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Eastern Geothermal Resources: Should We Pursue Them?

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With our increasing dependence on imported oil, it has become prudent to continually reexamine our domestic energy resources. Coal and nuclear energy, which are technically and economically viable energy sources today, are likely to be subject to increasing regulatory restrictions as a result of environmental and political issues. Therefore, a great deal of effort and funding have been expended by industry and government in a highly diversified pursuit of alternate energy sources. Thus far, however, no one source has been found to hold promise as a panacea for replacing imported oil in the near future. It is time to recognize the very real possibility that there may not be a single source of energy that can satisfy all our needs. Our national energy policy should be directed toward stimulating the development of the energy source that is most suitable economically, technically, environmentally, and politically for each application.

Summary. A geothermal resource that consists of hot water at moderate temperatures (below 125°C) underlies many areas in the central and eastern United States. Programs funded by the Department of Energy have revealed that this resource is definable and economically competitive with conventional fuels for use in direct heat applications. The resource, therefore, has the potential for reducing our dependence on the imported oil used for space heating. However, front-end costs and risks to explore, drill, test, and evaluate the magnitude of the resource have inhibited development. The question is, therefore, how much federal stimulation will be needed to convince private capital to exploit this widespread low-quality energy source.

Geothermal resources, where technically and economically viable, are attractive because they are generally not in conflict with political and environmental issues. For the San Francisco area, for example, this energy source is the most economical method of producing electricity, and plans for its growth far exceed those for other resources in that area.

In the 37 states east of the Rockies, there are no known geothermal resources that can produce electricity in the near term. Water at moderate temperatures, however, does exist at shallow depths in many areas of the central and eastern United States and can be used directly for residential space heating, agriculture, district heating, and industrial processing. Of all the forms of geothermal energy, this moderate temperature, hydrothermal resource is the most widespread and does not require the development of any new exploitation technology. If this hot water can be economically recovered, it has the potential for substantially reducing our use of imported oil.

To determine the viability of these resources, an assessment of the deep hydrothermal flow regime is required to target regions of high fluid saturation, temperature, and enhanced permeability. The resources will then need to be proven by a drilling program and a demonstration of the resource utility.

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Types of Resources

The resources discussed here are those that can be used for direct heat applications and not simply the use of groundwater as a reference for heat pumps. Most direct heat applications commonly require temperatures above 45°C, which, based on the variations in the earth's geothermal gradient, can occur at depths between 1 and 2 kilometers. Several categories of resources exist. A classification system for eastern geothermal resources (Table 1) must differ from the generic one used in the West, which is based on the type of heat source (*1*). Since most heat sources in the East are not known, the resources require a different basis for classification.

Since water is the likely medium to be used for extracting heat from rock, eastern resources can be divided into two categories based on the availability of naturally occurring water: hot, dry rock (HDR) and hydrothermal systems (see Table 1). Hydrothermal systems can be divided into two categories, which differ in their respective mechanism for the transfer of heat, conduction versus convection.

The dominance of one or the other of these methods of heat transfer is a function of the geologic environment. Conduction will be the main heat transfer mechanism unless the correct conditions exist for convection (for example, temperature difference and fault zones). Hydrothermal resources that are conduction-dominated can cover large areas and include lithostatically pressured (geopressured) and hydrostatic aquifers. The heat in these fluids is derived from direct contact with the rock; vertical circulation is not extensive. Convection-dominated resources are more local in extent but can circulate large quantities

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Table 1. Classification of geothermal resources in the eastern United States (see Fig. 1).

Sedimentary basins	Examples
Hot, dry rock systems	
Conduction from concentration of radioactive material beneath veneer of insulating sediments	Buffalo, New York, Appalachian Basin; Peoria, Illinois, Illinois Basin; Wallops Island, Virginia, Atlantic Coastal Plain
Basement crystalline complex	
Deep, thick sedimentary units	
Hydrothermal systems	
Conduction-dominated	
Hydrostatic aquifers	
Unconsolidated sediments	Atlantic and Gulf Coastal Plains
Sedimentary rock	
Primary permeability	Madison Limestone–Williston Basin
Secondary permeability	Oriskany Sandstone–Appalachian Basin
Lithostatically pressured aquifers (geopressured)	Gulf Coastal Plain; Anadarko Basin
Convection-dominated (adiabatic circulation)	
Fracture-fault zone	Hot Springs, Arkansas
Fault-fed aquifers	Rough Creek Fault, Illinois Basin; Champlain Valley, New York

of water from great depths to shallower depths. These two mechanisms represent end-member situations; many real systems may be combinations of both mechanisms.

