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INSTRUMENTATION TECHNOLOGY UTILIZED IN GEOTHERMAL EXPLORATION AND WELL LOGGING

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ABSTRACT

Instrumentation technology utilized in geothermal exploration and well logging is largely borrowed from the petroleum and minerals fields. Most modifications of surface techniques reflect the particular geologic objectives of the geothermal project. Modifications are usually made to field procedure and data interpretation rather than to instrumentation. However, DOE/DGE and private industry have sponsored and continue to sponsor improvements in instrumentation. Borehole instrumentation for geothermal applications is a special problem. Many geothermal wells, particularly those intended for electric power generation, have temperatures exceeding design specifications of most logging tools and components. Sandia Laboratories, Albuquerque, New Mexico, have a DOE/DGE program to advance the state-of-the-art instrumentation technology for geothermal borehole logging tools. Presently, logging is either not done or is limited to tools designed for higher temperature, commonly deep, petroleum exploration wells.

In recent years, instrumentation technology, common to many resource exploration programs, has improved significantly through incorporation of state-of-the-art electronic hardware. Greater sophistication in data collection and real time processing has been accomplished using micro- and mini-computer technology. Specialized chips such as A/D and D/A converters, V/F and F/V converters, lower power line drivers and digital systems have greatly enhanced data quality and increased recording efficiency. Utilization of state-of-the-art computer peripherals such as cassettes, floppy disks and interactive graphics terminals have been introduced in field systems in recent years and the trend is to greater use of these devices. Real time data processing and interpretation are the design goals for current and future geophysical exploration and well logging field systems.

INTRODUCTION

Complete geothermal exploration programs commonly include several methods from the four fields of geology, hydrology, geochemistry and geophysics, including well logging. Exploration strategies for high temperature geothermal resources have been presented in the literature (1) and the strategies emphasize that integration of several geoscience techniques is essential to successful exploration programs. Borehole logging (or well logging) is included in almost all exploration programs where at least one hole has been drilled; a minimum logging program would be the measurement of temperature with depth in the drill hole(s).

Since 1974, the Department of Energy, Division of Geothermal Energy (DOE/DGE), and its predecessors, have had programs to improve and to develop cost-effective techniques for geothermal exploration and development (2). The status and needs of exploration technology for geothermal resource applications were first examined in 1975 (3) and later in 1977 (4 and 5). These studies, although recognizing the utility of many methods, noted that certain seismic and electrical methods deserved particular attention. The studies recognized the need for deeply probing, commercial magnetotelluric (MT) equipment and active electromagnetic (EM) systems that would be able to operate over the frequency range of 10^{-3} to 10^{3} Hertz. Interpretation algorithms for a variety of electrical prospecting systems for two- and three- dimensional earth models were also needed. Active and passive seismic methods, routine in petroleum and solid earth studies, respectively, were recognized as useful methods for geothermal exploration. However some new technology was required and modified field proceedures and interpretation techniques were clearly needed since geothermal resources are commonly located in complex geologic environments. Borehole logging technology had a special problem. Commercially available logging tools were not designed for the high temperatures encountered in geothermal wells and most logging proceedures and interpretation techniques had been developed for geologic envirnoments quite different from those encountered in geothermal areas.

In this paper we will review developments in MT, EM, active and passive seismic and borehole technology for geothermal exploration. Several instruments are in the proto-type stage of development or testing. However progress in many areas has been significant, particularly in areas of field techniques and in software and hardware development.

GEOPHYSICAL EXPLORATION INSTRUMENTATION ELECTRICAL/ELECTROMAGNETIC METHODS

Conventional minerals exploration geophysical methods such as gravity, magnetic (ground and airborne), grounded electode resistivity, spontaneous potential and electromagnetic methods are commonly employed in geothermal exploration. In recent years significant advances have been made in field techniques and instrument technology to many of these methods, particularly for magnetotelluric (MT), controlled source audio-magnetotelluric (CSAMT) and low frequency electromagnetic (EM) methods.

The MT method is a popular geophysical exploration method used in geothermal exploration. It has been used in 71% of the Basin and Range geothermal exploration programs conducted through the DOE/DGE Industry Coupled Program (1). Only the gravity method is used as often as the MT method.

