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GEOHERMAL RESOURCE ASSESSMENT OF THE
NEW ENGLAND STATES

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TABLE OF CONTENTS

<u>TOPIC</u>	<u>PAGE</u>
Introduction	1
Results of the Survey	3
Summary of the Geologic History of New England	4
Tectonic Setting	6
Bourguer Gravity Anomalies in New England	10
Seismicity	14
Lineament Patterns in New England	20
Heat Flow	21
New England Ground Water Resources	27
Use of Ground Water as an Energy Source	30
Thermal Springs in New England	31
Lebanon Springs - Sand Springs Area of New York and Massachusetts	32
New England Water Well Temperatures	40
Specific Regions of Initial Interest	40
The White Mountain Region	45
The Narragansett Basin	46
The Connecticut Valley	48
The St. Johnsbury Thermal Anomaly	52

LIST OF FIGURES

		<u>PAGE</u>
Figure 1	The New England States	2
Figure 2	Location of Major Structural Features in New England	7
Figure 3	Recorded Seismic Events in New England from 1534 to 1977	16
Figure 4	Recorded Seismic Events in New England for period October 1975 to June 1978	17
Figure 5	Distribution of Mapped Faults in New England	19
Figure 6	Major Lineaments in New England	22
Figure 7	Heat Flow in New England	25
Figure 8	Geologic Cross Sections in Western Massachusetts	34
Figure 9	Geothermal Gradients in Western Massachu- setts and Adjacent New York and Vermont	37
Figure 10	The Mesozoic Basin of the Connecticut River Valley	49

LIST OF TABLES

		<u>PAGE</u>
Table 1	Heat Flow in New England	4
Table 2	Chemical Analyses of Springs in Williamstown, Massachusetts	36
Table 3	Silica Contents and Water Temperatures	38
Table 4	Temperature Gradients	39
Table 5	Partial Chemical Analyses in ppm of Waters from Selected Wells in New England Bedrock	41,42
Table 6	Water Temperatures from Selected Bedrock Wells of Massachusetts	43,44

Geothermal Resource Assessment of the New England States

Introduction

On July 1, 1980, a two year program to conduct an assessment of the geothermal resource potential of the New England region (Fig. 1) was initiated under contract DE-FC07-80RA50272 between the Department of Energy and Amherst College of Amherst, Massachusetts, at a funding level of \$65,000. Subsequently a six month no-cost extension was granted to terminate the study at the end of 1982. Most of the field work was conducted during the summer months, with laboratory work and literature searches being pursued during the academic year.

Even though, for geologic reasons, there appeared to be only a small possibility that hydrothermal geothermal resources might occur in the region, the existence of warm springs in western Massachusetts, the abnormal radioactivity in certain plutonic rocks in the region, and the high population and industrial density justified a survey at a low level of funding.

Since modern day earth scientists, except for hydrologists and ground water geologists, pay little or no attention to springs and their characteristics, it was necessary to go back and pursue the early geological literature concerned with New England and this in itself raised a problem. Early investigators wrote in a most prosaic style and rarely had indices in which specific features were listed, so often it was necessary to read an entire work in search of clues to

FIGURE 1: The New England States

springs of unusual character. Within these works the location of features are also vague and frequently given in terms of the current land owner and structures.

Early visits were made to the offices of the State Geologist, the State Energy Office, and the Water Resources Division Office of the U. S. Geological Survey, in search of information relating to springs and wells in the region. Compilation of geological and geophysical data have been made and compared in search of areas that could serve as targets for more detailed investigations.

Results of the Survey

With the exception of Sand Springs in Williamstown, Massachusetts, there are no identifiable hydrothermal geothermal resources in the New England region. The radioactive plutons of the White Mountains of New Hampshire do not, apparently, contain sufficient stored heat to make them a feasible target for an induced hydrothermal system such as exists at Fenton Hill near Los Alamos, New Mexico. The only potential source of low grade heat is the large volume of ground water contained within the unconsolidated sediments related to the Pleistocene glaciation of the region.

During the course of the survey an unusual and unexplained thermal anomaly was discovered in St. Johnsbury, Vermont, which is described towards the end of this report.

Summary of the Geologic History of New England

The oldest exposed rocks in New England (Plate I) are part of the Grenville Group of Precambrian age and crop out in the core of anticlinal uplifts in western Vermont, Massachusetts and Connecticut. These rocks contain a long history, which includes repeated periods of sedimentation, deformation, metamorphism and intrusion. Rocks of Grenville age are believed to underlie virtually all of New England. The Grenville orogeny ended about 950 million years ago.

In Late Precambrian time rifting of the landmass containing the Grenville rocks occurred producing what some geologists term the "proto-Atlantic" ocean. Late Precambrian and Early Paleozoic sediments and volcanic material were deposited forming a continental shelf, slope and rise. Present day western New England contains rocks that were probably formed on the continental slope, with volcanic island arcs farther to the east. Continued erosion of the land mass to the west and north permitted the encroachment of the ocean westward creating large epeiric seas covering most of New England and the region to the west by Late Cambrian time and into Ordovician time.

The "proto-Atlantic" ocean began to close by Middle Ordovician time and deformation commenced with the advent of the Taconic orogeny. This deformation caused folding, thrusting, uplift and granodiorite intrusions of the Oliverian and Highlandcroft Magma Series (Plate II). The orogeny affected northern Maine and western New England and adjacent New York east of the Hudson River producing an elevated land mass. Erosion and sedimentation produced another sequence of continental margin sediments in Silurian and Devonian times but situated farther to the east in cen-

tral Vermont, Massachusetts and Connecticut.

All of New England was again subjected to intense deformation (the Acadian orogeny) during Late Devonian time, producing intense metamorphism and intrusion of the New Hampshire Magma Series (Plate II). Erosion of the resulting mountain chain produced deltaic deposits that spread over much of the region during Pennsylvanian time. Large swampy areas developed on the deltaic deposits ultimately producing coal. These deposits are preserved today in Rhode Island and adjacent Massachusetts in the Narragansett Basin (Plate I).

In Late Pennsylvanian time or Early Permian time deformation again affected the region during the Appalachian orogeny, which in New England caused the folding, low grade metamorphism and granitic intrusion (Narragansett Pier granite) in Rhode Island and eastern Connecticut and Massachusetts.

Rifting began in Late Triassic time as a result of regional warping and associated faulting. Nonmarine, red fluvial and dark lacustrine sediments and basalts filled the rift valleys and basins into Jurassic time, creating the rock sequence now preserved in the Connecticut River Valley of Massachusetts and Connecticut and a much smaller basin in southwestern Connecticut.

In Late Jurassic time the present Atlantic Ocean began to open and the present continental shelf, slope and rise began to develop. While the oldest dated rocks in the shelf pile are of Jurassic age the oldest exposed rocks (at Martha's Vineyard) are of Cretaceous age. Associated with the opening of the Atlantic Ocean was the formation of a large group of calderas during Jurassic and Cretaceous time. The calderas and associated volcanic activity were centered in the middle of New Hampshire

forming the alkalic igneous rocks of the White Mountain Magma Series (Plate II).

With the end of the volcanic activity the New England region has been subject to erosion with the exception of the advance of continental glaciers during Pleistocene time. The terminal morraines of the last advance are found in Massachusetts on Cape Cod, Martha's Vineyard and Nantucket Island. With the retreat of the ice sheet glacial till and lake deposits were spread unevenly over the entire region.

Tectonic Setting

The entire region of New England is essentially the northern extension of the Appalachian Mountains orogenic belt which in New England has been divided by Zen (1968) into several broad zones. (Fig. 2). Each of the zones forms a tectonically distinct geologic unit and usually has a distinct stratigraphy. It is perhaps easiest to discuss the zones from west to east across the structural grain of New England.

