SwRI Proposal No. 14-3306
August 9, 1985

A proposal for

INVESTIGATION OF THE SELF-POTENTIAL MEASURED
FOR ISOLATED ROCK SAMPLES

Submitted to

The Townsend Brown Foundation
P.O. Box 1565
Avalon, CA 90704

Prepared by

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Institute Scientist

Approved:

T. E. Owen

Thomas E. Owen, Director
Department of Geosciences

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON

TABLE OF CONTENTS

I. INTRODUCTION

Southwest Research Institute has been contracted by the Townsend Brown Foundation in regard to replicating and extending experiments associated with the measurement and long-term recording of the self-potential of isolated basaltic rocks. Of particular interest in relation to this experimental study are the observable variations in the measured data, which exhibit diurnal, weekly, seasonal, semiannual, and annual periodicities. In response to the request for proposal, a project is described which is aimed at conducting a thorough and critical examination of the reported self-potential phenomena.

Self or spontaneous potentials within the earth are well known and have been utilized for mineral exploration for over 150 years. One of the earliest applications of self potential measurements was reported by R.W. Fox[(1)] in 1830 in which he utilized self potential measurements along the walls of mines to locate sulphide deposits. These potentials within the earth originate most often from electrochemical reactions, particularly reduction-oxidation (redox) processes. The self potentials produced by a sulfide body are nomrally producted by redox reactions. Water from the surface containing desolved oxygen produces an oxidizing region over a part of the sulfide body while other parts of the surface are in a reducing environment. The resultant difference of potential between different parts of the body produces a current flow and an associated potential gradient which is measurable at the surface of the earth. Other electrochemical reactions can occur at the interface between different types of materials. For example, self-potentials are high at contacts between shale and sandstone. If this region is penetrated by a borehole, currents can flow in the borehole fluid between the two layers thus producing a potential gradient which may be measured in the borehole. Selective diffusion or absorption of ionic charges can also produce electric potentials between one type of geologic material and another. Electrokinetic charge separation resulting from the flow of ground water or borehole fluids through the porous medium can also produce spontaneous potentials. Thermoelectric generation of currents and, hence, natural potential gradients has also been observed, particularly in geothermal regions.

A careful review of the various processes which produce self potentials within the earth has failed to identify a process which is likely to produce similar electric potentials across an isolated rock sample. However, the experiment conducted by T.T. Brown has shown a measurable potential. The purpose of the proposed project is therefore to design and carry out experiments which will lead to definite identification of the source of the potentials previously observed. There are a variety of well known physical phenomena which could have produced the observed deflections of the strip chart recorder in the previous experiments. Since there are many possible sources and

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(1) Fox, R.W. (1830) "On the Electromagnetic Properties of Metalliferous Veins in the Mines of Cornwall" Philosophical Transactions of the Royal Society, 130,399.

potentially valid explanations of the observations, a systematic and comprehensive investigation must be planned in order to assure that definitive results are obtained. Within the scope of the proposed project,it should be possible to answer the questions concerning the origin or cause of the previous observations to the satisfaction of all concerned, assuming that observations similar to those obtained by T.T. Brown can be repeated.

II. TECHNICAL DISCUSSION

A. The Previous Experiment

The description of the experiment conducted by T.T. Brown described in Attachment A of the request for proposal is summarized as follows: "An oval-shaped basaltic rock, approximately 3 in. x 5 in. x 8 in., from the rim of the ancient Koolau volcano on Ohau, Hawaii, is thoroughly oven-dried and copper electrodes are painted on opposite sides. The rock is then covered with an insulating plastic sheath and enclosed in several layers of aluminum foil which is grounded. A 5-megohm wire-wound precision resistor (Shallcross) is attached to provide an electrical load. The load causes the freely-floating self-potential of the rock to drop from approximately 300 mV to a mean value of approximately 50 mV. The rock and resistor are encased in an electrically-shielded constant-temperature box controlled to 0.1°C. BNC shielded cable connects the rock to a double-throw one-hour timing switch, thence to a strip-chart recorder as shown in the diagram. When the switch is in Position 1 for one minute, the recorder is directly connected to the rock. When in Position 2, for the remaining 59 minutes, the recorder is connected to a fixed 50 mV constant (battery-fed) source."