There are very few known geothermal resource areas in the central and eastern United States, aside from the warm springs that occur in the folded and faulted parts of the Appalachian and Ouachita mountain forelands, which extend from New York to Arkansas. Most of these springs have temperatures only slightly above the mean annual temperature of the groundwater, but some do contain water at temperatures above 60°C. In the past, certain of these resources have been used for agriculture, bathing, and space heating. However, because of their relatively low temperatures and isolated locations, these occurrences are not attractive candidates for widespread development. The favorable aspects of this type of resource are that the resource temperatures are well known, the flow rates are large and easily measured, and no new technological development or extensive resource confirmation program is required.

What is most significant about these resources, aside from their regional occurrence, is the physical process that they demonstrate: the ability for water to circulate naturally to depths greater than 3 km in the Paleozoic rocks of the Appalachian Basin (*2*), absorb heat from the rocks, and bring the heat to the surface as a natural heat-exchange medium. This phenomenon, if it exists elsewhere or at greater depths, could produce highly favorable conditions for geothermal energy utilization.

All of the sedimentary basins of the eastern United States where deep drilling has occurred are known to contain hot waters at depth (Fig. 1). The Tuscaloosa Formation, which underlies Alabama and other Gulf states, contains water at temperatures of 50°C at depths of 1.2 km (*3*). Water from wells drilled into the Tuscaloosa has been used at health spas at Dothan, Alabama, for more than 40 years. Similarly, the Madison Limestone in the Williston Basin, which underlies much of the western Dakotas, contains water at 37° to 73°C (*4*). The heat may be due to above-average heat flow or natural fault-controlled, deep-circulation processes evident at the Appalachian warm springs.

This association of hot water in the deeper parts of many sedimentary basins in the central and eastern sections of the United States is the result of the following favorable geologic characteristics: (i) local or subregional areas of above-average heat flow; (ii) sedimentary sequences that commonly contain multiple horizons of permeable strata that serve as aquifers or reservoirs; (iii) deep aquifers that are commonly insulated from the surface by thick layers of shale or other horizons with low thermal conductivity; and (iv) fractured horizons, fault zones, and solution zones that locally increase the permeability. The following facts also make many of the eastern sedimentary basins an attractive exploratory frontier: (i) extensive subsurface exploration (including drilling) and geophysical surveys provide a large data base for geothermal exploration; (ii) proven mechanical models exist for locating zones of enhanced permeability in sedimentary basins (*5*); and (iii) drilling techniques and costs are known.

