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Christopher D. Henry and Robert A. Morton*

Trans-Boundary Geothermal Resources of Texas and Mexico[†]

Potential geothermal resources of the Texas–Mexico border region include (1) convective geothermal systems in Trans-Pecos Texas, Chihuahua, and Coahuila and (2) geopressured geothermal systems containing methane in South Texas, Tamaulipas, and Nuevo Leon. The convective geothermal systems are characterized by hot springs and shallow hot wells located along normal faults. The maximum measured temperature is 90°C, and the maximum temperature estimated from chemical geothermometers is 160°C. Most temperatures are considerably lower. None of the waters are hot enough to generate electricity. The highest temperature waters could be used for industrial or space heating but, except for those in the Hueco Tanks area near El Paso and Juarez, occur too far from population centers.

Tertiary sandstones that formed at great depths beneath southern Texas and northwestern Mexico contain substantial quantities of thermal energy and methane. The methane occurs partly as free gas but mostly as solution gas in hot overpressured brines. The solubility of methane in these brines is directly related to formation temperature and fluid pressure and inversely related to salinity of formation water. Production tests of geopressured aquifers in Texas have yielded 5.2 to 9.0 m³/m³ of gas composed mostly of methane but also containing CO₂ in concentrations ranging from 6% to 20%. These low gas concentrations indicate that the formation waters are saturated with methane at reservoir conditions. The lower Rio Grande Embayment has some of the highest temperatures and pressures and lowest salinities in the Gulf Coast region and is a favorable area for development of geothermal energy and unconventional gas. However, reservoir quality is generally poor in this area because of extremely low permeabilities. Consequently, commercial development of these alternate energy resources will depend largely on transfer of new heat conversion technology, improved well stimulation techniques, and increased gas to water ratios.

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CONVECTIVE GEOTHERMAL SYSTEMS OF CHIHUAHUA, COAHUILA, AND TRANS-PECOS TEXAS—INTRODUCTION

Evidence for geothermal potential in the Rio Grande area of Chihuahua, Coahuila, and Trans-Pecos Texas includes (1) the presence of numerous hot springs and shallow wells producing anomalously hot water (up to 90°C), (2) high geothermal gradients (approximately 40°C/km) in deep oil-test wells in the area, and (3) a favorable geologic setting in the Basin and Range Province, which is the site of successful geothermal exploration in other parts of the United States. Because subsurface data are sparse, most of our knowledge of the geothermal potential comes from study of surface geology and the geologic setting, geochemistry, and hydrology of geothermal waters. To evaluate the resource, we need to know the maximum temperatures, amounts, and chemical quality of geothermal waters. Facets of the geology and geochemistry discussed below can reveal much about these characteristics.

The Rio Grande area lies in the Basin and Range Province, which is characterized by north- and northwest-trending mountain blocks separated from similar trending basins by normal faults (fig. 1). The mountain ranges are composed of a variety of rock types of several different ages including Precambrian metamorphosed igneous and sedimentary rocks, Paleozoic to Mesozoic (Cretaceous) sedimentary rocks, and Tertiary volcanic and volcanoclastic rocks. The Tertiary igneous activity ceased about 20 m.y. ago and is too old to provide heat to any of the geothermal systems. Displacement along the normal faults during the last 25 m.y. dropped the basins down relative to the adjacent mountain ranges. At the same time that they were being downdropped, the basins filled with debris eroded off the ranges. Rocks similar to those in the ranges occur within the basins but are buried by up to 1.5 km of basin fill. The faults were created by extension and subsequent thinning of the Earth's crust in an approximate east-west direction.

Hot springs and wells occur along the border from the Hueco Tanks area near El Paso and Juarez to the Big Bend area of Brewster County, Texas, and Coahuila (fig. 1; table 1). The highest temperature waters are restricted to two areas: (1) Hueco Tanks, which has measured temperatures in shallow wells as high as 71°C,¹ and (2) Presidio Bolson, which has temperatures as high as 90°C at Ojo Caliente in Chihuahua and from 70° to 80°C in the Gulf Wells in Presidio County, Texas.² Only these two areas are likely to have geothermal waters with reservoir temperatures

1. Henry and Gluck, *A Preliminary Assessment of the Geologic Setting, Hydrology, and Geochemistry of the Hueco Tanks Geothermal Area, Texas and New Mexico*, 81-1 GEOLOGICAL CIRCULAR OF THE UT AUSTIN BUREAU OF ECONOMIC GEOLOGY 47 (1981).

2. Henry, *Geologic Setting and Geochemistry of Thermal Water and Geothermal Assessment, Trans-Pecos Texas*, 96 UT AUSTIN BU. ECON. GEOL. REP. OF INVESTIGATIONS 48 (1979).