As a part of the proposed project, this experiment will be duplicated as nearly as possible including the use of the same type of strip chart recorder and wiring arrangement. In addition, other arrangements of this experiment will be conducted which will be designed to test or identify the possible sources of the observed potential and variations with time.

B. Electric Potentials and Fields

Static and quasistatic electric fields, or potential gradients, arise from chemical, thermal, or mechanical charge separation mechanisms or from induction by a time varying magnetic field. With respect to isolated rock samples, the only self-contained mechanisms which would produce a potential gradient within the rock are electrochemcial or thermoelectric. Since the experiment was conducted with the rock in a temperature-controlled environment, thermoelectric effects within the rock itself are not likely to be the source of the observed potential. Electrochemical processes probably do occur within the rock and would be dependent upon moisture content. However, if the rock is macroscopically homogeneous in its chemical and physical properties, then no net potential difference across the surface of the rock would be expected. For a potential difference to be produced by electrochemical reactions, some nonuniformity and anisotropy must exist which determines a unique direction within the rock. This requirement for a unique directional property within the rock becomes clear with regard to the question of which electrode on the rock will be positive and which will be negative. It is possible that the electrodes used to contact the rock develop a polarization and, hence, a potential difference between the metal electrode and the rock. This electrode polarization will balance out to zero if the two electrodes are of the same material and of equal area.

From these arguments it seems unlikely that the observed potentials originate from any physical or chemical reactions which are associated with the composition or structure of the rock. If these conclusions are correct, then the rock could be replaced by an equivalent electrical circuit without affecting the measured potential.

There may be an explanation for the observed potentials other than energy generation or energy conversion within the rock. Although thermoelectric phenomena within the rock are improbable because of the temperature-controlled environment, the strip-chart recorder and other parts of the electric circuit do not appear to have been in the controlled temperature enclosure. Thus, it is possible that some thermoelectric effect occurred between the components within the enclosure and those exposed to ambient temperature. Another possible origin of the observed data could be electrostatic fields which affect the strip chart recorder or other parts of the circuit which were not located within the shielded enclosure. For example, the normal fair weather electric field near the surface of the earth is of the order of 140 volts per meter although it may reach much higher values during thunderstorm activity. This fair weather field has a mean diurnal variation of 40 to 50 volts/meter measured over the ocean.[(2)] When using sufficiently high impedance instruments, it is possible for this field to produce measurable potentials within the circuit.

Magnetic induction would not at first appear to be a likely source of the observed potentials since time varying fields are required and the induced voltages would also be time varying. Even if the period of the alternating field were much longer than the one minute measurement time it would not necessarily be synchronized with the measurement cycle and would thus produce both positive and negative potential readings. On the other hand, if some element in the circuit should act to partially rectify the alternating currents, then even ambient radio frequency fields could become a possible source of the observed potential.

There are thus many possible sources of the observed recorder deflections. In any experimental measurement of this type, great care must be exercised to identify and eliminate all extraneous sources. With careful planning of the experiments and a thorough scientific approach to the investigation, it should be possible to determine the source of any potentials which cannot be eliminated and to explain any changes in these potentials.

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(2) Pierce, E.T., "Some Topics in Atmospheric Electricity," in Recent Advances in Atmospheric Electricity-Proceedings of the Second Conference on Atmospheric Electricity, 1958, Pergamon Press.

III. PROPOSED PROGRAM

A. Task A - Review of Literature and Past Experiments

The first task of the proposed program is an in-depth literature search and review of related past experiments. This task is expected to require two months although additional literature findings will be reviewed throughout the project as new material is identified. The initial literature search will utilize Southwest Research Institute's access to several computer-based information retrieval services. The initial concentration of the search will be on published observations of self potential produced by isolated rock samples. In addition, however, the search will be expanded to include publications on all related phenomena and other long-term measurements of small electric potentials. All identified papers will be reviewed to establish their relevance to the project. Those papers which appear to contain relevant information will be studied in detail and an interim report summarizing the results of the literature search will be prepared and submitted to the Townsend Brown Foundation.