The westernmost zone associated with the Appalachian orogenic belt lies mostly outside of New England. This zone, termed the foreland, consists of rocks that are chiefly Cambrian to Middle Ordovician quartzites and carbonate rocks overlain by Middle Ordovician shale. The zone is to the immediate west of the orogenic belt and includes the rocks in the Hudson Valley and the Champlain lowland. The degree of deformation is very slight but increases to the east.

A north-south trending belt of metamorphosed Lower Paleozoic carbonate rocks forms the next zone, termed the Middlebury-St. Albans Synclinoria. The rocks correlate lithologically and stratigraphically

FIGURE 2: Location of major structural features in New England

with those of the foreland. They have, however, undergone two periods of deformation (the Taconic and Acadian orogenies). To the south the rocks are folded recumbently. The degree of folding diminishes northward and in western Massachusetts and Vermont the rocks are broken by thrust faults (Plate I). Within this belt of folded and faulted rocks is a zone of allochthones that slid into place from the east. They represent a facies that is intermediate between the platform sequence of the foreland and volcanic-bearing eugeosynclinal rocks. During Middle Ordovician time these masses slid into their present position as submarine "sheets", and are composed of rocks that range in age from Cambrian to Middle Ordovician.

The next zone eastward is dominated by large massifs of Precambrian rocks. In the New England region they are the Green Mountain massif (Vermont) the Berkshire massif (Massachusetts) and the Housatonic and New Milford massifs (Connecticut). They are the cores of large anticlinoria, the limits of which extend beyond the exposures of the Precambrian rocks.

The next zone to the east of the massifs consists of eugeosynclinal Paleozoic rocks that are intensely sheared, folded and metamorphosed to varying degrees. These comprise the western limb of the Connecticut Valley-Gaspe synclinorium. In New England this zone can be subdivided into two subzones. The western subzone consists of a homoclinal sequence dipping eastward off the massifs. The eastern subzone consists of domes superimposed upon isoclinal and possible recumbent folds. Ultramafic rocks are associated with both subzones.

The same eugeosynclinal sequence of rocks is exposed in the next zone, the Bronson Hill Anticlinorium, but here the structure consists

of a series of knappes with a second line of gneiss domes superimposed on the nappes. The domes extend from northwestern New Hampshire to Long Island Sound.

The Merrimack Synclinorium comprises the next zone. It extends from northern Maine through central New Hampshire into eastern Massachusetts and Connecticut. Stratigraphically, rocks of this zone correspond to those in the Connecticut Valley-Gaspé Synclinorium from which they are separated by the gneiss domes of the Bronson Hill Anticlinorium.

The coastal belt is composed of a heterogeneity of eugeosynclinal rocks containing a large volume of volcanic and nonmarine rocks. These are probably of Ordovician, Silurian and Early Devonian age. There are also rocks of possible Precambrian age in southwestern New England.

Superimposed on these zones of pre-Arcadian rocks are two sequences of younger non-marine rocks, namely the Pennsylvanian age Narragansett and Boston basins and the Triassic-Jurassic age basin of the Connecticut River Valley. Both of these sequences probably covered most of New England at the time of deposition but have subsequently been removed by erosion.

The zones outlined above, with the exception of the Triassic-Jurassic basin, have been variously affected by one or more orogenies since the beginning of Paleozoic time, and evidence of additional orogenic events can be found in the Precambrian rocks. The Paleozoic orogenic events provide a useful reference for gross division of the stratigraphic column as used on the geologic map (Plate I).

The Taconic orogeny affected rocks of Cambrian and Ordovician age, so rocks of those ages are grouped as one unit on the geologic map.

This orogeny was apparently long lived, beginning in isolated localities in the Middle Ordovician and may include some events that occurred as late as Late Silurian time. The time between the Taconic and Acadian orogenies is represented by the deposition of Silurian to Middle Devonian rocks in New England. The Acadian orogeny had far greater effect on New England than either the Taconic or the later Appalachian orogenies, producing a higher grade of metamorphism and a large volume of plutonic rocks, which persisted from preorogenic to post-orogenic time. It was also responsible for the formation of the synclinoria and anticlinoria and the formation of most of the nappes. The Appalachian orogeny affected the late Paleozoic rocks of eastern Massachusetts and Rhode Island.

The Triassic-Jurassic detrital and volcanic rocks are confined to the partly fault-bounded basin in central Massachusetts and Connecticut, are unmetamorphosed and therefore truly post orogenic. Thus in New England the late tectonic events appear to be restricted to high-angle faulting accompanied by volcanism and the emplacement of the White Mountain Magma Series.

Bouger Gravity Anomalies in New England

The first gravity map of the region was prepared by Longwell (1943) and covered a portion of southern New England. It was followed by a map and report by Woolard (1948) covering most of New England. These, and subsequent more detailed investigations (Bean, 1953; Joyner, 1963; Bromery, 1967; Diment, 1968; Kane and Bromery, 1968; Kane, 1970) have been combined by Kane et al. (1972) to produce a Bouguer gravity map

of the region. The gravity map accompanying this report (Plate III) is a modification of the map of Kane et al. (1972).

Negative gravity values are dominant throughout New England and exceed -70 milligals in northwestern Massachusetts, southeastern Vermont and central New Hampshire. Positive gravity values exceeding +40 milligals are located in southwestern Connecticut and in the Cape Ann region north of Boston (Plate III).

Gravity trends are mostly north-south in western and southern New England and shift to a northeasterly trend in the rest of the region becoming most pronounced in Maine. The diversity in trend correlates in a general way with lithology and structure (Plate I).

Regional gravity anomalies are considered to be the result of variation in crustal thickness (Kane et al., 1972). Local anomalies appear as a sharp steepening of gradients and local closure of isogals. In New England the best defined cause of local, steep anomalies are masses of plutonic rock, the most common being felsic plutons associated with gravity lows. The pile of sedimentary rock in the Narragansett and Boston Basins does not produce a gravity low, probably as a result of the low grade metamorphism that accompanied the Appalachian orogeny. Likewise, the thick pile of post-tectonic sediments in the Connecticut River Valley does not give any indication of there being an associated gravity low probably due to their thorough cementation (in part of section by iron carbonate and iron oxide) and the presence of lava flows.

The regional gravity field correlates well with major geologic features, with gravity highs overlying broad areas of uplift and the lows over broad areas of subsidence and deposition (Longwell, 1943; Woollard, 1943). Two of the regional lows occur over large felsic plutons, one

being the White Mountains of central New Hampshire within the Merrimack Synclinorium and the other in extreme northeastern Vermont within the Connecticut Valley-Gaspe Synclinorium.

The correspondence between tectonic features and major gravity features is apparent on a large scale, but does not hold in detail as noted by Diment (1968). Note, for example, the offset of gravity and tectonic highs in extreme western Massachusetts. It would seem, therefore, that the regional anomalies are caused by major crustal or crust-mantle structures of considerable vertical extent that are sometimes masked by geologic features within the upper crust such as the multiple thrusting of thin crustal sheets in western New England.

The predominate regional features of the western part of New England are the positive linear gravity high and the adjacent gravity low to the west (Plate III). Diment (1968) concluded that the principal cause of the high is the relative uplift of dense lower crust material while the low results from the depression of less dense crustal material into the more dense mantle. The gravity field in extreme western New England shows a range in gravity values over the relatively short distance of 125 km from + 40 mgals in southwestern Connecticut to - 65 mgals along the New York-Massachusetts border. This is in sharp contrast to the range/distance relationship in the rest of New England.

Another regional gravity low is more subdued and narrower than that in extreme western New England and occurs along the southern Vermont-New Hampshire border and extends into central Massachusetts. This low corresponds well with the Bronson Hill Anticlinorium which is composed of mantled gneiss domes and nappes. While local gravity lows appear

over the domes, the more extensive feature is probably the result of the presence of a broad band of low density felsic material at depth below the anticlinorium.