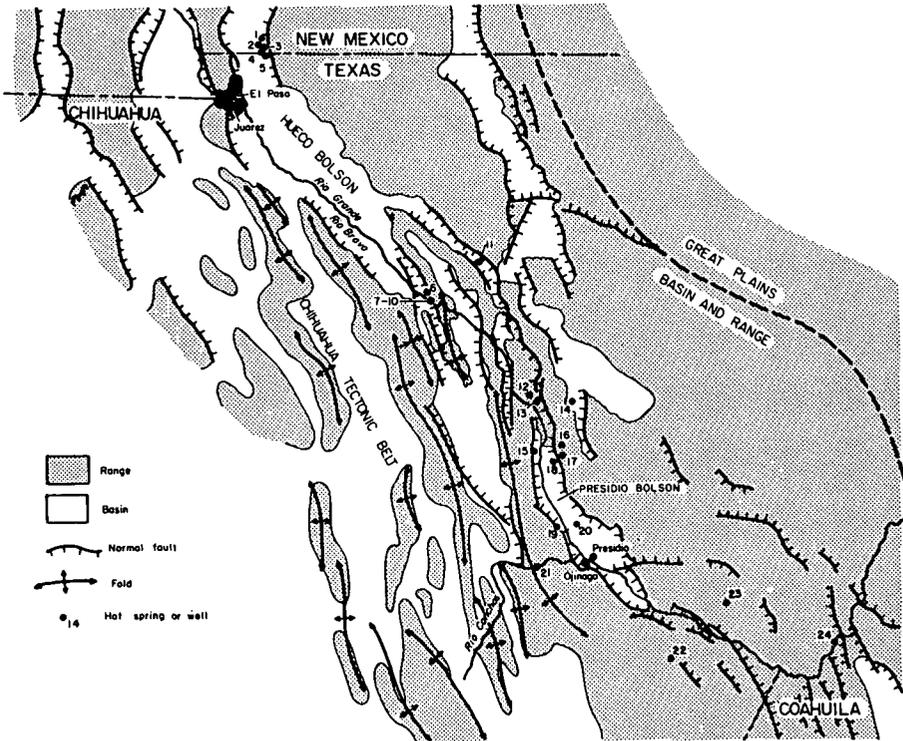


FIGURE 1

STRUCTURAL GEOLOGY, HOT SPRINGS, AND HOT WELLS OF THE RIO GRANDE REGION OF TRANS-PECOS TEXAS, CHIHUAHUA, AND COAHUILA.

greater than about 100°C. The maximum surface or well temperature of thermal waters in other areas is only 47°C; geochemical evidence, discussed below, suggests that their reservoir temperatures are no more than about 60°C.

Geothermal Model

Almost all hot springs occur along normal faults that act as conduits for the rise of hot water from depth. The geothermal water is simply meteoric water that has circulated to a sufficient depth to be heated and then returned to the surface. The hot water rises to the surface because of the hydraulic gradients between areas of recharge and discharge. The hydraulic gradient is controlled primarily by the difference in elevation between recharge area and discharge area but also by the difference in density between cold recharge water and hot discharge water.

Two factors are required to generate the hot springs or wells: a source

TABLE 1
HOT SPRINGS AND WELLS OF THE RIO GRANDE AREA, TEXAS, CHIHUAHUA, AND COAHUILA

Name	Depth	Flow Rate ^b	T°C		Total Dissolved Solids	Chemical Type
			Measured	Calculated		
1 Well N-11*	227 m	—	61	75-105	8,980	1
2 Well M-11*	153 m	—	50	66-96	1,170	1
3 Well N-9*	137 m	—	71	80-110	12,500	1
4 Hot Well*	300 m?	—	—	—	—	1
5 Santa Cruz Well	137 m	—	58	—	7,860	1
6 Red Bull Spring	—	50 l/min.	37	56	960	3
7 Indian Hot Springs	—	400 l/min.	47	60	6,770	1
8 Indian Hot Springs	—	?	44	60	7,280	1
9 Indian Hot Springs	—	?	34	60	7,430	1
10 Indian Hot Springs	—	?	40	60	8,230	1
11 Hot Wells	305 m	—	40	30	300	3
12 Gulf-Swafford	874 m	5700 l/min.	69	135-160	1,700	1-2
13 Gulf-Presidio	958 m	8300 l/min.	72	94-122	1,250	1-2
14 Capote Springs	—	400 l/min.	37	57	330	3
15 Ojo Caliente	—	>1000 l/min.	70-90	102-134	2,240	1-2
16 Nixon Spring	—	3 l/min.	32	65	510	3
17 Briscoe Well	27 m	?	41	60	810	3
18 Kingston Hot Springs	—	75 l/min.	45	55	550	3
19 Rancho Cipres	—	?	35	67	3,920	1
20 Las Cienegas	—	1000 l/min.	30	60	720	3
21 Peguis Spring	—	1000 l/min.	36	35	610	2
22 San Carlos Spring	—	?	32	57	720	2
23 Terlingua Well	232 m	—	42	45	1,300	2-1
24 Hot Springs	—	?	41	36	880	2

*New Mexico

^bFlow of spring or artesian well

^c1 = Na-Cl-SO₄; 2 = Ca-Mg-HCO₃-SO₄; 3 = Na-HCO₃

of heat and permeable flow paths to transport the water to the heat and back to the surface. The source of heat to the thermal waters of Texas and Chihuahua is the Earth's thermal gradient, which is abnormally high in the Rio Grande area. Gradients measured in deep oil tests along the Rio Grande range from 36° to 43°C/km compared with normal values of 20°C/km found in Texas away from the Rio Grande.³ The higher gradient is due to thinning of the Earth's crust and uplift of mantle isotherms by extension during Basin and Range faulting during the last 25 m.y. Circulation of water to a depth of 2 to 3 km in an area with a gradient of 40°C/km would increase the water temperature by 80° to 120°C above its surface temperature.