The MT method is simply the measurement of local variations in the earth's natural, timevarying electric and magnetic fields. The electric currents in the earth are called telluric currents. Measurements made between 10 and 10,000 Hz are called audiomagnetotelluric measurements. A schematic of the magnetic field spectrum is shown in Figure 1 (6). The source of the fields above 1 Hertz is primarily worldwide thunderstorm activity and below 1 Hertz is primarily the complex interactions of charged particles from the sun with the earth's magnetic field. The earth/ ionosphere cavity acts as a wave guide that control propagation of these electromagnetic waves. Certain resonances occur and are noted in Figure 1. Note that the amplitude increases with decreasing frequency. The field strength change is sufficiently large over the frequency band of interest that the instruments are designed to record data over finite bandwidths. Typically, data are recorded over four to six overlapping bands. An example of four recording bandwidths is

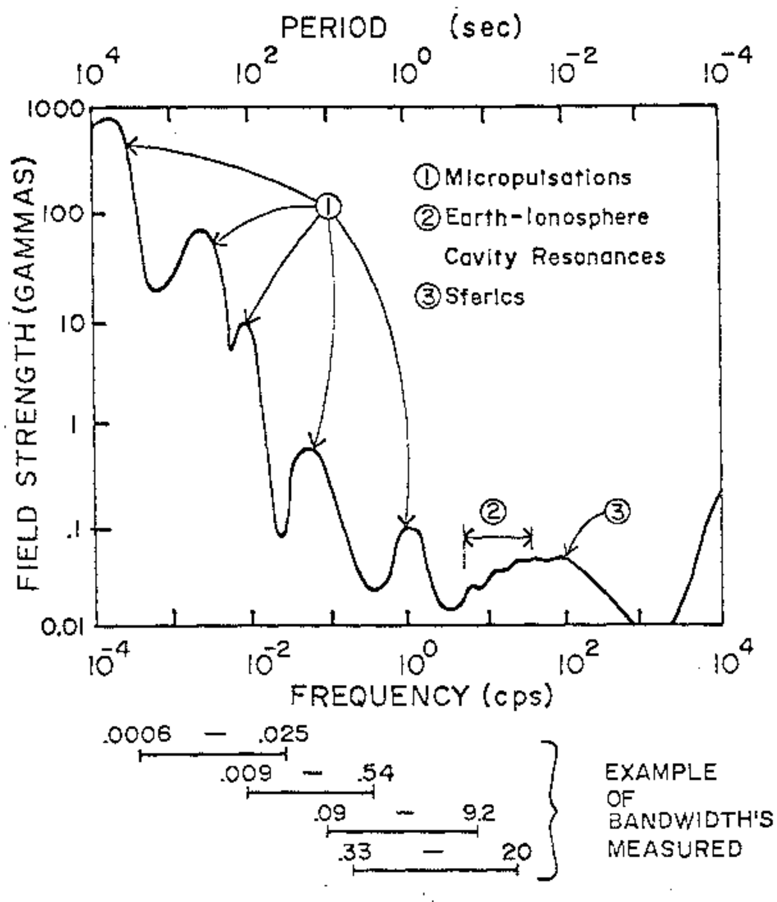


Figure 1: Earth's magnetic field strength between 10^{-4} and 10^4 Hz showing four bands that might be measured by an MT system (6,7).

shown in Figure 1 (7). Also, the wide frequency range recorded makes it necessary to record several bandwidths since digitizing rates needed to sample at least at a rate twice the highest frequency recorded change over the total frequency range. The band overlap allows for comparison of results computed from each band and for comparison of noise levels between bands.

Three significant improvements in the MT method in recent years is (1) the removal of bias from the recorded data, (2) the introduction of in-field data processing, and (3) the increased capability of numerical modeling. Earth electrical impedance has been calculated from magnetotelluric data using autopowers and cross powers (7) of the measured electric and magnetic field components. However, it was well known that this approach severly biases the impedance estimates if noise is present in the measured field. It has been shown that using the measured fields at a second, remote site to compute various crossproducts with data from the main site removes or significantly reduces the bias in the impedance estimates (8, 9). The removal of bias depends on the noise being uncorrelated between the two sites.

