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Geothermal resources of southwestern New Mexico and southeastern Arizona

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GEOTHERMAL RESOURCES OF SOUTHWESTERN NEW MEXICO AND SOUTHEASTERN ARIZONA

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Abstract—A geologic inventory of the discharge sites of convective geothermal systems points to a common geohydrologic setting. Tectonic and erosional stripping of Cenozoic and Mesozoic aquitards has exposed discharge windows which channel outflow of thermal water. Discharge occurs through windows of structurally high and permeable bedrock at low elevations on or near perennial drainage. Discharge is either at the surface or into near-surface aquifers. Low-relief horst blocks which intersect Laramide uplifts and mid-Tertiary cauldron ring-fracture zones are favorable sites. The geologic and physiographic setting of known systems strongly supports forced convection.

Conductive hydrothermal resources are found in late Tertiary basins which contain sediments of low thermal conductivity. As a consequence, temperature gradients between 35 and 45°C/km are typical even with background or regional heat fluxes.

Current uses of convective resources in the region include space heating and hot water for New Mexico State University and heat for more than 15 acres of greenhouses. Conductive resources are mostly subeconomic because of high costs and risks associated with deep wells.

INTRODUCTION

Geothermal resources in southwestern New Mexico and adjacent southeastern Arizona are compared with salient regional geologic and physiographic features. Rather than discussing these resources in a general way, two hydrothermal resource categories are reviewed. These categories are defined according to their predominant thermal regime or heat-transfer process. This approach is useful because each type of resource tends to have its own unique geologic setting.

This paper presents an overview of the geologic settings of the region's geothermal resources and describes current resource use and development. Sufficient geologic data are available to interpret a broad regional framework for geothermal resource occurrence.

RESOURCE CATEGORIES

Geothermal resources occur where heat flow from the earth's interior is elevated. Terrestrial heat flow includes conduction and convection. Where flowing water transports heat, convective hydrothermal resources are possible. Free convection will occur when thermally induced buoyancy overcomes resistance to flow. Shallow, intense heat sources and high permeability encourage free convection. Heat provided by shallow silicic magma bodies and fracture permeability in fault zones are favorable geologic settings for free convection.

Differences in water-table elevation can produce ground-water flow, and hydraulic potential associated with a sloping water table is capable of driving deeply circulating ground-water flow (Toth, 1963). This forced convection can extract significant heat from depth and concentrate it at shallow levels (Morgan et al., 1981; Smith and Chapman, 1983; Woodbury and Smith, 1985). Large variations in the water-table level, accompanying high topographic relief and large subsurface structures, enhance the strength of convective thermal effects. In addition, local free convection in high-permeability fault zones can add to thermal effects from otherwise predominantly forced convection.

Conductive heat transfer dominates where the vertical component of ground-water flow is exceedingly restricted, typically less than one centimeter per year. Where this occurs, deep-seated and confined aquifers can provide reservoirs for conductive hydrothermal resources.

RESOURCE RECOGNITION

Discharges from convective systems are easily recognized. Springs and wells tapping discharge flows are anomalously warm. Statistical analysis of regional spring and well temperatures shows that unusually warm springs are at least 16°C warmer than the mean annual air temperature (MAT; Witcher, 1981a). Thermal wells intersecting convective systems typically have surface discharge temperatures that exceed the MAT by at least 16°C and have an estimated or measured shallow temperature gradient that is greater than 75°C/km. Deep wells that discharge water with temperatures greater than 16°C above the MAT but have estimated temperature gradients less than 45°C/km probably indicate conductive-type geothermal resources.

PREVIOUS STUDIES

The geologic settings for the region's geothermal resources have been discussed by many workers. Chapin et al. (1978), Elston (1981), and Elston et al. (1983) point out that several geothermal systems in southwestern New Mexico occur along ring-fracture zones of mid-Tertiary cauldrons. Swanberg (1975), Jiracek and Smith (1976), and Elston et al. (1983) observe that late Tertiary fault zones apparently control other geothermal systems.

A model of forced convection through Tertiary basin-fill sediments was presented by Harder et al. (1980) and Morgan et al. (1981). This model places shallow geothermal resources at hydrologic outlets or constrictions of late Tertiary basins. Also, Harder et al. (1980) and Morgan et al. (1981) present convincing arguments against magma-driven hydrothermal convection in most of the region's geothermal systems.

Important site-specific geothermal resource studies in the region include Jiracek and Smith (1976), Dellechaie (1977), Smith (1978), Morgan et al. (1979), Witcher (1981b, 1981c, 1982), Icerman and Lohse (1983), Elston et al. (1983), Gross and Icerman (1983) and Snyder (1986). Regional geothermal map and data compilations and discussions are found in Summers (1976), Mariner et al. (1977), Swanberg (1978, 1979, 1983), Elston (1981), Stone and Witcher (1982), Witcher et al. (1982) and Norman and Bernhardt (1982). Decker and Smithson (1975), Reiter and others (1975, 1978), Sanford and others (1979) and Shearer and Reiter (1981) provide important data and discussion of heat flow and regional thermal regimes.

PHYSIOGRAPHIC SETTING

Southwestern New Mexico and adjacent southeastern Arizona are situated in the southern Basin and Range province. This province includes two subdivisions, the Mexican highlands and the Datil-Mogollon volcanic field (Fig. 1). The eastern portion of the Mexican highlands is often referred to as the southern Rio Grande rift tectonic province.

In the Mexican highlands, relatively narrow north- and northwest-striking mountain ranges are separated by wide and generally undissected alluvial plains. Internal drainage exists for most basins except



FIGURE 1. Physiographic map of New Mexico and Arizona showing the study area and extent of Rio Grande rift.

for those astride the Gila, San Pedro and San Simon Rivers and the Rio Grande. Animas, Lucero, Playas and Willcox playas typify the region's internal drainage.

The Blue, Gila, Mimbres and San Francisco river systems are entrenched in the Datil-Mogollon volcanic field to form deep and rugged canyons between mountain ranges and adjoining meses. Mesa surfaces represent former alluvial plains and pediments prior to drainage entrenchment and integration with regional stream systems. The San Agustin plain west of Socorro is an undissected exception with internal drainage into the San Agustin playa.