Magma chambers resulting from recent igneous activity are the source of heat to most commercial geothermal power plants but are not present in the Rio Grande area of Texas and Chihuahua. The igneous rocks present in this area are more than 20 m.y. old and have lost their initial heat. Although very high temperature waters (>200°C) are not restricted to igneous geothermal systems, the lack of young igneous activity suggests that no high-temperature geothermal waters will be found in the Rio Grande area.

Flow paths of geothermal waters consist of three parts: downward movement (recharge), lateral movement in the subsurface, and rise to the surface (discharge). The sites of discharge are readily identified by the presence of hot springs or shallow hot wells. Almost all hot springs in Texas and Chihuahua occur along normal faults that act as conduits for the rise of the hot water from depth. Typically the springs occur along normal faults within or at the edge of sediment-filled basins created by Basin and Range faulting and extension (fig. 1). Thus discharge is localized in relatively small areas.

Areas of recharge and lateral movement in the subsurface are more difficult to identify. Recharge probably occurs in the various mountain ranges adjacent to the basins along the Rio Grande and is spread over a much wider area than discharge. The water then moves laterally through the subsurface and up along faults. Although the subsurface flow paths are not well known, they are probably short. The area is compartmentalized by faults that should restrict lateral flow. Also, the chemical composition of geothermal waters suggests that they have traveled only short distances.

Because most hot springs occur in or adjacent to permeable sediments filling the basins, some hot water could discharge into the sediments

3. Henry, *Crustal Structure Deduced from Geothermal Studies, Trans-Pecos Texas*, in CENOZOIC GEOLOGY OF THE TRANS-PECOS VOLCANIC FIELD OF TEXAS, 19 UT AUSTIN BU. ECON. GEOL. GUIDEBOOK 39-47 (A. Walton and C. Henry, Eds. 1979).

without reaching the surface. Thus, the discharge estimates of table 1 are minimum values. The presence of several hot wells where there are no hot springs both in the Hueco Tanks area (table 1; nos. 1-5) and in parts of Presidio Bolson (table 1; nos. 12 and 13) shows that at least some geothermal circulation is occurring but not reaching the surface. Thus, there may be additional "unexposed" geothermal areas elsewhere in the Rio Grande area.

Geochemistry

The thermal waters generally fall into three chemical groups that can be related to subsurface host rocks: (1) Na-Cl-SO₄ waters that have contacted evaporite deposits or brines; (2) Ca-Mg-HCO₃-SO₄ waters that have contacted carbonate rocks (limestones); and (3) Na-HCO₃ waters that have been in contact with Tertiary volcanic and volcanoclastic rocks and basin-fill sediments derived from the volcanic rocks. The composition of water from several springs and wells is gradational between two types, probably because the waters contacted more than one rock type or because the waters mixed in the subsurface.

The Na-Cl-SO₄ waters have high dissolved solids, ranging up to 12,500 mg/l, and have high concentrations of potassium, lithium, and boron in addition to the three major ions. The composition develops from solution of evaporites, including halite and gypsum, or from incorporation of brines in the geothermal water. Na-Cl-SO₄ waters in the Hueco Tanks area gain their dissolved solids from contact with Permian evaporites or from mixing with brines within Hueco Bolson. Other Na-Cl-SO₄ waters occur in Presidio Bolson and at Indian Hot Springs (fig. 1; table 1); these waters contact Jurassic evaporites in the Chihuahua Tectonic Belt. In general, the highest temperature waters are of this type or a type transitional to the Ca-Mg-HCO₃-SO₄ water.

Ca-Mg-HCO₃-SO₄ waters have moderate dissolved solids (600 to 900 mg/l) resulting from solution of calcite and dolomite in Cretaceous limestones. These geothermal waters occur in the Big Bend area and in Presidio Bolson. Many of the hottest and more dilute Na-Cl-SO₄ waters (table 1; nos. 12, 13, and 15) are intermediate in composition with the Ca-Mg-HCO₃-SO₄ waters. Because waters in these three samples probably contact both limestones and evaporites, they share characteristics of both types.

Na-HCO₃ waters contain low to moderate dissolved solids (300 to 1,000 mg/l) resulting from hydrolysis of silicate minerals or volcanic glass in volcanic rocks. Geothermal waters with this composition occur dominantly in Presidio Bolson and are similar to many cold ground waters in the area.

Chemical Constraints on Use

There are no severe chemical constraints on use of any of the geothermal waters. In general they do not contain excessive trace element concentrations that would require reinjection or other special treatment. However, higher temperature waters, which are more likely to be used, generally have higher dissolved solids than the lower temperature waters (table 1). Fortunately none of the waters have excessively high dissolved solids. The most serious problems would probably be with the high dissolved solids found in waters in the Hueco Tanks area. The waters are too concentrated for most other uses, including irrigation, and disposal could be a problem. Other potential problems include (1) moderately high boron concentrations in the Na-Cl-SO₄ waters, which would preclude their use in irrigation, (2) high fluorine concentrations, which are common in ground water whether hot or cold in Trans-Pecos Texas, and (3) calcite precipitation, which could clog plumbing systems that use the geothermal waters.

