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*Candidate Sites
for Future Hot-Dry-Rock Development
in the United States*

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CANDIDATE SITES FOR FUTURE HOT DRY ROCK DEVELOPMENT IN THE UNITED STATES

by

Fraser Goff and Edward R. Decker

ABSTRACT

Generalized geologic and other data are tabulated for 24 potential hot dry rock (HDR) sites in the contiguous United States. The data show that HDR resources occur in many geologic and tectonic settings. Potential reservoir rocks at each prospect are described and each system is categorized according to inferred heat sources.

The Fenton Hill area in New Mexico is discussed in detail because this region may be considered ideal for HDR development. Three other prospectively valuable localities are described: The Geysers-Clear Lake region in California, the Roosevelt Hot Springs area in Utah, and the White Mountains region in New Hampshire. These areas are singled out to illustrate the roles of significantly different geology and geophysics, reservoir rocks, and reservoir heat contents in possible HDR developments.

I. INTRODUCTION

The Los Alamos National Laboratory has been compiling and evaluating geothermal and related data for the conterminous United States since hot dry rock (HDR) was shown to be technically feasible in 1977. This research involves many geologic, geophysical, and geochemical projects, and much effort has been devoted to evaluations of sites that could be used for future HDR developments. The program has many objectives. For example, Quaternary

volcanic terranes in the western United States are being studied to determine if the large amount of heat in local impermeable rocks can be extracted by HDR techniques. Related research focuses on continental heat flow studies in an effort to show that HDR resources are not restricted to young volcanic terranes, or to areas that border active hydrothermal systems. This paper demonstrates that HDR potential occurs throughout the conterminous United States by synthesizing geologic and other pertinent data for 24 prospectively valuable localities. The Fenton Hill prototype system in New Mexico is discussed in detail because it provides baseline data for future developments. Three other prospects are also elaborated upon to show that HDR potential exists in significantly different reservoir rocks, heat flow provinces, and tectonic settings.

II. LOCATIONS AND CHARACTERISTICS OF HDR PROSPECTS

A. Basic Data for the Prospects

Table I presents a list of generalized geologic and other basic data for the 24 localities that the Los Alamos National Laboratory has been investigating as part of its responsibilities to compile pertinent information on possible second sites for development of HDR. The data are presented in this way to "highlight" the salient features of the prospects, and interested readers are encouraged to examine the listed references for more details on the geology and geophysics of each locality and bordering areas.

The prospects listed in Table I have been scrutinized in several ways. Many sites have been thoroughly investigated by the U. S. Geological Survey Geothermal Research Program (i.e., Long Valley Caldera, California) or by other groups such as the University of Utah Research Institute (i.e., Roosevelt Hot Springs, Utah). For such areas, we conducted limited additional investigations and evaluated them for their HDR potential. Two prospects in Arizona (Aquarius Mountains and Castle Dome) were identified initially by correlations of various geophysical anomalies. Subsequent investigations were designed in part to develop HDR exploration strategy (West and Laughlin 1979; Goff et al. 1979; Aiken and Ander 1981a; Gutmann 1981). Many sites in the central and eastern parts of the U. S. were recognized by heat flow and thermal gradient work that was partially sponsored by the Los Alamos National Laboratory (Hodge et al. 1981; Costain et al. 1979; Costain and Glover 1980;

TABLE I

HDR PROSPECTS TOGETHER WITH DATA ON POSSIBLE RESERVOIR ROCKS
AND ESTIMATED CONDUCTIVE GRADIENTS AND SUBSURFACE TEMPERATURES

No. ^a	Prospect	Geothermal Regime ^b	Province and/or General Geology	Type of Reservoir Rock	Age (If known); Formation	Grad. ^c °C/km	Depth ^d km	Temperature °C		References
								2 km	5 km	
1.	Aquarius Mtns., AZ	TT	Boundary of Basin and Range and Colorado Plateau	Plutonic and metamorphic	Precambrian	35-41	5	~95	~200	West and Laughlin (1979); Goff (1979); Goff et al. (1979); Aiken and Ander (1981a)
2.	Castle Dome, AZ	TT	Southern Basin and Range	Metasediments	Livingston Hills Fm?; Mesozoic	55	>3.5	~130	>200	Gutmann et al. (1980); Aiken and Ander (1981b); Gutmann (1981)
3.	Springerville, AZ	YI(TT)	Colorado Plateau; SW end of Jemez Lineament; Springerville basalt field, age: 4.0-0.8 Myr.	Plutonic (and metamorphic?)	Precambrian	50	≥4	~100	~200	C. Stone (Az. Bur. Mines oral commun., 1979); Laughlin et al. (1979; 1981)
4.	Clear Lake Region, CA	YI	California Coast Ranges east of San Andreas transform zone; Clear Lake volcanic field, age: 2.0-0.01 Myr	Metasediments and greenstone	Franciscan Assemblage; Mesozoic	~80	≥2	~200	≥350	Hearn et al. (1976a,b); McLaughlin and Stanley (1976); Isherwood (1976); Goff et al. (1977); Donnelly-Nolan (1981); Hearn et al. (1981)
5.	Coso Hot Spgs, CA	YI	Boundary of Basin and Range and Sierra-Nevada; Coso volcanic field, age: 1.1-0.04 Myr	Plutonic (and metamorphic?)	Sierra-Nevada Batholith; Mesozoic	35-45	>2	~140	≥250	Duffield et al. (1980); Fournier et al. (1980); Combs (1980); Plouff and Isherwood (1980); Duffield and Bacon (1980)
6.	Long Valley Caldera, CA	YI	Boundary of Basin and Range and Sierra-Nevada; silicic caldera, age: 0.7 Myr - 450 yr.	Plutonic (and metamorphic?)	Sierra-Nevada Batholith; Mesozoic	38	>3	~150	~250	Bailey et al. (1976); Steeples and Iyer (1976); Hill (1976); Kane et al. (1976); Mariner and Willey (1976); Lachenbruch et al. (1976); Gambill (1981)
7.	Salton Trough, CA	YI(TT)	On-land oceanic rift; SE end of San Andreas transform zone; minor silicic volcanism, age: 0.06-0.01 Myr.	Plutonic (and metamorphic?)	Southern California Batholith; Mesozoic	--	≥3	--	≥250	Elders (1979); Muffler and White (1969); Hill (1977); Twehey (1977); Palmer (1975); Wollenberg et al. (1980)
8.	Mountain Home, ID	TT(YI)	Northern Snake River Plain; possible continental rift; abundant Quaternary basaltic volcanism.	Plutonic	Idaho Batholith; Cretaceous	60-70	≥3	~130	>250	Brott et al. (1978); Arney et al. (1980, 1981)

