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Mining the Earth's Heat: Hot Dry Rock Geothermal Energy

Springer

The HDR Test Site at Fenton Hill, New Mexico, in late 1991

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Dedication

We dedicate this book to those who labored over many years to take the hot dry rock concept from simply a novel idea to a proven reality. Their imagination, creativity, long-term commitment, and hard work led to the outstanding technical achievements that are described in detail herein. Those achievements have laid a solid foundation for the development of HDR geothermal energy as a major energy resource for the 21st century and beyond.

Legal Statement

Acknowledgments

The 23 years of pioneering experiments that constituted the Los Alamos National Laboratory's Hot Dry Rock Project would not have been possible without the support of numerous entities, beginning with the U. S. Atomic Energy Commission (AEC). Its successor federal agencies, the Energy Research and Development Administration (ERDA) and the U. S. Department of Energy (DOE), continued the funding of the HDR effort. And from 1980 to 1986, the government of Japan and the Federal Republic of Germany also contributed, through an agreement developed under the auspices of the International Energy Agency (IEA).

The authors would like to particularly acknowledge the enthusiastic and unwavering support for the HDR concept shown by the late John E. (Ted) Mock, who directed the U. S. Department of Energy's geothermal program from 1982 to 1994, the period spanning the development and testing of the deeper Phase II reservoir at Fenton Hill, New Mexico, and by Allan Jelacic, now retired, who assumed leadership of the DOE's Division of Geothermal Energy following Dr. Mock's retirement in 1994. The financial support provided under their leadership made possible many of the technical achievements described herein and helped launch the production of this book, which no doubt will serve as one of the HDR Project's principal legacies.

It was through the persistent efforts of the late Mort Smith that the early funding was obtained for the nascent HDR Project. Without his efforts, there never would have been a Fenton Hill. Mort also inspired us to prepare this book and was a constant source of valuable information until his death.

Bob Potter, who originated the hot dry rock concept at Los Alamos, deserves special recognition. His unique expertise helped elucidate the initial drafts of several chapters of this book. Jim Thomson, a key member of the HDR field operations team responsible for the highly automated and reliable operation of the surface plant during the Long-Term Flow Test, provided much helpful technical input on the surface equipment and downhole operations. In addition, we thank Bert Dennis, the able leader of the Instrumentation Group during the HDR Project (starting with the Barley Canyon experiments in 1972), for his help in preparing the Appendix.

Thanks are also due the hundreds of hard-working scientists and engineers associated with the Fenton Hill HDR Project, who produced the reports from which portions of this book are drawn. The results cost them countless days and nights of effort, often under the pressure of deadlines and foul weather.

We would also like to recognize those who assisted in the practical aspects of preparing this volume for publication. Ruth Bigio, who left the Laboratory a few years ago, provided initial versions of several of the figures. Andi Kron, Los Alamos National Laboratory geologist-turned-cartographer/technical illustrator, was responsible for all of the final figures in the book. She not only exercised laudable patience as we made endless changes to them, but her skill with graphics and her own scientific and technical background enabled her to improve many of them. The formatting and composition are the fine work of Carrie Dittmer (Dittmer Design, Golden, CO). Carrie has earned our particular gratitude for her dedication, good humor, and responsiveness in the face of multiple revisions of the manuscript. We thank Vicky Musgrave of the Los Alamos National Laboratory Research Library for expeditiously resolving problems with a number of the references; and Iosif Hriscu of the Halliburton Company (Duncan, OK) for help with some technical drilling details and terminology.

Finally, we would like to express our thanks and appreciation to our many colleagues around the world who took an interest in the Fenton Hill HDR Project. Many of them provided us with insights that both directly and indirectly contributed to the wide range of HDR issues summarized in this book.

Preface

The hot dry rock (HDR) geothermal energy concept was born of the recognition that the heat of the earth represents an almost inexhaustible source of clean, thermal energy for mankind. It was the pioneering efforts of Bob Potter and Mort Smith, two visionary scientists at Los Alamos National Laboratory in New Mexico, that led to the development of an effective and robust method of recovering useful energy from the vast regions of hot rock in the earth's upper crust. The heat from that rock—as Smith put it—"represents the largest and most broadly distributed supply of directly usable thermal energy that is accessible to man." In the ensuing years, other researchers at Los Alamos would help to make Potter and Smith's dream a reality.

