200 km. High-gain record sections will be required to delineate Pn in this direction. It would also have been helpful if the line had been a few kilometers longer in this direction.

A secondary arrival with an apparent velocity of 6.6 km/sec is well-defined, especially beyond 150 km.

A well-developed shear or Rayleigh wave with a velocity near 3.5 km/sec is present in both directions from the shot point.

The first arrivals recorded to the southwest for a distance of 180 km indicate a Pg phase with a velocity of 6.1 km/sec. This is a good example of data that need to be played back at much higher gains. The first arrivals are very clear on a few traces and could undoubtedly be much improved on the other weaker traces.

Beyond 180 km an apparent velocity of 8.5 km/sec represents Pn. This velocity is probably an updip velocity as explained by a low apparent reversed Pn recorded from Shot Point 4 and indicated by the delayed segment about 300 km southwest on the Shot Point 1 record section.

A high amplitude secondary phase with an apparent velocity of 6.7 km/sec probably represents P*, a refracted wave from a deeper layer in the crust.

Shot Point 3

Data from Shot Point 3 unfortunately were recorded in only one direction, to the southwest, because of a delay in explosives shipment. However, this loss is probably not serious as data from adjacent Shot Points 2 and 4 can be used to delineate the structure in this area.

The data from Shot Point 3 are very similar to those recorded from Shot Point 2. First arrivals can be defined by two lines, Pg with an apparent velocity of 6.2 km/sec, and a mantle refraction (Pn) with an apparent velocity of 8.0 km/sec.

Here again a well-defined secondary arrival with an apparent velocity of 6.6 km/sec is evident.

Shot Point 4

The data to the northeast of Shot Point 4 show an apparent Pg phase with a velocity of 6.2 km/sec to a distance of 180 km. Beyond 180 km, very weak earlier arrivals represent the Pn phase with a velocity that has tentatively been determined as about 7.8 km/sec. The phase is poorly defined on the field playback record section. However, higher-gain playbacks will in all probability improve the data. The 7.8 km/sec Pn correlates well with the high 8.5 km/sec Pn recorded to the southwest from Shot Point 2. This would indicate a slight dip approximately 2° to the northeast. The lower crustal layer P* (velocity near 6.7 km) is not well defined from Shot Point 4.

To the southwest, a Pg phase with a velocity of 6.2 km/sec is recorded to a distance of 200 km. Beyond 200 km the first Pn arrivals show an apparent velocity of 8.5 km/sec, which indicates that the northeast dip of the mantle continues.

Shot Point 5

The position of Shot Point 5 is very near the boundary of the continental crust to the northeast and an oceanic type crust to the southwest, as determined previously from gravity and other studies. As a result the data recorded to the northeast are very complicated and will require further study to delineate the structure.

The first arrivals to a distance of 200 km appear to represent several phases with velocity ranging from 6.0 to 6.7 km/sec. Beyond 200 km the first arrivals show a poorly defined Pn velocity of near 8 km/sec.

The data to the southwest show a remarkable change from the data recorded from Shot Points 1 through 4.

A low Pg velocity, 5.7 is indicated out to a distance of only 75 km as compared to 180 km for the previous shot points. Beyond 75 km the first arrivals show a Pn phase with a velocity of 8.1 km/sec.

Shot Point 6

Data from Shot Point 6 (Red Sea shots) were recorded to a distance of 500 km to the northeast.

Near the shot point the first arrival shows a velocity of 4.5 km, probably a phase traveling through the upper sedimentary rocks. Beyond 30 km the velocity increases;

however, the data are recorded only on a few stations, and an accurate velocity will be difficult to determine although it appears to be about 6.5 km/sec.

Beyond 60 km the first arrivals, although very weak probably due to low-gain playbacks, indicate a Pn phase with a velocity near 8 km/sec.

This phase disappears near Shot Point 5 at a distance of 175 km as would be expected at the edge of the oceanic crust.

From 175 km to 250 km the first arrivals appear to be complicated refracted waves. Beyond 250 km to 475 km the first arrivals show a very well defined Pn(?) phase with a velocity of 8.5 km/sec. This phase is several seconds later than the 8.2 km/sec Pn near the shot point. The 8.5 km/sec phase is higher than would be expected for a normal mantle velocity and may be a refraction from a deeper layer in the mantle. Further study using various schemes such as ray tracing, amplitude studies, and so forth will be required to delineate this transition zone from oceanic to continental crust.

PRELIMINARY INTERPRETATION

A tentative gross crustal structure has been computed using the field record sections and making the following assumptions:

(1) The crust consists of two discrete homogeneous, isotropic layers: an upper layer that exhibits a compressional velocity of near 6.0 km/sec, and a lower layer with a velocity near 6.7 km/sec.

(2) The crust-mantle boundary, the Mohorovicic discontinuity, is a sharp boundary.

(3) The velocity does not increase with depth within the two crustal layers.

(4) No "hidden" low-velocity layers are present.