Anomalously warm springs and wells almost always occur adjacent to perennial drainage at lower elevations (Fig. 2). Most thermal wells and springs are found in dissected areas of the Datil-Mogollon volcanic field and bordering regions of the Mexican highlands. Topographic relief and density of perennial drainage is greatest in these regions.

The physiographic setting of the anomalously warm thermal springs and wells strongly suggests that forced convection is a dominant process. The ground-water models of Toth (1962, 1963), Freeze and Witherspoon (1966, 1967) and Hitchon (1969) appear to provide useful analogs to describe the geohydrology of the region's thermal springs. These models predict discharge of deeply circulating ground water at low elevations along perennial regional drainage.

GEOLOGIC SETTING

Cenozoic geology in the region is dominated by three major tectonic episodes: (1) the Laramide orogeny; (2) a mid-Tertiary extensional and volcanic event; (3) a late Tertiary episode of rifting.

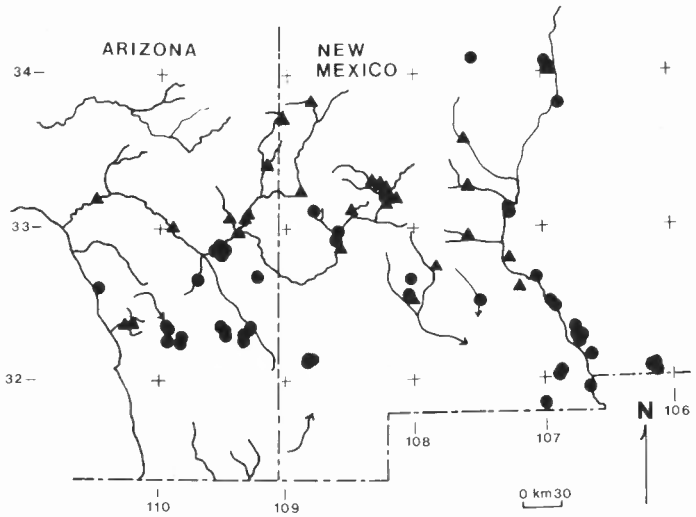


FIGURE 2. Comparison of convective geothermal systems with regional drainage. Triangles are thermal springs. Circles are thermal wells.

Laramide (Late Cretaceous to Eocene) deformation includes several large north- and west-northwest-trending, basement-involved uplifted terranes that exhibit one to five kilometers or more of structural relief (Davis, 1979; Seager, 1983). On many uplifts, Paleocene to lower Miocene rocks rest unconformably upon Paleozoic and Precambrian rocks. Cretaceous clastic rocks and syntectonic Laramide basin-fill sediments that act as aquitards are either absent or thin over the uplifts.

Mid-Tertiary volcanism was the result of a profound lithospheric thermal disturbance. Much of the region was covered by a blanket of volcanic flows and associated volcaniclastic sediments, averaging one km in thickness. Locally, volcanic piles up to five km in thickness fill cataclysmic cauldron subsidence features 10 to 50 km in diameter (Marjaniemi, 1968; Elston, 1984; Ratté et al., 1984), or fill large long-lived (10 to 15 my) elongated depressions greater than 30 by 70 km (Seager, 1973; Creasey and Krieger, 1978; Wahl, 1980). In a 1.7-million-year interval between 29 and 27 my, nine cauldrons are known to have erupted more than 6,000 cubic kilometers of ignimbrite (McIntosh et al., 1986).

Elston (1984) proposed significant extensional strain in order to allow room for the passive emplacement of magma bodies that fed the cauldron eruptions. Studies by Chamberlin (1983) and Chamberlin and Osburn (1986) indicate that severe extensional strain distended some of these areas. Temporal and spatial association of intensely extended terranes with some ring-fracture zones and cauldrons is given a thermophysical basis in the models of Morgan et al. (1986). Flow of large volumes of water through highly extended zones is indicated by pervasive potassium enrichment (Chapin and Lindley, 1986). Juxtaposition of rocks with very different hydrologic properties occurs along many ring-fracture zones as a result of faulting, intrusion and hydrothermal alteration. Local unroofing of permeable rocks by slumping and landslides probably accompanied cauldron collapse in other areas. Vertical ground-water flow is possible within all of these ring-fracture settings, especially in fractured and brecciated intrusive masses. Elsewhere in the region some mid-Tertiary basaltic andesite flows and ash-flow tuff units are very permeable and make excellent aquifers (Heindl, 1967).

Basin and Range topography was blocked out mostly by large normal faults, beginning about 12 to 9 million years ago (Seager, 1975; Eberly and Stanley, 1978; Scarborough and Peirce, 1978; Seager et al., 1984; Morgan et al., 1986). This late Tertiary rifting, now essentially quiescent, has left an en echelon series of north- and northwest-trending sediment-filled basins or grabens and half grabens.

In general, the geology of late Tertiary basins in the region is conveniently divided into five hydrogeologic units (Fig. 3): (1) basement, which includes all pre-Laramide rocks (pre-Upper Cretaceous rocks); (2) Laramide volcanic and clastic rocks; (3) mid-Tertiary volcanic rocks; (4) mid-Tertiary proto-Basin and Range sediments (pre-12 my) and (5) upper Tertiary basin-fill sediments. Each unit is distinguishable on the basis of structural setting, amount of deformation, degree of induration, lithology and water-bearing properties.

