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PERSPECTIVE AND TRENDS: FUTURE OF GEOTHERMAL EXPLORATION TECHNOLOGY

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Perspective and Trends:
Future of Geothermal Exploration Technology

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Perspective and Trends:
Future of Geothermal Exploration Technology

Introduction

Due to the precipitous decline in oil/gas prices and the resulting decline in the demand for alternative energy sources (at least in the short-term of $\sim$ 2–3 years) future trends of geothermal exploration technology are uncertain, at best. As long as the demand for new electric generating capacity and oil/gas prices remain low, there will be few societal or financial incentives to explore except where current obligations dictate a course of action, or where good prospects can be acquired at distress level prices and favorable conditions. At the same time we are in a situation where there is little money available to improve our current exploration technology. This is indeed unfortunate because at a time when it is more important than ever to reduce the front-end exploration and drilling costs, we are temporarily mired in the technologies of the late 1970s. Field exploration and development costs remain high, roughly equal to the total cost of the surface plant facilities, and it seems clear that developers must be concerned about reducing the number of non-essential and non-productive holes drilled, and reducing the costs of drilling and the associated logging and well testing. As you can see from the first figure (Fig. 1) geothermal wells cost two to three times more than the average oil/gas well (Carson and Lin, 1981; Dolenc et al., 1983).

Over the last 20 or so years geothermal exploration has had a close relationship with oil and gas exploration. Much of the initial expertise related to geothermal exploration, drilling and reservoir engineering was brought into the geothermal industry by engineers from the oil/gas industry. Due in large part to the Geothermal Development Act (Public Law 73-410), geothermal exploration

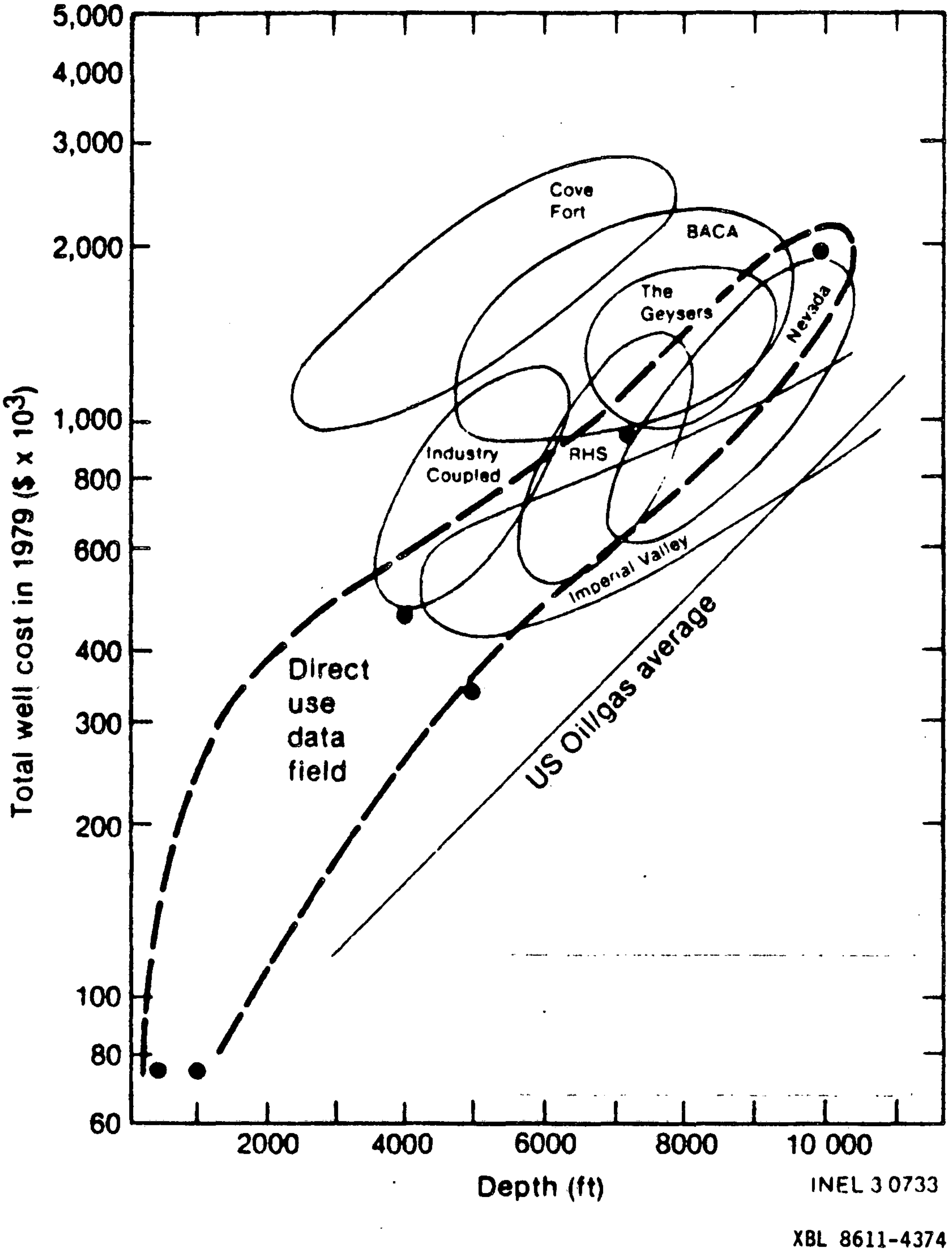

Figure 1. Comparison of geothermal and oil/gas well costs (Carson and Lin, 1981; Dolenc et al., 1983). The fields represent well costs in several high temperature geothermal systems, and costs of eleven low-to-moderate temperature (direct use) wells.

acquired a separate identity. New technologies were developed through federally-supported programs, and the geothermal program would actually return to the oil/gas industry many cost-saving benefits such as improved elastomers, hard rock drill bits, improved exploration techniques, new geophysical interpretation codes and reservoir simulation modeling codes. Because the price paid by utilities for geothermal steam is coupled to the price of crude oil and because technologies of oil/gas and geothermal exploration are closely related historically it may be instructive to begin this consideration of geothermal exploration by looking at prevailing conditions in oil/gas exploration.

I don't have to remind the audience that these are not good times in oil/gas exploration. An enormous number of exploration jobs have been lost, and whole exploration staffs have been dismantled. Worried about the worsening situation, Norm Neidell (1986) has pondered the crippling of the industry, viewing as a likely end result a domestic industry unable to replace reserves and having lost its most experienced and talented people. He argues that

> "high technology exploration and exploitation methods offer a profitable alternative to dismantling operating organizations . . . (but) . . . the locker room strategy of fighting harder and doing more with less is most ineffective when we continue to do the same old thing."