This book tells the story of the pioneering experiments at Fenton Hill, near Los Alamos, which produced the world's first and—to date—only true HDR reservoirs. They were created in deep regions of jointed basement rock that had subsequently been tightly resealed by the deposition of secondary minerals (the almost universal situation where sufficient time has followed the period of deformation that produced the jointing).

As manager of the Hot Dry Rock Project during a period that yielded some of the most fruitful and significant technical results, I was particularly well positioned for the task of analyzing and synthesizing the findings from the numerous Fenton Hill tests and experiments. Over the past twelve years, the demands of writing this book have led me to carry out an exhaustive review of those findings and to revise and/or reinterpret them as called for—in light of present knowledge concerning the behavior of deep, jointed, crystalline basement rock in general and of confined, man-made HDR reservoirs in particular.

Some readers may find the length and level of detail of certain chapters excessive. But it should be noted that this book is intended not only to provide information useful to future exploiters of heat from the deep earth, but also to serve as the complete and definitive report on the 23 years of HDR operations at Fenton Hill—written from the perspective of one who was deeply involved from start to finish. To facilitate the reader's grasp of the most important events and findings, Chapter 2 has been structured as an "Executive Summary."

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PART I

Hot Dry Rock Geothermal Energy: History and Potential of the Newest and Largest Renewable Energy Resource

Chapter 1
Serendipity—A Brief History of Events Leading to the Hot Dry Rock Geothermal Energy Program at Los Alamos

How far back in our past did humans begin to use hot water and steam coming from vents in the earth's surface to improve their lives? Did they make stops at such sites while moving from place to place, bathing in the warm pools or using the waters for cooking, and eventually construct villages near hot springs? We can only imagine in what ways man first availed himself of the earth's heat; but we can assume that human populations in various areas sooner or later encountered hot waters that were bubbling up to the surface after having been raised to high temperatures by circulation through deep, hot rock—and that they made use of the heated water.

In modern times, geothermal energy has been exploited through drilling into permeable zones within the earth's crust that are characterized by high heat flow. If the reservoir of hydrothermal fluid is sufficiently large, the depths are accessible to drilling, the temperatures are high enough, and the rock is sufficiently permeable, hot fluids can be brought to the surface for conversion to electrical power or for direct-heating use. But areas possessing these attributes (such as Larderello, Italy, where deep hydrothermal fluids have been commercially exploited for electricity generation since the early 1900s) are rare. In many regions, exploratory boreholes have been drilled to depths where temperatures were sufficiently high, but the permeability of the rock was negligible and only small amounts of fluid were present—in other words, the rock was hot, but essentially dry. The next logical step, then, was to consider *engineering* geothermal reservoirs in the far more numerous regions of the earth where rock at drilling-accessible depths was hot but contained no open, interconnected joints or faults.

The concept of extracting heat from man-made geothermal reservoirs originated in the early 1970s, at the Los Alamos Scientific Laboratory (now the Los Alamos National Laboratory) in New Mexico.[1] Established by the

[1]Much of this early history of hot dry rock (HDR) geothermal energy has been abstracted from the many papers written by HDR pioneer Morton C. Smith. His untimely death in 1997 brought an end to the detailed history of the HDR Program he had embarked upon. Fortunately, we already have the first volume, entitled *The Furnace in the Basement, Part I—The Early Days of the Hot Dry Rock Geothermal Energy Program, 1970–1973*. Published in 1995, it is superbly researched, extremely readable, and highly recommended as additional reading. The second volume, for which he had completed a great deal of the work, will be published by the authors of this book as soon as possible.

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U. S. Army, then transferred to the Atomic Energy Commission (AEC) in the mid 1940s, the Laboratory[2] had as its primary mission the design and testing of nuclear weapons. So how did the scientists working there become involved in developing a unique form of renewable energy? The first serendipitous circumstance was the truly multidisciplinary character of the Laboratory and the uniquely "research-friendly" environment it offered. To design and test weapons required the efforts not only of weapons experts, but also of engineers, chemists, physicists, geologists, geophysicists, hydrologists, and health scientists. And to stay in the lead technologically required the "campus" atmosphere of freedom for creative thinking that was then the Laboratory's hallmark, as well as the kind of dedication for which Los Alamos scientists were known.