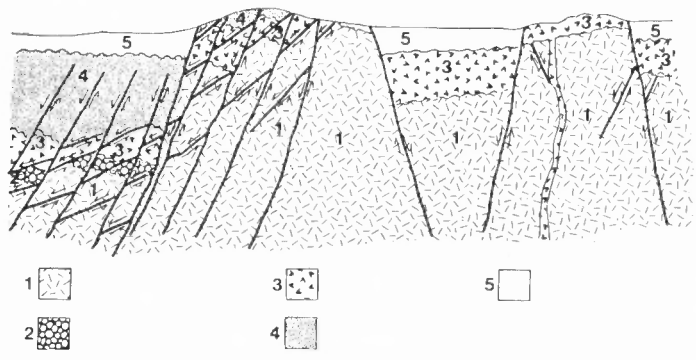


FIGURE 3. Generalized diagrammatic cross section showing major hydrogeologic subdivisions within late Tertiary basins. Patterns within the numbered boxes represent: (1) basement pre-Upper Cretaceous rocks; (2) Laramide clastic and volcanic rocks; (3) mid-Tertiary volcanic rocks; (4) mid-Tertiary proto-Basin and Range sediments; (5) upper Tertiary basin-fill sediments.

Clay-rich fluvial, lacustrine and playa sediments of units 2, 4 and 5 provide important confining hydrologic units. Because these sediments are frequently low in quartz and carbonate minerals, they have low thermal conductivity. Important aquifers are found in carbonate rocks of unit 1, in fractured volcanic rocks of unit 3 and in coarse clastic sediments of unit 5. Sediments composing unit 2 and unit 4 are usually highly indurated and act as aquitards, although fracture permeability is also possible.

CONDUCTIVE HYDROTHERMAL RESOURCES

The most extensive hydrothermal resource base in the region occurs in late Tertiary basins. This resource occurs in a predominantly conductive thermal regime. Temperature gradients up to 70°C/km are possible over short vertical intervals (<100 m) in the interiors of late Tertiary basins even though only regional or background heat fluxes are transmitted to the surface. This is a consequence of basin-fill sediments with low thermal conductivity. Temperature gradients between 35°C/km and 45°C/km are common. Temperature or water produced from wells approximately 300 meters deep in these basins is typically 26 to 36°C.

An important example of an area with conductive resource potential is the Safford basin, Arizona (Fig. 4). The Safford basin is an asymmetrical graben complex bounded by a major fault zone on the south and southwest. The basin is underlain by a series of faulted stair-step blocks which rise upward to the north and northeast to form the Gila, Whitlock and Peloncillo Mountains. At least three km of clastic sediments fill the basin. Three hydro-stratigraphic subdivisions are observed as one moves toward the basin center: (1) a sand and conglomerate facies; (2) a silt and clay facies and (3) an evaporite facies. Several deep (>300 m) wells in the basin produce artesian flows of 35 to 50°C water from the sand and conglomerate facies. The intertonguing and overlying silt and clay facies provides a confining caprock of low thermal conductivity.

CONVECTIVE RESOURCES

Convective hydrothermal systems can be difficult to understand. More often than not, only the nature of discharge is known with any confidence. Heat sources, circulation frameworks, recharge sources and deep reservoir temperatures can only be inferred without deep drilling and extensive geochemical and geophysical surveys. Sometimes even after extensive study, data conflict for many systems. Therefore, a useful but limited approach is to take a geologic inventory of the discharge settings. Anomalous temperature in spring or well discharges is a reliable criteria for defining the existence of convective systems.

Thermal spring discharge sites and thermal well production zones indicate that convective systems in the region are mostly contained in

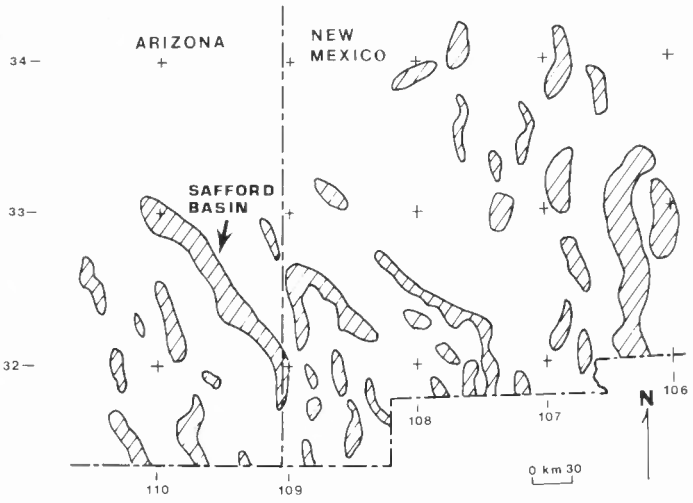


FIGURE 4. Map showing deep late Tertiary sediment-filled basins with conductive geothermal resource potential.

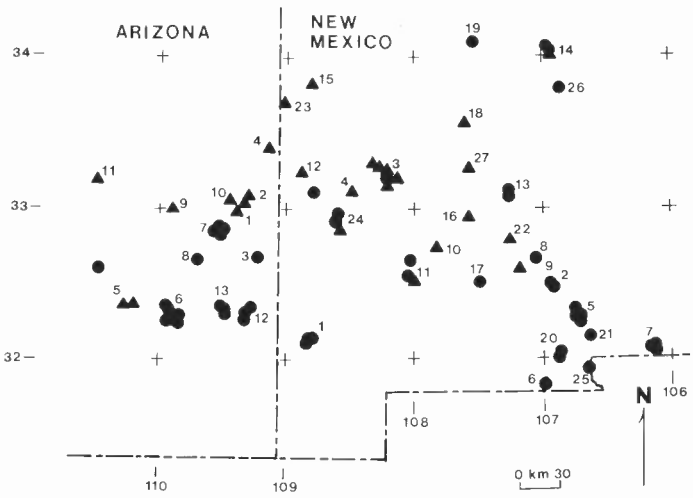


FIGURE 5. Location map of convective systems listed in Table 1. Triangles are thermal springs. Circles are thermal wells.

Tertiary volcanic rocks, Paleozoic carbonate rocks and Precambrian plutonic and metamorphic rocks (Table 1; Fig. 5). The chemical quality of thermal water generally reflects reservoir lithology. Systems known to circulate through Paleozoic carbonate rocks and Precambrian crystalline rocks average 3700 milligrams per liter (mg/L) total dissolved solids (TDS) and the TDS is nearly always more than 1000 mg/L. Thermal waters believed to circulate only in Tertiary volcanic rocks average about 500 mg/L TDS. Evidence for mixing of thermal water and nonthermal water exists only for Clifton Hot Springs, Arizona and the Lower Frisco, New Mexico systems (Table 1; Mariner et al., 1977; Witcher, 1981b). Therefore, discharges from the remaining systems probably cool conductively and retain their basic chemistry.