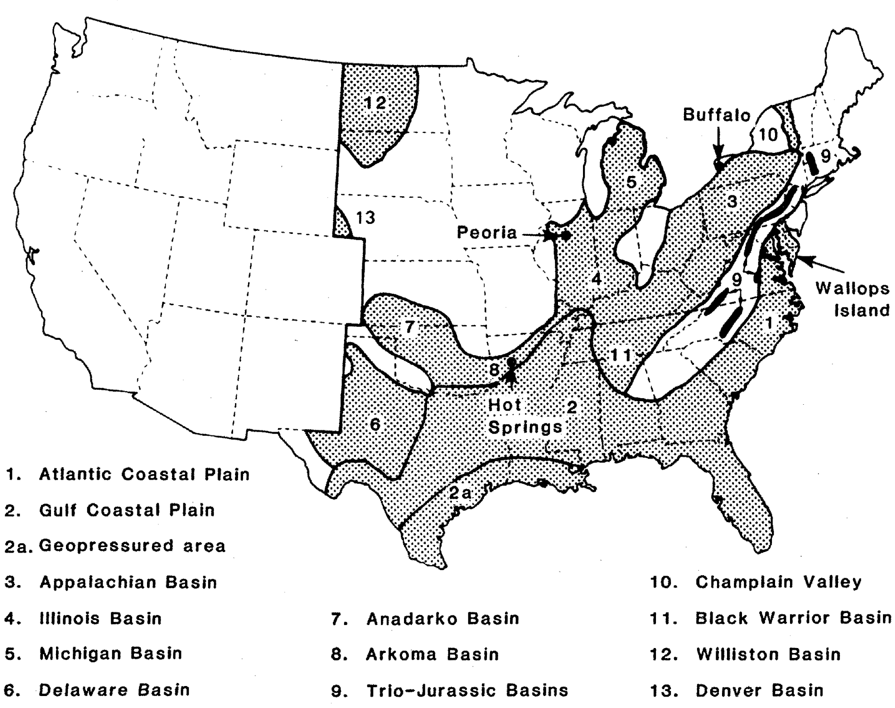

Fig. 1. Sedimentary basins of the central and eastern United States.

Nature of the Resource

The geothermal resources that are the focus of this article are the hydrothermal brines that occur naturally at depths of thousands of meters in the sedimentary basins in the central and eastern United States (Fig. 1). In order for these hydrothermal basin brines to be useful in meeting our energy demands, they must be easily extractable and be of sufficient extent to ensure a long life for the resource. Sedimentary formations with good primary permeabilities (connecting systems of intergranular voids) may contain an extensive reservoir of hot water. However, when buried to great depths, most sedimentary horizons become relatively impermeable because of compaction and cementation.

In addition to primary permeabilities, secondary phenomena, for example, dissolution and fracturing, may provide the greatly enhanced permeabilities needed for fluid extraction. Solution cavities are common in easily dissolvable carbonate formations or carbonate-cemented clastic formations (sandstones). Fracturing occurs most extensively along fault systems and in the more competent and brittle formations (siliceous facies or dolomite) and can produce permeabilities of 35 darcys (*6*). In recent years the petroleum industry has recognized the significance of fractures (*7*) and the occurrence of fractured reservoirs restricted to particular fracture facies (*8*). The existence of fracture facies in sedimentary basins and our ability to locate and map them increases the potential of finding appropriate conditions for the extraction of hydrothermal energy.

The deep hydrologic regime of sedimentary basins has not been extensively evaluated. Recent investigations (*5*) of the hydrothermal and structural evolution of the Appalachian (Paleozoic) and Newark (Trio-Jurassic) basins have provided an insight into the occurrence of brines. These investigations revealed that many fracture zones in the sedimentary and basement rocks of sedimentary basins remain open at great depths and provide channels for the occurrence and circulation of brines. Although common on old fractures, hydrothermal minerals of Mesozoic and Cenozoic age were rarely observed to fill the younger fracture zones. The orientations, magnitudes, and locations of these circulation-controlling fracture systems can be determined. These conclusions are supported by exploratory oil and gas drilling results, which document the open nature of naturally occurring vertical fractures and the dominant role they play in fluid migration (*9*).

However, the argument can still be made that some channelways at depths of 1 to 2 km may have become sealed over long periods of time. If this is true, large circulating systems may exist only in areas of active subsurface faulting where fault zones are continuously reopened. In the central and eastern United States, only a few areas provide well-documented evidence of recent faulting near the surface (*10*). However, several deep sedimentary basins are noted for their recurrent seismicity, for example, the Illinois Basin, Newark Basin, Champlain–Hudson Valley Basin, and parts of the Appalachian Basin. In these areas, the focal depths for the majority of earthquakes indicate that faulting is occurring at shallow depths, less than 4 km (*11*), thus continuing to reopen fracture and fault zones and enhancing the permeabilities. In addition to seismicity, the high differential horizontal stresses that have been measured throughout the northern Appalachian Basin as well as the mid-continent (*12*) ensure that fractures and faults remain open at depth and allow for the continual circulation of brines.