During the time period of Task A, a review of the previous self-potential experiments will be conducted in addition to the literature search. The Townsend Brown Foundation will be asked to supply any other information available for this review. The purpose of this review is, in part, to insure that the experimental tests are repeated with the equipment arranged as nearly as possible in the same manner as that used in the previous experiment. In addition, a complete review of the previous work may identify other test factors or conditions which should be included in the new experiments.

B. Task B - Final Design of the Experiments

Following the literature search and review of the previous experiments, final designs for the new experiments will be formulated. Based upon knowledge gained during Task A, the tentative experiments outlined under Task C below will be changed or other experiments added. The revised design of the experiments will be submitted to the Townsend Brown Foundation for review and approval prior to the start of Task C.

C. Task C - Experiments

The experiments which will be conducted during this project will be designed with the objective of obtaining a full explanation of all observed electric potentials. The starting point, however, will be to repeat the past experiment conducted by T.T. Brown, with the experimental apparatus being as identical to the original test arrangement as possible. For this experiment, the Townsend Brown Foundation will be asked to supply the original apparatus, if available, or otherwise a complete description and specifications so that a duplicate test set-up may be fabricated. The original rock specimen or a similar rock specimen will also be required. The ability to repeat the earlier observations is necessary before an explanation of the results can be achieved.

Additional experiments will be conducted using an automated digital data recording system. The controller and data logger to be used in this system will consist of a Hewlett Packard 9825 desktop computer available in the Department of Geosciences. This computer will be made available for long-term dedicated use. The other data acquisition equipment required for the tests will be purchased as part of the project. The equipment recommended for this purpose is:

HP Model 3497A Data Acquisition/Control Unit
with Option 001 - 5½ Digit Digital Voltmeter and
Option 010 - 20 Channel Relay Multiplexer

This data acquisition system can be controlled by the HP9825 desktop computer to record data from up to 20 measurement channels at preprogrammed time intervals. The Digital Voltmeter supplied as option 001 of this system has resolution down to one microvolt and an input impedance of 10^9 ohms. The accuracy of this system should be more than adequate for the proposed experiments. The calibration of this system will be periodically checked using a standard voltage cell. In addition to this data acquisition system, three shielded temperature controlled chambers will be constructed or purchased.

The experiments tentatively planned to be conducted include:

Experiment #1: A second rock similar to that used in the repeat of the original experiment will be prepared in an identical manner and the potential monitored by the digital data acquisition system. This experiment will be conducted on a long-term monitoring basis and the data obtained will be compared with that of the repeat of the original experiment. The Townsend Brown Foundation may be asked to assist in obtaining suitable rock samples.

Experiment #2: The temperature, pressure, and humidity both inside of the environmental chamber and outside of the chamber will be recorded.

Experiment #3: An arrangement identical to Experiment #1 will be established except that the rock will be replaced by carbon resistors connected between the electrodes. The resistance value will be set to the measured resistance of the rock used in Experiment #1.

Experiment #4: If non-random electric potentials are observed in the other experiments then another experimental arrangement will be established which can be changed and tested without disturbing the long-term monitoring experiments. This last experiment will primarily be used to determine the origin of potentials recorded by the other experiments. When an outside source of potential is found which can be eliminated, then the other experiments will be modified to eliminate this source. If all observable electric potentials are eliminated by modification of the long-term experiments, or definitely identified as to their origin, then the project will be considered to have been completed.

D. Task D - Final Report

A final report describing all work performed on the project and all findings resulting from the experiments will be prepared and submitted to the Townsend Brown Foundation.

IV. PROJECT STAFFING AND TASK/TIME SCHEDULE

The overall technical direction of the project will be the responsibility of Dr. B.M. Duff who is expected to devote at least 360 hours of time to the project. Mr. James C. Biard and Mr. David A. Anderson will assist in carrying out the experiments and together are expected to devote about 700 hours of time to the project. Professional Data sheets for these key individuals are included. In addition, a senior technician will assist in various ways. Dr. T.E. Owen, Director of the Department of Geosciences, will be available for consultation. The Task/Time Schedule on the next page presents a 15-month calendar schedule recommended for conducting the proposed project tasks. This schedule includes one visit by the Project Leader to the Townsend Brown Foundation in California during Task A.