Developments at Los Alamos

Under the directorship (1945–1970) of Norris Bradbury, Los Alamos researchers were openly encouraged to "come up with ideas"—a challenge that was taken up by, among others, a group of chemists led by Eugene S. ("Robbie") Robinson. Robinson's group was interested in new techniques for drilling deep holes into the earth; it was not only the possible practical applications that sparked their interest (the "Mohole" deep earth sampling project was under consideration at the time), but also a kind of fascination about what could be done, what could be found, "down there."

Conventional drilling was based on the use of drill bits made of very hard materials that could break and grind solid rock. In 1960, members of Robinson's group conceived the notion that if the rock could be rendered liquid—melted—its penetration might be easier and faster (particularly as depth, and therefore rock temperature, increased), as well as cheaper. In early experiments, refractory metals such as tungsten and molybdenum, electrically heated to incandescence, were readily pushed through samples of igneous rock. These experiments confirmed that the energy needed to melt rock is similar to the energy required to break and pulverize it (on the order of 1 kcal/cm^3). The group then embarked on the developmental work that led to the creation of a rock-melting penetrator.

The new device proved capable of steady-state drilling through basalt boulders (the debris—glass particles—being pneumatically ejected as drilling progressed). In porous volcanic rocks, such as ash-fall tuffs, the penetrator was able to consolidate the rock as it advanced, creating a high-density glass lining for the hole—which eliminated the need to eject debris. The coupled heat-transfer and hydrodynamic behavior of the rock-melting process was analyzed through a new solution of the Navier–Stokes equations that was developed by B. B. McInteer, a member of Robinson's group (Armstrong et al., 1965).

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[2]In this book we use "Los Alamos" and "the Laboratory" interchangeably to refer to the Los Alamos National Laboratory.

Although lack of funding terminated the rock-melting project in early 1963, the ensuing years saw considerable private speculation within the group about possible new advances in this area. In early 1970, at Norris Bradbury's direction, Robinson assembled an interdisciplinary ad hoc committee (Fig. 1-1) to study a rock-melting drill based on a new concept. Known as the "Nuclear Subterrene," this device would be powered by a compact nuclear reactor instead of by electricity; it would transmit thermal energy via heat pipes to a refractory metal shell surrounding the reactor (Robinson et al., 1971). Such a device would be capable of much more efficient boring of significantly larger holes (up to several meters in diameter) than the electrically powered rock-melting penetrator—opening up numerous applications for which smaller-scale drilling and excavating was costly and time-consuming (such as bores and tunnels for underground transport of gases, liquids, cargo, and people; large underground cavities for waste disposal or for storage and preservation of various materials; underground chambers for high-temperature and high-pressure processing operations; shafts for mining and exploration; underground laboratories for scientific studies; and—not least—the creation of man-made geothermal energy systems).

Fig. 1-1. The Ad Hoc Committee on Rock-Melting Drills (clockwise from left): Don Brown, Bob Potter, Bob Mills, B. B. McInteer, John Rowley, Mort Smith (behind Rowley), and Dale Armstrong.
Source: *The Atom*, 1971

In addition to most of the original members of the rock-melting project, the committee included experts in needed disciplines, and outside consultants were called upon for assistance with specialized matters. The committee conducted its study through most of 1970 and summarized its conclusions—how the Subterrene would be constructed, how it would work, and its principal applications—in a report for submission to Harold Agnew, the new Laboratory Director. The report would essentially be a proposal for the establishment of a major program to develop the Subterrene.

It was as part of this process that another link in the serendipitous chain was forged: Bob Potter, an influential and creative member of Robinson's team, had long been interested in the application of deep-drilling technology to the recovery of geothermal energy, which would involve accessing the hot crystalline rock typically found deep in the earth's crust. Potter's imagination was sparked by an article in the *Journal of Geophysical Research* describing hydraulic fracturing experiments carried out at the Oak Ridge National Laboratory (Sun, 1969). Using the hydraulic fracturing technology developed by the petroleum industry to access "tight" hydrocarbon reservoirs, Oak Ridge was investigating whether fracture systems could be created in the sedimentary layers of the earth's crust for the disposal of radioactive waste. Potter reasoned that if hydraulic fracturing could be used to develop fracture systems in sedimentary rock, the technology could also be used to fracture[3] crystalline rock.