Measured and Calculated Temperatures

The hot springs and wells of the Rio Grande area fall into two groups defined by their measured temperatures (table 1). One group has moderate temperatures, up to 47°C; the other group has higher temperatures, up to 90°C. Springs and wells of the first group occur throughout the area, but those of the second group occur only at Hueco Tanks northeast of El Paso and Juarez and in the northern part of Presidio Bolson (table 1; nos. 12, 13, and 15).

Geothermal waters almost invariably lose some heat when they rise to or near the surface. Thus the measured temperature of the water is a minimum temperature, and the maximum temperature of the water at depth may be slightly or significantly higher than the measured value. The maximum temperature can be estimated from the chemical composition of the water, especially its silica concentration, if several assumptions are met.⁴ Unfortunately, because the assumptions are rarely totally met, the temperatures determined from chemical geothermometers are, at best, estimates and are subject to interpretation.

Table 1 lists temperatures calculated from the silica geothermometer based on the interpretation of geothermometry of Henry.⁵ The calculated temperatures for most hot springs and wells are only slightly greater than their measured temperatures, probably because the waters flow rapidly to the surface and have little time to cool. However, several waters,

4. See Henry, *supra* note 2, and Fournier, White, and Truesdell, *Geochemical Indicators of Subsurface Temperatures Part 1: Basic Assumptions*, 2 U.S. GEOL. SURV. J. OF RESEARCH 259-62 (1974).

5. See Henry, *supra* note 2.

particularly the higher temperature ones in the Presidio Bolson area, have calculated temperatures considerably greater than their measured temperatures. Nevertheless, no estimated temperatures are greater than about 160°C, well below what is needed for present electrical generation.

Area Assessment and Conclusion

Only two areas have sufficiently high temperatures for development of geothermal energy: the Hueco Tanks area and Presidio Bolson. Even in these two areas, temperatures are not high enough to generate electricity by currently available technology.

In the Hueco Tanks area, maximum water temperatures are probably about 100°C. The water may be usable for space or industrial heating, particularly because of its proximity to El Paso and Juarez. High dissolved solids in the water preclude its use for most other purposes and may present some problems of disposal. However, since Rio Grande water in the El Paso–Juarez area also has relatively high dissolved solids, disposal into the Rio Grande may be feasible. A major uncertainty is the amount of water available. Hydrologic testing to determine water availability is necessary before it can be considered a significant resource.

Maximum temperatures in Presidio Bolson are at least 100°C and possibly as high as 160°C. This is the only area with conceivable potential for electric power generation; however, even here it is highly unlikely. Water from the Gulf Wells and Ojo Caliente (table 1; nos. 12, 13, and 15) have moderate dissolved solids that should not preclude any uses. High rates of artesian flow from the Gulf Wells suggest that water for non-electrical uses is abundant. However, the extremely low population density in the area makes such use unfeasible. The only major population center, Ojinaja-Presidio, is 100 km to the south. Transportation of the hot water this distance is impractical. A geothermal resource for these towns would need to be found much closer.

Potential trans-boundary problems are few. Because each geothermal flow system is small, they should not overlap the border. Development of a geothermal resource in one country should not lead to depletion of the resource in the other country. Disposal of geothermal water containing high dissolved solids concentrations into the Rio Grande could be a problem.

GEOPRESSURED GEOTHERMAL SYSTEMS OF SOUTH TEXAS, TAMAULIPAS, AND NUEVO LEÓN— INTRODUCTION

Over the past decade significant progress has been made toward delineating and describing alternate energy sources associated with geopressured sediments of the Gulf Coast region. Research efforts, primarily