V. SOUTHWEST RESEARCH INSTITUTE QUALIFICATIONS AND RELATED EXPERIENCE

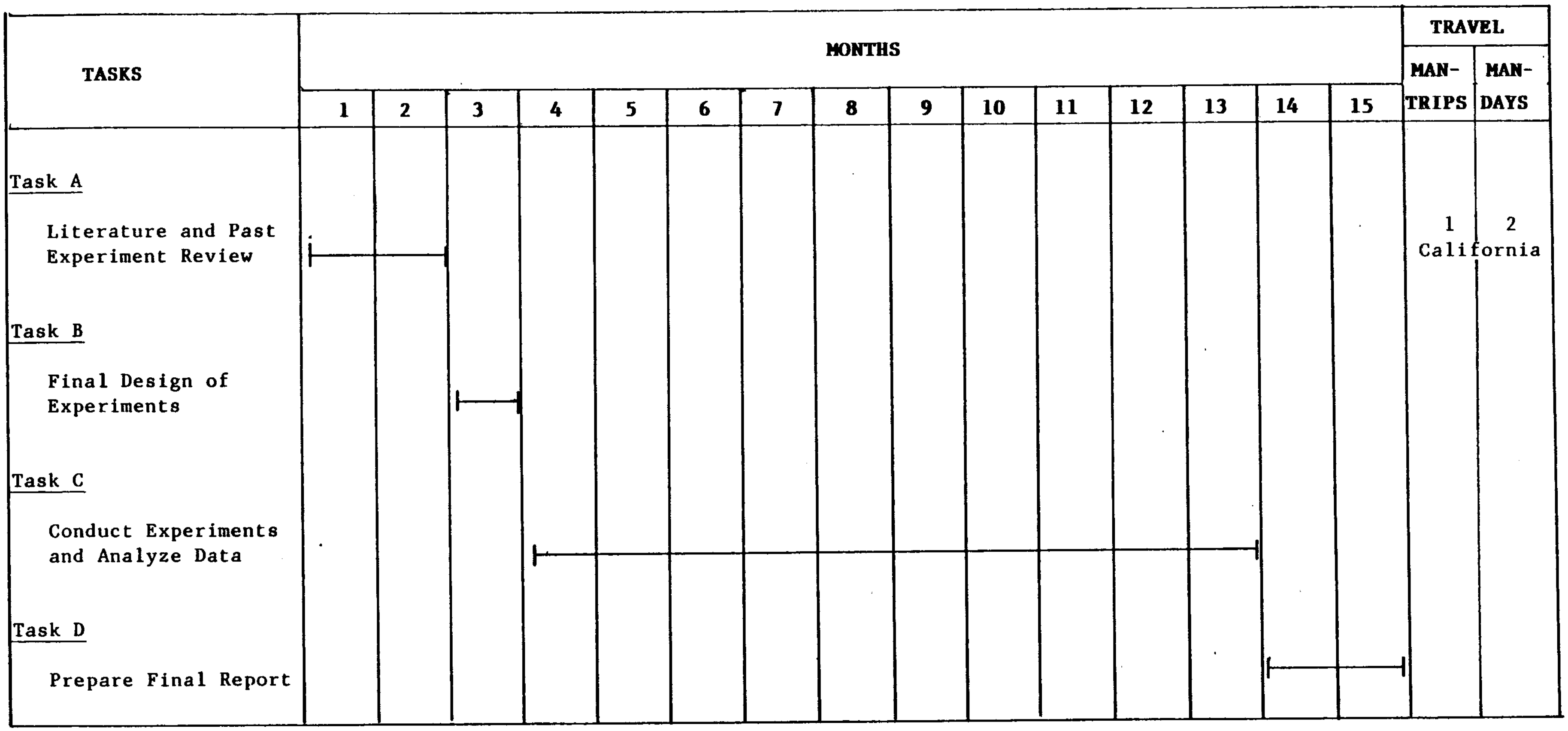
A. General

Southwest Research Institute is a not-for-profit research corporation operating under the laws of the State of Texas to serve government, industry, and individuals in the fields of applied research, development, and engineering. Present Institute employment is 2024 of whom 863 are professional level scientists and engineers involved directly in technical work. The professional staff has over 697 degrees from more than 160 colleges and universities, including 102 doctorates in special fields of science and engineering.