The Oak Ridge experiments provided other insights that were pivotal as Potter's aspirations for the Subterrene became more and more drawn in the direction of geothermal applications. The experiments involved two relatively shallow wells: an injection well, down which water was pumped at a pressure that would induce fracturing of the surrounding rock (through slots cut in the casing); and an observation well, located about 30 ft (9 m) to the west. By the time about 9000 gal. (34 000 L) of water had been pumped into the injection well, a sudden rise in pressure was noted in the observation well, indicating that the hydraulically induced fracture (or fractures) had intersected that well. It became clear that such fractures could extend tens to hundreds of meters into the surrounding rock. This finding, in combination with the knowledge that rocks become progressively hotter with depth, made it only a short step to the next realization: the idea began to jell that, at depths where rock temperatures were hot enough for commercial applications, hydraulic fractures could serve as underground flow paths for a heat-mining system. Heat from the fracture surfaces would be transferred to fluid pumped into them via the injection well, and the hot fluid would then be

[3]Today, we often use the more accurate term "pressure-stimulate"—it now being clear that crystalline rock is characterized by pre-existing networks of joints or fractures that have become sealed by mineral deposition and are reopened through hydraulic pressurization.

brought back to the surface via the second (production) well—an efficient means of recovering geothermal heat. The hot dry rock geothermal energy concept was born.

Building on Potter's concept, Mort Smith postulated that (owing to the combined effect of increasing temperature, increasing overburden stress, mineral alterations, and deposition of secondary minerals) both the porosity and permeability of crustal rock would diminish progressively with depth. He believed this geologic situation—the presence of low-porosity hot rock at depth—to be extremely common throughout the world, in contrast to the rarity of natural hydrothermal systems. If HDR was exploitable, then, nearly every area of the world could, given adequately deep boreholes, be considered to possess an abundant geothermal resource at depth.

Mort Smith and Don Brown, who were knowledgeable in conventional rotary drilling techniques, then supplied the final link in the chain of serendipitous events: they reasoned that the development and testing of an HDR system need not wait for success in the Subterrene Program, but could proceed in parallel, using then-available oilfield drilling equipment. Most of the committee—and especially Potter, McInteer, Smith, and Brown—concurred that HDR was at least as important as the Subterrene. When the proposal was submitted to Director Agnew in November 1970, therefore, it contained (as Appendix F) a detailed presentation of Bob Potter's HDR concept and the suggestion that once the Subterrene Program was under way, a second major program be instituted to develop HDR geothermal energy systems. (The document was reproduced by Mort Smith in a more polished form the following April, for use as a "sales tool" [Robinson et al., 1971].)

Note: The Nuclear Subterrene would never be developed. In 1973, under the leadership of John Rowley, the Program would be redirected from an emphasis on large-diameter tunneling and boring applications to support of geothermal drilling and exploration. With the approach of a worldwide oil crisis (the Arab oil embargo of 1973), which was driving renewed interest in alternative energy technologies, it was difficult to argue against the logic of developing HDR geothermal systems as soon as possible. Moreover, anticipated major cutbacks in the Laboratory's multimillion-dollar Rover Program—to develop a hydrogen-cooled nuclear rocket engine for space exploration—was creating a need for new programs at the Laboratory. (By 1976, lack of interest in Washington would lead to a withdrawal of funding and cancellation of the Subterrene Program. Fortunately, the HDR Project would be the beneficiary, at least in terms of manpower.)

Hot Dry Rock in Its Infancy

In March 1971, the Laboratory's newly appointed Associate Director for Research, Richard Taschek, launched the Hot Dry Rock Geothermal Energy Development Project—as yet unfunded—under the leadership of Mort Smith and with Eugene Robinson as coordinator. The HDR concept would be patented three years later (Potter et al., 1974).[4]

In those early years, the HDR Project at Los Alamos was very informal. The "geothermal group" began by gathering and studying available information on the geology and geophysics of geothermal areas, as well as on hydrology, drilling, rock mechanics, reservoir management, and hydraulic fracturing. Physicists working with the group modeled the efficiency of heat extraction from an HDR reservoir (Harlow and Pracht, 1972). Early on, a closed-loop earth circulation system was envisioned that would incorporate heat exchangers at the surface to transfer the heat from the hot geofluid (pressurized water) to another working fluid—a so-called binary cycle. Such a system would have the advantages of being simple, safe, and environmentally benign, and could be designed on the basis of existing technology.