In general, the temperatures of basinal brines and the enclosing rock increase with depth, but the rate of increase, the geothermal gradient, varies laterally. The average thermal gradient of the crustal rocks in the eastern United States is between 15° and 25°C per kilometer. This gradient is the product of heat flow from within the earth and the thermal conductivity of the rocks through which the heat flows. Birch *et al.* (*13*) showed that the flow of heat measured at the surface is a combination of heat flow from the mantle and heat generated in the crust. It is believed that this heat is generated by the breakdown of minor amounts of radioactive elements such as uranium, thorium, and potassium; where these elements are concentrated, higher heat flow results. Such heat-producing elements are found in thick sequences of shales, large disseminated uranium deposits, and some granitic intrusions. Where the heat source is covered by a kilometer or more of cap rock of low thermal conductivity, the heat is insulated from the surface and a potential thermal resource exists.

Bottom hole temperatures have been recorded in hydrocarbon exploratory wells throughout the sedimentary basins of the United States. Using these data, a joint committee of the American Association of Petroleum Geologists and the U.S. Geological Survey has produced a map of subsurface temperatures across much of the United States (*14*). Even if there are significant errors in the individual temperatures and variations in the recording methods, the trends shown on this map, which are commonly based on hundreds or thousands of points, must be fairly indicative of realistic values of subsurface temperatures.

In addition to identifying areas of above-average subsurface temperatures, hydrocarbon exploration has provided a great deal of information on stratigraphy, structure, reservoir fluids, and production characteristics. Drilling records indicate intersections with highly permeable, fractured aquifers that produced large amounts of artesian flow. In some areas, 15 barrels (1 barrel = 159 liters) of water are produced for every barrel of oil. These data can be used to model the potentiometric surface of deep aquifers, to interpret rate and direction of flow, and to estimate amounts of circulation along fault zones (*15*).

Interior Basins

High subsurface temperatures and an appropriate thickness of sediments with low thermal conductivity necessary for conduction-dominated hydrothermal resources occur in parts of the Appalachian, Illinois, Anadarko (Oklahoma), Arkoma (Arkansas), Williston (Dakotas), Michigan, Black Warrior (Alabama), and Delaware (Texas) basins (Fig. 1). Carbonate horizons (for example, Knox Formation, Lockport Dolomite, Madison Limestone) that occur in these mid-continent, Paleozoic sedimentary basins contain extensive networks of solution cavities that serve as channelways for basinal brines. Similar channelways occur along fracture zones in nonsoluble units such as the Potsdam, Oswego, and Oriskany sandstones in the Appalachian Basin, which are potentially good gas and water producers (water has flowed from wells at the surface at 1850 liters per day) (*16*). Complex fault-controlled circulatory systems also occur at depth in these basins. Bond (*15*) identified the mixing of formation waters in the Illinois Basin between horizons at elevations a kilometer apart. He concluded that circulation driven by increased buoyancy caused by thermal effects occurs along major vertical fault zones. Such convection-assisted systems are certainly expected since the process is so well illustrated in the convection-dominated systems of the Appalachian foreland. In areas of extensive subsurface data, the locations of aquifer systems are well known. But, in general, little evaluation of the deep basin hydrothermal flow regime has been done. Such a study should be the focus of further research.

Coastal Plains

The Atlantic and Gulf coastal plains also provide favorable locales for hydrothermal resources. Only limited subsurface data exist for the coastal plain sedimentary sequence between New York and Florida, since it is not a petroleum province. Much more is known for the coastal plains between Florida and Texas. These sequences are largely semi- to unconsolidated sands, silts, and clays and are water-saturated. Because of the lack of cementation, the availability, extractability, and recharge of water is controlled largely by primary permeabilities and may be locally uniform within any one lithologic unit. Data from deep wells in these areas indicate that the lower Cretaceous units have permeabilities on the order of hundreds of millidarcys (*17*). These are low values relative to aquifers with good secondary permeabilities, but, depending on the thickness and extent of the aquifer, these units may be productive for years. Geothermal resource targeting programs at Virginia Polytechnic Institute and State University have been directed toward an investigation of the Atlantic Coastal Plain for the past 3 years as part of the Department of Energy (DOE) resource assessment program. Under the direction of J. Costain, investigators have been developing and refining a geophysical targeting model for locating radiogenic, heat-producing plutons beneath the sedimentary sequence (*18*).