TABLE I (cont)

No. ^a	Prospect	Geothermal Regime ^b	Province and/or General Geology	Type of Reservoir Rock	Age (If known); Formation	Grad. ^c °C/km	Depth ^d km	Temperature °C		References
								2 km	5 km	
9.	Crisfield, MD	CR	Atlantic Coastal Plain	Plutonic and metamorphic	Paleozoic basement of "Piedmont" type	30	≥8	~60	~135	Costain et al. (1979); Costain and Glover (1980); D'Appolonia (1981); Smith et al. (1981)
10.	New Madrid, MO	CR	Midcontinent region; possible Precambrian "failed" rift.	Plutonic and metamorphic	Precambrian	13-26	>8	~45	~110	Braile et al. (1979); von Frese et al. (1980); Zoback et al. (1980); Hinze et al. (unpub. data, 1980); Roy et al. (1980)
11.	Western Nebraska	CR	Midcontinent region; NE corner of Denver Basin.	Plutonic and metamorphic	Precambrian	32-36	>6	~60	~135	Dennis (1972); Lidiak (1972); Watern (1978); Gosnold (1980); Hinze et al. (unpub. data, 1980)
12.	White Mountains, NH	CR	White Mountains intrusive series bordered by pelitic metasediments	Plutonic and metamorphic	Conway Granite, Jurassic; Littleton Fm., Devonian	25-27	≥7	~60	~130	Osberg et al. (1978); Birch et al. (1968); Roy et al. (1968a); Hoag and Stewart (1977); Wetterauer and Bothner (1977)
13.	Rio Grande rift, NM	TT(YI)	Continental rift; abundant Quaternary basalt volcanism	Plutonic and metamorphic	Precambrian	25-55	≥3.5	~90	>200	Chapin (1979); Chapin and Seager (1975); Baldrige (1979); Cordell (1978); Brown et al. (1979); Kelley (1979); Manley (1979); Edwards et al. (1978); Reiter et al. (1975); Goff and Grigsby (1982); Decker and Smithson (1975); Reiter et al. (1978)
14.	Valles Caldera, NM	YI	Junction Rio Grande rift and Jemez Lineament; silicic caldera, age: 1.1-0.05 Myr.	Plutonic and metamorphic	Precambrian	60	≥3	~150	≥300	Smith and Bailey (1966, 1968); Smith et al. (1970); Doell et al. (1968); Bailey et al. (1969); Dondanville (1978); Tester and Albright (1979); Murphy (1980); Laughlin (1981); Goff et al. (1981); Goff and Grigsby (1982); Potter (1973); Reiter et al. (1976)
15.	Zuni Uplift, NM	YI(TT)	Colorado Plateau; near SW end of Jemez Lineament; abundant Quaternary basalt volcanism; age: 4 Myr-present	Plutonic and metamorphic	Precambrian	25-65	4	~100	≥200	Laughlin and West (1976); Levitte and Gambill (1980); Laughlin et al. (1979); Ander et al. (1980, 1981)
16.	Desert Peak, NV	TT	Northern Basin and Range	Metasediments; granite intrusive	Jurassic-Triassic; Tertiary	15 ^e	≥2.2	210	>260	Benoit et al. (1980)

TABLE I (cont)

No. ^a	Prospect	Geothermal Regime ^b	Province and/or General Geology	Type of Reservoir Rock	Age (If known); Formation	Grad. ^c °C/km	Depth ^d km	Temperature °C		References
								2 km	5 km	
17.	Dixie Valley, NV	TT	Northern Basin and Range	Metasediments; granodiorite intrusive	Triassic	70	≥3	~150	>250	Keplinger and Assoc (1977, 1978); MacKay Minerals Research Inst. (1980)
18.	Cayuga Lake, NY	CR	Eastern Appalachian Plateau	Plutonic and metamorphic	Precambrian	36 ^f	≥7	~90	--	Hodge et al. (1981)
19.	East Aurora, NY	CR	Eastern Appalachian Plateau	Plutonic and metamorphic	Precambrian	32 ^f	8	~70	--	Hodge et al. (1981)
20.	Elmira, NY	CR	Eastern Appalachian Plateau	Plutonic and metamorphic	Precambrian	36 ^f	≥7	~80	--	Hodge et al. (1981)
21.	Brothers Fault Zone, OR	YI(TT)	NW-trending fault zone cutting volcanics of High Lava Plain	Rhyolite intrusives; stratified basalt	Undivided volcanics; Late Tertiary to Quaternary	50-75	>3	>100	>250	MacLeod et al. (1976); Blackwell et al. (1978)
22.	Mt. Hood, OR	YI	Cascade stratovolcano overlying older volcanics	Stratified basalt	Eocene?	~65	≥3	≥115	>250	Hull (1979)
23.	Vale, OR	TT	Western Snake River Plain	Stratified basalt	Flood basalt, Tertiary	60-90	≥3	~120	~300	Blackwell et al. (1978); Lillie and Couch (1979)
24.	Roosevelt Hot Spgs, UT	TT(YI)	Boundary Basin and Range and Colorado Plateau; rhyolitic volcanism, age: 0.8-0.5 Myr	Plutonic and metamorphic	Mineral Mtns. Pluton, Tertiary; Precambrian gneiss	55-60	>2	~180	>300	Chapman et al. (1978); Evans and Nash (1978); Glenn et al. (1981); Nielson et al. (1978); Robinson and Iyer (1979); Sibbett and Nielson (1980); Sill and Bodell (1977); Ward et al. (1978); East (1981); Carrier and Chapman (1981)

^a No. refers to number shown in Figs. 1 and 2.

^b Abbreviations for nature of geothermal regime: YI refers to young igneous heat source associated with Quaternary volcanic field; TT to thermal anomaly in region characterized by young tectonic activity and perhaps lithospheric extension; CR to pre-Quaternary terrane with heat flow from crustal radioactivity and other sources in relatively stable lithosphere. Symbols for other aspects of a regime are in parentheses.

^c Conductive gradient in deeper impermeable zone, if known; otherwise estimated from shallow thermal gradient boreholes.

^d Minimum depth required to establish HDR reservoir (not depth to crystalline and/or impermeable basement rocks).

^e Conductive gradient below 2700 m; isothermal at ~210°C from 975-2700 m.

^f Gradient may be less in deep Precambrian basement.