The Los Alamos team believed that man-made geothermal systems could be created in the deep crystalline "basement" almost anywhere that geothermal gradients were high enough for heat mining to be commercially attractive—the principal economic issue being the cost of drilling. Without the means to explore far and wide, they went looking "just over the hill" west of Los Alamos, in the Jemez Mountains. The major feature of this area is the Valles Caldera, formed only about 1 million years ago.

Along the trace of the bounding ring-fracture, post-caldera eruptions of rhyolitic lavas occurred as recently as about 50 000 years ago. Primarily inside the physiographic rim, hot springs and a few fumaroles were surface indicators of a large thermal resource (magma body) underlying a portion of the caldera; and extensive faulting suggested subsurface joint permeability, making the caldera a prime target for hydrothermal geothermal exploration and development. In the 1970s and 1980s, in an independent effort (funded mainly by the U. S. Department of Energy [DOE] and the Public Service Company of New Mexico), the Union Oil Company of California carried

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[4]The HDR patent was written by Don Brown, with the able assistance of Paul Gaetjens, a Laboratory patent attorney. Almost the entire HDR concept was Bob Potter's; Mort Smith added a section on the augmentation of heat production through thermal stress cracking, and Don Brown contributed a section on a single-well heat production concept using insulated, coaxial casing. (Later, to honor Eugene Robinson—the Project's financial "godfather" in the early days, who was suffering from terminal cancer—Don Brown replaced his name as third author with that of Robinson.)

out extensive drilling and testing along a major northeast-trending fault structure within the caldera. They did find a high-temperature hydrothermal system, but its power-generation potential was only about 25 MW_e, half that required (at that time) to make a commercial venture feasible.

The Los Alamos team reasoned that recent volcanic activity along the ring-fracture would have produced a region of elevated temperature that would extend radially outward from the caldera at least several miles. In late 1971, the measurement of geothermal gradients in a number of shallow, augered holes surrounding the caldera verified this hypothesis and showed that the western flank was particularly attractive for HDR development. In early 1972, four deeper holes were drilled in that area for measuring temperature gradients and heat flows. Three of these holes were located roughly along an arc parallel to and 2–3 miles (3–5 km) west of the ring-fracture; the fourth was located 4.5 miles due west of the ring-fracture.

As shown in Table 1-1, the heat-flow values for the three holes closest to the caldera (A, B, and C) were found to be uniformly high—in the range of 5–6 cal/cm^2 • sec (worldwide average heat flow is about 1.5 cal/cm^2 • sec). In contrast, the heat flow for hole D was only about one-third as high.

Table 1-1. Heat-flow values in intermediate-depth test holes

	Hole A	Hole B	Hole C	Hole D
Date completed	10 Apr 1972	13 Apr 1972	16 Apr 1972	18 Apr 1972
Distance from ring fault (mi)	2.0	2.4	3.0	4.5
Depth (ft)	590	650	750	500
Heat flow (cal/cm^2 • sec)	5.13×10^{-6}	5.50×10^{-6}	5.88×10^{-6}	2.20×10^{-6}

The Precambrian-age crystalline basement rocks of the area were thought to lie about 2600 ft below the surface. Similar rocks, when tested at university laboratories, had proved to be nearly impermeable, indicating that a basement-rock environment such as that found in the Jemez Mountains could be ideal for testing and development of the HDR concept. On the basis of these findings, the team selected the Fenton Hill area, just west of the Valles Caldera (Fig. 1-2). An essentially nonvolcanic terrain, Fenton Hill exhibited elevated thermal gradients; the crystalline basement rock lay at reasonable depths; and the entire region was public land, part of the Santa Fe National Forest.