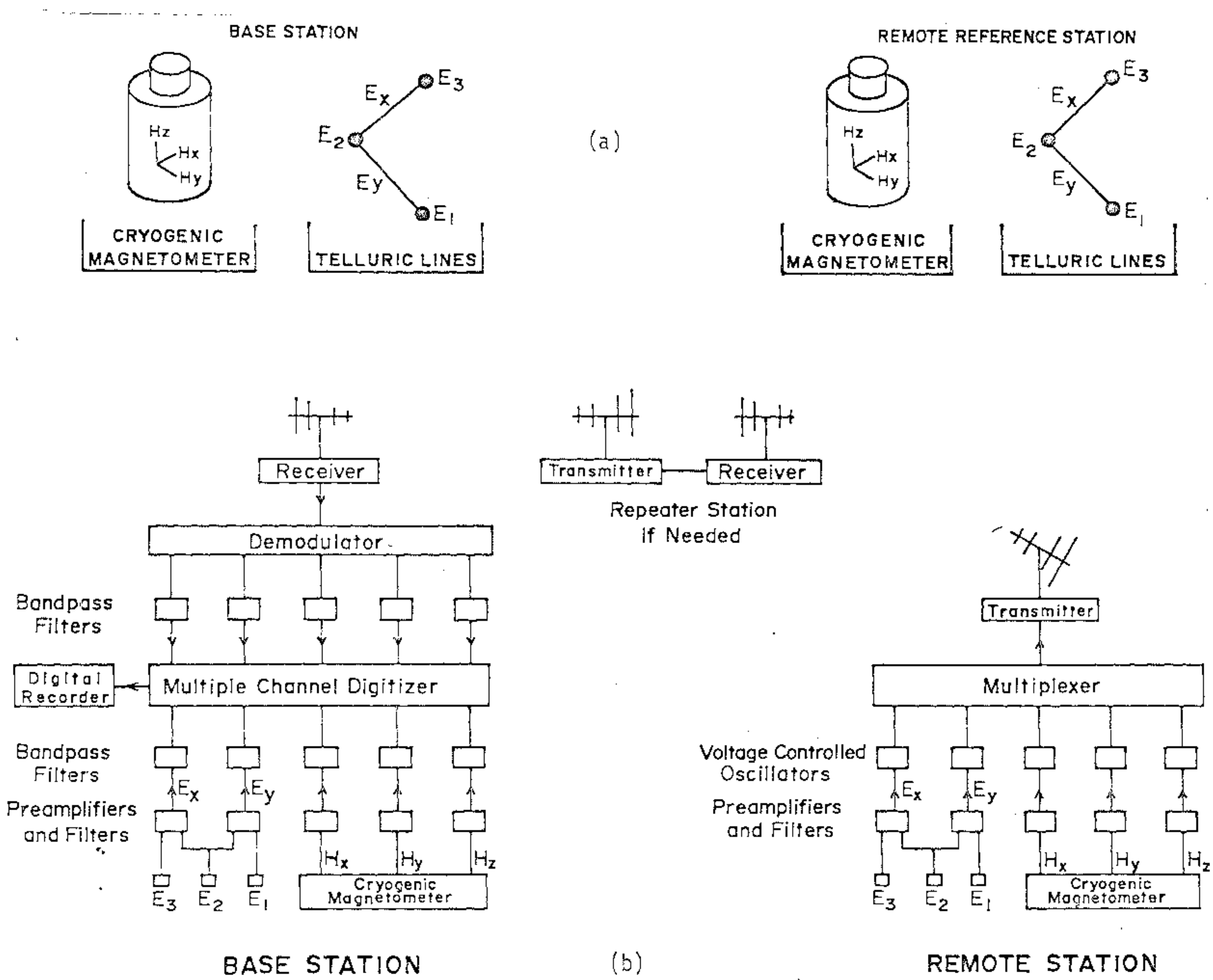


Figure 2: Configuration of a MT system utilizing a base and a remote station, a) depicts measurement of the five field components (10) and b) depicts the recording and processing system (8).

Figure 2 depicts the MT method; a typical field system is indicated in Figure 2a and the block diagram of a typical data acquisition system is shown in Figure 2b. Two, horizontal, orthogonal components of the electric field are measured using grounded wires and three, orthogonal components of the magnetic field are measured using a cryogenic magnetometer (8, 10). The magnetometers have a nominally flat response from dc to 400 Hz, 3dB point. The high frequency roll off is determined by a single pole, 6-dB/octave filter at the magnetometer input. A second single pole filter with a 3-dB point at 50 Hz can be produced by enclosing the magnetometer in a carefully shaped aluminum can. The filters limit the effect of high frequency transients and cultural noise (10). The grounded wires are terminated with $Cd\text{-}CdCl_2$ or $Cu\text{-}CuSO_4$ porous pots or lead electrodes. All input signals are amplified and filtered for the frequency band being recorded. The data are digitally sampled and are stored on floppy disc or nine-track tape. One available system (10) utilizes four LSI-11 microcomputers, each with 128K of memory; one LSI-11 is a master with two satellite microcomputers dedicated to the two five channel MT stations. The third satellite microcomputer computes crosspowers. The system also consists of three floppy disk drive, three CRT's, an extended memory unit, an I/O (CRT) terminal and a printer plotter. THe data are processed and preliminary interpretation made in the field. The in-field processing permits quick evaluations of data quality, site selection and survey parameters. Presently, one-dimensional (layered) earth models are used for in-field interpretations and most interpretations made in the office. However, recent advances in two- and three-dimensional earth modeling techniques should facilitate more sophisticated in-field and laboratory data interpretation. These interpretation advances have given integrity to the MT method and provide a means to exploit fully the information contained in MT data. The long period data allows deep probing of the earth without the need for transmitters; it is a logistically cost-effective technique.