During its 1984 Fiscal Year, Southwest Research Institute received gross revenues of $120,516,364 derived from more than 950 active projects. Sixty-six percent of these revenues were derived from research and development services for private industry and 34 percent from services for various agencies of government. The Institute does not engage in production manufacturing; however, it is particularly well qualified to perform applied research and development and to provide one-of-a-kind prototype quantities of experimental devices and equipment. Because it does not depend upon production contracts, the Institute is able to provide thorough and unbiased services regarding the survey, design, analysis, evaluation, selection, and recommendation of various technical approaches and equipment. Many past programs have been performed at the Institute because of this unbiased technical position.

Southwest Research Institute performs research and development work in a wide variety of technical fields as illustrated by the titles of its various research divisions and departments. These include:

Applied Physics
Automotive Research
Chemistry and Chemical Engineering
Electromagnetics
Electronic Systems
Engineering Sciences



TASK/TIME SCHEDULE

Engines, Fuels, and Lubricants
Instrumentation Research
Quality Assurance Systems and Engineering
Structures Research and Ocean Engineering
U.S. Army Fuels and Lubricants Laboratory

In addition to the operating divisions and departments representing the the various scientific and engineering disciplines, the Institute maintains several well-equipped in-house support facilities to provide a complete research and development capability. These include a Library facility presently containing more than 85,000 bound volumes and over 175,000 technical reports, a complete Machine Shop facility, and an up-to-date Editorial, Printing, and Reproduction facility.

Southwest Research Institute has its principal facilities and headquarters in San Antonio, Texas; however, active operating centers are also maintained in other locations. The SwRI-Houston Office is a primary center for air- and water-pollution studies. The Institute also maintains offices in Washington, D.C.

B. Electronic Systems Division

The Electronic Systems Division is comprised of four departments: Geosciences, Data Systems, Communications, and Bioengineering. The Department of Geosciences conducts applied research and development programs in geophysical instrumentation, specialized grophysical exploration systems, and electronic instrumentation. The Department of Data Systems performs digital system engineering and software development for applications in automatic testing, data management, and digital control. The Department of Communications provides in-depth experience in advanced communications hardware and electromagnetic compatibility. The Department of Bioengineering is engaged in the study of behavioral effects of electric power system fields and rehabilitation engineering for the handicapped.