Fig. 1.

Contour map of heat flow in the conterminous United States (from Sass et al. 1981). Numbers locate HDR prospects listed in Table I.

Fig. 2.

Conductive thermal gradient map of conterminous United States by Kron and Heiken (1980). Magma-hydrothermal systems with large component of convective heat transport (i.e. Salton Trough, CA) do not show on this map (see also, Guffanti and Nathenson 1980). Numbers locate HDR prospects listed in Table I.

Hinze, unpublished data, 1981). Two prospects, Crisfield in Maryland and Mountain Home in Idaho, were investigated in more detail by organizations that were subcontractors to the Laboratory (Arney et al. 1980, 1982; Schubert et al. 1980). Some of the other sites were initially drilled as conventional geothermal prospects and came to our attention when little or no hot fluids were encountered (e.g., Mt. Hood, Oregon). Although other prospects will be found as research continues, the list in Table I shows that regions of HDR interest occur in a wide variety of geologic and tectonic settings within the United States.

The numerical data in Table I are not discussed in detail herein because some of the estimates will change when future research is completed. Briefly, the conductive gradients were calculated from measurements of underground temperatures at each locality. Measurements deeper than 500 m were emphasized, if they were available. Otherwise, the gradients were estimated from measurements in shallower drill holes. The depths to "possible" HDR reservoirs were then estimated from downward continuation of conductive gradients and local geology and geophysics, on the conservative assumption that a temperature of 200°C is required for generation of electricity. Thus these figures are estimates for depths to an ambient temperature ($\sim 200^\circ\text{C}$) and they do not necessarily provide information on the subsurface locations of impermeable units in each locality. Finally, temperatures were estimated for depths of 2 and 5 km at each locality. These depths can be reached with current drilling technology. The data for depths of 2 and 5 km also can be used to compare areas, or perhaps to estimate the thermal energy that may exist in the 2- to 5-km interval in each system.

B. General Characteristics of the HDR Prospects

It is evident from Table I that the HDR prospects may be placed in three general groups: (1) Quaternary igneous-hydrothermal systems; (2) thermal anomalies in regions with young and/or current tectonic activity; and (3) pre-Quaternary plutonic-metamorphic complexes. As may be seen in Figs. 1 and 2, the prospects with the shallowest high temperatures are in the high heat flow and high thermal gradient areas of the western United States.

The Quaternary igneous-hydrothermal systems occur in large, geothermally anomalous areas that are characterized by young volcanic activity; for example, the Valles Caldera in New Mexico and The Geysers-Clear Lake region,

California. Abundant silicic volcanic rocks occur in each locality, as do elevated seismicity and perhaps active tectonic extension (Goff and Waters 1980). The heat flow anomalies in most of the prospects are subcircular, and one interpretation of these patterns is that many of the areas are underlain by shallow silicic magma chambers. The temperatures of the associated hydrothermal convection systems often exceed 150°C (see Table I).

Many of the young igneous systems have been explored in reasonable detail because it is known that large, shallow reservoirs of superheated water or steam can be profitably developed for production of electricity. However, analysis of energy data tabulated by Smith and Shaw (1979) and by Brook et al. (1979) indicates that generally <10% of the heat in igneous systems is contained in hydrothermal fluids (G. Heiken, Los Alamos National Laboratory, unpub. calc., 1981). The rest is in rocks and crystallizing magma that border or underlie the convecting fluids and it appears that much of the country rocks are impermeable. Thus, the major portion of the heat in young igneous systems will have to be developed by HDR or similar methods, if it is utilized.

Suitable HDR reservoir rocks occur below the unfaulted flanks and the larger fault blocks in the moat areas in the Valles Caldera in New Mexico and in the Long Valley Caldera in California (Gambill 1981). The general locations of possible reservoirs in the other young igneous terranes cannot be determined without additional geologic and geophysical studies of the complex and variable structure of these prospects.

Prospects in the tectonically active areas are associated with continental or oceanic rifts (e.g., Rio Grande rift or Salton Trough), or they occur in large areas that are undergoing tectonic extension (e.g., western Great Basin). All of these systems are characterized by high regional heat flow, and elevated seismic activity. If there is evidence for Quaternary volcanism, the dominant volcanic rock usually is basalt. The Salton Trough, however, contains small amounts of silicic volcanics and is also characterized by several large hydrothermal systems at temperatures $\geq 200^{\circ}\text{C}$.

The other prospects appear to be underlain by small or intermediate volume hydrothermal reservoirs that are primarily at temperatures $\leq 150^{\circ}\text{C}$. At all of these prospects, the subsurface hydrothermal fluids tend to be localized in faults and fractures at the boundaries between basins and horsts or in permeable Tertiary to Quaternary sediments that fill the basins. Inasmuch as

the average thermal conductivity of the relatively unindurated Cenozoic sediments is low, conductive temperatures at the bottoms of the thick sections of such units are likely to be high. Thus suitable reservoir rocks for HDR development in these areas could be impermeable parts of basement or bedrock below the central portions of the larger sedimentary basins.

All of the other prospects are in pre-Cenozoic igneous and metamorphic rocks that occur in the central and eastern parts of the United States. These areas are characterized by low seismic activity, low-to-normal geothermal gradients ($\leq 30^\circ\text{C}/\text{km}$), and, except for the high flux [>1.9 heat flow unit (HFU) ($1 \text{ HFU} = 1.0 \mu\text{cal}/\text{cm}^2\text{s} = 41.8 \text{ mW}/\text{m}^2$)] in the White Mountain Batholith in New Hampshire, low to normal heat flow (≤ 1.5 HFU). There is no evidence for subsurface hydrothermal systems in any of the areas. The high flux and calculated subsurface temperatures in the White Mountain Batholith are in part due to the unusually high radioactivity of the Conway and Oseola granites (see Birch et al. 1968; Osberg et al. 1978). The tabulated temperatures at the other pre-Cenozoic prospects are thought to be partly explained by higher conductive gradients that should occur in low conductivity sediments that overlie higher conductivity crystalline bedrocks or basement.

Very deep holes (≥ 6 km) would have to be drilled to reach temperatures ($\sim 200^\circ\text{C}$) adequate for generation of electricity in the pre-Cenozoic prospects. Thus a reasonable alternative may be to use shallower holes and current HDR technology to develop space heat from these and other low-temperature systems. Future extraction of heat energy from such systems would be expensive and suitable reservoir rocks would have to be located with additional heat flow and other geophysical measurements.