The controlled source audiomagnetotelluric (CSAMT) method is simply a method whereby an artifical source field is created and measurements are made at a distance such that the source field approximates a plane wave. Selected frequencies between 10 and 10000 Hz are used. The advantages of the CSAMT method over the MT or AMT methods are (1) the true structure of the source field is known, (2) there is direct control over signal-to-noise and (3) the MT signals in the audio band are commonly low level (see Figure 1).

The Earth Science Laboratory Divison (ESLD) of the University of Utah Research Institute has designed and built a frequency domain digital receiver for Geotronics Corporation, Austin, Texas. The receiver specifications are listed in Table 1. The system has been designed around RCA-1802 CMOS microprocessor chip and a LSI 8x8 multiplier. The microprocessor is interfaced with a user dedicated HP-33E calculator. The HP-33E calculator has been programmed to perform a number of computations and further programming is planned. Although the receiver was designed primarily to operate as a induced polarization/resistivity receiver, it can be used with appropriate coils or a cryogenic magnetometer in combination with grounded wires to measure CSAMT data. ESLD has a program to test this sytem over a known geothermal resource. The receiver could be used for time-domain measurements and the tests may include these measurements.

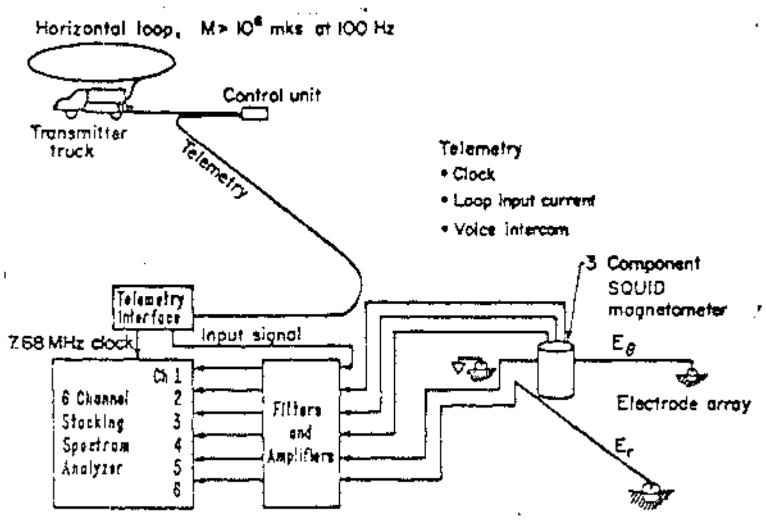
EM methods used in geothermal exploration are borrowed largely from the minerals industry. Most methods employ wire loops and/or grounded wires for transmitters and receivers. To look deeper into the earth it is necessary to generate strong fields that produce measureable secondary fields due to weak conductors at depth. Receivers and signal detection methods must optimize signal-to-noise ratios. Lawrence Berkeley Laboratory, Berkeley, California has developed, through a DOE/DGE program, an EM-60 system and have tested it at the Panther Canyon thermal anomaly, Grass Valley, Nevada. A schematic of the current EM-60 system (11) is shown in Figure 3.

The transmitter coil, 100m in diameter, has 4 turns of #6 wire and is powered by a 60 kW, 400 Hz 3-phase alternator linked to a Hercules gasoline generator. The system is designed to transmit square-wave pulses between 10^{-3} and 10^{3} Hz at up to 400 amps. The receiving system is similar to the one described earlier for the MT system. The