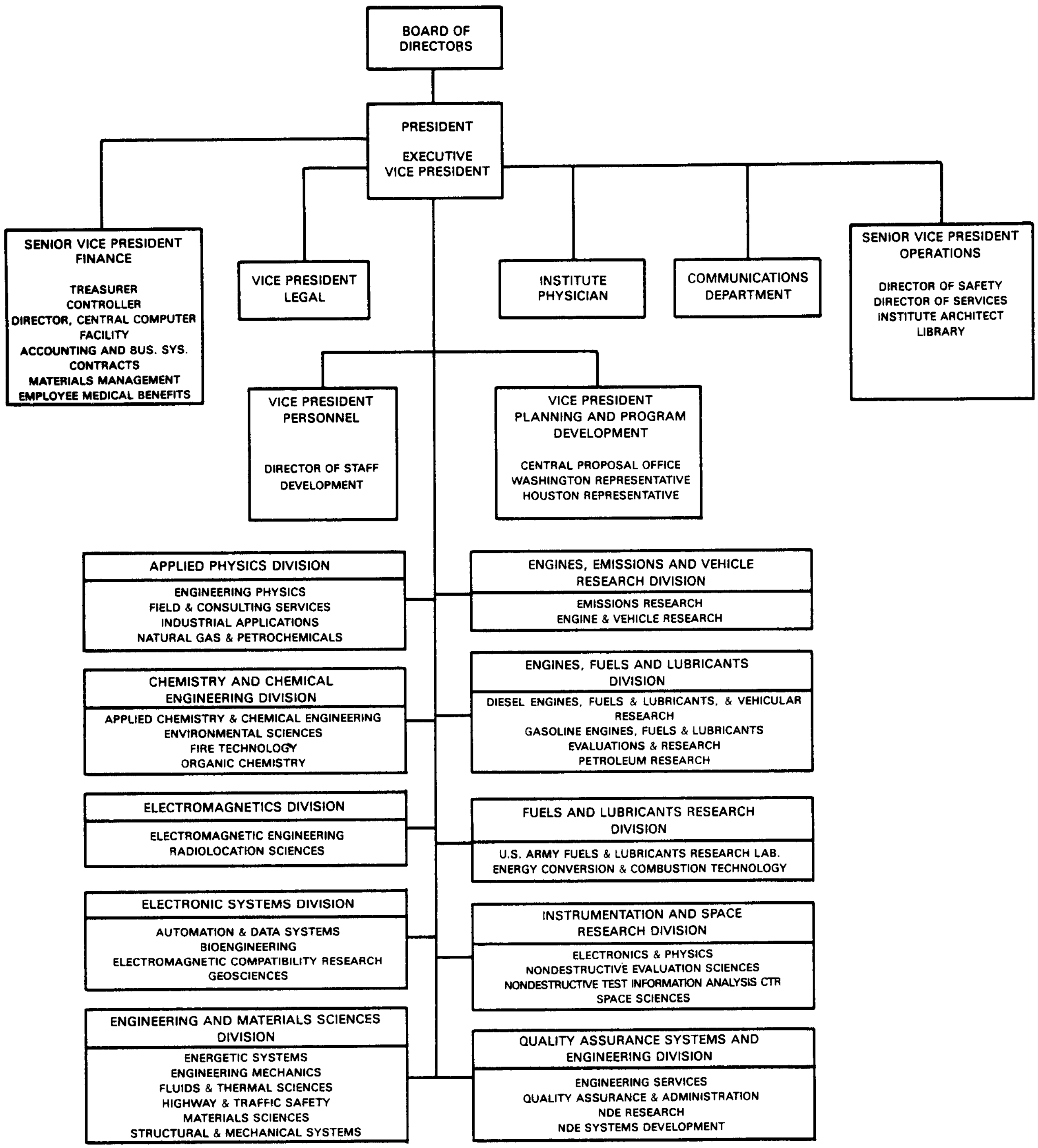
C. Department of Geosciences

The Department of Geosciences is organized to explore and develop advanced concepts and methodology in geophysical and geosciences applications and to demonstrate those techniques and instrumentation in practical field studies. The principal technical applications of this work involve borehole geophysical probes, high-resolution seismic and electrical exploration methods and equipment, ground-penetrating electromagnetic and radar techniques, and environmental monitoring instrumentation. In addition to these developments, geophysical applications and demonstration tests are being performed in probing both wet and dry boreholes for formation fracture conditions, detecting geologic anomalies in coal seams and mine roof structures, surface surveys to map man-made tunnels and abandoned mines, and collection of baseline environmental climatic data at nuclear waste repository field sites. Recently completed projects in Geosciences have included seismic methods for emergency mine communications, detection and delineation of soil sinkholes and ground subsidence anomalies, experimental analysis of electromagnetic parameters of oil shale, development of harmonic radar systems, military intrusion detectors, and remote battlefield sensors.

APPENDIX A

Southwest Research Institute
Organization Charts
and
Personnel Professional Data

SOUTHWEST RESEARCH INSTITUTE
ORGANIZATION CHART



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REVISED JULY 1985

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4/85

BOB M. DUFF, Ph.D.
Institute Scientist
Department of Geosciences
Electronic Systems Division

B.S. in Physics, Texas Technological College, 1952
M.A. in Physics, The University of Texas, 1959
Ph.D. in Applied Physics, Harvard University, 1971

Dr. Duff is a specialist in electromagnetic theory and techniques for experimental measurement of electromagnetic phenomena and has presented papers on antennas and scattering problems, measurement techniques, and numerical solutions of electromagnetic problems. Prior to receipt of his Ph.D., Dr. Duff's experience included work on the development of specialized radio receiving and signal identification systems. His graduate studies for the doctorate concentrated on electromagnetic theory, with acoustics and applied mathematics as minor areas. During these graduate studies, he was also actively involved in the development of a low frequency, satellite borne, radio astronomy antenna. His doctoral thesis was an experimental analysis of coupled, electrically thick, cylindrical antennas. At Northeastern University and the University of Mississippi, he taught electromagnetic theory courses at both the undergraduate and graduate levels, as well as other electrical engineering courses. While at the University of Mississippi, he developed extensive laboratory facilities including automated systems for the measurement of current and charge distributions induced on antennas and scattering structures. In addition, he has worked on numerical solutions for the potential, current, and field distributions in direct current systems; measurement of antenna properties when mounted on finite image planes; properties of antennas in a plasma environment; numerical solutions for antenna and scattering problems; and time domain measurement techniques.