III. PROTOTYPE SYSTEM AND THREE REPRESENTATIVE PROSPECTS

The preceding discussion focuses on general characteristics of the 24 HDR prospects. The following sections emphasize four areas: the prototype system just west of the Valles Caldera in New Mexico, and one locality from each of the general groups listed in Table I. The three untested localities are not singled out as "favored" or "most likely" HDR prospects. Instead, our purposes are to illustrate the salient characteristics of these different and perhaps better-known systems.

A. Estimates of Heat Stored in Prismatic Volumes of Rock Below Each System

One of the important objectives of HDR and other geothermal resource evaluations should be to obtain estimates for the amounts of existing heat (geothermal resource base) in a prospect. A refinement of this estimate is to determine that part of the resource base reachable by current drilling technology (recoverable resource base; see Muffler 1981, p. 181-185). We make no attempt in this paper to estimate what fraction of the recoverable resource is economically extractable by HDR methods because there are too many variables to consider. On the other hand, comparisons of the recoverable resource base at each of the four systems described herein have economic implications.

In light of these considerations, the recoverable resource base at the four localities can be compared by the conductive heat that may exist in rectangular prisms of rock below each system. Each prism was assumed to have the same volumetric specific heat, the thermal properties of the systems were assumed to be constant with depth and lateral position, and the heat flow in each area was assumed to be uniform. Each prism was further assumed to have the same area perpendicular to its thickness, and thicknesses were permitted to change in the direction of depth below each prospect. These assumptions are drastic simplifications of the real situations at each locality for several reasons; for example, conductivity, gradient and thus heat flow almost certainly change with position in a complex area like Clear Lake in California, and there is evidence for convective heat transfer near many of the prospects. However, more sophisticated approaches are precluded by the sparse data for each locality. It is our belief also that the calculations permit reasonable first attempts at comparing the systems.

The conductive heat Q stored in each prism was calculated using a simplified form of the following expression:

$$Q = c A \int_{x_1}^{x_2} T(x) dx \quad . \quad (1)$$

Here, A is the area of each section perpendicular to the length of the prism, c is the volumetric specific heat, and x_1 and x_2 are the depths to the top and bottom, respectively, of the prism. $T(x)$ is the temperature as a function of x (depth) in the prism. For convenience and because we are mainly interested

in first-order comparisons, A was taken to be 10^{11} cm^2 (10 km^2) and $T(x)$ was set equal to the average temperature ($\bar{T}$) of the prism. The depths x_1 and x_2 were taken from Table I, as were the temperatures used for calculations of average values. Specific heat c was set equal to $0.6 \text{ cal/cm}^3\text{-}^\circ\text{C}$, a commonly accepted value for crystalline rocks in the crust (after Lachenbruch and Sass 1977; 1978).

The basic parameters and calculated results for the four localities are listed in Table II. These data suggest that the localities with Quaternary volcanic rocks generally contain more conductive heat per unit surface area, despite the fact that the lengths of the assumed prisms are not the same for all of the systems. The actual amounts of conductive heat stored beneath some of the prospects may be very large; for example, calculations with $A = 5 \times 10^{11} \text{ cm}^2$ (50 km^2) yield 115 and $83 \times 10^{18} \text{ J}$, respectively, for the Clear Lake and Roosevelt Hot Springs areas ($10^{18} \text{ J} = 1 \text{ Quad}$). Inasmuch as the total energy consumption of the United States is currently about $80 \times 10^{18} \text{ J}$ per year, it is clear that efficient HDR installations at these and other prospects listed in Table I could supply a significant fraction of the United States' energy requirements. Diment et al. (1975) estimate that the United States possesses $2.8 \times 10^{25} \text{ J}$ to a depth of 10 km beneath the surface.

B. The Prototype System in Fenton Hill in New Mexico

Fenton Hill is about 0.5 km outside the southwestern boundary of the Valles Caldera in north-central New Mexico (Figs. 3 and 4). A successful HDR reservoir has been established in Precambrian biotite granodiorite between 2.6 and 2.9 km in the subsurface; prior to injection, the average temperature of the reservoir area was about 180°C (Laughlin 1981; Goff and Grigsby 1982). During the last extended test, the prototype system generated 1-2.5 MW of thermal power per day for a period of 300 days. A second system is now under construction that utilizes wells completed to depths of 4.0 and 4.5 km. It is hoped that a "near commercial" system will be constructed when hydraulic fractures join the two wells; this system is designed to produce 20-50 MW of thermal power per day.

The Valles Caldera is a 1.1 Myr silicic volcanic complex that represents the culminating stage of evolution of the Jemez Mountains volcanic field (Smith and Bailey 1966, 1968; Bailey et al. 1969). Rhyolitic domes, flows, and pyroclastics as young as 0.05 Myr occur in the moat area of the caldera

TABLE II

ESTIMATES OF HEAT BENEATH 10 km² AREAS AT THE PROTOTYPE HDR SITE AT FENTON HILL IN NEW MEXICO AND THREE OTHER SELECTED PROSPECTS

	^a Geothermal Regime	Minimum Temperature of Reservoir (Electrical), °C	^b $\bar{T}$, °C	^b x_1 , km	^b x_2 , km	^b Q , 10 ¹⁸ Joules
Valles Caldera, NM; Fenton Hill area	YI	200	265	5	3	12.6
Clear Lake region, CA	YI	200	325	5	2	23.2
Roosevelt Hot Spgs, UT; Milford Valley	TT(YI)	200	265	5	2.3	17.0
White Mountains, NH; Conway Granite	CR	150	185	8	5.7	10.0

^a Symbols same as in Table I.

^b Values directly follow temperature data in Table I for the assumption that electricity may be produced at reasonable depths.

(Doell et al. 1968). A moderate sized hydrothermal system at temperatures of 260-320°C occurs at depths in the range 800 to 3000 m beneath parts of the resurgent dome (Dondanville 1978). A 50 MW(e) power plant was proposed to utilize the hydrothermal resource, but it now appears that this system is too small to produce the necessary energy. Measurements of heat flow in shallow holes in the neighborhood of the caldera are in the range 3.0-7.0 HFU (Reiter et al. 1976; Potter 1973).