The regional trend of the gravity field in the eastern two thirds of New England is northeast and parallel to the principal trend of the Appalachians. The regional field diminishes northwestward from the Gulf of Maine to the Canadian border. In Maine the local variations in the gravity field are associated with differences in lithologies, except in southeastern Maine over rocks that lie within the sillimanite isograd. (Plate III). Local gravity lows with sharp closure occur over Devonian age plutons. The large, elongate gravity low in northern Maine along the International Boundary is associated with the lower Paleozoic rocks of the Connecticut Valley-Gaspé Synclinorium. In southwestern Maine, most of New Hampshire, eastern Massachusetts, eastern Connecticut and western Rhode Island there is little correspondence between gravity lows and the Devonian age plutons. This large area of New England contains rocks that have been metamorphosed to sillimanite grade. Thompson and Norton (1968) have concluded that rocks within the sillimanite isograd were buried to at least 20 km based on metamorphic mineral equilibria. Exposure of these rocks at the surface may well indicate that the deep erosion accompanying uplift has removed most of the Devonian age felsic plutons. The deep gravity lows over the White Mountains are caused by the plutons of Jurassic and younger age which postdate the metamorphic event.

There is also a notable correspondence between gravity lows and topographic highs over much of New England, suggesting that the highlands are isostatically balanced by low density masses at depth. A major exception is the gravity low associated with the Green Mountain-

Sutton Mountain anticlinorium and the gravity low just westward over the Lake Champlain lowland. Since both of these regions are underlain by masses of complexly overthrust sheets of rock it is presumed that the crust in this region possesses enough lateral strength so that the load imposed by the overthrust sheets (the anticlinorium) is supported by the underthrust sheet (the lowland).

Seismicity

The level of seismicity, and the accordingly varied earthquake intensity, varies greatly from place to place in the northeastern United States. Although the region does not lie in a belt of major seismic activity, many earthquakes have been recorded since arrival of the first European settlers, and one area, Moodus, Connecticut, was sacred to the Indians because of the numerous tremors occurring there. The largest recorded seismic event (estimated intensity of VIII) occurred off Cape Ann, Massachusetts in 1755. Currently about 30 to 40 earthquakes are recorded yearly in the New England region.

Within New England there are certain areas (Figure 3) of higher seismicity which appear to have remained stable over the last 300 years according to available historical records (Hadley and Evine, 1974). Recent, more accurately measured earthquake epicenters (Figure 4) for the period from October 1975 to June 1978 (Chiburis et al., 1978) fall within those areas of higher seismic activity in central New Hampshire and southern New England. However, the rate of activity within the areas of higher historical seismicity has been varied. For example, the area around Boston and Cape Ann was active in the first half of the Eight-

eenth Century but has been quiet in more recent times. (Compare Figures 3 and 4).

Sbar and Sykes (1973) discussed the concentration of epicenters between Boston and Ottawa, Canada and suggest that the epicenters form a seismic zone. While it appears that a clustering of epicenters forms a zone from the north end of Lake Champlain to Ottawa, extension to the southeast is far from certain. The area of north-trending clustering of epicenters in eastern New Hampshire and the low seismicity belt of Vermont and Western Massachusetts conform to the regional structural trend and cut across the proposed Boston-Ottawa seismic belt of Sbar and Sykes.

A number of different causes have been called upon to explain the seismic activity in New England. Isostatic adjustment following deglaciation, stress accumulations at the borders of bodies of mafic rock due to density contrasts, reservoir filling and faulting have all been suggested as the possible causes for the seismic activity. None of these suggested causes can fully explain the distribution pattern of New England earthquakes, however.

Isostatic rebound due to ice unloading is certainly possible for the cause of some of the events, but in two areas of high seismic activity along the Maine coast the crust is sinking. The largest concentration of mafic rocks in New England lies within the belt of low seismicity of Vermont. Earthquakes do appear to be spatially related to the Mesozoic calderas in New Hampshire. The filling of the large Quabbin Reservoir in central Massachusetts has not generated any noticeable change in the local seismic activity. Movement along fault segments is considered the most likely cause of the earthquakes. Fault plane solu-

FIGURE 3: Recorded seismic events in New England from 1534 to 1977 (From Barosh et al., 1979)

FIGURE 4: Recorded seismic events in New England
for the period October 1975 to June 1978.
(From Chiburis et al., 1978)

tions made from seismograph records from New England also suggest indirectly that the earthquakes originate on faults. However, there is no record of any surface fault movement accompanying a New England earthquake and nowhere in the literature is there any mention of an active fault. Since detailed mapping in New England has only begun in the 1930's there is not enough information available to reveal a basic tectonic pattern. Eastern Massachusetts and Connecticut are now known to be highly faulted and the rest of southern New England is probably equally as faulted (Figure 5). As for northern New England there has been little detailed mapping, but where it has been completed suggests that faults are abundant. The present evidence suggests major northeast zones of faulting across New England, with north and northwest trends being less abundant.

Major problems arise when attempting to date faults or periods of faulting. Many of the mapped faults in New England are of a compressional nature and are of Paleozoic age (225 to 600 m.y.), which may have been selectively reactivated. Also, there are very few areas of Mesozoic (65 to 225 m.y.) rock and virtually no Tertiary (1.8 to 65 m.y.) rocks, and where they do exist they are mantled by glacial till. The age of faults that cut the Mesozoic rocks is unknown but must predate the Cretaceous peneplanation that affected all of New England.

It would appear that areas of high seismicity are associated with zones of known or probable faults, but not with the zones of Paleozoic age compressional faults found in western New England. Zones of Mesozoic age high angle extensional faults are in some cases areas of high seismicity: the Champlain lowland, the southern Connecticut River Valley, the Narragansett Bay area, and the White Mountains of New Hampshire.

FIGURE 5: Distribution of mapped faults in New England

Except for seismic events in and near the White Mountains, the active areas of the New England region that have been instrumentally recorded occur in lowlands, bays, and major river valleys. These geomorphic features are directly related to the geology of the region. The lowlands are underlain by weak or soft rocks or have formed by extensional faulting and subsidence. Historic earthquake activity in New England therefore may be related to extensional faulting and may indicate minor rifting (Barosh, 1979).

Lineament Patterns in New England

The Mesozoic basins of Connecticut were studied by Hobbs and the first lineament maps were prepared in 1901, 1904, and 1911. He was among the first to recognize the existence of regional topographic lineaments. This pioneering work drew much attention and disbelief. More recently D. U. Wise and his students at the University of Massachusetts, Amherst, have been conducting fault, fracture and lineament studies in New England, particularly in western Massachusetts and Connecticut.

Wise (1976) noted that throughout New England the most pronounced linears are oriented N20E, N25W and N70E, of which the N25W set is the most pervasive. These linears cross all major tectonic boundaries in New England and hence must post-date the Paleozoic metamorphic events and the Late Paleozoic to Middle Mesozoic basin and caldera formation.

Comparison of the linear trends (Figure 6) and the faults of the

region (Figure 5) clearly shows that the topographic linears are not great fault lines. However, Truesdell and Wise (1975) show that the linear trends correlate with small (up to a few meters displacement) fault orientations in a restricted area of western Massachusetts. Whether this correlation holds throughout all of New England is unknown at this time.

Wise (1976) interprets the linears in New England as beginning as incipient faults of a few tens to a few hundreds of kilometers of length following regional stress trajectories. They may become small faults, fault zones or zones of more intense development of joints. In the case of joint concentrations the joints need not parallel the zone itself, but merely be more intensely concentrated within the zone. Once formed these linears will maintain their existence, even penetrating sedimentary cover, by concentrating along them tidal strains, younger tectonic strains or the effects of propagation of seismic waves. At the surface the zone, be it fractured or faulted, provides easy access for ground water and deeper weathering to allow etching and preservation as elements of the topography.