Dr. Duff is presently engaged in the design and development of specialized antennas for ground penetrating electromagnetic systems operating either in boreholes or on the surface. He is also responsible for work involving the application of borehole elctromagnetic techniques for probing and/or imaging localized geologic anomalies for interpreting the structural integrity of the ground for construction purposes. Additionally, he is involved in the development of data analysis techniques for surface and borehole geophysics measurements including electromagnetic, resistivity and seismic. A major program under his direction was the development of an automatic, controlled-source, audio magnetotelluric exploration system for use in detecting and mapping abandoned underground coal mine workings in the Eastern coal districts of the U.S. Most recently, he has been involved in the probing of horizontal boreholes for site evaluation ahead of tunnel construction and various signal analysis problems in bioengineering.

PROFESSIONAL CHRONOLOGY: Research scientist, Defense Research Laboratory, The University of Texas, 1952-62; graduate student, teaching assistant and research assistant, Harvard University, 1962-6; associate professor, Northeastern University, 1966-70; part-time post doctorate research fellow, Harvard University, 1970-3; associate professor, The University of Mississippi, 1973-7; Southwest Research Institute, 1977-(senior research scientist, 1977-9; staff scientist, 1979-84; institute scientist, 1984-).

Memberships: Institute of Electrical and Electronics Engineers, IEEE Antenna and Propagation Society, Sigma Xi (Scientific Research Society of North America), Sigma Pi Sigma (Physics Honor Society), Eta Kappa Nu (Electrical Engineering Honor Society), Tau Beta Pi (Engineering Honor Society), Society of Exploration Geophysicists.

Rev Nov/84

JAMES C. BIARD
Research Scientist
Department of Geosciences
Electronic Systems Division

B.S. in Physics, Abilene Christian University, 1981
Graduate Studies in Physics, Michigan State University, 1982
M.S. in Physics, Pennsylvania State University, 1985

Mr. Biard's academic career has included both experimental and theoretical work, with emphasis on computer-based models and data analysis. At Abilene Christian University, he helped construct a high-vacuum system for solid-state physics applications and helped develop a computer program to model the response of pion-nucleon resonances in elementary particle physics experiments.

As part of his graduate work at Michigan State University and Pennsylvania State University, Mr. Biard was part of a team that designed, constructed, installed, and operated a set of electrostatic drift chamber detectors for Experiment PS 183 at the CERN Research Laboratories in Geneva, Switzerland. He also developed a computer data analysis program to process the data from the detectors and used this to optimize their operation. He spent 15 months at CERN as a participant in the experiment while completing his master's degree.

Since joining Southwest Research Institute, Mr. Biard has been involved in developing data acquisition and analysis programs for ground-penetrating radar systems for geophysical and geotechnical applications.

PROFESSIONAL CHRONOLOGY: Research assistant, Abilene Christian University, 1979-81; Michigan State University, 1981-2; Pennsylvania State University, 1982-5; Southwest Research Institute, 1985-.

Membership: Sigma Pi Sigma.

Apr/85

DAVID A. ANDERSON
Research Analyst
Department of Geosciences
Electronic Systems Division

B.S. in Physics, Southwest Texas State University, 1983
B.S. in Computer Science, Southwest Texas State University, 1983

As a member of the Advanced Concepts Section, Department of Geosciences, Mr. Anderson's main responsibility is programming the various portable computers that interface to unique geophysical probes and systems under development in the Department of Geosciences for control and data acquisition. His work involves programming on a wide variety of machines such as the Control Data Corporation Cyber-172, Hewlett-Packard 9000 and Hewlett-Packard 9826.

Mr. Anderson has programming experience in various computer languages including FORTRAN, PASCAL, BASIC and Assembly and he is familiar with a variety of operating systems including Unix.

PROFESSIONAL CHRONOLOGY: Southwest Research Institute, 1981-(contract programmer, 1981-3; research analyst, 1984-).