The Jemez Mountains occur at the intersection of the Jemez Lineament and the Rio Grande rift (Mayo 1958; Chapin et al. 1978). Volcanism along the Lineament began in the Miocene and has continued into the Holocene. The Jemez fault zone occurs in the southwestern part of the Jemez Mountains and trends toward the resurgent dome of the caldera (Fig. 3). This fault zone may have resulted from the combined effects of lineament formation and western-most rift faulting in the area during Miocene to Holocene time (Goff et al. 1981). In the central part of the mountains, the Jemez volcanic pile is mainly composed of intermediate and silicic rocks that were erupted during the past 10 Myr (Bailey et al. 1969; Smith et al. 1970). These units overlie late Tertiary sediments in the Rio Grande rift and Paleozoic and Mesozoic sediments of the Colorado Plateau. The Paleozoic and younger units overlie Precambrian igneous and metamorphic basement (Fig. 4).

Drilling at Fenton Hill suggests that the Cenozoic and Paleozoic rocks are about 0.73 km thick (Laughlin 1981). The Precambrian section between 0.73 and 2.93 km is largely made up of a metamorphic complex, that is roughly 75

Fig. 3.
 Maps showing relationship of Jemez Mountains to the Rio Grande rift and Jemez Lineament (a) and the Valles Caldera region (b).

Fig. 4.

Cross-section of Jemez Mountains along line E-W (Fig. 3) showing location of Fenton Hill with respect to Valles Caldera. White area beneath eastern caldera shows where additional geophysics and deep drill holes are needed to resolve structure and stratigraphy.

percent gneiss (Laughlin 1981). Precambrian schist is interlayered with the gneiss, and the gneiss is intruded by at least three igneous bodies. The prototype downhole heat-exchange system was created in the thickest Precambrian intrusive, a biotite granodiorite between 2.59 and 2.98 km (Laughlin 1981). The basement is shallow and free of young and tectonically active faults because Fenton Hill is west of the zone of collapse and resurgence that characterizes the Valles Caldera.

The deepest part of the prototype or Phase I system is at 2900 m subsurface, where the undisturbed ambient temperature is estimated to be 195°C. From measurements in two holes in this system, the gradient in the basement was calculated to be ~60°C/km (Sibbitt et al. 1979). The Phase II system is designed to show commercial feasibility of the HDR extraction process. The lower portions of the two holes in this system are oriented at angles of 35° from vertical toward the caldera and the holes bottom in a layered succession of metamorphic rocks. The thermal gradient in basement in the bottom of the deeper hole is 90°C/km, and the bottom-hole temperature at 4500 m is ~325°C (Dash et al. 1981). One interpretation of the relatively higher gradients and temperature at depth in the Phase II system is that the drill holes may be near a buried high-temperature hydrothermal cell near the edge of the caldera. Alternatively, the greater depths of the Phase II holes may mean that their deeper sections are near magma or very young igneous rocks crystallized below the caldera. The geologic evidence for a large silicic magma chamber under the region (Kolstad and McGetchin 1978; Smith and Bailey 1968; Dondanville 1978) may be consistent with young, high-temperature rocks below Fenton Hill, as is the seismic evidence for temperature induced attenuation of P and S waves in the neighborhood of the caldera.

The data in Table II imply that a 20 km^3 volume of rock beneath a 10 km^2 area at Fenton Hill contains $12.6 \times 10^{18} \text{ J}$ of thermal energy on the assumption that the reservoir is at an average temperature of 265°C. If the economically extractable energy from this volume is only 10% of the calculated value, the resulting fraction of $1.2 \times 10^{18} \text{ J}$ is still a significant amount of thermal energy. Consider that the prospectively valuable area in the vicinity of the caldera must greatly exceed 10 km^2 , if crystalline basement rocks occur at depths $\leq 5 \text{ km}$ elsewhere in the borders and moat area of the structure. Additionally, Smith and Shaw (1979) estimate that $8.4 \times 10^{21} \text{ J}$ of heat could be stored in the upper 10 km of the crust in the Jemez Mountains. Thus continued

improvements of drilling, hydro-fracturing, and heat-extraction technology could lead to successful HDR systems in several parts of the region.

As an example, the Pajarito Plateau is 5-10 km east of the Jemez Mountains where regional heat flow averages 2.7 HFU (Reiter et al. 1978)(Fig. 4). Here, suitable HDR reservoir rocks exist as down-faulted blocks of Precambrian basement below insulating sediments filling the western part of the Rio Grande rift (Goff and Grigsby 1982). We may speculate also that comparable prospectively valuable HDR systems occur elsewhere in the rift at areas with similar geologic structure, stratigraphy and tectonism. This view is consistent with high heat flow, low bedrock radioactivity and late Cenozoic volcanism in the rift (Reiter et al. 1975, 1978; Decker and Smithson 1975; Decker et al. 1975; Edwards et al. 1978).

C. The Geysers-Clear Lake Region in California

There is evidence for two high-temperature geothermal provinces in The Geysers-Clear Lake region, northern California (Goff et al. 1977). A vapor-dominated province occurs in the vicinity of The Geysers, where as of January 1982, steam-generated electricity of ~908 MW(e) constitutes the largest amount produced at any geothermal field in the world today. To the north and east, widely spaced drill holes in the Clear Lake area suggest that there is another geothermal province underlain by a complex distribution of wet and dry hot rocks. The two provinces are separated by the Collayomi fault zone (Fig. 5), a major right-lateral strike-slip fault in the San Andreas system (Donnelly et al. 1976).

Geologic and geophysical studies strongly suggest that the high subsurface temperatures in this region are explained by shallow (≤ 10 km) magmatic heat sources. This view is consistent with very young (2.04-0.01 Myr) domes, flows and minor pyroclastics in the Clear Lake volcanic field (Hearn et al. 1976a, 1976b; Donnelly 1977; Donnelly et al. 1977; Donnelly-Nolan et al. 1981). A large subcircular gravity low of ~30 mgal that is centered in the volcanic field can be explained in terms of an underlying magma chamber (Isherwood 1976), as can large (1 s) P-wave delays in the region (Iyer et al. 1981). The magma is inferred to be silicic because extrusive dacites and rhyolites are more voluminous than basalts and andesites (Hearn et al. 1978, 1981). Some of the flows are large; in particular, Mt. Konocti is mainly composed of ~35 km³ of dacite that was erupted in the last 0.4 Myr.

The older bedrocks in the area are Jurassic to Eocene graywackes, argillites, greenstones, and ophilitic rocks (now, mostly serpentinite) of the Franciscan assemblage and coeval Great Valley sequence (Fig. 6). These rocks are typically metamorphosed to zeolite grades. The Franciscan assemblage was thrust beneath the Great Valley sequence and associated oceanic crust along an eastward dipping subduction zone in early Tertiary time (McLaughlin and Stanley 1976; McLaughlin 1981). This regional thrust zone, termed the Coast Range Thrust, is generally recognized by serpentinite along the upper plate. As subduction continued, older Franciscan rocks were "shingled" into a series of imbricate thrust slabs above younger Franciscan units (Fig. 6). This complicated structural configuration has been modified by extensive right-lateral strike-slip faulting (Fig. 5) related to the San Andreas transform zone.