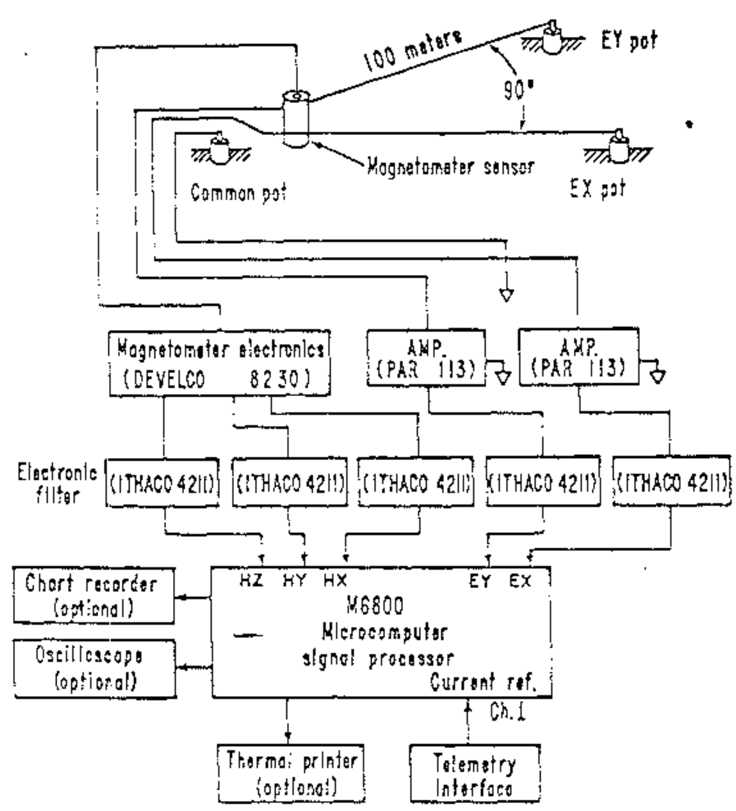
Four Channels
0.001 Hz to 2000 Hz, .001 to 1000 Hz in 1, 2, 3.3, and 5 steps
Simulataneous Sine Wave and Square Wave Detection
Single switch selects all operating parameters including gain and sp breakout.
Capability to use detected 3rd and 5th sine wave harmcoics
16 digit LED alpha-numeric display
Programs stored in ROM's
Power line notch filter
12 volt Gel-Cell power supply - up to 10 hrs use before charging.
Oscillatory accuracy $1x10^{-27}$/24 hrs after warmup
weight 27 lbs (12.3Kg)
size 14"w x 12"d x 12"h
phase accuracy ±180 degrees with .01 degrees resolution
Two operating modes:
Mode 1: (.001 to .33 Hz)
High pass digital filter for telluric noise rejection
2: After each cycle and up to 16 cycles computes and displays running average phase and standard duration for any one of 4 channels
3: 512 samples per cycle
4: After 16 cycles, cumulative results are displayed
Mode 2: (.5 to 1000 Hz)
1: Stacks 64 cycles (.5 to 10 Hz) increasing to 1024 cycles of 1000 Hz; computes and displays average phase
2: 512 samples/cycle up to 10 Hz decreasing to 8 samples/cycle at 1000 Hz (2000 Hz is available at 4 samples/cycle, 2048 cycles stacked).
In either mode amplitude is read 200 microvolt to 10 volts with 3 1/2 digit accuracy (both sine and square wave detection amplitudes available).

Table 1: Specifications of Geotronix Receiver

three magnetic field components are detected with a cryogenic magnetometer and the electric fields are detected with grounded wires. The interpreted data from Grass Valley, Nevada were compared to results obtained using the convetional dipole-dipole resistivity method. The EM-60 data interpretation was limited by the available techniques; a one-dimensional model was interpretation for each transmitter-receiver separation. A two-dimensional earth model was used to interpret the resistivity data. However, the results compare favorably and the chief advantage of the EM-60 system is that it is



A low frequency electromagnetic prospecting system



EM Receiver station

Figure 3: a)Sketch of the EM-60 System (11), b)block diagram of one configuration for a EM-60 receiver station (12).

more cost effective. For an equivalent areal coverage, the EM-60 requires less labor and less time than a conventional dipole-dipole system.

Conventional petroleum, active seismic and earthquake, passive seismic geophysical methods are also used in geothermal exploration. Active seismic methods, primarily reflection seismology, are used, with suitable field and interpretation changes, much as they are used by the petroleum industry. However, some recent work has produced improved passive seismic technology.

Passive seismic methods, including ground noise, microearthquakes and teleseismic (P-wave delay) data, are commonly used in early stages of exploration. These methods, which are typically less expensive than active methods, are borrowed primarily from the earthquake and engineering fields. Passive methods have potential for locating structures, delineating the resource, mapping spatial variations of Poisson's ratio and monitoring fluid production and injection.