Heat Flow

To date there have been seventeen heat flow measurements completed

FIGURE 6: Major lineaments in New England (after Wise, 1976)

within the New England States. A detailed discussion of the thermal history is contained in Birch et al. (1968). The locations of the heat flow sites are given in Table 1 and Figure 7. The geologic distribution of the sites shows that the majority have been confined to Paleozoic-Mesozoic plutonic rocks in New Hampshire (eight), Massachusetts (two) and Maine (two). The three sites in Vermont are located in the Precambrian core of the Green Mountain anticlinorium. Of the twelve sites positioned in plutonic rocks three are located in the highly radioactive Conway granite (185 m.y.) of the White Mountain Magma Series, and the remainder in New England rocks of the New Hampshire Magma Series (360 m.y.). The highest heat flow values (Q) in New England are found in the Conway granite and the lowest in the Precambrian rocks of Vermont.

Since the bulk of the heat flow determinations in New England have been made in New Hampshire from rock of Devonian age or younger, Birch et al. (1968) have postulated a thermal history for New England (i.e., New Hampshire) beginning with Lower Devonian time. At that time there already existed in New Hampshire about 10 km of Ordovician and Silurian sediments deposited over a span of 100 m.y. Starting in Devonian time the rate of deposition increased and 15 km or more of deposits accumulated over a span of 50 m.y., which was followed by deformation, uplift and intrusion of the New Hampshire Magma Series comprising the Acadian orogeny. Erosion and uplift continued throughout the rest of Paleozoic time. During Triassic time another period of volcanism began in New England accompanied by the emplacement of the White Mountain Magma Series of which the Conway Granite represents the final phase. Since that time New England has been subject of slow uplift and erosion with a minor interruption during the Pleistocene glacial advance.

TABLE 1
HEAT FLOW IN NEW ENGLAND

<u>LOCATION</u>	<u>Heat Flow</u>	
	<u>Microcal/cm² sec.</u> <u>Topographic</u> <u>Corrected</u>	<u>Geologic</u> <u>Corrected</u>
Blue Hill, ME	1.44	1.30
Casco, ME	1.80	1.63
Brewster, MA	1.16	1.29
Cambridge, MA	1.20	1.20
Chelmsford, MA	1.63	1.48
Millers Falls, MA	1.67	1.51
Bradford, NH	1.59	1.44
Concord, NH	1.73	1.57
Durham, NH	1.08	0.98
Fitzwilliam, NH	1.63	1.48
Kancamagus, NH	2.27	2.13
North Conway, NH	1.89	1.95
North Haverhill, NH	1.34	1.21
Waterville, NH	2.15	2.21

From Birch et al., 1968

FIGURE 7: Heat flow in New England

The net effects of varying rates of sedimentation, intensity of metamorphism and the depths of emplacement of plutonic rocks (15 km for the New Hampshire Series versus 6 km for the Conway Granite) and erosion rates have altered the normal heat flow regime such that corrections have to be applied. However the magnitude of the "geological" corrections is not great (Table 1).

The correction for erosion effects are best applied to sites in New Hampshire, namely Bradford, Concord, Fitzwilliam and also Chelmsford, Massachusetts and Casco, Maine, all of which lie within the belt of deep Paleozoic sedimentation. Less certain is the application of erosion-rate correction at Blue Hill, Maine, North Haverhill and Durham, New Hampshire, and Millers Falls, Massachusetts. However, for the above Birch et al. (1968) have calculated a mean geothermal gradient of $18.3^{\circ}\text{C}/\text{km}$ from averaged measured gradients with a mean value of $20.2^{\circ}\text{C}/\text{km}$ thus providing a reduction of 9.4% in the topographically corrected values for heat flow. For the heat flow values calculated for the sites in the White Mountain Magma Series (North Conway, Kancamagus and Waterville, New Hampshire) a correction factor of $1.6^{\circ}/\text{km}$ was subtracted from the gradients. The same correction factor has been applied to the gradients measured at the three sites in Precambrian rocks in Vermont. In the case of the site at Brewster, Massachusetts on Cape Cod, a 10% upward correction was applied to take into consideration the deposition of about 100 meters of sand following the retreat of the Pleistocene glaciers.

M. P. Billings (1964) prepared a map (unpublished) in which he contoured "equivalent uranium" (eU) for Maine, New Hampshire and Vermont. The quantity eU was used to show the gamma activity from uranium, thorium and potassium in terms of the amount of uranium and daughter products in

equilibrium required to produce the same effect. Although the formula used by Billings ($eU_{\text{gamma}} = U + 0.48\text{Th} + 3K$; U and Th in ppm, K in percent) is different from that to calculate equivalent uranium for heat generation ($eU_{\text{thermal}} = U + 0.27\text{Th} + 0.37K$), eU_{gamma} is roughly proportional to A, the rate of heat generation per cm^3 . Therefore a correlation between heat flow (Q) and A also provides a correlation between heat flow and eU. Birch et al. (1968) noted a strong correlation between heat flow values and eU contours of Billings and concluded that contours of bedrock eU can be converted to heat flow contours with errors on the order of $0.2 \text{ microcal/cm}^2 \text{ sec}$ for the region.

Heat flow values for the Precambrian anorthosite in the Adirondack Mountains of New York average $0.8 \text{ microcal/cm}^2 \text{ sec}$ and this value is attributed to be the contribution of the lower crust and mantle to the flux. Subtracting that amount from the calculated heat flow in the Conway Granite leaves $1.2 \text{ microcal/cm}^2 \text{ sec}$ to be supplied by radioactive decay in the granite. Assuming even distribution of radioactive elements in the granite, Billings et al. (1968) calculate upper limit of the thickness of the Conway Granite to be 6 km, which is reasonable agreement with an estimate of 4.5 km thickness required to explain the gravity low (Joyner, 1963).

New England Ground Water Resources

Most of the ground water resources in New England lie in the region defined by the U. S. Water Resources council as the Glaciated Appalachians region, the exception being Nantucket, Martha's Vineyard and Cape Cod which lie in the Coastal Plain ground water region. In the region aver-

age annual temperature ranges from 3.3°C (38°F) in northern Maine to 10°C (50°F) in Connecticut, Rhode Island and southeastern Massachusetts. The annual average precipitation ranges from 1000 mm (40 in.) in the north to 1140 mm (45 in.) in the south. By 1975 ground water constituted twenty-three percent of the total fresh water withdrawals in the nation. In New England ground water contributed twelve percent of the total fresh water withdrawals.

Most of the New England region is underlain by impermeable crystalline rocks from which small amounts of ground water are retrieved for domestic and livestock supplies from fracture zones. Sedimentary rocks in the region consist of carbonate and clastic sequences. The carbonate rocks, consisting of limestone, dolomite and calcareous shales, occur in the Hoosatic River Valley in western Massachusetts and Connecticut and in the Aroostock Valley in northern Maine. Wells drilled in carbonate rocks can produce substantial ground water supplies if large solution openings are penetrated in the zone of saturation. The non-carbonate sedimentary rocks are mostly confined to the Connecticut River Valley lowland and consist of shale, sandstone, arkose, conglomerate and interbedded basalts. The sedimentary rocks yield small to moderate supplies, some wells providing as much as 19L/s (300 gal/min).

In parts of New England low grade metamorphosed sedimentary rocks yield small to moderate supplies of water. Rocks of this type, consisting of metaconglomerate, argillite, phyllite, slate and marble, occur widely in Maine, in western Massachusetts and western Connecticut, northwest of Boston, and in the Boston and Narragansett Basins of eastern and southeastern Massachusetts and southeastern Rhode Island. In a few places supplies up to 32L/s (500 gal/min) are obtained from strongly frac-

tured zones.