Dry steam at 240°C is produced at The Geysers. Most of the steam is produced from secondary fractures in Franciscan metagraywacke. From studies of some 200 exploration and production wells, suitable reservoir rocks extend as deep as 3700 m.

In contrast to The Geysers area, only 16 or so deep test wells have been drilled in the province northeast of the Collayomi fault zone. High-temperature fluids were penetrated in two areas, one in the known hydrothermal system at Sulphur Bank Mine and one in a Quaternary fault zone at Sulphur Mound Mine (Fig. 5). The other wells are described as hot and dry (Table III), suggesting that large portions of the area are underlain by impermeable bedrocks.

From the evidence for high temperatures and impermeable rocks at depths of 2-3 km, the region around Clear Lake may be a large HDR prospect. The best subsurface reservoir rocks could be metagraywackes and greenstones in the Franciscan. Rocks of the Great Valley sequence may be less suitable as HDR reservoirs because they are less deformed and typically are metamorphosed to a lower grade. The subsurface distribution of suitable reservoir rocks is not accurately known because they are covered by Clear Lake Volcanics. However, a large synform of folded and faulted Great Valley sequence rocks and serpentinite in the southwest part of the Clear Lake volcanic field (Hearn et al. 1976b; McLaughlin 1978; Stanley et al. 1973; Goff et al. 1977) probably should be avoided during initial HDR exploration. Other parts of the volcanic field also could be troublesome because circulating waters may occur in the vicinity of the contact between the igneous and metamorphic units or along major fault

Fig. 5.

The Geysers-Clear Lake region showing major faults, outline of The Geysers steam field (dashed line) and Clear Lake Volcanics. White areas are primarily Jurassic to Eocene basement rocks. Dots show locations of deep wells drilled outside of steam zone (Table III).

Fig. 6.

Stylized cross-section of The Geysers-Clear Lake region (modified from McLaughlin 1977).

TABLE III

DATA FROM SELECTED DEEP GEOTHERMAL WELLS IN THE CLEAR LAKE REGION, CALIFORNIA
(See Fig. 5 for locations.)

No.	Name	Operator	Depth, m	BHT, °C	Formation ^a at depth	Comment
<u>Wells that are hot and 'dry'</u>						
1	S&B #1	Aminoil USA	~3400	very hot ^b	Fran	Dry
2	B&R Unit #1	Aminoil USA	~3400	very hot ^b	Fran	Dry
3	Bouscal #1	Republic	2770	very hot ^b	GV-Sp-Fran	Dry
4	Sullivan #1	E.B. Towne	1970	193	Sp	Dry-abandoned
6	Kettenhofen #1	Getty-Magma-Thermo.	1910	210 ^c	GV-Sp-Fran	Dry-abandoned
7	Magma-Watson #1	Magma-Dow Chem.	1755	>200	GV-Sp-Fran	Dry-abandoned
8	Jorgensen #1	Union Oil	~3100	very hot ^b	Fran	Marginal water entry
9	Borax Lake #1	Phillips Pet.	~3100	hot ^b	Fran	Dry
10	B-J #1	Aminoil USA	3150	hot ^b	Fran	Dry
11	Torchio-Ferro #1	Cordero-Sun Oil	2445	126	Fran	Dry-abandoned
12	Audry #1	Phillips Pet.	~3100	very hot ^b	Fran	Dry
<u>Wells that are hot and 'wet'</u>						
5	Neasham #1	Occidental-Republic	3015	>260 ^d	Sp-Fran	Water entry @ 2615 m
13	Sulphur Bank #1	SB Geothermal Power	168	>100	Fran	Abandoned
14	Bradley #1	Earth Energy	643	208	Fran	Abandoned
15	Bradley #2	Earth Energy	1226	163	Fran	Abandoned
16	Clear Lake #1	Magma	460	135	Fran	Abandoned

^a Fran = Franciscan Assemblage; Sp = Serpentinite; GV = Great Valley Sequence

^b Confidential Information

^c Goff et al. (1977)

^d K. Neasham, Lakeport, CA

zones. Thus, early HDR exploration should focus on the areas of exposed Franciscan and Great Valley units around the margins of the volcanic field or on the zone of Franciscan rocks that presumably underlies the eastern part of the volcanic field.

We estimate that there are $23\text{--}24 \times 10^{18}$ J of conductive heat in a 2 km deep, 30 km^3 prism of rock below the Clear Lake area, if the mass has a surface area of 10 km^2 and an average temperature of 325°C (Table II). This is a very conservative estimate of the actual amount of subsurface heat in the region because the dry exploration holes with high temperatures are

distributed over an area of at least 300 km^2 , and there is evidence for impermeable units at depth in areas bordering the steam field at The Geysers. For example, at least $700 \times 10^{18} \text{ J}$ of conductive heat could exist in the subsurface, if it is assumed that a 500 km^2 area in the region is underlain by rocks at a mean temperature of $\sim 200^\circ\text{C}$ between 2 and 5 km.

Although very high subsurface temperatures occur in The Geysers-Clear Lake area (Jamison 1976), it is not known if current hydro-fracturing techniques can be used to control fracture orientations in a HDR reservoir in deformed metasediments and metavolcanics. Another uncertainty in future HDR development is that thermal and mineral springs in the area may mean that hydrothermal fluids and/or systems exist at many places in the subsurface although they are generally restricted to fault zones. This could complicate HDR development at localities near The Geysers and at three apparently discrete hydrothermal systems to the south and east (Calistoga, Sulphur Bank Mine, and Wilbur Hot Springs). Elsewhere in the area, however, geologic evidence suggests that faulting controls the distribution of the fluids, and chemical studies indicate that most thermal waters do not originate in large subsurface reservoirs (Goff 1979).

Because virtually nothing is known about hydro-fracturing of highly deformed low-grade metamorphic rocks, the staff at the Los Alamos National Laboratory would like to conduct experiments in at least one moderately deep (1-2 km) hole in the Clear Lake area. A successful experiment would imply that HDR systems could be established in many metamorphic terranes in the western United States.