One example of a recently developed passive field system for microearthquake detection and analysis is the Automated Seismic Processing (ASP) system developed at Lawrence Berkreley Laboratory (13). The ASP is a low power (1 watt/channel), 16-bit, in-field seismic data processing computer designed around the RCA 1802 COSMAC CMOS microprocessor. The ASP system is sketched in Figure 4. The present system is structured with 15 microcomputers (the WORKERS) in parallel that pass preprocessed data to a main microcomputer (the BOSS) for final processing. Software has been developed to handle all data I/O and processing which includes checking data integrity, sampling the data up to 100 samples/sec, and performing automatic operations such as FFT. All routines except the FFT perform floating point arithmetic operations. The first ASP system has been successfully tested and a second system is under construction.

GEOTHERMAL WELL LOGGING INSTRUMENTATION

Well logging technology used in geothermal investigations has been borrowed largely from the petroleum industry (14). Most logging is done by logging companies whose principle business is service to the oil and gas industry. A number of logging objectives are common to both the geothermal and petroleum industries since the production of fluids from a reservoir is the ultimate goal of both industries. However, geothermal wells may have temperatures exceeding the

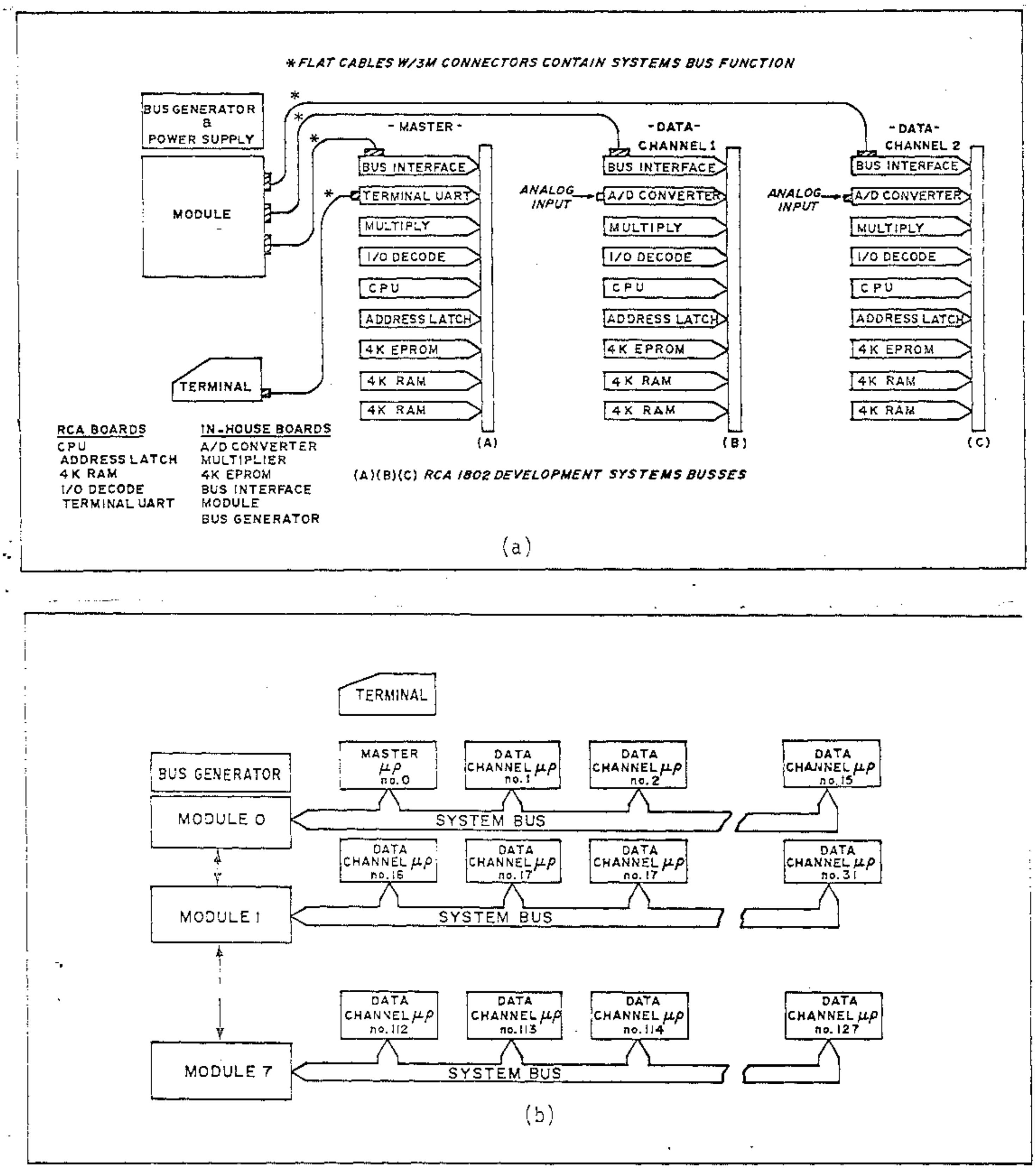


Figure 4: (a) Block diagram, two-channel prototype seismic data acquisition/processing system and (b) block diagram of 128-channel seismic field system, illustrating 16-channel modular architecture (13).

design specifications of available logging tools. The objective of the DOE/DGE program at Sandia Laboratories is to develop, in the near term, components to withstand temperature to 275°C and in the long term components to withstand temperatures to 350°C (15 & 16).