Fault-Bounded Basins

The Trio-Jurassic sedimentary basins that occur beneath and west of the Atlantic Coastal Plain also hold promise. These basins, which occur in New York, New Jersey, Connecticut, Massachusetts, Pennsylvania, Maryland, Virginia, North Carolina, and South Carolina, consist of thick sequences (up to 3 km) of consolidated sandstones and shales and are bordered, dissected, and underlain by major fault systems (*19*).

The permeabilities of the sedimentary rocks within these basins are generally controlled by fracturing both parallel to and at high angles to the bedding planes. Permeabilities along the fault zones can range from high to low, depending on the state of alteration. Some fault zones in the basins and at the borders are not permeable since they are well mineralized or contain gouge. However, this is not universally the case. Brecciated zones along the Ramapo border fault of the Newark Basin in New Jersey and New York are hundreds of meters wide and are "open," allowing for the vertical circulation of water (*20*). Abundant mineralization occurs on these faults, but these minerals have been fractured after their growth, thus reopening the fault zone. The evidence suggests that the main hydrothermal circulation and mineralization episode followed diabase intrusion 165 million years ago (*21*) and was associated with major faulting that continued into the Cenozoic (*22*). Present shallow seismicity along the fault system indicates that the faults are active and open at depth today (*11*). Uranium concentrations occur in the adjacent and underlying Precambrian gneisses as well as in the local roll-front type uranium deposits within the overlying sandstone horizons of the basin. These radiogenic, heat-producing deposits are in some areas insulated by thick sequences of low-conductivity mudstones and shales.

The Champlain-Hudson Valley, which occurs on the eastern border of New York and the western borders of Massachusetts and Vermont, is underlain by a thick sequence (possibly 3 km) of Paleozoic sediments. Major north-south to northeast faults with large dip-slip components border the valley on the west. These faults are thought to have as much as 2 to 3 km of vertical displacement across them. Neotectonic investigations (*23*) in this region suggest that these faults may still be active. The north-south basin coincides with one of the main regional seismic trends in New England and the southward projection of the highest thermal gradient area in the east. Within this valley and in the vicinity of Saratoga, New York, springs, which are along a major fault trend, yield carbonated water (diluted basinal brines). Putnam *et al.* (*24*) have geochemically analyzed these waters and concluded that a shallow heat exchange zone on the order of 100°C should exist within the basin.

Application of the Resource

The temperatures expected to be encountered in the upper 3 km of the crust in the eastern United States will not be high enough to generate commercial amounts of electricity (200°C water is probably needed for this application). Therefore, the most widespread use of the water could be for space heating of residences, office buildings, or industrial complexes. Typical temperatures found in a household are 65°C for domestic hot water and 45°C for circulated hot air.

A recent market study, conducted on the northern half of the Atlantic Coastal Plain, identified potential users of a low-temperature geothermal resource (*25*). In the Delmarva Peninsula, the largest and most compatible energy consumer is the poultry industry. The yield from several geothermal wells could be used in evisceration plants for scalding and cleanup. Other large appropriate industries are vegetable and seafood processing; grain, timber, and tobacco drying; and small bottling companies. Two undeveloped industries that may be attracted to an area where cheaper energy is available would be greenhouse nurseries and fish farming.

The technology for using moderately hot water is available today. A combination of water well and oil field technology would be required. Downhole pumps are available from the oil industry and are being used in similar resource settings (TRW-Reda pumps in the Paris Basin) (*26*). Surface heat exchangers and distribution systems are analogs to those now in use for economic district heating systems in Sweden. In the disposal of the cooled brine by means of reinjection wells, we can use the experience gained from deep liquid waste disposal projects of the past dozen years. A tutorial narrative describing the steps necessary for the development and application of geothermal energy has been prepared for several of the eastern states (*27*).

Economics

Economics play a large part in the successful application of any resource. Retrofitting existing facilities can prove to be much more costly than the initial designing for the hydrothermal resource. A low-temperature resource may not be effective in a conventional radiator; however, in designing a new facility, expanded radiators could easily be installed.

A recent report (*28*) analyzed the cost of using the hot water beneath the Atlantic Coastal Plain of Delaware, Maryland, New Jersey, and Virginia to determine how this process compares with fossil fuel combustion for space heating. Wellhead costs (appropriate for site-specific industrial uses) and delivered costs were determined for three types of residential communities (single family residences, garden apartments, and condominiums).