D. Roosevelt Hot Spring Area in Utah

The Roosevelt Hot Springs occur in faulted and fractured rocks on the west side of the Mineral Mountains in southern Utah. A water-dominated geothermal system at temperatures $\geq 260^\circ\text{C}$ occurs beneath the (currently dry) springs. The hydrothermal system has been explored in reasonable detail, and a 20 MW(e) power plant is planned for utilization of the high-temperature fluids.

Although this area is very close to the border of the Colorado Plateau, the Mineral Mountains and Milford Valley to the west comprise a horst-graben structure that clearly is in the Basin and Range province. The region is

tectonically active (Ward et al. 1978), and the regional heat flow exceeds 2.5 HFU (Chapman et al. 1978; Carrier and Chapman 1981).

The combined effects of young igneous activity and local geology may explain the unusually high thermal output in this region. A young igneous heat source is consistent with 0.01 Myr basaltic flows and cones in the area, and the 0.8-0.5 Myr rhyolitic domes, flows and ash-flow tuffs along the crest of the Mineral Mountains (Evans and Nash 1978). The meaning of the Quaternary igneous activity is obscure, however, because the volume of the silicic volcanics is small, the geophysical evidence for a shallow magma chamber is inconclusive and the known hydrothermal system is 5 km or so west of the axis of the rhyolitic volcanism (Fig. 7). Also, a high temperature of 230°C was recorded at a depth of 3.855 km in Milford Valley in Well Accord 1-26, a dry hole that is about 8 km west from the known hydrothermal system (Fig. 7). This observation suggests that some of the high subsurface temperatures are due to conductive effects of a high regional heat flux below thick accumulations of low conductivity Tertiary alluvium in the regional sedimentary basins.

The known hydrothermal system is localized in a highly fractured graben east of the Opal Mound (Dome) Fault (Fig. 7). The proposed HDR resource area is west and south of the fault, where bottom-hole temperatures in four holes are in the range 200-300°C, and the gradients are in the range 55-60°C/km (Fig. 7, Table IV). The depths of these hot dry holes are in the range 2-4 km, and they all bottom in Precambrian gneiss and/or Tertiary granite. A cross section of the region is shown in Fig. 8. Similar crystalline rocks occur in the core of the Mineral Mountains and below the area with known hydrothermal resources.

We calculate that there is about 17×10^{18} J of conductive heat in a 2.3 km deep, 27 km^3 volume of rock beneath the Roosevelt Hot Springs-Milford Valley area, if the average temperature of the mass is taken to be 265°C and if the area of the upper surface of the prism is 10 km^2 (Table II). East (1981) conservatively estimates, however, that the prospectively valuable HDR prospect area in Milford Valley could be 160 km^2 ; therefore, some 250×10^{18} J of stored heat could exist below this region. East's data also imply that the area with HDR potential is about 8 times larger than that underlain by known hydrothermal resources.

The Roosevelt Hot Springs area has many characteristics that make near-term HDR development feasible. The subsurface temperatures are adequate for

Fig. 7.
Roosevelt Hot Springs area, showing locations of hot dry wells.

Fig. 8.
Cross-section of Roosevelt Hot Springs area (modified from Nielson and Sibbitt 1978). The region of hot dry rock interest lies west of the Opal Mound Fault.

TABLE IV
DATA FROM SELECTED DEEP GEOTHERMAL WELLS IN ROOSEVELT HOT SPRINGS REGION, UTAH
(See Fig. 7 for locations.)

No.	Name	Operator	Depth, m	BHT, °C	Formation at depth	Comment
1	Well 82-33	Phillips Pet.	--	--	Gneiss-Granite	Dry; data proprietary
2	Well 9-1 ^a	Phillips Pet.	2049	227	Gneiss-Granite	Dry
3	Utah State 52-21 ^b	Getty Oil	2281	202	Gneiss-Granite	Dry
4	Acord 1-26 ^b	MCR Geothermal	3855	230	Gneiss-Granite	Dry; heat flow = 3.5 HFU

^a Glenn et al. (1981)

^b East (1981)

generation of electricity, and technology exists to drill and hydro-fracture the crystalline reservoir rocks. HDR-based electricity also could be channelled into existing power lines because a 20 MW(e) plant is planned for the area. Finally, leasing might not be extremely competitive because most of the current interest focuses on the water-dominated systems, with the number of producers being small. The availability of water for HDR development in the area is one issue that is not addressed herein because agricultural interests around the nearby town of Milford may compete for potable water. Environmental and civil issues are not expected to be insurmountable obstacles because the area is remote and essentially a desert.

The regional geology and geophysics (horst-graben structure, young igneous rocks, high heat flow, etc.) of this prospect are very similar to those of other localities in the Basin and Range. A successful HDR system in the Roosevelt area could therefore serve as a prototype for other installations in similar parts of the western Great Basin.

E. White Mountain Batholith in New Hampshire

The White Mountain Batholith is a deeply eroded plutonic complex that formed over an interval of about 90 Myr in the late Mesozoic (Osberg et al. 1978). The batholithic rocks intrude quartz-mica schists of the Littleton Formation and a binary granite of the New Hampshire Magma series. These older rock units are of Devonian age.

All phases of regional igneous activity terminated in the Mesozoic. The area is not characterized by Holocene seismic and tectonic activity. There is no documented evidence for large hydrothermal reservoirs in the batholith.

The White Mountain Magma series is composed of several large intrusives and a less-voluminous sequence of volcanic tuffs, flows, and breccias (Fig. 9; Osberg et al. 1978). The Conway Granite, the Osceola Granite, and the Albany Quartz Syenite are the largest plutons in the batholith. The contacts between all of the intrusives are very steep or vertical (Osberg et al. 1978). From regional gravity and density data, the Conway and Osceola granites could be 5 to 7 km thick in the central part of the batholith (Osberg et al. 1978). The thicknesses of the plutons may vary with location in the complex; for example, gravimetric interpretations by Joyner (1963) imply that the average depth of batholith-Littleton Formation density contrast is 4.5-4.6 km, and gravity modeling by Wetterauer and Bothner (1977) and Osberg et al. (1978) indicates that the granitic rocks in the southeastern part of the structure are only 2-3 km thick (Fig. 10). The modeling by Osberg et al. (1978) also indicates that the pluton thicknesses change from 6-7 km to 2-3 km over a lateral distance of about 7 km in the eastern half of the batholith (Fig. 10).