Comparison of convective systems with a Tertiary subcrop map reveals that nearly all discharges occur over Laramide (or older Mesozoic) uplifts (Fig. 6). Furthermore, low-relief or detritus-covered horst blocks provide an additional setting for several convective systems, as do the ring-fracture zones of several mid-Tertiary cauldrons. All of these settings have common characteristics. They are structurally high and usually expose faulted and fractured bedrock.

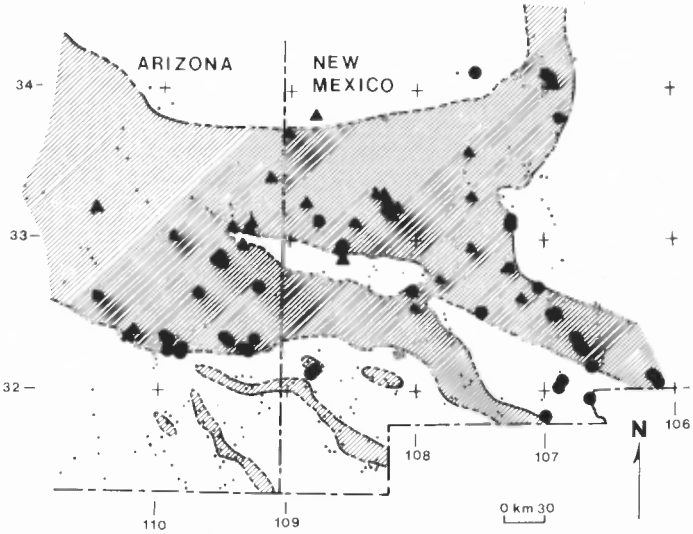


FIGURE 6. Comparison of convective geothermal systems with a generalized Tertiary subcrop map. Pattern indicates areas where Paleocene to lower Miocene rocks unconformably overlie Paleozoic and Precambrian rocks (Laramide and Mesozoic uplifts). Dots are borehole and outcrop data control. Triangles are thermal springs. Circles are thermal wells.

TABLE 1. Summary of convective geothermal systems. Geologic settings are keyed as follows: L—Laramide or Mesozoic uplift; CC—Tertiary cauldron complex; HB—late Tertiary horst block; RD—regional drainage. Reservoir lithology symbols are: Ts—Tertiary clastic sediments; Tv—Tertiary volcanic rocks; Tvi—Tertiary rhyolite dike or plug; Pz—Paleozoic carbonate rocks; Mz—Cretaceous carbonate rocks.

	SYSTEM	LOCATION TOWNSHIP/RANGE	TEMP C	TDS mg/L	DEPTH m	RESERVOIR LITHOLOGY	GEOLOGIC SETTING L	CC	HB	RD
		NEW MEXICO								
1.	Lightning Dock	T25S, R19W	80-110	1100-1200	<150	Tv, Pz	X	X	X	
2.	Radium Springs	T21S, R1W	65-75	3600-3700	<100	Tvi, Pz	X	X	X	X
3.	Gila Hot Springs	T13S, R13W	55-75	400-500	<100	Tv	X?	X?		X
4.	Turkey Creek	T14S, R16W	65-75	200-300	springs	Tvi	X?	X	X	X
5.	Las Cruces East Mesa Tortugas Mtn	T23S, R2E	60-70	1900-2100	180-400	Tv, Pz	X	X	X	X
6.	East Potrillo	T29S, R1W	60-70	N/A	<300	Mz, Pz	X		X	
7.	Hueco Tanks	T26S, R8E	60-75	8700-9000	140-230	Pz	X?		X	
8.	Rincon	T19S, R2W	50-60	1100-1200	<150	Tv, Pz	X		X	X
9.	San Diego Mtn	T19S, 1W	50-60	N/A	<200	Tv, Pz, Pe	X		X	X
10.	Mimbres Hot Springs	T18S, 10W	50-60	300-350	springs	Tv, Tvi	X	X	X	X
11.	Faywood Hot Springs	T20S, 11W	50-60	450-550	springs	Tv	X		X	X
12.	Lower Frisco	T20S, 20W	45-55	1100-1400	springs	Tv	X?	X	X	X
13.	Hot Springs (T. or C.)	T13S, R4W	35-45	2300-2500	<100	Pz	X		X	X
14.	Socorro	T3S, R1W	35-45	300-1950	<100	Tv, Pz, Pe	X	X	X	
15.	Upper Frisco	T5S, R19W	35-40	200-250	springs	Tv	X?			X
16.	Hillsboro	T16S, R7W	30-40	550-600	springs	Ts, Tv	X	X	X	X
17.	Nutt	T21S, R6W	30-40	N/A	<200	Ts, Tv	X	X?		
18.	Ojo Caliente	T8S, R7W	30-40	500-550	springs	Tv, Pz	X	X	X	X
19.	San Agustin	T2S, R7W	30-40	250-300	<100	Ts, Tv	X?			
20.	Afton	T26S, R1E	30-35	550-600	130-200	Ts, Tv			X	
21.	Vado	T25S, R3E	30-35	2000-2200	<100	Ts, Tvi, Tz	X?		X	X
23.	Frieborn Canyon	T7S, R21W	30-35	150-200	springs	Tv	X?		X	X
24.	Cliff	T15S, R17W	30-35	400-450	<100	Ts, Tv	X	X?		X
25.	Canutillo	T27S, R3E	30-35	300-350	200-250	Ts, Mz	X?		X	X
26.	Bosque	T6S, R1E	30-35	12700-12900	<100	Ts, Pz	X			X
27.	Winston Warm Springs	T12S, 7W	30-35	1350-1450	springs	Tv, Pz	X		X	X
		ARIZONA								
1.	Gillard Hot Springs	T5S, R29E	75-85	1200-1300	springs	Ts, Tv	X			X
2.	Clifton Hot Springs	T4S, R30E	45-75	6000-15000	springs	Tv, Pz, Pe	X		X	X
3.	Hot Well	T9S, R30E	70-75	N/A	<100	Tv	X		X	
4.	Hanna Creek Hot Springs	T1N, R31E	50-60	650-700	springs	Tvi	X?	X?	X	X
5.	Hookers Hot Springs	T13S, R21E	50-55	250-350	springs	Tv	X		X	X
6.	Willcox	T12S, R24E	35-55	250-1300	200-460	Ts, Tv	X			
7.	Buena Vista	T7S, R27E	35-50	1000-1100	100-140	Ts, Tv	X		X	X
8.	Artesia	T8S, R26E	35-50	600-3000	200-500	Ts	X			X
9.	Indian Hot Springs	T5S, R24E	45-50	2900-3000	springs	Ts	X			X
10.	Eagle Creek	T4S, R28E	40-45	650-700	springs	Tv	X			X
11.	Coolidge Dam Hot Springs	T3S, R18E	35-40	2350-2450	springs	Pz	X		X	X
12.	San Simon	T13S, R30E	35-45	250-400	250-350	Ts	X			X
13.	Bowie	T13S, R28E	35-45	200-700	200-460	Ts	X			X