Neidell may have an overly pessimistic view, but what oil exploration people all agree on, more or less, are these points:

1. There have never been exploration panaceas.
2. New technology will evolve, but new technology simply for its own sake will not suffice in today's economic climate.
3. Best efforts to do more with fewer people and leaner exploration budgets has never been a good long-term solution.

During the last two years or so oil companies have attempted to retain a technological base by redirecting activities to "low-cost pursuits" that can be handled by a small staff. These pursuits mainly involve reprocessing and reinterpreting existing seismic data using the newest computer techniques and vastly improved and lower cost computer capabilities, such as microcomputer-based workstations. Seismic data reprocessing using new graphical display techniques and 3-D seismic interpretations seems to be the only active area in an otherwise dismal exploration picture. On the surface this may seem like a prudent short-term strategy, but is it? A preliminary answer, as of 1985–1986, is that it is not working. Exploration groups have been effectively dismantled; the most senior and experienced professionals are among the hardest hit categories. During the same time, the percentage of successful wells drilled in the search of new fields, the traditional measure of exploration effectiveness, dropped to 14.8% in 1985 from 17.6% in 1984 and 17.1% in 1983, and from close to 20% during the exploration intensive years of 1979 and 1980 (Petroleum Information, 1986). Failure to replace domestic reserves coupled with the shutting-in of thousands of stripper wells is a sure guarantee for a return to higher energy costs and a renewed demand for geothermal energy resources.

In the present unsettled energy climate, can geothermal exploration make progress? Coupled to the low demand for new geothermal plants due to the present lower demand for new electric generating capacity, many companies have sharply curtailed geothermal exploration, concentrating on extending the boundaries or productivities of known fields. Unlike the situation in oil/gas exploration, geothermal exploration groups cannot be productive by immersing themselves in data reprocessing, hoping to pull out a few choice "nuggets" for drilling. Until the geothermal industry regains the incentives and the confidence that it has the technical and economic strength to move forward to explore, develop and evaluate new resources, geothermal exploration will be in a declining state.

A. Geothermal Exploration Review

Before I consider where we could be going in geothermal exploration, it is instructive to look back to 1977–1978 to recall the then perceived impediments to effective exploration. Through the auspices of ERDA, predecessor to DOE, representatives from industry, academia and government engaged in a series of workshops to identify the most pressing technical problems and help advise the federal exploration technology program directed by ERDA.

On the left-hand-side of Table I, compiled from Ball et al. (1979), is a list of the major perceived problems and needs in 1977–1978. My opinion on the state-of-the-art today is shown on the right-hand-side of the table. More detailed information on the current state-of-the-art in exploration techniques is given by Wright et al. (1985) and Goldstein (1986). However, returning to the list, it may be instructive to recall that the list was assembled at a time when most of the more promising hydrothermal-geothermal systems/prospects had been identified and classified by the U.S. Geological Survey (Muffler et al., 1979), and many of the high-temperature systems were under lease and being explored.[1] There also emerged from this exploration work a shared opinion that many of the geophysical and borehole methods were neither technically nor cost effective. Among other problems, there were deficiencies in high-temperature instruments and in the concept and practice of many geophysical methods, including the interpretation of the data. Also lacking was a sound appreciation and judgment, usually developed from experience, on how to relate the geophysical results to subsurface conditions and processes. It was considered essential that these deficiencies be remedied so that industry could discover and exploit the large number of new reservoirs that were needed to help solve the national energy problem.

To meet the federal objective of increasing the rate of geothermal energy utilization from 500 MWe (1978) to 4,000 to 6,000 MWe (1985) and to over

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[1] See Tables III and IV for general information on the U.S. Geothermal Resource Base.

Table I

Exploration Technology Problems and Needs 1978
(Ball et al., 1979)

A. Surface Geophysics	**Present Status**
Electrical & EM Techniques and Instrumentation	Considerable progress made 1978–1980, but still a long way from perfecting the techniques.
Seismic Techniques Fault and Fracture Detection	Considerable progress made in passive seismic; fault and fracture detection research continues.
B. Foward Modeling Programs	
• 2-D, 3-D Electrical and EM	More cost-effective 2-D and 3-D foward codes available and in general use.
• Geohydrology and Thermally Driven Flows	Some progress made in 2-D inverse codes for DC resistivity, magnetotellurics and joint DC-MT.
C. Thermal Methods	
• Downhole Instrumentation	Good instrumentation available, much better appreciation of how to interpret temperature profiles in terms of geohydrology with help from other geophysical logs.
• Interpretation of Thermal Data	
D. Rock and Formation Fluid Properties	
• Petrophysical Properties Needed for Interpreting Geophysics, Well Logs, and Reservoir Simulation	Steady progress made; information data base still far from adequate.

Table I

Exploration Technology Problems and Needs 1978
(Ball et al., 1979)

E. Refinement of Geochemical Techniques	**Present Status**
• Water-Rock Interactions	
– Zoning of Authigenic Minerals	Steady progress has been made through site-specific mineral zoning studies at several reservoirs.
– Trace Element Analysis Hg, As	Trace element analysis becoming routine.
– Gases He, Hg, H, Rn	Proper use and interpretation of gas geochemistry still unknown.
• More Reliable Chemical-Geothermometers	Remains a point of debate. Better recognition of limitations such as disequilibrium conditions.
F. Logging Technology	
• High Temp Instrumentation	
– Electronic and Mechanical Components to 275 ° C	Electronic and mechanical components good to 200–225 ° C.
– Elastometers, Ceramics and Metals	Materials good to 275–300 ° C.
– Log Interpretation	Log interpretations improving.