The wide range of information needed for this study revealed the importance of data on site-specific geologic and economic conditions. The significant conclusions were that geothermal energy on the Atlantic Coastal Plain can be used in the residential sector at costs below those for electrical-resistance space heating, and, in some cases, at costs only slightly above current oil and natural gas prices (1978 prices). Favorable industrial situations should allow for use of the resource at costs well below current prices for traditional fuels. It can therefore be inferred from these conclusions that, in areas of geothermal resources, no other alternate source can compete economically with geothermal energy.

Risks and Impediments to Geothermal Exploration and Development

If the results described above are appropriate for resources occurring in large portions of the central and eastern United States, why then are these resources not being expeditiously developed by industry? To answer this question, one must realize that in any exploration program there are considerable risks and there are always impediments to development.

The basic risks are those attendant during the exploration phase. Subsurface exploration for energy sources is always risky because it is expensive to drill to great depths into unknown environments. Targeting programs are commonly conducted to reduce the amount of risk prior to drilling. However, these programs can also become expensive when surficial geophysical techniques are used. A successful geothermal well requires that a horizon be intersected that contains both ample heat and water. Therefore, even with a targeting program, there are still large risks that are site-specific and require drilling and testing. Tests of reservoir performance and water quality must also be conducted to determine if the well shows enough promise for further development. The yield and the life expectancy of the resource must be estimated.

Additional difficulties that can impede the development of hydrothermal resources include the following:

1) In many states the legal framework is not conducive to the development of geothermal energy. Few laws exist in the eastern states to define the owner of the resource and the person who has a charter to develop it. Without these definitions, development may become ensnarled in prolonged litigation. The National Council of State Legislators under contract to DOE is presently assisting Delaware and Virginia in producing a favorable legal framework for geothermal energy development.

2) Education of the public, lawmakers, regulators, and industrial leaders is needed to reveal the existence and attractiveness of geothermal resources.

3) Front-end costs for drilling, pumping, distribution, and a reinjection system (where necessary) decrease the attractiveness of exploration, although life-cycle costs are quite competitive with conventional energy sources.

4) Venture capital is difficult to find for low-quality energy that can be used only for site-specific applications.

5) Environmental rules and permit regulations have not been written for geothermal activity; existing laws are often too strict or are not appropriate.

6) Maintenance problems and costs of operation are not known for the types of hydrothermal systems expected in the central and eastern United States.

Several programs to remove the impediments are under way. However, the completion of a demonstration project may be required.

Advantages

In a development situation where attractive economics are balanced by unknown risks, other qualities of an enterprise become important. One of the most attractive aspects of geothermal energy is that it is an indigenous resource to many eastern states. Other attributes include the following: (i) It may be considered a renewable resource; (ii) once installed, the price is stable; (iii) the supply is secure if the resource is properly managed; (iv) there is little or no environmental hazard expected; (v) the resource is available in many energy-poor states; and (vi) many potential resource areas coincide with population centers.

The advantages of geothermal energy development should be attractive. It might behoove us, therefore, to investigate ways to remove the risks and impediments in order to stimulate the widespread development of this resource.

Programs to Stimulate Development

Under the direction of DOE, several programs are presently under way that are aimed at reducing the risks and impediments. However, the main cause for the present lack of investor confidence results from a general lack of knowledge of the resource itself. The following questions need to be answered for each resource area: (i) the location of the prospective resource, (ii) the quality of energy (extractable heat) as a function of depth, (iii) the ease of exploitation (aquifer performance), (iv) the quality of the water, and (v) the life of the resource (water plus heat). These questions can only be answered by exploration, drilling, and testing programs.

The main variable involved in developing an exploration strategy is to determine the amount of applied research needed to target the drilling site. An argument can be made that the best way to stimulate geothermal development is to expend funds on immediate wildcat drilling. This view, based on what we already know about the subsurface in many areas from hydrocarbon exploration, emphasizes the importance of test data in proving a resource. The approach suggests limiting the targeting phase and proceeding with the drilling and testing phase.