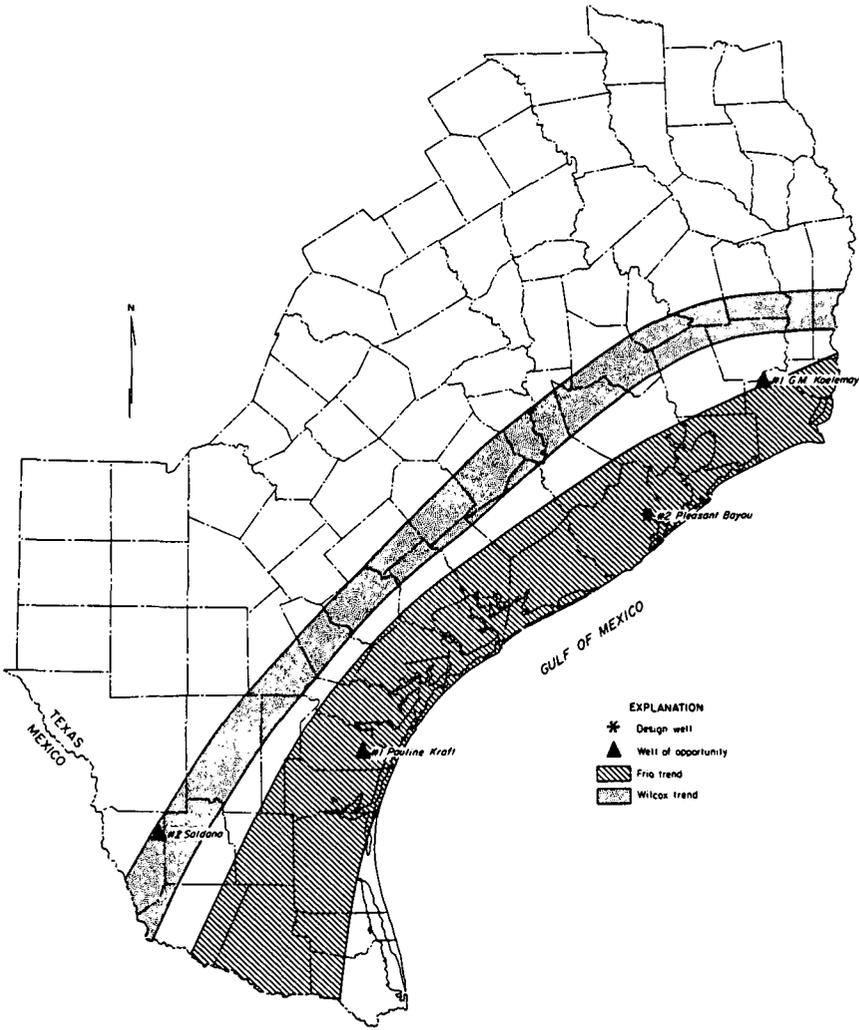


FIGURE 2

PROSPECTIVE AREAS OF GEOPRESSURED-GEOTHERMAL SEDIMENTS WITHIN THE WILCOX AND FRIO PRODUCING TRENDS AND THE LOCATIONS OF TEST WELLS IN TEXAS.

funded by the U.S. Department of Energy, have recently led to the identification of several areas (fig. 2) that appear favorable as sites for production of geothermal resources, including methane dissolved in hot brines. Several prospective areas are located in the lower Rio Grande Embayment, where some of the highest temperatures and pressures and lowest

salinities have been measured.⁶ Potential areas of geothermal resource development undoubtedly extend into Mexico, although specific sites have not been identified.

Estimates of in-place methane resources for the Gulf Coast region vary widely, but even conservative estimates of 5,700 Tcf⁷ represent a substantial target for new gas supplies from an area where the infrastructure for exploration and marketing is well developed. Moreover, the geopressured energy resources have direct applications where moderate temperatures and methane are used for drying and refining processes. The burgeoning industry in the lower Rio Grande Valley would lend itself to development of geopressured energy if wells could sustain high rates of production for extended periods. However, it appears unlikely that high-volume water production will be achieved soon from individual wells in this area.

Geologic Setting

Depositional and structural styles of the Gulf Coast region are typical of sedimentary basins where deltaic systems are fed by drainage of continental proportion. These basins receive enormous volumes of clastic detritus, mainly as wedges of sand and mud, that are characterized by thick sequences comprising three major lithofacies (interbedded sand and shale, massive sandstone, and massive shale). Within each clastic wedge, time correlative units as well as vertically stacked sequences exhibit an orderly succession of lithologies related to depositional environment. The upper interbedded sands and shales, massive sandstones, lower interbedded sands and shales, and massive shales closely correspond to fluvial, proximal delta/strandplain, distal delta/shelf, and prodelta/shelf and slope environments that are found progressively farther from shore and in deeper water.

When deposited, the massive shales of deep-water origin have low densities and are water saturated. These properties together with sediment loading cause unstable conditions that initiate and sustain movement of faults, slumps, and diapirs. Such features are prominent where rapid deposition occurred along shelf margins. Most major growth faults were formed contemporaneously with rapid deposition and were located near the depocenters, thus causing substantial thickening of the sedimentary

6. Wallace, Taylor, and Wesselman, *Use of Hydrogeologic Mapping Techniques in Identifying Potential Geopressured-Geothermal Reservoirs in the Lower Rio Grande Embayment, Texas*, 1 PROCEEDINGS: THIRD GEO-PRESSURED GEOTHERMAL ENERGY CONFERENCE G11-G188 (1977).

7. Dorfman, *Evaluation of Natural Gas from Geopressured Zones*, 7 AMER. GAS ASSOC. GAS SUPP. REV. 1-4 (1978).

sequence. Both progradational and aggradational processes were responsible for infilling the basin; however, thickest deposits formed during regressive (progradational) episodes. Regional transgressions of considerable duration were also important in basin development because they record periods when deltaic sedimentation was minor while marine deposition, primarily shale, was widespread.

With increased time and depths of burial, the sediments were subjected to increased temperatures and pressures; they also underwent diagenetic alterations that included stages of compaction, cementation, and commonly, leaching of cements and mineral grains. The thick shale sections formed permeability barriers that retarded or prevented the migration of fluids normally expelled from the compacting sediments. Pore waters trapped beneath these permeability barriers became abnormally pressured by the weight of the overburden and acted as thermal barriers by reducing heat flow through the sediments.

Regional Trends

Although most Tertiary sediments of the Gulf Coast Basin are geopressed at great depths (4 to 5 km) and contain some gas in solution, the Wilcox Group (Eocene) and the Vicksburg and Frio Formations (Oligocene) are the primary candidates for exploitation of entrained methane along the Texas-Tamaulipas border. These geothermal corridors (fig. 2) are also prolific oil and gas producers owing to the vast number of sandstone reservoirs that have structural and stratigraphic closure. Miocene deposits that underlie eastern Cameron County and extend offshore (fig. 3) also contain potential geothermal reservoirs.