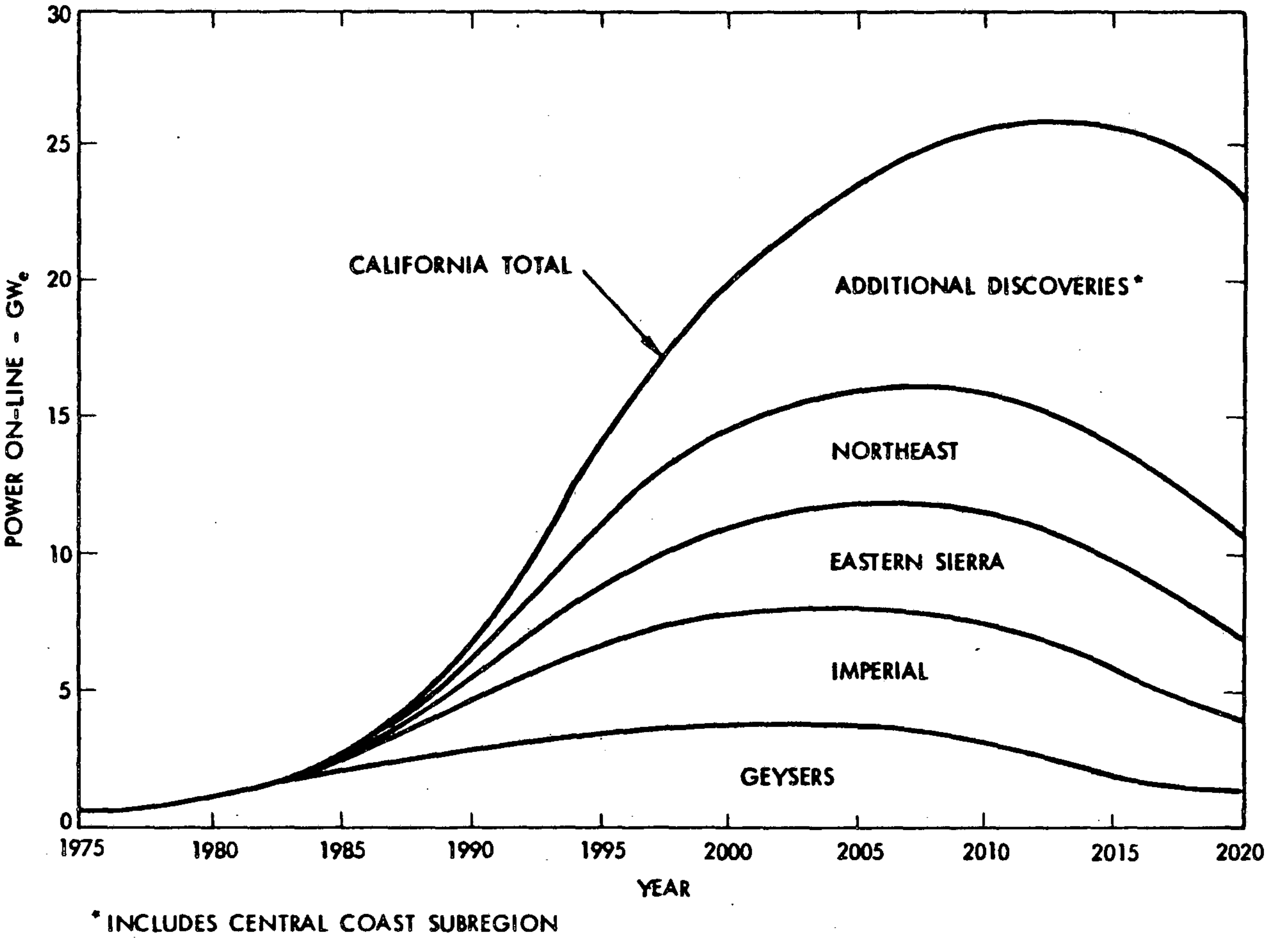

Figure 2. A scenario for geothermal growth in California (Fredrickson, 1977).

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20,000 MWe (2000), ERDA and its advisors[2] estimated that some 1500 new prospects had to be evaluated. This would entail the targeting, drilling, and testing of thousands of temperature gradient-heat flow and deep exploration/production holes between 1978 and 2000. Inasmuch as most of these new prospects would necessarily be geologically concealed or "blind" targets, there was no doubt that this would have been an awesome exploration undertaking, even after factoring in the 1978 view that industry would surely be producing electric power from hot dry rock resources by the year 2000, and even geopressured resources would be contributing to the total energy picture by then.[3]

As it turned out instead, 1980–1981 was the temporary high-water mark for geothermal exploration in the USA. Although there are no published annual drill hole completion/success records to use as a specific guide to geothermal exploration activity,[4] we can get a relative measure of exploration activity from the annual expenditures for geophysical data acquisition in the search for both new geothermal resources and at existing fields.

Table II, based on annual geophysical activity reports compiled by the Society of Exploration Geophysicists (SEG), shows the dollar amounts expended for geothermal/geophysical exploration worldwide and in the USA during the years 1974 through 1985. Although not all geophysical work is reported to the SEG, one can see that exploration, measured in the sense of new data acquisition, peaked in 1981 in the USA, and somewhat later, about 1982, outside the USA. A number of economic factors contributed to the down-turn that began in 1983. From a cursory view of the Table II, it seems that peak expenditures in the USA correlate with the culmination of federally-supported programs, the time lag in

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[2] A scenario of geothermal energy development in California is illustrated in Figure 2 (Fredrickson, 1977).

[3] The estimated cost of exploring 1500 prospects would be in the range of $1.5 to 2.5 billion (1979 dollars) based on a Basin-and-Range exploration architecture (Ward, 1977; Ball et al., 1979).

[4] Meridian Corporation will be tabulating for the DOE *Geothermal Progress Monitor* all exploration, development, and injection wells and thermal gradient holes deeper than 1000 feet (G. Beeland, personal communication, 1986).

Table II

Geothermal-Geophysical Data Acquisition Expenditures*
($ 000)

Year	Worldwide	USA
1974	1276	1243
1975	2783	2064
1976	1007	437
1977	2302	1447
1978	1804	2132
1979	4921	3641
1980	6328	3541
1981	13674	7225
1982	10934	2708
1983	7992	1295
1984	1584	688
1985	1271	401

*Data from Annual Geophysical Activity Reports, Soc. Expl. Geophys., Tulsa.

the peak of the worldwide expenditures represents, I think, the time it took to export U.S. technology to the more exciting geothermal prospects overseas. If one examines how geophysical exploration monies were spent during those peak years one will discover that electrical (dc resistivity) and electromagnetic expenditures (magnetotelluric and controlled-source) increased markedly. This I believe can be traced to the great strides made in improved techniques and interpretation made in the USA. The incoming Reagan administration took the view in 1980 that federally-supported geothermal research directed to the hydrothermal type of system was no longer needed; industry could carry on perfectly well. As a result major components of the Hydrothermal Technology Program, such as Exploration Technology and Reservoir Engineering, have been cut back severely. The DOE Hot Dry Rock and Geopressured Research Programs were less affected due in part to strong political influences. In contrast to the higher-grade hydrothermal resources, hot dry rock and geopressured resources are commonly seen by industry as marginal at best. The geothermal industry may monitor these DOE program activities, but does not actively explore for these resource types. I will therefore limit this discussion to the hydrothermal resource.

Steps Toward Lower Cost Exploration

Exploration managers know how to operate and stretch their exploration budgets during lean years. Three procedures are usually followed:

1. Exploration is confined to areas where an established land position exists, or where a favorable farm-in situation can be obtained.
2. Expenditures for new data acquisition are curtailed and more effort is given to areas where a good data base exists as one can be acquired through data trades.
3. Drilling expenditures are reduced by cutting back on the number of new holes drilled. This cuts costs dramatically, but it is a counter-productive strategy if carried on too long.

Because drilling is usually the largest segment of an exploration budget (Fig. 1) it would seem that the areas with the greatest potential for reducing costs and increasing exploration effectiveness are in finding ways to reduce the number of non-essential exploration holes and the marginal-to-nonproductive production-type wells. The next speaker, Jim Dunn, will speak specifically on the subject of geothermal drilling. However, because drilling is an important component of exploration, I will also say a few words on this subject.