An alternate approach has been followed in the ongoing DOE program for the Atlantic Coastal Plain. Under this program, a deep well has recently been drilled after 3 years of targeting studies. This particular area, however, had not been explored extensively for oil or gas, and little was known about subsurface temperatures or the geothermal potential. With such limited data, an extensive targeting program to develop basic data was needed in this new frontier (*18*).

The program in the Atlantic Coastal Plain concentrated on identifying areas geophysically that might prove to be good heat sources. Other new frontiers for subsurface exploration (for example, the Champlain Valley and the Mesozoic basins) may also require heat source targeting programs. However, this approach is not necessary in the interior basins of the United States (for example, the Illinois Basin), because areas of high subsurface temperatures are already known from hydrocarbon exploration. In these basins, a deep test well may be very profitably drilled and tested without long-term targeting programs.

What needs to be known and evaluated in these areas of high subsurface temperatures is the availability of easily extractable water. Instead of heat source investigations, therefore, an analysis of the deep hydrothermal flow regimes is needed prior to selecting a site for drilling. This analysis is necessarily limited by the data available from drilling and should require a much shorter time to complete than heat source evaluations.

The following two-pronged program is designed to assess the deep hydrologic and thermal regimes of the sedimentary basins and consequently reduce the risks associated with geothermal exploration in all the sedimentary basins of the eastern United States. First, targeting programs should be continued and expanded in areas considered as new frontiers. Second, and more important for near-term energy demands, hydrologic studies of deep sedimentary basins should be made in areas of high subsurface temperatures to locate zones of fluid saturation and enhanced permeabilities as an aid in selecting drill sites. These studies should be followed by a major drilling and pump testing program in areas where a population center coincides with these three favorable geologic conditions (heat, water, and enhanced permeability). Such a program could be initiated immediately and could produce results that may be beneficial to 20 of the 30 eastern states. A phased program could call for drilling to begin in 1981 on the most favorable resource areas, with all attractive areas assessed by 1986.

Such a plan has recently been developed (*29*). The program called for in the plan is not costly. It could be done in conjunction with other programs of exploratory drilling, for example, the Eastern Gas Shales Project, continental drilling, and waste disposal. Personnel of the state geologic surveys could perform much of the work during their basic data-gathering programs. Costs could be shared by potential users. However, federal funding, organization, and stimulation could help guarantee a systematic approach. The exploratory drilling program should then be followed immediately by a demonstration project at a key resource area to help remove operational, legal, and other impediments to development. It would be important for the demonstration to deal with all legal and environmental requirements to clear the way for further developments by private enterprise.

Conclusions

This general discussion identifies some of the evidence of hydrothermal or geothermal resources in many of the central and eastern parts of the United States. Enough evidence exists to warrant a thorough investigation of this potential. The economic attractiveness and national need for domestic energy sources justify the need for such an exploratory program.

To fairly evaluate the resource, it will be necessary that many wells be drilled; this drilling must be preceded or accompanied by a series of geologic, geophysical, and hydrologic tests. This is the only way that some of the risks attendant upon the development of these reservoirs can be removed. After identifying favorable resources through the drilling program, the remaining impediments to development can be reduced through the experience gained from a demonstration project in which the resource is used for residential or industrial space (or process) heating.

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From Diyls to Ylides to My Idyll

Georg Wittig

Chemical research and mountaineering have much in common. If the goal or the summit is to be reached, both initiative and determination as well as perseverance are required. But after the hard work it is a great joy to be at the goal or the peak with its splendid panorama. However, especially in chemical research—as far as new territory is concerned—the results may sometimes be quite different: they may be disappointing or delightful. Looking back at my work in scientific research, I will confine this talk to the positive results (*1*).

Some 50 years ago I was fascinated by an idea which I investigated experimentally. The question was how ring strain acts on a ring if an accumulation of phenyl groups at two neighboring carbon atoms weakens the C–C linkage and predisposes to the formation of a diradical (for brevity called diyl) (Fig. 1). Among the many experimental results (*2*) I choose the synthesis of the hydrocarbons **1** and **4** (*3*), which we thought capable of diyl formation. Starting materials were appropriate dicarboxylic esters, which we transformed into the corresponding glycols. While these were obtained under the influence of phenylmagnesium halide only in modest yield,

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