SYNTHESIS

Geohydrologic windows are outcrop and subcrop terranes underlain by permeable rock where confining aquitards have been erosionally or tectonically stripped away. These structurally high, permeable-bedrock windows at low elevations apparently provide the discharge sites for most of the region's convective systems. The discharge windows protrude through Cenozoic and Mesozoic confining units to allow outflow of thermal water. Windows channel vertical ground-water outflow. Buried and low-relief horst blocks are favorable sites for windows, especially those horsts which intersect Laramide uplifts and mid-Tertiary cauldron ring-fracture zones. In these areas, confining units tend to be absent or thin. In nearly all areas, fault zones tend to be the locus of fracture permeability in bedrock aquifers; although fracturing associated with folding or intrusions may have important permeability in some areas. Fractured and discordant rhyolite-dacite dikes, plugs and domes which pierce confining units provide additional favorable discharge sites.

RESOURCE USE AND DEVELOPMENT

At present, the conductive hydrothermal resource is mostly subeconomic due to the high costs, risks and slow return on investment for deep (>300 m) wells. This is especially true for wells that are coupled to low-enthalpy direct-use applications. In New Mexico, the development and use of conductive hydrothermal resources has not occurred. However, several hot-flowing wells in the Artesia area near Safford, Arizona are used in commercial mineral baths.

Several forced convective hydrothermal resources are under development or currently used in the region (Table 2). The Las Cruces East Mesa-Tortugas Mountain geothermal system has been tapped to supply heat for space heating and hot water at New Mexico State University (NMSU) in Doña County at Las Cruces. NMSU is one of the largest direct-use geothermal operators in the nation. The NMSU system, developed and constructed with a 1.5 million dollar investment from the State of New Mexico ($829,000) and combined research funding from the U.S. Department of Energy and the New Mexico Research and Development Institute (NMRDI) ($671,000) saves approximately one hundred fifty thousand dollars in natural gas costs annually. This system, in operation since February 1982, uses between 6 and 12 liters per second of 62°C water produced from wells less than 300 meters deep. Geothermal waters from the production wells are passed through a gas separator to remove dissolved carbon dioxide. The waters are then passed through a plate-type stainless steel heat exchanger, where the heat is extracted. The geothermal waters, with their heat removed, are then recharged back into the reservoir margin via an injection well.

Also at NMSU, the Energy Institute operates a geothermal greenhouse research facility. Commercial greenhouses are rapidly becoming the most common and largest users of geothermal water in the region. Abundant sunshine, a favorable labor and business climate and low-cost geothermal heat make the greenhouse business attractive.

In the Animas Valley, Hidalgo County, New Mexico, the Lightning Dock geothermal system supplies heat to three greenhouse operators. Burgett Nurseries (10 acres) and the Beal Company (1 acre) greenhouses produce flowers, mostly roses. The roses are air freighted out of Tucson to markets across the nation. The McCants (<0.5 acre) greenhouse grows potted plants. The Lightning Dock field yields 90 to 107°C water from wells less than 150 meters deep.

In 1987, four acres of geothermally heated greenhouses became operational at Radium Springs in Doña Ana County, New Mexico. Geothermal wells for the Radium Springs facility were drilled under a State of New Mexico cost-shared drilling program. Funding ($100,000) was provided to the New Mexico Energy, Minerals and Natural Resources Department by the legislature, and the program was administered by the NMSU Energy Institute. Seven participants drilled wells and the Radium Springs project, managed by Alexander Masson, Inc., is the first to become commercially operational. The greenhouses are heated with 70°C geothermal water produced from wells less than 150 meters deep. The Masson greenhouses at Radium Springs employ about 40 persons and additional greenhouse acreage is planned using current productions wells. Tax revenue generated by the Radium Springs project alone will repay the State's entire investment in the cost-shared drilling program in two or three years.

In addition to direct-use geothermal applications, small-scale electrical power generation has been done in Grant County at Gila Hot Springs by D. A. Campbell. Gila Hot Springs is in a very remote location and has abundant low-temperature (74°C) geothermal water. A U.S. Department of Energy Appropriate Technology grant enabled Mr. Campbell to purchase and install a Rankine-cycle generator, using an organic working fluid, capable of 10 kw electrical power.

TABLE 2. Resource use and development in the region. Resource numbers are the same as in Table 1.