I understand that drilling costs are as low now as they can be. Drilling companies are hoping just to hang on and earn a small profit. Further slight cost reductions that might accrue due to better technology, such as longer-wearing rock bits and improved methods for dealing with lost-circulation, are not likely. According to Peter Lysne (Sandia National Laboratory) drilling company philosophy is not to drill more cheaply, rather to drill better.

At the risk of sounding too simplistic it seems to me that an important first step toward lowering costs in the early stages of exploration would be to reduce, as much as possible, holes that could be classified as non-essential. By this I mean, by way of example, we would like to avoid drilling into the distal or discharge end of a laterally flowing thermal system. This a long-standing problem. Stated another way, "distinguishing between wells drilled in a low-to-moderate temperature system and moderate temperature wells drilled on the flanks of a high temperature system is one of the most difficult problems in geothermal exploration" (Edmiston and Benoit, 1984). The early exploration drilling done at the Cerro Prieto geothermal field and the Long Valley caldera typify this problem. The key to meeting this objective is to develop as rapidly as possible a conceptual picture for the hydrothermal circulation system.

During the later stages of exploration, once the initial discovery is confirmed and exploratory drilling involves the drilling of production-type holes, we would want to avoid drilling marginal or non-producing wells. This requires better abilities to target wells that intersect both the high-temperature zones and the producing fractures. At this stage we would hope to have a fairly accurate idea of where the major thermal aquifers and zones of high permeability are. For example, does the system have stacked reservoirs?, where are the major zones of vertical permeability?, what is the orientation of and controls on open fractures?

The third step toward lower cost and more effective exploration is related to the drilling process itself. Smarter drilling will eventually lead to certain economies for the developers. Today we are seeing a trend in geothermal exploration drilling away from rotary drilling as practiced in the oil/gas industry toward continuously-cored diamond drill holes using wireline-retreived core barrels. The advantages of this type of drilling are (1) the core samples provide the geologist, geochemist and geophysicist with a great deal of valuable information that is otherwise hard to discern from chip samples and geophysical wireline logs, and (2) the drilling can continue without the need to cement off lost circulation zones. Disadvantages of this type of drilling in geothermal areas is that slim holes are hard to flow for sampling purposes, drilling is presently limited to holes less than about 4500′ deep, and stuck rods/twist-offs are a problem because of unstable hole conditions (i.e., squeezing ground) commonly encountered.

According to Pete Lysne of the DOE Drilling Office at the Sandia National Laboratories, problems and limitation of diamond-drill coring may be remedied by the use of hybrid rigs that can drill deeper holes (to say 2 or 3 km) and suffer fewer mechanical difficulties than the presently available diamond core rigs. To do this one can envision a beefed up wireline coring system using an oil field rig whose hoisting capacity is adequate to handle a tougher drill string. I understand that a rig of this type, based on a Longyear design, has drilled a continuously-cored hole to 9000 feet at a geothermal prospect in Japan.

Subsurface Imaging for More Effective Exploration

If the main cost reduction and improved effectiveness in the exploration process is to come about from smarter siting of holes, and if the prospects to be explored will have less obvious surface manifestations to guide the explorationist, there will have to occur some major technical innovations in our exploration methods. Just as the steady improvements in reflection seismology have contributed to the discovery of new oil fields, new methods will be needed to find the concealed geothermal fields. Unfortunately, the improvements in reflection seismology have not yet had a significant impact on geothermal exploration. The concept of using seismic waves to image features related to geothermal reservoirs is appealing, but it hasn't worked out for various reasons:

1. General lack of good acoustic impedance boundaries (reflectors).
2. Energy absorbing near-surface volcanics, and severe statics corrections.
3. Velocities are extremely variable, both vertically and horizontally, due to complex geology and hydrothermal metamorphism.

Where seismic data have been processed properly over a geothermal field it has been done with a great deal of perserverence and difficulty. Figure 3 shows one example of a depth section over a geothermal field. The data were migrated with a finite element method to bring out some important fault features, one of which, H, correlates to a major upflow zone of thermal water into a reservoir tapped by the two wells shown (Blakeslee, 1984).

I would next like to mention a few techniques that show indications of being able to image the subsurface in ways that may ultimately prove important to geothermal exploration and development.

1. Vertical Seismic Profiling

Seismic observations in well and a surface source have been used for many years as a way to obtain a sonic velocity log (Gal'perin, 1974). The approach has evolved into Vertical Seismic Profiling (VSP) which has proven to be helpful in resolving deeper reflectors that are missed with conventional surface surveys.

VSP requires a downhole detector (geophone) that is mechanically clamped against the wellbore at intervals of from 10 to 100 feet, depending on the application. Surface sources, usually mechanical vibrators, are located at various offset distances and azimuths around the well. If one wanted to do so, one could carry out a high-ray-density, 3-D survey around the well looking for subtle structural features related to faults, for example. To realize the full potential of VSP several seismologists have effectively argued that a 3-component geophone be used in conjunction with both compressional (P) wave and shear (S) wave surface sources (Crampin, 1984). The three-component geophone, when used with radially and tangentially vibrating sources (with respect to the hole), detects and can be used to distinguish between an SV[5] and an SH wave. In our experiments at The Geysers and in Japan we confirmed that these shear waves propagate at

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[5] The SV wave produces a vertical component of particle motion and the SH wave produces only horizontal components of particle motion.