Reservoir Continuity

The sandstone reservoirs that produce hydrocarbons also serve as potential geothermal aquifers. Massive sandstones that occur stratigraphically throughout the Tertiary section and cover a broad area (fig. 3A) mark the positions of former nearshore deposition. Most of these sand bodies were originally deposited in distributary channel or delta-front environments, or as strandplains and barrier islands in interdeltic areas. When originally deposited, many of these sand bodies formed extensive aquifers with considerable lateral extent.

Today, however, reservoir continuity is controlled not only by depositional environment but also by growth faults that are ubiquitous in the Gulf Coast Basin. The structural style of the lower Rio Grande Embayment is dominated by growth faults and attendant fold development, shale ridges, and shale diapirs. Geopressed aquifers in the area are best

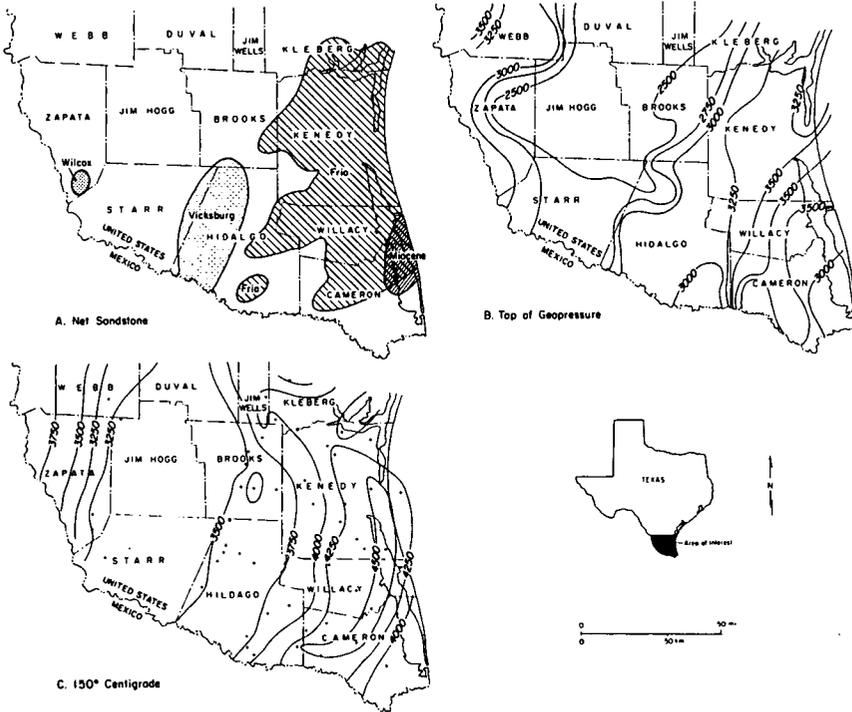


FIGURE 3.

GENERALIZED MAPS FOR SOUTH TEXAS showing (A) areas where Upper Wilcox and Miocene net sandstone thickness exceeds 150 m and where Vicksburg and Frio net sandstone thickness exceeds 300 m; (B) subsea depth to the top of geopressure (15.8 kPa/m); and (C) subsea depth to 150°C isotherm. Depths in meters. Data modified from Gregory, Dodge, Posey, and Morton, *Volume and Accessibility of Entrained Methane in Deep Geopressed Reservoirs—Tertiary Formations of the Texas Gulf Coast*, UT AUSTIN BU. ECON. GEOL. REP. TO THE DEP'T OF ENERGY 387 (Div. Geothermal Energy Contract No. DE-AC08-78ET01580 (1980)).

developed where they are intersected by regional structural trends, such as the Wilcox fault zone, Vicksburg–Frio flexure, and McAllen fault system. As a result, areal extent of sandstone reservoirs is limited.

Reservoir Quality

Flow characteristics of methane-bearing aquifers depend mainly on porosity and permeability; rock compressibility can also affect production after reservoir pressure declines. Primary porosity and permeability are

inherited from the depositional environment; however, these primary properties are altered as the rock compacts and is cemented.

To some degree, porosity and permeability are related to age, but more importantly, they are related to depth of burial, degree of compaction, and consolidation history. Perhaps the most important of the known processes is secondary leaching, which can significantly improve the porosity of geopressured reservoirs.⁸

Reservoir quality is also affected by sandstone composition. Along the south Texas coast and extending into Mexico, sandstones of the Vicksburg and Frio Formations contain more volcanic and carbonate rock fragments and feldspar than Frio sandstones of the upper Texas coast, which contain more quartz and less feldspar. In contrast, sandstones of the middle Texas coast are intermediate between the other two extremes.⁹ Because unstable rock fragments are abundant and the regional thermal gradient is high, geopressured sandstones near the Rio Grande delta generally exhibit low porosities and permeabilities and poor reservoir quality compared with the upper Texas coast and Louisiana.

Fluid Properties

The solubility of methane in geopressured aquifers depends chiefly on formation temperatures, fluid pressures, and formation water salinities.¹⁰ The regional distribution of each parameter is independent of the others, but each depends at least partly on regional and local geological conditions.

Subsurface temperatures and temperature gradients for Tertiary sandstone reservoirs generally increase gulfward and southwestward along the Texas coast (fig. 3C). Temperature gradients are greatest in the structurally active Rio Grande Embayment. Field measurements from thousands of wells indicate that fluid temperatures in the geopressured zone range from 93° to 149°C, but bottom-hole temperatures greater than 175°C are rarely encountered even at present drilling depths.