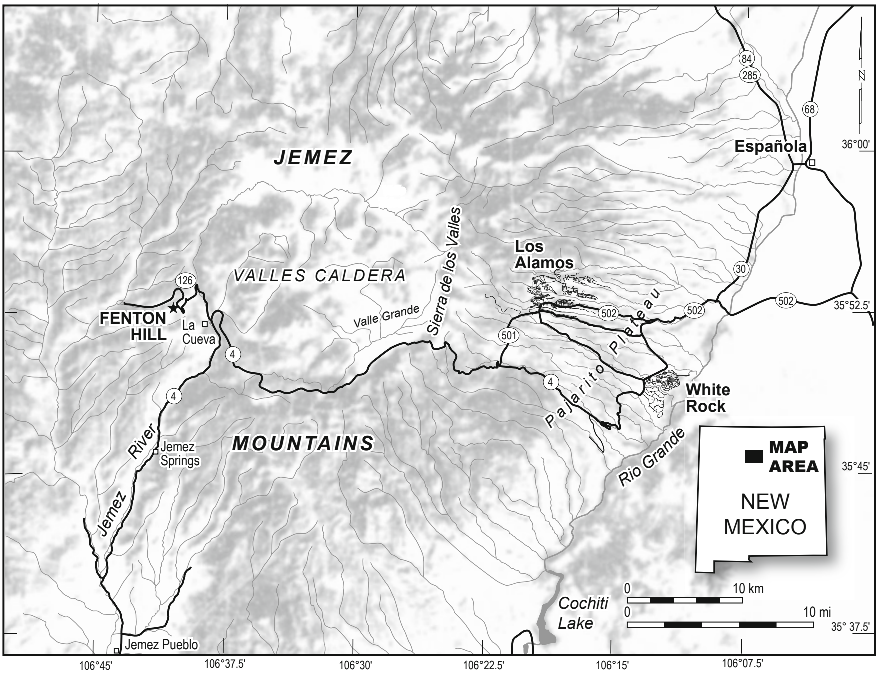

Fig. 1-2. The region west of Los Alamos. The Fenton Hill area is shown west of the Valles Caldera.

A site in Barley Canyon, located on the arc formed by heat-flow test holes A, B, and C, was picked. It was decided to drill in the canyon bottom, which would reduce the amount of drilling by some 300 ft, thereby saving considerable time and money (but this would later prove to be a mistake, when thawing of the very heavy snowfall of the winter of 1972–73 turned the work area into a muddy bog).

In the spring of 1972, the drilling of the first deep exploratory borehole, Granite[5] Test No. 1 (GT-1), was begun. Precambrian crystalline basement rocks were encountered at 2105 ft (642 m), and by June 1 the hole had reached a depth of 2430 ft (741 m), some 325 ft into the basement. After being cased to a depth of 2400 ft with 5-in.-diameter, 13 lb/ft K-55 casing, the hole was deepened 145 ft by continuous coring. The final depth was 2575 feet (785 m), 470 ft into the crystalline basement. An examination of the drill cuttings obtained during the first 325 ft of basement drilling (before the casing was set) showed that the rock was primarily augen gneiss. The

[5]Although the term "Geothermal Test Hole" appears in numerous HDR publications and reports, the original term—and the one that was used in the permits and original paperwork—was "Granite Test Hole."

rocks penetrated during the continuous-coring phase were 50 ft of true granite, 40 ft of gneiss, and finally 55 ft of amphibolite. This first exploratory borehole exhibited a bottom-hole temperature of 100.4°C and a mean gradient of over 100°C/km—outstanding for any geothermal area.[6]

Figure 1-3, an enlarged view of the Valles Caldera and the region to the west, shows the location of GT-1 in relation to the caldera and the four heat-flow holes. (Most of the area known at that time as Baca Location No. 1 is currently the Valles Caldera National Preserve.)