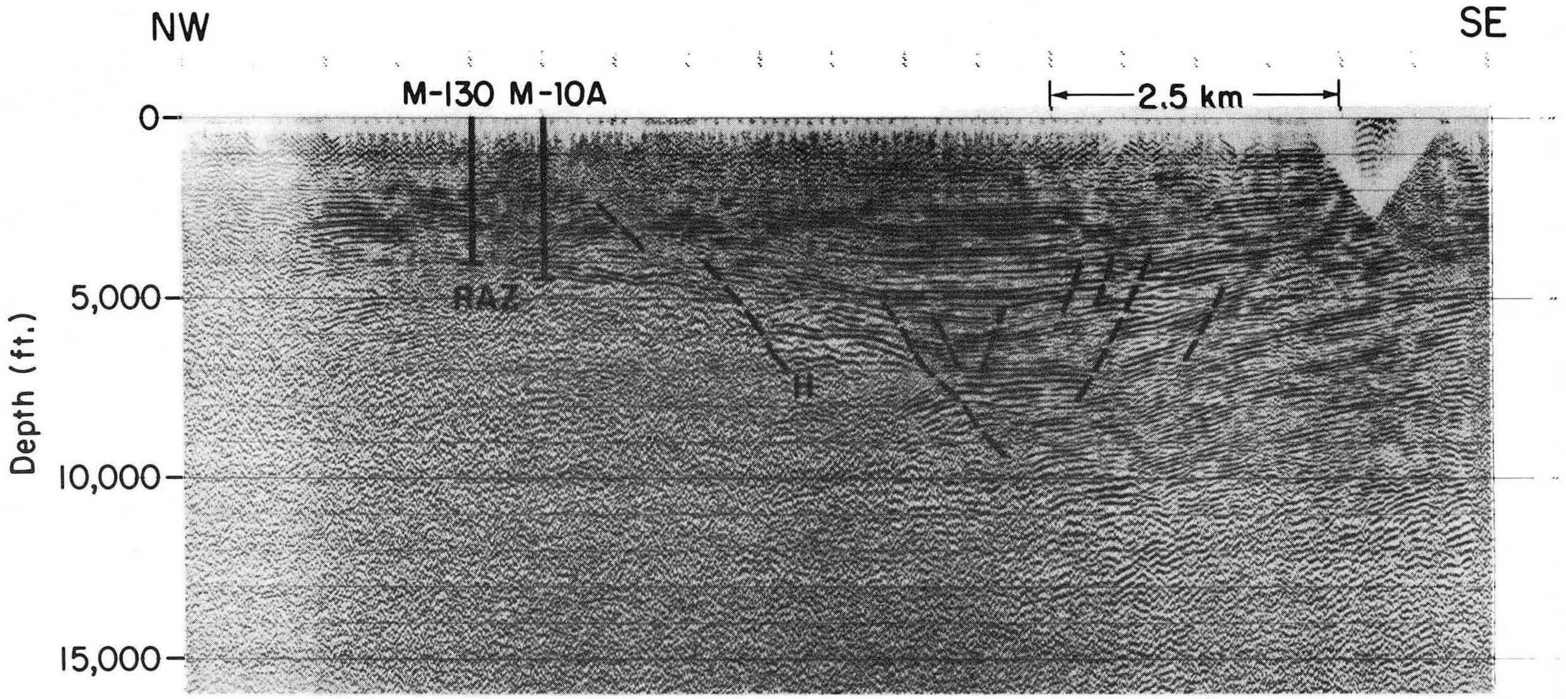

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Figure 3. A migrated depth section over the Cerro Prieto geothermal field, Mexicali Valley, Baja California, Mexico. Wells M-130 and M10A are two of the wells tapping the shallow, α-reservoir at a depth of 3600–4000 feet. Deeper wells have intersected a deeper reservoir at a depth of 6500–7000 feet. Reflection seismology does not give any clue as to the reservoir regions, but an important zone of vertical permeability, the H fault, can be picked out (Blakeslee, 1984).

different velocities (Majer et al., 1986). Interestingly, in both the field experiments and in laboratory experiments on metal models the shear wave anisotropy can be directly attributed to fractures. The shear wave anisotropy at The Geysers was evidenced by an 11% velocity difference between the SH- and SV-polarized waves (Fig. 4). The direction of maximum anisotropy was consistent, to a first order, with the known direction of the dominant fractures in the greenstone caprock. At this stage there is growing experimental and theoretical evidence that shear wave anisotropy can be related to fracture parameters. The technique has not yet been extended to reservoir depths. A particularly important step is to determine whether the direction of a deep fracture system can be distinguished from the direction of shallower fractures when the two directions are different.

Whether the technique can be used to give an estimate for the average fracture separation is also not known at this time. Theoretical work by Schoenberg (1983) suggests that the SV and SH velocity differences are related to a parameter called fracture stiffness which in turn is related algebraically to the average distance between a set of parallel fractures.

One of the principal difficulties we face in testing and exploiting the effect of fractures on seismic anisotropy is the lack of good instruments for the geothermal environment. Although high temperature tools exist, none are reliable over an extended period of time at temperatures much in excess of 225 ° C or in steam-filled holes. Tool failure occurs because of the high temperatures and leakage at the O-ring seals.

2. 3-D Geotomography

Geotomography is a general term that can be applied to a variety of geophysical methods in which a 2-D or 3-D paramerterized view of the earth is obtained by studying velocity and/or attenuation characteristics between many transmitter and receiver points (Fig. 5). Geotomography may be carried out

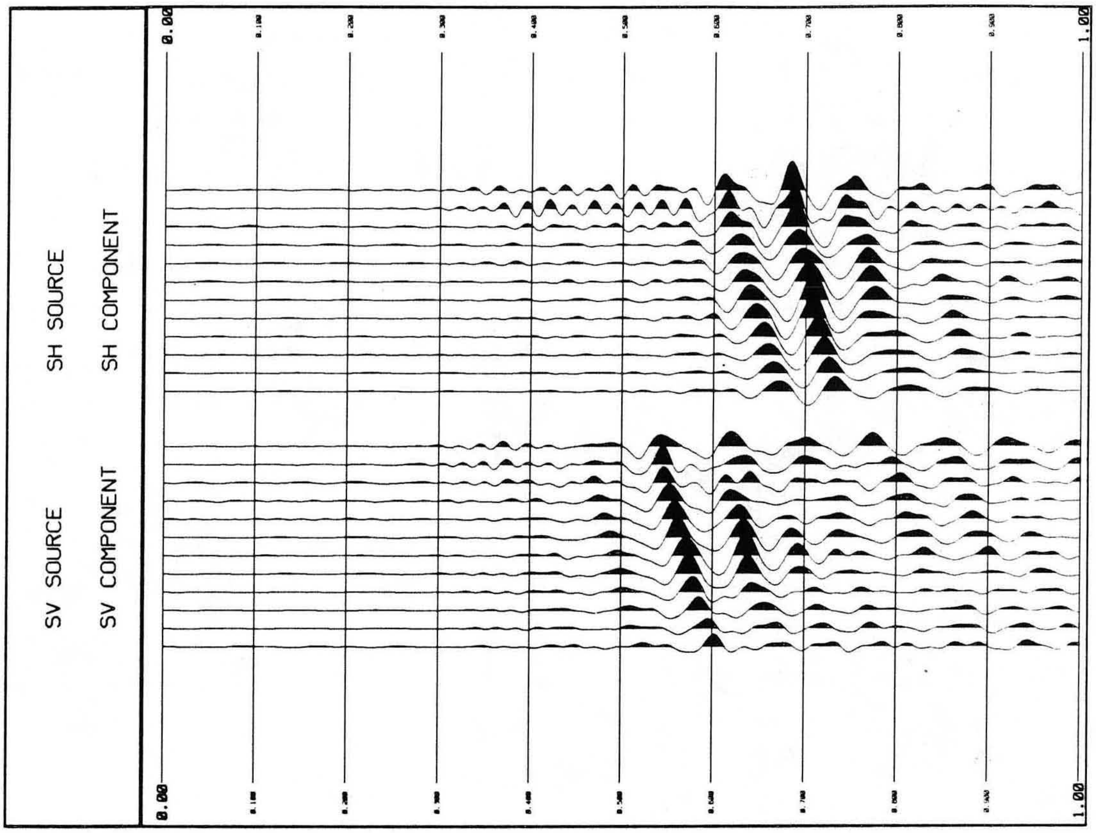

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Figure 4. Seismograms from downhole, 3-component geophones at various depths in a well with a shear wave vibrator as the surface source. The arrival times for the SV source, SV component are about 11 percent faster than for the SH source, SH component. The shear wave splitting is related to the fracture greenstones (Majer et al., 1986).