The Sandia program is outlined in Table 2. Sandia does some of the work but subcontract a substantial part of the study to various universities and private industries. Private industry is also independently making significant technology improvements (17).

Table 2: Geothermal Logging Instrumentation Program Objectives

(From Geothermal Logging Instrumentation Development Steering Committee Meeting, Dec. 5, 1979, Houston, Texas. Courtesy A. F. Veneruso)

Phase I. Develop Prerequisite Components and Capabilities

*Demonstrate the feasibility of 275°C electronic components

*Transfer technology to industry

*Demonstrate basic 275°C logging tools

*Stimulate industry application and R&D

Phase II. Develop Full Complement of Essential Capabilities

*Provide the full complement of essential 257°C electronics

*Extend lifetimes of 275°C electronics and cables beyond 100 hours

*Demonstrate the technology required to produce the full suite of geothermal logging tools

*Investigate feasibility of 350°C technology

*Stimulate industrial appliction and R&D

The early task undertaken by Sandia was to test available electronic components under high temperature conditions (18). Commonly available resistors, capacitors, conductors, interconnections and active devices were tested for 1000 hours at 300°C. Evaluation included survival of this test and a minimum change in electrical parameters between 25°C and 300°C. The studies demonstrated thick film resistors and capacitors and silicon junction field effect transitors had quite favorable characteristics.

Table 3 summarizes technology recently or soon available for geothermal well logging. Some problems with cable, cable heads, down hole circuitry and tool design features have been solved.

INTERPRETATION SOFTWARE DEVELOPMENTS

A significant effort has been and continues to be given to development of interpretation algorithms for electrical methods. A few years ago almost all interpretation schemes available to the public were for homogeneous or layered-earth models and for a variety of sources. In recent years advances in computing 2- and 3-D earth models

Item	Temperature
Logging Cable	
Teflon TFE	315°C
PFA	260°C
Metal Sheath	390°C
Cable Heads	315 & 260°C
Hybrid Circuits for Downhole (Voltage regulator and A/D converter)	275°C
Tools	
Acoustic Borehole Televiewer	
a) high temperature acoustic transducer	275°C
b) improved acoustic window	
c) elemination of slip rings	
Temperature (Prototype)	275°C

Table 3: Summary of some recently or soon available well logging technology.

with various sources have been made. Table 4 summarizes the present state of available software to model four types of earth models and for five types of sources. The algorithms with an asterisk were developed specifically

Earth Models	homogeneous half-space	layered earth	2-D earth	3-D earth
Sources	closed form solution	closed form solution	*1.finite element 2.finite difference *3.integral equation	*1.integral equation *2.hybrid finite element integral equation
Short grounded wires	Closed form solution	Hankel transform integrals	under development	1.integral equation
"Infinite" (long) grounded wires	Closed form solution	Fourier transform integrals	1.finite element 2.finite difference 3.integral equation	
Small loops (dipoles)	Closed form solution	Hankel transform integrals	1.finite element	1.integral equation (limited application)
Large loops	Closed form solution	Hankel transform integral	Under development	

Table 4: Available interpretation algorithms of electrical methods (19).

to meet the needs of the geothermal industry. Several combinations of sources and earth models are still being studied. Hybrid finite- element and integral-equation solutions are anticipated to be successful.

The plane wave solutions, applicable to the MT and AMT methods are complete. However, solutions for complex earth models and systems such as the EM-60 discussed here are not yet available. THe development of virtual memory storage and cheaper computer technology has greatly aided the development of the advanced software. Computer programs that compute resistivity over a 2-D earth for a grounded pair of electrodes requires on the order of 250k bytes of memory using a finite element algorithm. A 3-D earth plane wave EM field combination requires over 1M byte of memory using an integral equation solution.

Well log interpretation in geothermal environments has been complicated by the lack of tool calibration for non-sedimentary rocks, and by lack of experience interpretation in complex, igneous and metamorphic rock environments. Advances have been made through private industry efforts and the DOE/DGE Geothermal Log Interpretation program at the Los Alamos Scientific Laboratory (20, 21).