(5) Delays due to surface inhomogeneities or elevation changes are negligible.

A schematic crustal model for the entire profile is shown in figure 15. The thickness of the upper crustal layer between Shot Points 1, 2, 3, and 4, and from Shot Point 5 to the northeast appears to be quite consistent and averages approximately 23 km. The total crustal thickness as computed varies from 35 to 45 km and averages 40 km.

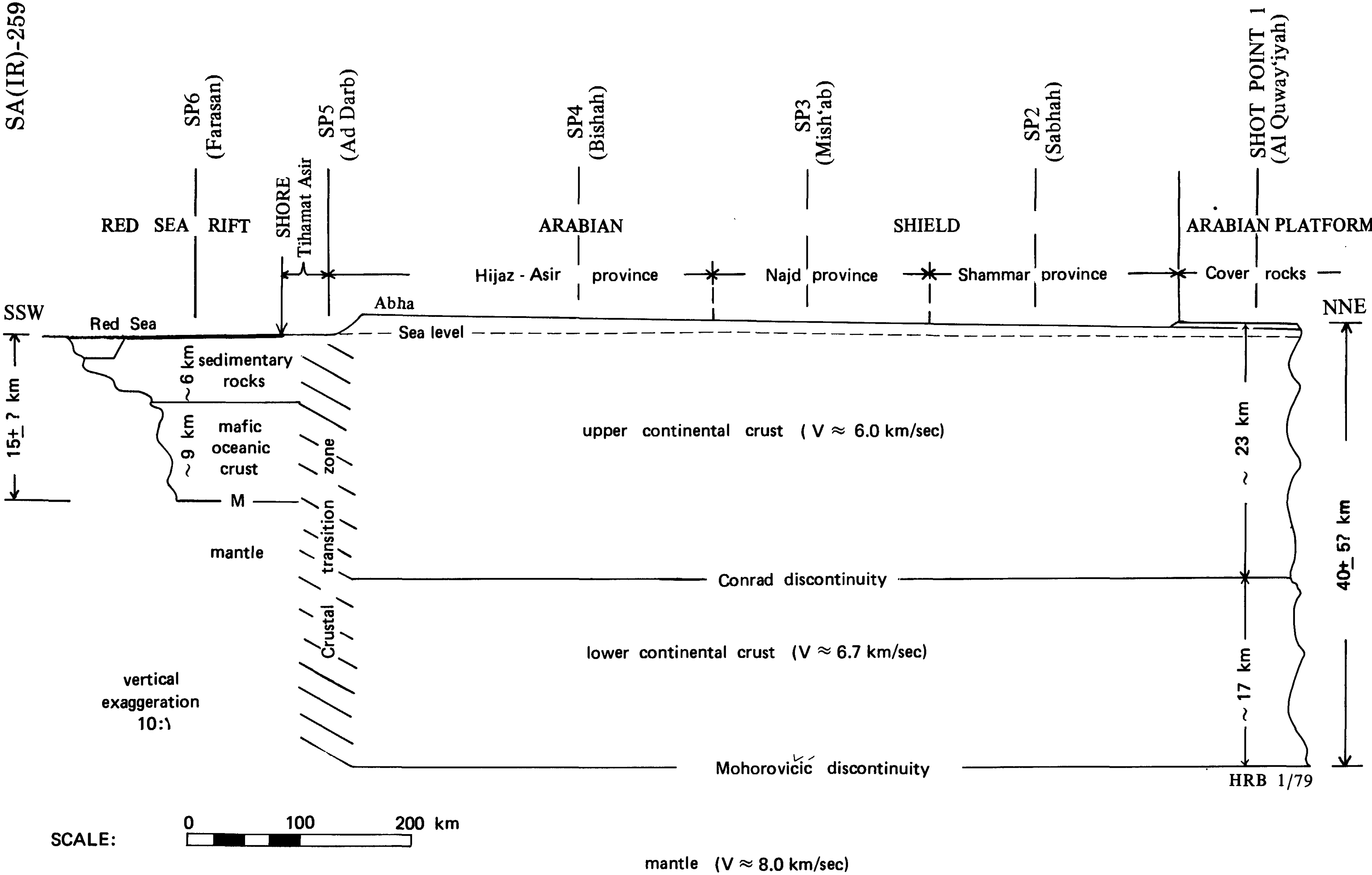


Figure 15.– –Schematic crustal model of southwest Saudi Arabia derived from preliminary interpretation of seismic deep-refraction profile recorded February, 1978.

The data indicate a dramatic change in the crust at Shot Point 5. The data southwest from Shot Point 5 and at Shot Point 6 indicate that the upper crustal layer thins to approximately 9 km and the total crust thickness is near 15 km.

The assumptions and simplications listed above probably make the estimate of uncertainty in thickness calculations meaningless at this stage of the interpretation. The crustal model shown in figure 15 is strictly a schematic approximation, and the crustal model that will be computed from the refined data will undoubtably change somewhat and indeed may be quite different.

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