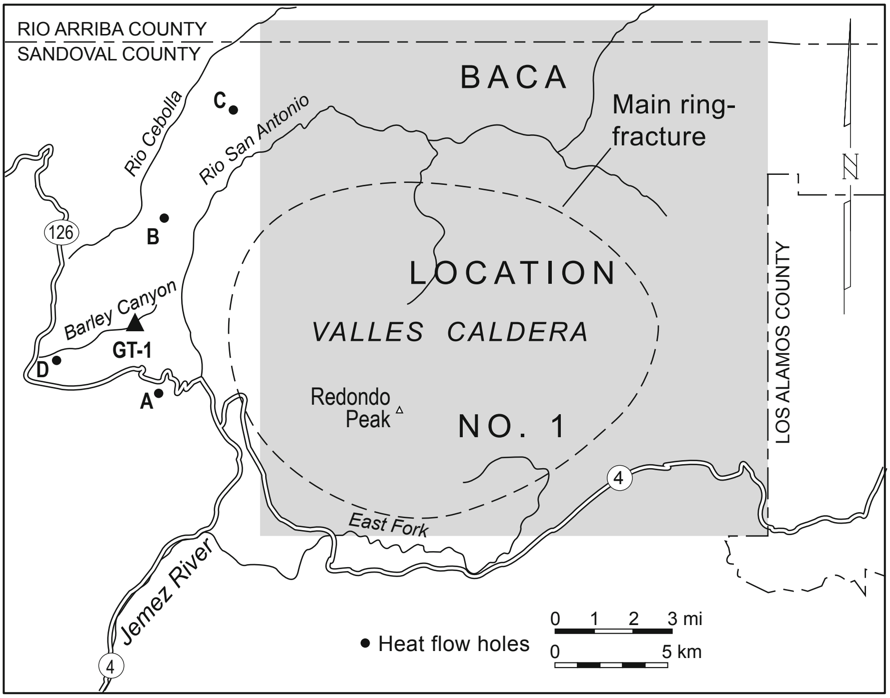

Fig. 1-3. Enlarged view of the Valles Caldera area, showing GT-1 and the four heat-flow test holes (A, B, C, and D). The dashed line delineates the trace of the main ring-fracture.
Adapted from Smith, 1995

[6]As would be discovered later, all the heat-flow and temperature-gradient measurements made in the Fenton Hill area were strongly affected by the hot aquifer originating from the caldera and flowing to the west on top of the Precambrian surface.

The First Experiments in Hydraulic Fracturing

In early 1973, a series of hydraulic fracturing experiments were conducted—with considerable difficulty—in the 145-ft continuously cored Precambrian interval of GT-1.[7] These first-ever "fracturing" experiments in deep, hot crystalline rock were intended to verify the suitability of such rocks for field testing of an HDR reservoir.

In conventional hydraulic fracturing of sedimentary formations containing petroleum or natural gas, a "packed-off" interval[8] of the borehole is pressurized until the overpressure fractures the borehole wall. According to the then-accepted theory of hydraulic fracturing in unjointed sedimentary formations ("homogeneous" isotropic rock) in regions where the earth stresses are typical (i.e., the maximum earth stress is vertical), the induced fracture should be vertical, planar, and normal to the axis of the least principal earth stress, which acts horizontally. With continued pressurization, the fracture should extend radially outward from the borehole for hundreds of feet, forming what is referred to as a "penny-shaped vertical fracture." This theory, which had its origin in the classic 1946 paper by I. N. Sneddon, formed the basis for the original HDR system design (Fig. 1-4).

But when the Los Alamos team applied this simple theory to the hydraulic fracturing of the Precambrian crystalline rocks penetrated by GT-1—as though this melange of ancient metamorphic and igneous rocks were "unflawed and homogeneous"—they made a serious error in judgment. Worse, that error would be perpetuated in HDR geothermal programs carried out later in other countries and in HDR research conducted by several universities (much of which, at least initially, was supported by Los Alamos). The investigators all assumed that a single fracture would be created and that it would be penny-shaped and vertical, providing a large area for the transfer of heat from the fractured hot rock to the circulating fluid.

It is important to note that this concept was not abandoned until the early 1980s (even later in Japan). Eventually, both the British HDR team working at Rosemanowes[9] and the Los Alamos team realized that, except for possibly a short distance immediately adjacent to the borehole wall, hydraulic fracturing was not actually breaking open intact crystalline rock against its inherent tensile strength. Rather, perhaps with one exception (see

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[7] These experiments are more thoroughly covered in Mort Smith's excellent report on the early days of HDR, *The Furnace in the Basement, Part I* (Smith, 1995).

[8] The interval to be fractured is isolated between a pair of removable seals called "packers." This "straddle" packer assembly is connected by a pressure line ("frac" string) to high-pressure pumps on the surface.

[9] From 1977 to 1988, personnel from the Camborne School of Mines carried out the first large-scale geothermal research project in Europe, in the Carnmenellis granite (Cornubian Batholith) of a former granite quarry at Rosemanowes, in the southwestern Cornwall peninsula.