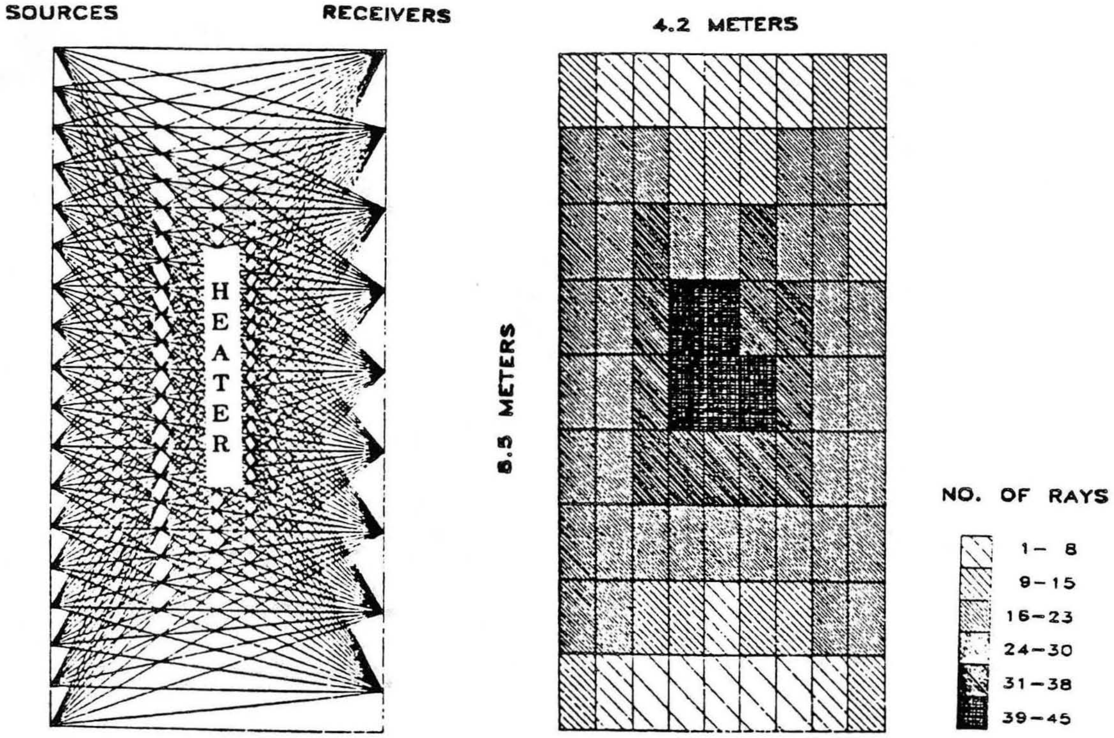

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Figure 5. An example of a cross-hole seismic-acoustic tomography experiment. The figure on the left shows the raypaths used in the algebraic reconstruction; the figure on the right shows the number of rays intersecting each pixel (Peterson, 1986).

between boreholes as done by Peterson (1986) for seismic-acoustic energy, and by Lager and Lytle (1977) for high-frequency electromagnetic energy. Geotomography may also be carried by using a surface-to-subsurface combination of sources and receivers. In this regard, one of the better-known techniques involves the recording of natural earthquakes by means of a geophone array distributed over the region of interest. The first arrivals from large, distant earthquakes (teleseisms), and/or from the many small amplitude earthquakes (microseisms) that frequently occur in and around geothermal areas are picked from the records and processed to determine velocity variations. In the case of the teleseisms, the raypaths are nearly vertical (small angles of incidence). However, in the case of the local microearthquakes the raypaths may have a wide range of angles of incidence, and therefore can be far more effective for sampling the volume of interest and for providing greater resolution of velocity variations. The analysis of teleseismic P-wave velocities has been applied to several geothermal areas by M. Iyer and his co-workers at the U.S. Geological Survey, but the technique never caught on for geothermal exploration. The reasons for this are the long observation times needed to sample teleseisms coming from all four quadrants, and the low resolution. With a 12 or 16 station array the typical resolution (the volume of a pixel of velocity information) is a cube 5 km on a side, and this is far too coarse for exploration purposes. Moreover, the interpretation suffers from the inherent problem that near-surface anomalies are smeared out into deeper levels, i.e., lack of good vertical resolution.

While it may not be an exploration panacea, let's examine next an actual example of the results of a 3-D tomographic exercise using local earthquakes. The interpreted results shown in Figure 6 were prepared by Edi Kissling, a Swiss seismologist, who has worked with the U.S. Geological Survey on the problem of imaging the area of the Long Valley caldera, located on the eastern edge of the Sierra Nevada. The caldera outline is shown by the elliptical trace in the figure. The seven color tones represent the percent velocity change, layer by layer, from a good 1-D velocity model. The blank, uncolored, regions are pixels that were