The most productive sources of ground water in New England are unconsolidated sediments, which consist of glacial and glaciofluvial deposits and the reworked glacial deposits in present day river and stream valleys, termed watercourse aquifers. Thomas (1952) defines watercourses as hydrologic units that include both surface water of a river channel and the ground water in the alluvium that forms the flood plain. The glacial deposits in New England consist mostly of stratified drift (sand and gravel) with moderate to high permeability. The watercourse aquifers provide the highest yields of ground water with some individual wells yielding up to 125L/s (2000 gal/min) due to hydraulic continuity between the river and surrounding porous and permeable glacial outwash that underlies the flood plain. With the retreat of the glacial ice front northward at the close of Pleistocene time large volumes of melt water produced deep river channels, which were later filled with alluvium. With the reduction in discharge and subsequent land uplift that accompanied the glacial retreat, many of these river courses have been greatly reduced in size and some completely abandoned, and remain today as deep valleys filled with alluvium. They have an extent, thickness and permeability far greater than present streams could possibly produce, and some no longer form any part of the present drainage system. However, the opportunity for recharge may, in many cases, be limited to direct infiltration from precipitation and the perennial yield is likely to be less than that of the watercourse aquifers.

The contribution of ground water to the total discharge of a river is the base flow. The mean stream flow (Sinnott, 1982) for the New England Region has been determined to be about $258 \times 10^2 \text{ m}^3/\text{d}$

$(68 \times 10^9 \text{ gal/d})$. Using a conservative estimate of a base flow of forty percent of the mean stream flow of the entire region the average total yield of groundwater to discharge is about $102 \times 10^{23} \text{ m}^3/\text{d}$ ($27 \times 10^9 \text{ gal/d}$). The large volume of lateral discharge of ground water in glacial till and alluvium that mantles all of New England therefore will in most cases dilute and mask any heated water that might be discharged at the bedrock surface.

Use of Ground water as an Energy Source

Technology Property Associates (TPA) of Burlington, Massachusetts, has constructed an office building that uses ground water for both heating and cooling purposes as a backup for the primary solar energy system. The system is maintained and operated by Aerospace Systems, Incorporated which states that although the system was designed as a backup, the water-to-water heat pump is able to extract 3 1/2 times more useable energy from water than an electrical resistance heating element could produce, and could be the primary energy source in a properly designed building in New England.

The extraction of energy from water courses has been proposed for the City of Stamford, Connecticut, through which the Rippowan River flows. The proposer, Wormser Scientific Corporation of Stamford, notes that the ground water conditions in Stamford are well known as the result of over 500 borings taken in conjunction with planning and construction of a 130 acre urban renewal project and the earlier construction of Interstate Highway I-95.

Two main shallow aquifers traverse Stamford in a N-S direction and one of these is rated as being capable of supplying 2.8 million gallons

per day on average for consumptive use, i.e., without any return of the water to the aquifer. The water temperature varies between 10°C (50°F) and 11°C (52°F) annually. The proposer (personal communication, Wormser Scientific Corporation) plans to extract water from the aquifer to cool structures and return this water, now warmer by 5° to 8°C by their calculations, to the aquifer at a different location. It is this system that currently is in use in the TPA structure. They state that the direct distribution aquifer cooling system uses about 10% of the electrical energy requirements needed to operate a conventional air conditioning cooling system. Heat pumps in the heating mode extract heat from ground water at 10°C and amplify it using a compression refrigeration cycle to around 37°C (100°F) for heating purposes. The reinjected water will be cooled to around 5°C , but the amount of water removed and reinjected into the aquifer will be a small fraction of the total volume available.

The very large volume of ground water available in New England makes this resource a potential source of energy using water interface heat pumps.

Thermal Springs in New England

Seepage springs are abundant in New England, especially at the contact of glacial till and bedrock. There are some springs, however, that are fracture controlled and apparently circulate meteoric water to sufficient depth to become heated by the normal geothermal gradient.

A search of the literature, particularly that of the nineteenth century, was conducted to establish the existence of any possibly warm

springs. In a report on the geology of Vermont, Adams (1848) makes note of Morgan Spring in the center of Bennington as possibly being a warm spring. Stearns et al. (1937) report that the spring was listed again in 1934 as a thermal spring with a temperature of 11.7°C (53°F) which is 4°C above the mean annual temperature. The spring is not listed by Waring (1965) nor Berry et al. (1980) and a visit to the area failed to locate the spring.

Daubney (1839) reported another slightly warm spring at Cannan, Vermont, but no subsequent listing could be found, nor could the spring be located.

Hitchcock (1861, p. 174) in a report on the geology of Vermont noted a number of springs producing calcareous deposits. When visited these proved to be normal ground water springs in a carbonate terraine.

Lebanon Springs - Sand Springs Area of New York and Massachusetts

Both Lebanon Spring in eastern New York and Sand Spring in Williamstown, Massachusetts have somewhat elevated temperatures that have been utilized for a number of purposes over the past decades. Lebanon Spring is located in the northwest corner of the Pittsfield west 7 1/2 quadrangle and lies about 17 miles south-southeast of Sand Springs.

At Lebanon Spring a 400 room hotel named Columbia Hall was built in 1794. The structure was removed in 1928 ironically because of the high cost of conventional heating. The Rutland Railroad laid a mile long pipe line from the spring in 1906 for recharging locomotive boilers. After abandonment of the railroad about thirty local families tied into the line and use the warm waters for domestic purposes. At the present time

there is no use of the spring waters related to elevated temperature.

Sand Spring has been in use since pre-Colonial times. Carlin (1972) states that the spring was used by area Indian tribes as a landmark and campground for hunting and war parties, lying near the intersection of a north-south trail and the Mohawk Trail. A health spa, Graylock Hall, containing 26 large baths and 6 sunken bathing pools was built in the 1880's. A bottling works was added in 1893 and ceased production in 1972.

The most recent geological study of the Lebanon and Sand Springs by Dunn Geoscience Corporation for New York State Energy Research and Development Authority (1981) states that the thermal waters issue from Cambro-Ordovician rocks involved in the thrust belt of western New England and eastern New York. They interpret the elevated water temperatures to be the result of deep ground water circulation along permeable zones created along thrust fault planes. In the case of Lebanon Springs, Cambrian age phyllites have been thrust westward over Ordovician dolomite, and the dolomite has been as a result tensionally fractured to provide permeability (Fig. 8). Since the geothermal gradients in the area do not appear to be high it is estimated that water circulation to about 1 km depth could account for the 22°C (72°F) measured at Lebanon Spring.

The thermal springs at Williamstown, Massachusetts, may occur in a slightly different geologic setting. The springs occur at three locations; each location forming the apices of a triangle approximately one mile distant from each other. Unfortunately the detailed bedrock geology is obscured by surficial materials at the point of issue for each spring. At Sand Spring itself the thermal water with a temperature of 24°C (76°F) flow may be along the contact of Cambrian quartzite thrust over Ordovician limestone (Fig. 8). The remaining two springs appear to issue from a

FIGURE 8: Geological cross sections in western Massachusetts. Section locations shown on Figure 9B. Section A-A' shows the warm springs at Williamstown, MA, are associated with high angle reverse faults involving the Cambro-Ordovician Stockbridge group (OCs) and the Cambrian Cheshire formation (Cc). Section B-B' shows the Lebanon Springs emerging at the contact of the Ordovician Wallomsac formation (Ow) and the Stockbridge group after ascending on the thrust fault about 1000' to the southeast. (Modified from NYSERDA Report 81-4 prepared by Dunn Geoscience Corporation).

fault zone within the Ordovician dolomite. The water temperatures were recorded as 19.5°C (67°F) for the northern and 20°C (68°F) for the southern spring. Since the geothermal gradients in the vicinity of Williams-town are not elevated it would appear that deep circulation of ground water is the source of the heated waters.

Hansen et al. (1974) have analyzed the waters from wells at Sand Springs (Table 2). The warm waters are represented by analyses S'2, S'2a and S'8. It is obvious that there exists a direct correlation between temperature and SiO_2 content, suggesting that the waters of Sand Spring probably attain a higher temperature at depth. The flow rate at the springs is approximately 24,000 gallons per hour (Waring, 1965).

The New York State Energy Research and Development Authority report (1981) prepared by Dunn Geoscience Corporation gives the results of a survey of water chemistry, temperature and measured gradients, which included a portion of western Massachusetts and southwestern Vermont. The silica contents and measured water temperatures at the surface are given in Table 3, and locations on Figure 9.