Jun/84

THOMAS E. OWEN
Director
Department of Geosciences
Electronic Systems Division

B.S. in Electrical Engineering, Southwestern Louisiana University, 1952
M.S. in Electrical Engineering, The University of Texas, 1957
Ph.D. in Electrical Engineering, The University of Texas, 1964

Dr. Owen is a specialist in acoustics, geophysics and electronic engineering and has presented papers on sonar transducers, data acquistion systems, elastic surface wave phenomena, oceanographic instrumentation, high-resolution seismic exploration techniques, and advanced earth resistivity exploration systems and applications.

His experience in acoustics includes work in electro-acoustic transducer design and fabrication for sonar and other underwater acoustic systems, microphones for both subaudible and ultrasonic sound, and transducers for generating and detecting elastic waves in both homogeneous solid materials and in the earth. He has developed instrumentation systems for airborne sound propagation and measurements, data transmission and communications in underwater acoustics and sonar, an airborne acoustic system for the measurement of surface winds and speed of sound averaged over large areas, and methods of passive battlefield vehicle location and tracking using characteristic sounds emanated by such targets. Other experience includes theoretical studies of shockwave propagation in the atmosphere and ray acoustic analyses of low-frequency sound waves in the earth-tropopause long range propagation zone.

His experience in geophysical applications includes work in seismic, electrical and electromagnetic properties of various earth materials, instrumentation development and field applications of high-resolution seismic reflection methods, analysis and development of deep-penetrating earth resistivity survey methods, and development of state-of-the-art ground-penetrating radar techniques for geologic probing applications. He has developed military-field equipment for perimeter surveillance and intrusion detection using footstep-induced vibrations in the ground, a man-portable seismic pulse-echo system for detection and mapping of shallow man-made tunnels in soil, and remote battelfield seismic sensor systems for automatic location and tracking of ground vehicles. Other experience in seismic geophysics includes experimental evaluation of seismic methods for emergency communications in underground mines, design and evaluation of dry-hole seismic measurement techniques for precision compressional and shear wave velocity logging in boreholes, high-resolution seismic reflection surveys for detecting and mapping subsurface cavities and tunnels in rock, and borehole seismic reflection probing of drilled formations for geotechnical evaluations for underground construction projects. His doctoral dissertation was a detailed analysis of communication techniques employing elastic wave transmission through the earth.

His experience in electrical and electromagnetic applications in geophysics includes developmental studies of high-resolution earth resistivity survey methods, instrumentation for *in situ* measurements of electromagnetic parameters of soils and rock materials, and design analyses of ground-penetrating radar techniques for both surface and borehole geologic probing applications. This work has involved the development of advanced earth resistivity techniques for detecting and mapping subsurface geologic anomalies and tunnel structures, innovation of advanced earth resistivity data processing and interpretation methodology, development of VHF ground-penetrating pulse radar for shallow tunnel detection, experimental nanosecond-pulse radar antennas for borehole operation, and high-resolution FM-CW radar system design and performance analyses for roof coal thickness measurements in underground mines. Other experience in electrical and electromagnetic instrumentation has entailed design and development of electrostatic field and charge density meters for use in tanker ship explosion hazard studies and adaption of VHF ground-penetration radar techniques to problems in detection of buried pipelines and hazardous ordnance objects.

Technical activities under Dr. Owen's guidance in the Department of Geosciences pertain to the research, design, development, and field application of geophysical instrumentation, high-resolution geologic probing techniques using seismic, electrical and electromagnetic methods, and the analytical study and development of advanced concepts in geophysics. Projects in these various applications are being performed for military, government, and private industry clients.

PROFESSIONAL CHRONOLOGY: U.S. Navy, 1952-4; research engineer, undersea warfare division, Defense Research Laboratory, University of Texas, 1955-60; assistant professor of electrical engineering, University of Texas, 1957-60; Southwest Research Institute, 1960-(senior research engineer, 1960; manager, 1960-71; assistant director, 1971-6; director, 1976-).

Memberships: American Association for the Advancement of Science, American Geophysical Union, Acoustical Society of America, Institute of Electrical and Electronics Engineers, Society of Exploration Geophysicists, Society of Professional Well Log Analysts, Sigma Xi Eta Kappa Nu, Tau Beta Pi.

Rev Mar/84