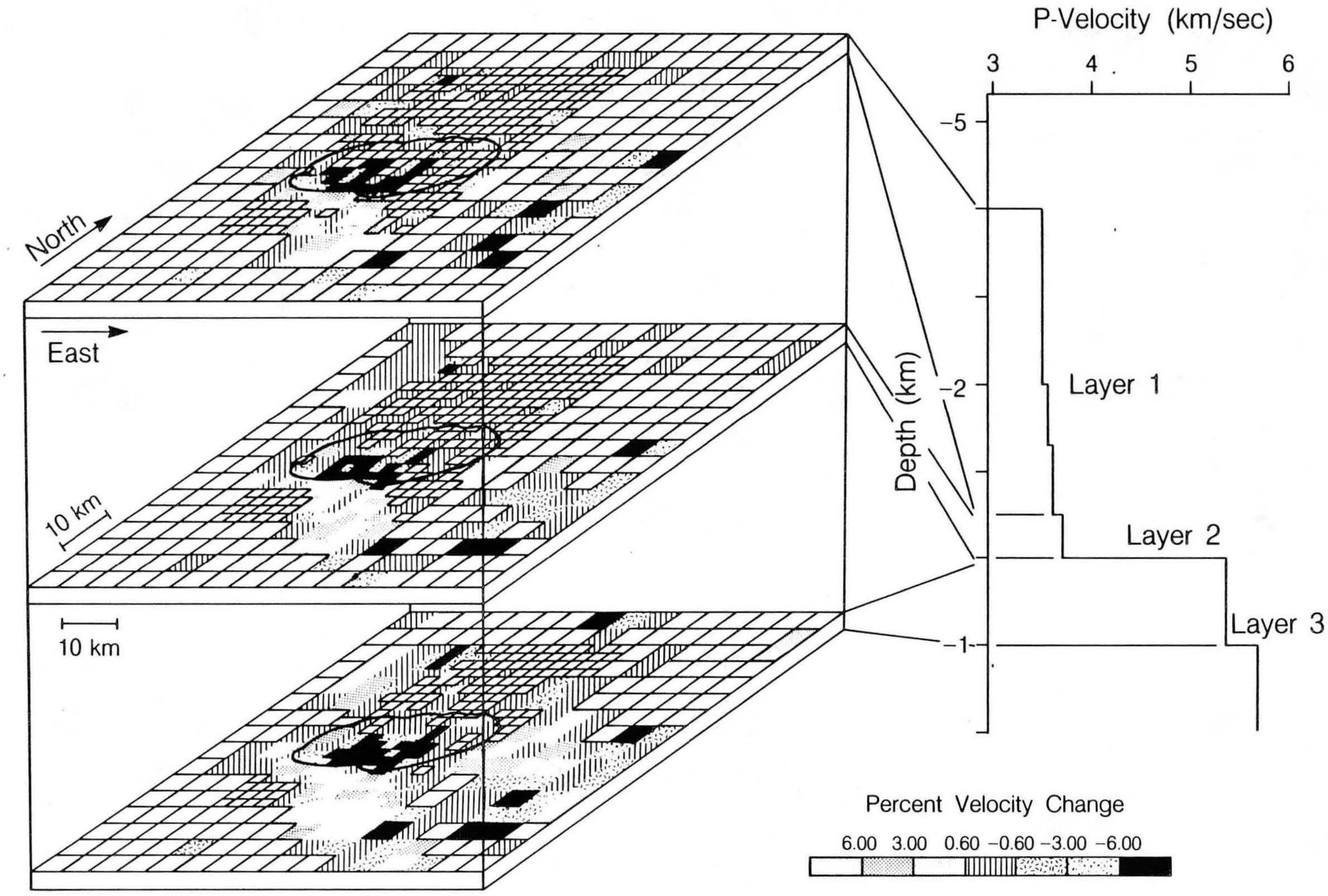

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Figure 6. The shallow portion of a 3-D seismic geotomography of the Long Valley caldera region, California (E. Kissling, 1986, personal communication).

intersected by no or too few raypaths. Because the number of events and raypaths used in the analysis is very large (over 8000 earthquakes and 100,000 raypaths were analyzed) and the number of model parameters is also very large, the simultaneous inversion of the full system of linear equations would require an enormous amount of computer memory and time, and would be totally computationally impractical. However, Kissling (1984) used an iterative first-approximation method similar to the algebraic reconstruction technique (ART) used in medical imaging (CAT scanning). The numerical technique gives a reasonably good spatial resolution for reasonable computational burden so long as one has both well-located events and a well-averaged 1-D initial velocity model. The degree of resolution is a function of the number of rays passing in different directions through a volume element.

The pink-to-red tones are where the block velocities are slower than the 1-D model; the blue tones are regions where the block velocities are faster (e.g., metamorphics). Black lines correspond to blocks close to the 1-D model. Of particular interest are the connected regions with the pink-to-red colors. The lower velocity regions may have a lithologic explanation; e.g., thick wedges of non-welded tuff, glacial till and sediments. On the other hand, these regions may correspond to volumes of fractured and hydrothermally altered volcanics and basement rocks. Notice that the region corresponding to the resurgent dome and its periphery have P-wave velocities more than 6% slower than the local average. This anomaly could be explained as due to a highly faulted and fractured region (i.e., rocks with a lower Young's modulus are more easily deformed by stresses). The high degree of faulting has been confirmed by geologic mapping. We know also that periphery of the resurgent dome has a high degree of vertical permeability, as evidenced by the numerous hot and warm springs that occur.

The 3-D geotomography results would suggest that the resurgent dome area is a discharge area, but the larger questions regarding the location of the heat source(s) and the pattern of hot and cold water flow remain unanswerable without a great deal of additional information.

The technique described has a number of limitations. It can only be applied in seismically active areas with a good distribution of local earthquakes. In addition, long observation times are needed, a huge amount of earthquake data must be edited and processed, and a great deal of geologic expertise must also be employed. Certain improvements in the technique are possible. For example, one could use tighter, 3-component geophone arrays for higher spatial resolution and for the added information of the shear waves.

3. Electromagnetic Imaging

Attempts to image the crust with electromagnetic waves to depths of 2 to 3 km have not been successful, by and large, compared to the work using elastic waves (seismic) techniques. The reason is mainly one of physics. Elastic energy propagates through the earth as waves with a short enough wavelength and low enough attenuation to offer good resolution of geological features to depths of several kilometers. On the other hand, the earth is so conductive (relative to the air) that electromagnetic waves obey a diffusion equation and waves that are low enough in frequency (< 1 Hz) to penetrate to depths of interest lack good resolving power. The magnetotelluric technique, widely used in geothermal and oil/gas exploration, offers the best approach to deep exploration, but it is plagued by various interpretational problems due to (a) local, 3-D surface conductors, and (b) large, distant conductors outside the area of investigation. Attempts to draw MT technology closer to seismic technology have been slow and only marginally successful. What we would like to have is an electromagnetic method capable of giving us a geoelectric cross-section comparable in information content to a well-processed seismic section. During the last few years, workers have been experimenting with a variation of MT, named EMAP by its originator Francis Bostick at the University of Texas. Now offered commercially, EMAP relies on a very long profile of continuous electric field data across an area. Electric dipoles are placed end-to-end along a continuous line and the horizontal magnetic field is measured simultaneously over a wide range of frequencies. A spatially weighted function (filter) is selectively applied to the computed impedances at each frequency. The wavenumber filtering suppresses the deleterious effects of near-surface conductors (which have a bad habit of propagating their effects throughout a data set). The processed EMAP cross-section shown in Figure 7 has a resemblance to a seismic cross-section. In the ten-level gray scale (log divisions) the darkest bands are the most resistive regions, the lighter bands are more conductive zones. In this actual field example, one can see two large resistive discontinuities and an intervening basin. The resistor on the right is due to a belt of metamorphic rocks. The lowermost layers are made flat (1-D) due to the lack of lateral information because of the finite length of the E-field line. EMAP overcomes the problem of under sampling and therefore it improves lateral resolution. However, because the impedance are filtered, it may be argued that vertical resolution of specific features is not as good as with conventional MT.