The White Mountains are a potentially valuable HDR prospect because the regional heat flow is high [1.8-2.2 HFU (after Birch et al. 1968; Roy et al. 1968b; Simmons and Mann in press)]. The radiogenic heat productions of the rocks in the White Mountain Magma series are also high, with average values for the Conway Granite, the Osceola Granite, and the Albany Quartz Syenite being about 20-25 HGU, 18 HGU, and 11 HGU, respectively (Birch et al. 1968; Osberg et al. 1978) ($1 \text{ HGU} = 1 \times 10^{-13} \text{ cal/cm}^3 \text{ s} = 0.418 \mu\text{W/m}^3$). Radiogenic heat in the plutons may account for much of the heat flow in the batholith because the combined flux and heat production data for the Conway Granite can be explained in terms of pluton thicknesses (6-7 km) that agree with some of those inferred from modeling of gravity (see Birch et al. 1968; Roy et al. 1980; Osberg et al. 1978). On the other hand, geophysical evidence for crustal thickening and relatively higher electrical conductivity below the region (Taylor and Toksöz 1979; Bailey et al. 1978; Cochrane and Hyndman 1974) may mean that the heat flow from the lower crust and upper mantle in the White Mountains is greater than that in adjacent parts of the Appalachian orogen (see also Osberg et al. 1978).

Measurements of near-surface (<1 km) geothermal gradients in various plutons in the batholith are in the range 25-30°C/km (Birch et al. 1968; Simmons and Mann in press). These near-surface values may not be accurate estimates of the deeper gradients in the area for at least two reasons: (1) downward

Fig. 9.

Generalized geologic map of larger rock masses of the White Mountain Batholith together with generalized geology of bordering units. After Creasy (1974, Plate I) and Osberg et al. (1978, Figs. 9 and 13). Line A-A' is approximate location of section through three-dimensional gravity model of eastern part of the batholith (see Fig. 10).

Fig. 10.

Section through three-dimensional gravimetric model of the eastern part of the White Mountain Batholith modified from Osberg et al. (1978, Fig. 11). Approximate location of section is shown in Fig. 9.

continuations of the high radioactivity of the plutons implies curvature in the geotherm for the upper crust; and (2) thin parts of the batholith could be underlain by units with different thermal conductivities and heat productions. Equilibrium temperature-depth models for the upper crust (≤ 15 km) in the region are presented by Osberg et al. (1978) and Decker (unpublished report, Los Alamos National Laboratory, 1981). Their models indicate that minimum equilibrium temperatures at depths of 6 and 8 km in the region are about 115 and 150°C, respectively, if the crust is composed of high conductivity Conway Granite. In contrast, the calculated temperatures at 6 and 8 km are respectively about 185 and 250°C, if radioactivity and conductivity decrease downward and a 5- to 6-km-thick batholith is underlain by lower conductivity units in the Littleton Formation. As is evident in Table I, we estimate that the conductive temperatures are reasonably close to 60 and 130°C at 2 and 5 km, respectively, in the batholith.

We speculate that 185°C is a reasonable upper bound for the mean temperature of a 2- to 3-km-thick prism of rock that is centered near 7 km below the White Mountains, much deeper than any geothermal well yet drilled. The amount of conductive heat in a 20- to 25-km³ volume of rock in this depth interval would be about 10.0×10^{18} J (Table II). This simple calculation suggests that very deep and thus costly drilling would be needed if an HDR extraction system were used to develop electrical power using high-temperature fluids at this depth and perhaps other currently known prospects in the eastern United States.

The successful fracturing of Precambrian granodiorite at Fenton Hill in New Mexico implies that HDR reservoirs could be readily established in the plutonic members of the White Mountain magma series. From the gravity and geothermal data, however, some of the plutons are only 2-3 km thick and reservoir rocks at temperatures of 150-200°C could be 6-7 km deep. Thus one ambiguity in HDR development in the White Mountains is that high-temperature reservoirs might have to be created at great depth in foliated and distorted schists and gneisses in the Littleton Formation, or perhaps in underlying metamorphosed units in the Amonoosuc Volcanics (see Osberg et al. 1978). This view suggests that more data on fracturing of metamorphic rocks should be obtained before high-temperature HDR installations are proposed for the White Mountain region.

IV. CONCLUDING REMARKS

This study indicates that there is a large HDR resource base in the United States (Muffler 1979). The compiled data also indicate that the shallowest high-temperature systems are in the western part of the country, where gradients and heat flux are high and there is much evidence for late Cenozoic volcanism and tectonic activity. Viable prospects also may exist in the central and eastern parts of the United States. However, the eastern prospects have not experienced large-scale tectonism or igneous activity in the Cenozoic. The combined flux and radioactivity data for the middle and eastern parts of the country imply that deep (≥ 6 km), very costly drilling would be needed if current HDR technology were used to generate electricity.

The Fenton Hill area and other localities in the neighborhood of the Valles Caldera in New Mexico may be considered "ideal" prospects for HDR development because they are underlain by shallow granitic basement rocks and there is evidence for temperatures of at least 200°C at depths less than 5 km. When other prospects are considered, the Roosevelt Hot Springs area in Utah also is a very viable prospect because the temperatures in the granitic bed-rock are $\geq 200^{\circ}\text{C}$ and the depths to suitable reservoir are in the range 2-4 km. The Clear Lake area in northern California is characterized by similarly high temperatures ($160\text{-}260^{\circ}\text{C}$) at tractable drilling depths (< 4 km), but future HDR development of this prospect is uncertain because oriented fractures must be created and maintained in heretofore unstudied metasediments and metavolcanics in the strongly distorted Franciscan section. In contrast, current HDR technology could be used to create reservoirs in the plutons in the White Mountain Batholith in New Hampshire. However, development of this region would be very expensive because thermal and gravity modeling indicates that very deep holes (≥ 6 km) would have to be drilled in igneous or metamorphic rocks, if the objectives are to produce HDR-based electricity. This conclusion implies that it may be more reasonable to use HDR techniques to develop space heat at this and other eastern prospects, unless deep drilling of crystalline rocks becomes more cost effective or if the expense of exploration for fossil fuels rises in the future. We cannot be as specific about HDR potential at the other localities discussed herein, except to note that the shallowest, high-temperature systems are in high heat flow zones and tectonically active parts of the western United States.

Finally, several nongeologic factors must be considered during the selection of future HDR sites. For example, the availability of injection waters must be considered, as must environmental issues, existing power networks, public visibility and acceptance, and competition with conventional geothermal interests. These factors were not discussed in this paper because our purposes have been to describe and tabulate the geologic and geophysical characteristics of the prospects for which we have a sufficiently large body of data.

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