The feasibility of utilizing the thermal waters of Sand Spring for domestic heating purposes appear to be good. The water quality is excellent; the water temperature is approximately 14°C above that of normal ground water and the flow rate (400 gal/min) more than adequate.

Some geothermal gradients in western Massachusetts and southwestern Vermont are abnormally high and increase into eastern New York. The background geothermal gradient appears to fall in the range of $5 - 7^{\circ}\text{C/km}$. The abnormally high gradients (Figure 9, Table 4) form a north-northeast trending zone extending from Lebanon Springs New York to the vicinity of Pownal, Vermont, and range up to four times the

TABLE 2CHEMICAL ANALYSES OF SPRINGS IN WILLIAMSTOWN, MASSACHUSETTS

Local Well #	S2	S2a	S3	S6	S7	S8	S9
Temp. °C	21.0	22.0	11.0	8.1	22.0	17.8	8.9
SiO ₂ (mg/l)	13.0	12.0	0.5	4.2	12.0	7.2	0.6
Fe (ug/l)	20.0	20.0	10.0	--	20.0	20.0	10.0
Mn (ug/l)	0	0	0	--	0	0	0
Ca (mg/l)	21.0	23.0	24.0	18.0	25.0	46.0	36.0
Mg (mg/l)	11.0	8.8	4.2	3.0	8.9	11.0	11.0
Na (mg/l)	3.3	2.0	1.3	0.3	2.0	1.9	1.9
K (mg/l)	1.3	0.9	0.2	0.1	0.9	0.6	0.8
HCO ₃ (mg/l)	116.0	118.0	84.0	68.0	114.0	177.0	154.0
CO ₃ (mg/l)	0	0	0	0	0	0	0
SO ₄ (mg/l)	8.6	8.1	7.5	6.0	8.1	11.0	6.5
Cl (mg/l)	2.0	1.0	0.4	0.1	1.3	0.8	0.6
F (mg/l)	0.1	0.1	0.2	0.0	0.1	0.1	0.2
NO ₃ (mg/l)	0.4	1.0	1.0	4.2	0.4	0.7	1.1
pH	8.2	7.8	7.7	7.7	8.1	8.0	8.1

From Hansen et al., 1974

FIGURE 9: a) Geothermal gradients ($^{\circ}\text{C}/\text{km}$) in western Massachusetts, New York and Vermont. Communities shown are: B = Burlington, VT., PO = Pownal, VT., W = Williamstown, MA, P = Pittsfield, MA, and LS = Lebanon Springs, NY.

b) Location of wells listed in Table 3. The cross-sections in Figure 8 are located near Williamstown (A-A') and Lebanon Springs (B-B'). (Modified from NYSERDA Report 81-4 prepared by Dunn Geoscience Corporation.)

TABLE 3SILICA CONTENTS AND WATER TEMPERATURESWestern Massachusetts and S. W. Vermont

<u>Sample Number</u>	<u>NAME</u>	<u>Silica ppm</u>	<u>T(°C)</u>	<u>LOCATION</u>
<u>MASSACHUSETTS:</u>				
1	Shyffer	5.9	7.2	Deerhill Rd., Richmond, MA.
2	Leab	5.6	11.9	Rt. 43, Hancock, MA.
3	Monette	5.7	11.8	Rt. 43, Hancock, MA.
4	Fenander	5.3		Rt. 43, Hancock, MA.
5	Locke	6.1	8.3	Oblong Road, Williamstown, MA.
6	Greylock H. S.	6.7		Williamstown, MA.
7	Mt. Hope Farm	6.3		Williamstown, MA.
8	Rhodes	5.5		Hancock Road, Williamstown, MA.
9	White	6.1		Oblong Road, Williamstown, MA.
10	Jericho Valley Motel	5.2		Rt. 43, Hancock, MA.
11	Hamilton	4.2		Hancock, MA.
<u>VERMONT:</u>				
12	Sheldon	6.5	10.3	Rt. 396, NY/VT border
13	Gen. Cable	9.2		Rt. 396, N. Pownal, VT.

TABLE 4
TEMPERATURE GRADIENTS

Eastern New York and Adjacent Vermont and Massachusetts

<u>LOCATION</u>	<u>DEPTH (METERS)</u>	<u>GRADIENT (°C/km)</u>
Pownal, VT.	220	23.63
Hancock, MA.	140	14.82
Hancock, MA.	155	17.03
Rt. 43 & Rt. 22, Stephentown, N. Y.	145	14.72
Stephentown Center, N. Y.	185	21.60
Rt. 43, Hancock, MA.	130	18.36
Wyomack Road, South Stephentown, N. Y.	160	24.68
West Road, Lebanon Springs, N. Y.	80	10.83
Saltbox Farm Road, Hancock, MA.	190	7.72
Bailey Road, Hancock, MA.	260	9.06
Bailey Road, Hancock, MA.	125	6.73
Churchill Road, Pittsfield, MA.	160	7.01
Off Rt. 22, Stephentown, N. Y.	80	12.40
Vt. Route 9, Bennington, VT.	105	3.86
West Road, West Richmond, MA.	185	7.95

apparent normal gradient (from 6.7 to 23.6° C/km.). However no additional thermal springs and no wells pumping heated waters have been located.

New England Water Well Temperatures

Since most of the consumptive water supplies in New England are derived from surface storage reservoirs and the bulk of the ground water contribution to that supply is derived from unconsolidated glacial sediments, only a small fraction comes from wells driven to bedrock. Although the rocks of the region are highly fractured and faulted, water wells intersect only a minute fraction of these structures and therefore provide a very small sampling of the fluids possibly circulating within them.

Water temperatures from bedrock wells range from 6°C (41°F) at Presque Isle, Maine from a 94m (310') well to 19°C (67°F) at Somerset, Massachusetts, from a 457m (1500') well (Table 5). Most water temperatures fall below 13°C (55°F) and in Massachusetts, which contains the largest number of drilled wells, the average temperature is 11.4°C (Table 6).

Specific Regions of Initial Interest

Based upon geological and geophysical studies certain areas in New England were considered to have the highest potential for the possible existence of hydrothermal geothermal resources. These included the White Mountains region of central New Hampshire, the Narragansett Basin of Massachusetts and Rhode Island, the Connecticut River Valley extending from Connecticut north into Vermont, and the overthrust belt of western Massa-

TABLE 5
Partial Chemical Analyses in ppm of
Waters from Selected Wells in New England Bedrock

<u>Location</u>	<u>Depth (m)</u>	<u>Source Rock</u>	<u>T(°C)</u>	<u>SiO₂</u>	<u>Ca</u>	<u>Mg</u>	<u>Na</u>	<u>K</u>
<u>MASSACHUSETTS:</u>								
Abington	15	Gneiss	7.2	9.6	12	3.3	8.8	1.2
Brockton	31	Gneiss	7.8	11	22	5.3	4.9	.6
Duxbury	33	Gneiss	8.9	5.3	8.4	2.0	4.1	1.4
E. Bridgewater	25	Gneiss	11.1	17	16	8.4	8.3	1.0
Taunton	64	Argillite	11.7	24	15	2.5	14.0	1.1
Mattapoisett	7	Argillite	9.4	25	37	9.1	11.0	3.7
Lynnfield	180	Schist	7.8	17	14	5.0	7.3	1.2
Wilmington	125	Schist	9.5	11	23	5.8	13.1	1.9
Middleborough	7	?	9.4	11	3.2	2.0	5.8	.5
Adams	146	Quartzite	10.8	17	6.6	1.4	1.1	.3
Windsor	45	Gneiss	9.7	13	16	6.2	5.3	.7
Charlemont	77	Gneiss	9.4	15	9	5.7	4.2	.4
Goshen	32	Gneiss	9.5	12	10	6.8	5.0	.6
Bernardston	?	Gneiss	9.8	17	13	7.2	6.1	1.1
Hardwick	61	Gneiss	10.1	21	11	6.2	7.3	.9
Belchertown	56	Gneiss	10.6	18	14	5.2	4.1	.6
Easthampton	143	Triassic	12.3	21	29	2.6	4.2	.5
Florence	92	Triassic	11.9	25	31	4.3	3.0	.5
Hatfield	?	Triassic	12.6	31	27	5.2	4.6	.7
Barre	?	Gneiss	10.1	14	7	5.8	3.6	1.1
Boxford	?	Gneiss	10.0	8	17	4.8	8.0	1.8
Georgetown	?	Gneiss	10.0	15	22	9.0	14.0	1.5
Newbury	37	Gneiss	11.1	13	13	4.4	59.0	2.2
Egermont	30	Limestone	10.0	6.9	0.2	0.1	103.0	0.2
Washington	15	Gneiss	13.3	12	22	7.4	2.5	4.9
Williamstown	113	Limestone	8.9	6.6	23	13	1.1	0.7
Gill	40	Sandstone	13.3	11.0	24	15	4.3	1.1
Chicopee	34	Shale	12.8	15.	96	19	18	1.5