Geopressures, or pressure gradients, in excess of 10.5 kPa/m are controlled more by facies changes than by depth of burial. The top of geopressure occurs near the base of the massive sandstones and within the underlying sands and shales. Because pressure gradients are related to these lithologic changes, depths to the top of geopressure progressively

8. Loucks, Dodge, and Galloway, *Sandstone Consolidation Analysis to Delineate Areas of High Quality Reservoirs Suitable for Production of Geopressured Geothermal Energy*, EG-77-05-5554 U.S. DEPT. OF ENERGY CONTRACT REP. 98 (1979).

9. Bebout, Loucks, and Gregory, *Frio Sandstone Reservoirs in the Deep Subsurface Along the Texas Gulf Coast*, 91 UT AUSTIN BU. ECON. GEOL. REP. OF INVESTIGATIONS (1978).

10. Blount, Price, Wenger, and Tarullo, *Methane Solubility in Aqueous NaCl Solutions at Elevated Temperatures and Pressures*, ET-78-5-07-1716 U.S. DEPT. OF ENERGY CONTRACT REP. 38 (1979).

increase to a maximum and then decrease in a seaward direction (fig. 3B). Depths generally range from 1,800 to 3,600 m in older onshore sediments,¹¹ whereas depths as great as 5,450 m and as shallow as 900 m are encountered in younger sediments beneath the Louisiana shelf.¹²

These repetitious patterns of increasing and decreasing depth to geopressure across the coastal plain and continental shelf are associated with each major depositional cycle except the Wilcox Group. For Wilcox sediments, the top of geopressure progressively decreases from 3,900 to 2,400 m in a downdip direction.¹³ Pressure gradients below the top of geopressure range from hydrostatic (10.5 kPa/m) to near lithostatic (22.6 kPa/m), depending on the depth of interest and the local geological conditions.

Along the lower Rio Grande, equilibrium formation temperatures of 150°C are encountered at depths ranging from 3,200 to more than 4,000 m (fig. 3C), and pressure gradients approaching 15.8 kPa/m occur at depths ranging from 2,500 to 3,500 m (fig. 3B). As expected, the subsurface distribution of these properties closely parallels major structural and stratigraphic trends.

For example, highest temperatures and pressure gradients occur at relatively shallow depths in eastern Zapata and Webb Counties, as well as eastern Starr and central Brooks Counties. These geopressed geothermal highs coincide respectively with the Wilcox and Vicksburg fault zones. Similar relationships are observed in western Cameron and Willacy Counties where the Frio Formation is highly faulted.

Formation water salinity is probably the least understood but most important factor that governs methane solubility. Despite numerous conceptual models, a hypothesis explaining salinity patterns has not emerged. According to log calculations, salinity variations are extreme even within an area and at most depths. Systematic changes in salinity with depth or within a stratigraphic unit have been explained by dissolution of buried evaporites, membrane filtration by clay minerals, or gravity separation induced by tectonic stresses. Because of these and other reports, low salinities were generally expected below the top of geopressure; however, sandstone aquifers specifically tested for geothermal resources have yielded waters with salinities ranging from 10,000 to more than 200,000 mg/l.

11. Bebout, Loucks, and Gregory, *supra* note 9; see also Bebout, Weise, Gregory, and Edwards, *Wilcox Sandstone Reservoirs in the Deep Subsurface Along the Texas Gulf Coast: Their Potential for Production of Geopressed Geothermal Energy*, DE-A505-76ET28461 U.S. DEPT. OF ENERGY CONTRACT REP. 219 (1979).

12. See Wallace, Taylor, and Wesselman, *supra* note 6.

13. See Bebout, Weise, Gregory, and Edwards, *supra* note 11.

TABLE 2
GEOPRESSURED GEOTHERMAL WELL TESTS IN TEXAS

	Well		
	<i>General Crude—DOE Pleasant Bayou No. 2</i>	<i>Lear Petroleum G. M. Koelemay No. 1</i>	<i>Riddle Oil Co. Saldana No. 2</i>
County	Brazoria	Jefferson	Zapata
Formation	Frio	Yegua	Wilcox
Depth	4466 m	3552 m	2972 m
Porosity	18%	20%	16%
Permeability	150 md	—	7 md
Temperature	149°C	125°C	149°C
Pressure	76,245 kPa	64,735 kPa	45,726 kPa
Salinity	132,000 mg/l	15,000 mg/l	13,000 mg/l
Gas/Water	5.2m ³ /m ³	6.3–7.0 m ³ /m ³	5.9–9.0 m ³ /m ³
CO ₂	10.5%	6.2%	20%

However, chemical analyses of produced formation fluids indicate that deep subsurface waters in the lower Rio Grande Valley are generally low in total dissolved solids (see table 2).¹⁴

Preliminary Test Results

Design Well Program

The first well specifically designed and drilled to test geopressured geothermal resources, General Crude Oil/Department of Energy Pleasant Bayou No. 2 (fig. 2), penetrated 200 m of sandstone with temperatures greater than 149°C. The perforation interval of the producing well (4,463 to 4,482 m) coincides with the massive portion of a relatively thick sandstone interpreted as a bed-load fluvial channel.¹⁵ In situ properties of this geothermal reservoir are given in table 2.