CONCLUSIONS

Significant progress has been made in recent years in improved field techniques, instrument technology and interpretation software. All improvements can be traced to use of state of the art electronics and computer technology. A review of recent developments and a look at current research activities indicates a promising future for geothermal exploration technology developments.

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REFERENCES

1. S. H. Ward, H. P. Ross and D. L. Nielson, "A Strategy of Exploration for High Temperature Hydrothermal Systems in the Basin and Range Province," submitted to AAPG Bulletin, 1980.

2. L. Ball, J. W. Salisbury, P. R. Kintzinger, A. F. Veneruso and S. H. Ward, "The National Geothermal Exploration Technology Program," Geophysics Vol. 44, No. 10, pp. 1721-1737, 1979.

3. U. S. Geological Survey, "Workshop on geophysical methods applied to detection, delineation and evaluation of geothermal resources," Univ. of Utah, 1975, USGS Grant 14-08-6-191.

4. S. H. Ward, ed., "Program review: resource evaluation, reservoir confirmation and exploration technology", Univ. of Utah report 78-1701.b.5.1, May 1978.

5. N. E. Goldstein, R. A. Norris and M. wilt, "Assessment of surface geophysical methods in geothermal exploration and recommendations for future research", Lawrence Bekeley Laboratory report LBL-6815, 1978.

6. W. H. Campbell, "Geomagnetic pulsations", in Matsushita and Campbell eds., Geophysics and geomagnetic phenomena, Academic Press, N.Y., pp. 1398, 1967.

7. K. Vozoff, "The magnetotelluric method in the exploration of sedimentary basins", Geophysics, Vol. 37, No. 1, pp. 98-141, 1972.

8. T. D. Gamble, W. M. Goubau and J. Clarke, "Magnetotellurics with a remote magnetic reference", Geophysics, Vol. 44, No. 1, pp. 53-68, 1979.

9. T. D. Gamble, W. M. Goubau and J. Clarke, "Error analysis for remote reference magnetotellurics", Geophysics, Vol. 44, No. 5, pp. 959-968, 1979.

10. Woodward-Clyde Consultants, "Real time magnetotellurics", Woodward-Clyde Consultants company document, pp. 67.

11. M. Wilt, J. H. Beyer and N. E. Goldstein, "A comparison of dipole-dipole resistivity and electromagnetic induction sounding over the Panther Canyon Thermal Anomaly, Grass Valley, Nevada", Geoth. Res. Council, Trans, Vol. 4, pp. 101-104, Sept., 1980.

12. H. F. Morrison, N. E. Goldstein, M. Hoversten, G. Oppliger and C. Riveros, "Description, field test and data analysis of a controlled source EM system (EM 60)", Lawrence Berkeley Laboratory Report LBL-7088, 1978.

13. T. A. McEvilly, E. L. Majer, J. Bartschi, J. Heinsen and R. O'Connell", ASP (Automated Seismic Processor)", Lawrence Berkeley Laboratory Earth Science Division Annual Report, 1979.

14. L. E. Baker, A. B. Campbell and R. L. Hughes, "Well Logging Technology and Geothermal Applications: A Survey and Assessment with Recommendations", Sandia Laboratories Report, SAND 75-0275, pp. 76, 1975.

15. A. F. Veneruso, "Geothermal Logging Instrumentation Development Program Review", geothermal Technology Division 4742, Sandia Laboratories, Albuquerque, New Mexico, Dec., 1979.

16. A. F. Veneruso and J. A. Coquat, "Geothermal Logging Instrumentation", MIDCON 178, Professional Program, Session 15, Paper 1, pp. 7, 1978.

17. T. A. Garney and R. E. Roesner, "Development of a Wireline Service for use in Producing Geothermal Wells,", Geoth. Res. Council, Trans., Vol. 4, pp. 329-332, Sept., 1980.

18. O. W. Palmer, "Hybrid Microcircuity for 300^{o}C Operation", IEEE Trans. on Parts, Hybrids and Packaging, Vol. PHP-13, No. 3, pp. 252-257, Sept., 1977.

19. G. W. Hohmann, personal communication, 1980.

20. S. K. Sanyal, L. E. Wells and R. E. Bickmann, Geothermal Well Log Interprettion State of the Art Final Report", LA-8211-MS Informal Report, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 1980.

21. W. E. Glenn, H. P. Ross and J. W. Atwood, "Review of Well Logging in the Basin and Range Known Geothermal Areas", SPE 9496, SPE 55th Annual Fall Technical Conference and Exhibition, Dallas, Texas, Sept., 1980.