Conclusions

In conclusion, it seems like a safe bet that the demand for geothermal energy can only increase in the not-too-distant future, and it will be accompanied by a resurgence in geothermal exploration. Exploration problems and costs will also increase unless innovative new methods can be developed for more effective exploration of the better concealed hydrothermal systems. In this talk I have tried to give a few examples of where current research in seismic and electromagnetic imaging may eventually lead to practical technologies for exploration. These are technologies that will provide a relatively high resolution, 2-D and 3-D parameterized picture of the earth to depths of two to three km. Parameters discussed include P- and S-wave velocities and electrical resistivity. However, this new technology will not suffice unless several other important components exist and work together:

1. a receptive industry with talented scientific people who will know how to apply these techniques and who will have the experience to make the necessary geologic interpretations,

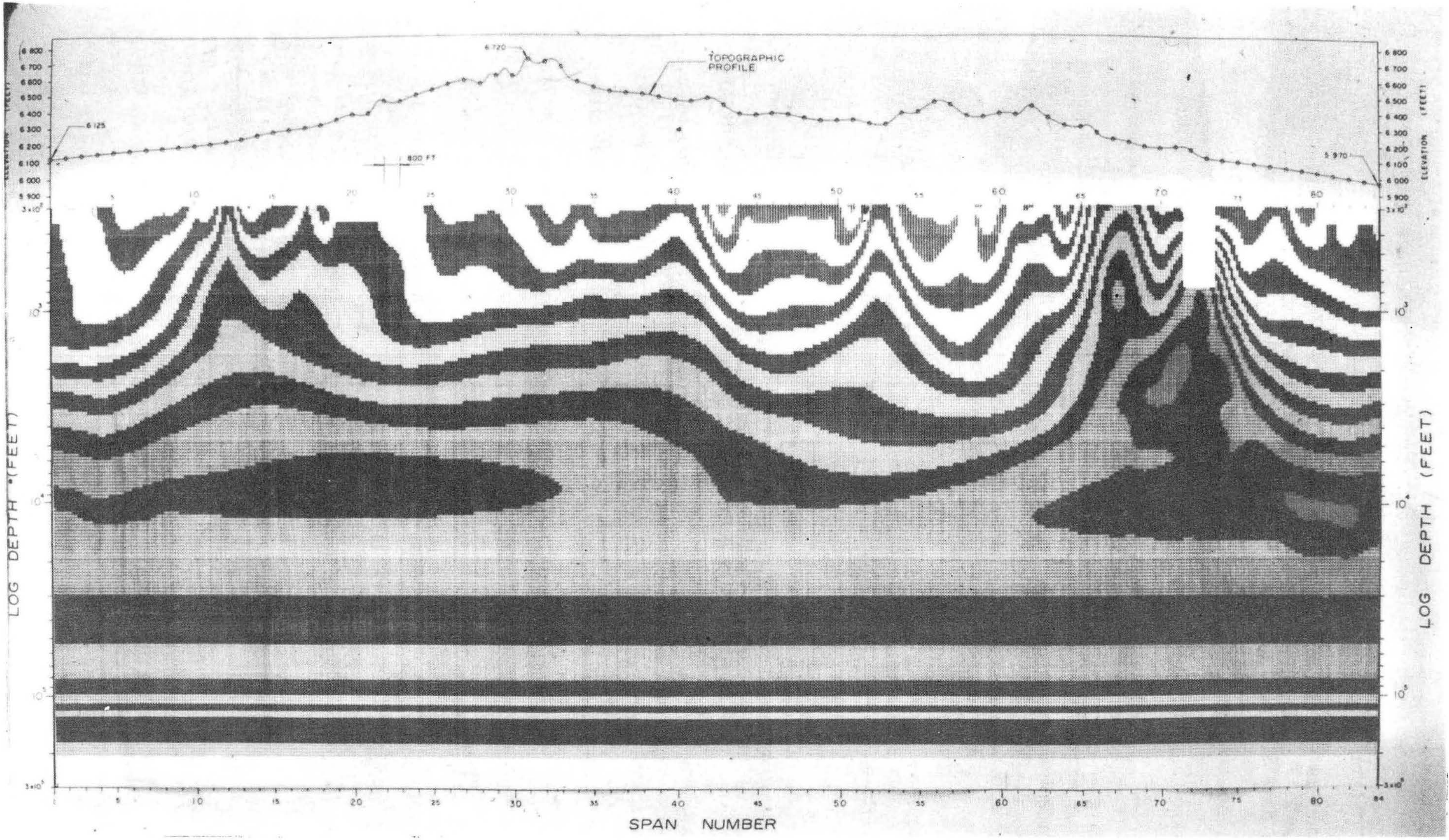

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Figure 7. A computer processed geoelectric cross-section made from an EMAP survey in Nevada (C. Torres-Verdin and F. Bostick, 1986, personal communication). The darker shades are the most resistive rock. The resistor on the right is due to a belt of metamorphic rocks.

2. the resources from the public sector to continue to do the basic research in the techniques and to develop and test the necessary prototype hardware, including better high-temperature downhole tools,
3. an exploration service industry prepared to help in technique development and to promote the commercialization of the technologies.

In this three-way exploration partnership, the weakness of any one component could be critical to the success of future exploration activities. The second of these components is one that I have been closest to through my work at the Lawrence Berkeley Laboratory, one of the institutions who have been involved in the National Geothermal Technology Program directed by DOE. I will therefore take this brief opportunity to get up on my soapbox. We have witnessed the serious decline in this program as a result of political decisions and budgetary constraints in Washington. Our hope is that this trend can be reversed. If it isn't reversed, the geothermal industry and the nation will eventually suffer the frustration, missed opportunities, and higher costs due to an inability to find and develop new geothermal reservoirs outside the known fields.

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Table III

Energy Conversions

1 BTU = 1055 Joules
1 BTU = 252 cal
1 Quad (Q) = 10^{15} BTU
1 Quad = 12,500 MWe
1 GWe (gigawatt electric) = 1000 MWe

1 Cubic Foot Natural Gas = 1000 BTU (thermal)
1 Barrel Crude Oil = 5.6×10^{6} BTU (thermal)
1 Barrel Crude Oil = 1640 kwHr (electric)
1 Quad $\sim 10^{9}$ bbl crude oil (20% conversion efficiency)

Table IV

Hydrothermal-Geothermal Resource Base in the USA (including Alaska and Hawaii) (Muffler et al., 1979)

High Temperature Vapor-Dominated Systems (> 150°C)	$\sim$ 500 Q or $\sim$ 100 billion bbl crude oil
High Temperature Liquid-Dominated Systems (> 150°C)	$\sim$ 4300 Q or $\sim$ 700 billion bbl crude oil
Intermediate Temperature Systems (90–150°C)	$\sim$ 4900 Q or $\sim$ 800 billion bbl crude oil

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