The reservoir was tested at rates up to 3,500 m³ of water per day with only a minor pressure decline. Pressure drawdown and buildup curves indicate that no permeability barriers were encountered within 4.8 km of the well bore. Gas to water ratios for this large aquifer ranged from 3.78 to 5.22 m³/m³.

14. Swanson, Oetking, Osoba, and Hagens, *Development of an Assessment Methodology for Geopressured Zones of the Upper Gulf Coast Based on a Study of Abnormally Pressured Gas Fields in South Texas*, E(11-1)-2687 ERDE CONTRACT 75 (1976).

15. See Bebout, Loucks, and Gregory, *supra* note 9.

Wells of Opportunity

In addition to the design well, short-term tests have been obtained from two other wells in Texas (fig. 2, table 2) and six wells in Louisiana. These wells were originally drilled for conventional hydrocarbons and abandoned as noncommercial prior to testing for solution gas from geopressured aquifers. The objective sands ranged from early Eocene to late Miocene in age; temperatures ranged from 112° to 149°C; pressures ranged from 45.7 to 91.1×10^3 kPa; salinities ranged from 13,000 to 191,000 mg/l; and gas concentrations ranged from 3.6 to 9.0 m³/m³ of water. The test results show that formation waters are saturated with respect to methane at in situ conditions. Moreover, the tests indicate relatively high concentrations of CO₂.

Status of Development

Despite favorable formation properties near the Texas–Mexico border, the Riddle Saldana No. 2 test (fig. 2, table 2) of entrained methane was discouraging because low permeabilities prevented the necessary production of large water volumes. Swanson and others¹⁶ reported that permeabilities for South Texas geopressured sandstones rarely exceed 10 md and are frequently less than 1 md. They also reported that some aquifers would not produce water because the effective permeabilities are extremely low. This condition has resulted in tight gas sand designations for certain reservoirs in the area. The added price incentives and massive hydraulic fracturing are necessary even for conventional gas production. Consequently, Swanson concluded that development of geopressured geothermal energy was unlikely and that even if development were technologically feasible, commercialization would require gas prices considerably above rates for extant gas contracts. Although large-scale development is unlikely, geopressured geothermal resources could be economically competitive with other alternate energy sources if technology (1) improves well stimulation techniques, (2) develops lower temperature heat converters, or (3) increases gas to water ratios of produced fluids.

Although some sandstone reservoirs may be continuous across the border, growth faults and shale diapirs have disrupted most reservoirs so that they are areally limited. Moreover, permeabilities are so low that development in one country should have no effect on geothermal reservoirs in the other country. High salinities in the geothermal fluids will generally require subsurface disposal.

16. See Swanson, Oetking, Osoba, and Hagens, *supra* note 14.

RECURSOS GEOTERMICOS DE LA FRONTERA TEJANA-MEJICANA

Los potenciales recursos geotérmicos de la región fronteriza tejana-mejicana incluyen 1) sistemas geotérmicos convectivos que se encuentran en el área trans-Pecos de Tejas, en Chihuahua, y en Coahuila, y también 2) sistemas geotérmicos geopresionados ubicados en el sur de Tejas, en Tamaulipas, y en Nuevo León, los cuales contienen metano. Los sistemas convectivos se caracterizan por manantiales y por someros pozos calientes situados a lo largo de las fallas geológicas. La temperatura máxima de estos sistemas llega a un nivel medido de 90 grados centígrados, y la máxima, calculada a base de geotermómetros químicos, alcanza los 160 grados C. La mayoría de las temperaturas no suelen llegar a estos niveles. Ningún agua de estos sistemas es de calor suficiente para producir electricidad. Las de temperatura más alta podrían usarse para calefacción industrial o del hogar, salvo que las aguas del área de Hueco Tanks, en la vecindad de El Paso y Juárez, se encuentran demasiado lejos de los centros de población.

Areniscas terciarias que se formaron a grandes profundidades bajo el superficie en Tejas y en el noroeste de Méjico contienen sustanciales cantidades de energía térmica y de metano. El metano ocurre en forma de gas libre, pero la mayor parte se encuentra como gas disuelto en salmueras calientes y sobrepresionadas. La solubilidad del metano tiene relación directa con la temperatura de su formación y con la presión del fluido, y tiene relación inversa a la salinidad del agua de formación. Algunas pruebas de producción de los acuíferos geopresionados en Tejas han producido 5.2 hasta 9.0 m³/m³ de gas compuesto principalmente de metano, y que también contiene CO₂ en cantidades que fluctúan entre seis y 20 por ciento. Estas relativamente pequeñas concentraciones de gas indican que las aguas de formación están saturadas de metano bajo condiciones de depósito. Las bahías de la región estuarina del Rio Grande muestran algunas de las temperaturas y presiones más altas, y salinidades más bajas del litoral del Golfo Méjico. Este es un área que favorece el desarrollo de la energía térmica y la producción de gas inconvencional; pero al mismo tiempo, los depósitos de agua son de calidad inferior a causa de la permeabilidad insuficiente. Por consecuencia, el desarrollo comercial de estos recursos alternativos de energía dependerá en gran parte en el aumentado desarrollo de la tecnología nueva de conversión de calefacción, estimulación de pozos, y de aumentación de la proporción de gas en el agua.