<u>Location</u>	<u>Depth (m)</u>	<u>Source Rock</u>	<u>T(°C)</u>	<u>SiO₂</u>	<u>Ca</u>	<u>Mg</u>	<u>Na</u>	<u>K</u>
<u>CONNECTICUT:</u>								
Granby	100	Triassic	12	12	8.1	1.1	39.0	.6
Simsbury	91	Gneiss	10.5	12	8.5	1.9	2.1	.6
Avon	31	Triassic	12.2	13	19	1.8	3.5	.4
Avon	26.5	Gneiss	10.4	10	5.7	1.6	2.2	.4
Framingham		Triassic	12.8	24	26	9.3	6.0	.5
Framingham	132	Triassic	10.5	16	17	1.3	20.0	.8
Framingham	107	Triassic	12.2	13	31	5.3	3.7	.6
Bristol	46	Gneiss	11.6	27	17	7.8	6.7	1.4
Southington	130	Triassic	10	24	35	3.6	5.5	3.6
Plainville	67	Triassic	12.8	20	31	7.9	4.6	1.4
Bloomfield	185	Triassic	11	17	28	15	7.8	1.1
Glastonbury	76	Gneiss	12.8	15	6.3	1.3	3.6	1.7
Manchester	183	Triassic	12.8	14	27	10	2.3	.8
Portland	36	Gneiss	11.	12	33	5.3	9.1	1.9
<u>MAINE:</u>								
Presque Isle	94	Limestone	6	8.5	7.4	14	6.0	.5
Raymond	181	Granite	6.5	16	27	4.6	8.4	.6
Vassalboro	76	Schist	10.5	13	29	9.7	3.5	3.6
Charlestown	72	Schist	9.8	8.4	26	9.5	-	-
Newport	37	Limestone	9.8	8.5	73	7.0	2.3	.5
Monson	96	Slate	9.6	-	4.8	1.6	3.7	1.4
Bucks Harbor	52	Rhyolite	10.7	14	35	3.8	-	-
North Berwick	84	Schist	9.8	13	23	3.1	8.2	3.1
<u>VERMONT:</u>								
Bennington	42	Gneiss	9.7	14	8.2	5.3	6.9	.7
West Dover	26	Gneiss	9.9	16	13	9.6	4.4	.5
Newfane	35	Gneiss	8.9	11	21	5.1	3.9	.6
Chester	14	Serpentine	8.3	13	7	14.2	2.1	.4
Danby	21	Marble	9.4	9	29	13.	3.4	.8
Ludlow	11	Schist	9.1	14	11	6.2	4.5	1.2
Hartland	13	Schist	9.2	15	17	8.1	3.1	.6
Rutland	22	Schist	9.4	17	19	7.2	4.7	1
Pittsfield	15	Gneiss(?)	10.6	19	11	7.9	6.3	.8
Barre	22	Granite	7.8	21	9	4.7	7.2	3.1

TABLE 6

Water Temperatures from Selected Bedrock Wells of Massachusetts

<u>LOCATION</u>	<u>DEPTH (m)</u>	<u>TEMPERATURE (°C)</u>
<u>Western Massachusetts:</u>		
Dalton	194	7.8
Dalton	156	10
Dalton	58	10
Great Barrington	156	10.6
Lee	196	10
New Marlborough	9	7.2
Pittsfield	193	7.8
Stockbridge	75	9.4
Williamstown	152	12.8
Williamstown	113	8.9
Greenfield	47	9.4
Chicopee	138	8.9
Chicopee	155	13.3
Chicopee	246	13.9
Chicopee	215	9.4
Springfield	160	9.5
Springfield	105	10
<u>Southeastern Massachusetts:</u>		
Acushnet	30	14.4
Easton	64	12.8
New Bedford	7	10
New Bedford	15	15.6
New Bedford	12	10.1
New Bedford	4	12.2
North Attleboro	152	12.2
North Attleboro	105	7.2
Rehoboth	30	13.3

<u>LOCATION</u>	<u>DEPTH (m)</u>	<u>TEMPERATURE (°C)</u>
Rehoboth	35	11.1
Rehoboth	34	12.2
Rehoboth	49	13.3
Rehoboth	93	10.6
Rehoboth	12	13.4
Seekonk	40	13.8
Swansea	60	13.9
Swansea	29	12.6
Somerset	457	17
Somerset	305	19
Taunton	154	13.7
Taunton	19	12.1
Taunton	154	12.2
Taunton	64	12.0

Northeastern Massachusetts:

Boxford	56	11.0
Chelmsford	22	12.2
Dracut	53	12.3
Lowell	46	12.7
Newbury	59	9.3
Newbury	37	11.2

chusetts and Vermont. While no potential resource can be postulated for any of these regions as a result of this study a discussion of each is given herein to explain their selection.

The White Mountain Region

There has been much speculation over the past few years concerning the possibility of there being moderately high temperatures at depth within certain plutons that are a part of the White Mountain Magma Series. The relatively young plutons range in age from 110 to 182 m.y. (Tilton and Davis, 1951; Folard, 1970). Billings and his students (Billings, 1928; Billings and Williams, 1935; Henderson, 1949; Moke, 1946; Smith and others, 1940) delineated eight plutonic rocks of differing composition, which are considered to be consanguineous. Billings (1945) concluded that the intrusives were emplaced by cauldron subsidence and stoping. Geophysical studies on the Merrymaking stock in New Hampshire (Griscom and Bromery, 1968) support the suggestion of Chapman (1968) that the plutons represent cumulates and that they crystallized as flooded intrusions with mafic rocks at depth.

The White Mountain Magma Series is composed of a group of plutonic and volcanic rocks that range in composition from gabbro to syenite. Of these, biotite granites near Conway and Waterville, New Hampshire, give the highest heat flow values (1.95 to 2.21 HFU - see Figure 7) of any so far determined in New England. The high heat flow is attributed by Birch et al. (1968) to the abnormally high concentrations of uranium, thorium and potassium contained in the granites. Osberg et al. (1978) have determined that the concentration of radioactive elements is fixed in allanite, huttonite, thorite and zircon, and dispersed in biotite, feld-

spar and quartz.

Birch et al. (1968), apparently using simple assumptions about the shape of the plutons and the distribution of the radioactive elements, calculated that the surface heat flow could be generated in plutons 6 to 10 km thick and would reach temperatures of 150° to 200°C at depths of between 4 and 5 km. Osberg et al. (1978) concluded from detailed gravity studies that the Conway granite is between 4 and 5.25 km thick. They further conclude from temperature modeling that the high heat flow which Birch et al. (1968) attributed to being derived primarily from concentrations of radioactive elements in the granites is open to question. Osberg contoured the heat flow values and suggests the existence of a north northeast trending ridge of high surface heat flow which he interprets to represent a "bump" in background heat flow. He suggests that the heat flow entering the crust at 10 km depth is larger (1.3 HFU) than elsewhere in New England (the 0.8 HFU value of Birch). Using the higher value for heat entering the upper crust they derived a temperature distribution model giving temperatures of 76° to 110°C at 5 km and 93° to 135°C at 5.25 km.