	RESOURCE	LOCATION TOWNSHIP/RANGE	USE	TEMPERATURE C
		NEW MEXICO		
1.	Lightning Dock	T25S, R19W	A. Greenhouses (11 acres)	80-110
2.	Radium Springs	T21S, R1W	A. Greenhouses (4 acres) B. Mineral Bath	65-75
3.	Gila Hot Springs	T13S, R13W	A. Space Heating B. Greenhouse (1 acre) C. Small-Scale Electrical Power Generation	55-75
5.	Las Cruces East Mesa-Tortugas Mtn	T23S, R2E	A. Space-Heating NMSU Campus G. Greenhouse (<1 acre)	60-70
13.	Hot Springs (T. or C.)	T13S, R4W	A. Space-Heating B. Mineral Baths	35-45
		ARIZONA		
8.	Artesia	T3S, R26E	A. Mineral Baths	35-50

SUMMARY AND CONCLUSIONS

Several geologic factors are associated with convective geothermal systems in southwestern New Mexico and southeastern Arizona. They are listed below according to their relative size or extent.

1. Mesozoic and Laramide uplifts provide regions where Mesozoic and early Tertiary aquitards are thin or absent.
2. Low elevations adjacent to regional drainage provide ideal discharge sites for deep-seated regional ground-water flow systems.
3. Mid-Tertiary cauldron ring-fracture zones can provide a variety of geologic settings favorable to vertical ground-water flow as either recharge or discharge.
4. Some low-relief and buried late Tertiary horst blocks expose fractured and permeable bedrock aquifers. Middle and upper Tertiary aquitards are thin or absent over the horsts.
5. Some fractured Tertiary rhyolite-dacite dikes, plugs and domes pierce aquitards to allow outflow of deep-seated thermal ground water.
6. Favorable reservoir rocks are found at depth.
7. Late Tertiary and Quaternary faults may provide fractured volumes of rock or they may act as aquitards to divert ground-water flow vertically.

Factors 1, 2 and 6 nearly always apply on a regional scale; while various combinations of other factors such as 3, 4, 5 and 7 provide local sites for convective system occurrence.

Conductive hydrothermal resources are most favored in the following settings:

1. Large and deep (>1 km) late Tertiary sediment-filled basins may store large amounts of hot (>35°C) water at depths greater than 300 meters.
2. Late Tertiary basins with widespread and thick sequences of clayey fluvial, lacustrine or playa deposits can have temperature gradients between 35 and 45°C/km. Other late Tertiary basins with mostly alluvial and coarse-grained fluvial sediments have lower temperature gradients and they are less likely to have predominantly conductive thermal regimes.

Development and use of the convective resources have a bright future and are in their infancy. Exploitation of the conductive resource base is problematical. However, deep irrigation and water-supply wells in the Lordsburg, Deming and White Sands areas encountering hot water may offer excellent development opportunities in New Mexico. Hot artesian wells in the Safford and Willcox basins, Arizona may offer similar development opportunities.

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REFERENCES

Chamberlin, R. M., 1983, Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico—a summary: New Mexico Geological Society, Guidebook 34, p. 111–118.

Chamberlin, R. M. and Osburn, G. R., 1986, Tectonic framework, character, and evolution of upper crustal extensional domains in the Socorro area of the Rio Grande rift, New Mexico: Arizona Geological Society, Digest 16, p. 464.

Chapin, C. E., Chamberlin, R. M., Osburn, G. R., White, D. W. and Sanford, A. R., 1978, Exploration framework of the Socorro geothermal area: New Mexico Geological Society, Special Publication 7, p. 115–129.

Chapin, C. E. and Lindley, J. E., 1986, Potassium metasomatism of igneous and sedimentary rocks in detachment terrains and other sedimentary basins: Arizona Geological Society, Digest 16, p. 118–126.

Creasey, S. C. and Krieger, M. H., 1978, Galiuro volcanics, Pinal, Graham, and Cochise Counties, Arizona: U.S. Geological Survey, Journal of Research, v. 6, p. 115–131.

Davis, G. H., 1979, Laramide folding and faulting in southeastern Arizona: American Journal of Science, v. 279, p. 543–569.

Decker, E. R. and Smithson, S. B., 1975, Heat flow and gravity interpretation across the Rio Grande rift in southern New Mexico and West Texas: Journal of Geophysical Research, v. 80, p. 2542–2552.

Dellechaie, F., 1977, A geological and hydrochemical study of the Animas geothermal area, Hidalgo County, New Mexico: Geothermal Resources Council, Transactions, v. 1, p. 73–75.

Eberly, L. D. and Stanley, J. B., Jr., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geological Society of America Bulletin, v. 89, p. 921–940.

Elston, W. E., 1981, Assessment of the geothermal potential of southwestern New Mexico: New Mexico Research and Development Institute, Report EMD 2-67-2123, 39 p.

Elston, W. E., 1984, Mid-Tertiary ash-flow tuff cauldrons, southwestern New Mexico: Journal of Geophysical Research, v. 89, p. 8733–8750.

Elston, W. E., Deal, E. G. and Logsdon, M. J., 1983, Geology and geothermal waters of Lightning Dock region, Animas Valley and Pyramid Mountains, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 177, 44 p.

Freeze, R. A. and Witherspoon, P. A., 1966, Theoretical analysis of regional ground water flow: 1. Analytical and numerical solutions to the mathematical model: Water Resources Research, v. 2, p. 641–656.

Freeze, R. A. and Witherspoon, P. A., 1967, Theoretical analysis of regional ground water flow: 2. Effect of water-table configuration and subsurface permeability variation: Water Resources Research, v. 3, p. 623–634.

Gross, J. T. and Icerman, L., 1983, Subsurface investigations for the area surrounding Tortugas Mountain, Doña Ana County, New Mexico: New Mexico Research and Development Institute, Report 2-67-2238(2), 70 p.

Harder, V., Morgan, P. and Swanberg, C. A., 1980, Geothermal resources in the Rio Grande rift—origins and potential: Geothermal Resources Council, Transactions, v. 4, p. 61–64.

Heindl, L. A., 1967, Groundwater in fractured volcanic rocks in southern Arizona: International Association of Science and Hydrology, Publication 74, v. 2, p. 503–513.

Hitchon, B., 1969, Fluid flow in the western Canada sedimentary basin: 1. Effect of topography: Water Resources Research, v. 5, p. 186–195.