The Osberg study therefore suggests only minor temperature increases within and beneath the Conway and related granites. Field observations and literature search of the region yield no evidence of any springs or ground waters of even slightly elevated temperatures. Thus it appears unlikely that there is any potential for low temperature hydrothermal geothermal resources associated with the plutons of the White Mountain Magma Series.

The Narragansett Basin

Lyons and Chase (1976) report that the carboniferous rocks of the

Narragansett Basin (Figure 2, Plate I) are predominantly conglomerate, arkose, graywacke, siltstone and shale with some coal. Only rough estimates of the total thickness of the sedimentary sequence are possible due to the scarcity of outcrop, rapid facies changes and structural complexities. The thickness probably lies between 2000 and 12000 feet. Mutch (1968) concluded that the region was an isolated inter-montane basin characterized by rapid deposition of various types of fluvatile sediments. He also believes the total thickness of the sequence to be close to 12000 feet. The more pelitic sediments have been metamorphosed to slate and phyllite and the metamorphic grade increases southward to staurolite grade in parts of southern Rhode Island. The sedimentary rocks are highly indurated and the permeability quite low. Frimpter and Maevsky (1979) report that in many core samples from test borings healed and unhealed fractures and slickenside surfaces were common, indicating that these rocks had undergone brittle deformation. Where the fractures are open ground water occurs under pressure, but yields are low. During 1977 the U.S.G.S. conducted pump tests on twelve observation wells and yields ranged from 0.36 to 30 gal/min with very slow recovery after pumping was stopped in all but one case. Four wells yielded water with temperatures above the normal 10 - 11°C ground water temperatures in the Basin. Two wells at Bristol, Rhode Island, both yielded water with the temperature at 15°C (59°F), and the water remained salty throughout the pump test. Two wells at Somerset, Massachusetts, one 1000 feet and the other 1500 feet deep, gave very low yields of water at 17°C (63°F) and 19°C (67°F) respectively. The deeper well is located about 100 feet from the shore of Narragansett Bay and the specific conductance of the water rose from 510 to 880 during a three hour pump test indicating salt water inflow into

the well. The elevated temperatures in the Somerset wells are probably caused by inflow of discharge from the nearby Brayton Point New England Power plant.

The Connecticut Valley

The present day Connecticut Valley is a topographic low developed by the erosion of Mesozoic age detrital sedimentary rocks. Geologically it is an asymmetrical structural trough or elongate basin that is fault-bounded on the eastern margin (Fig. 10). The development of the trough was controlled by physical differences in the underlying Paleozoic metamorphic rocks. The north-south trend follows zones of weakness defined by the low grade metamorphic rocks of the Connecticut Valley-Gaspé synclinorium, which separate the zones of mantled gneiss domes of the Berkshires to the west from the domes of the Bronson Hill Anticlinorium to the east. The geometry of the edges of the basin is influenced by local basement structures, especially the dipping flanks of the domes.

The Mesozoic age basin is divided into two sub-basins to the north and south of Amherst, Massachusetts. The northern portion, known as the Deerfield Basin, contains less than 1 km of detrital sediments and volcanics. The southern and more extensive part of the structural feature is known as the Hartford Basin, which extends south from Amherst to Long Island Sound. The thickness of Mesozoic age rocks exceeds 4 km under Springfield, Massachusetts. The two basins are separated as the result of a large intrusion of tonalite of Devonian age (the Belchertown Complex) that cuts across the rocks of the Connecticut Valley-Gaspé Synclinorium and into the west flank of the Bronson Hill Anticlinorium thus disrupting the north-south zones of structural weakness between the two

FIGURE 10: The Mesozoic Basin of the Connecticut River Valley is fault controlled on the eastern margin, and divided into two sub-basins separated by the Devonian age Belchertown intrusive complex (BC). Cities located are Amherst (A) and Springfield (S), Massachusetts and Hartford (H) and New Haven (NH), Connecticut. The western edge of the basin is an erosional contact denoted by the double-dotted line.

belts. Subsidence of the two basins was greatest on the eastern side along a westerly dipping listric fault system so the general dip of the Mesozoic rocks is to the east.

Wise (1979) and his students have been conducting detailed studies of the structures related to the basins and a number of patterns have emerged. They show that a trend of N30-40°E extensional structures dominates the region, especially within and east of the basins. These structures are represented by basalt dikes, veins, joint sets and normal faults. They conclude that much of the eastern border fault zone of the basins is composed of segments of faults of this type. In areas where the trend of the basin parallels the structural N30-40E trend the movement on the faults is dip slip, the trend is interpreted as being the regional extension direction during the early to middle stages of basin formation. Late stage movements on the faults controlling the basin appear to be of a strike-slip nature as indicated by slickensides on the fracture and fault planes.

Portions of the Belchertown intrusive complex contain an unusual amount of allanite, a member of the epidote group containing up to 3% thorium and rare earths. It was thought that the heat provided by radioactive element decay might be trapped by the overlying Triassic-Jurassic sedimentary rocks and provide a heat source for any deep circulating waters. Unfortunately the distribution of allanite is quite sporadic, and the principal concentration is found in that part of the complex which lies on the west side of the structural basin and is covered by only a thin veneer of sedimentary rocks. There are no known water wells in the area which penetrate into bedrock, since most of the valley region between the exposures of the complex to the east and west is man-

bled by a thick cover of glacial sediments.

The faults that bound the basin on the east side of the Connecticut River Valley are thoroughly cemented, show no evidence of any movement in historic time and are aseismic. Wells that do penetrate into the Triassic-Jurassic rocks show no evidence of elevated temperatures (see Table 5). One well, in Hadley, Massachusetts, was reported (Gruy Federal, personal communication) to be 250 feet deep and yielding water at 15.6°C (60°), but attempts to locate the well failed. This well, and all wells in Hadley, would overlie the buried Belchertown complex but are completed in glacial sediment. All town wells are 70 feet deep or less and do not exceed 11°C (52°F).

The St. Johnsbury Thermal Anomaly

During the course of field investigation an unusual thermal anomaly was discovered in the town of St. Johnsbury in northeastern Vermont.

The town is underlain by Siluro-Devonian schists which are mantled with thick ice-contact glacial sediments forming broad terraces. The owner of the residence at 115 Main Street reported a small roughly circular area of about 15 feet diameter next to the house upon which snow would melt and only moss would grow, and further that this occurrence had been noted in diaries of former occupants in the 19th century.

During April and May, 1981, several visits to the site were made, and a series of auger holes drilled to lengths up to 8 feet. A probe recorded temperatures varying from 96°F to 105°F . The material in which the holes were drilled is a clean, dry sand. The following is an

exerpt from a letter dated June 28, 1981 from the property owner.

"In the afternoon I noticed again what I have noticed in the past, a slight gassy smell coming from the hole. Thinking it might be swamp gas in small quantity I eventually decided to try lighting it with a match, so at 5:15 p.m. I did so, and the hole burst into flame and kept on burning. Since there are now five holes in the hot area, I tried them all with matches and all burst into flame, though none as powerfully as the new hole. I should have done this last summer for I recall the gassy smell when I dug a hole with a shovel in the hot area."

The local utilities company has no record of any gas line in the area.

The source of the gas and the heat remains unexplained.

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GEO THERMAL ASSESSMENT
OF THE
NEW ENGLAND STATES

PLATE I

GEO THERMAL ASSESSMENT OF THE NEW ENGLAND STATES

PLATE II

GEO THERMAL ASSES SMENT
OF THE
NEW ENGLAND STATES

PLATE III

GEOHERMAL ASSESMENT
OF THE
NEW ENGLAND STATES

PLATE IV

MAGNETICS
MAGNETIC ANOMALIES IN GAMMAS
CONTOUR INTERVAL 400 GAMMAS