Icerman, L. and Lohse, R. L., 1983, Geothermal low temperature reservoir assessment in Doña Ana County, New Mexico: New Mexico Research and Development Institute, Report NMERDI 2-69-2202, 188 p.

Jiracek, G. R. and Smith, C., 1976, Deep resistivity investigations at two Known Geothermal Resource Areas (KGRA's) in New Mexico—Radium Springs and Lightning Dock: New Mexico Geological Society, Special Publication 6, p. 71–76.

Mariner, R. H., Presser, D. D. and Evans, W. C., 1977, Chemical, isotopic and gas compositions of selected thermal springs in Arizona, New Mexico and Utah: U.S. Geological Survey, Open-File Report 77-654, 42 p.

Marjaniemi, D. K., 1968, Tertiary volcanism in the northern Chiricahua Mountains, Cochise County, Arizona: Arizona Geological Society, Guidebook 3, p. 209–214.

McIntosh, W. C., Sutter, J. F., Chapin, C. E., Osburn, G. R. and Ratté, J. C., 1986, A stratigraphic framework for the eastern Mogollon-Datil volcanic field based on paleomagnetism and high-precision $^{40}Ar/^{39}Ar$ dating of ignimbrites—a progress report: New Mexico Geological Society, Guidebook 37, p. 183–195.

Morgan, P., Harder, V., Swanberg, C. A. and Daggett, P. H., 1981, A ground water convection model for Rio Grande rift geothermal resources: Geothermal Resources Council, Transactions, v. 5, p. 193–196.

Morgan, P., Seager, W. R. and Golombek, M. P., 1986, Cenozoic thermal, mechanical and tectonic evolution of the Rio Grande rift: Journal of Geophysical Research, v. 91, p. 6263–6276.

Morgan, P., Swanberg, C. A. and Lohse, R. L., 1979, Borehole temperature studies of the Las Alturas geothermal anomaly, New Mexico: Geothermal Resources Council, Transactions, v. 3, p. 279–288.

Norman, D. I. and Bernhardt, C. A., 1982, Assessment of geothermal reservoirs by analysis of gases in thermal water: New Mexico Research and Development Institute, Report EMD 2-68-2305, 130 p.

Ratté, J. C., Marvin, R. R. and Naeser, C. W., 1984, Calderas and ash-flow tuffs of the Mogollon Mountains, southwestern New Mexico: Journal of Geophysical Research, v. 89, p. 8713–8732.

Reiter, M., Edwards, C. L., Hartman, H. and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado: Geological Society of America Bulletin, v. 86, p. 811–818.

Reiter, M., Shearer, C. and Edwards, C. L., 1978, Geothermal anomalies along the Rio Grande rift in New Mexico: Geology, 6, p. 85–88.

Sanford, R. M., Bowers, R. L. and Combs, J., 1979, Rio Grande rift geothermal exploration case history—Elephant Butte prospect, south-central New Mexico: Geothermal Resources Council, Transactions, v. 3, p. 609–612.

Scarborough, R. B. and Peirce, H. W., 1978, Late Cenozoic basins of Arizona: New Mexico Geological Society, Guidebook 29, p. 253–260.

Seager, W. R., 1973, Resurgent, volcano-tectonic depression of Oligocene age, south-central New Mexico: Geological Society of America Bulletin, v. 84, p. 3611–3626.

Seager, W. R., 1975, Cenozoic tectonic evolution of the Las Cruces area: New Mexico Geological Society, Guidebook 26, p. 241–250.

Seager, W. R., 1983, Laramide wrench faults, basement-cored uplifts and complementary basins in southern New Mexico: New Mexico Geology, v. 5, p. 1–8.

Seager, W. R., Shafiqullah, M., Hawley, J. M. and Marvin, R. F., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, p. 87–99.

Shearer, C. and Reiter, M., 1981, Terrestrial heat flow in Arizona: Journal of Geophysical Research, v. 86, p. 6249–6260.

Smith, C., 1978, Geophysics, geology and geothermal status of the Lightning Dock KGRA, Animas Valley, New Mexico: New Mexico Geological Society, Guidebook 29, p. 343–348.

Smith, L. and Chapman, D. S., 1983, On the thermal effects of groundwater flow: 1. Regional scale systems: Journal of Geophysical Research, v. 88, p. 593–603.

Snyder, J. T., 1986, Heat flow in the southern Mesilla basin with an analysis of the East Potrillo geothermal system [M.S. thesis]: Las Cruces, New Mexico, New Mexico State University, 252 p.

Stone, C. and Witcher, J., 1982, Geothermal Energy in Arizona: Arizona Bureau of Geology and Mineral Technology, Open-File Report 83-12, 398 p.

Summers, W. K., 1976, Catalog of thermal waters in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 4, 80 p.

Swanberg, C. A., 1975, Detection of geothermal components in groundwaters of Doña Ana County, southern Rio Grande rift, New Mexico: New Mexico Geological Society, Guidebook 26, p. 175–180.

Swanberg, C. A., 1978, Chemistry, origin and potential of geothermal resources in southwestern New Mexico and southeastern Arizona: New Mexico Geological Society, Guidebook 29, p. 349–351.

Swanberg, C. A., 1979, Chemistry of thermal and non-thermal groundwaters in the Rio Grande rift and adjacent tectonic provinces; *in* Reicker, R. E., ed., Rio Grande rift: Tectonics and Magmatism: American Geophysical Union, Washington, D.C., p. 279–288.

Swanberg, C. A., 1983, The geothermal resources of New Mexico: New Mexico State University Energy Institute, Map, scale 1:500,000.

Toth, J., 1962, A theory of ground-water motion in small drainage basins in central Alberta, Canada: Journal of Geophysical Research, v. 67, p. 4375–4387.

Toth, J., 1963, A theoretical analysis of ground-water flow in small drainage basins: Journal of Geophysical Research, v. 68, p. 4795–4812.

Wahl, D. E., Jr., 1980, Mid-Tertiary volcanic geology in parts of Greenlee County Arizona, Grant and Hidalgo Counties New Mexico [Ph.D. dissertation]: Tempe, Arizona, Arizona State University, 147 p.

Witcher, J. C., 1981a, Thermal springs of Arizona: Arizona Bureau of Geology and Mineral Technology, Fieldnotes, v. 11, p. 1–4.

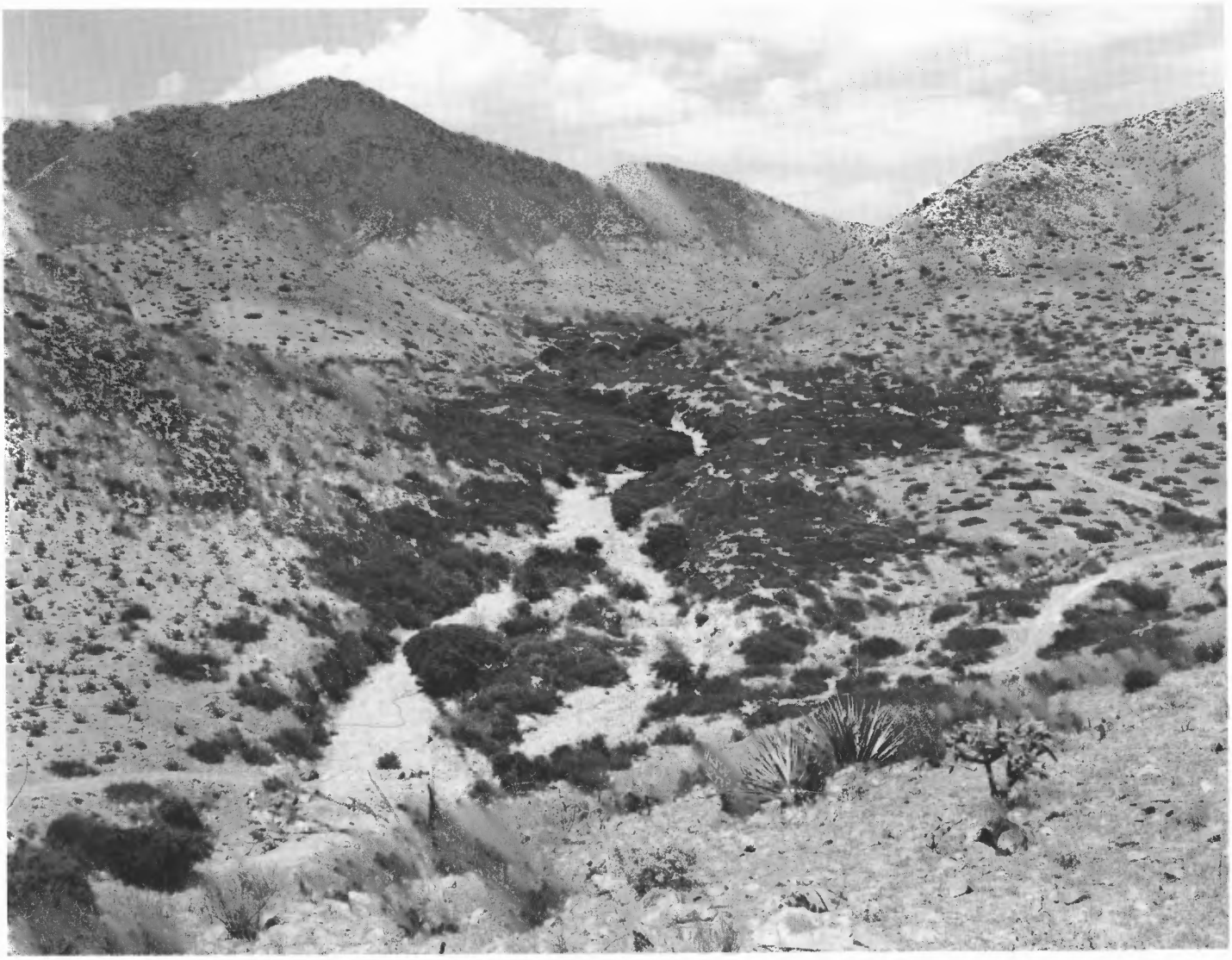
Witcher, J. C., 1981b, Geothermal energy potential of the lower San Francisco River region, Arizona: Arizona Bureau of Geology and Mineral Technology, Open-File Report 81-7, 141 p.

Witcher, J. C., 1981c, Geothermal resource potential of the Safford-San Simon basin, Arizona: Arizona Bureau of Geology and Mineral Technology, Open-File Report 81-26, 125 p.

Witcher, J. C., 1982, Geothermal resource potential of the Willcox, Arizona, area: Arizona Bureau of Geology and Mineral Technology, Open-File Report 82-4, 39 p.

Witcher, J. C., Stone, C. and Hahman, W. R., Sr., 1982, The geothermal resources of Arizona: Arizona Bureau of Geology and Mineral Technology, Map, scale 1:500,000.

Woodbury, A. D. and Smith, L., 1985, On the thermal effects of three-dimensional groundwater flow: Journal of Geophysical Research, v. 90, p. 759–767.



Broken Jug Pass and site of Sylvanite, Little Hatchet Mountains. View is N51°E. According to the Hachita 15′ topographic map published by the USGS in 1918, the mining camp of Sylvanite occupied the slightly dissected valley floor to the right of the wash. The crest of Broken Jug Pass is upstream about 1.5 km. Area in foreground underlain by diorite intruded into steeply southwest-dipping U-Bar Formation. Hills to left and right of Broken Jug Pass are mostly monzonite intruded into west-dipping Hell-to-Finish Formation. These stocks are part of the Sylvanite intrusive complex (Zeller, 1970) and Sylvanite composite stock (Lasky, 1947). Shrubby mesquite forms a nearly continuous cover on the valley floor adjacent to the wash. Dark trees along the wash are mainly hackberry. Camera station in SE ¼ SE¼, sec. 33, T28S, R16W. Altitude about 1577 m. W. Lambert photograph No. 87L52. 25 July 1987, 3:35 p.m., MDT.